SAND2015-8244R

APPENDIX E

FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	Deep Borehole Field Test Specifications/M2FT-15SN0817091
Work Package Title and Number	FT-15SN081709 Borehole Test Design - SNL
Work Package WBS Number	1.02.08.17
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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

Bruce Kirstein Bruce Kirstein (Rev 1, 9/22/15)

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 Specifications

Fuel Cycle Research & Development

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

Sandia National Laboratories
Albuquerque, New Mexico
September, 2015
FCRD-UFD-2015-000132 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	Technical Review and Sandia programmatic review (Tracking Number 342077) of several typographical corrections, and changes to off-normal cost data in Appendix C, which affect Appendix D and tables in Sections 5 and 6.

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Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

ALARA	As low as reasonably achievable
API	American Petroleum Institute
bbl	Oil barrel, equal to 42 U.S. gallons
BOP	Blowout preventer
BWR	Boiling water reactor
CB	Characterization Borehole
CFR	Code of Federal Regulations
DBD	Deep borehole disposal
DBFT	Deep Borehole Field Test
DOE	U.S. Department of Energy
DZ	Disposal zone
EZ	Emplacement zone (see DZ)
FoS	Factor of safety
FTB	Field Test Borehole
HEPA	High efficiency particulate arrestance
ID	Inner diameter
ISMS	Integrated Safety Management System
HLW	High-level waste
LLW	Low-level waste
MUA	Multi-attribute utility analysis
NEPA	National Environmental Policy Act
OD	Outer diameter
PWR	Pressurized water reactors
QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
RD&D	Research, Development and Demonstration
RFP	Request for Proposals
ROM	Rough order of magnitude
SFT	Spent Fuel Test
SNL	Sandia National Laboratories
SOP	Standard operating procedures
TBD	To be determined
TD	Total depth
WCS	Waste Control Specialists
WM	Waste management
WP	Waste package

Acknowledgments

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

1. Introduction

1.1 Purpose and Scope for This Report

This report documents conceptual design development for the Deep Borehole Field Test (DBFT), mainly the test packages (not containing waste) and the system for demonstrating emplacement and retrieval of those packages in the 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 describes a current reference DBD concept, and analyzes key design options for disposal, to guide selection of options for the DBFT. The most important of these options is the emplacement mode, i.e. whether packages are emplaced using a wireline or a string of drill pipe (with a drill rig). This choice is analyzed using cost and risk models, in Sections 5 and 6. Other emplacement mode options are also identified and discussed.

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. Design issues are identified, and priorities are developed for further conceptual design development and additional engineering analysis, anticipating future design activities.

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 work and published literature on scientific drilling, characterization methods, waste packaging and handling, industrial deep-hole drilling and construction, and downhole operations. Hence it is anticipated that this report will lead to completion of conceptual design, then preliminary and final design, fabrication and testing, and demonstration of waste emplacement in a deep borehole.

1.2 Overview of Deep Borehole Disposal Concept

Deep borehole disposal consists of drilling a deep borehole into crystalline basement rock, emplacing packages containing nuclear waste into the lower portion of the borehole, and sealing the upper part of the borehole. Deep borehole disposal of high-level waste (HLW) has been considered an option for geologic disposal for many years (NAS 1957). International efforts over the last half-century on disposal of HLW and spent nuclear fuel have primarily focused on mined repositories. Evaluations of DBD were conducted in several countries (O'Brien et al, 1979; Woodward–Clyde Consultants 1983; Juhlin and Sandstedt 1989; Heiken et al. 1996; NIREX 2004; Anderson 2004; Gibb et al. 2008). An updated conceptual evaluation of DBD and a preliminary performance assessment have also been completed (Brady et al. 2009). These studies have identified no fundamental flaws regarding safety or implementation of the DBD 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 waste packages 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 near-surface environment. The disposal zone in a single borehole could contain about 400 waste packages of approximately 18.5 ft length. The borehole seal system primarily could consist of alternating layers of compacted bentonite clay, cement, and cement/crushed rock backfill.

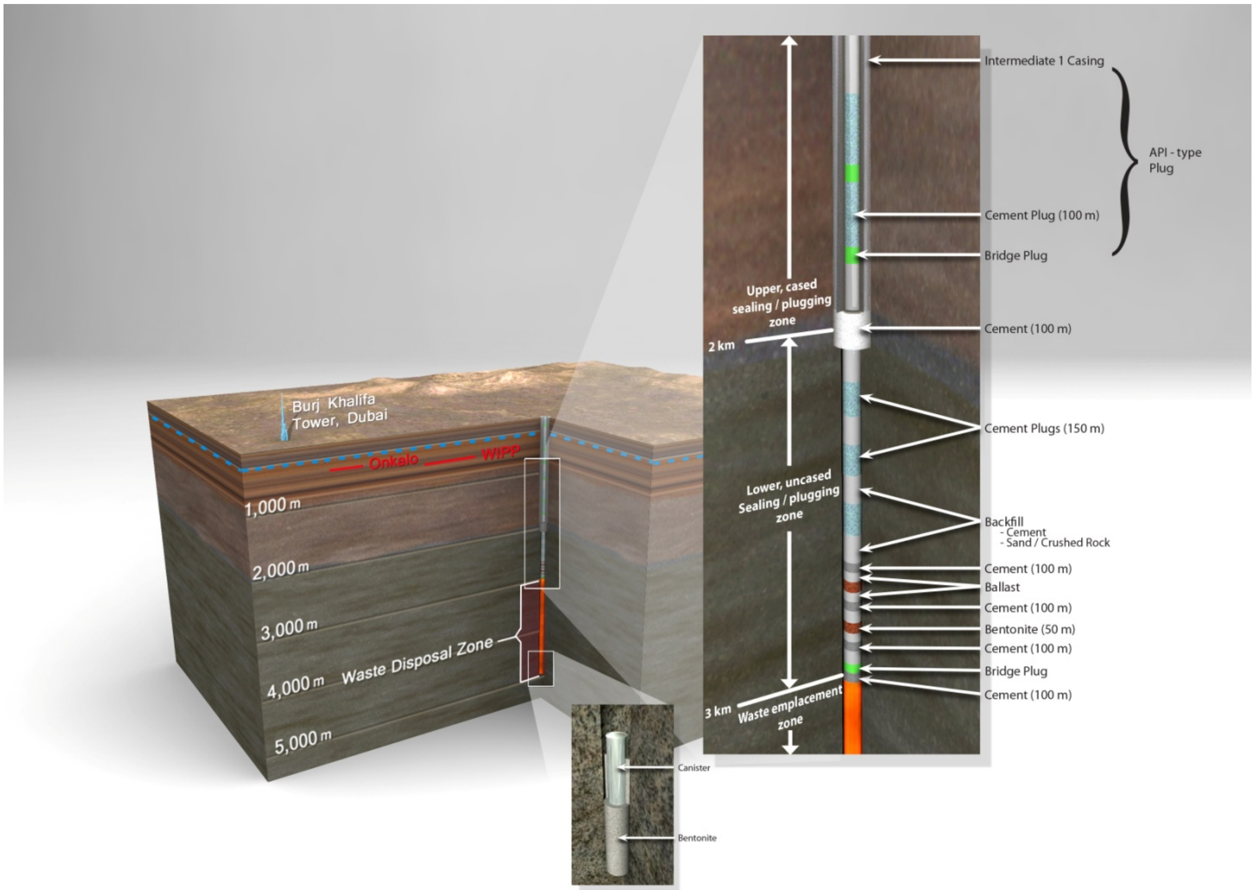

Figure 1-1. Generalized concept for DBD of radioactive waste. The dashed blue line indicates typical lower extent of useable fresh groundwater resources.

Several factors suggest that the DBD concept is viable and safe. Crystalline basement rocks are relatively common at depths of 2 to 5 km in stable continental regions, suggesting that numerous geologically appropriate sites exist. Existing drilling technology permits the reliable construction of sufficiently large (17-inch) diameter boreholes to a depth of 5 km at an estimated cost of about $27M each (Arnold et al. 2011, for subsequent holes, for drilling and completion only). 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. Groundwater density stratification due to salinity would oppose upward thermal convection from heat-generating waste. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance sorption of many radionuclides, leading to limited mobility in groundwater.

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).

In the deep borehole Research, Development, and Demonstration (RD&D) plan (DOE 2012) these goals are divided between two technical areas comprising the *science thrust* and the *engineering thrust*. These areas are elaborated as follows:

- Advance the DBD option from its current conceptual status to potential future deployment as a disposal system. The DBFT will include constructing a deep borehole, emplacing and retrieving test waste packages (*engineering thrust*), and downhole scientific sampling and testing, and supporting experimental programs (*science thrust*). No nuclear waste materials will be used in the DBFT.
- The DBFT includes characterization of an actual site, including long-term monitoring, and generic assessment of postclosure safety (*science thrust*). Scientific investigations will be developed and prioritized in a risk-informed manner, with greatest priority placed on activities needed for understanding the safety and waste isolation attributes of the DBD concept.
- The DBFT includes deep borehole drilling and completion, and emplacement of test waste packages (*engineering thrust*). Engineering development will be prioritized in a similar manner, with greatest priority placed on those activities most needed to assure operational and postclosure safety of a disposal system.

Every effort will be made to use existing drilling and borehole construction methods to meet the requirements of DBD. It is anticipated that the DBFT will also support the objectives and goals listed above, by:

- Fostering collaboration with industry, academia, national laboratories, and international participants. The DBFT will involve a diverse range of technical fields.
- Informing nuclear waste regulators and policymakers. The DBFT RD&D program can provide technical rationale for new regulations that control DBD.
- Providing policymakers with information on resource commitments that would be needed to field a DBD program.

1.3.1 Scope of DBFT

The basic structure of the DBFT is described in the RD&D Roadmap (DOE 2012). A 5-year schedule of major milestones for the DBFT and DBD R&D has been established based on the RD&D Roadmap. There are four major RD&D tasks:

Field Test Site Selection – Locate the DBFT boreholes at a site with technical characteristics that are reasonably representative of those considered best for DBD. In addition to establishing site selection guidelines, this task will also provide land access and regulatory permits for borehole construction and field testing.

Borehole Drilling and Construction – Establish DBFT borehole requirements, develop a borehole design, support the procurement of drilling and construction services, and ensure that the completed boreholes meet requirements.

Science Thrust – Identify and resolve data gaps in understanding the DBD environment. Data are needed for generic postclosure safety assessment, corrosion behavior of materials at depth, and construction of the disposal system.

Engineering Thrust – Confirm the engineering feasibility of the DBD concept, including package receipt and transfer to the borehole, and safe emplacement and retrieval. This task will also include design and fabrication of test packages and other unique equipment that may be needed. It will also provide documentation of testing requirements, operational procedures, and measures to ensure worker safety.

The engineering thrust is focused on the conceptual design, engineering analysis, final design, fabrication, testing, and demonstration of a waste package emplacement/retrieval system. It is also focused on borehole drilling and construction, and sealing technologies. Planning and execution for a FTB will concentrate on using existing technology, ensuring technical success, and schedule/budget performance.

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 test, but significant occupational hazards will 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 policies 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 (16,400 ft) total depth. This is likely attainable using existing technology (Beswick 2008) although few similar boreholes have been drilled in crystalline rock. Construction of liners, casings, and other features 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.

All downhole activities associated with the DBFT will contribute to another objective: to develop operational experience. Various characterization methods will be tried, some of which may not have been used in the crystalline basement, at *in situ* temperature, salinity, etc. Experience gained from the DBFT can be used to characterize other sites with similar geologic characteristics. The waste handling and handling technologies used for DBFT packages will be similar to the state of practice, but the packages will be different configurations and could be heavier than many containers used for nuclear waste. Emplacement and retrieval of waste packages in the FTB will be novel, with some precedents in oil and gas industry, but with new equipment designs and different reliability objectives.

Another objective of the DBFT is to develop the sealing system for disposal boreholes, based on laboratory investigations of sealing material behaviors, and modeling/simulation. Sealing requirements will be developed (generic, or based on site-specific information), 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 deployed can be conducted when planned DBFT activities have concluded.

1.3.4 Field Test Design and Implementation Process

The engineering demonstration parts of the DBFT will begin with conceptual design, for which this report is the first deliverable, and proceed to final design, fabrication, testing, and demonstration in the FTB. Sealing R&D will be conducted throughout this timeframe. These phases will be executed over a 4-year period beginning in FY15 and culminating in FY19 (Figure 1-2).

The DBFT project schedule (SNL 2014) has been updated to include a decision point after 3 months of drilling the Characterization Borehole (CB), whether to go forward with the procurement of services to drill the FTB. Depending on the outcome, the DBFT package emplacement/retrieval demonstration may be conducted in the CB.

1.3.5 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, by the successful bidder pursuant to a current Request for Proposal (RFP) (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 led by Sandia National Laboratories (SNL). Engineering services will contracted for the DBFT engineering activities (Figure 1-2), which were initiated by SNL but will transition to the engineering support contractor.

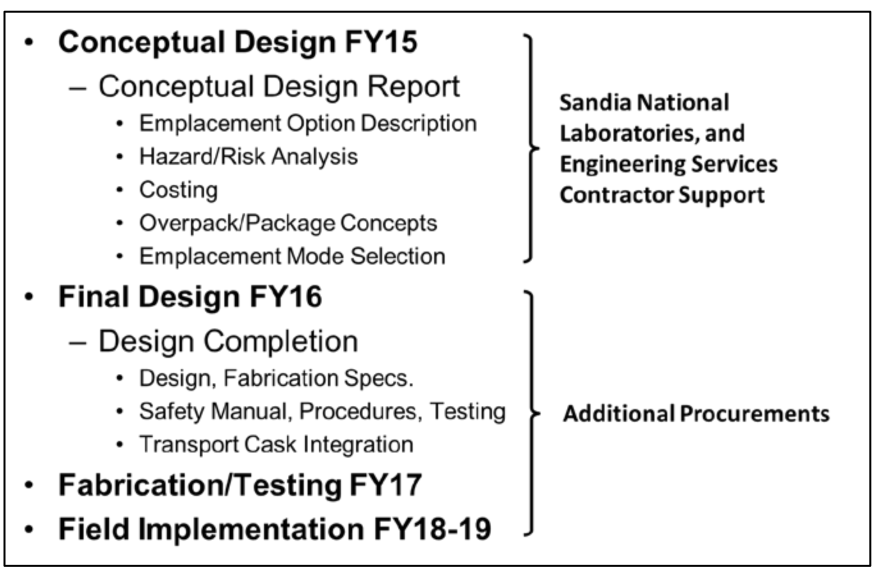

Figure 1-2. DBFT engineering RD&D multi-year program.

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2. Basis for DBFT Design

This section presents technical information about the reference deep borehole disposal concept and emplacement method options, other equipment, and the requirements and assumptions proposed to move the design process forward. English units are used intentionally because of their prevalence in the oilfield industry, without offering metric equivalents in order to avoid possible confusion. Metric units are used primarily in discussing the key transition depths in the disposal borehole, for describing force, torque, temperature and power, and for discussing results published elsewhere for other projects.

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 include worker safety, accidents, and the potential for operational failures (e.g., waste packages stuck in the borehole above the disposal zone). 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 related to thermally driven fluid flow and the effectiveness of the seals system, as evaluated in by Brady et al. (2009). Some aspects of the reference design concept involve tradeoffs between preclosure and postclosure safety considerations (e.g., fully cased borehole in the waste disposal zone vs. the ability to set seals against the borehole walls within the disposal zone). Given the extent of waste isolation performance credited to natural barriers operational safety objectives including safely emplacing waste packages in the disposal zone, were generally favored in these tradeoffs.

Key elements of the postclosure safety case are related to long-term isolation of the deep geologic environment of the crystalline basement. A key element of the safety case is the demonstration that deep groundwater is very old and has been isolated from the surface or near-surface for very long periods of time (on the order of 10^6 years or longer). Such a demonstration will likely rely on geochemical indicators such as salinity, and isotopic indicators using environmental tracers such as noble gases. 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). High salinity at depth also indicates old groundwater and precludes use of deep groundwater as a drinking water source. Increasing salinity with depth promotes stable stratification based on fluid density, and tends to oppose thermal convection from waste heat. Absence of overpressured conditions at depth is expected at favorable locations for deep borehole disposal. 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). The effectiveness and durability of borehole seals are also important elements of the safety case and are addressed through a borehole disposal concept that includes multiple barriers in the borehole above the waste disposal zone.

The preclosure safety case will be supported by engineering design studies and testing of important components of the deep borehole disposal system. Important elements of the preclosure safety case include surface handling equipment and procedures, waste package integrity during emplacement operations prior to borehole sealing, and the emplacement configuration and procedures. Preclosure radiological risks during nominal conditions are limited to radiation exposure of workers. Preclosure radiological risks associated with off-normal conditions include worker radiation exposure and surface contamination caused by waste package breach following an accident such as dropping a waste package or pipe string, or by waste package recovery after one or more packages becomes stuck above the disposal zone. External events may also be a factor in preclosure radiological safety, such as flooding, extreme weather, seismicity, and sabotage.

2.2 Disposal System Architecture

System architecture for the Disposal Borehole, and for Waste Packaging, Handling and Emplacement, is presented in Tables 2-1 and 2-2. 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. 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 system architecture is presented in outline form, for both wireline and drill-string emplacement methods, although only one of these (or a derivative method) will be carried forward for the DBFT.

2.3 Functional and Operational Requirements for Disposal System and DBFT

This section presents design requirements and controlled assumptions for the Waste Packaging, Handling and Emplacement System (as defined in Section 2.2) as part of the DBFT (SNL 2014a). The utility of the DBFT engineering activities depends on how well they simulate actual conditions of disposal. This section reflects this "inheritance" by presenting parallel sets of requirements for waste disposal and the DBFT, where it is technically possible and not premature to do so. A second purpose of this section is to inform the planning for drilling, construction, and characterization 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, waste package design and emplacement requirements, borehole construction requirements, and sealing requirements. Assumptions are included if they could impact engineering design. Design solutions are avoided in the requirements discussion.

The basic description of the DBFT, and reference design for a disposal system, follow the current project technical baseline (Arnold et al. 2011, 2013, and 2014; SNL 2014a). Prototype waste packages developed for the DBFT, and the system to demonstrate emplacement and retrieval, will be based on, but not necessarily the same as those described in this previous work. Importantly, this information will be updated as design proceeds, and as non-technical requirements and criteria are developed (e.g., safety, health, security, safeguards, QA, etc.).

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 listed in Tables 2-3 and 2-4.

Where information is to-be-determined (TBD), the reasons include present lack of definition for: 1) disposal mission with respect to waste forms; 2) siting and depths of DBFT boreholes and disposal boreholes; 3) future deep borehole waste disposal project organization and scope; 4) regulations specific to future waste borehole disposal 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. Requirements and assumptions may be revisited when additional information is available in these areas.

Table 2-1. Waste packaging, handling and emplacement system architecture

Architecture Outline (Subsystems)	Applicability Discussion	
	Wireline Emplacement	Drill-String Emplacement
Waste Package/Overpack		
Tubular Section	All packaging concepts call for a tubular section (which controls waste volume and overall length), upper shield/structural end plug, lower structural end plug, and a closure plug (threaded or welded).	
Shield End Plug		
Structural End Plug		
Closure Plug		
Threaded Plug		
Welded Plug		
Wireline Latch/Fishing Neck	Require engineering development (see Sections 2.7.2 and 3.2).	
Impact Limiter		
Basket	Holds pre-canistered waste (e.g., Cs/Sr capsules separately or already assembled in canisters). Not needed for bulk granular waste forms.	
Package Transportation		
Shielded Transportation Cask	Emplacement concepts are presented in this report, that would use the same waste package transportation components for both wireline and drill-string emplacement.	
Truck Transporter		
Package Surface Handling/Transfer		
Shielded Transfer Cask	Emplacement concepts are presented in this report, that would used the same transfer cask (or a single cask for transportation and package transfer to the borehole), crane (for lifting and up-ending), and cask details.	
Waste Package Transfer Fixture		
Cask Lift and Up-Ending		
Shielded Cask Doors		
Lifting and Rotation Restraints		
Cask Placement and Anchoring	Simple lift and translation to the receiving flange/platform.	Lateral movement of the cask under the drill rig, within the substructure, and positioning over the borehole.
Waste Package Staging (Borehole – Surface)		
Receiving Collar/Flange	Emplacement concepts are presented in this report, that would use similar receiving flange/platform, mud surge control (for emplacement), and blowout preventer features.	
Mud Control		
Blowout Preventer		
Wireline Winch	For raising/lowering waste packages.	
Wireline Support	Headframe	
Shielding	Surface structure built around well head.	Basement with ceiling shield.

<table>
<tr><th rowspan="2">Architecture Outline (Subsystems)</th><th colspan="2">Applicability Discussion</th></tr>
<tr><th>Wireline Emplacement</th><th>Drill-String Emplacement</th></tr>
<tr><td>Basement</td><td rowspan="12"></td><td rowspan="9">Basement concept provides shielding for package string assembly, and also accommodates BOPs and mud control, while limiting rig floor height and maintaining transportation/transfer cask operations at grade level.</td></tr>
<tr><td>Power Slips</td></tr>
<tr><td>Power Tongs</td></tr>
<tr><td>Elevator Ram</td></tr>
<tr><td>Ceiling Shield</td></tr>
<tr><td>Structural Frame</td></tr>
<tr><td>Guidance Casing Hanger</td></tr>
<tr><td>Well head Flange</td></tr>
<tr><td>Sump</td></tr>
<tr><td>Breakaway Sub</td><td>Prevents hoisting WP out of transfer cask</td></tr>
<tr><td>Rig Sub-Structure</td><td>Part of drill rig.</td></tr>
<tr><td>Transfer Carrier</td><td>Positions transfer cask over well head</td></tr>
<tr><td>Backup Power Supply</td><td colspan="2">Backup power for waste package staging operations.</td></tr>
<tr><td>Emplacement</td><td colspan="2"></td></tr>
<tr><td>Wireline</td><td rowspan="7">High-quality, commercial grade wireline equipment (electromechanical package release may be purpose-designed).</td><td rowspan="7"></td></tr>
<tr><td>Cable</td></tr>
<tr><td>Cable Head</td></tr>
<tr><td>Wireline Tools (gamma, CCL, sampler)</td></tr>
<tr><td>Electromechanical Release</td></tr>
<tr><td>Weak Point</td></tr>
<tr><td>Wireline Winch</td></tr>
<tr><td>Drill Rig</td><td rowspan="7"></td><td rowspan="7">Modern, highly automated rig and downhole equipment. (Weak point would be provided on the lead instrumentation package.)</td></tr>
<tr><td>Draw Works</td></tr>
<tr><td>Iron Roughneck</td></tr>
<tr><td>Power Slips</td></tr>
<tr><td>Drill Pipe</td></tr>
<tr><td>Double Release</td></tr>
<tr><td>Lead Package</td></tr>
<tr><td>Backup Power Supply</td><td colspan="2">Backup for emplacement operations.</td></tr>
<tr><td>Borehole Qualification</td><td colspan="2" rowspan="2">Logging tools to run before waste emplacement, after cementing, and whenever integrity of the waste emplacement guidance casing is suspected.</td></tr>
<tr><td>Acoustic Caliper</td></tr>
</table>

Architecture Outline (Subsystems)	Applicability Discussion	
	Wireline Emplacement	Drill-String Emplacement
Gauge Ring/Basket		
Safety Control (Interlocks)		
Cask Doors	Prevent dropping packages during staging.	
Breakaway Sub		Prevent and mitigate inadvertent cask door opening, over-lifting packages against restraints, inadequate joint makeup, string slipping in tongs, over-limits on draw works pull and travel.
Slips and Tongs		
Visual Indication		
Position Sensors		
Rotation Sensors		
Rig Draw Works Tension and Travel		
Wireline Winch Tension and Speed	Prevent and mitigate over-tension and over-spooling. Detect downhole radiation leaks.	
Wireline Logs and Samplers		
Control Room	Operator station for staging, emplacement and safety control (interlock) subsystems.	
Backup Power Supply	Backup for safety control system.	
Monitoring and Measurement		
Borehole Fluid Level	Hydrophone monitoring for downhole conditions.	
Acoustic Emission	Casing vibration monitor for downhole conditions.	
Casing Condition		Measurements made ahead of each package string during emplacement.
Wireline Condition	Automatic monitoring for broken strands, birdcage, electrical integrity, etc.	
Radiation Detection	Detectors and samplers run with every package or package string.	
Load on Bottom		Crush box (with annunciator?) to inform operator when string is on bottom.
Dummy Packages	Run in to test hole conditions.	Dummy string to test hole conditions or for initial qualification.

Table 2-2. Disposal borehole architecture

<table>
<tr><th rowspan="2">Architecture Outline (Subsystems)</th><th colspan="2">Applicability Discussion</th></tr>
<tr><th>Wireline Emplacement</th><th>Drill-String Emplacement</th></tr>
<tr><td>Borehole – Subsurface</td><td colspan="2"></td></tr>
<tr><td>Depth/Diameter</td><td colspan="2" rowspan="8">Follow reference borehole concept described in Section 2.6.1 for both wireline and drill-string emplacement (following Arnold et al. 2011).</td></tr>
<tr><td>Casing/Liner Plan</td></tr>
<tr><td>Overburden Interval</td></tr>
<tr><td>Seal Zone</td></tr>
<tr><td>Disposal Zone</td></tr>
<tr><td>Guidance Casing Tieback</td></tr>
<tr><td>Mud Check Valve</td></tr>
<tr><td>Liner Hanger/Guide</td></tr>
<tr><td>Plug and Cement – Emplacement</td><td colspan="2"></td></tr>
<tr><td>Drillable Bridge Plug</td><td colspan="2" rowspan="3">Bridge plugs can be set with pressure (instead of explosive charges), on a pipe string or coiled tubing. The same string can place cement. Select disposal zone completion concept (for examples, see Section 2.6.2).</td></tr>
<tr><td>Cement Handler</td></tr>
<tr><td>Coiled Tubing Unit</td></tr>
<tr><td>Sealing</td><td colspan="2"></td></tr>
<tr><td>Liner Removal</td><td colspan="2" rowspan="3">Cut and remove intermediate liner in seal zone. Install alternating low-permeability sealing materials (e.g., clay) and rigid support materials (cement plugs).</td></tr>
<tr><td>Low-Permeability Seals</td></tr>
<tr><td>Support Plugs</td></tr>
<tr><td>Borehole Plug and Abandon</td><td colspan="2"></td></tr>
<tr><td>Cement Plug</td><td colspan="2" rowspan="2">Plug and abandon from the top of the seal zone to the surface, following API recommendations and permit requirements.</td></tr>
<tr><td>Surface Completion</td></tr>
</table>

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 Integrated Safety Management System (Department of Energy), the Environment, Health & Safety program of the American Petroleum Institute, the Oil and Gas Extraction Safety program (National Institute for Occupational Safety and Health), and the Engineered Safety program at Sandia National Laboratories. The broadest of them 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 broadly accepted safety and environmental precepts are followed. Accordingly, full implementation of the ISMS program of the sponsoring Department of Energy 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, and so on. The particulars of such a program are beyond the scope of the DBFT, and are TBD.

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 DBFT will not involve radioactive materials, except for sealed logging sources, which will be removed. For the DBFT to simulate waste disposal operations, this means that 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 waste package handling operations will make use of shielding, but for the DBFT such shielding may be simulated.

2.3.3 Security and Safeguards Requirements

Safeguards and security of nuclear materials is beyond the scope of the DBFT. Much is known about the potential for the assumed waste forms to self-protect, and the security and safeguards considerations for waste storage and transportation. One connection to the DBFT is the size of canisters and waste packages used to disposition relatively small, highly radioactive sealed sources (Table 2-3).

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.

2.3.5 Other Statutory and Regulatory Requirements

The National Environmental Protection Act (NEPA) is applicable to any future Federal 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 or Environmental Impact Statement) will be determined and implemented prior to initiating field activities.

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 will vary with location, and may vary between the DBFT and any future waste disposal activities. These state and local permits will be secured after the location of the DBFT is identified.

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 TBD. For the DBFT, no radioactive waste or hazardous waste will be transported to the site, nor will such wastes be introduced to the Characterization and Field Test Boreholes.

2.3.6 Functional Requirements

The DBFT has multiple objectives including development and demonstration of scientific characterization methods for evaluating site suitability. Borehole drilling and construction, and DBFT engineering development and implementation activities, will be integrated with the overall program and consistent with evaluation of the safety and feasibility of deep borehole disposal. In other words, the overall program is expected to include rock and groundwater sampling, flow testing, geophysical logging, and other characterization activities, with which the other DBFT activities (drilling, construction, demonstration) must not interfere.

For future waste disposal activities, the characterization objective may also apply as each disposal borehole is constructed. 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, and is TBD.

Design for future waste disposal will ensure that nuclear criticality cannot occur in handling and disposal of actual waste. For the DBFT, no nuclear waste and no nuclear materials capable of criticality will be used, other than sealed sources used for well logging (Section 1.2).

The potential waste forms for deep borehole disposal include powerful emitters of penetrating radiation (gamma, neutron), so the DBFT engineering design will include accommodation for appropriate shielding.

The functions of borehole fluid include mechanical support of the borehole wall, and lubrication of drill string and wireline operations, in addition to flushing of cuttings during drilling. Fluid also provides buoyant support to downhole tools and waste packages. 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 emplacement fluid in the disposal zone of a waste disposal borehole may have different properties than drilling fluid, or completion fluid used above the disposal zone.

2.3.7 Operating Requirements

Operating requirements for actual waste disposal will be developed in large part based on experience from the DBFT, and are therefore TBD. However, a number of operational requirements on the DBFT can be inferred based on desired features of the disposal system.

Borehole disposal overpacks (and canisters that contain the waste, as applicable) will be loaded and sealed by welding at specialized nuclear material handling facilities. Thus, waste packages will be delivered to the disposal site sealed, and in condition ready for direct emplacement in the disposal borehole. Welding provides a permanent seal and has been a preferred closure solution for mined geologic disposal in repository R&D programs.

Materials used in the Characterization Borehole (CB) and in the Field Test Borehole (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 technically challenged. An important part of the Material Control program will be chemical or stable isotopic 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 will also benefit future waste disposal operations by limiting interference with future characterization data collection, and limiting potential impacts to waste isolation after waste borehole sealing and closure.

To prevent stuck waste packages, a verification method such as wireline logging will be used immediately prior to package emplacement or retrieval operations to verify the condition of guidance casing. 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 waste package emplacement/retrieval operations.

2.3.8 Performance Criteria

Some basic performance criteria 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.

As noted previously the DBFT has multiple objectives, and the engineering demonstration is one part of the overall program. Accordingly, 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 disposal zone. For future waste disposal boreholes this requirement is focused on any confirmatory data to be collected, the nature of which is TBD.

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 is adopted (Table 2-3). This service lifetime should be reasonably conservative because of 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

Borehole lineal 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 (328 ft) apart over the extent of the disposal zone, if the collar spacing is at least 200 m (656 ft). 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 waste packages (or tubulars during drilling and construction). Dogleg severity (typically expressed in degrees per change in apparent 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 of tool joints (controls stiffness), and buoyant weight.

If waste packages are lowered a few at a time on a wireline, then the main impact of doglegs occurs during borehole construction. If waste packages are emplaced in long strings on drill pipe, then another impact may occur during emplacement because of the relatively small radial clearance between waste packages and guidance casing. Maximum dogleg severity for the DBFT is TBD and will be determined by engineering analysis prior to drilling. The possibility that dogleg severity may be strongly limited (e.g., to accommodate drill-string emplacement of long strings of waste packages) means that directional drilling capability should be assumed (Table 2-4).

As a practical matter all boreholes will have some deviation so that drill pipe, waste packages, wireline tools, etc., will slide or rest against the “low” side. This means that waste packages and downhole tools will generally contact the casing, so the internal surface of the casing should be flush.

The reference design of Arnold et al. (2011) for heat-generating waste specifies slotted or perforated liner in the disposal zone, to allow heated fluid to escape to the formation rather than building up pressure that could damage plugs or seals. This requirement is specified here for disposal boreholes, but not for DBFT boreholes. Heater tests such as that proposed for the CB (Vaughn et al. 2012) could place additional requirements on borehole construction, but are TBD.

In disposal boreholes the seal zone will be uncemented, and both the guidance casing and the intermediate casing in this zone (nominally 2 to 3 km depth) will be removed for sealing (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 is planned. For the DBFT Characterization Borehole casing removal is not required because the hole will not be sealed. Casing removal can be problematic especially after long periods of time. For DBFT follow-on testing activities consideration may be given to demonstrating casing removal, and what happens if the casing becomes stuck.

The reference disposal concept calls for bridge plugs within the guidance casing, spaced about 200 m (656 ft) apart in the disposal zone, with approximately 10 m (33 ft) of cement placed over each bridge plug to bear the weight of waste packages (Arnold et al. 2011). If the annulus between the borehole wall and the guidance casing is not also cemented, then the 13-3/8 inch slotted guidance casing will support the weight of up to 400 waste packages and ten cement plugs, a total of approximately 1.8×10^6 pounds, in column loading. The reference design allows for cement to run into the annulus where its movement would be impeded by heavy, oil-based emplacement mud. The total cement volume would be equal to the casing volume plus the annular volume, over the 10-meter cemented interval. A measurement to the top of the finished cement plug would be used to determine successful installation.

To provide greater assurance that excessive compression of the guidance casing will not occur, the annulus could also be cemented in some or all of the cement plug intervals. One way to do this would be to use an inflatable annular casing packer at the same elevation as the casing bridge plug. The same measurement to the top of the cement plug would confirm installation. This method would control the cement, support the guidance casing, and ensure that there are uncemented intervals in the disposal zone between cement plugs for emplacement fluid, and dissipation of fluid pressure caused by waste heating (see Section 2.6.2 for more discussion of completion options).

For the DBFT, plugs will not be installed in the Characterization or Field Test Boreholes in a manner that could interfere with availability of the boreholes for additional testing. This does not preclude installing cement at the bottom of either borehole in conjunction with (i.e., before or after) installation of guidance casing.

2.3.10 Waste Packaging Requirements

Reference waste package sizes (Arnold et al. 2011) were determined using common sizes for drill bits and casing. A range of diameters is available for disposal overpacks (and borehole and casing sizes), but two sizes are being considered for the DBFT: small and large. As discussed below, for the larger packages (both test and actual disposal waste packages) the maximum diameter that could be achieved is 11 inches, and for the small packages it is 5 inches. These limits are consistent with borehole diameter and casing designs documented in the reference design (Arnold et al. 2011). Overpack internal length will be nominally 5 m, to accommodate various waste forms (including spent fuel as analyzed by Arnold et al. 2011).

The diameter of waste packages that can be run in standard sized casing depends on the radial clearance. Radial clearance between the waste packages and the casing internal diameter (ID) controls the potential for packages to become stuck, especially if assembled in long strings (up to 40 packages; Arnold et al. 2011). Radial clearance 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.

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 0.25 inches which was controlled by off-the-shelf buttress-type connectors with outer diameter of 12.1 inches. For this analysis, the minimum radial clearance for large-size disposal overpacks is set to 0.7 inches, giving a maximum package diameter of 11 inches, for the 12.49-inch drift within 13-3/8 inch casing (Arnold et al. 2011). Applying the same minimum radial clearance to small overpacks the maximum package diameter is approximately 5 inches for the nominal ID of 7-inch casing.

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 (which may be stuck). Waste packages may be loaded in compression when strings are set on the bottom of the borehole (or on intermediate plugs).

Hydrostatic loading combined with axial and bending loads constitute the maximum loading condition. The maximum design hydrostatic pressure for test waste packages is 9,560 psi (65 MPa) based on assumed fluid density in a 5-km column (Table 2-4). The minimum hydrostatic pressure for waste disposal packages is 7,350 psi (50 MPa) based on the density of pure water (temperature effect on density is minor). The maximum pressure for actual waste packages is TBD because it depends on the properties of the so-called emplacement mud, and how it is introduced.

A minimum factor of safety (FoS) of 2.0 with respect to yield stress, for numerical analysis of elastic deformation, will be used for the waste package. The FoS should be reasonably conservative, comparable to those used in other critical systems (e.g., pipelines, rigging, etc.).

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 could preclude contaminated wellbore fluid from reaching the overburden directly). For actual waste disposal overpacks, the design FoS will depend on results obtained in the DBFT, and is therefore TBD.

Temperature rise from emplacement of waste will vary with waste characteristics and canisterization, increasing the maximum disposal zone temperature (at the package surface). For Cs/Sr capsules stacked end-to-end the peak temperature rise for the hottest capsules emplaced in granite in 2020 would be approximately 100 C° (Section 4.5). Considering that these capsules will more likely be disposed of ten years later, and that most of the capsules are cooler than the hottest ones, the maximum temperature rise will be 80°C and the maximum package surface temperature will be approximately 250°C (see thermal results in Section 4.5). The calculations show that the disposal zone will approach peak temperatures within a few hundred days after emplacement (although true peak values will take years) and therefore peak temperatures can be assumed for analysis of conditions during the operational period for waste emplacement and borehole sealing. Note that the saturated vapor pressure of water at 250°C is 576 psi (3.9 MPa; Weast and Astle 1981, p. D-169) so that boiling will not occur for water-based fluids.

Heated testing is not currently planned for the FTB, so the maximum test waste package temperature will be 170°C. Design of tools or test packages to be used in a borehole thermal test, for example in the CB, are TBD.

Waste packages will have flush external surfaces, with API standard tapers at diameter changes (e.g., at joints between packages, or where the package body meets connectors fixed at each end). The smooth, tapered exterior will prevent hangup on casing joints, shoes, collars, etc. The requirement applies to both test waste packages and waste disposal packages.

Package connections for drill-string emplacement will include: 1) a threaded connection to packages below; and 2) a threaded connection to drill pipe above for emplacement or fishing. Package connections for wireline emplacement will include a releasable cable head and a fishing neck, both located on top. The package bottom will include a threaded connection for attaching additional hardware such as instrumentation, centralizers, shock absorbing materials, etc.

Package connections will have sufficient strength to withstand mechanical loads during emplacement, retrieval, and fishing of stuck packages (or package strings, if packages are threaded together). Thrust and rotation conditions required to engage or disengage connections downhole must be consistent with capabilities of drill-string, wireline, or coiled tubing delivery systems (as applicable).

Waste package containment is required through all phases of disposal operations, until the borehole is sealed. Additional containment longevity may be required depending on the disposal environment, waste radionuclide half-life, and other characteristics. Thus, for longer-lived radionuclides the containment lifetime might be increased to supplement natural barrier performance, through choices of disposal overpack materials, fabrication methods, treatments, and engineered controls on the disposal environment. These considerations do not apply to DBFT test waste packages, which will be retrieved immediately. The DBFT will demonstrate that waste 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.

Test waste packages will have negative buoyancy in emplacement fluid of the maximum density (see assumptions 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 waste packages, and includes the weight of loaded waste, but the maximum fluid density in disposal boreholes is TBD.

2.3.11 Waste Package Emplacement and Retrieval Requirements

The foremost requirements are that waste 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 waste disposal boreholes, retrieval could involve removal of all cement, plugs, and other obstructions, as necessary to access the disposal zone. For the DBFT FTB retrieval means that packages are 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. Package retrieval may be performed using a different method than used for emplacement (e.g., emplaced by wireline, retrieved using a drill string).

One of the technical criteria for site suitability for waste disposal is no significant upward flow of groundwater from the disposal zone due to natural hydraulic gradients. This could mean that there is no significant upward gradient from the disposal zone to the ground surface. In that case blowout preventers would not be needed, unless required by permit or regulation. Nevertheless, requirements for blowout preventers on waste disposal boreholes will depend on site-specific conditions and history of nearby drilling activities. For the DBFT, blowout preventers could be required especially if history is not available from prior drilling. Accordingly, test waste package emplacement and retrieval equipment will be designed to function with or without blowout preventers in place on the FTB well head.

During emplacement operations waste packages will be connected to the emplacement equipment (i.e., either drill pipe or a wireline), and transferred from a transportation or transfer cask to the borehole. For drill-string emplacement, this will involve holding one or more packages stationary in the hole, while additional packages or pipe sections are threaded on. Two or more redundant holding mechanisms (e.g., doors, slips, and/or rams, which serve other functions as well, except for the slips) will bear the weight of the string as up to 40 waste packages are assembled in a string, and more than 100 lengths of pipe are added. For wireline emplacement operations, two or more redundant mechanisms will hold the package and block the wellbore when the wireline is connected. For both cases, the holding mechanisms will be redundant so that single-point electrical, hydraulic or mechanical failures cannot cause release of a package or string, resulting in: 1) one or more waste packages dropped in the borehole, potentially onto other packages; or 2) a drill string dropped onto packages connected to its lower end, or onto packages already emplaced.

Fluid level in the hole (in the guidance casing, assuming isolation from the intermediate casing) should be closely monitored during emplacement, plugging, and sealing operations, particularly if drill-string or coiled tubing is used (these methods displace more fluid than wireline). This can be accomplished using mud ports at the well head, and a trip tank that allows for close monitoring to check for fluid losses and over-pressure conditions. For 5-inch drill pipe lowering a string of 40 waste packages, minimum trip tank volume would be approximately 200 bbl.

2.3.12 Borehole Sealing Requirements

In waste disposal boreholes the seal zone will be completed with a low-permeability material (less than 10^{-16} m^2 permeability) that seals against the borehole wall. Sealing material installed proximal to the disposal zone will function at temperatures up to approximately 200°C and retain its properties throughout the thermal period which could last up to 2,000 years after emplacement depending on the type of heat-generating waste. Note that seals would be installed over a 33-ft (10-m) cement plug above the top package in the disposal zone, and that because of heat dissipation only a portion of the overall seal zone would be subject to elevated temperature from waste heating.

Seals will resist mechanical loading (e.g., from casing corrosion, borehole wall collapse, or from the weight of an overlying fluid column). 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.

2.3.13 Characterization Testing Requirements

These requirements provide for a relevant testing program that minimizes unnecessary activities and test interference in the DBFT. Testing requirements for future waste disposal boreholes will depend on the types of measurements and samples required.

2.4 Design Assumptions for Disposal System and DBFT

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, vitrified HLW, HLW in sealed capsules, and spent fuel. The waste forms to be considered in a future deep borehole waste disposal system are TBD.

The depth of DBFT boreholes is assumed to be 5 km, to facilitate design of test waste packages and emplacement/retrieval equipment. The actual depth of the Characterization and Field Test Boreholes 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.

Waste packages strings 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 disposal zone. For the DBFT there are no plug installations planned (Section 2.3.9), so this assumption limits to 40 the maximum total number of test waste packages that could be emplaced in the FTB.

The minimum density of fluid anywhere in disposal boreholes (used for buoyancy calculations, not an average), and in DBFT boreholes when waste 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 waste 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 waste package buoyant weight limits can be met, or after all waste 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 waste packages are also present is assumed to be 1.3× the density of water (~10.8 lb/gallon). This value is based on engineering judgment as to the average fluid density that will be needed during emplacement of waste packages. The basement rock will be crystalline and significantly framework-supported, so formation overpressure is not expected. This means that formation fluid pressure will be close to that imposed by the fluid column, which may contain brine. If the emplacement fluid has the same density as the natural fluid column, and includes some clay for lubricity and viscosity, the resulting density could be 1.3× the density of water. Note that this density is used to compute static pressure, and that pressure transients will likely occur during operations (and must be controlled).

Greater mud or fluid densities may be used in drilling and completion activities, but waste packages will be introduced only after these activities are complete. An emplacement fluid program could be used to flush drilling mud from the completed hole. In the reference concept (Arnold et al. 2011) the emplacement borehole will be fully lined with casing (cemented in the overburden, mostly uncemented in the crystalline basement) before such flushing would be done.

An important consideration is the density of formation fluids that may influence the borehole fluid composition and density. The density of saturated sodium chloride brine is approximately 10 lb/gallon, or 1.25× pure water. Other salts may be present in basement brine such as $CaCl_2$, which may further increase brine density. Concentrated brine in the basement may therefore have density that exceeds 1.3× the density of water, in which case a stratification scheme might be used in the borehole to control the maximum average fluid density that determines downhole pressure. The maximum average fluid density in waste disposal boreholes is TBD.

Finally, the overburden is assumed to be sediments that could, in principle, be overpressured with respect to a column of pure water. For a large overpressure of 1 psi/ft the pressure at 2 km (6,560 ft) depth would be 6,560 psi compared to 2,940 psi for pure water. Such a pressure could exceed the casing external pressure limits discussed in Section 2.6.1. However, this condition is unlikely in a geologic setting selected for waste disposal, and lack of an upward hydraulic gradient is one criterion for siting the DBFT (SNL 2014a).

Definition of test package failure to include any detected containment breach or leakage is assumed in order to simplify interpretation of DBFT results. Thus, for waste disposal operations the method of detection must be selected to correspond to a critical level of radiological hazard.

Uncontrolled dropping of test waste packages in a test borehole, or uncontrolled dropping of drill pipe onto one or more packages in the test borehole, may lead to package breach. For this definition the drop-in method of package emplacement (Bates et al. 2011) would be considered controlled, as would package retrieval activities (i.e., planned fishing of waste packages).

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 (3,280 ft) is assumed to be 2°/100 ft. These values are marginal with respect to whether directional drilling equipment will be needed. 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. Dogleg severity at these levels is not expected to produce significant additional stress in a string of waste packages with threaded joints (Section 4.1).

The DBFT will not involve demonstration of waste package storage at the borehole site. For actual disposal operations it is possible to construct and license a storage facility nearby or on-site. Such a facility would be within the state of industry practice, but is beyond the scope of the DBFT. A similar statement can be made about facilities to fabricate, load, and close (weld) waste packages. Packaging of waste materials will require a hot cell, and may require welding, inspection, or other technologies that are not readily implemented in the field. For the DBFT, test packages will be sealed, inspected, and tested in non-radiological facilities before being delivered to the site.

The DBFT Characterization and Field Test Boreholes 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.

An assumption on maximum waste package weight is provided for handling system, emplacement system, and canister design. Beginning with the reference design (Arnold et al. 2011) the loaded waste package will have a dry weight of approximately 4,620 lb based on the following assumptions on a steel disposal overpack: 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 were assumed to be 367 pressurized water reactor rods (at 2.39 kg/rod).

Using higher strength tubing for the package body, the wall thickness can be reduced thereby reducing weight (Section 4.1). 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 waste package weight, and that the DBFT is not intended to specifically investigate spent fuel disposal in boreholes, nor to promote rod consolidation as a solution.

Displaced volume is ~12.2 ft^3. The buoyancy will be 990 lb in emplacement fluid with density of 1.3× pure water (and 760 lb in pure water). The net buoyant weight of a loaded waste package in emplacement fluid will therefore be approximately 3,630 lb (3,860 lb in pure water).

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	
(Applicable requirements for radiological hazard identification and analysis, safety-in-design, and related measures for deep borehole disposal are TBD.)	**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, welding/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.	**Radioactive Materials –** Radioactive sealed sources will be used for well logging. No other designated radioactive materials nor any radioactive wastes will be used in the DBFT.
	Test Design to Demonstrate Radiological Protection Capability – DBFT waste package handling, emplacement, and retrieval shall be performed so as to demonstrate that radiation exposure to workers could be effectively limited.
2.3.3 Safeguards and Security Requirements	
(Safeguards and security requirements for deep borehole disposal of radioactive waste are TBD.)	**Field Site Security** – Security of field operations shall conform to standard practices of drill site management. (Safeguards requirements are not applicable; see Radioactive Materials above.)
	Self-Protection – Prototype waste packages shall be designed with dimensions (size, weight) that would promote self-protection of actual packaged wastes.
2.3.4 Quality Assurance Requirements	
(QA requirements for deep borehole disposal are TBD.)	**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 TBD.	**NEPA** – The National Environmental Protection Act is applicable to test borehole drilling, testing, and borehole plugging/abandonment activities.
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.
(Applicability of injection well regulations such as 40CFR144 to deep borehole disposal of radioactive wastes is TBD.)	**Radioactive Waste** – No radioactive waste shall be introduced to the Characterization Borehole and the Field Test Boreholes, nor shall radioactive waste be transported onto or stored at the site.
	Hazardous Waste – No designated hazardous waste shall be introduced to the Characterization and Field Test Boreholes.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
2.3.6 Functional Requirements	
Safe Disposal – Borehole drilling, construction, emplacement, sealing and closure activities shall promote safe disposal of radioactive wastes.	**Effective Characterization/Evaluation** – Borehole drilling, construction, testing, emplacement, and retrieval activities shall support evaluation of the safety and feasibility of deep borehole disposal.
Nuclear Criticality – Design, handling, and emplacement of waste packages must preclude any possibility of nuclear criticality.	**Nuclear Criticality** – No fissile materials or wastes shall be used for the DBFT.
Waste Forms for Disposal – The deep borehole disposal system shall be designed to safely dispose of spent nuclear fuel and HLW forms that emit penetrating radiation (gamma, neutron).	**Test Design for Waste Forms** – The DBFT shall simulate disposal of waste forms for disposal, with respect to package dimensions (size, weight) and demonstrated capability for radiological protection.
2.3.7 Operating Requirements	
(Operational requirements for waste disposal operations are TBD.)	**Test Waste Package Sealing** – Test packages shall be sealed by welding, at the facility of origin.
	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 site.
	Material Control – Materials used in the Characterization and Field Test Boreholes shall be restricted to those on a list maintained by the 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 for mud or cement) that are used in subsurface operations or otherwise introduced to the DBFT boreholes, will be tagged with 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 waste package emplacement operations.
	Borehole As-Built Drawings - Accurate as-built dimensional drawings shall be maintained for all assemblies (e.g., downhole tools, waste packages, etc.) and strings (e.g., casing, drill pipe, collars, etc.) introduced to the Characterization and Field Test Boreholes. The intended purpose for such drawings is use in fishing operations.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
2.3.8 Performance Criteria	
Waste Handling, Emplacement and Packaging 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 (not leak) and shall be maintained in control at all times during emplacement and retrieval demonstration operations.
Confirmatory Data Collection – Drilling and construction of waste disposal boreholes shall be conducted to allow collection of confirmatory data, and to promote waste isolation performance of the disposal system. The nature of confirmatory data collection during waste disposal borehole preparations is TBD.	**Characterization Data Collection** – Drilling and construction of the Characterization and Field Test Boreholes shall be conducted to allow characterization of the hydrogeologic setting including the overburden, seal zone, and the waste disposal zone.
Disposal Borehole Service Life – Borehole construction, completion, and associated surface facilities shall be designed with service lifetime of 10 years, or long enough to accommodate safe disposal operations and sealing, whichever is greater.	**Field Test Borehole Service Life** – Service lifetime of the Characterization and Field Test Boreholes shall be 10 years, considering casing corrosion, creep, and other significant time-dependent processes.
2.3.9 Borehole Design and Construction	
Borehole Deviation – Waste disposal borehole(s) shall be constructed so that: 1) horizontal deviation does not exceed 50 m; and 2) maximum dogleg severity specifications are met (TBD).	**Field Test Borehole Deviation** – The Field Test Borehole shall be constructed so that: 1) horizontal deviation does not exceed 50 m; and 2) maximum dogleg severity specifications are met (see Table 2-4).
	Characterization Borehole Deviation – The Characterization Borehole shall be constructed so that: 1) horizontal deviation does not exceed 100 m; and 2) maximum dogleg severity specifications are met (see Table 2-4).
Casing Internally Flush for Emplacement – Completion casing, or guidance casing if used, shall be internally flush with uniform diameter over the full borehole length.	**Casing Internally Flush for Testing** – Completion casing, or guidance casing if used, shall be internally flush with uniform diameter over the full borehole length.
Disposal Borehole Diameter – Disposal borehole and casing diameters shall permit emplacement of waste packages with sufficient radial clearance.	**Characterization Borehole Diameter** – Borehole and casing diameters shall permit emplacement of test packages up to 5 inches in diameter (see Section 2.3.10 Waste Packaging Requirements).
	Field Test Borehole Diameter – Borehole and casing diameters shall permit emplacement of test packages up to 11 inches in diameter at (see Section 2.3.10 Waste Packaging Requirements).
Relieve Thermal Expansion – Casing, grout, and other features of disposal zone completion, shall accommodate thermal expansion of fluid due to waste heating, by allowing flow into the surrounding rock without breaching borehole	(Requirements for managing thermal expansion in a heater test or other temperature changes in the Characterization and Field Test Boreholes are TBD.)

Waste Disposal Requirement	Deep Borehole Field Test Requirement
plugs or seals.	
Sealing Zone – Permanent seal(s) shall be installed in a borehole interval directly above the disposal zone.	**Test Borehole Sealing** – Permanent seals shall not be installed in the Characterization or Field Test Boreholes.
Seal Zone Casing Removal –Casing shall be removed from borehole seal zone(s), exposing the borehole wall rock where borehole seals are to be set.	**Casing Removal from Test Boreholes** – Removal of casing from the Characterization Borehole is not required. In the FTB the uncemented guidance casing, and the intermediate casing design to removed for borehole sealing, shall be removed as part of the DBFT demonstration.
Disposal Zone Plugging – Plugs shall be installed in the disposal zone to stabilize stacks of waste packages and limit axial compressive loading of packages.	**Test Borehole Plugging** – Plugs shall not be installed in the Characterization or Field Test Boreholes in a manner that could interfere with availability of the borehole for additional testing.
Disposal Zone Plug Removal – Plugs installed in the disposal zone shall be designed for possible removal to facilitate waste retrieval.	(The Characterization and Field Test Boreholes will not be used for waste disposal. See Section 2.3.11 and associated requirements for the definition of retrieval to be used in the DBFT.)
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 including transport, handling, emplacement, and borehole sealing. Also, no leakage of borehole fluid into packages shall occur during these activities.	**Test Waste Package Containment** – Test packages shall prevent leakage of borehole fluid into the packages during repeated emplacement and retrieval testing operations.
Waste Package Containment Longevity – Containment lifetime after borehole sealing and closure shall be consistent with the licensed safety strategy.	(Test waste packages will be retrieved, so there are no requirements on containment longevity after the conclusion of testing.)
Waste Package Mechanical Integrity – Waste packages shall maintain mechanical integrity (structural, dimensional) during transport, handling, emplacement individually or in strings, and sealing.	**Test Waste Package Mechanical Integrity** – Test packages shall maintain mechanical integrity (structural, dimensional) during transport, handling, emplacement individually or in strings, and retrieval.
Disposal 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 is TBD.	**Test Disposal Zone Pressure** – Test waste packages shall perform 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.	**Test Waste Package Factor of Safety** – FoS for mechanical analysis shall be 2.0 with respect to minimum yield strength, as applicable to failure modes leading to test package breach during handling, emplacement, and retrieval operations.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
Waste Package Temperature During Emplacement – Waste packages shall perform at package-surface temperatures up to 250°C after emplacement.	**Test Waste Package Temperature** – Test packages shall perform at test package temperatures up to 170°C.
(Disposal waste package radial clearance will be determined sufficient based on the DBFT results and is TBD.)	**Small Waste Package Diameter** – Small test waste packages will be up to 5 inches in diameter.
	Large Waste Package Diameter –Large test waste packages will be up to 11 inches in diameter.
Waste Package Flush Exterior – The exterior waste package surface, including connectors, shall be flush and free of roughness that could hang up on casing joints, hangers, collars, etc., when moving upward or downward.	**Test Waste Package Flush Exterior** – The exterior test package surface, including connectors, may have detents or collars but shall be otherwise flush and free of steps or ridges that could hang up on casing joints, hangers, collars, etc., when moving upward or downward.
Waste Package End Tapers – Both ends of each waste package shall be tapered to facilitate emplacement and retrieval, whether packages are connected in a string or handled individually.	**Test Waste Package End Tapers** – Test packages or strings of packages, shall be tapered at the top and bottom ends to facilitate emplacement and retrieval.
Waste Package Connections – Waste packages shall have integral features for connection to: 1) other waste packages below; 2) drill pipe or other packages above; and 3) wireline above for emplacement or fishing. Connections must have sufficient strength to withstand mechanical loads during emplacement by wireline and drill-string methods, and during potential retrieval prior to sealing and closure.	**Test Waste Package Connections** – Test packages shall have integral features for connection to: 1) other test waste packages below; 2) drill pipe or other packages above; and 3) (for wireline packages only) wireline above for emplacement or fishing. Connections must have sufficient strength to withstand mechanical loads during emplacement and retrieval by wireline and drill-string methods.
Waste Package Length (Large) – Minimum internal length of the waste package (disposal overpack) shall be 5 m to accommodate various waste forms.	**Test Waste Package Length (Large)** – Test package internal length shall be up to 5 m to simulate waste disposal package dimensions.
Waste Package Length (Small) – Minimum internal length of the waste package (disposal overpack) shall be 5 m to accommodate various waste forms.	**Test Waste Package Length (Small)** – Minimum internal length shall be up to 5 m to simulate waste disposal package dimensions.
Waste Package Buoyancy – Waste packages, including the waste load, shall have negative buoyancy in borehole fluid (density TBD) to prevent package flotation.	**Test Waste 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 flotation.
2.3.11 Waste Package Emplacement and Retrieval	
Waste Package Emplacement – Waste packages shall be emplaced at the intended positions in the disposal zone, and shall not become stuck anywhere else in the disposal borehole.	**Test Waste Package Emplacement and Retrieval** – Test packages shall be emplaced at their intended positions and shall not become stuck anywhere within the Field Test or Characterization Boreholes.

<table>
<tr><th>Waste Disposal Requirement</th><th>Deep Borehole Field Test Requirement</th></tr>
<tr><td>(The circumstances necessitating retrieval of waste packages and the means by which retrieval would be accomplished are TBD.)</td><td>Retrieval – The term retrieval shall be taken to mean that test waste packages are emplaced, released, then reattached and hoisted from the borehole.</td></tr>
<tr><td>(The need for well head blowout prevention equipment in waste disposal boreholes is TBD.)</td><td>Field Test Well head Preventer – Test waste package emplacement and retrieval equipment shall be configured so that these operations can be performed with a blowout preventer stack in place if required.</td></tr>
<tr><td>Emplacement System Redundancy – The well head and emplacement apparatus shall have redundant means for holding packages and/or drill pipe so that single-point failures cannot result in dropped waste packages or drill pipe.</td><td>Emplacement System Redundancy – The well head and emplacement apparatus shall have redundant means for holding packages and/or drill pipe during rigging or tripping so that single-point failures cannot result in dropped test waste packages or drill pipe.</td></tr>
<tr><td>Borehole Fluid Density – The minimum density of any fluid filling the borehole when waste packages are emplaced shall be that of water, and the maximum density shall be controlled, and is TBD.</td><td>Borehole Fluid Density – The minimum density of fluid at any depth in the borehole, and the maximum average fluid density from the surface to any depth in the borehole, shall be controlled (see Table 2-4).</td></tr>
<tr><td colspan="2">2.3.12 Borehole Sealing</td></tr>
<tr><td>Seal Permeability – Borehole seals shall form a low permeability barrier to fluid flow within the borehole. Seal material shall have permeability less than 10^{-16} m^2.</td><td rowspan="5">DBFT Borehole Plugging and Sealing - The Characterization and Field Test Boreholes 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 is planned as part of the DBFT.</td></tr>
<tr><td>Seal-Borehole Contact – Borehole seals shall form a low-permeability contact with the borehole walls to prevent bypass flow at the interface.</td></tr>
<tr><td>Borehole Seal Durability – Borehole seals shall perform at in situ temperature, or if installed proximal to the disposal zone, at up to 200°C through the duration of the thermal period.</td></tr>
<tr><td>Seals Environment – Borehole seals shall resist mechanical loading from overlying materials in the borehole, retaining low-permeability properties.</td></tr>
<tr><td>Redundant Seal Design – Seals and sealing materials shall be designed to provide redundant performance.</td></tr>
</table>

Waste Disposal Requirement	Deep Borehole Field Test Requirement
2.3.13 Characterization Testing	
(Testing, logging, sampling, and other data collection requirements for disposal boreholes are TBD.)	**Safety Basis for Testing** – Testing, logging, sampling, and other data collection shall be directly linked to the deep borehole disposal safety case.
	Testing Baseline – Testing, logging, sampling, and other data collection, and disposition of samples, shall be specified in a testing baseline.
	Test Interference – Surface and subsurface testing activities shall be evaluated prior to deployment to determine whether they may significantly interfere with other testing activities.

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

Controlled Assumptions	
Waste Disposal Assumption	**Deep Borehole Field Test Assumption**
(Specific waste forms to be disposed of in deep bore-holes, at specific sites or geologic settings, are TBD.)	**Demonstrating Disposal of Waste Forms** – The DBFT will demonstrate technologies for disposal of waste packages that are designed to contain granular waste forms, HLW glass, HLW in sealed capsules, or spent nuclear fuel.
(Borehole total depth for borehole disposal of radioactive waste is TBD.)	**Test Borehole Total Depth** – The Characterization and Field Test Boreholes will be 5 km in depth.
Waste Package Strings – The number of packages in a string is limited to 40, and the number of packages stacked in the disposal zone is also limited to 40.	**Test Waste Package Strings** – When test waste packages are emplaced in the borehole by any method, the number is limited to 40.
(Leakage control requirements for waste packages during operations are TBD.)	**Test Waste Package Failure** – For testing purposes package failure can be determined on destructive examination, by detection of borehole fluid residue.
(The need for packaging or waste storage facilities in the field, proximal to disposal borehole locations, is TBD.)	**Test Waste Package Storage On-Site** – Test packages may be stored temporarily on-site, in a safe manner consistent with the objectives of the DBFT.
	Test Waste Packaging and Storage Demonstrations – The DBFT will not demonstrate the means of packaging actual wastes, or the storage of packages containing actual waste, in the field proximal to borehole locations.
(Long-term control and ownership of sites for deep borehole disposal of radioactive waste are TBD.)	**Site Ownership at DBFT Conclusion** – Assume that control of the field site and borehole(s) will be transferred to a different entity, or a different purpose, at the conclusion of the DBFT. Thus, the Characterization and Field Test Boreholes will be left in serviceable condition, to the extent possible.
(The need for directional drilling for disposal boreholes is TBD, and may depend on whether waste packages are emplaced using a wireline method, or lowered in long strings on drill pipe.)	**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 Characterization and Field Test Boreholes.
(Maximum density of borehole fluid when waste packages are present is TBD.)	**Borehole Fluid Maximum Average Density –** Average borehole fluid density is assumed to be less than or equal to 1.3× the density of pure water, between the surface and the waste package location, at in situ conditions.
Waste Package Delivery Rate – Assume one package per day can be delivered to the disposal site for disposal (Section 2.6.6).	(No assumption is needed for test package delivery rate because they will not contain radioactive waste.)

2.5 Previously Developed Waste Package Emplacement Concepts

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. Several previous studies evaluated feasibility and recommended technologies (Arnold et al. 2011). 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 the year 2000. Juhlin and Sandstedt (1989) concluded that deep boreholes with diameter up to 32 inches, suitable for disposal of used nuclear fuel, could be drilled and constructed to a depth of 4 km but at a total disposal cost greater than for the KBS-3 mined repository concept that is currently in license review in Sweden.

The Woodward–Clyde (1983) study included a relatively detailed concept for surface handling facilities and waste packaging design. It would require a separate 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 for insertion of the unshielded waste packages into the borehole. Hoag (2006) presented a waste package intended to contain a single pressurized water reactor (PWR) assembly or multiple boiling water reactor (BWR) assemblies, filled with silicon carbide grit as packing material to resist external hydrostatic pressure on the waste package. Juhlin and Sandstedt (1989) considered alternative packaging concepts constructed with titanium or copper, with nominal 5-m length and 0.5-m outer diameter.

Several relevant design elements and procedures were successfully developed and implemented for the Spent Fuel Test – Climax program at the Nevada Test Site (Patrick 1986). The program demonstrated the handling of commercial PWR used nuclear fuel in a mined repository environment in granite. Canisters containing used fuel assemblies were lowered by a heavy-duty wireline through a 20-inch cased borehole into a transfer vehicle situated in a gallery approximately 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 a diameter of 14 inches and length of approximately 15 ft, and contained a single PWR fuel assembly. Transport and surface handling of loaded waste packages was accomplished using a truck and shielded transport cask system that up-ended the cask to a vertical position over the borehole (Figure 2-1). Test operations were conducted successfully, safely, and with minimal radiation exposure to workers.

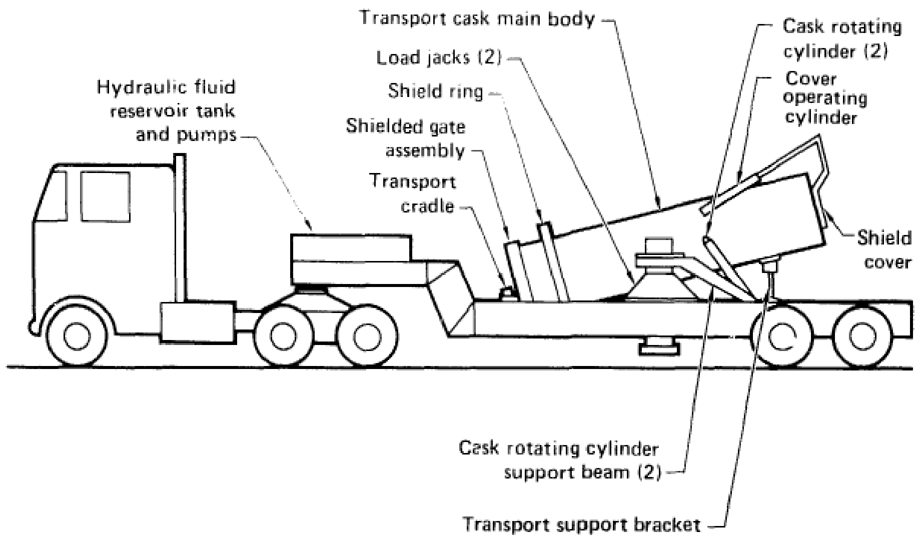

Figure 2-1. Transportation and canister emplacement system for the Climax spent nuclear fuel test (Patrick 1986).

2.6 Reference Waste Disposal Concept

The following brief discussion identifies some of the key features of the reference disposal concept, and aspects that are not yet well defined (e.g., completion of the disposal zone). For more complete description of the concept and how it could be used for disposal of different waste forms, the reader is referred to baseline documents (Arnold et al. 2011; 2014).

2.6.1 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). The FTB is designed to represent the configuration of disposal boreholes, based on currently available generic (non-site specific) information. The reference FTB design concept including casing plan is depicted in Figure 2-2.

Current geothermal practice is relevant because geothermal resources are usually found in hard, igneous rock and because the flow rates in geothermal production require large-diameter holes. Given that comparison, the drilling will most likely be done with a large, but conventional, drill rig using either rotary pipe and hard-formation roller-cone bits (tungsten-carbide insert, journal bearing) or possibly a downhole turbine with diamond-impregnated bits.

The requirements on the minimum distance between waste disposal intervals in adjacent holes and dogleg severity (Tables 2-3 and 2-4) could necessitate directional drilling. There are several ways to accomplish this using commercially available technology.

Further discussion of borehole drilling and construction is provided by Arnold et al. (2011), and the reference concept discussed in this report has changed only slightly from that work. In general, the borehole is designed from the bottom up to the surface casing (for which the depth is limited to that which can be safely drilled without a blowout preventer). The expected depth and

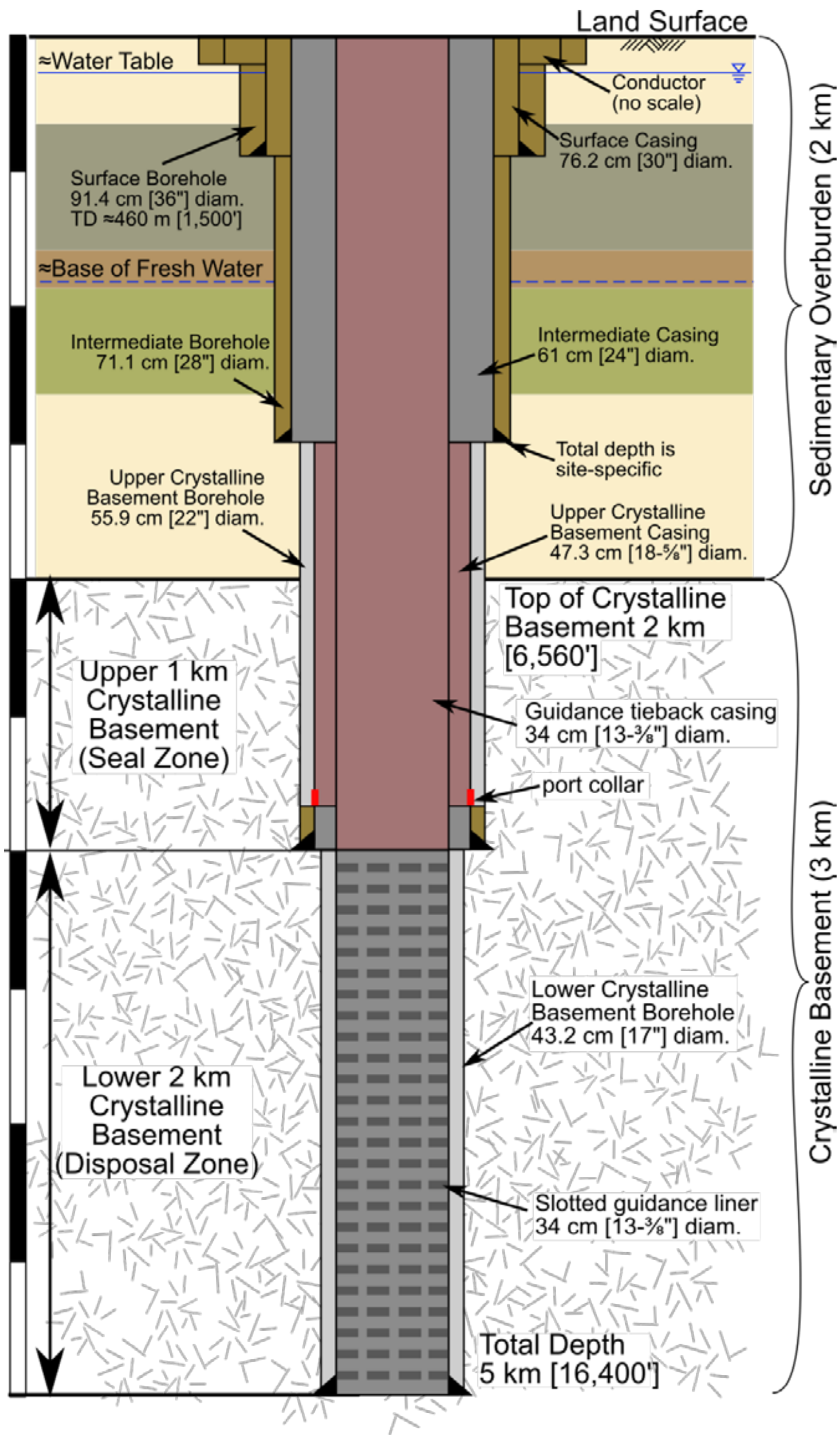

Figure 2-2. Field Test Borehole schematic. Dark gray represents permanent casing, pink represents casing to be removed, olive represents cemented annulus, light gray represents uncemented annulus. Seal and Disposal Zones refer to Arnold et al. (2011) design; no permanent seals or radioactive waste will be included in the DBFT.

diameter of the waste disposal zone will determine the wellbore geometry and casing program and most of the drilling equipment and casing selections will follow from those criteria.

Collapse pressure is shown with other casing specifications in Table 2-5. Formation pressure is not expected to be high enough to collapse casing filled with pure water, given the desired characteristics of the site. However, the likely existence of NaCl or $CaCl_2$ brine could increase the density of formation water by 30% or more, in which case mud weight can be adjusted to prevent collapse. This might limit the use of lightweight oil-based mud.

Table 2-5. 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 1	24	0.688	22.437	174	125,000	1170
Intermediate 2	18.63	0.693	17.052	136	125,000	1140
Guidance liner	13.38	0.380	12.459	54.5	56,000	1130
Guidance tieback	13.38	0.380	12.459	54.5	56,000	1130
See Arnold et al. (2011) for casing specifications and discussion of required fluid levels.						

The guidance casing consists of 2 km (6,560 ft) of 13-3/8 inch liner (54.5 lb/ft) hung from 3 km, and 3 km (approximately 10,000 ft) of 13-3/8 inch casing hung as a tieback from the surface. The lower hanger will be set in 18-5/8 inch casing, and will include a guide for the tieback. Above this hanger there would be a port collar as indicated in Figure 2-2, for cementing the lower end of the 18-5/8 inch intermediate liner, to support the lower 13-3/8 inch casing. The tieback hanger at the surface will be flanged to the surface casing and the blowout preventer above (see Section 2.6.4). At the lower end of the tieback, above the shoe, a mud check valve will be installed (not shown in the figures). This check valve will allow mud to be pumped down the 18-5/8 inch annulus and back up the tieback if one or more waste packages becomes stuck between the surface and 3 km during emplacement.

2.6.2 Disposal Zone Completion

Two important design questions for disposal zone completion are selection of an emplacement fluid, and the manner and extent of cementing for mechanical support. Injection of higher-viscosity grout (e.g., cement) around a stack or string of waste packages is not effective if done from above, after the packages have been emplaced. Hence the emplacement fluid would be circulated into the zone before waste emplacement.

In the reference design of Arnold et al. (2011) a synthetic oil based mud containing dehydrated bentonite was recommended as the emplacement fluid, along with cementing as discussed below. Although the waste packages would not be cemented in place, the high concentration of bentonite in the mud could provide support as it slowly hydrated. Emplacement mud could also provide lubrication for emplacement of long package strings, and retrieval if necessary. Other choices for emplacement fluid could include aqueous mud (which might be selected for higher weight and simpler chemical interactions with radionuclides), and brine (to condition the hole for hydrochemical similarity to waters in the host formation). Another important characteristics of the emplacement fluid is compatibility with the cement used in the disposal zone.

The functions of the guidance casing in the disposal zone include:

- Guide waste packages or strings of packages
- Support stacked waste packages so the ones at the bottom of the hole are not crushed
- Facilitate plugging to support stacks of waste packages, by guiding bridge plugs and cement, and providing a place to set the plugs even if the borewall is broken out. The cement plugs can also limit thermal convection of emplacement fluid throughout the entire disposal zone.

The guidance casing in the disposal zone will be suspended from a hanger at approximately 3 km depth, because the 2 km of 13-3/8 inch casing below that could buckle if set down on the bottom. The plan for emplacing up to 40 waste packages, then a bridge plug and 10 m (33 ft) of cement before emplacing more packages, will put the weight of all the waste packages, plugs, and cement on the guidance casing. Therefore the annulus around the guidance casing must be at least partially cemented to distribute the load to the surrounding host rock. Several approaches are available for cementing the guidance casing:

a) Before waste emplacement, circulate emplacement fluid throughout the disposal zone. The emplacement fluid would be heavy so it doesn't mix upward during emplacement operations. When cement plugs are set between stacks of waste packages, extra cement would be allowed to leak through perforations into the annulus, providing support to the casing.

b) Annular casing packers could be used for more precise cementing. One annular packer would be connected in the guidance casing string wherever a cement plug is needed. An emplacement fluid would first be circulated throughout the annulus, then cement would be squeezed through pre-drilled perforations above each annular packer, before waste emplacement. This would simplify installation of cement plugs later, which would involve precisely known quantities of cement. The approach would ensure that emplacement fluid occupies the annulus wherever waste packages are emplaced (with some loss of flexibility concerning where they are emplaced). Note that if the emplacement fluid is important to waste isolation, the waste packages could be centralized to maximize the potential benefit. However, the centralizing ribs or arms could increase the possibility of getting packages stuck.

c) A third alternative would hang waste package strings (using drill string emplacement) from casing hangers set in the guidance casing. This could eliminate the bridge plugs and cement plugs installed during emplacement, cutting down on the potential for cement debris in the hole. But the guidance casing would still require support from fully or partly cementing the annulus. And the disposal zone could require plugs anyway, so that it is not hydraulically connected over its entire length.

d) Another option would cement the entire disposal zone guidance casing annulus during construction, using perforations. The casing would then be cleaned out and filled with emplacement fluid. This would simplify waste emplacement because cement plug location would not be critical and smaller, more precisely known amounts of cement could be used. It would install cement, not emplacement fluid, in the annulus where waste packages are emplaced.

The guidance casing will probably be perforated by drilling holes at the size and locations needed. The functions of these perforations include:

- Dissipate pressure when waste packages or strings of packages are lowered
- Not allow too much fluid surge when emplacing waste packages or tripping out, to limit the flux of debris from the annulus into the casing
- Control surge when one or more packages is accidentally dropped, to limit terminal sinking velocity
- Allow heated, expanding fluid to escape to the annulus after waste packages are emplaced

Note that pressure dissipation could be achieved with many perforations, while controlling surge means limiting the number. Conventional slotted liner would be weaker than unperforated casing, it would leak cement, and it could potentially allow too much pressure dissipation if waste packages were accidentally dropped in the hole. Mud surge in or out through casing perforations could bring debris into the emplacement path, foul the emplacement fluid and generally increase the probability that waste packages or strings of packages could get stuck. The size, location and number of perforations would be designed with these objectives.

Selection the disposal zone completion design from among these or other alternatives is beyond the scope of this report. As discussed in Section 3, the DBFT will not involve stacking waste packages in the guidance casing, setting cement plugs, or completing the disposal zone for waste emplacement.

2.6.3 Disposal Operations

Once borehole construction is complete in preparation for waste emplacement, borehole qualification can proceed. Qualification would consist of monitoring the borehole fluid level and acoustic emissions, and surveying the casing or wireline condition, over a period of weeks or a few months. The objective would be to increase confidence in borehole and casing stability over the projected duration of waste emplacement. This phase could also include running in a dummy package, or a string of dummy packages, to verify operation of the emplacement equipment and clearance in the borehole (especially at known doglegs, for drill-string emplacement).

Immediately prior to emplacing a waste package or string of packages, 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 is intended to identify any waste leakage into the borehole fluid. The gauge ring would be sized slightly larger than the waste packages, 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.

Each waste package would arrive at the site in a purpose-built Type B shipping cask, on a purpose-built truck-trailer. Depending on shielding requirements, one or more waste packages can be carried in a shipping cask. The Woodward–Clyde (1983) 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. Even though the Woodward–Clyde waste packages would have been shorter (less than 4 m overall length), the resulting triplet of packages would have required a longer transfer cask, higher elevation of the rig floor, and a deeper rig basement.

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

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

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

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

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

The Spent Fuel Test-Climax developed and deployed a purpose-built surface transport cask similar to that described above (Patrick 1986; DOE 1980). The SFT-Climax cask was not certified as a Type B shipping cask, however, its design provides an analogue for DBD application. The top lid of the Climax shipping cask was made of steel approximately 7 inches thick, attached by means of a hinge. The top lid was opened and closed by a double-acting hydraulic cylinder attached to the cask body. The bottom lid was a sliding door assembly with steel doors approximately 18 inches thick. The sliding doors were electrically actuated, and moved on lubricated slides driven by lead screws. The Climax shipping cask was made mostly of steel, and weighed approximately 90,000 lb (45-inch OD, 18-inch ID, and 18-ft length).

2.6.4 Drill-String Emplacement Option

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

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

A reinforced-concrete basement excavation will be constructed around the conductor and surface casing (Figures 2-3 and 2-4). The choice of construction methods, basement cross section, and other details will depend on site conditions (e.g., deep unconsolidated soil vs. bedrock). The basement structure will need to withstand loading at the ground surface by the emplacement workover rig (see discussion of surface pad below). The rig will exert forces on the order of 10^6 pounds at various locations close to the excavation. The basement could be circular or rectangular in cross section, and lined with steel or concrete. The basement floor will be reinforced concrete with footings to support load-bearing structural components (i.e., either the walls, or an internal structural frame).

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

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

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

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

The basement will have a ceiling at grade level that shields the rig above from gamma radiation emanating from waste packages when they are located in the basement interval. The ceiling will also support the shipping cask during waste package transfers. It will consist of two or more movable plates of steel or prefabricated reinforced concrete. The plates will be keyed and bolted together in place, forming a load-bearing platform with a central hole (Figures 2-3 and 2-4).

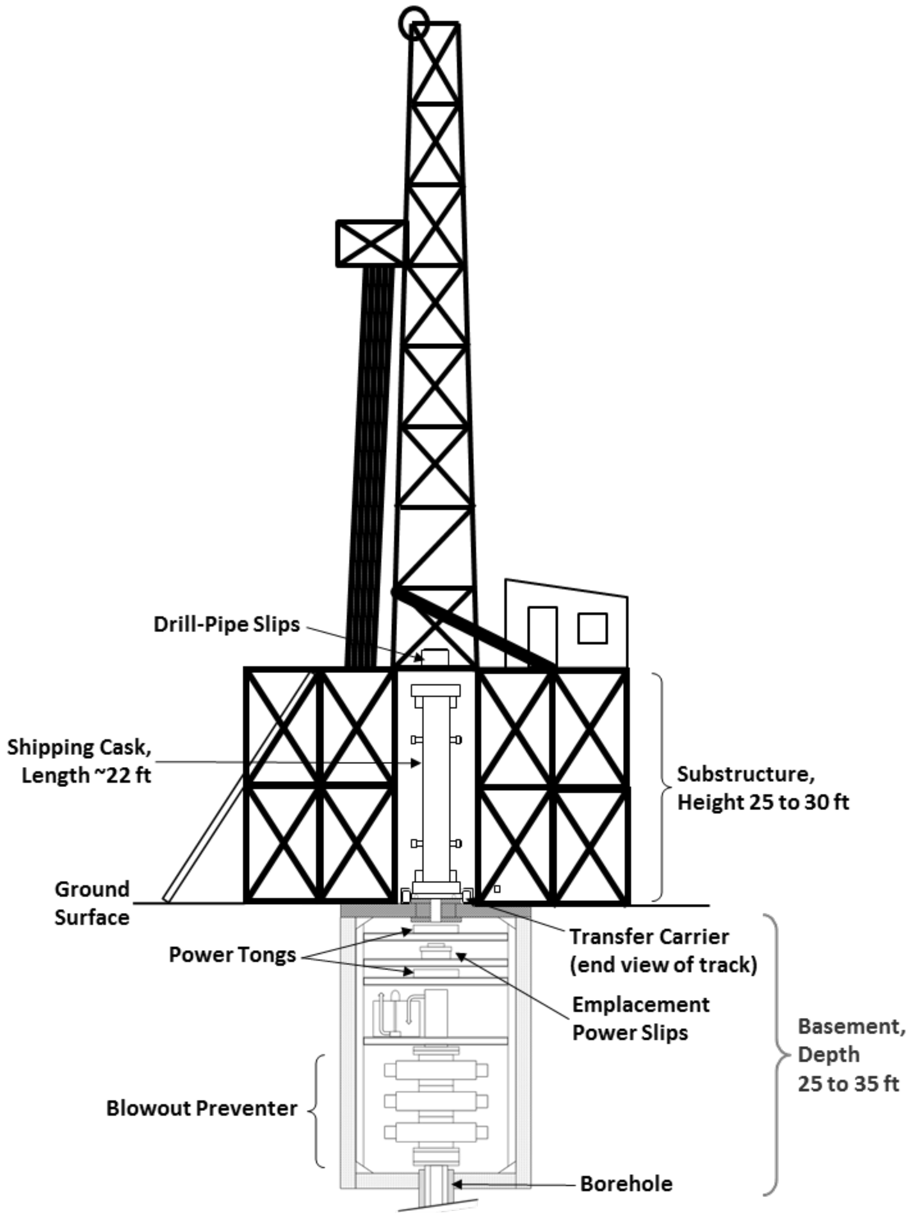

Figure 2-3. Schematic of emplacement workover rig, basement, transport carrier, and shipping cask in position for waste emplacement (not to scale).

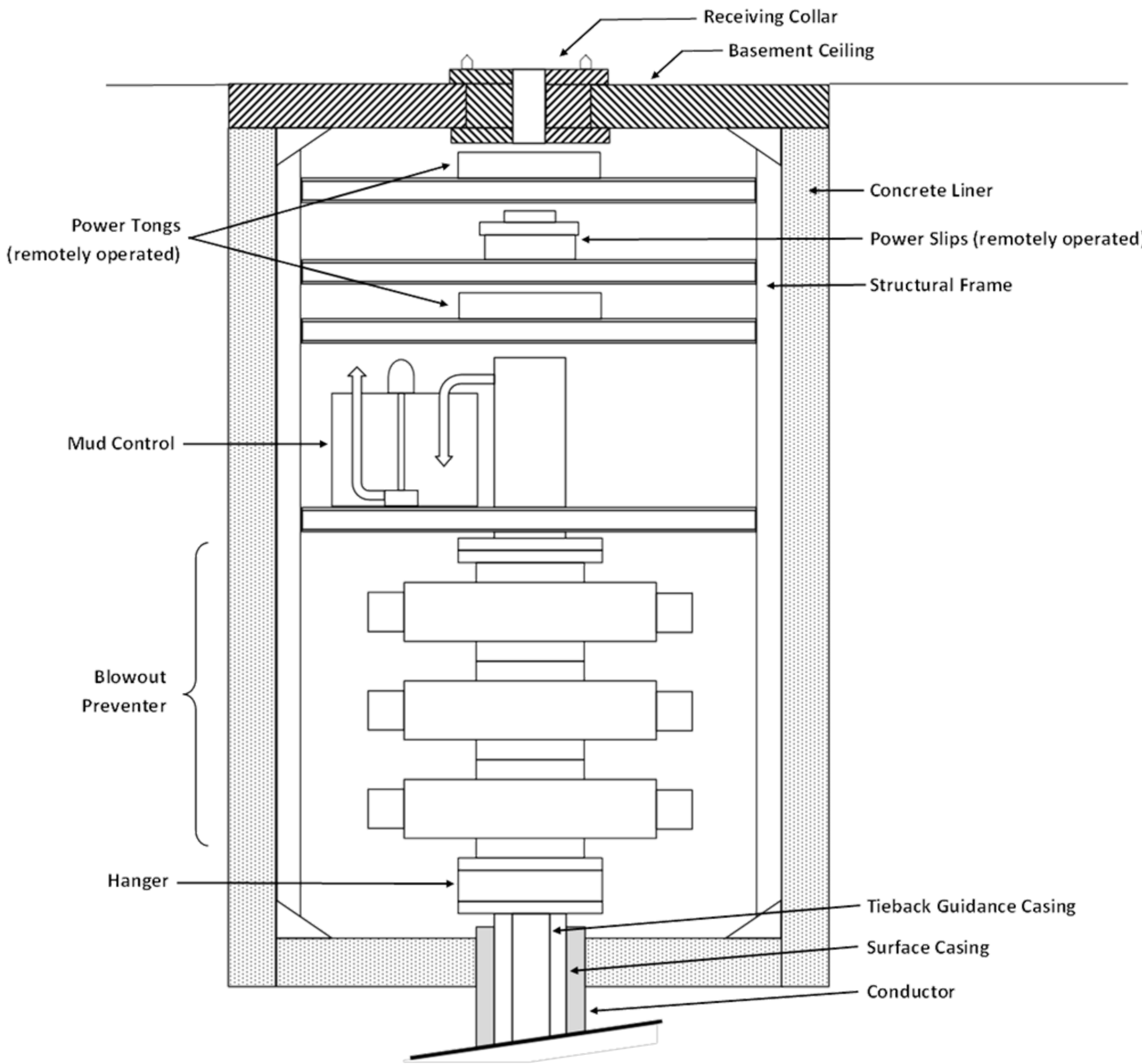

Figure 2-4. Basement concept for drill-string emplacement (not to scale).

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

A receiving collar will be installed in the central hole in the ceiling, aligned with the borehole. The functions of the receiving collar are to: 1) anchor the shipping cask and transporter platform over the borehole; 2) guide the shipping cask into position over the borehole; 3) provide shielding between the basement ceiling and the shipping cask; and 4) provide a central hole for access to the borehole, that is a clearance fit with the waste package upper end to limit radiation leakage. The receiving collar and basement ceiling will support weight of the shipping cask (at least 66,000 lb, the weight of a hollow steel cylinder with 12-inch wall, plus heavy doors), and the waste package, at an appropriate FoS (Section 2.3.10). The shipping cask will be present only when assembling or disassembling strings of waste packages. The receiving collar and basement ceiling will also resist an inadvertent upward pull by the rig hoist, sufficient to release the breakaway sub (greater than the weight of a string of waste packages, or approximately 200,000 lb).

Emplacement power slips will be installed below the receiving collar and above the BOP (Figures 2-4 and 2-5). The function of these slips will be to grip the package string and prevent vertical movement during string assembly (or disassembly if required). The power slips will be remotely and hydraulically actuated. A separate set of slips at or just below the rig floor will be used to hold the drill string as pipe joints are made up or broken down during trips into/out of the borehole.

Figure 2-5. Example of power slips (courtesy of National Oilwell Varco).

A remotely operated power tong will be installed just below the power slips to prevent rotation of the package string when making joints in the string (Figure 2-6). An upper set of remotely operated tongs above the slips will be used to thread packages onto the string held below. Breaking of joints in the package string (e.g., if the string must be removed from the borehole) will also use both sets of tongs.

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

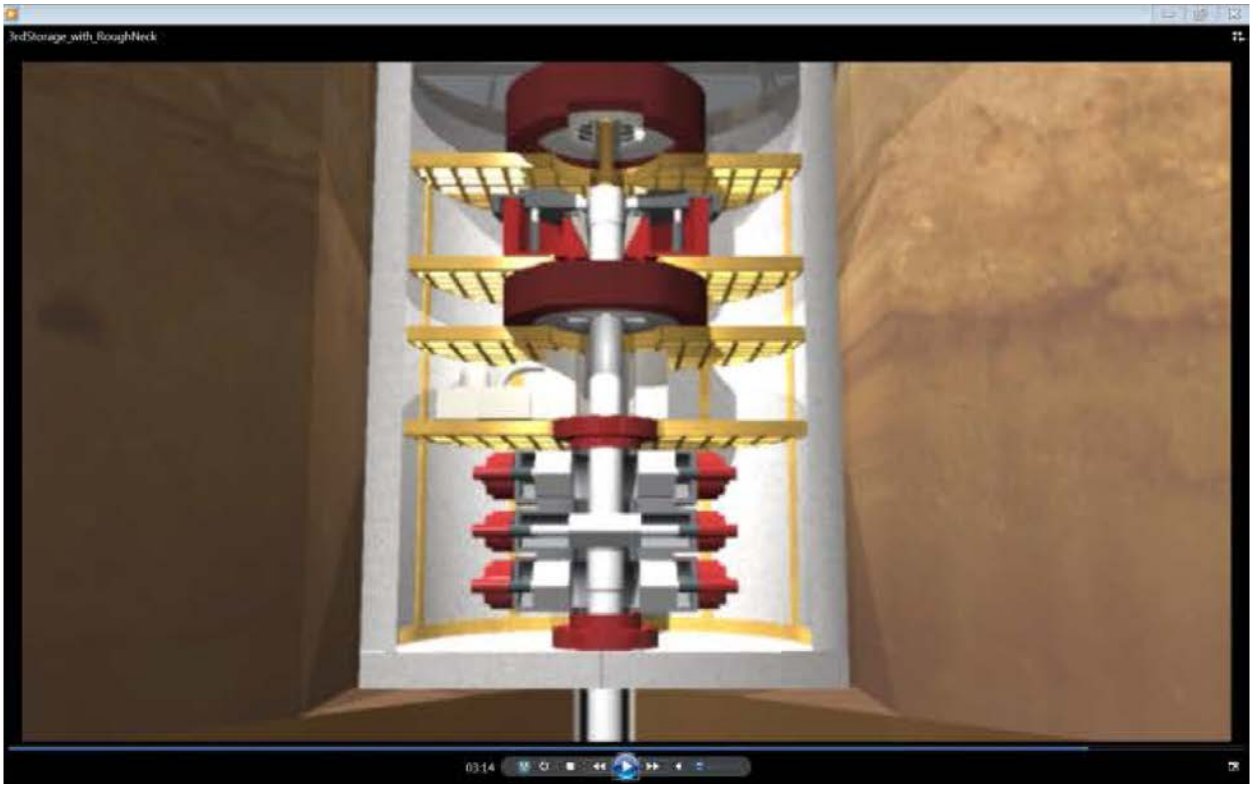

Figure 2-6. Cutaway visualization of basement including (from top down): upper tongs, power slips, lower tongs, mud control, three blowout preventers, and the guidance casing hanger.

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

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

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

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

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

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

Transfer Carrier Installation – Following the Woodward-Clyde (1983) concept, a track-mounted transfer carrier will deliver the shipping cask over the last 50-ft distance to the borehole. It will consist of a platform mounted to four wheel trucks that run on a steel track. The wheel trucks will grip the track both above and below so that they cannot be derailed. The track will be part of a rigid steel frame that is anchored to the surface pad. The track will be approximately 6 ft wide, straddling the borehole, precisely aligned (Figure 2-7). Mechanical details of the transfer carrier are to-be-determined (TBD).

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

Figure 2-7. Visualization of transportation/transfer cask mounted on transfer carrier, on a track under the rig floor, leading to the well head.

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

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

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

The combined weight of waste packages and drill pipe will be approximately 468,000 lb based on 154,000 lb buoyant weight for 40 waste packages in pure water, and 314,000 lb for 15,660 ft of drill pipe at 20 lb/ft. The heaviest lift for the emplacement workover rig will be removal of the guidance liner tieback (approximately 550,000 lb, assuming 10,000 ft of 13-3/8 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 wall thickness. Several approaches are available to deal with the weight of drill pipe while maintaining an FoS, including: 1) use lighter weight pipe (e.g., 16 lb/ft or less in steel or aluminum) in the lower part of the hole, and heavier pipe (20 lb/ft) in the upper part; and/or 2) lower fewer waste packages at a time in the lower part of the hole, since waste packages will comprise about a third of the total string weight.

Making and breaking threaded drill pipe joints is one of the riskiest tasks in a drilling operation from the standpoint of worker safety and improperly made joints. Accordingly, it is recommended that an "iron roughneck" (Figure 2-8) be used to make and break drill pipe joints. Iron roughnecks clamp the bottom pipe section while a rotary wrench turns the top section. The example shown stands about 10 ft tall in the stowed position, and handles pipe from 3½ to 10 inches in diameter with maximum make-up torque of 100,000 ft-lb and break-out torque of 120,000 ft-lb. It is pedestal mounted to the rig floor. The "iron roughneck" is not fully automated; an operator stands at a control panel. It does not necessarily increase the speed of pipe joint operations but it improves safety and reliability by reducing variability and the potential for human error. Whereas modern fully automated rigs are available, the "iron roughneck" represents a compromise that can be used with a wide range of rig types and could achieve similar reliability in joint tending.

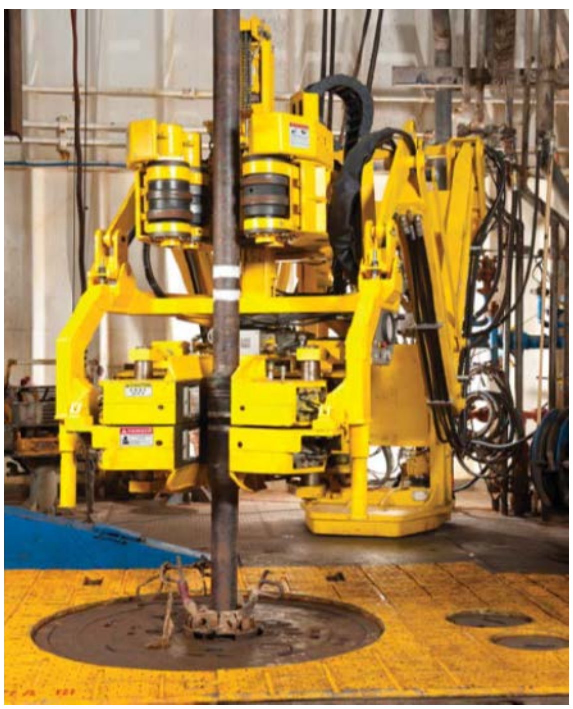

Figure 2-8. Mechanical "iron roughneck" pipe joint tender (Wrangler Roughneck 120 TM).

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 Steps – Before the shipping cask is placed over the borehole, a borehole qualification procedure will be run to ensure safe condition of the borehole (Section 2.6.3). A crane would lift the shipping cask by one end from the trailer and lower it onto the transfer carrier (Figure 2-7). The shipping cask would be aligned using index pins, and bolted onto the transfer carrier. The transfer carrier then slowly moves down the track and positions itself over the borehole receiving collar. Additional steel guides high in the rig substructure could further stabilize the cask in its vertical orientation. The transfer carrier wheels, track, and drive mechanism could be optimized for safety and control. Kneeling jacks at each wheel of the transfer carrier would lower the cask down onto the receiving collar, where it would be clamped or bolted in place.

Emplacement Steps – After the shipping cask has been bolted/secured to the receiving collar, the following steps will be used to make up a string of waste packages in the borehole and then use drill pipe to lower the string of packages to the emplacement interval in the borehole. The number of packages in a string is up to 40 (Table 2-4).

1. Remotely open the upper door on the shipping cask (shielding is provided by the shield plug integral to the waste package).
2. Attach the breakaway sub (for use in making up waste package strings, see text) to the rig hoist (e.g., using an elevator device).
3. Verify radial restraining bolts on lower end of shipping cask (restrain waste package from spinning when threading on drill string).
4. Remotely attach the breakaway sub (pin) to the threaded connection on the upper end of the waste package (box) inside the Type B shipping cask, with minimum torque sufficient for picking up the waste package (without shearing the rotation restraining bolts).
5. Back out the rotation restraint bolts from lower end of shipping cask (free the waste package).
6. Slightly lift the waste package with the breakaway sub (permanently fixed range-limiting blocks or pins will prevent waste package from being withdrawn beyond the shield).
7. Check status of breakaway sub, cask doors, basement power slips, basement tong, “elevator” ram, drill pipe ram, and blind ram (these are interlocked).
8. Remotely open the lower door on the shipping cask.
9. If this is the first (lowermost) instrumentation package (see text), then remotely lower the instrumentation package so it is in the correct position, grip it with both the power slips and the “elevator” ram, engage the basement tong (prevents rotation), and apply weight to set the slips.
10. Remotely open blind ram and drill pipe ram.
11. If this is a subsequent waste package in a string, remotely lower the package onto the previous package in the slips.

12. Rotate the breakaway sub/waste package using the automated tender at the rig floor, and make the threaded connection with the previous package.
13. Verify threaded connection between packages (e.g., log makeup torque).
14. Disengage basement tong and “elevator” ram.
15. Slightly lift the package string to disengage the emplacement power slips.
16. Lower the string so it is in correct position, grip it with both the power slips and the “elevator” ram, engage the basement tong, and apply weight to set the slips.
17. Disconnect the breakaway sub and raise it back through the shipping cask.
18. Close upper and lower shipping cask doors.
19. Reverse handling steps (see above) to remove shipping cask.
20. Repeat handling steps (see above) and steps 1 through 18, to add additional waste packages to the string.
21. After final waste package is added, reverse handling steps (Section 2.4.2) to remove shipping cask.
22. Remove the breakaway sub and attach the J-slot device to the first stand of drill pipe.
23. Thread the J-slot device into the top waste package using an extension sub if necessary to reach the box thread in the emplacement power slips. Torque the connection.
24. Verify threaded connections between drill string and package string (e.g., log makeup torque).
25. Disengage basement tong and “elevator” ram.
26. Slightly lift the package string to disengage the emplacement power slips.
27. Lower string into position for adding a stand of drill pipe.
28. Actuate the drill pipe slips (on the rig floor) and basement pipe ram (and/or emplacement power slips).
29. Add another stand of drill pipe; make the joint with the “iron roughneck.”
30. Disengage the basement pipe ram.
31. Slightly lift the string and disengage the drill pipe slips (and emplacement power slips if used).
32. Lower string into position for adding another stand of drill pipe, or lower string into emplacement position (if on bottom).
33. Repeat steps 28 to 32 until emplacement depth is achieved.
34. With the string secured in the drill pipe slips, attach a rotation device (e.g., kelly).
35. Disengage the basement pipe ram.
36. Slightly lift the string and disengage the drill pipe slips (and emplacement power slips if used).

37. Gradually lower the string until the force on the bottom is within specification to operate the J-slot safety joint.
38. Disengage the canister string using the J-slot safety joint.
39. Hoist the string into position for removing the rotation device.
40. Actuate the drill pipe slips, basement pipe ram, and emplacement power slips if used.
41. With the string in the slips, remove the rotation device.
42. Disengage the basement pipe ram.
43. Slightly lift the string and disengage the drill pipe slips (and emplacement power slips if used).
44. Hoist the string into position for removing another stand of pipe.
45. Actuate the drill pipe slips, basement pipe ram, and emplacement power slips if used.
46. Remove another stand of drill pipe, breaking the joint with the "iron roughneck."
47. Repeat steps 42 to 46 to trip out of hole.
48. Remotely close the blind ram.

Waste packages would be emplaced in the disposal zone in strings of up to 40, with a total length that will depend on the internal waste cavity length, with allowance for end plugs, fittings and inter-penetration of threaded connectors. Each waste package string would be lowered to the waste disposal zone and would rest on the bottom of the borehole in the case of first string or on the bridge plug and cement emplaced above the previous waste package string for subsequent canister strings. The waste package string would then be disengaged from the drill pipe using the J-slot assembly. A bridge plug and cement would be set above the waste package string prior to the emplacement of the next waste package string. The bridge plug would be set some distance above the top of the uppermost canister in the string to allow for differential thermal expansion of the steel waste package string from the heat generated by the waste.

2.6.5 Wireline Emplacement Option

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

Surface Pad – A steel-reinforced concrete pad, approximately 25 feet on a side, will be poured around the well head at grade level, as a base for the BOP shield and other items. The pad construction will include footings for the headframe discussed below.

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

A robust radiation shield will be constructed around the BOP (Figure 2-10). The shield will consist of two concentric, large diameter, corrugated metal culverts set up vertically and coaxially with the BOP. The height of the culverts will be just taller than the BOP. The culverts will be assembled from curved, corrugated structural plates, with flanges that are bolted together. The inner culvert will have flanges on the inside, and the outer culvert will have flanges on the outside, to access bolts for disassembly.

Figure 2-10. Schematic of BOP shield, top plate and shipping cask in position for waste emplacement (not to scale, and headframe not shown).

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

A top plate on the shield will be made in two semi-circular sections, pre-fabricated from reinforced concrete. The pieces will form a hole at the center for the surface casing, and they will be keyed together to limit radiation shine. The plates will be bolted down to the shield walls described above. The top plate pieces will have shielded doors for ventilation and worker access. A heavy, cylindrical steel receiving collar will fit into the hole and bolt to a flange on a section of 24-inch casing that is attached to the well head stack (Figure 2-11). The receiving collar will provide an interface to the shipping cask and a clearance fit for insertion of waste packages (limiting gamma shine through the gap). The culverts and collar will support the weight of the shipping cask (at least 66,000 lb as discussed previously) and the waste package, with an appropriate FoS. Functionally, this receiving collar will be identical to that described for drill string emplacement. The shipping cask inside diameter will also be a clearance fit with the waste package, to limit radiation shine as the package is lowered into the borehole. The BOP shield, top plate and collar will be designed for removal after waste emplacement operations are complete.

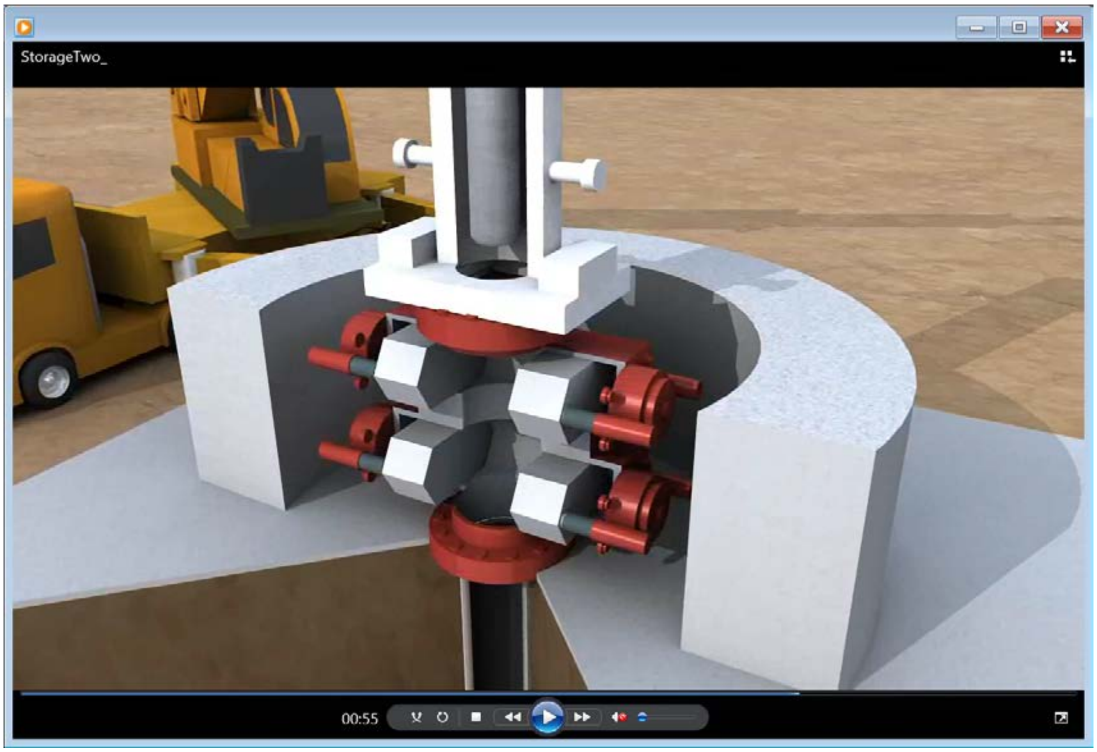

Figure 2-11. Detail of well head inside BOP shield, with doors opening in preparation for lowering waste package (mud handling equipment and headframe not shown).

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

Hoist and Wireline – A standard truck- or skid-mounted wireline unit with at least 20,000 ft of modern wireline such as Schlumberger Tuffline® will be used. This example has 7-conductors, and uses double-armor made from corrosion resistant steel, fully encapsulated (fully blocked) with a high-temperature synthetic polymer. The armor is torque-balanced so that "seasoning" is not required. It has a minimum 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 of the wireline is approximately 5,800 lb (350 lb per 1,000 ft at 16,400 ft, in pure water), and the maximum buoyant weight of a reference waste package is approximately 3,860 lb (Section 2.4) giving a total maximum wireline tension of 9,660 lb, plus the weight of the cable head and any additional logging tools, and subs used on the waste package.

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

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

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

The additional cost and potential safety implications associated with detecting and replacing damaged tubing, and the 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 limited tubing life. Note that even with wireline emplacement operations, coiled tubing would still be used to set cement plugs as discussed below.

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 set up over the borehole. The reinforced concrete surface pad would include headframe footings. 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 probabilities for failure during waste package handling and emplacement. A similar fixed headframe was used for the Spent Fuel Test – Climax (Patrick 1986).

Cable Head – An electrically actuated cable head will release packages in the emplacement position. Examples of this type of equipment include the Haliburton RWCH® (releasable wireline cable head) and the Schlumberger SureLOC® 12000. Off-the-shelf tool designs will need to be modified to: 1) minimize the length and cost of the hardware left in the hole with each package; 2) to ensure appropriate load rating; and 3) to achieve the function of release only without load (see Sections 2.7 and 3.3).

Boom-Type Crane –A crane will be used to remove impact limiters from the transportation cask, hoist transportation casks onto the BOP shield receiving collar, and to support the coiled-tubing injector.

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

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

Completion/Sealing Workover Rig – After waste emplacement a workover rig will be mobilized to remove the guidance liner tieback (approximately 540,000 lb as discussed previously) and the intermediate casing section from the seal zone (approximately 3,000 ft of 18-5/8 inch casing). The same rig will be used for seals emplacement and plugging of the disposal borehole.

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

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

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

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

Emplacement Steps – After the shipping cask has been bolted/secured to the receiving collar, the following steps will be used to lower individual waste packages to the disposal zone by wireline:

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

13. Repeat handling steps (see above) and steps 1 through 12 above, to emplace additional waste packages.

2.6.6 Emplacement Rate Discussion

Drill-String Emplacement Rate-of-Progress – Drill pipe will 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 waste packages will take approximately 15 hr, and the round-trip time will be approximately 32 hr (15-hr trips and 2 hr for package release).

Wireline Emplacement Rate-of-Progress – Reference rate for lowering waste packages would be comparable to lowering bridge plugs (6,000 ft/hr or 1.7 ft/sec; Arnold et al. 2011). The rate of waste package emplacement will be controlled by the maximum waste package sink rate, which in turn depends on: 1) radial clearance (minimum 0.7 inches, Section 2.3); 2) borehole fluid viscosity (temperature dependent); and 3) waste package buoyant weight. Assuming a sink rate of 1.7 ft/sec is feasible, and that the wireline would be respooled at twice this rate, the round-trip time for wireline emplacement would be approximately 6 hr. In addition, the wireline descent rate for the first 1 km (3,280 ft) would be limited to 0.5 ft/sec to control load transients that could break the wireline with a waste package attached (see Section 2.7.1 and Appendix B).

Logistical Controls on Emplacement Schedule – As discussed in Section 2.4, it is assumed that one shipping cask/waste package per day can be delivered to a disposal facility. This estimate is based on operational experience at the WCS site in Andrews, Texas. A paper describing the operation (Britten 2013) states that their initial handling rate was one package every four days, which was later improved to one package every three days (verbal communication). Three or more packages are active in the process, giving a throughput of one per day.

The proposed operations at a disposal facility will likely be faster because: 1) there is no need for intermediate waste transfers to other vessels prior to emplacement; and 2) waste packages will have no external contamination.

It is estimated above that approximately 32 hours will be required to lower one string of 40 packages to the emplacement interval, but it will take approximately 40 days to accumulate the 40 packages. In addition, placing a bridge plug and a cement plug will require additional equipment and two to three days per interval.

This rate of emplacement (averaging approximately one per day) has implications for logistics at a disposal facility. For the reference borehole, approximately 430 workdays will be required to emplace the 400 waste packages and 10 cement plugs. Additionally, there will be holidays and weather days (e.g., an additional 5%). A similar rate of emplacement will be achieved with wireline emplacement, particularly if operations are limited to daylight hours.

Self-Emplacement ("Drop-In") – With a guidance liner running from the surface to TD, and the borehole filled with an emplacement fluid with controlled properties, it could be possible to allow waste packages to sink freely into disposal position. Terminal velocity was estimated by Bates et al. (2011) to be on the order of 8 ft/sec for similar waste packages (Section 4.2). Impact-limiting crushable materials with properties suitable for this application are readily obtained.

Note that if slotted casing is used in the disposal zone, the waste package terminal velocity could be significantly greater.

2.6.7 Waste Packages

In this work the term *disposal overpack* refers to a heavy-wall, sealed container that withstands the downhole environment, and contains one or more thin-wall waste canisters. Waste canisters will be loaded and sealed at the point of origin for the waste, and may contain Cs/Sr capsules, or bulk granular waster forms. Such pre-packaged wastes are identified as *canistered wastes*. The disposal overpack could be loaded and sealed at an upstream hot-cell facility (not necessarily at the waste point-of-origin since the canistered waste could be readily transported).

Alternatively, bulk granular waste such as the DOE-owned, granular calcine waste form, could be loaded directly into a heavy-wall *waste package* at the point of origin using a design concept such as the flask-type concepts described below. The waste package would be sealed in a hot-cell facility at the waste point-of-origin.

The term *waste package* is also used more generally for the final, sealed vessel, that is ready for emplacement in a deep borehole, regardless of its size or whether it is a flask-type or internal-flush design.

Borehole Environment – All packaging concepts presented in this report are intended to ensure that the waste is isolated from the borehole, in a one-atmosphere pressure environment, at downhole temperature, in a 16,400 ft deep borehole containing fluid that has average density (from the surface to the waste package) 1.3× that of pure water, for at least 10 years. Additional design requirements are presented in Section 2.3.

Waste Forms – Waste packages will contain bulk waste material (e.g., granular solids) in a thin-wall canister that is used for upstream handling and storage, or they will be loaded with bulk granular waste directly. In either case, the overpack or package must maintain containment during emplacement operations and borehole plugging and sealing (until breach after permanent closure). From the exterior, the directly loaded waste package and the disposal overpack for thin-wall canisters will be similar in appearance.

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

Design Factor of Safety – A minimum FoS will be used for mechanical analyses of the waste packages (Section 2.3). Packages and connections between packages (if applicable) will have sufficient strength to withstand mechanical loads during emplacement, retrieval, and fishing of stuck packages (or package strings, if packages are threaded together).

Package Dimensions – To simplify design and fabrication, oilfield tubing or casing is used in the packaging concepts presented here, for the tubular portion of the packages. For the packages with a maximum OD of 11 inches, the conventional tubing size is 10-3/4 inch OD x 8-3/4 inch ID. For the smaller packages the conventional casing size is 5-inch OD x 4-inch ID.

Waste package length has not been finalized. The overall external length used in this report is 18.5 ft, which includes an internal waste cavity length of 16.4 ft (5 m), the shield plug and lower end plug, connection threads, and a small separation of welds from connector threads to limit heat damage. Arnold et al. (2011, page 37) presented a reference external length of 15.75 ft; the additional length adopted here will increase the internal dimension of the waste cavity to 16.4 ft (controlled by requirements, Section 2.3). It will add a 1-ft thick shield plug at the upper end (Figure 2-12), thicken the lower endcap for structural strength, and allow increased separation of welds from the connector threads to limit heat damage. The 18.5-ft overall length is a maximum, chosen to accommodate commercial PWR fuel, and the package length can be adjusted by varying the length of the tubular part. The handling and emplacement systems could accommodate shorter packages, with certain complications noted in Sections 2.6.4 and 2.6.5.

Package Weight and Buoyancy – It is estimated that the loaded waste packages will have a dry weight of 4,620 lb (for the reference size package with 11-inch outer diameter). The basis for this is provided in the assumptions (Section 2.4). Granular waste forms would probably be less dense, and the package wall thickness could be smaller with higher strength material. From Section 2.4, the reasonably bounding buoyant weight of a loaded waste package is 3,630 lb in 1.3× drilling mud, or 3,860 lb in pure water.

For the small-diameter packages (concept Options 3 and 4 below) the buoyant weight of each package is calculated to be 690 lb, assuming that each package contains eight Cs/Sr capsules, and that each capsule weighs up to 44 lb including a thin-wall canister or basket (the weight of each capsule is approximately 22 lb or less; Randklev 1994).

Package String or Stack Weight – If 40 reference-size waste packages (11-inch OD) are assembled in a string and hung in the borehole, the axial tensile loading from the combined weight is estimated to be approximately 154,000 lb (buoyant weight in pure water). A compressive load of similar magnitude will be produced when the package string is emplaced on the bottom, at rest. For a similar string of forty smaller diameter (5-inch OD) packages the axial loading from the combined weight will be approximately 27,600 lb.

When a string of packages is set down on the bottom of the hole, before it is disconnected from the drill pipe, the compressive load on packages will be controlled by the rig hook load, as well as friction between the string and the guidance casing. This load will be controlled in order to limit compressive loading of the safety release device (Section 2.6.8). The maximum load on the lowermost reference-size package could approach 500,000 lb (the weight of the drill pipe and the package string). If the full weight of the string is set down on the bottom, the axial stress in the lowermost package could increase by approximately 20,000 psi (not considering eccentric or point loading). Engineered measures to prevent load surge through the package string should be considered, such as a crush-box at the bottom of each string that would reduce hook load by a noticeable amount and limit load on the bottom (until the maximum range of crush-box deformation was reached).

When packages are stacked one-by-one in the borehole, the number is also limited to 40 to limit axial loading of the bottom package. A plug must be set in the guidance casing before more packages can be emplaced. The selection of 40 packages is a remnant of previous studies (Arnold et al. 2011). Such a limit controls the total weight of the drill string (packages plus drill pipe) during drill-string emplacement, and also controls the column loads on the guidance casing between cement plugs. A greater number makes more efficient use of the disposal zone by limiting the number of cement plugs. A maximum of 40 is specified (Section 2.3), but the number can be adjusted down based on engineering analysis and safety considerations (see Section 5.6.3 for discussion of the risks involved).

Packages must be designed for axial loads (i.e., 154,000 or 27,600 lb), transient loads during handling and emplacement, and hydrostatic pressure of 9,560 psi. If the package is subjected to bending (because the guidance casing is curved over the length of a package string) then there are additional tensile and compressive loads that the package must withstand. The effects from these axial loads on the collapse strength of the tubular portion of the packages are addressed by the stress analysis described in Section 4.1.

Downhole Temperature – At 16,400 ft depth the in situ temperature could be as high as 170°C, and for heat-generating waste the peak package surface temperature could be 250°C (Section 2.3). The former temperature is the maximum (unheated) in situ temperature for test waste packages, and for actual waste packages if they produce little heat. The latter temperature is loosely based on thermal analysis for packages containing Cs/Sr capsules (Section 4.5). Drilling and emplacement operations will circulate cooler fluid, but borehole fluid temperature will recover to formation temperatures after a few weeks without circulation.

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). The 110 ksi material analyzed in Section 4.1 retains 87% of its normal yield strength at 200°C (Renpu 2011). Various manufacturers also provide estimates of this design factor. Tenaris reports an average value of 86% for their 55 ksi yield strength casing. Grant Prideco reports 74% and Hunting 82% for their 80 ksi yield strength casing.

Package Connections – The use of standard threaded connections on both ends of each package will allow multiple emplacement options. The packages can be emplaced singly, or threaded together into a string of packages for emplacement (and retrieval). Drill pipe can be connected directly into the top of a waste package for drill-string emplacement (with an adapter if necessary), or a latch adapter can be connected to the top of each waste package for wireline emplacement. For drill pipe connections with reference-size packages, it is assumed that 4-1/2 inch drill pipe would be used.

Package connections for drill-string emplacement will include: 1) a threaded connection to the packages below; and 2) a threaded connection to the package or drill pipe above. Package connections for wireline emplacement of single packages will include a releasable latch and a fishing neck attached to a threaded connection on top, and a threaded connection on the bottom for attaching an impact limiter, possibly combined with additional hardware such as instrumentation, centralizers, etc. Whereas multiple packages could be emplaced with a wireline (and meet service load limits), it would require a means to thread packages together at the surface which would increase cost and complexity of the method.

Package Fabrication, Testing, Loading and Sealing – Waste packages will be fabricated and tested prior to waste loading, at upstream non-radiological fabrication facilities. They will be loaded with waste, sealed by welding, and tested for containment integrity at specialized upstream nuclear material handling facilities. Welding provides a permanent seal and has been a preferred closure solution for mined geologic disposal in repository R&D programs. They will be delivered to the disposal site sealed, with proper adapters attached, ready for direct emplacement in the disposal borehole. The addition of adapters to waste packages (e.g., wireline latch and fishing neck, and impact limiter) must be accommodated by the waste cavity internal length and/or the internal dimensions of the shipping cask.

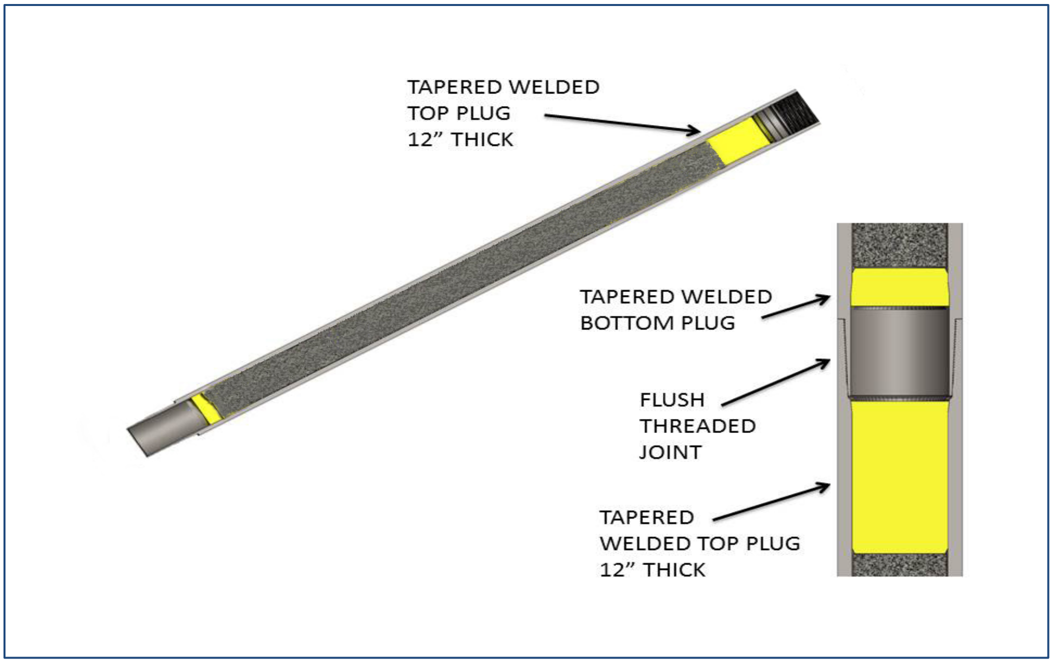

Figure 2-12. Waste package concept (internal-flush example shown).

In summary, the external characteristics of the reference-size waste package are:

- Maximum outer diameter 11 in.
- Overall length 18.5 ft.
- Dry loaded maximum weight 4,620 lb.
- Buoyant weight approximately 3,630 lb in 1.3× drilling mud (3,860 lb in pure water at room temperature).
- Radiologically hot (e.g., containing Cs/Sr capsules).
- Thermally hot (e.g., 100 to 300 W per meter of length).

Waste packages will be designed for a nominal lifetime of 10 yr (Section 2.3) during which they may be exposed to brine with significant concentrations of chloride, Na, Ca, and possibly Mg ions.

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

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

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

A release mechanism (a J-slot safety joint was proposed by Arnold et al. 2011) will be threaded onto the topmost waste package in each string to be lowered. The safety joint must be readily released once the package string is resting on the bottom in the disposal zone, and it must allow for re-engagement if retrieval is necessary (see Section 2.6.8).

Packages for wireline emplacement – Waste packages for wireline emplacement will essentially be the same as described above, but emplaced individually on an electric wireline. They will have the same threaded joints, but specialized subs will be threaded on the top and possibly the bottom. As discussed above, the upper sub will have a neck that mates with an electrically actuated releasable cable head. The lower sub will have a threaded connection for attachment of an impact limiter. Mechanical loads on these connections will generally be smaller than for drill-string operations, however, the packages and the subs must be configured to sustain the compressive load of a string of up to 40 stacked packages during emplacement.

Waste Packaging Concepts – Using package outer diameters of 10.75 and 5 inches as a starting point, four package concepts are presented based on the emplacement method options and packaging constraints described in Section 2. The packaging options are:

- Option 1 – 10-3/4 inch OD flask-type waste package for bulk waste, for use with a 13-3/8 inch OD guidance casing
- Option 2 – 10-3/4 inch OD internal-flush type package for canistered waste, for use with a 13-3/8 inch OD guidance casing
- Option 3 – 5-inch OD flask-type package for stacked 2.6-inch OD Cs/Sr capsules, for use with a 7-inch OD guidance casing
- Option 4 – 5-inch OD internal-flush type package for stacked, Cs/Sr capsules up to 3.3-inch OD, for use with a 7-inch OD guidance casing

Option 1 – This is a reference-size, 10-3/4 inch OD flask-type (narrow filling port) waste package for bulk waste. It uses conventional API tool joints (regular or numbered) and attaches them to the tubular package body via friction welding (Figure 2-13). This manufacturing technique is commonly used to construct drill pipe ends. A chamfer is included on the inboard end of each end plug so that the massive plug does not interfere with friction welding by acting as a heat sink.

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 NC77 or equivalent thread could be used. This arrangement provides a smooth exterior package profile. For drill-string emplacement a detent collar groove would be machined in the lower end plug, and a collar machined on the upper end plug, to provide redundant points for gripping the package in the basement slips and pipe ram during package string assembly.

Granular waste could be loaded through the fill port on the upper (box) end of the package (Figure 2-14). A tapered, threaded plug would then be threaded into the port for initial containment of the waste. A cover plate would be welded over the plug. The true aspect ratio of Option 1 (length to diameter) is shown in Figure 2-15.

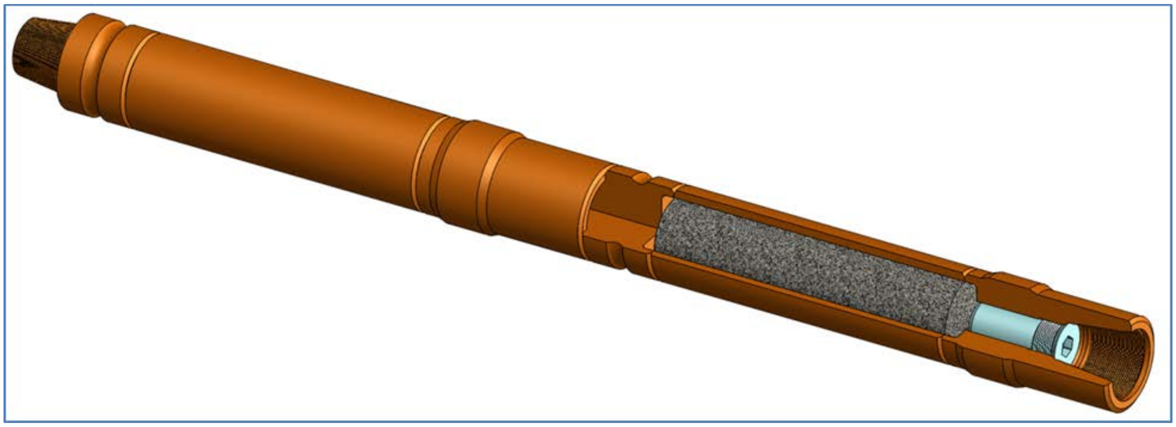

Figure 2-13. Option 1 (shown as 2 packages with aspect ratio shortened for illustration)

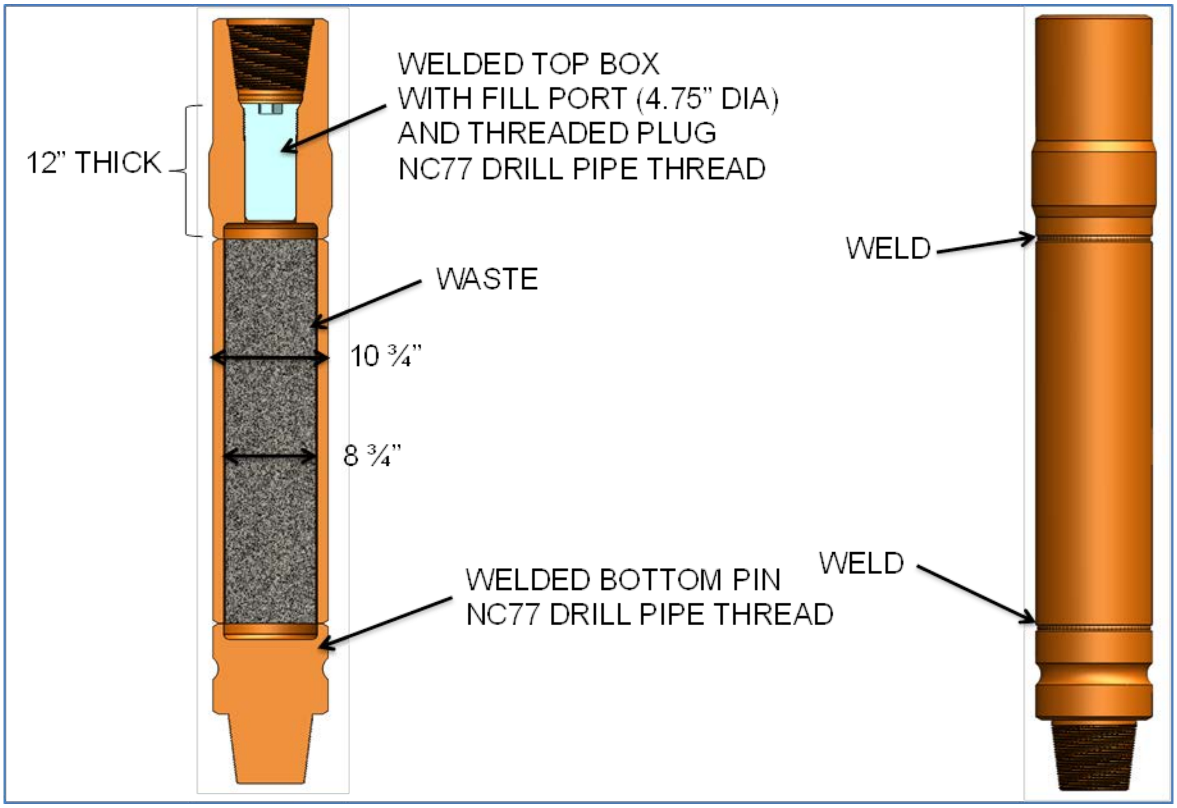

Figure 2-14. Option 1 details (aspect ratio shortened for illustration).

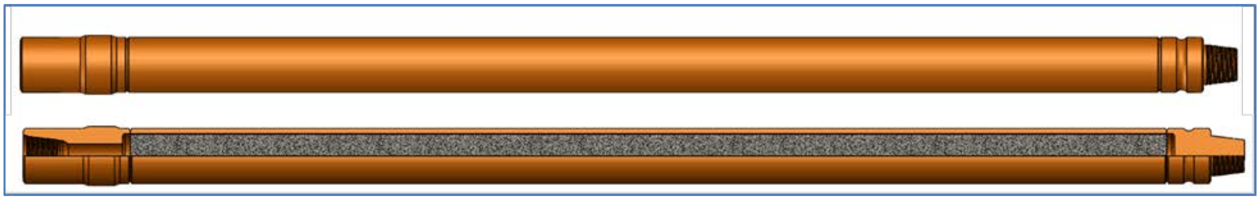

Figure 2-15. Option 1 shown at true aspect ratio.

Advantages identified for Option 1 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; 4) the external surface is smooth, and gripping features can be machined into the end plugs; and 5) use of a detent at the lower end plug (instead of a collar) does not decrease radial clearance. Disadvantages include: 1) welds in the axial load path; and 2) makeup of pipe thread joints requires pipe dope; and 3) use of an external collar at the upper end (for drill-string emplacement) impacts radial clearance.

Option 2 – This is a 10-3/4 inch OD internal-flush type overpack for canistered waste, for use with a 13-3/8 inch OD guidance casing. Option 2 uses an external upset semi-flush casing with welded internal plugs to contain canistered waste (Figure 2-16). The threaded connection would be a Tenaris MAC II® or equivalent. The dovetail shaped threads provide a tight seal against external pressure, but are not ideal for repeated makeup/breakout applications. To prevent damage to the threads when the plugs are installed, the closure welds would be recessed beyond the threaded portion of of the body tube (Figure 2-17).

Canistered waste would be loaded through one end, then contained by a plug welded in place. Canister OD for the concept shown here would be limited to approximately 8.75 inches. Note that for a 10-3/4 inch OD casing the external upset diameter is 11.23 inches, providing approximately 0.1 inches less radial clearance with the guidance casing than the design requirement (Section 2.3).

Advantages identified for Option 2 include: 1) based on standard size casing that; 2) no welds in axial load path; and 3) dovetail threads provide good sealing against external pressure. Disadvantages include: 1) the combination of size (10-3/4 inch OD), material (110 ksi yield), and connections could require a custom mill run; 2) dovetail threads are not designed for repeated assembly/disassembly; and 3) the external upset increases OD by 0.23 inches beyond the 11-inch diameter requirement (Section 2.3).

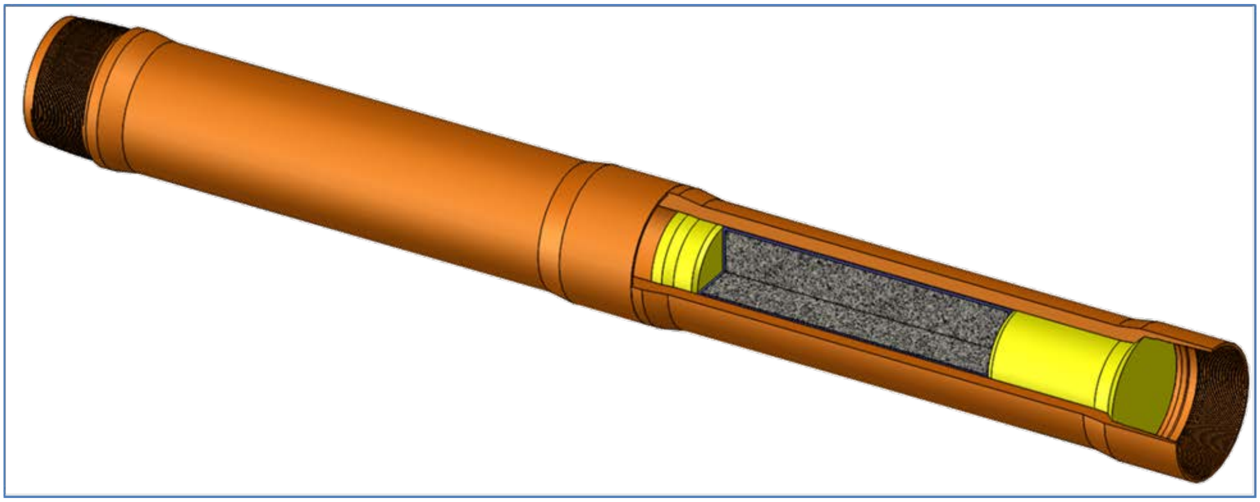

Figure 2-16. Option 2 (shown as 2 packages with aspect ratio shortened for illustration).

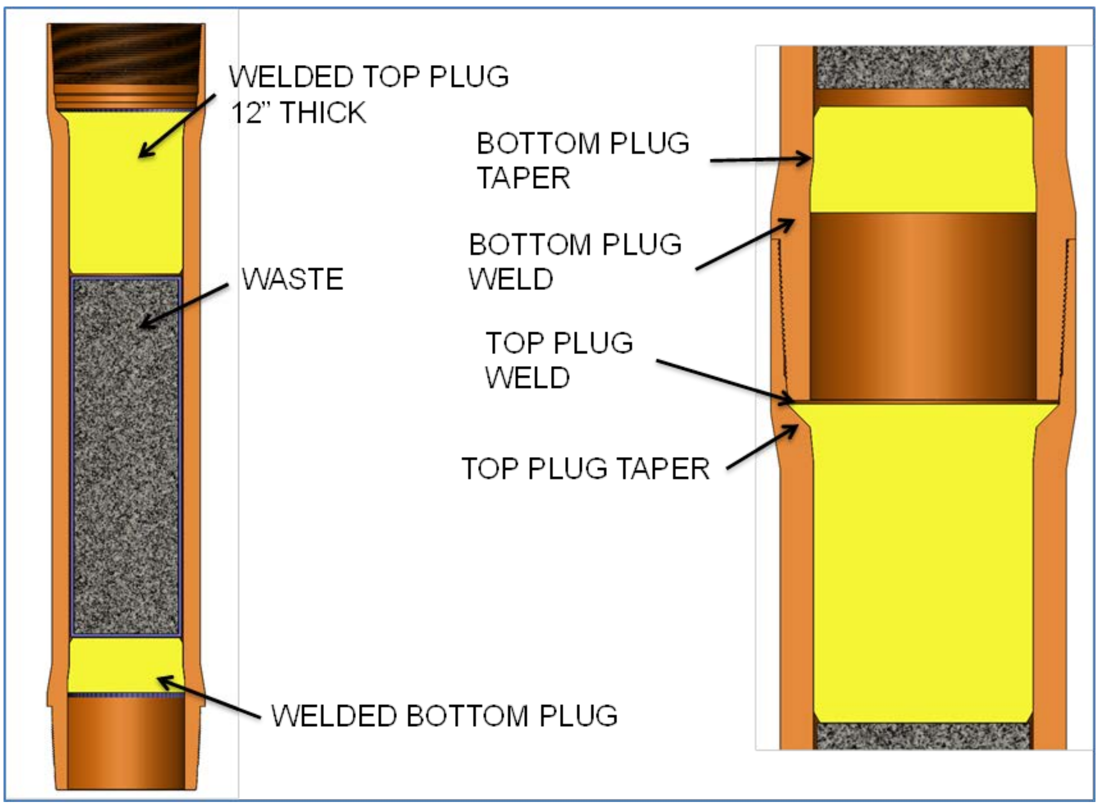

Figure 2-17. Option 2 details (aspect ratio shortened for illustration).

Option 3 - This a flask-type overpack designed for 2.6-inch OD Cs/Sr capsules inside a 5-inch OD overpack (Figures 2-18 and 2-19). Option 3 is a smaller version of Option 1, sized to receive Cs/Sr capsules stacked end-to-end (Figure 2-16). The overpack would be based on 5-inch OD, 4-inch ID casing with welded end plugs at each end. The threaded connections at each end would be API NC38 or equivalent, providing a smooth exterior surface. The friction welded fabrication method, and provisions for welding in the end plug design, would be the same as for Option 1. For drill-string emplacement a detent collar groove would be machined in the lower end plug, and a collar machined on the upper end plug, to provide redundant points for gripping the package in the basement slips and pipe ram during package string assembly.

The welded box end has a fill port to allow loading of Cs/Sr capsules (which may be enclosed in a thin-wall canister), possibly with an internal basket or centralizer for stabilization. A tapered, threaded plug would then be threaded into the port for initial containment of the waste. A cover plate would be welded over the plug. The true aspect ratio of Option 3 (length to diameter) is shown in Figure 2-17.

Advantages of Option 3 for disposal of Cs/Sr capsules 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; 4) the external surface is smooth, and gripping features can be machined into the end plugs; and 5) use of a detent at the lower end plug (instead of a collar) does not decrease radial clearance. Disadvantages include: 1) welds in the axial load path; and 2) makeup of pipe thread joints requires pipe dope; and 3) use of an external collar at the upper end (for drill-string emplacement) impacts radial clearance.

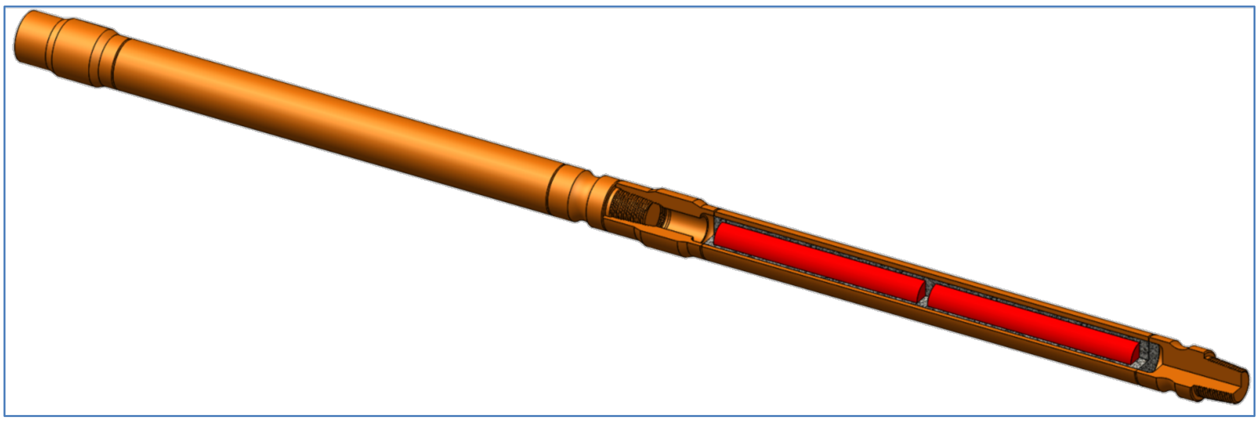

Figure 2-18. Option 3 (shown as 2 packages with aspect ratio shortened for illustration)

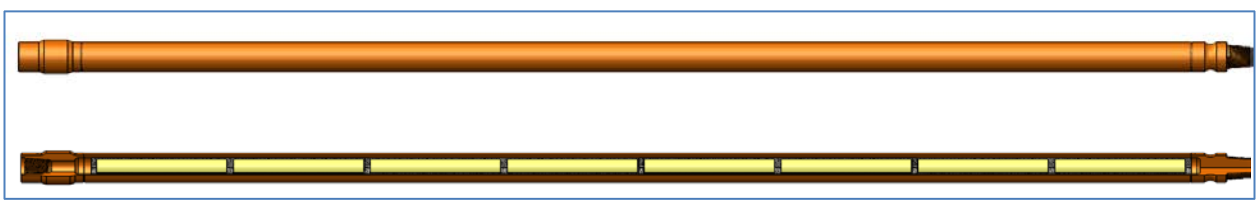

Figure 2-19. Option 3: Small diameter overpack with eight Cs/Sr capsules packed axially

Option 4 - This an internal-flush overpack option for the larger (up to 3.3-inch OD) Cs/Sr capsules. This design is based on commercial casing with a 5-inch OD and 4-inch ID (Figure 2-20). The connection is 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. To prevent damage to the threads when the end plugs are installed, the closure welds would be recessed beyond the threaded portion of of the body tube (see Figure 2-17 for a similar arrangement). The dovetail shaped threads provide a tight seal against external pressure, but are not ideal for repeated makeup/breakout applications.

Similar to Option 2, waste packages would be contained by a welded plug, after loading. If the canister OD is substantially less than 4.0 inches, a basket or centralizer can be used to hold it in place for handling and transport. For the nominal 18.5-ft length, these overpacks could be loaded with up to eight Cs/Sr capsules (like Option 3). They could also be made up in shorter lengths, for fewer capsules, and threaded together. As long as the total length is less than the nominal 18.5 ft length, the connected packages could be handled as one (e.g., wireline emplacement).

With flush casing the wall thickness does not allow for cutting detent grooves for holding the package in the basement. Accordingly, for drill-string emplacement external collars would be welded at the upper and lower ends for gripping by the slips and pipe ram. For collar height of 0.25 inches, this would provide approximately 0.25 inches less radial clearance with the guidance casing than the current design requirement (Section 2.3).

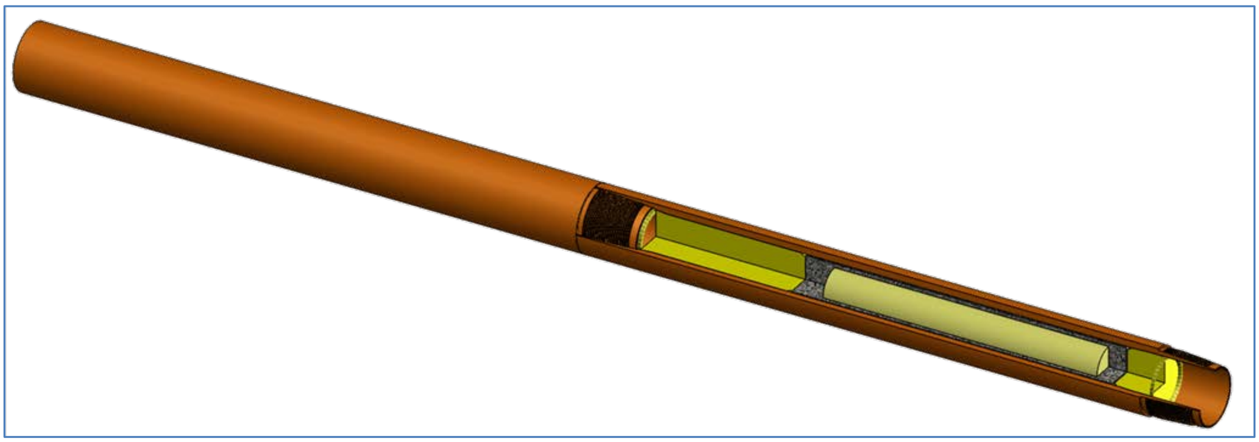

Figure 2-20. Option 4 (shown as 2 packages with aspect ratio shortened for illustration)

Advantages of Option 4 for disposal of Cs/Sr capsules include: 1) use of standard size casing; 2) no welds in the axial load path; and 3) dovetail threads provide a good seal. Disadvantages include: 1) dovetail threads are not designed for repeated assembly/disassembly; and 2) external-flush casing requires the addition of external collars for drill-string emplacement, which could increase the maximum OD beyond the 5-inch maximum diameter requirement (Section 2.3).

Modular Attachments – Each of the concepts described above can be used with either the wireline or drill-string emplacement methods. The modular design of the packages allows for threaded connection with adjacent packages, or for the addition of threaded adapters and attachments for lowering the waste packages into the borehole.

A modular impact limiter could be placed on each package to mitigate the effects of impact if a package is dropped during wireline emplacement (Figure 2-21, and Section 4.3). A similar attachment could be used on the lowermost package in a string, for drill-string emplacement, to limit axial load transients when the string is set on bottom.

For wireline emplacement, an adapter on the upper end of each package would include a wireline latch and fishing neck (Figures 2-21 and 2-22). The recessed latch would allow the packages to stack in the disposal zone without damaging the latches.

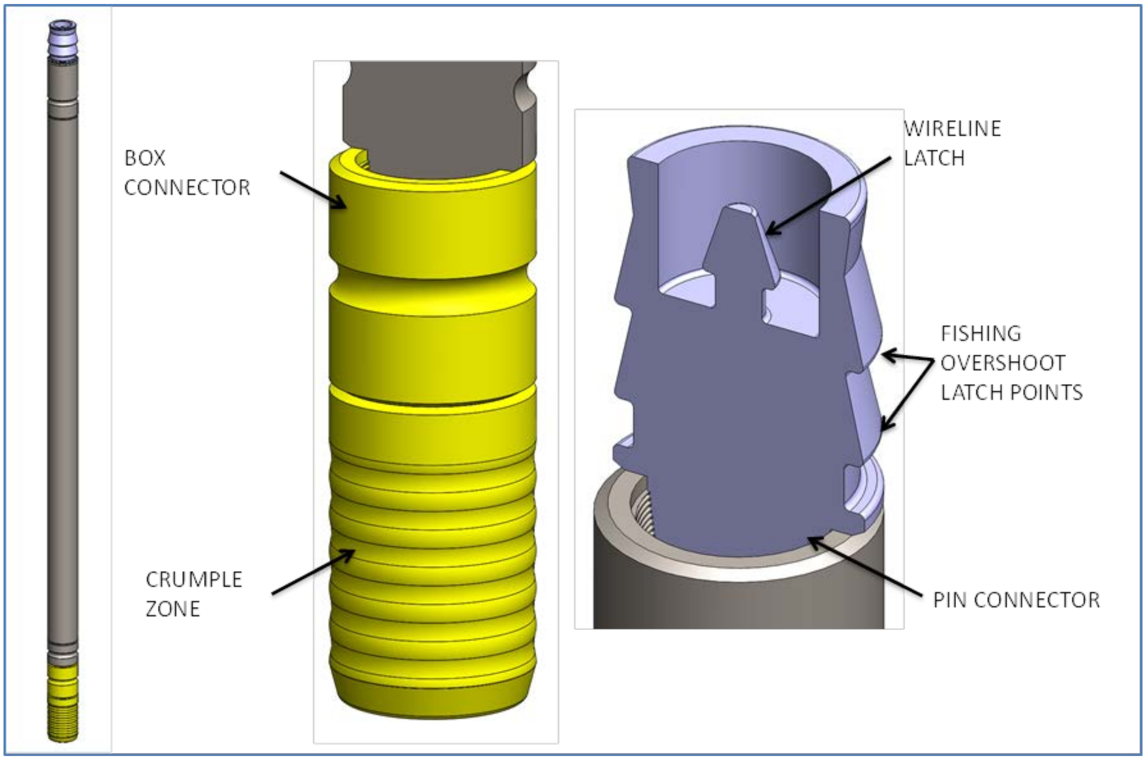

Figure 2-21. Modular impact limiter and wireline latch/fishing neck.

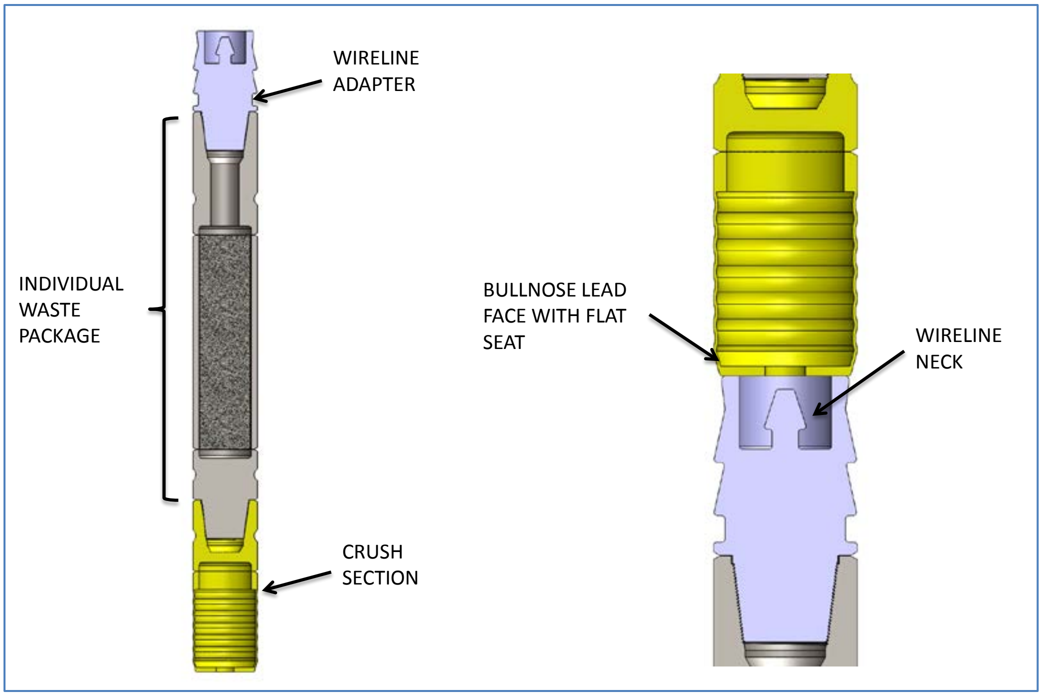

Figure 2-22. Package assembly for lowered individually on wireline (aspect ratio shortened for illustration).

2.6.8 Downhole Emplacement/Retrieval Equipment

According to the 2011 reference design concept (Arnold et al. 2011) the top of an assembled string of 40 waste packages would have a J-slot (also called a J-sub) safety joint threaded into the top package and the bottom of the drill pipe string. The J-slot is released by applying down-force and rotation. It allows for reengagement if retrieval is necessary, and can be configured to allow injection of mud or cement immediately after release without tripping out.

Premature release of a J-slot safety joint on the trip in with a string of waste packages, is a potential initiating event for dropping the string, leading to possible waste package breach and contamination of the borehole (Section 5 and Appendix B). The force and rotation required for release might occur on the trip in from helical deviation and friction in the borehole. Other commercially available, double-release type devices could provide additional reliability (e.g., the dual-disconnect load-carrying innerstring adapter from Haliburton). Such devices operate using force and rotation, combined with an independent control such as dropping a steel ball through the drill pipe. For risk analysis the additional reliability of double-release devices was assumed.

Fishing could be needed if a package becomes stuck during wireline emplacement. If the emplacement wireline setup fails to free a stuck package, it can be released and potentially reconfigured for greater pull (e.g., if stuck near the surface). The wireline latch and fishing neck that would be used (see Section 2.6.7 for examples, for wireline emplacement) will be developed and tested as part of the DBFT demonstration.

The impact limiter described in Section 2.6.7 and analyzed in Section 4.3, is an important feature in the risk analysis (Section 5). It will be further developed and tested as part of the DBFT demonstration, as it significantly reduces the probability of waste package breach associated with dropping a waste package.

2.6.9 Sealing and Plugging

Figure 2-23 illustrates the primary components of the borehole sealing system. In the lower sealing section, sealing components will be emplaced in the unlined, open interval above the port collar near the bottom of the 18-5/8 inch liner (Intermediate 2, Figure 2-2). The liner in the uncemented interval will be cut off just above the cement and port collar, and removed prior to sealing. In this interval the seals will act directly against the rock surface. At several locations, two cement plugs will bracket a bentonite or bentonite and sand mixture seal. A ballast of silica sand or crushed rock will be emplaced between the cement and bentonite to limit chemical interaction.

Figure 2-23 also shows sealing components to be emplaced in the upper sealing section in 24-inch (Intermediate 1, Figure 2-2). The majority of this interval will be filled with cement, or cement with sand and finely crushed rock, which will act as both plugging and backfill materials. Bridge plugs will be installed to create an API-type plug or to partition the segments with cement plugs and/or backfill. The lower part of the 24 inch Intermediate 1 casing will be supported by a cement seal.

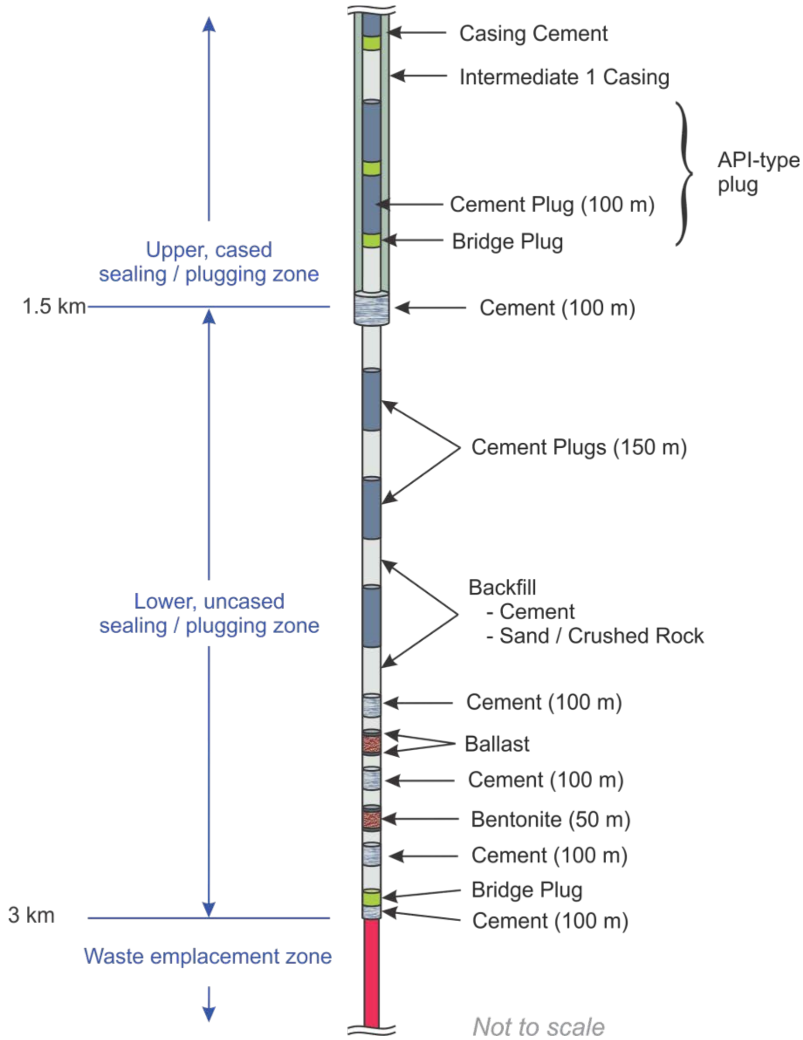

Figure 2-23. Borehole sealing, plugging, and backfilling concept schematic (Arnold et al., 2011).

2.7 Disposal System Conceptual Design Questions

A number of design enhancements were identified as clearly risk-significant according to the risk insights described in Section 5:

a) Disposal zone completion and guidance casing perforations, consistent with multiple objectives identified in Section 2.6.2.
b) Emplacement fluid selection consistent with disposal zone completion, and terminal sinking velocity in the event of a dropped package (mainly for wireline emplacement).
c) Design waste packages for a range of temperature that could be encountered with heat-generating waste.
d) Develop downhole release mechanisms for wireline and drill-string emplacement.
e) Design impact limiters to achieve needed performance, without contributing to the likelihood of packages getting stuck on trips in (e.g., not snagging) or after impact, on retrieval (e.g., by use of a weak point).

In addition, other design/procedural enhancements were identified in review of the emplacement concepts (Cochran and Hardin 2015) by the subject-matter expert panel (Appendix A). These are described in the following sections, grouped according to whether they were assumed for the risk analysis to be part of the disposal system, or they are recommended for further evaluation.

2.7.1 Disposal System Enhancements Assumed for Risk Analysis

The following list (f) through (gg) was assumed to be part of the disposal concept, for the risk analysis described in Section 5. These items should be considered for incorporation in the DBFT (Section 3):

General:

f) Add a mud check valve on guidance casing above 3 km, to permit reverse circulation in case a package or string of packages gets stuck (a rig will be on-site for fishing).

g) Before every package or string of packages is emplaced, run acoustic caliper (for casing collapse and wear, and mud 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).

h) Run gauge ring with junk basket before bridge plug installation, and after every cement job.

For wireline emplacement:

i) Use fixed headframe instead of a mobile crane, to hold wireline sheaves for emplacement (more reliable); head frame dimensioned to accommodate installation of shipping cask by crane, and wireline setup above cask (approx. 75 ft high).

j) Specify that power supply and interlock connections to the shipping or transfer cask are incorporated in the same cable/plug.

k) Specify no splices in wireline.

l) Specify wireline sheaves with cable capture locks to prevent jump-off.

m) Specify that backup winch power supplies, hydraulic and electrical, are available on-site.

n) Specify a hydraulic cable-tension limiter on the wireline winch, set below the downhole tool passive weak point setting, for surface operations.

o) Integrate the wireline winch drive, winch brakes, and hydraulic tension limiter with the safety control (interlock) system.

p) Integrate the downhole weight tool output with the safety control (interlock) system.

q) Apply intensive QA/QC on assembly of package release and cable head release tools.

r) 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.

s) If wireline packages become stuck, release the wireline and mobilize a drill rig. Don't strip the wireline within pipe because the risk from losing control is greater than that from the package dropping.

t) Add a weak point and a remotely actuated release at the cable head (in addition to the remotely operated package release).

u) Make both the package release and the remote cable head release operable only without load so the package (or tool string) must be on the bottom or stuck.

For drill-string emplacement:

v) Use a double-release mechanism for package string release instead of a J-slot mechanism.

w) Perform preventative maintenance, inspection, and testing on rig equipment, drill pipe, and basement equipment after every package string is emplaced (before more waste packages are inserted in the hole).

x) Use two power tongs in basement, to make up package connections (instead of combining tongs in the basement with rig tongs or an iron-roughneck on the rig floor).

y) Re-design power tongs with self-clearing mechanism for lock-up. Independently monitor torque (e.g., where tong unit is mounted to support frame in the basement).

z) Monitor both torque and rotation during package joint makeup, to detect cross-threading. Also use visual (camera) inspection.

aa) Monitor rotation of the package string during makeup (which is not supposed to happen) to avoid spinning in the slips which could initiate a drop.

bb) Neutralize rig rotary table for string makeup and tripping in, and monitor with safety control (interlock) system (prevent spinning a package string or drill string in the slips).

cc) Incorporate rig draw works and rigging interlocks (load, range of travel) into safety control (interlock) system.

dd) Monitor mud pressure during all circulation operations to detect blockage and pipe joint overpressure.

ee) Specify new, not used drill pipe for every emplacement rig (less likelihood of an unknown defect caused by overpressure, such as a blown joint that leaks pressurized circulation fluid and will eventually fail from erosion).

ff) Use a heavy impact limiter on the lower end of every package string, to assist in setting the string down without overloading, prior to release.

gg) If the release mechanism (e.g., J-slot) fails to release, cut the pipe using an explosive wireline tool run inside the pipe string (safer than tripping out with the full string).

2.7.2 Potential Disposal System Enhancements for Further Evaluation

The following list (a) through (p) was recommended by the subject-matter expert panel for further consideration in the DBFT engineering demonstration design process.

General

a) Bring 18-5/8 inch casing to the surface, fully cemented, to control contamination in the event of a package breach. Also, the BOP could be installed on a smaller casing (18-5/8 instead of 24 inch) which would partly offset the cost of the additional 2 km of casing. A larger casing could limit surge during trips into the hole with waste packages, and make it easier to negotiate doglegs and less likely to get stuck on debris. Would need to consider behavior of accidentally dropped packages at the transition to the disposal zone guidance casing (nominally at 3 km depth).

b) Use an emplacement fluid that does not contain mud or other solids that can settle, producing solids that could cause packages to become stuck.

Wireline Emplacement

c) Make shipping or transfer cask part of the BOP system (if BOPs are required for emplacement):
    i. Flanged stuffing box attached to top of cask, with O-ring seal against cask body, thickness to provide additional shielding, with possible lead lining, and pressure containment at the minimum of BOP rating or cask internal pressure rating.
    ii. Stuffing box flange could also be rated to restrain upward pull on package from winch (instead of bolts or pins).
    iii. Make cask lower flange on the transportation/transfer cask, and lower door enclosure pressure-tight, for example, using oilfield-type flanged connections and a BOP-type blind ram for the lower doors.

d) Double-redundant winch hydraulic drive and pneumatic brakes.

e) Pins or edges on upper surfaces of lower cask doors, so that doors cannot be opened with package weight on them. Also limit door actuation force electrically or hydraulically.

f) Specify wireline inspection standards (in addition to, or in lieu of wireline contractor standard procedures).

g) Add mud circulation equipment at the site during wireline emplacement, to recirculate and clean the hole after installing a cement plug, and before emplacing another stack of packages.

h) Set drillable bridge plugs with pressure on coiled tubing, in lieu of wireline bridge plugs that typically use an explosive charge.

i) Develop a hydraulic shock absorber at cable head to limit dynamic loads on the trip in.

Drill-String Emplacement

j) Use packages with API pipe thread connections, not casing threads, to the extent possible to lower the likelihood of cross-threading.

k) Specify top-drive rig to eliminate equipment (e.g., elevator) and operational steps that contribute to drops.

l) Develop a downhole impact limiter/annunciator that produces an event detectable at the surface, signifying that the string is setting on the bottom at the minimum weight for release.

m) Use stabbing connectors (made for larger diameter casing) instead of threaded connectors, for waste packages (eliminate tongs and tightening). Add a remotely operated mechanical release for stabbing connectors, in the basement.

n) Store package strings in the upper part of the borehole, i.e., like a “kill string” in development wells, during string assembly (keep the string cool, and allow worker access to the basement for maintenance).

o) Allow room in the basement for possibly installing a snubbing unit (injector for drill pipe) if a package string gets stuck.

p) Use a conveyance casing, i.e., a large-diameter casing that is sealed at the bottom, and held in place at the well head. Waste packages are stacked inside the conveyance casing using a wireline (thus no basement tongs are needed), then the entire casing is lower into place using a drill string. To maintain a casing path for the conveyance casing, using the same size waste packages, a larger diameter borehole is needed in the disposal zone.

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3. DBFT Conceptual Design Description

The deep borehole disposal concept, and options for waste packaging and emplacement, are presented in Section 2. A simple architecture for the disposal system (Tables 2-1 and 2-2) is adapted here to show what features of the disposal system will be included in the DBFT (Tables 3-1 and 3.2). The scope of the selection of DBFT features includes the test borehole configuration, test waste packaging, and handling and emplacement.

3.1 Borehole Drilling and Construction

The characterization borehole will be part of the DBFT but is not addressed by conceptual design activities discussed here, which are focused on demonstrating waste packaging and emplacement/retrieval. Demonstration activities will include drilling the field test borehole (FTB). Details of drilling and construction are discussed elsewhere (Kuhlman 2015) and are subject to change when the Drilling and Testing Plan is developed (DOE 2015). The FTB configuration will be very similar to disposal boreholes described in Section 2.6.1, and will provide a guidance casing for emplacement/retrieval of test packages. Sealing and plugging of the FTB will not be demonstrated as part of currently planned DBFT activities (Table 3-2).

3.2 Test Package Concepts

Test packages will be designed for downhole pressure, in situ temperature, and other conditions identified in Sections 2.3 and 2.4 as specific to the DBFT. Both small (Cs/Sr capsules) and large (reference size) packages (Section 2.6.7) will be designed for possible fabrication and testing in small or large boreholes (e.g., the Characterization or Field Test Boreholes). Test packages should have threaded connectors at each end suitable for wireline or drill-string emplacement, or for attachments such as wireline connections, instrumentation packages or impact limiters. The package connections used for waste disposal can be optimized at a future time.

Package configurations will be integrated to the extent practical with upstream waste generator and waste management facility requirements (e.g., length of small packages that could contain Cs/Sr capsules). This includes the waste package internal dimensions, and aspects of closure and sealing that could impact upstream facilities. However, the use of a basket that fits into the dimensional envelope and holds waste capsules or canisters, is beyond the scope of the DBFT.

One objective of the DBFT will be to test more than one packaging concept, if resources permit. For example, the flask-type and internal-flush concepts presented in Section 2.6.7 have important differences that could affect performance, but are also potentially important to waste generators. Each of these could be subjected to drop testing, and tested at other off-normal (accident) conditions, in addition to borehole emplacement/retrieval. Multiple test packages will be fabricated to demonstrate repeatable fabrication and testing results, and for destructive testing. The extent of testing, and the number of test packages required, will be determined in final design.

3.3 Test Package Emplacement and Retrieval

The DBFT will implement a disposal emplacement concept that is similar either to the wireline or drill-string concepts presented and evaluated in this report. Multiple test packages will be emplaced, as a string or stacked in the borehole, then retrieved using the same equipment. Emplacement and retrieval operations will be repeated to evaluate procedures, demonstrate operability, and develop performance data such as reliability statistics.

The handling and emplacement equipment used in the DBFT can be simplified as indicated in Table 3-1 (for both the wireline and drill-string emplacement options). The goal of simplification for the DBFT demonstration is to focus available resources on those aspects of emplacement operations that are most risk significant. For example, among the risk insights presented in Section 5, wireline overtension and drill-string drops are risk-significant for the respective emplacement methods.

Impact limiters could substantially limit the consequences of drop events, preventing accidental waste package breach. Credit for impact limiters on single packages was taken in the risk analysis for wireline emplacement (Section 5), but not for the drill-string method because it involves much greater masses with greater sinking velocities. The effectiveness of impact limiters should 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).

The safety control system (interlocks) is shown in Table 3-1 as being minimized for the DBFT. The consequences of dropping packages or getting them stuck during the DBFT demonstration, while potentially 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, or rig draw works 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, nor is monitoring of drill-string contact with the bottom (because the consequences of test package damage are limited).

3.4 DBFT Conceptual Design Questions

All questions raised in the introduction to Section 2.7 are important to the DBFT, especially:

- Develop the disposal zone completion and guidance casing perforation scheme.
- Select an emplacement fluid consistent with disposal zone completion and terminal sinking velocity in the event of a dropped package.
- Design test packages for a range of in situ temperature.
- Develop and demonstrate package or package-string release mechanisms for wireline or drill-string emplacement (see Section 2.6.8). Additional investigation is warranted prior to selection of a device for the DBFT demonstration, to evaluate failure rates on both emplacement and retrieval.
- Design and test impact limiters, without getting stuck on trips in or on retrieval (after impact).

In addition, the following design/procedure enhancements were assumed for risk analysis to be included in the disposal system (Section 2.7.1) and are also important for the DBFT because they require additional engineering development and testing, and/or because they could significantly improve the likelihood of DBFT demonstration success:

General:

a) Before every package or string of packages is emplaced, run acoustic caliper (for casing collapse and wear, and mud 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).

b) Run wireline gauge ring with junk basket before running in a bridge plug on wireline, and after every cement job (see item Section 2.7.2, which includes a recommendation to run pressure-actuated bridge plugs on coiled tubing or drill pipe, instead of explosive-actuated wireline bridge plugs).

For wireline emplacement:

c) Specify no splices in wireline.

d) Specify wireline sheaves with cable capture locks to prevent jump-off.

e) Specify a hydraulic cable-tension limiter on the wireline winch, set below the downhole tool passive weak point setting, for surface operations.

f) Use very slow speed on trip in (0.5 fps max.) to avoid cable hangup and breakage. Limit speed to 2 fps deeper (e.g., more than 2,000 ft).

g) Add a weak point and a remotely actuated release at the cable head (in addition to the remotely operated package release).

h) Make both the package release and the remote cable head release operable only without load so the package (or tool string) must be on the bottom or stuck.

For drill-string emplacement:

i) Use a double-release mechanism for package string release instead of a J-slot mechanism.

j) Perform preventative maintenance, inspection, and testing on rig equipment, drill pipe, and basement equipment after every package string is emplaced (before more waste packages are inserted in the hole).

k) Use two power tongs in basement, to make up package connections (instead of combining tongs in the basement with rig tongs or an iron-roughneck on the rig floor).

In addition, the subject-matter expert panel (Appendix A, Section 2.7.2) recommended other enhancements for further evaluation, and the following may be appropriate for consideration in the DBFT:

General:

l) Use an emplacement fluid that does not contain mud or other solids that can settle, producing solids that could cause packages to become stuck.

For wireline emplacement:

m) Specify wireline inspection standards (in addition to, or in lieu of wireline contractor standard procedures).

For drill-string emplacement:

n) Use packages with API pipe thread connections, not casing threads, to the extent possible to lower the likelihood of cross-threading.

o) Develop a downhole impact limiter/annunciator that produces an event detectable at the surface, signifying that the string is setting on the bottom at the minimum weight for release.

p) Use stabbing connectors (made for larger diameter casing) instead of threaded connectors, for waste packages (eliminate tongs and tightening). Add a remotely operated mechanical release for stabbing connectors, in the basement.

Table 3-1. Waste packaging, handling and emplacement system for disposal and the DBFT

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	**Deep Borehole Field Test**
Waste Package/Overpack		
Tubular Section	See Section 2.6.7.	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 Sections 2.6.4 and 2.6.7.	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.
Sensors		
Telemetry		
Weak Point		
Basket	See Section 2.6.7.	Not required (bulk inert material can be added to test packages for weight).
Package Transportation		
Shielded Transportation Cask	See Section 2.6.3.	Shielding and truck transporter can be mocked-up for demonstration. Transportation cask may not be needed if a transfer cask is used.
Truck Transporter		
Package Surface Handling/Transfer		
Shielded Transfer Cask	See Section 2.6.3.	A transfer cask with mock-up shielding can be used, and either loaded directly with packages at the DBFT site, or loaded elsewhere and used for transportation also (no radioactive waste).
Waste Package Transfer Fixture		A transfer fixture is not needed if the same cask is used for both transportation and emplacement demonstration.
Cask Lift and Up-Ending		Cask handling features of the system would be fully simulated (for either wireline or drill-string emplacement). Shielding could be mocked-up to
Shielded Cask Doors		
Lifting and Rotation Restraints		

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	**Deep Borehole Field Test**
Cask Placement and Anchoring		save cost and weight.
Waste Package Staging (Borehole – Surface)		
Receiving Flange/Platform	See Sections 2.6.4 and 2.6.5.	Cask support and mud surge control will be fully simulated (for both wireline and drill-string emplacement method demonstration).
Mud Control		
Blowout Preventer	See Sections 2.6.4 and 2.6.5.	Design will include BOPs until it is clear that they will not be required by permitting authorities.
Wireline Winch	See Section 2.6.5.	Wireline winch functions will be fully simulated (for demonstrating wireline emplacement).
Wireline Support	See Section 2.6.5.	A crane could be used in lieu of the headframe described in Section 2.6.5.
Shielding	See Sections 2.6.4 and 2.6.5.	Shielding can be mocked-up.
Basement	See Section 2.6.4.	Basement concept can be minimized for demonstration (for drill-string emplacement). See Section 2.7 for design options that could simplify basement operation. Note that some sub-grade basement construction would be needed to accommodate the BOP, slips (and possibly tongs also), and the transfer cask, under the rig floor. (These components are not used in wireline emplacement.)
Power Slips		
Power Tongs		
Elevator Ram		
Ceiling Shield		
Structural Frame		
Guidance Casing Hanger		
Well Head Flange		
Sump		
Breakaway Sub		
Rig Sub-Structure	See Section 2.6.4.	A sub-structure is needed to demonstrate drill-string emplacement.
Transfer Carrier	See Section 2.6.4	A conveyance is needed to position the shipping cask atop the well head, under the rig.
Backup Power Supply	Backup power is included as a mitigating factor in hazard analysis (Section 5).	Backup power will not necessarily be needed for demonstration if it can be shown that loss of power will not result in undue occupational safety risk to workers, breakage of critical equipment, or waste package drops.

Architecture Outline (Subsystems)	Applicability Discussion: Disposal	Applicability Discussion: Deep Borehole Field Test
Emplacement		
Wireline	See Sections 2.6.5 and 2.6.8.	Wireline functions will be fully simulated, for demonstrating wireline emplacement. This includes engineering development of the electro-mechanical package release mechanism, impact limiters, and other critical components.
Cable		
Cable Head		
Wireline Tools (gamma-ray, casing collar locator, fluid sampler)		
Electromechanical Release		
Weak Point		
Wireline Winch		
Drill Rig	See Sections 2.6.4 and 2.6.8..	Drill rig functions will be fully simulated, for demonstrating drill-string emplacement. Automated equipment (iron roughneck, power slips and tongs) will be evaluated for damage to test packages.
Draw Works		
Iron Roughneck		
Power Slips		
Drill Pipe		
Double Release		
Lead Package		
Backup Power Supply	Backup power was considered a mitigating factor in hazard analysis for a disposal system (Section 5 and 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 test package drops.
Borehole Qualification	See Section 2.6.3.	Borehole qualification procedures will be fully simulated in the DBFT, for either wireline or drill-string emplacement.
Acoustic Caliper		
Gauge Ring/Basket		
Safety Control (Interlocks)		
Cask Doors	Prevent dropping packages during staging.	The safety control system is not necessarily needed for DBFT demonstration of wireline or drill-string emplacement, because the consequences from off-normal events are inherently less than for waste disposal. DBFT operational risk without a safety interlock system is addressed by sensitivity studies (Section 5).
Breakaway Sub		
Slips and Tongs		
Visual Indication		
Position Sensors		
Rotation Sensors		

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	Deep Borehole Field Test
Rig Draw Works Tension and Travel Wireline Winch Tension and Speed	Prevent and mitigate over-tension and over-spooling.	The safety control system is not necessarily needed for DBFT demonstration of wireline or drill-string emplacement, as noted above.
Wireline Logs and Samplers	Detect downhole radiation leaks (see Section 2.6.3).	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 Sections 2.6.4 and 2.6.5.	Not required for DBFT demonstration because the duration of operations will be limited.
Backup Power Supply	Backup power is included as a mitigating factor in risk analysis (Section 5).	Backup power is not required for DBFT demonstration because off-normal event consequences are limited.
Monitoring and Measurement		
Borehole Fluid Level Acoustic Emission Casing Condition Wireline Condition	See Section 2.6.3.	Monitoring will be fully simulated for demonstration of either wireline or drill-string emplacement.
Radiation Detection	See Section 2.6.3.	Radiation detection is not required for demonstration.
Load on Bottom	See Section 2.6.4.	Not required for demonstration (packages will be recovered for inspection, and consequences of breach are slight).
Dummy Packages	See Section 2.6.3.	Not required with use of test packages for demonstration.

Table 3-2. Emplacement borehole implementation in the disposal system and the DBFT.

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	**Deep Borehole Field Test**
Borehole – Subsurface		
Depth/Diameter	See Section 2.6.1.	Field Test Borehole construction will be fully simulated in the DBFT demonstration.
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 2.6.3.	Not required for demonstration. No plugs are planned to be installed in the Field Test Borehole.
Cement Handler		
Coiled Tubing Unit		
Sealing		
Liner Removal	See Section 2.6.8.	Not required for demonstration. No seals or plugs are planned to be installed in the Field Test Borehole.
Low-Permeability Seals		
Support Plugs		
Borehole Plug and Abandon		
Cement Plug	See Section 2.3.5.	Plugging and abandonment of the DBFT boreholes is not planned (see assumption on Site Ownership at DBFT Conclusion, Table 2-4).
Surface Completion		

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References for Section 3

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.

DOE (U.S. Department of Energy) 2015. *Request for Proposals (RFP) – Deep Borehole Field Test (July 9, 2015)*. Solicitation Number DE-SOL-0008071. U.S. Department of Energy, Idaho Operations Office, Idaho Falls, ID.

Kuhlman, K. 2015 (in prep.). *Conceptual Design and Requirements for Characterization and Field Test Boreholes*. FCRD-UFD-2015-000131. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

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4. Supporting Engineering Analyses

4.1 Waste Package Stress Analysis

The packaging options analyzed are are described in Section 2.6.7. 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 2.4 and discussed in Section 2.6.7 (the results presented here are not significantly affected by the discrepancy). Finite-element stress analysis was performed using SolidWorks Simulation® software. The discussion of factor of safety (FoS) in this section does not take into account reduction of yield strength at elevated temperature, and FoS values should be reduced by approximately 87% (Section 2.6.7).

Stress Analysis for Option 1

A stress analysis of the design was performed using Solidworks Simulation. An external pressure of 9,600 psi was applied over the exterior surfaces. An axial tension force of 154,000 lbf was applied through the threaded connection. The results of the stress analysis are shown in Figure 4-1. As expected, the highest von Mises stresses (a measure of the maximum multiaxial 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 material yield strength of 110 ksi, this provides a FoS around 1.9. This is consistent with the analytical solutions discussed by Su and Hardin (2015).

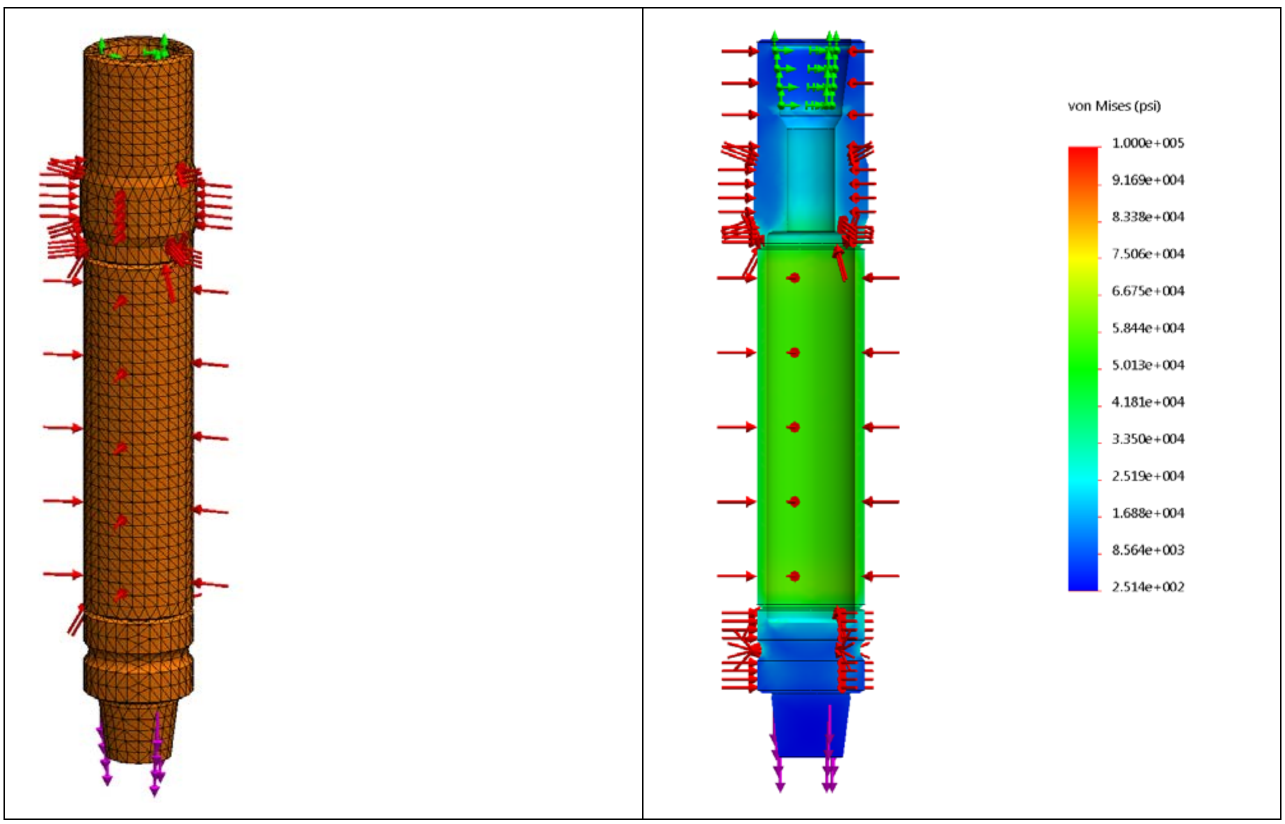


Figure 4-1. Option 1 stress analysis with 9,560 psi external pressure and 154,000 lbf tension (aspect ratio shortened for illustration).

Stress Analysis for Option 2

Two configurations were analyzed: 1) threaded connections between packages leak, so that borehole pressure reaches the internal plugs (Figures 4-2 and 4-3); and 2) threaded connections between packages do not leak. The contact between the plugs and the overpack body is treated as a bonded line contact at the 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 von Mises stress at the interior surface of the tubing is approximately 40 ksi (Figure 4-3). If the connection does not leak, the maximum stress is approximately 46 ksi. 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.

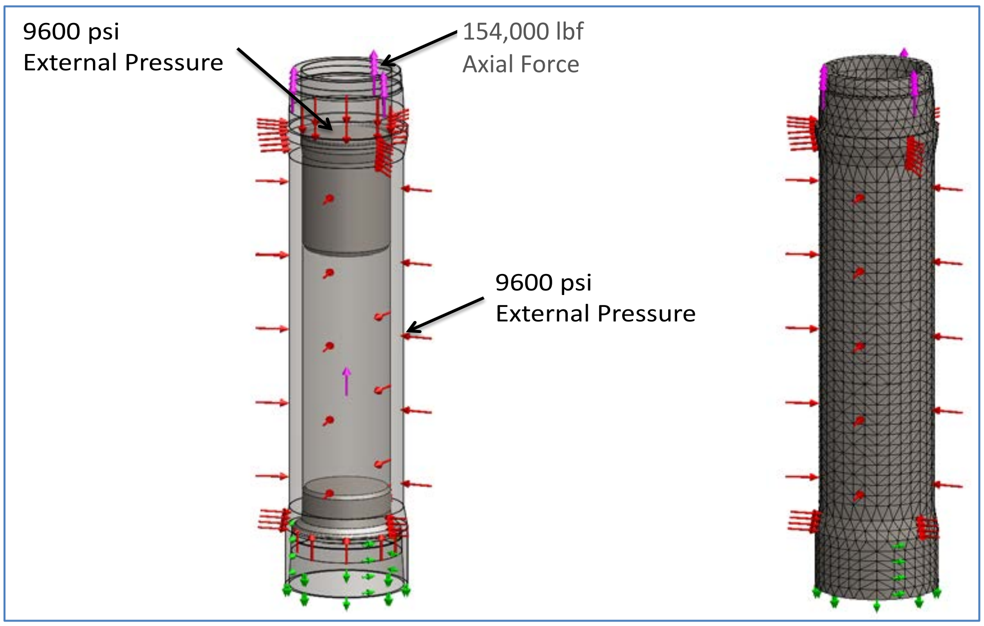


Figure 4-2. Option 2 simulation loads and mesh (aspect ratio shortened for illustration).

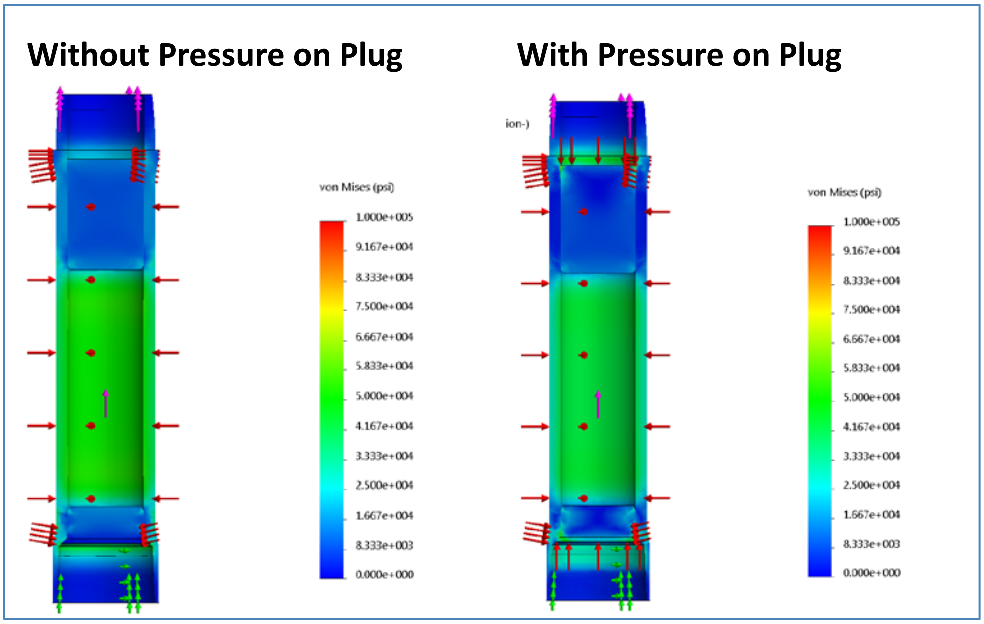


Figure 4-3. Option 2 stress analysis (aspect ratio shortened for illustration).

Stress Analysis for 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 packages on the bottom in the disposal zone. The stress analysis results are consistent with the analytical calculations for external pressure and axial loading (Figure 4-4). For the combined loading, the maximum von Mises stress at the inner wall of the casing is approximately 43 ksi. For material with 110 ksi yield strength, this results in a factor of safety of approximately 2.6.

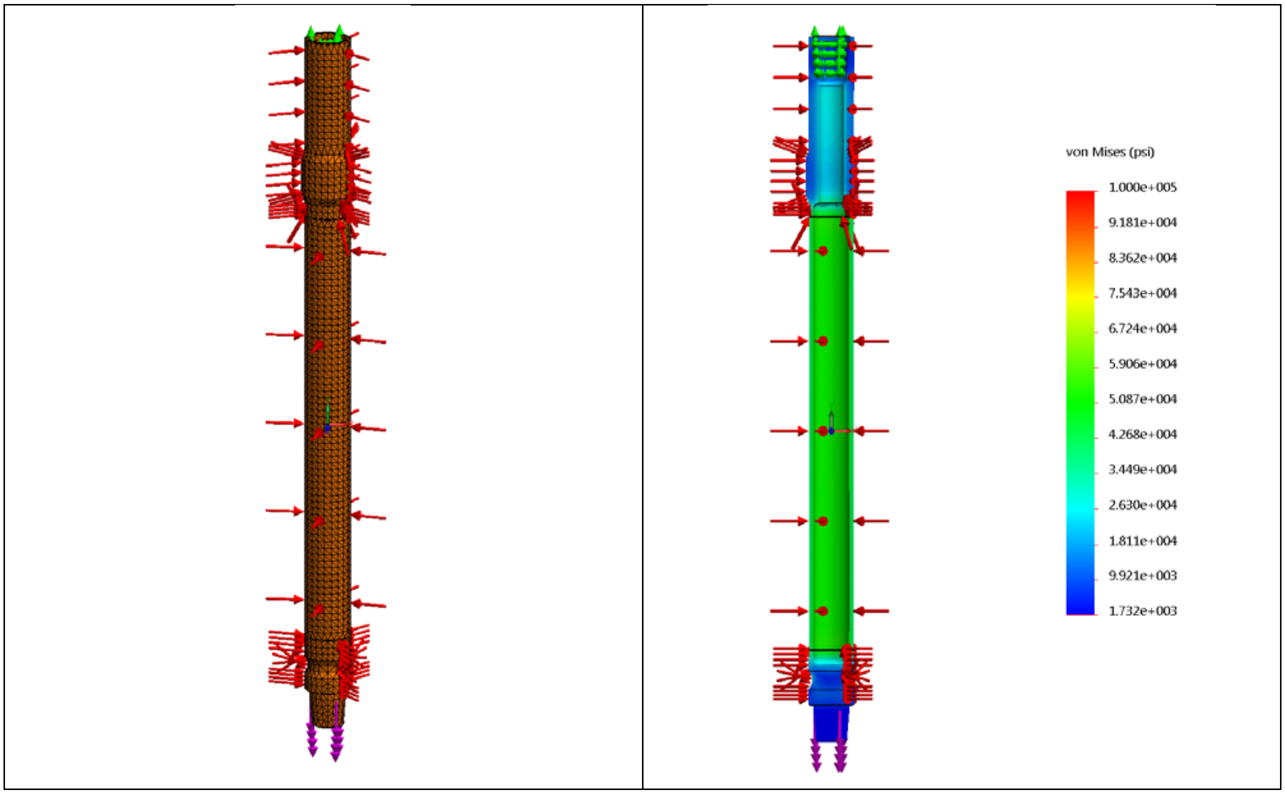


Figure 4-4. Option 3 stress analysis (aspect ratio shortened for illustration).

Stress Analysis for Option 4

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

The stress analysis results are consistent with the analytical calculations for external pressure and axial loading (Figure 4-5). For the combined loading, the maximum von Mises stress at the inner wall of the tubing is approximately 42 ksi. For a material with 110 ksi yield strength, this results in a FoS of approximately 2.6.

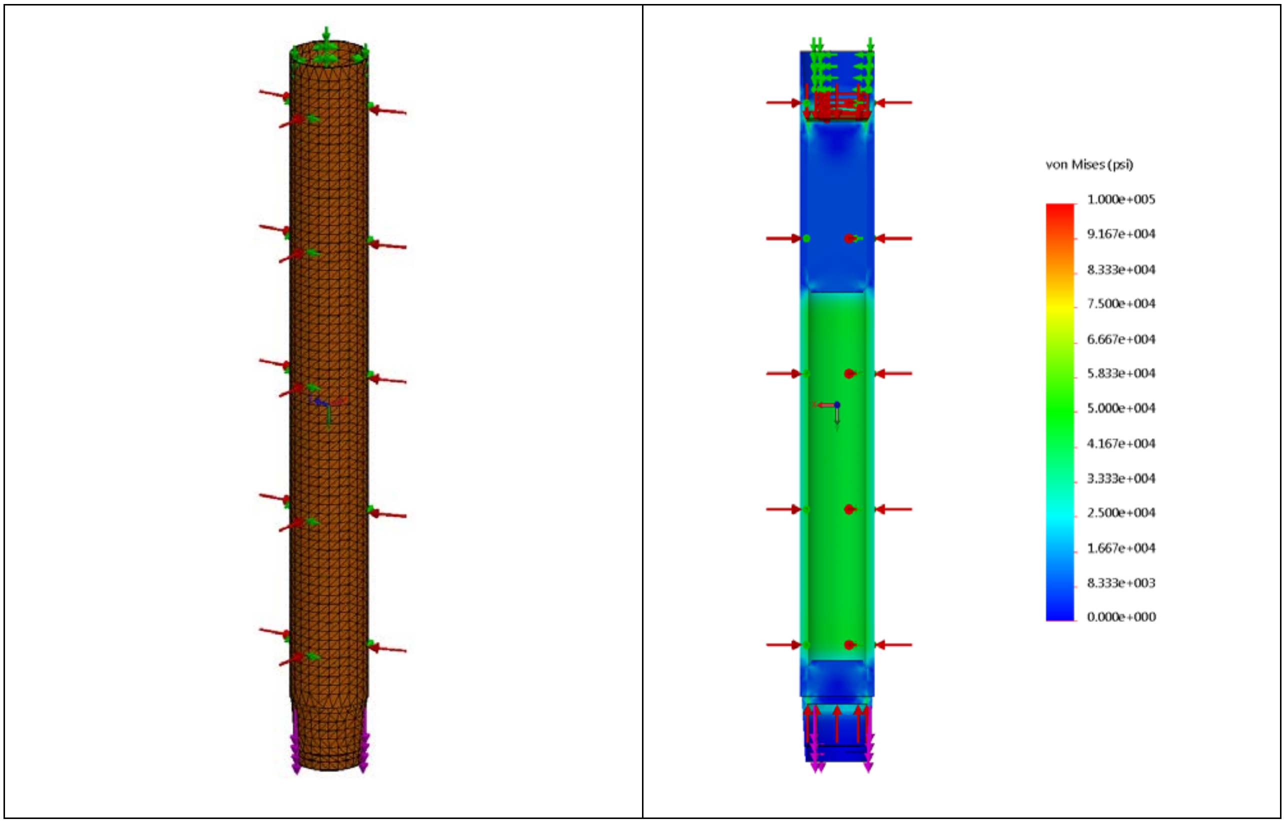


Figure 4-5. Option 4 stress analysis (aspect ratio shortened for illustration).

Effect of Axial Stresses on Collapse Pressure of the Package

According to Section 2 of API Bulletin 5C3 (*Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties - Sixth Edition*), the yield strength collapse pressure for a pipe under external pressure is given by Equation (4-1). This pipe analysis 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.

$$P_{yp} = 2Y_p \left[\frac{\left({}^{D}\!/_{t} \right) - 1}{\left({}^{D}\!/_{t} \right)^2} \right] \tag{4-1}$$

If the pipe is also subjected to tensile axial stress, then the collapse pressure is reduced and becomes:

$$P_{CA} = P_{yp} \left[\sqrt{1 - 0.75 \left[\frac{\left(S_A + P_i \right)}{Y_p} \right]^2} \right] - 0.5 \left(\frac{S_A + P_i}{Y_p} \right) \tag{4-2}$$

If the effect of borehole curvature is considered, then there is additional stress on the pipe due to bending. The build rate or dogleg severity is typically given in °/100 ft. For a given build rate, the radius of curvature of the borehole is given by Equation (4-4).

$$\alpha = \frac{x^{\circ}}{100\,ft} \tag{4-3}$$

$$\rho = \frac{180}{\pi \cdot \alpha} \tag{4-4}$$

According to beam theory, the bending moment imparted on the package is:

$$M = \frac{E \cdot I}{\rho} \tag{4-5}$$

where E is the modulus of elasticity, I is the area moment of inertia, and ρ is the radius of curvature. From that, the normal stress at the outer diameter of the pipe is given by Equation (4-6):

$$\left(\sigma_z\right)_0 = \frac{M \cdot \left(OD/2 \right)}{I} \tag{4-6}$$

For a drill string in contact with casing, the pipe is subject to non-uniform bending. If it is assumed that the contact between the package and the casing occurs at the joints (Figure 4-6), then the additional tensile stress caused by point-loaded bending is given by Equation (4-8) (Gourgoyne et al. 1986):

$$K = \sqrt{\frac{F_a}{EI}} \tag{4-7}$$

$$\left(\sigma_z\right)_{\max} = \left(\sigma_z\right)_0 \frac{6KL_j}{\tanh\left(6KL_j\right)} \tag{4-8}$$

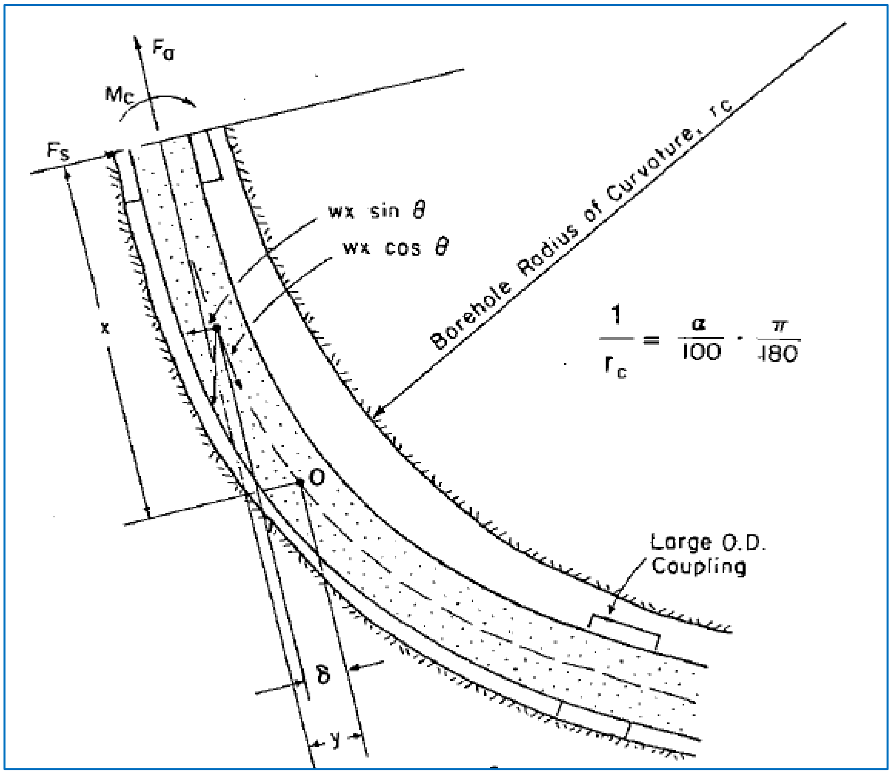


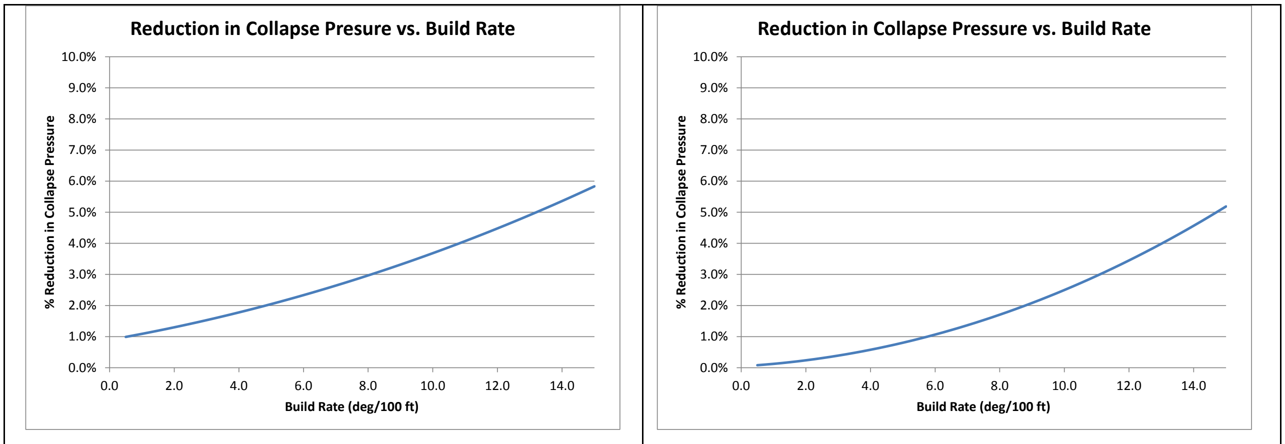
Figure 4-6. Borehole curvature illustration (Gourgoyne et al. 1986).

Based on the operational requirements, nominal 11-inch OD packages and 5-inch OD packages are considered for analysis. The appropriate tubing or casing dimensions are used as the basis for the collapse pressure estimates shown in Table 4-1. Using steel grade P-110 with 110 ksi yield strength, each design concept provides a factor of safety of approximately 2.0 against yielding due to external hydrostatic load of 9,600 psi.

Table 4-1. Collapse pressure for tubular portions of packages (110 ksi yield strength material).

OD (inches)	ID (inches)	Nominal Collapse Pressure (psi)
10.75	8.75	18,560
5.0	4.0	19,600

The anticipated effect of temperature is a reduction in yield strength of the material and a corresponding decrease in the factor of safety (see Section 2.6.7). The appropriate reduction factor, and accommodation in the design, will depend on the final material selected.



5.0” OD Casing (19,600 psi collapse)	10.75” OD Tubing (18,560 psi collapse)

Figure 4-7. Reduction in collapse pressure due to build rate.

Figure 4-7 shows that bending of the package, due to a curvature of the guidance casing (as illustrated in Figure 4-6), will have minimal effect on the collapse strength of the tubular portion of the packaging.

4.2 Terminal Sinking Velocity

With a guidance liner running from the surface to TD, and the borehole filled with an emplacement fluid with controlled properties, it could be possible to allow waste packages to sink freely into disposal position. Terminal velocity was estimated by Bates et al. (2011) to be on the order of 8 ft/sec for waste packages with diameter of 13.4 inches, radial clearance of 0.93 inches, and water as the emplacement fluid (with viscosity reduced for in situ temperature). Waste package weight in the analysis was the same as the maximum weight estimated for reference-size packages in this report (Section 2.4). Note that if slotted casing is used in the disposal zone, the waste package terminal velocity could be greater.

The flow regime involved with packages sinking in casing is turbulent, with Reynolds number on the order of 10^4 or greater (Bates et al. 2011). Frictional resistance is dominated by fluid flow up the annulus between the package and the casing. The upward speed of this flow is greater than the downward speed of the package. Results could be sensitive to bleed off through perforations in the guidance casing, depending on formation permeability and whether there is a contiguous return path for fluid in the annulus around the guidance casing.

For disposal using the reference concept described in Section 2 the radial gap would be slightly smaller, and the emplacement fluid would likely have higher viscosity than pure water. Accordingly, terminal sinking velocity could be significantly smaller than 8 ft/sec which would mitigate accidental drops, but slow down emplacement speeds. Also, the pressure surge effect could be greatly increased, especially for drill-string emplacement, adding risk from damage to the guidance liner.

4.3 Impact Limiters

A linear energy-balance calculation is used to compute the force characteristics of an impact limiter, to arrest a waste package at terminal velocity. It is assumed that energy absorbing material (e.g., Hexcel Tube-Core®) is available in cylinders with any length and diameter, crush strength of 0.5 to 55 MPa, and fully crushed length of 35% initial length. Hexcel (2015a,b) reports 30% fully crushed length but a 5% allowance is made here for pre-crush.

The terminal velocity of single packages is assumed to be 8 ft/sec (2.5 m/sec) following Bates et al. (2011) for a package similar to the reference-size package (Section 2.6.7) in pure water at in situ temperature. The radial gap for DBFT packages would be smaller (0.7 inches; Section 2.3), the emplacement fluid would likely be more viscous than pure water, and the package length greater (18.5 ft compared to 16.4 ft used by Bates et al. 2011), all of which could produce slower sinking velocity.

Derivation

D = Package diameter
M = Package mass (or package-string mass, or package-string + drill-string mass)
V = Velocity (initial velocity for deceleration problem)
f_{cr} = Average crushing strength in pressure units
s = Crushing stroke
g = Acceleration of gravity
a = Average rate of deceleration

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

$$\frac{1}{2}MV^2 = \frac{\pi D^2}{4} f_{cr} s \tag{4-9}$$

so that

$$s = \frac{2MV^2}{\pi D^2 f_{cr}} \tag{4-10}$$

and deceleration rate is

$$a = \frac{V^2}{2s} = \frac{\pi D^2 f_{cr}}{4M} \tag{4-11}$$

Result

Using the softest crush strength noted above (0.5 MPa), and assuming that the impact limiter would have 80% of the area of the package (allowing for a taper), then a minimum limiter length of approximately 1.5 ft would be required, the deceleration rate would be 1.8 g, and the crushing force would be approximately 8,000 lb. This is much less than a stack of 40 waste packages, so impact limiters designed to this formula would collapse one-by-one during waste emplacement.

To address uncertainty as to package weight, sinking velocity, and other factors, a composite impact limiter could combine multiple elements with different crushing strength.

The fluid dynamics of different package dimensions and geometries, disposal zone completions, and emplacement fluid rheology (e.g. thixotropicity) will need to be more closely analyzed during design.

4.4 Energy Needed for Package Breach

This calculation provides an estimate of the effect of falling packages striking a stationary waste 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 waste packages is known and the kinetic energy of the falling waste packages is converted to strain energy in the stationary waste package.

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

$$KE = \frac{1}{2} m v^2 \tag{4-12}$$

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 waste package is given by

$$U = \frac{E \cdot A \cdot \delta_{\max}^2}{2L} \tag{4-13}$$

where E is the modulus of elasticity, A is the area of the waste 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 waste packages is given by

$$\delta_{static} = \frac{W \cdot L}{A \cdot E} \tag{4-14}$$

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

$$KE = U \tag{4-15}$$

Calculate mass of packages from weight of packages (more important in English units).

$$m = \frac{W}{g} \tag{4-16}$$

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

$$\delta_{\max} = \sqrt{\frac{m \cdot v^2 \cdot L}{A \cdot E}} \tag{4-17}$$

The corresponding maximum stress is given by

$$\sigma_{\max} = \sqrt{\frac{m \cdot v^2 \cdot E}{A \cdot L}} \;. \tag{4-18}$$

For waste packages each weighing 4,620 lb (2,100 kg mass) falling at 8 ft/sec (2.5 m/sec), the stress imparted on the impacted stationary package vs. the number of packages is shown in Figure 4-8. 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 x 8.75-inch ID waste package, the corresponding impulsive axial force is shown in Figure 4-9.

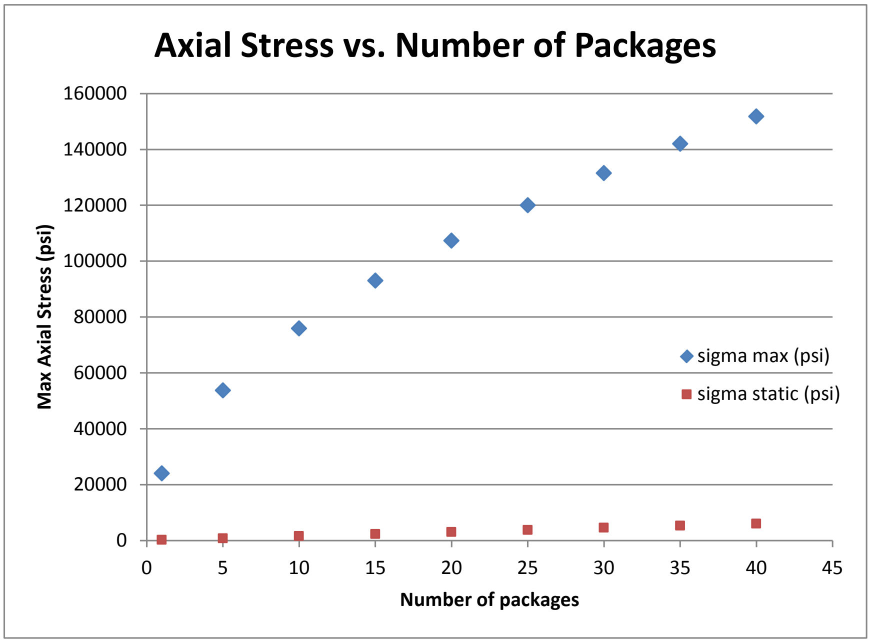


Figure 4-8. Static and impulsive axial stress due to falling waste packages.

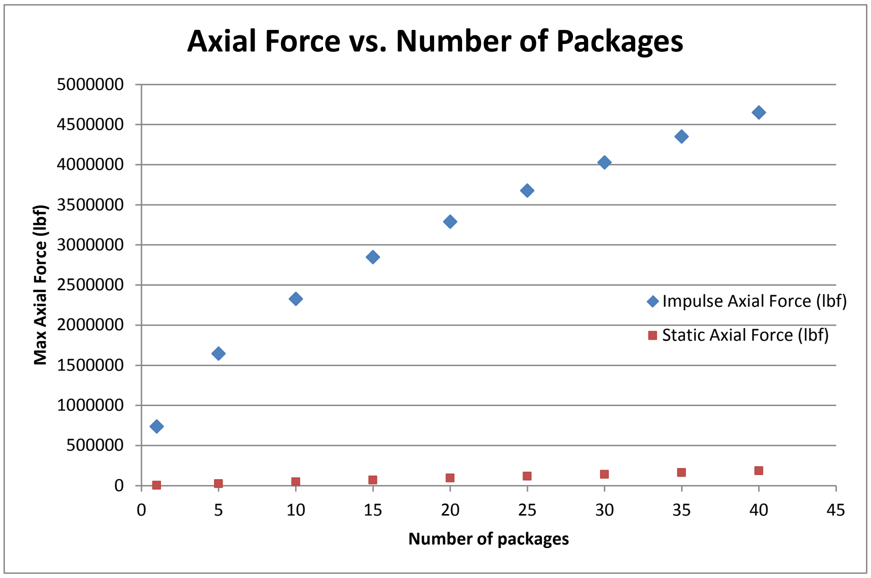


Figure 4-9. Static and impulsive axial force due to falling waste packages.

Using these impulse force estimates as external loads, several finite element simulations were conducted to determine the additional stress loads on the waste packages. For the calculation, the properties of steel were assumed, with linear elastic behavior. The forces were applied in a quasi-static manner. The induced stresses are compared to 110 ksi yield strength.

The additional axial load is combined with the external pressure from the weight of the emplacement fluid as shown in Figure 4-10. The additional load is assumed to be applied eccentrically over a 40° sector on the face of the box end of the waste package.

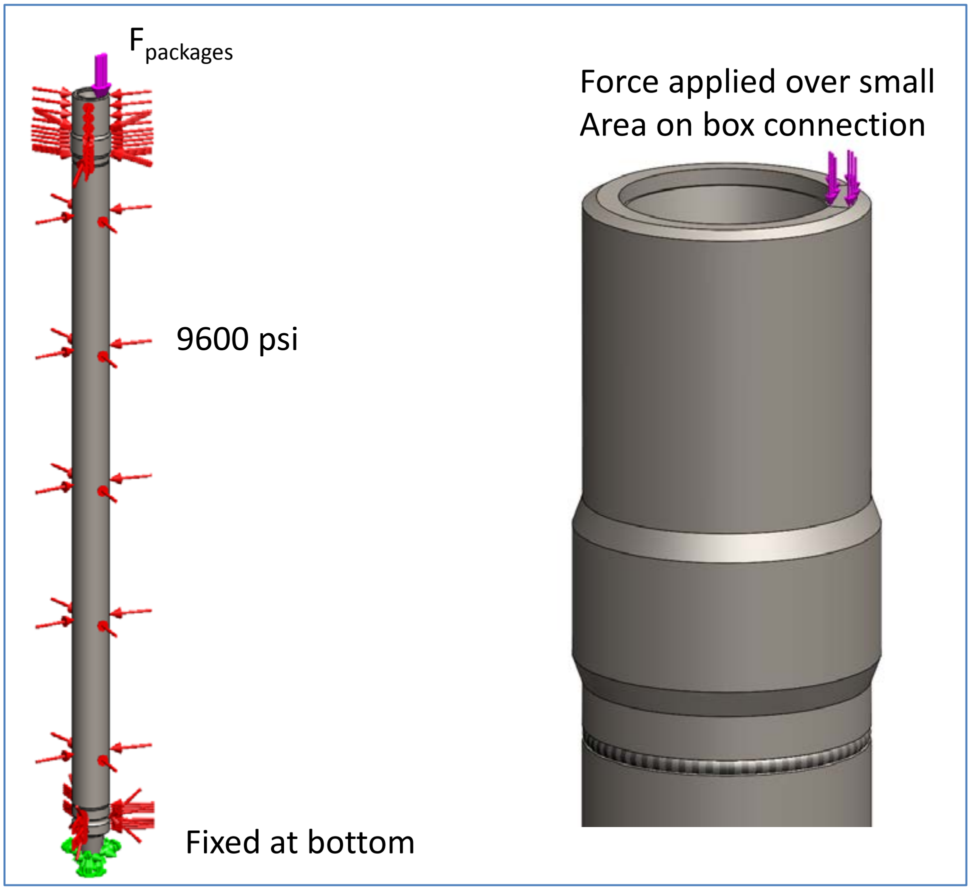


Figure 4-10. Waste package loading conditions.

For a single waste 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 (Figure 4-11).

For five to 20 waste packages (Figures 4-12 through 4-14) the yield regions extend beyond the point of impact and the joint. The stress levels exceed the yield strength of the material and vary throughout the tubular section.

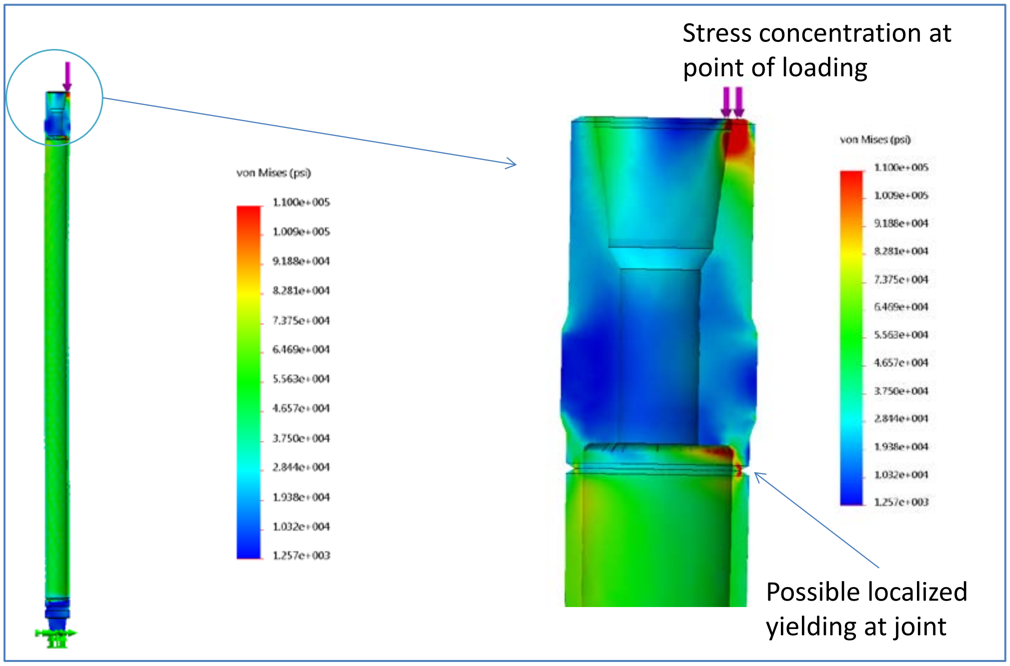


Figure 4-11. A single waste package falling (7.4×10^5 lbf impulse force, 20× horizontal exaggeration).

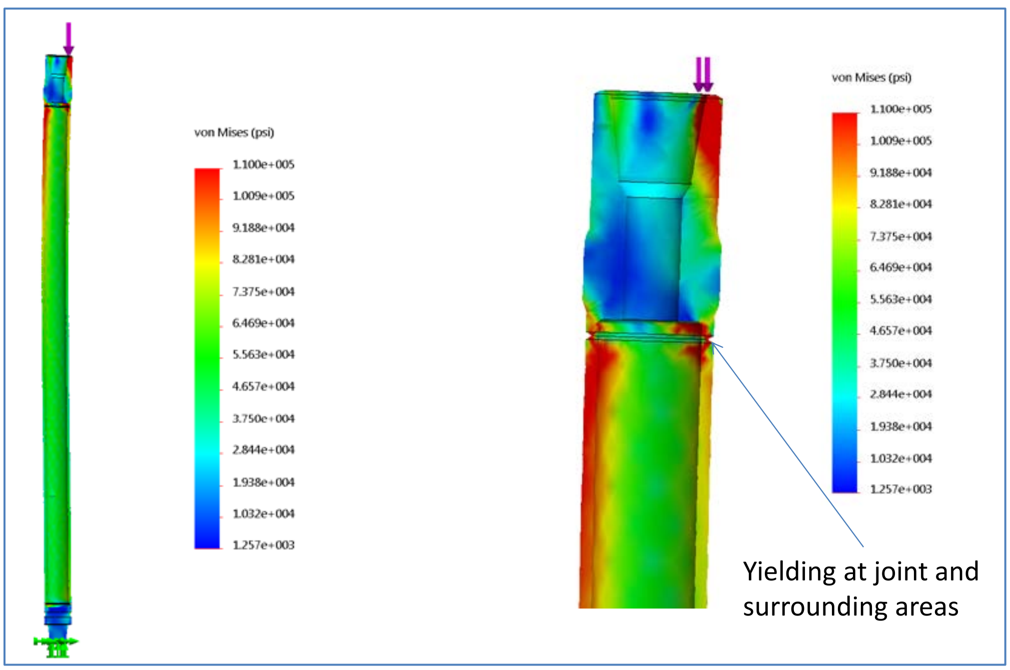


Figure 4-12. Five waste packages falling (1.6×10^6 lbf impulse force, 20× horizontal exaggeration).

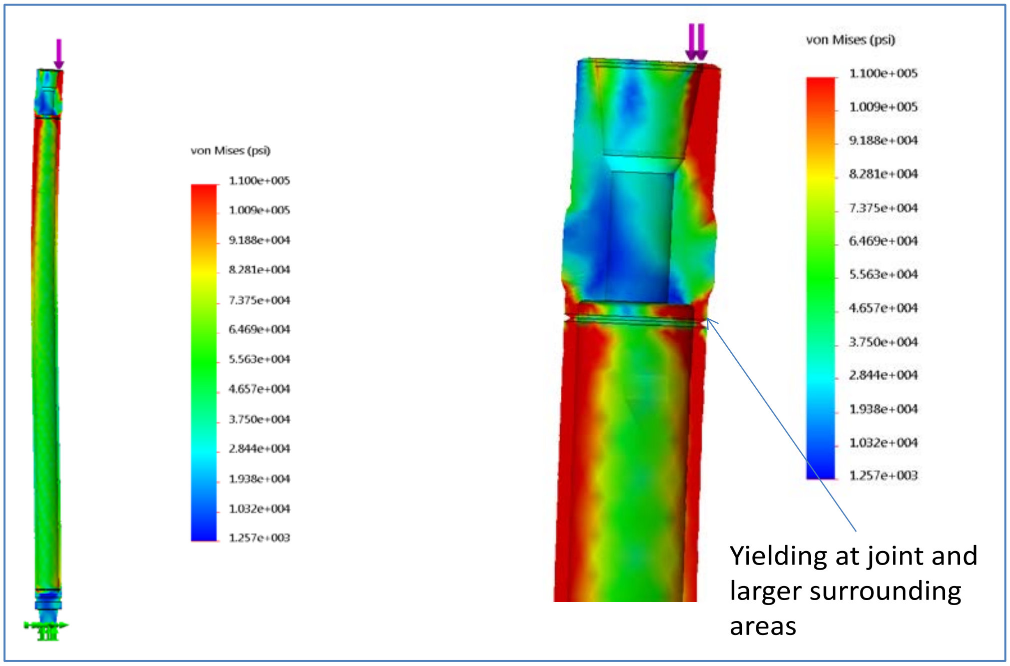


Figure 4-13. Ten waste packages falling (2.3×10^6 lbf impulse force, 20× horizontal exaggeration).

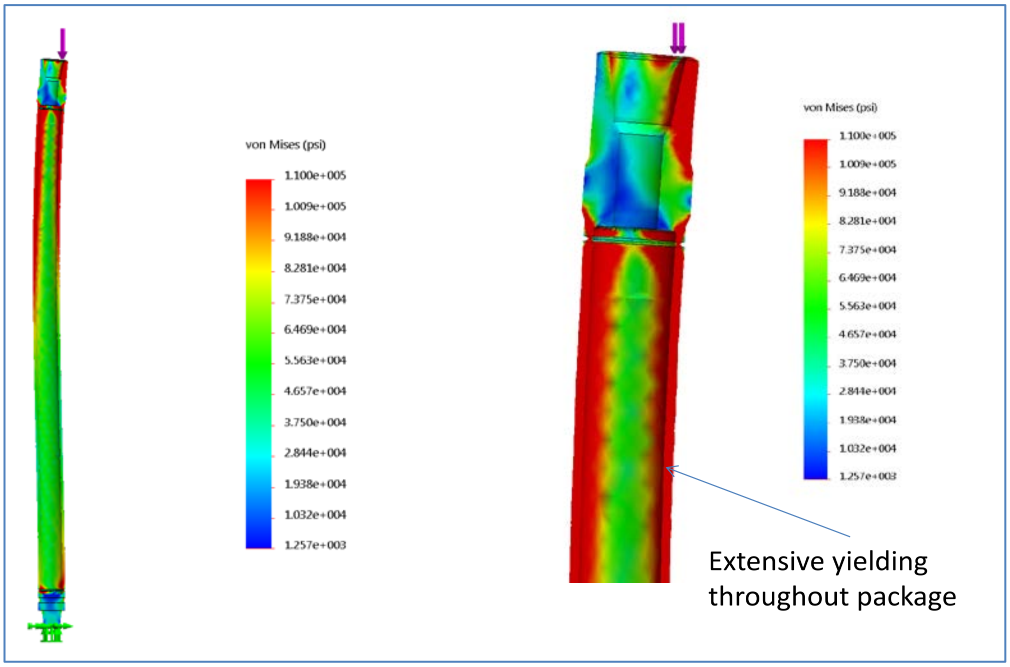


Figure 4-14. Twenty waste packages falling (3.3×10^6 lbf impulse force, 20× horizontal exaggeration).

Simulation results in areas where the stresses far exceed the yield strength of the material should be viewed with caution as there may be post-peak stress deformation behavior in those regions that is not captured accurately for the actual waste package material.

The conclusion from this calculation is that drops of more than one package moving at terminal velocity (assumed the same for single packages and multi-package strings), can produce extensive yielding in a target package. The calculation is conservative because it ignores energy loss to heat, and because impact deformation may be distributed across multiple packages. It may be non-conservative because it is quasi-static, so that localized strain energy storage and other inertial effects within the target package are not considered.

4.5 Thermal-Hydrology Simulations for Disposal of Cs/Sr Capsules in a Deep Borehole

Previous thermal-hydrology simulations looked at disposal of spent nuclear fuel in deep boreholes (e.g. Arnold and Hadgu 2013). In this calculation we look at thermal-hydrology modeling for the disposal of Cs/Sr capsules in a single borehole.

Thermal output of the capsules includes large variations as shown in Figure 4-15. For this analysis decaying heat data for the weighted average thermal output of all Cs capsules, or all Sr capsules, was considered. Emplacement was assumed to be in 2020.

Different configurations are possible for the disposal of the Cs/Sr capsules in a deep borehole depending on the size of canisters, borehole diameter and depth. In this analysis two possible configurations were considered as summarized in Table 4-2. The 2-capsule case has the capsules arranged end-to-end within a 1.083-meter long waste package or disposal overpack. This configuration could be emplaced in a borehole with disposal zone diameter of 8.5 inches. The 6-capsule case has the capsules arrange in two bundles of three stacked end-to-end. It would require a disposal zone borehole diameter of at least 12.25 inches (Arnold et al. 2014).

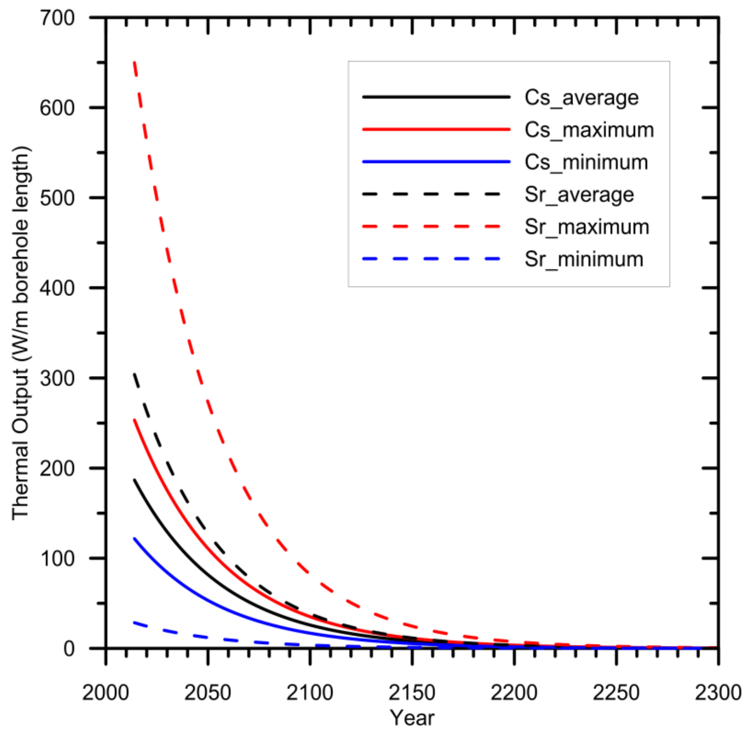


Figure 4-15. Projected thermal output from Cs and Sr waste capsules (from DOE 2014).

Table 4-2. Alternative disposal concepts for Cs and Sr capsules analyzed.

	2-Capsule	6-Capsule
Borehole Diameter (in)	8.5	12.25
Disposal Zone Casing O.D. (m)	0.178	0.273
Disposal Zone Casing I.D. (m)	0.162	0.245
Canister O.D. (m)	0.114	0.191
Canister I.D. (m)	0.089	0.165
Capsules per Layer	1	3
Number of Layers	2	2
Capsules per Canister	2	6

Thermal-Hydrology Modeling

For the thermal-hydrology simulations a single borehole with a total depth of 5 km was assumed. The model geometry includes an area of 2 km x 2 km and a depth of 6 km, with a vertical half-symmetry plane through the borehole. The mesh has 27,000 grid blocks. Initial conditions and rock material properties used are mostly the same as in Arnold and Hadgu (2013). The stratigraphy includes sedimentary rock above 1,500 m, and granitic rock below that to the total depth of the domain. For the sedimentary overburden, the parameter values given in Table 4-3 were used.

Table 4-3. Parameter values of sedimentary rocks.

Lithology	Permeability (m^2)	Porosity	Thermal Conductivity (W/mK)	Heat Capacity (J/kg °K)
sandstone	1×10^{-12}	0.30	3.5	840.
shale	1×10^{-15}	0.02	1.8	840.
limestone	1×10^{-13}	0.05	2.7	840.
dolomite	1×10^{-13}	0.05	4.0	840.

For granitic rock in the crystalline basement porosity of 0.01 and heat capacity of 880 J/kg°K were used. For this study we have selected the relationship of Stober and Bucher (2007) for permeability variation with depth in the granitic rock. The relationship is based on deep drilling into continental crystalline basement rock and thus is appropriate for thermal-hydrology analysis of nuclear waste disposal in deep boreholes. The relationship is

$$\text{Log}(k) = -1.38 \log(z) - 15.4 \quad (4\text{-}19)$$

where z is depth in km and k is permeability in m^2. The permeability of the borehole and the surrounding disturbed rock zone (within a cross-sectional area of 1 m^2) was increased by a factor of 10 to account for increased permeability in the disturbed rock zone and degradation of borehole seals. The analysis also used depth dependent thermal conductivity in the granitic rock (Vosteen and Schellschmidt 2003).

For the simulations the PFLOTRAN numerical software (Hammond et al. 2011) was used. The PFLOTRAN code supports high-performance parallel computing using many processors. Groundwater salinity stratification was not included.

Boundary conditions included specified atmospheric pressure at the ground surface, with a mean temperature of 10°C. The bottom boundary was no-flow, at a fixed temperature of 160°C. The temperature boundary conditions represent an average geothermal gradient of 25 °C /km. The system is initially at hydrostatic pressure conditions and the temperature gradient.

Waste Packages with 2 Capsules

For the 2-capsule case (Table 4-2) Cs and Sr capsules were placed in the lower part of the borehole between 5,000 m and 3,700 m depth. Half of the thermal output was applied because of symmetry considerations. Thermal-hydrology simulations were run to a total time of 10^5 years. Figure 4-16 shows temperature at selected depths as a function of time. Peak temperatures occur within 10 years after emplacement. The maximum temperature rise is about 50°C for both selected depths. Figure 4-17 shows vertical ground water flux in kg/m^2/year at the top of the disposal zone (3,700 m depth).

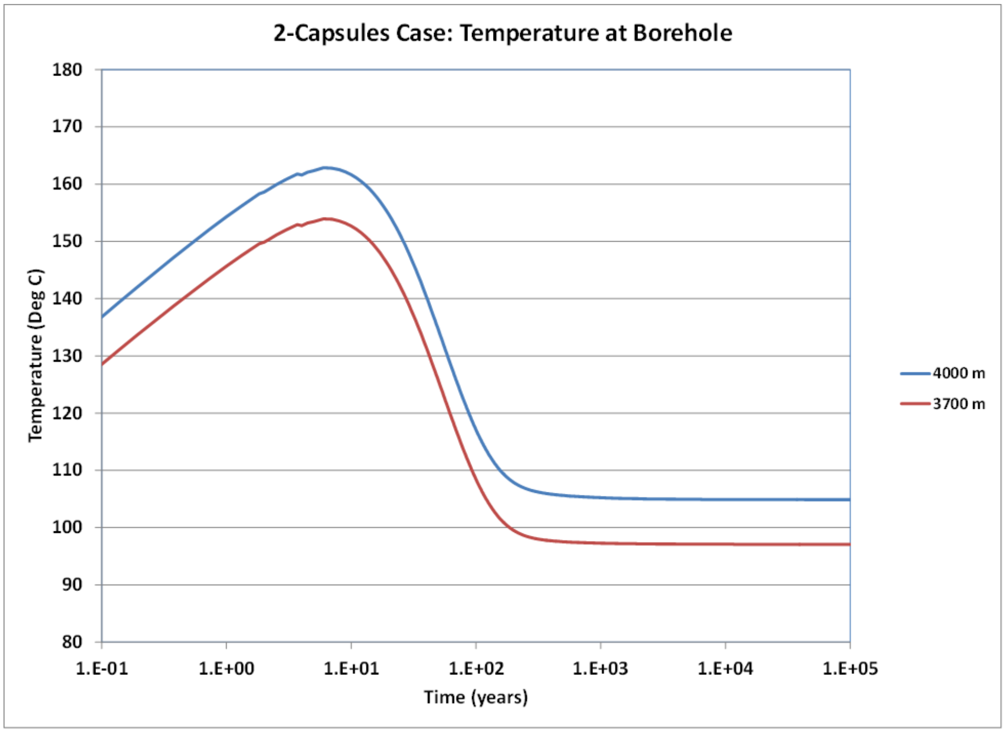


Figure 4-16. Simulated temperature vs. time in the borehole for the 2-capsule case at depths of 4,000 m and 3,700m (top of the disposal zone).

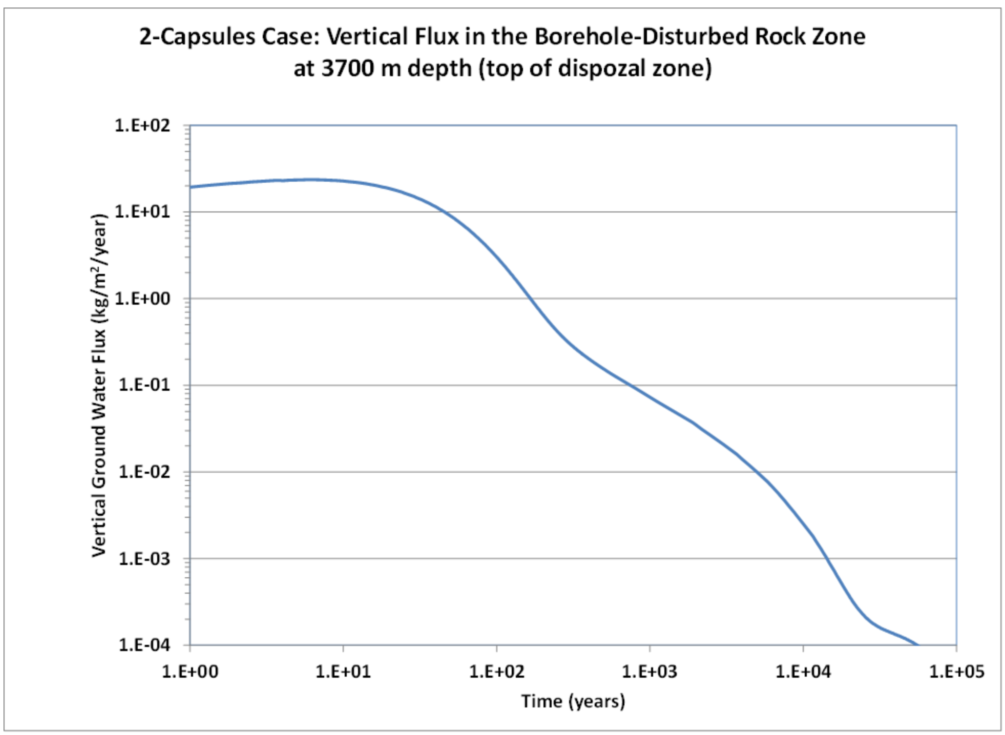


Figure 4-17. Simulated vertical groundwater flux vs. time in the borehole and the disturbed rock zone for the 2-capsule case at 3,700m depth (top of the disposal zone).

Waste Packages with 6 Capsules

Assuming the waste package for the 6-capsule case has the same length as for the 2-capsule case, the total length required to emplace all capsules would be 433 m. Thus, for these simulations the Cs and Sr capsules were placed in the lower part of the borehole between 5,000 m and 4,567 m depth. Thermal-hydrology simulations were run to a total time of 10^5 years. Figure 4-18 shows temperature at selected depths as a function of time. As with the 2-capsule case, peak temperatures occur within 10 years after emplacement. The simulated peak temperatures are higher than the 2-capsule case, with the maximum temperature rise about 125°C for both selected depths. Note that selection of maximum thermal output of the capsules (Figure 4-15) would result in greater temperature rise. For such a case delayed emplacement (aging) would reduce the thermal output. Figure 4-19 shows vertical ground water flux in kg/m^2/year near the top of the disposal zone. The vertical groundwater flux is also greater than for the 2-capsule case.

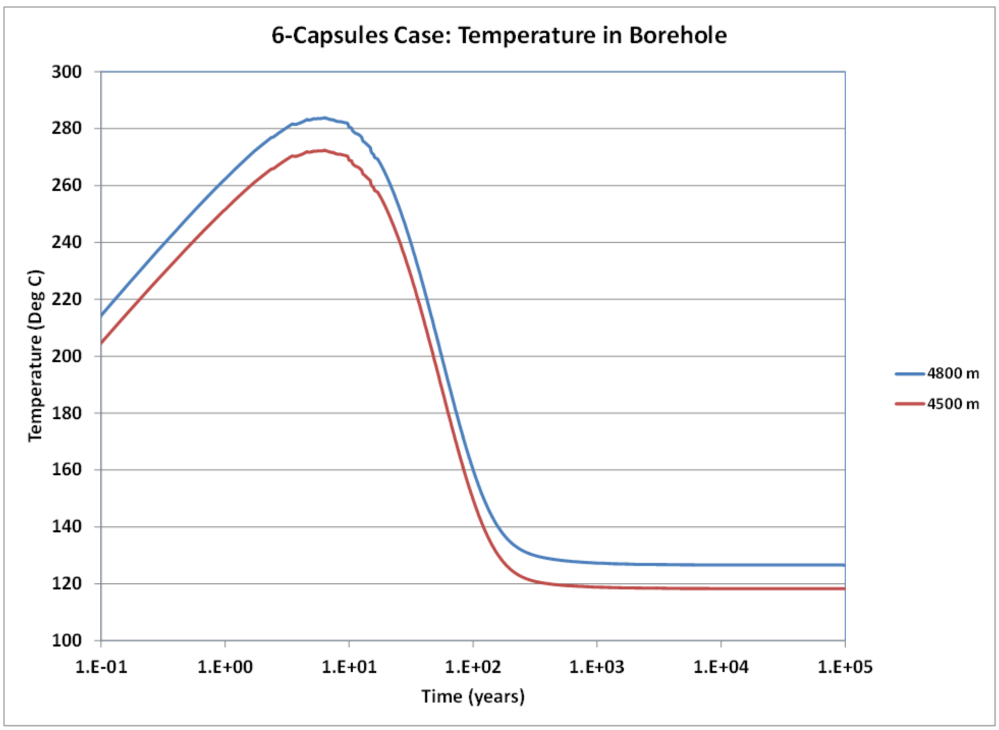


Figure 4-18. Simulated temperature vs. time in the borehole for the 6-capsule case at depths of 4,800 m and 4,500m.

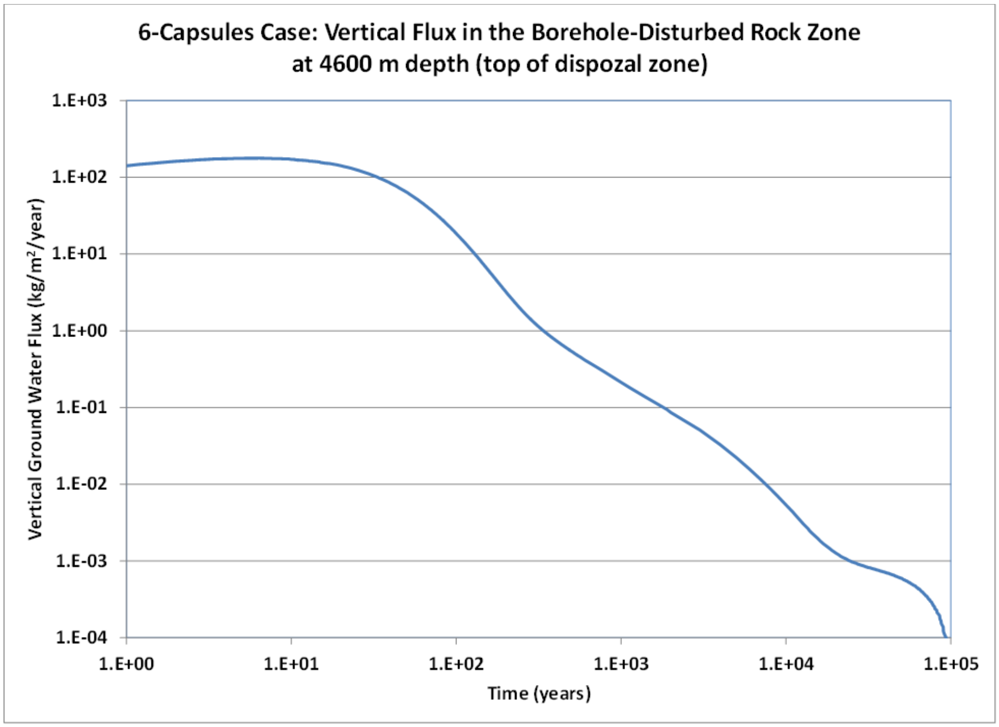


Figure 4-19. Simulated vertical groundwater flux vs. time in the borehole and the disturbed rock zone for the 6-capsule case at 4,600m depth (top of the disposal zone).

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5. Engineering Design Selection Study

This section describes a study done to support the selection of an engineering concept for handling and emplacement of waste packages for the DBFT. Specifically, it describes the methodology used for the evaluation and comparison (Section 5.1), and the results of applying that methodology. Model inputs are described in Sections 5.2 through 5.4; initial results and sensitivity analyses are described in Sections 5.5 and 5.6.

5.1 Approach and Methodology

Decision analysis (Clemen 1997; Keeney 1982), and multi-attribute utility analysis (MUA) (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. Decision analysis methods and MUA methods in particular have been used by the DOE and by many other entities in the public and private sectors for decades to provide logically consistent analyses 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; Sandia National Laboratory 1991; Younker et al. 1992; Bechtel SAIC Company 2003).

5.1.1 Study Steps

Multi-attribute utility analysis is straightforward in concept. Three steps are typically followed to frame the analysis: Identify a set of *objectives* that an “ideal” alternative would achieve, define a set of *performance measures* (often called metrics or criteria) that provide a clear definition of each objective, and 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 (this step is often called “scoring” the alternatives). Then, if necessary, the performance of each alternative 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.

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 5-1 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 this structured approach to the evaluation and comparison of alternatives is that it promotes the identification and consideration of design modifications that enable each alternative to better meet decision-maker objectives. In particular, Sections 5.1.3 and 2.7.1, and Appendix B describe some of the engineering concept modifications identified during this study.

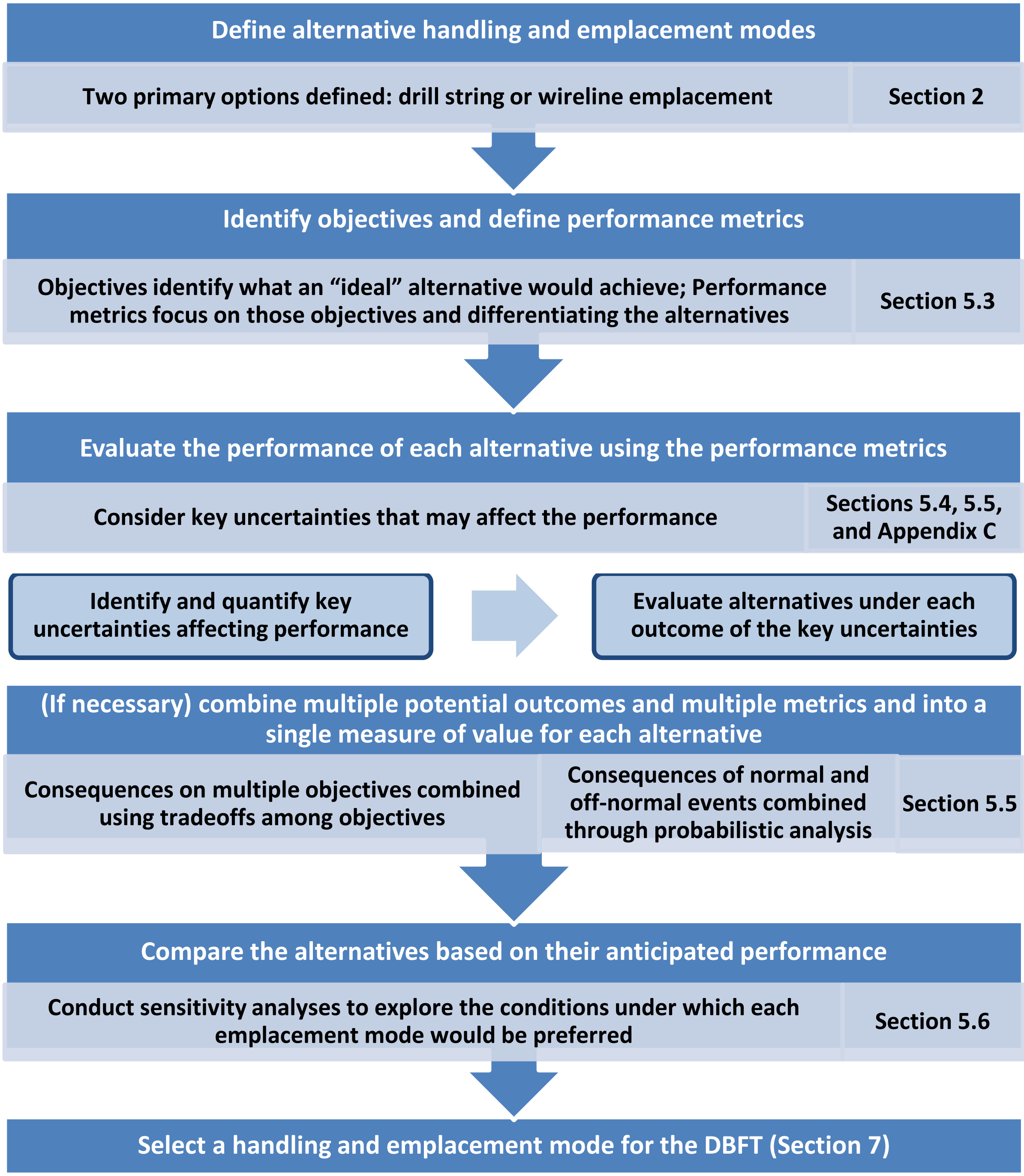


Figure 5-1. Steps in the engineering design selection study.

5.1.2 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 5.4 and Appendix B describe in more detail how various types of uncertainties were addressed in this analysis, using the principles of decision analysis and probabilistic risk analysis.

5.1.3 Expert Panel Input

Preliminary estimates for many of the steps and inputs outlined in Figure 5-1 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 Appendix A, 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 structured workshop to walk through all aspects of the analysis. During the workshop panel members provided critical review and updates of all the preliminary inputs. The panel:

- Reviewed the two emplacement modes and worked through the hazards analysis to identify what can "go wrong" during emplacement. 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. All of these design modifications are listed in Section 2.7, and several were incorporated in the descriptions of the emplacement modes in Section 2.6.
- Reviewed and updated the hazard analysis itself, including identifying and categorizing the basic events in the fault trees into roughly order-of-magnitude groupings based on estimated probability of occurrence; those inputs are reviewed in Section 5.4 and Appendix B.
- Provided detailed discussion and a modeling approach for the steps that could be taken if a waste package (WP) is stuck in the borehole during emplacement ("fishing"), and estimate the probabilities of different fishing outcomes. Those inputs are reviewed in Section 5.5.
- Reviewed and provided comments on the potential for radiological exposures, occupational safety, costs, and time for each of the identified outcomes. Those inputs are also reviewed in Section 5.5

5.2 Alternatives Evaluated

Many aspects of the engineering design have been sufficiently well-defined that no comparative evaluation of options was necessary. As described in Section 2 of this report, however, at least two viable alternatives for the emplacement mode were identified, without an obvious "winner:" drill-string emplacement and wireline emplacement.

The analysis focused exclusively on the potential *differences* between the emplacement modes, specifically those differences which might lead to different outcomes for the alternatives. Key assumptions included:

1) The DBFT will be conducted, and that all other elements of the design have been selected. Thus all issues other than waste emplacement mode are irrelevant to this study (e.g., this study does not address issues such as comparing deep borehole disposal to other disposal approach)
2) Many aspects of the disposal process will be identical between the emplacement options and *thus need not be considered or evaluated*. For example:
    a. All operations up to the movement of a WP to the top of the disposal borehole, including
        i. Drilling of the disposal boreholes: the number and characteristics of boreholes needed for the two emplacement modes are assumed to be identical, so the bulk of the costs and risks associated with drilling those holes is irrelevant to the analysis. Costs would differ between emplacement modes only if one mode requires more boreholes than the other.
        ii. Packaging and transportation of HLW and spent nuclear fuel to the disposal facility, and receipt of shipping casks at the facility.
        iii. Transportation of shipping casks to the borehole; up-ending and attaching the shipping casks to the disposal borehole
    b. All operations after emplacement of the last WP in a borehole, including:
        i. Plugging and closing each borehole
        ii. Closure, short-term and long-term monitoring of the disposal facility

The main differences between the two emplacement modes that were relevant in this analyses were:

- 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 waste package string emplaced. This lead package allows for monitoring of the borehole during emplacement. It also includes a designed weak point between the lead package and waste packages, which makes it easier to remove a string of waste packages in the event they get 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 disposal zone as a string. This difference leads to several important distinctions:
  - Wireline emplacement requires many more “trips” in and out of the borehole to emplace the same number of WPs that are emplaced with one “trip” via drill-string,
  - Drill-string emplacement requires many connections to be made before a trip is completed. WPs are connected together, connected to drill pipe, and the drill pipe stands are connected together as the WP string is lowered.
  - Drill-string emplacement leads to much heavier “loads” being emplaced, nominally the weight of 40 waste packages plus the drill pipe itself, and thus a higher likelihood of a WP breaching if a drop occurs.

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

5.3 Objectives and Performance Measures

As discussed above, MUA has been used extensively for more than 30 years to evaluate a wide variety of decisions, including many 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 5-1 summarizes that review and identifies objectives that are relevant to the comparison of emplacement modes.

For each of these objectives, it is necessary to develop one or more *performance measures (metrics)*: 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 which can be compared meaningfully by decision-makers.

Table 5-1. 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 to environmental or human receptors. Worker risks can be considered a "leading indicator" of any risks to the public (or to the environment) from off-normal events. The public will not be exposed to risks during normal operations, and 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.	Considered only through time required to dispose of a set quantity of waste, both through normal operations and with the potential occurrence of off-normal events. Necessary technologies exist for any emplacement mode being considered, and the emplacement mode will not lead to different impact on any of the other potential waste acceptance criteria typically considered.
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.
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 criteria related to worker radiological risks during off-normal events: if radiological exposures occur, public confidence in the DOE waste management program will suffer. 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.

Objectives	Relevance to Evaluation of Emplacement Modes
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. After emplacement and borehole sealing/plugging (i.e., after permanent closure) retrievability requirements as defined in current regulations such as 10CFR63, will not apply. If borehole-specific retrievability requirements are someday imposed, we assume that the selection of emplacement mode has no significant impact on the capability to much such future requirements.
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 will be associated with the disposal facility, but differences in those impacts between emplacement modes is 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 are not affected by the choice of emplacement mode

Based on a review of the nine commonly-used high-level objectives and many of the more detailed performance metrics related to each that are summarized in Table 5-1, and considering the key differences between emplacement modes outlined above and discussions with the expert panel described in Section 5.1.3, three metrics were identified for use in this analysis:

1. Radiological releases, measured using a Yes/no metric on whether detectible levels of radiation could 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. Excludes costs to drill and complete the initial borehole but includes any incremental costs to dispose of remaining WPs if a borehole loses emplacement capacity prior to successful disposal of 400 packages.

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. Incremental 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 oilfield industry, or 2) in handling packaged nuclear materials such as is done at licensed near-surface disposal facilities. In addition, rigorous safety procedures will be followed and worker injuries are expected to be very low under both emplacement options, so "normal" occupational safety risks were determined not to be a critical differentiator between the options. It was also noted that radiological risks to workers are mainly a function of whether radiological releases occur from breached waste packages, so the performance metric of "radiological releases" also provides information on the potential for risks to workers. The exclusion of normal occupational risks does not imply that worker risks are irrelevant to the comparison or to ultimate operations.

5.4 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 several uncertainties:

- Uncertainty about whether operations will proceed as planned; if not,
  - Uncertainty about what can go wrong and how likely adverse events are ("off-normal events")
  - Uncertainty about the ability to respond to and to mitigate the consequences of off-normal events,
- Uncertainty about the costs, timing, and occupational safety of each emplacement mode if emplacement operations proceed as planned and anticipated ("normal operations"),
- Uncertainty about the ultimate impacts in terms of radiological releases, occupational safety risks, and/or increases in the time or costs required to complete the disposal process if off-normal events occur.

Each type of uncertainty was addressed in this analysis.

5.4.1 Uncertainty About the Occurrence of and Response to 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 of this report describes a hazard analysis developed to (a) identify off-normal events importance to performance, and (b) 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 5-2 shows those top level failures and the off-normal event that results for each emplacement mode. Each of these is of concern because it leads to the potential for a WP to be breached and radiological release to occur, for disposal capacity to be lost, and for additional mitigation costs and for additional time to mitigate the off-normal event.

Table 5-2. Off-normal events considered for each emplacement mode.

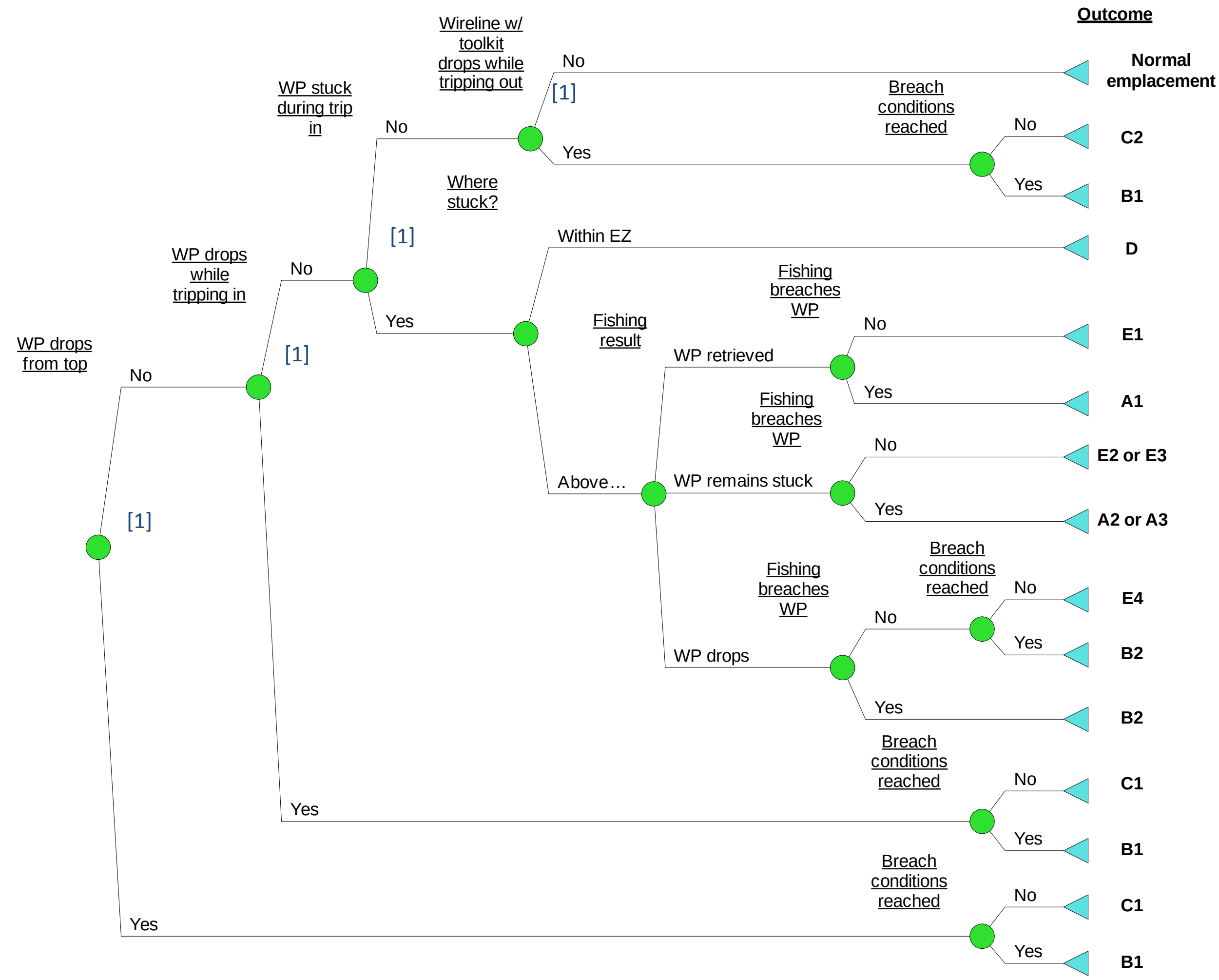
Wireline Emplacement	Drill-String Emplacement
A waste package (WP) is dropped from the top of the borehole	One or more connected waste packages (WPs) are dropped from the top of the borehole during assembly of a WP string
One WP is dropped during the trip in	A WP string is dropped during the trip in
One WP becomes stuck in the borehole during the trip in	A WP string becomes stuck in the borehole during the trip in
The wireline falls onto emplaced WPs during the trip out	The drill-string falls onto emplaced WPs during the trip out

Other potential off-normal events were identified and discussed with the expert panel (Section 2.7 and Appendix B). Some of these were adopted in consideration of the options, while others were identified for possible future engineering study. The latter set was determined not to be material to the comparison of emplacement modes.

If any one of the off-normal events identified in Table 5-2 occurs, uncertainty remains about what would happen next. Figures 5-2 and 5-3 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, represent the four off-normal events; the top branch indicates a favorable outcome (no drop, package not stuck, etc.) and the lower branch indicates occurrence of the off-normal events. As indicated in figures, the probabilities for each of these events are calculated in the fault trees described in Appendix B of this report.

Subsequent to any off-normal event, there are one or more events that can lead to different outcomes, as shown in the trees. 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 the WP is stuck, and the ability to retrieve or “fish” the WP successfully. These event trees represent one result of the expert panel workshop described in Section 5.1.3.



Note: [1] indicates the probability of the event comes from fault tree calculations described in Appendix B

Figure 5-2. Wireline event tree, per waste package, with outcomes illustrated ("EZ" = disposal zone).

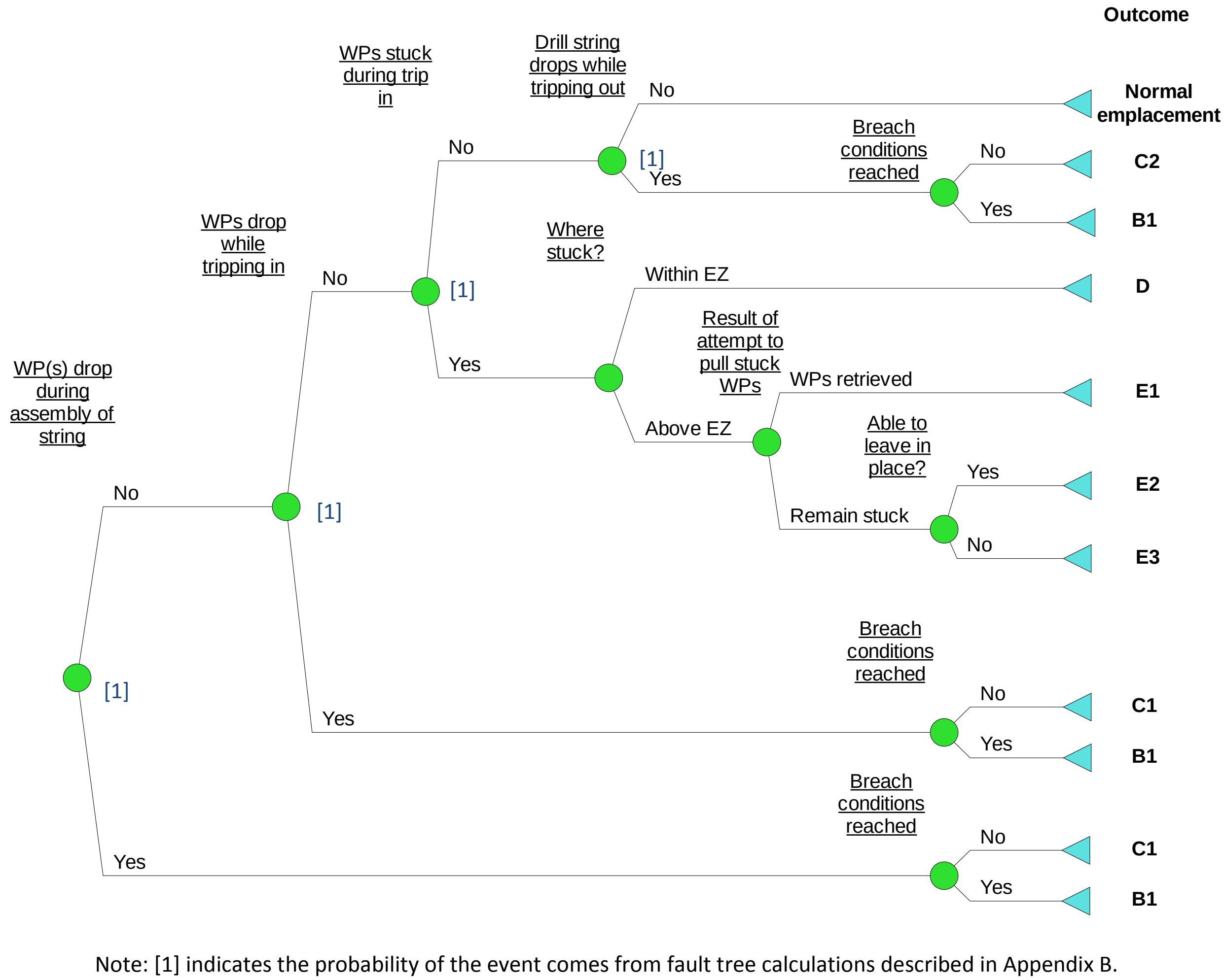


Figure 5-3. Drill-string event tree, per waste package string, with outcomes illustrated (“EZ” = disposal zone).

5.4.2 Uncertainty About Impacts Under 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 contributor to overall costs. As these costs are time-dependent, that makes the total time required to emplace package 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 Appendix C estimate, it is very likely that the costs for the other will also be much higher). By focusing on the mean cost *difference* between options, it is less important to fully model uncertainty in the costs of each emplacement mode.

The initial discussion of 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 described in Appendix C. The initial cost estimates for normal operations were developed by project staff, and were updated to reflect the refinements in designs that resulted from the expert panel discussion outlined in Section 5.1.3.

5.4.3 Uncertainty About Outcomes and Impacts Under Off-Normal Operations

Figures 5-2 and 5-3 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 disposal zone (DZ).** A1, A2, and A3 differ in terms of the ultimate disposition of those breached WPs, and thus differ in response costs. All three outcomes include plugging and sealing the borehole, discarding all equipment used, and decontaminating the site.
  - A1: Breached WPs fished and removed
  - A2: One or more WPs not successfully fished and instead left in place above DZ; long term intensive 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 DZ**. The breached WP(s) are left in place, the borehole is plugged and sealed, equipment is discarded, and the site is decontaminated. B1 and B2 differ in terms of the events leading up to a breached WP in the DZ, 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 DZ)
- **C outcomes: Unbreached but possibly damaged WP(s) in the DZ**. Either 1 or more WP(s) dropped into the DZ without resulting in a breach, or the drill pipe or wireline was dropped onto emplaced WPs without resulting in a breach. 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
- **Outcome D: One or more WP(s) become stuck within the DZ** 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 DZ**. 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. E1, E2, E3, and E4 differ in terms of the result of the fishing attempt. In all cases, after fishing the DZ 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 DZ.
  - 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 DZ 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.

5.5 Initial Analysis

This section of the report details the initial inputs and the analysis results. As described above, preliminary estimates of many of these inputs were developed by project staff; those inputs were reviewed and modified by the expert panels during a three day workshop in August, 2015. The inputs below are the result of that expert panel discussion.

5.5.1 Model Inputs – Fault Trees and Failure Probabilities

Table 5-3 summarizes the initial failure probabilities used in this analysis. These probabilities were calculated through the fault trees, as described in Appendix B of this report.

Table 5-3. Failure probabilities used in the initial analysis.

Failure event	Initial Value
WP drops from top of borehole during wireline emplacement	1.12E-07 per WP
WP drops while tripping in during wireline emplacement	5.50E-05 per WP
WP gets stuck while tripping in during wireline emplacement	2.18E-05 per WP
Wireline drops onto emplaced WPs while tripping out during wireline emplacement	4.01E-06 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	8.03E-05 per WP string
Drill-string drops onto emplaced WPs while tripping out during during drill-string emplacement	1.39E-04 per WP string
* The initial analysis assumes strings of 40 waste packages for drill-string emplacement. The sensitivity of the results to this assumption are discussed in Section 5.6	

Basic Event Probabilities Used to Calculate Top-Level Failure Probabilities

As described in Appendix B, off-normal events can result from actions (e.g., human errors), component failures (e.g., winch failures), or a combination. The frequency of the off-normal event is calculated through the fault tree based on the probabilities of more fundamental basic events, which must be quantified. 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 design selection study, initial fault trees were developed by the project team and were extensively modified by the expert panel discussion described in Section 5.1.3. 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 results of the preliminary project team work and the modifications made by the expert panel. The expert panel also offered insights into how to categorize and represent the probabilities of the basic events in the fault tree, as an alternative to detailed assessment or development of individual failure rates for each individual event. Table 5-4 shows this categorization of the basic events and the initial probability that was assigned for each.

Table 5-4. 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 1/20 descent.
Human error - failure to detect a problem that exists	1.00E-02										See text for discussion of human error
Wireline damage not detected		trip		x	x						
Cable head or WP connection mis-assembly not detected		trip		x	x						
Debris dropped in borehole during operation not noticed or reported		dropped object				x				x	
Operator fails to notice or respond to signal that casing has collapsed		trip								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	
Human error - failure to take an action when requires; attempt to carry out an action at the wrong time											See text for discussion of human error
Blind ram left open		WP	x								
Attempt to open blind ram at wrong time		WP	x								
Attempt to open shipping cask door at wrong time		WP	x								
Attempt to operate wireline winch in wrong direction		trip	x								
Attempt to close shipping cask door at wrong time	1.00E-03	trip		x	x						
Attempt to close blind ram at wrong time		trip		x	x						
Attempt to release WP at wrong time		trip		x							
Attempt to release cable head at wrong time		trip		x	x						
WP or cable head connection misassembled		trip		x	x						
Failure to correctly run caliper log		trip				x				x	
Attempt to open basement slip at wrong time		WP					x				
Attempt to open elevator ram at wrong time		WP					x				
WP fall while attached to wireline is sufficient to break the line	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		

	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	
Active component generic failure rate (per demand)											
Caliper log fails to detect collapsed casing		trip			x				x		
Winch drive failure	1.00E-04	WP or trip	x								
Winch brake failure		WP or trip	x								
Draw works drive failure		WP or trip					x	x	x		
Draw works brake failure		WP or trip					x	x	x		
System interlock failure (for interlock to prevent operator from winching in the wrong direction during wireline operations)	1.00E-04	trip	x	x	x						This is a critical safety component to prevent dropping a WP from the top; interlock would be designed to a higher level of reliability
Wireline damage occurs that is 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.
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			

	Probability of occurrence	Rate (probability per...)	Wireline: Drop from surface	Wireline: Drop during trip in	Wireline: Drop during trip out	Wireline: WP stuck	Drill-String: Drop from surface	Drill-String: Drop during trip in	Drill-String: Drop during trip out	Drill-String: WP stuck	Basis / discussion
Passive component generic failure rate (per demand)											
WP connection mechanism fails to recognize load	1.00E-05	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
Rig slip opens inadvertently	1.00E-05	pipe stand						x	x		
Pipe ram opens inadvertently	1.00E-05	pipe stand						x	x		
Debris dropped into borehole by worker activity above (wireline or drill-string)	1.00E-05	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
"Other" debris in borehole sufficient to results in WP stick	1.00E-05	trip				x				x	Sources of "other" debris: friction from WP rubbing on casing; debris entering through the mud
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 under-torqued such that it will fail during use (but not immediately on bearing load)	1.00E-05	pipe joint						x	x		

			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**
Pipe joint cross-threaded such that it will fail immediately if not detected	1.00E-05	pipe joint						x			
Pipe joint cross-threaded such that it will fail during use (but not immediately on bearing load)	1.00E-05	pipe joint						x	x		
Elevator failure during drill pipe lift	1.00E-06	pipe stand						x	x		
WP string released prematurely	1.00E-06	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. Used 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} (or 10%) 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 waste package. 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 waste package, so we have the conditional event shown in the top row of Table 5-4: the probability that the misassembled cable head fails and drops a waste package. 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 5.6).

Human error rates. Many of the basic events in the fault trees are human errors. Estimating the frequency of various types of human error is a challenging problem in its own right. A simplified approach to carrying out human reliability analysis has been developed by the Nuclear Regulatory Commission and Idaho National Laboratories (Gertman et al. 2005). In this approach, eight "performance shaping factors" (such as stress, task complexity, worker experience, etc.) are used to determine the human error probability. For any specific task, the "baseline probability" is modified by the performance shaping factors that are relevant for that task. For diagnosis tasks, the baseline probability is 10^{-2}, and for action tasks the baseline probability is 10^{-3}. For this design study, human errors were identified as either diagnosis failures or action failures, and these baseline probabilities were used. Future refinements of this analysis could include a more focused assessment of the human error probabilities.

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 Section 5.6.

5.5.2 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 5-2 and 5-3. The initial probabilities were developed through the expert panel discussion: these probabilities and their bases are shown in Table 5-5. Sensitivity of the analysis results to these probabilities, and to the basic event probabilities in the fault trees, are described in Section 5.6.

Table 5-5. Event probabilities used in the initial analysis.

Event	Initial Value and Basis
Conditional probability that a WP or WP string is stuck above the disposal zone, 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 disposal zone; the amount of the disposal zone 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 disposal zone contains WPs, so 1 km of DZ and 1 km "above the DZ" are the equally likely potential regions were 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 is 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 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%.

Event	Initial Value and Basis
Able to leave a WP in place that is stuck above the DZ 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 DZ, but the ability to do so successfully is unknown. 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.

5.5.3 Model Inputs – Impact on Performance Metrics

If emplacement operations proceed without any problems, wireline emplacement was estimated to cost about $22.6 million and to require about 430 days of operations; drill-string emplacement was estimated to cost about $40 million and also to require about 430 days of operations. Table 5-6 summarizes each possible outcome identified on the event trees in terms of the three performance metrics: radiological releases, incremental time and incremental 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 5-6. Impacts on performance metrics for each outcome.

Outcomes	Radiological Release	Drill-string		Wireline	
		Days	Cost ($million)	Days	Cost ($million)
A1	Yes	965	$ 345	965	$ 307
A2	Yes	1330	$ 327	1330	$ 308
A3	Yes	1005	$ 349	966	$ 308
B1	Yes	945	$ 324	945	$ 301
B2	Yes	1330	$ 336	1330	$ 314
C1	No	409	$ 41	409	$ 24
C2	No	407	$ 42	407	$ 27
D	No	323	$ 41	323	$ 28
E1	No	600	$ 73	600	$ 44
E2	No	965	$ 120	965	$ 91
E3	No	640	$ 77	601	$ 45
E4	No	600	$ 53	600	$ 44

5.5.4 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 incremental cost of $19.2 million over wireline emplacement. While it is more likely to lead to incident-free emplacement 400 WPs in a borehole, it is more likely to result in a radiological release than is wireline emplacement (by a factor of about 55). 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.

Tables 5-7 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 5-7. Initial analysis results: wireline compared to drill-string emplacement.

	Initial Results	
	Wireline	**Drill-String**
Probability of incident-free emplacement of 400 WPs	**96.81%**	**99.22%**
Approximate total costs if successful ($ million)	**22.6**	**40.0**
Expected performance against the defined performance metrics		
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	430	434
Probability of radiation release	1.29E-04	7.04E-03
Outcome Probabilities		
Probability of a failure that leads to radiation release (Outcomes A and B)	**1.29E-04**	**7.04E-03**
Outcome A1	1.16E-04	0.00E+00
Outcome A2	2.32E-06	0.00E+00
Outcome A3	2.32E-06	0.00E+00
Outcome B1	0.00E+00	7.04E-03
Outcome B2	8.24E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	**8.45E-03**	**8.00E-04**
Outcome D	4.29E-03	4.00E-04
Outcome E1	3.75E-03	3.82E-04
Outcome E2	7.49E-05	9.00E-06
Outcome E3	7.49E-04	9.00E-06
Outcome E4	2.66E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	**2.33E-02**	**0.00E+00**
Outcome C1	2.17E-02	0.00E+00
Outcome C2	1.58E-03	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	4.41E-05	4.07E-03
Drop one or more WPs during trip in	2.16E-02	1.59E-03
Drop wireline or drill-string on trip out	1.58E-03	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04

5.5.5 Drivers of Initial Results

The most likely off-normal outcome for drill-string emplacement is Outcome B1: a breached WP in the disposal zone. This results from the relatively high likelihood that a WP string will be dropped (see the bottom four rows of Table 5-7) 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 5.6 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 disposal zone. 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 4.2), the potential effectiveness of impact limiters (Section 4.3), along with the robustness of package design concepts (Section 2.6.7) lead to an insignificant probability of breach due to a drop of a single package. For dropping a waste package string during drill-string emplacement, there is high likelihood of a breach (see bounding analysis in Section 4.4). 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.

5.6 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 D includes details for each of these sensitivity analyses, including the specific probabilities tested and the results in a form similar to Table 5-7.

5.6.1 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 disposal zone) – Using the logic described for estimating the initial probability described in Table 5-2, two sensitivity cases were identified. The represent the maximum and minimum credible conditional probabilities for being stuck above the DZ (p = 1 or 0.33).

The results are insensitive to these changes. Although doubling the conditional probability of being stuck above the DZ 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 ~30 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 that 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 difference 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 3×10^{-2} chance of breaching a WP during fishing is discussed above in Table 5-3. Sensitivity analyses considered lower (3×10^{-3}) and higher (10^{-1}) probabilities that fishing leads to breach, and also considered the possibility of breaching a WP while attempting to remove a stuck WP string (from 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 waste package, so the effect of increasing the probability of a breach during retrieval is negligible. For wireline operations to have the same risk of radiation release as drill-string operations, the probability of breaching a WP while fishing would have to be between 15% and 20%. 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 between the two emplacement modes is only a factor of 3. If the probability of breach from a dropped string was 50% and from a single dropped WP was 20%, 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.

5.6.2 Sensitivity to Failure Probabilities

In addition to exploring the impacts of changes to the probability of individual failures, we considered the sensitivity of the results to Sensitivity to four of the key event probabilities was explored.

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 sensitivity to this change. Reducing the changes of a cable break reduces the chances 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 98.6% (compared to the initial probability of 96.8%).

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 waste 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 90% 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 a factor of 5 lower than the probability of release from drill-string emplacement, and the expected cost differential remains about $19 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 $4{\times}10^{-2}$. 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 $4{\times}10^{-2}$. This represents a significantly greater risk and highlights the importance of casing collapse detection if drill-string emplacement is to be implemented.

5.6.3 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 waste packages. 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. Assuming that an impact limiter would be effective with strings of no more than 20 WPs, the decrease in risk per trip is overwhelmed by the increase in risk from the greater number of trips required.

5.6.4 Analysis of a DBFT Emplacement Demonstration With Reduced Safety Controls

Appendix B highlights the importance of an effective safety control (interlock) system to reduce the risks of human errors leading to dropped waste packages during wireline emplacement. To manage the scope and costs of the DBFT demonstration, however, the full interlock system is not recommended. To evaluate what effect that could have on the success of the demonstration, an analysis of wireline emplacement for nine and for 60 test packages was conducted, comparing results with: 1) full interlocks; 2) no interlock functions included; and 3) results as the most important interlock function is added back in. Each of these cases could be implemented using as few as three test packages, with repeated emplacement and retrieval. Table 5-8 summarizes the changes to the risk of package drops with the full safety control (interlock) system in place, with no interlock system, and with a minimal interlock system (preventing cask door closures that could shear the wireline).

If the full interlock system were implemented for the DBFT demonstration as described, the probability of incident-free emplacement of nine test packages is 99.9%, while for 60 packages it is 99.5%. Table 5-9 summarizes the likelihood of dropping, sticking, and breaching a test package during a demonstration of 9 or 60 packages, with the different levels of safety control functionality. Greater probability of incident-free demonstration could be achieved using more control functions (e.g., controlling when both doors at the surface can be open, and preventing the wireline winch from winding in the wrong direction). Note that with the risk model developed in this section, the only way a package can be breached in wireline emplacement is if it becomes stuck during emplacement and is then breached during fishing. Also note that planned retrieval of test packages is not explicitly represented in the model.

Table 5-8. Failure probabilities for wireline emplacement with different interlock effectiveness.

Failure event	Interlocks in Initial Fault Trees (Figure B-1 through B-4)	Initial Value (full interlocks)	No Interlocks	With Interlock for Door Closures at 10^{-1} Failure Rate
WP drops from top of borehole during wireline emplacement	Door interlock (prevent blind ram door and shipping cask door from being opened at the same time) plus system interlock (prevent operating the winch in the wrong direction).	1.12E-07	1.002E-03	1.002E-03
WP drops while tripping in during wireline emplacement	Door interlock (prevent cask door or blind ram door from closing at the wrong time and shearing the wireline)	5.50E-05	2.053E-03	2.53E-04
WP gets stuck while tripping in during wireline emplacement	None	2.18E-05	No change	No change
Wireline drops onto emplaced WPs while tripping out during wireline emplacement	Door interlock (prevent cask door or blind ram door from closing at the wrong time and shearing the wireline)	4.01E-06	2.002E-03	2.02E-04

Table 5-9. Probabilities for emplacement outcomes for the DBFT demonstration under different assumptions.

	Full Interlocks		No Interlocks		Interlock on Cask Door Closures	
# of test package emplacement/retrieval trials	**9**	**60**	**9**	**60**	**9**	**60**
Probability of incident-free DBFT demonstration	99.93%	99.52%	99.53%	73.71%	98.68%	91.51%
Probability that a test package is dropped	0.07%	0.48%	4.47%	26.29%	1.32%	8.49%
Probability that a test package gets stuck	1.96E-04	1.30E-03	1.92E-04	1.13E-03	1.95E-04	1.25E-03
Probability of a test package breach	2.94E-06	1.96E-05	2.88E-06	1.69E-05	2.92E-06	1.88E-05

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6. Summary and Recommendations

This report documents conceptual design development for the Deep Borehole Field Test (DBFT), mainly for the test packages (not containing waste) and the system for demonstrating emplacement and retrieval of those packages in the Field Test Borehole (FTB).

6.1 Disposal Concept Development

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 describes a current reference DBD concept, and analyzes key design options for disposal, to guide selection of options for the DBFT. The most important of these options is the emplacement mode, i.e. whether packages are emplaced using a wireline or a string of drill pipe (with a drill rig). This choice is analyzed using cost and risk models, in Sections 5 and 6. Other emplacement mode options including the use of coiled tubing, and the “drop in” method, are discussed in Section 2.

System Architecture

System architecture for the Disposal Borehole and the Waste Packaging, Handling and Emplacement parts of the DBD system is presented in Section 2.2. This is a starting point for design development, functional analysis, project management, and risk analysis activities. It is presented in outline form, for both wireline and drill-string emplacement methods, although only one of these (or a derivative method) will be demonstrated in the field. It does not include all aspects of borehole drilling and construction, or field site infrastructure, but it does include disposal borehole (and FTB) configuration. To be representative the DBFT should fit within the same architecture, possibly with down-selection of features for demonstration, as discussed in Section 3.3.

Requirements and Assumptions

Sections 2.3 and 2.4 present design requirements and controlled assumptions for the Waste Packaging, Handling and Emplacement System (Section 2.2). The information follows typical preparations for engineering design. It includes requirements on waste package design (e.g., for different waste forms) and emplacement, related aspects of borehole construction, and sealing of disposal boreholes. Assumptions are included where they impact design. It is presented as parallel sets of comparable requirements for waste disposal and the DBFT, and is intended to inform further design (including further requirements development) and planning for the DBFT.

Reference Disposal Concept

This report describes a reference disposal concept () that is based on previous work (Section 2.5; Arnold et al. 2011; Patrick 1986). The description (Section 2.6) emphasizes aspects that are not yet well defined, such as completion of the disposal zone, and aspects for which important options are available, such as waste package design and the emplacement method. Several waste packaging concepts are offered (Section 2.6.7) for small and large boreholes, and for bulk granular waste forms and waste that is pre-canistered at the point of origin.

The choice of emplacement methods is narrowed to: 1) emplacing packages one-by-one on an electric wireline, and 2) assembling strings of packages threaded together which are then emplaced by lowering on a string of drill pipe (Sections 2.6.4 and 2.6.5). The operation of each method is described in a series of steps that is used for hazard analysis (Sections 5.2 and 5.4, and Appendix B). Refinements to each concept were developed in the course of the study

(Section 2.7) and adopted in the analysis of hazards and costs for the options (Appendices B and C). A number of potential design or procedural changes were also identified and recommended for future evaluation (Section 2.7.2). Priority efforts for DBFT development are identified in Section 3.4 and included in the recommendations below (Section 6.3).

Proposed Scope of the DBFT Demonstration

The DBFT does not need to exercise all parts of the disposal system described above (see Table 2-1) to achieve the objective to demonstrate the performance of test packages, and their emplacement and retrieval in a deep borehole. The scope of the DBFT demonstration could be limited by minimizing or omitting the following:

- Basket to hold canistered waste inside the package/overpack
- Shielding (can be mocked-up if needed to show equipment integration)
- Safety control (interlock) system
- Backup power
- Transportation cask (if separate from the transfer cask)
- Transfer fixtures (if the same cask is used for transportation and transfer to the borehole)
- Wireline headframe (replace with a crane)
- Installation of cement plugs between strings/stacks of packages
- Sealing, plugging and abandoning the borehole

A proposed down-selection of features is presented in Tables 3-1 and 3-2 for both the wireline and drill-string emplacement options, using the system architecture introduced in Section 2.2 (Table 2-1).

6.2 Engineering Design Study

A multi-attribute utility analysis was done to support recommendation of an engineering concept for handling and emplacement of waste packages for the DBFT. The analysis used estimates of cost and risk for the disposal system, developed risk insights, and applied them to the emplacement mode selection. Description of the design study includes the methodology (Section 5.1), the initial results (Section 5.5), and sensitivity analyses (Section 5.6). Model inputs are described in Sections 5.2 through 5.4, and Appendix B.

To bring a broader perspective to the analysis and to engage expertise in drilling and wireline operations to help quantify the risks associated with each option, a panel of experts (Appendix A) was convened to review and update the model inputs. Panel members represented a range of expertise in drilling and wireline operations, nuclear equipment and operations, safety control systems, risk and reliability analysis, and other related areas.

Methodology

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 the design study. Appendix B describes the results of a hazard analysis that identified off-normal events importance to performance, and quantified the likelihood of those events. The hazard analysis identified four key “top level failures” that have the potential to lead to adverse consequences: 1) drops during waste package staging at the surface; 2) drops during trips in to emplace packages; 3) getting packages stuck on a trip in; and 4) dropping the emplacement equipment onto waste packages during a trip out (Table 5-2). Each of these leads to the potential for a WP to be breached and radiological release to occur, for disposal capacity to be lost, and for additional time and costs for mitigation. These four top-level failures were quantified for each emplacement option using fault trees (Appendix B and Table 5-3), and the probabilities were used in event trees for each option (Figures 5-2 and 5-3). Cost estimates for each normal and off-normal outcome on the event trees were developed (Appendix C and Table 5-6), and used along with the aggregated probabilities for each outcome (Table 5-7), and sensitivity studies (Section 5.6) to generate risk insights.

Results

Based on the initial inputs (hazard analysis and event probabilities) the design study results are summarized in Table 6-1 (based on Table 5-7).

Table 6-1. Design study results summary based on initial inputs.

	Initial Results	
	Wireline	**Drill-string**
Probability of incident-free emplacement of 400 WPs	**96.81%**	**99.22%**
Cost for successful emplacement with normal operations	**22.6**	**40.0**
Expected value of costs ($ million), considering both normal and off-normal events	**22.8**	**42.0**
Expected total time of operations (days), considering both normal and off-normal events	**430**	**434**
Probability of radiation release	**1.29E-04**	**7.04E-03**

The likelihood of emplacing 400 waste packages 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 waste package is about 55 times greater for the drill-string option, mainly because of the high incidence of breach if a heavy pipe string is dropped onto packages on the trip out, and the effective use of impact limiters on single packages that mitigate the consequences of drops during wireline emplacement.

Even though the cost of remediating some off-normal outcomes are estimated to be high (Appendix C) the probabilities of most of those outcomes are relatively low, so the expected cost (Table 6-1) for each option is dominated by the cost for normal operations.

Sensitivity Analyses

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. Of the various sensitivity analyses performed, sensitivity to input probabilities (Section 5.6.1) was found for:

- **Uncertainty about the likelihood of breaching a waste package while attempting to fish or remove a stuck package or package string**. Fishing is the only mechanism by which a package can be breached during wireline emplacement, whereas for drill-string emplacement there are many larger contributors to the possibility of breaching a package. For wireline operations to have the same risk of radiological release as drill-string operations, the probability of a breach while fishing would have to be 15% and 20%, and even so the expected costs of wireline emplacement remain $19M less than the drill-string options.
- **Uncertainty about the likelihood of waste package breach from drop events**. This sensitivity analysis compared the options after assuming both a lower probability of breach from dropping a package string (drill-string emplacement) and a higher probability of breach for dropping single packages (wireline emplacement). The results are sensitive only to dramatic changes. If the probability of a breach from package-string drops is decreased to 50% (from 100%), and the probability of a breach from single-package drops is increased to 5% (from zero), the difference in the probability of radiological release between the two options is a factor of 3, with greater release probability for the drill-string option.

For sensitivity to failure probabilities (Section 5.6.2), sensitivity was found for:

- **Operational and design changes aimed at reducing specific risks.** For example, a key risk for wireline emplacement is dynamic overtension during descent, leading to a wireline break. This sensitivity case assumed that operational changes decrease the probability of a dynamic overtension failure by a factor of 10. This change decreases the likelihood that a package is dropped on the trip in by nearly an order of magnitude, and increases the likelihood of emplacing 400 WPs without incident to 98.6%.
- **Likelihood that waste packages become stuck by debris.** This set of sensitivity analyses explored the impacts of reducing or increasing the basic event probabilities controlling getting stuck, by a factor of 10. Wireline results, in particular, are highly sensitive because: 1) debris is the principal way that a package can get stuck, and 2) the only way a package can be breached during wireline emplacement is if it gets stuck and is breached while fishing.
- **Likelihood of rigging failure while assembling package string**s. In the initial analysis a failure (drop) rate of 10^{-5} per lift was used for drill-string emplacement. This sensitivity case used a rigging failure rate of 10^{-4} per lift. Results are sensitive; the probability of incident-free emplacement of 400 WPs decreases to 96% (from 99%) and the probability of a radiological release increases to 4% per borehole. This represents a significantly higher risk and highlights the importance of rigging safety if drill-string emplacement is to be implemented.

Other sensitivity analysis that produced little or no impact on the initial results are described in Section 5.6. These include an interpretation that reducing the number of waste packages in a package string (e.g., from 40 to 20 or fewer) would not improve overall safety because the increased risk from dropping the drill string on trips out offsets any decrease in risk from smaller waste package strings.

6.3 Recommendations

The principal recommendation of this study is to use the wireline emplacement method for the DBFT demonstration, on the basis that if the method is used for actual disposal it would result in lower cost and less likelihood of a breached waste package and contamination of the borehole.

The disposal system features for wireline emplacement should be down-selected for the DBFT demonstration, to a set similar to that shown in Figure 6-1, with reduced scope of safety control (interlock) features (a cost-saving measure). A sensitivity study was performed using the risk model developed for the disposal system, to estimate the probability of successfully emplacing a small number of test packages in the DBFT demonstration (Section 5.6.4). The results show that some safety control system functionality is important to limit the probability of dropped test packages.

It is also recommended that the design team analyze the DBD concept development questions and DBFT priorities listed above and in Sections 2.7 and 3.4, including

- Develop the disposal zone completion and guidance casing perforation scheme.
- Select an emplacement fluid based on disposal zone completion and test package terminal sinking velocity considerations.
- Develop and test package release mechanisms, operable only without load, and evaluate failure rates on both emplacement and retrieval.
- Design and test impact limiters, and show that they do not become stuck during normal operations.
- Design test packages for a range of in situ temperature.

Analysis of the terminal sinking velocity of packages dropped in the borehole can provide input to selecting an emplacement fluid, designing impact limiters, and developing the disposal zone completion (e.g., perforations).

The engineering refinements (design and procedural) identified in Section 2.7.1 should be incorporated into the DBD concept and design for the DBFT demonstration.

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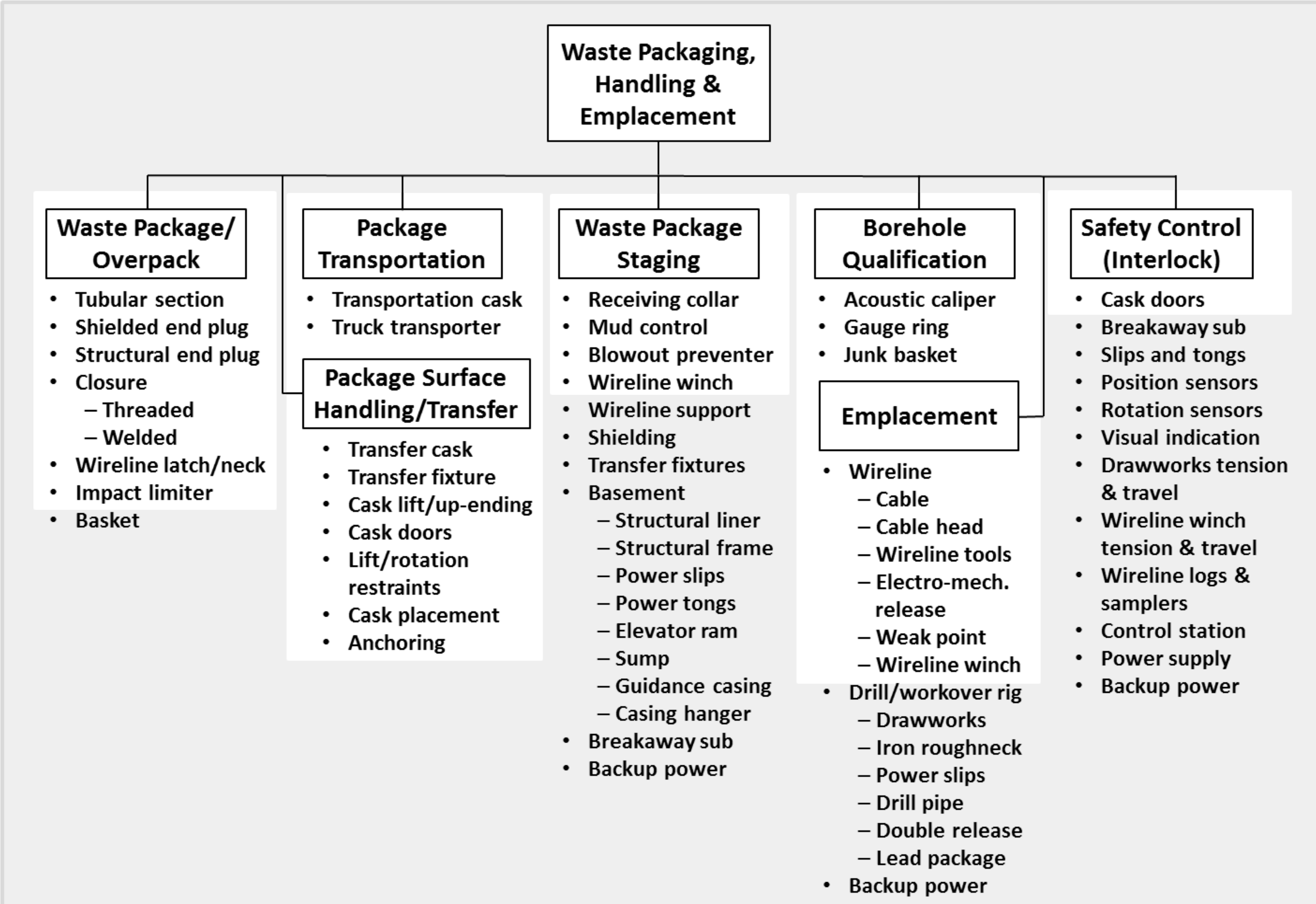

Figure 6-1. System architecture, highlighting down-selected features for wireline emplacement demonstration, for the DBFT.

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Appendix A. Subject Matter Expert Panel

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

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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 Table B-1. The top events calculated in this way are:

- Drop a waste package from the surface (or a waste package string, for drill-string emplacement)
- Drop a waste package (or a waste package string) during the trip in
- Get a waste package stuck (or a waste package string)
- Drop a wireline (or drill pipe string) onto waste packages 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).

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 simulation software so that it provides needed reliability for each emplacement function (but not necessarily the same level of reliability). For example, the interlock failure probability for controlling safety doors during wireline emplacement needs to be smaller than for monitoring under-torque and cross-threading during string makeup for drill-string emplacement. The level of design, testing, and maintenance needed to achieve safety system performance objectives depends on the nature of the processes being controlled.

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).

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

Drop a Waste Package from the Surface (Figure B-1) – Dropping a waste package through the lower cask doors and through the blind ram on the well head, 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 the door and ram depending on the state of the system. Thus, if the wireline is not connected and tensioned, neither would open. If the blind ram was open, the lower doors would not open, and so on. 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.

The safety control system would also protect against the operator inadvertently running the winch in the wrong direction, pulling up against the stops at the top of the cask and exceeding the weak point limit, dropping the tool string and package. This function is assigned the smallest probability of control failure (10^{-4}) because the safety control system is protecting against a human-caused single-point failure.

Safety control systems can be simulated using 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).

Other features could be incorporated in the design such as using a common plug for actuation and safety circuits, and pins or ledges on the sliding cask door to prevent opening while bearing the weight of the package.

Dropping a package due to wireline winch failure would be very rare, because the hydraulic drive system does not free wheel, and there are two pneumatic brakes (in a typical setup) with reverse operation so that one actuates when pressure is applied and the other when pressure is released.

Drop Waste Package During Trip In (Figure B-2) – Cable break 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. The more likely cause of a break is localized damage caused by momentary over-tension events that occur 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 quite 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 should be permitted in emplacement operations, or any other wireline operations taking place above waste packages 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 should 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 should be used and inspected and maintained regularly. Emplacement operations should not be conducted in cold weather when ice could accumulate on the wireline, sheaves, or support equipment.

A wireline could also break if the cask doors, or a ram on the well head, is closed inadvertently onto the cable. The safety control (interlock) system would be relied on to disable door or ram actuation during the trip in, subject to override in the event of a well control emergency.

Another way to drop a waste package is inadvertent actuation of the package release (between the tool string and the waste package) or the cable head release (allows the cable to disconnect from a stuck tool string). These electromechanical release mechanisms should both be designed so they cannot release when under load, i.e., while they are supporting the weight of the package. Such a passive feature would likely be more reliable than the safety control (interlock) system, and could decrease the probability of inadvertent human-caused actuation resulting in a drop, to insignificance (10^{-8} per trip).

The package release mechanism would be assembled by the wireline operators for each trip in, so there is a significant 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 mis-diagnosing a faulty assembly remains. The same risk is conservatively associated with the cable head release for every trip in, although this mechanism would only be reassembled after it is used in response to an off-normal event. This reflects the possibility of defect aging, or random differences in loading conditions on successive trips.

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 waste package to become stuck. To maximize reliability the emplacement path in the guidance casing should 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 should 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 should 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 waste packages 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) along with reverse circulation, is insufficient. Reverse circulation in the upper part of the guidance casing (above 2 km, or above 3 km depth if the casing shoe and hanger at 2 km are ported) 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 package to the casing (in which it is presumably stuck) and cutting the casing at the package joints 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). However, whereas limiters are made from soft, compliant materials they should be designed conservatively with tapers, cowling, etc. so they cannot catch on the casing or its components, deform, and cause the package to become stuck. Further, the deformable elements should have a breakaway feature so that if they do get stuck, the package can be pulled away and removed from the borehole with a low likelihood of getting stuck.

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.

Drop Wireline During Trip Out (Figure B-4) – Dropping the wireline or tool string on a waste package while tripping out, after the package is successfully emplaced on the bottom, is similar to dropping while tripping in, except: 1) the dynamic over-tension mechanism cannot occur, and 2) the package release mechanism is already released.

Table B-1. Summary of top-event probabilities for wireline and drill-string fault trees.

Fault Tree	Failure Probability	Primary Responsible Events
Wireline Emplacement		
Drop waste package from surface	1.12E-07 (per package)	Over-tension due to winding the wrong way against the stops.
Drop waste package during trip in	5.50E-05 (per package)	Most likely cause is wireline break due to dynamic over-tension if the package momentarily hangs up.
Waste package gets stuck	2.18E-05 (per package)	Most likely cause of getting stuck is debris such as residual cement from setting plugs.
Drop wireline during trip out	4.01E-06 (per package)	Contributing causes: cask door or blind ram shears wireline; wireline damage failure; cable head misassembled and causes release during trip out.
Drill-String Emplacement		
Drop packages while assembling WP string	4.08E-04 (per string)	Rigging Failure
Drop string and packages tripping into hole	1.60E-04 (per trip)	Elevator failure during lift with draw works not attached to string
WP/drill string get stuck during trip-in	8.03E-05 (per trip)	Casing collapse and lead package doesn’t detect collapse
Drop drill string on WPs during trip-out	1.39E-04 (per trip)	Elevator failure during lift with draw works not attached to pipe string

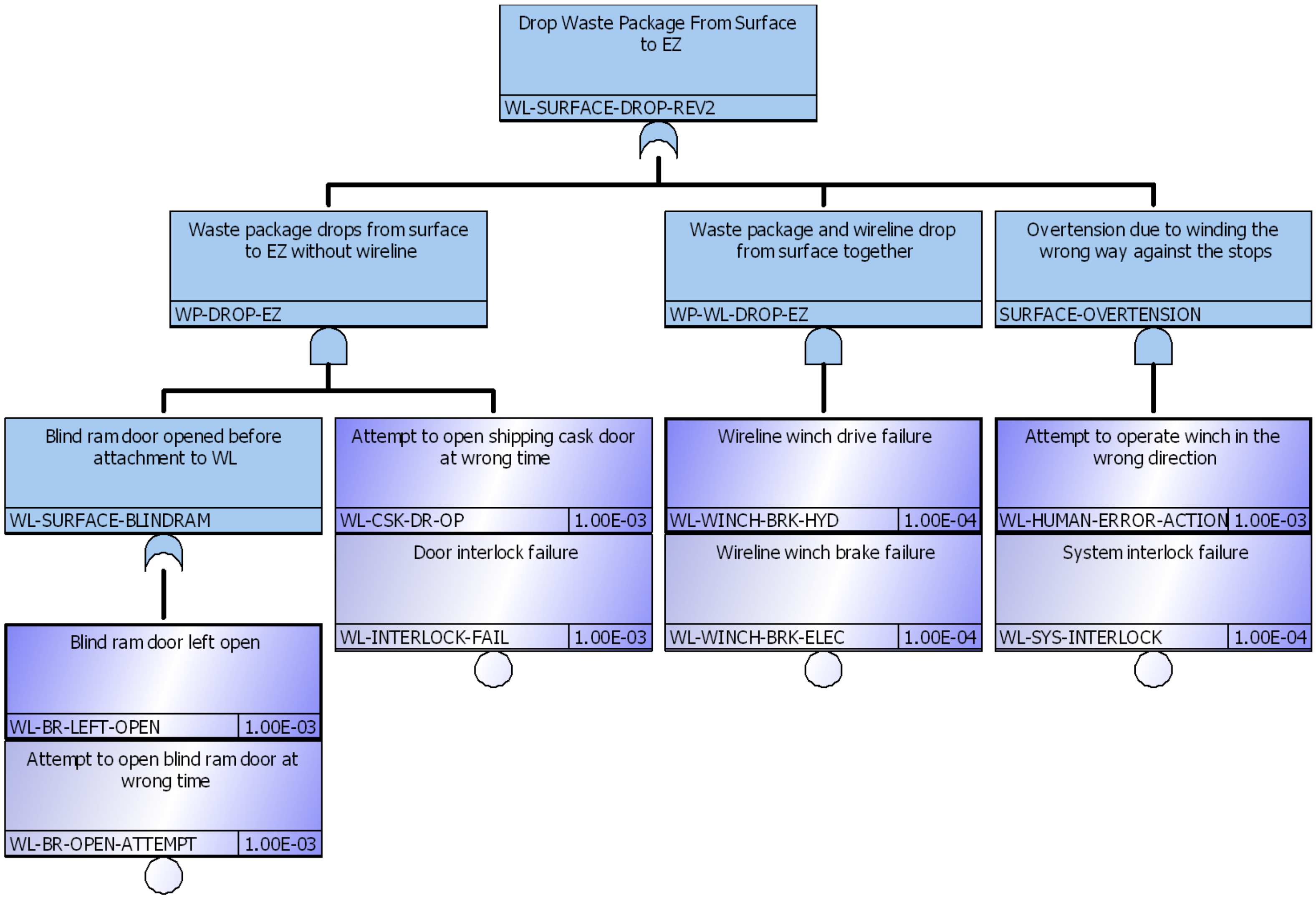

Figure B-1. Fault tree for dropping waste packages from the surface to the disposal zone, with wireline emplacement.

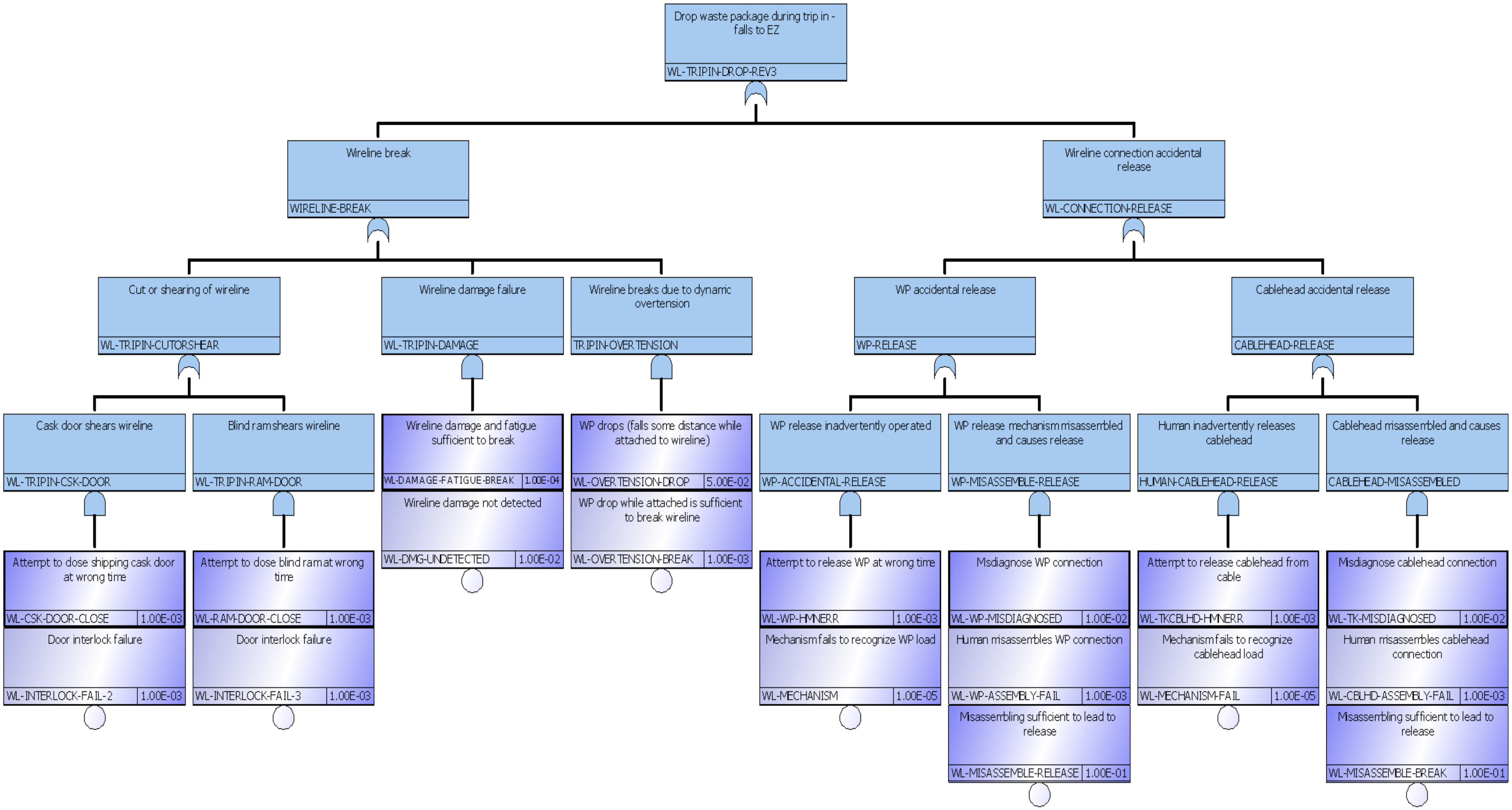

Figure B-2. Fault tree for dropping waste packages to the disposal zone, during the trip in, with wireline emplacement.

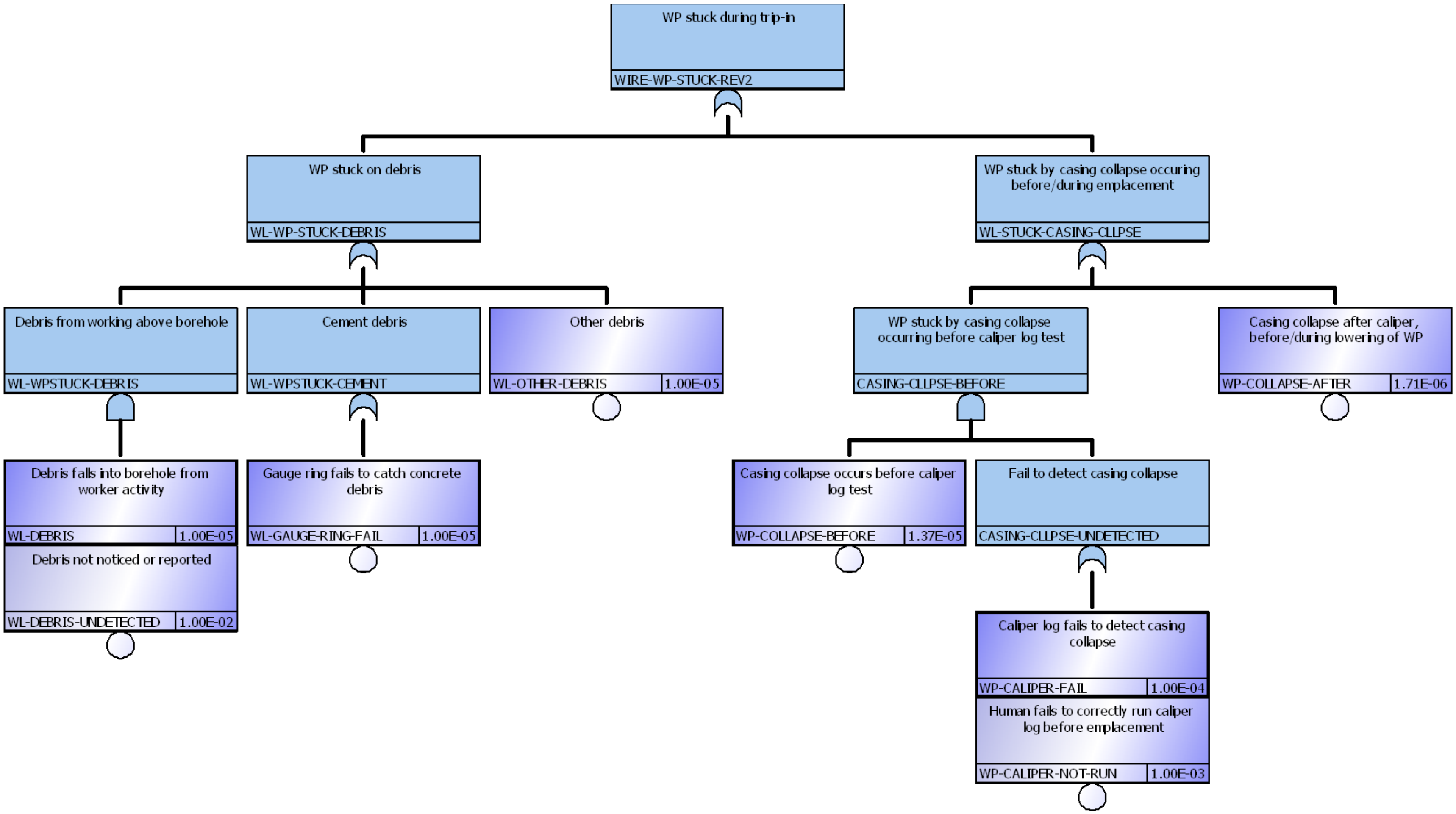

Figure B-3. Fault tree for getting stuck on the trip in, with wireline emplacement.

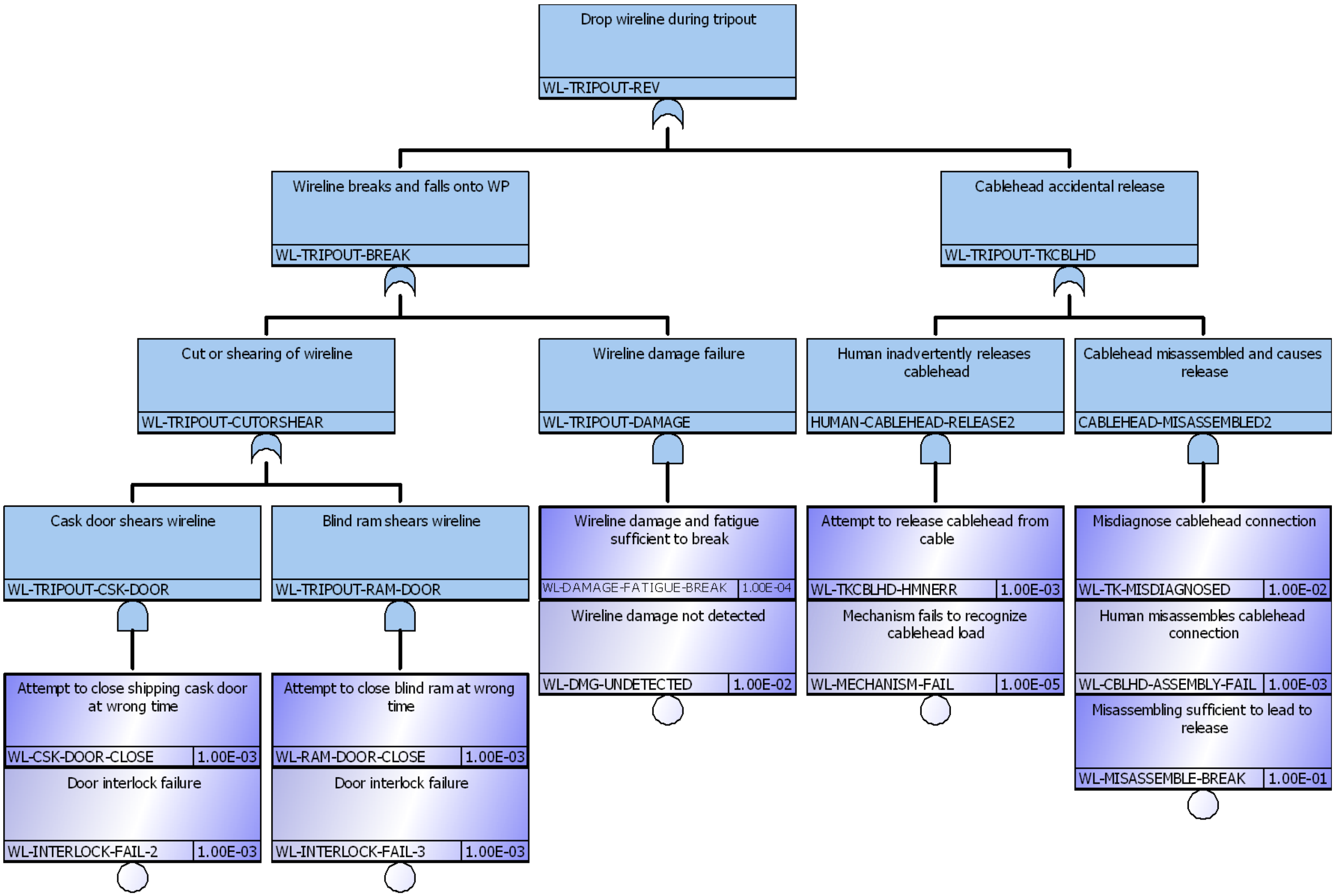

Figure B-4. Fault tree for dropping the wireline (and attached tools) on the trip out, with wireline emplacement.

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 similar manner as for 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. 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}. For handling waste packages the panel adopted 10^{-5} acknowledging that nuclear regulations could apply. To achieve additional reliability, the hoist and rigging used to assemble waste package strings could be engineered to reduce or eliminate single-point failures. 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 waste package string.

For consideration of improper makeup of threaded joints between waste packages, 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 waste packages 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, are also possible.

Drop Waste Package String During Trip In (Figure B-6) – Failure of the elevator used with the rig hoist 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. The average number of pipe stands (lifts) on the trip in is 138.

Failure of bad joints between waste packages caused by cross-threading or under-torquing 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 waste package joints, but 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.

Reliability of the release mechanism for package strings is discussed in Section 2.6.8. A higher reliability device (failure probability 10^{-5}) was assumed by the expert panel.

Failure of the rig slips, and the basement ram used as a backup, could occur due to human error, but is backed up by the safety control (interlock) system.

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.

Another potential failure mode is breach of waste packages 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 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 this was happening. Accordingly, it is not included in the fault tree (Figure B-6).

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 so that if it became stuck on the trip in, the waste packages could be separated from the lowermost package by pulling, and recovered.

For drill string emplacement, waste package strings are more likely to become stuck by a casing collapse 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 waste package 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 addition of specialized equipment to the rig basement to secure the stuck packages to the casing, then cut the casing at the joints 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.

Debris is the most likely cause of a string becoming stuck, possibly from cement as discussed previously for wireline. For casing collapse, the time interval between qualification of the borehole (gauge ring with junk basket, and acoustic caliper, run on wireline) and the trip in, is greater for drill-string operations and this is included in the fault tree. However, given the possibility of casing collapse, the probability of getting stuck is less than for wireline for the reasons given above.

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 are then associated with drops. The principal cause of drops is elevator failure, which is unlikely as discussed above. A secondary cause is failure of the rig slips and the basement ram 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 failure is very unlikely as discussed for the trip in.

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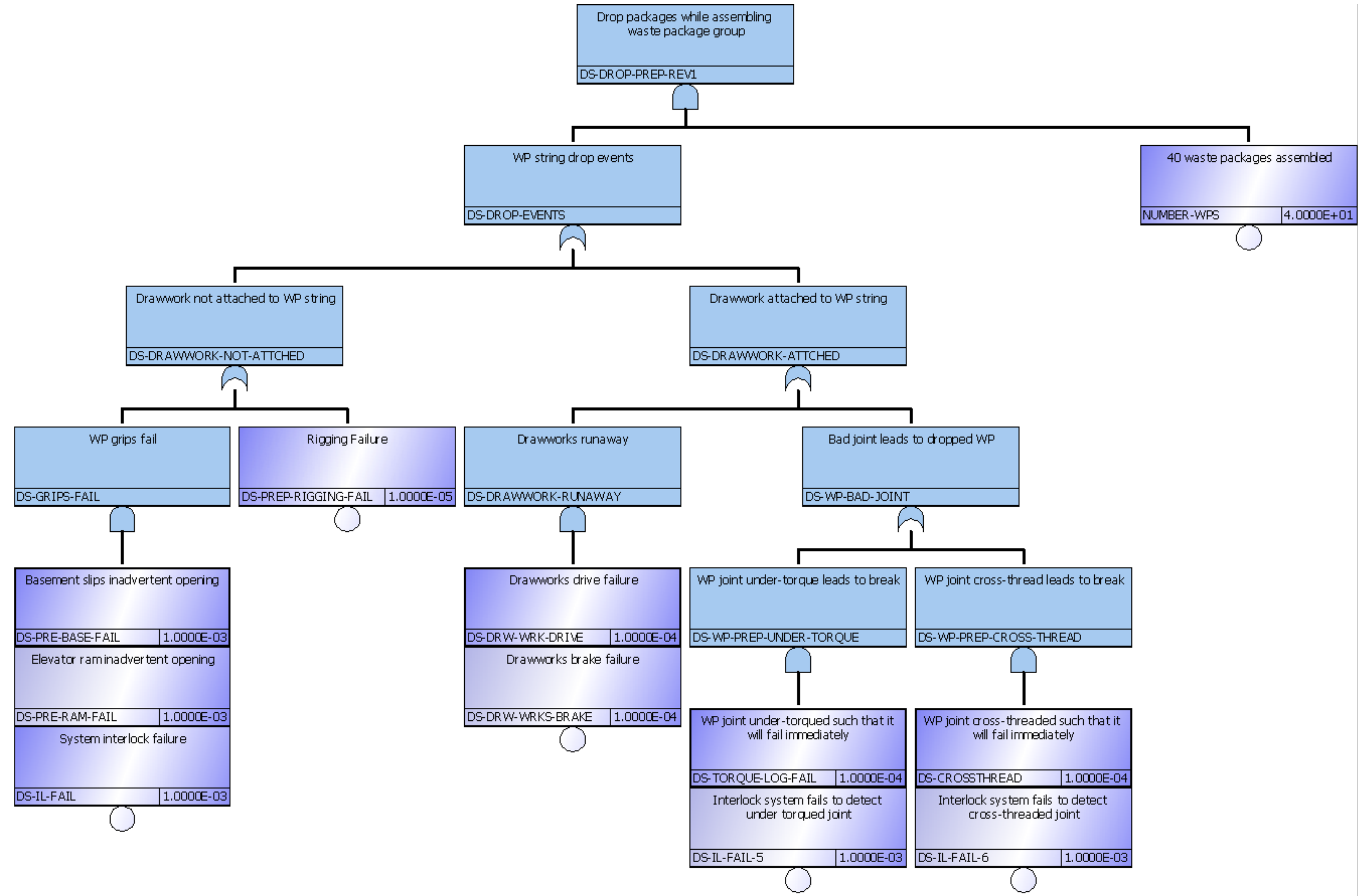

Figure B-5. Fault tree for dropping a waste package string from the surface to the disposal zone, with drill-string emplacement.

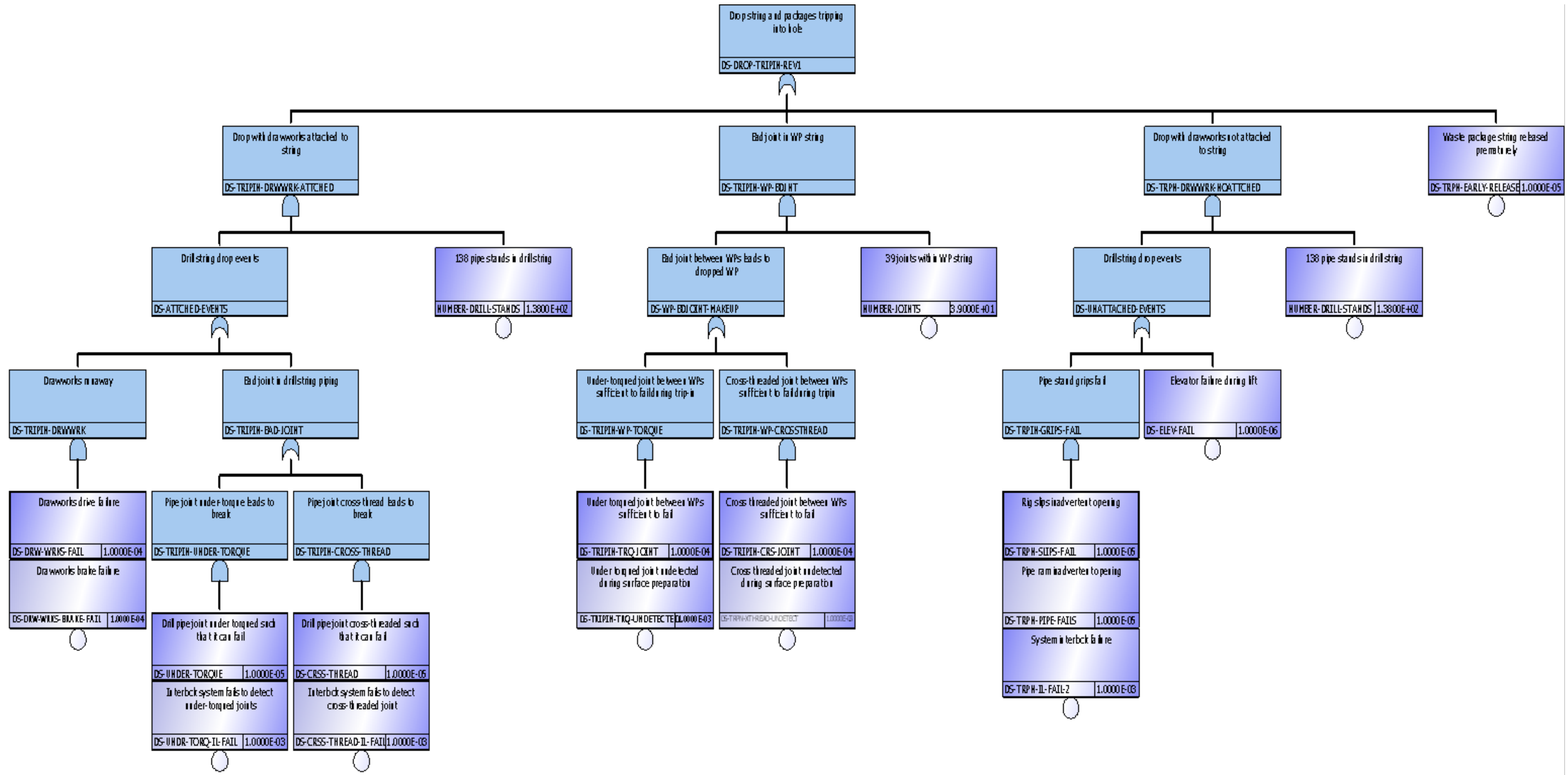

Figure B-6. Fault tree for dropping a string of waste packages to the disposal zone, during the trip in, with drill-string emplacement.

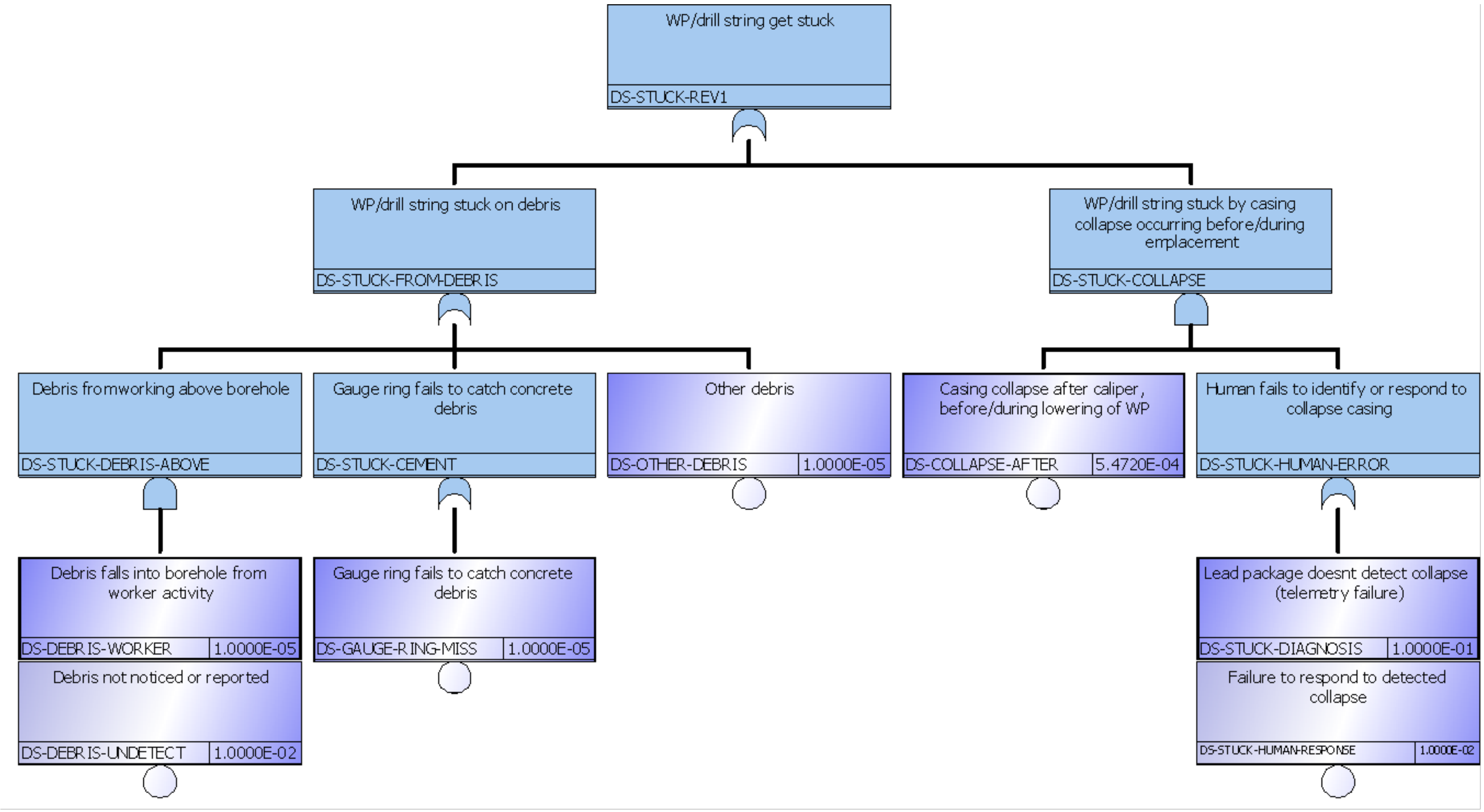

Figure B-7. Fault tree for getting stuck on the trip in, with drill-string emplacement.

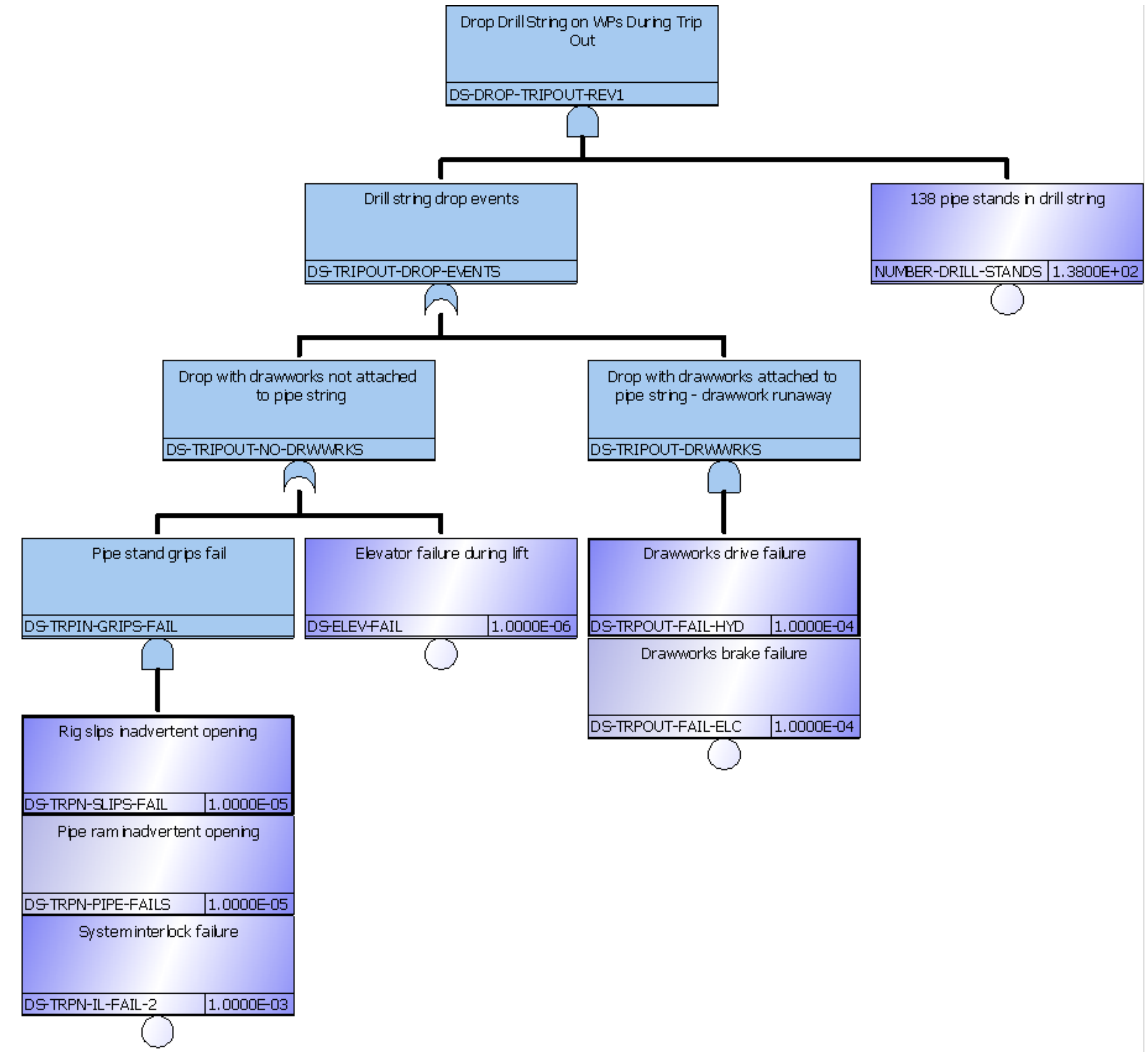

Figure B-8. Fault tree for dropping the pipe string on the trip out, onto waste packages, with drill-string emplacement.

References for Appendix B

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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 waste package 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 *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design* (Cochran and Hardin 2015). The intended use of cost information is a conceptual design study with the principal objective of recommending one of the emplacement methods based on cost-risk analysis.

The project costs estimated here are for emplacement operations only, and do not include costs that are common to both options. Transport of waste packages to the disposal site, handling of the cask

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 waste packages 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 mob./demob. 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 waste packages will not be thermally hot enough to affect performance of telemetry packages, cable head, or release mechanism. The maximum in situ temperature of 170°C (Section 2.3.10; 338°F, 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 Section 4.5), and downhole temperatures can be controlled if necessary by circulating the borehole fluid.

Accordingly, the cement plugs above each stand of waste packages in the disposal zone (see Sections 2.3.9 and 2.6.2) will not be heated significantly above in situ temperature. 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 – 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. For an initial field test rental is the clear choice, but once actual emplacement begins 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 waste package emplacement, would be deferred until after an initial, developmental phase of waste emplacement. Such future decisions would be informed by new cost estimates based on 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 waste packages 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 (see Cochran and Hardin 2015).

This discussion leads to the question whether it could be more efficient (i.e., cheaper) 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, 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 waste package (e.g., dropping the string) by an order of magnitude. Accordingly, for this study the drill-string method is estimated using strings of 40 packages, although this number could be changed (increased or decreased) if found to be safe and advantageous.

Basement for Wireline Option – The current concept for wireline emplacement uses an above-ground radiation shield around the wellhead. The waste package shipping cask would be placed on top of the shield by a crane. Cement plugs would be emplaced using a coiled tubing rig. If coiled tubing operations were prohibitively expensive as discussed above, 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 – 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 are 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 – 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 mod./demob. and daily rig costs for completion activities are they 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 permanently 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 (Cochran and Hardin 2015).

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 waste package delivery and emplacement from one per day, to 2, 3 and 4 per day. These average throughput rates could be achieved by the two options, considering estimated trip times for emplacement (Cochran and Hardin 2015).

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**	**Total**
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**	**Total**
Bridge plug	$ 10,000	$ 100,000
Cementing	$ 40,000	$ 400,000
Subtotal		$ 500,000
One-Time Costs		
Build pad and basement		$ 500,000
Build structural frame		$ 100,000
Build transfer track system		
Subtotal		$ 600,000
Total Drill-String Project Cost		**$40,015,000**
Wireline Option		
Time Dependent Costs	**Daily rate**	**Total**
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**	**Total**
Bridge plug	$ 20,000	$ 200,000
Wireline cementing survey	$ 40,000	$ 400,000
Coiled-tubing unit and cementing	$ 200,000	$ 2,000,000
Subtotal		$ 2,600,000
One-Time Costs		
Build pad and control room		$ 350,000
Build radiation shield enclosure		$ 100,000
Subtotal		$ 450,000
Total Wireline Project Cost		**$22,615,000**

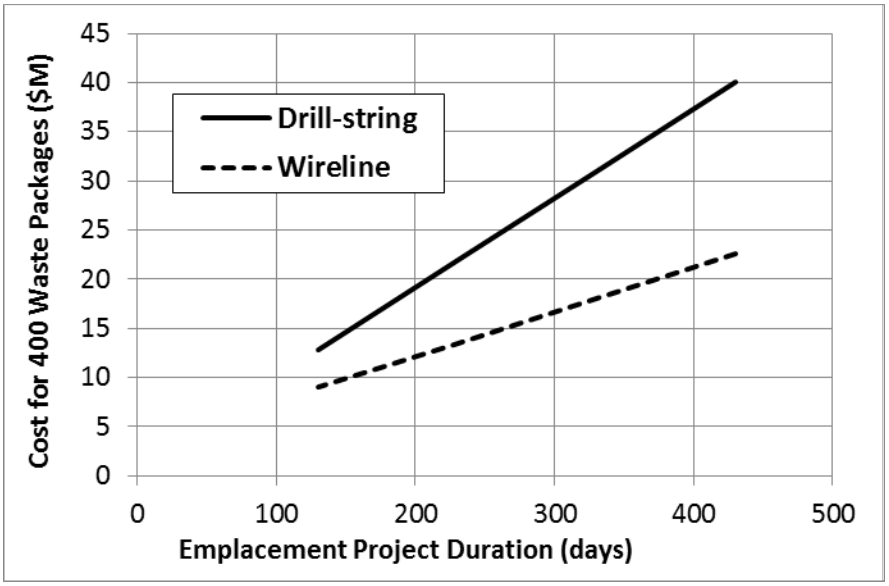

Figure C-1. Project cost vs. duration, for drill-string and wireline options.

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 (Table 1). 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 waste package 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

Outcome A – One or more waste packages (WPs) is breached above the disposal zone (DZ), 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 borehole 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, that activities will focus on stabilizing the spread of contamination at the surface and in the subsurface, retrieval of waste from above the DZ, 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).

Borehole fluid (i.e.,“emplacement mud”) will 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 DZ (A1 and A3) or fishing fails and one or more WPs are left in place (A2) (Table C-2). In both cases incremental 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.

Outcome B – One or more WPs is breached within the DZ. For Outcome B1, this occurs because one or more packages are dropped to the DZ, or a wireline or drill-string is dropped onto packages in the DZ. For Outcome B2, one or more packages becomes stuck above the DZ, and fishing is unsuccessful causing on or more breached packages to fall into the DZ.

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 borehole fluid circulation. It is assumed that no additional WPs will be emplaced in a borehole after breach, 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 low-level waste (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 borehole fluid (i.e.,“emplacement mud”) will be circulated out of 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.

Outcome C – Waste packages are dropped and come to rest intact unbreached within the DZ. 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.

Outcome D – One or more WPs becomes stuck in the DZ 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 waste packages (to free them) because they are already located in the DZ, 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 DZ below the stuck WP(s) will be cemented to the extent possible, then the borehole will be sealed and plugged. These cementing, sealing, and plugging activities (including casing removal) are within the scope of normal operations and are not costed here (Hardin 2015).

Outcome E –One or more unbreached WPs is stuck above the DZ. 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 DZ (A1) or fishing fails and one or more WPs are left in place (E2) (Table 1). In both cases incremental 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 – 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 DZ, 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 DZ.

Table C-2. 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	Incremental cost of emplacement operations (over costs for normal operations, wireline)	Time to emplace 400 WPs
A *A1 =* *A2 =* *A3 =*	Breached WP(s) stuck above DZ *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, incremental costs to seal and close in a contaminated environment, and loss of disposal capacity. For *A2* add costs for long-term (100-year) monitoring.	Incremental time equal to the downtime to implement each solution. To be developed
B *B1 =* *B2 =*	Breached WP(s) in DZ *Breach from dropping WP(s), or dropping wireline or drill-string onto WP(s)* *Breach from unsuccessful fishing above the DZ, with drop into the DZ*	Borehole decontaminated, and completely sealed and plugged with WP(s) in place in the DZ.		Yes	For *B1* include decontamination, LLW management, incremental costs to seal and close in a contaminated environment, and loss of remaining disposal capacity. For *B2* add the cost of fishing above the DZ.	
C *C1 =* *C2 =*	WP(s) dropped into DZ 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 DZ	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 DZ *Successfully fished* *Left in place* *Removed inside guidance casing* *Fishing unsuccessful, WP(s) drop to DZ*	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 DZ (*E2*); or sealed and plugged with WP(s) in DZ (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	~$17.4 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) breached above DZ; WP fished; hole plugged and sealed; all equipment discarded; site decontaminated					
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**	**$ 345,257,500**	**965**	**$ 307,057,500**	Include half of normal emplacement cost ($22.6M or $40.0M)
A2: As for A1 but fishing fails to retrieve WP(s) which are then left in place above DZ.					
A1 outcome	965	$ 345,257,500	965	$ 307,057,500	
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**	**$ 327,082,500**	**1330**	**$ 308,382,500**	
A3: As for A1 but WP(s) fished inside and with guidance casing, and removed.					
A1 outcome	965	$ 345,257,500	965	$ 307,057,500	
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 A2 cost	**1005**	**$ 349,457,500**	**966**	**$ 308,137,500**	
B1: WP(s) breached within DZ; no fishing; hole plugged and sealed; equipment discarded; site decontaminated.					
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**	**$ 323,657,500**	**945**	**$ 301,307,500**	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.					
B1 outcome	945	$ 323,657,500	945	$ 301,307,500	
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**	**$ 336,207,500**	**1330**	**$ 313,857,500**	
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 ~$40M (half of one interval between plugs is cemented without WPs)
Outcome C1 cost	**409**	**$ 41,014,250**	**409**	**$ 24,484,250**	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 ~$40M (one interval between plugs is cemented without WPs)
Outcome C2 cost	**407**	**$ 42,113,500**	**407**	**$ 27,453,500**	Include 90% of normal emplacement cost ($22.6M or $40.0M)
D: WP stuck in DZ; no breach; no fishing; cement up DZ; complete borehole sealing/plugging; 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 ~$40M (any string or WP; avg. travel through DZ is half, risk is over half that distance traversed)
Outcome D cost	**323**	**$ 41,011,250**	**323**	**$ 27,961,250**	Include 75% of normal emplacement cost ($22.6M or $40.0M)
E1: WP stuck above DZ; fished successfully; no breach; cement DZ and complete borehole sealing/plugging; 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 ~$40M (any string or WP)
Outcome E1 cost	**600**	**$ 72,557,500**	**600**	**$ 44,357,500**	Include half of normal emplacement cost ($22.6M or $40.0M)
E2: As for E1 but one or more WPs not fished, but left in place above DZ.					
E1 outome	600	$ 72,557,500	600	$ 44,357,500	
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Additional standby	365	$ 10,950,000	365	$ 10,950,000	
Outcome E2 cost	965	**$ 119,507,500**	**965**	**$ 91,307,500**	

Outcomes	Drill-String Days	Drill-String Cost	Wireline Days	Wireline Cost	Notes
E3: As for E1 but WP(s) fished inside and with guidance casing, and removed.					
E1 outome	600	$ 72,557,500	600	$ 44,357,500	
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**	**$ 76,757,500**	**601**	**$ 45,437,500**	
E4: As for E1 but WP(s) drop to bottom of DZ.					
E1 outcome	600	$ 72,557,500	600	$ 44,357,500	
(less costs for handling WPs)		$ (20,000,000)		$ (500,000)	
Outcome E4 cost	**600**	**$ 52,557,500**	**600**	**$ 43,857,500**	
F: Normal operations	**430**	**$ 40,015,000**	**430**	**$ 22,615,000**	

* 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 waste package 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 decayed to 2020 gives 50 MCi for all 1332 Cs-137 capsules.
- 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 x 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 x 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 one-m3 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. 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. September, 2014.

Cochran, J.R. and E.L. Hardin 2015. *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design*. SAND2015-6218. Albuquerque, NM: Sandia National Laboratories.

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. Design Study Sensitivity Analysis

This appendix provides the detailed results of the various sensitivity analyses conducted as part of the cost-risk study comparing wireline and drill-string emplacement methods. Section 5.6 describes the two main types of sensitivity analyses conducted (sensitivity to event probabilities and sensitivity to failure probabilities) and the rationale for each of the sensitivity cases, and summarizes the insights from these analyses.

In the following discussion and figures, the expressions disposal zone (DZ) and emplacement zone (EZ) are used interchangeably, referring to the bottom 2 km of a disposal borehole, for the reference concept (Section 2.6).

Figures D-1 and D-2 show the event trees for wireline and drill string emplacement modes, with each node in the tree labeled for easy reference in the discussion that follows. Initial probabilities for each event are also illustrated. For each event, probabilities must sum to one, so the probability is shown for only one branch (two branches are shown for the event with three possible outcomes).

D.1 Sensitivity to Event Probabilities

Four sets of sensitivity analyses were run to explore the effect of changes in the probabilities associated with various post-failure event. Table D-1 shows the probabilities used for each branch on the event trees for each sensitivity case; the purpose of each set of sensitivity analyses and the rationale for the range of values explored is summarized below. Detailed results for each set of sensitivity analyses are shown in Tables D-2 through D-5. Light green or light orange shading is used to highlight changes that might be worth noting in each case. Discussion of the implications of each set of sensitivity analyses is included in Section 5.6.

- **Sensitivity Analysis S1 – Sensitivity to uncertainty about where waste packages (WPs) get stuck (above or within the disposal zone).** Using the logic described for estimating the initial probability described in Table 5-2, two sensitivity cases are identified. S1a represents the first WP emplaced, where there is 2 km of DZ and 1 km above the DZ potentially available as a location for a WP to get stuck; S1b represents the last WP emplaced, where there is no remaining DZ so it is only possible to get stuck above the DZ.
- **Sensitivity Analysis S2 – Sensitivity to uncertainty about the challenge of removing stuck waste packages.** We consider both the possibility that the initial values overestimate the general success rate at WP fishing or removal (S2a), and the possibility that fishing WPs that are stuck during wireline emplacement is much more challenging that removing WP strings that are stuck during drill string emplacement (S2b).
- **Sensitivity Analysis S3 – Sensitivity to uncertainty about the likelihood of breaching a WP while attempting to fish or remove it**. As described in Table 2, the initial value for W_breach_fish assumes that if a human error occurs during fishing, the WP is breached. Case S3s assumes that only one in 10 such errors leads to a WP breach. Case S3b assumes instead a much higher likelihood of breaching the WP during fishing. Finally, the expert panel noted that if a casing collapse occurs, it is most likely to occur at a casing joint and that there is small but non-zero probability that a WP breach could occur. Case S3c sets the probability of breaching a WP while trying to remove it given drill string emplacement at half the probability of breaching during fishing operations.

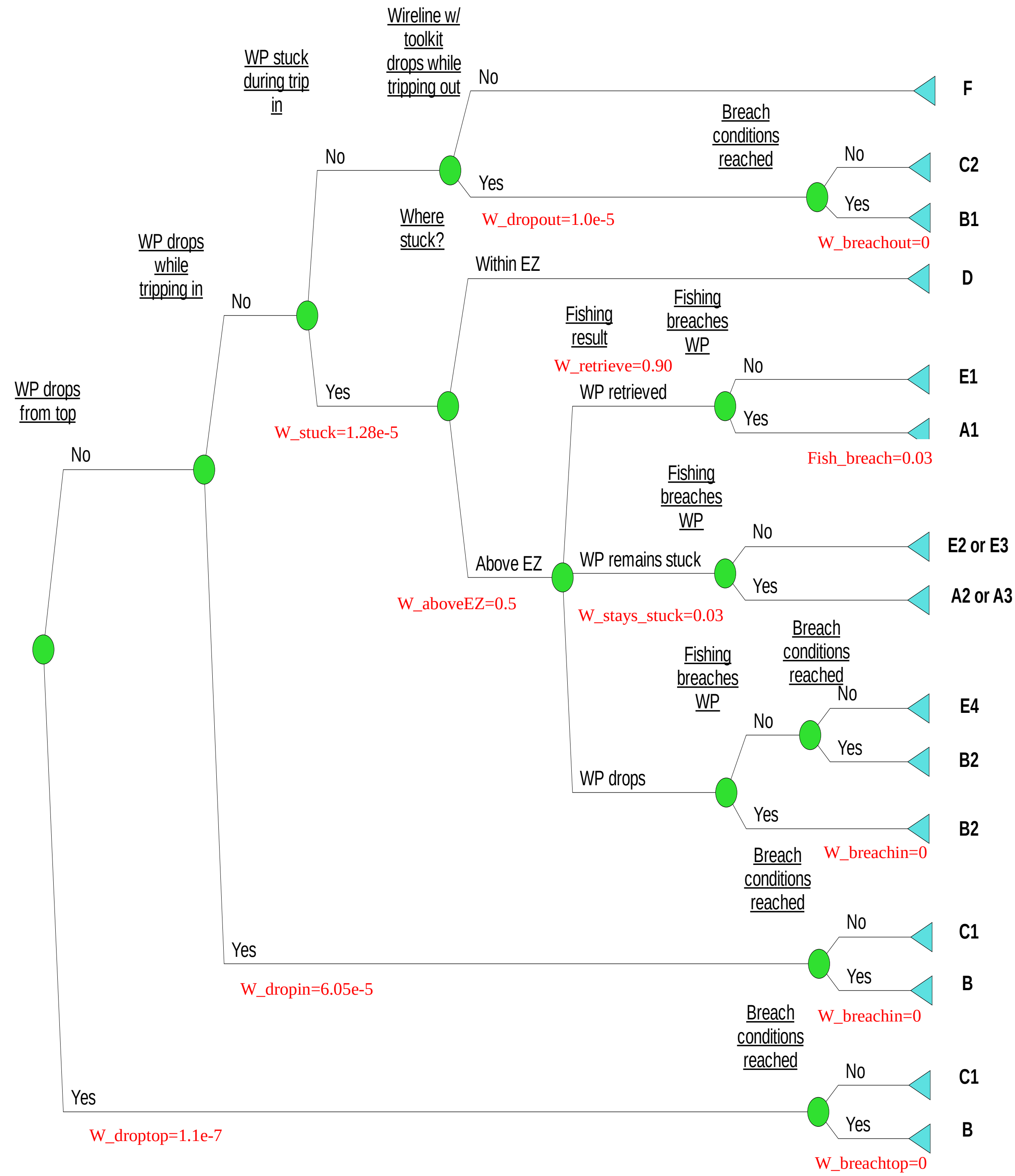
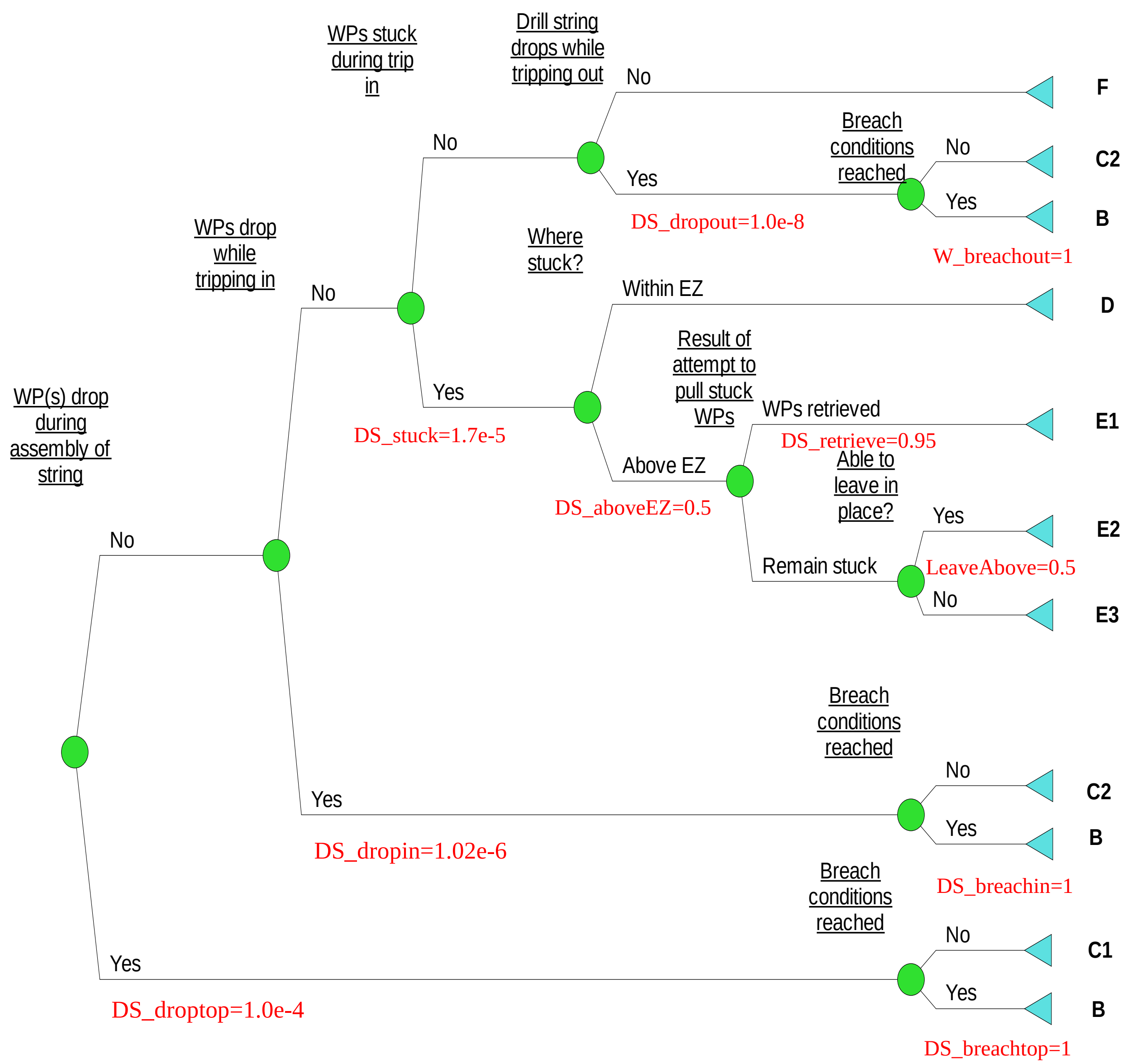


Figure D-1. Labeled wireline event tree, per package, with initial probabilities shown.



Additional note: Initial assumption is that a stuck WP can not be breached by any attempt to remove it. Sensitivity analyses will include consideration of that potential (not illustrated in this tree). DS_fishbreach will be used to represent this event.

Figure D-2. Labeled drill string event tree, per waste package string, with initial probabilities shown.

- **Sensitivity Analysis S4 – Sensitivity to uncertainty about the likelihood of WP breach from drop events**. For this set of sensitivity analyses, we explore 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).

Table D-1. Event probabilities, initial and sensitivity analyses.

	Initial Analysis	Sensitivity Analysis Cases (Initial values used unless other values are shown)								
		S1a	S1b	S2a	S2b	S3a	S3b	S3c	S4a	S4b
W_aboveDZ	0.5	0.33	1							
DS_aboveDZ	0.5	0.33	1							
W_retrieve (casing)	0.9			0.5	0.5					
W_stays_stuck (casing)	0.07			0.33	0.33					
W_falls (casing)	0.03			0.17	0.17					
W_retrieve (debris)	0.9			0.5	0.5					
W_stays_stuck (debris)	0.03			0.17	0.17					
W_falls (debris)	0.7			0.33	0.33					
DS_retrieve (casing)	0.95			0.65	0.95					
DS_stays_stuck (casing)	0.05			0.35	0.05					
DS_falls (casing)	0			0	0					
DS_retrieve (debris)	0.97			0.7	0.97					
DS_stays_stuck (debris)	0.03			0.3	0.03					
DS_falls (debris)	0			0	0					
Fish_breach	0.03					0.003	0.1			
DS_fishbreach	0							0.015		
W_breachtop	0								0.009	0.05
W_breachin	0								0.009	0.05
W_breachout	0								0	0
DS_breachtop	1								0.9	0.5
DS_breachin	1								0.9	0.5
DS_breachout	1								0.99	0.9

Table D-2. Results: Sensitivity to where waste package(s) are stuck.

	Initial results		S1a		S1b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	96.81%	99.22%	96.81%	99.22%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	42.0	22.9	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.4	433.6	431.1	433.8
Probability of radiation release	1.29E-04	7.04E-03	8.58E-05	7.04E-03	2.57E-04	7.04E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	8.58E-05	7.04E-03	2.57E-04	7.04E-03
A1	1.16E-04	0.00E+00	7.72E-05	0.00E+00	2.32E-04	0.00E+00
A2	2.32E-06	0.00E+00	1.54E-06	0.00E+00	4.63E-06	0.00E+00
A3	2.32E-06	0.00E+00	1.54E-06	0.00E+00	4.63E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	7.04E-03	0.00E+00	7.04E-03
B2	8.24E-06	0.00E+00	5.49E-06	0.00E+00	1.65E-05	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.49E-03	8.00E-04	8.32E-03	8.00E-04
D	4.29E-03	4.00E-04	5.72E-03	5.33E-04	0.00E+00	0.00E+00
E1	3.75E-03	3.82E-04	2.50E-03	2.55E-04	7.49E-03	7.64E-04
E2	7.49E-05	9.00E-06	4.99E-05	6.00E-06	1.50E-04	1.80E-05
E3	7.49E-05	9.00E-06	4.99E-05	6.00E-06	1.50E-04	1.80E-05
E4	2.66E-04	0.00E+00	1.78E-04	0.00E+00	5.33E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.33E-02	0.00E+00	2.33E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.17E-02	0.00E+00	2.17E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.58E-03	0.00E+00	1.58E-03	0.00E+00

Table D-3. Results: Sensitivity to the challenge of removing stuck waste package(s).

	Initial results		S2a		S2b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	96.81%	99.22%	96.81%	99.22%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	42.0	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	430.0	433.7	430.0	433.7
Probability of radiation release	1.29E-04	7.04E-03	1.29E-04	7.04E-03	1.29E-04	7.04E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.29E-04	7.04E-03	1.29E-04	7.04E-03
A1	1.16E-04	0.00E+00	6.44E-05	0.00E+00	6.44E-05	0.00E+00
A2	2.32E-06	0.00E+00	1.16E-05	0.00E+00	1.16E-05	0.00E+00
A3	2.32E-06	0.00E+00	1.16E-05	0.00E+00	1.16E-05	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	7.04E-03	0.00E+00	7.04E-03
B2	8.24E-06	0.00E+00	4.12E-05	0.00E+00	4.12E-05	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.45E-03	8.00E-04	8.45E-03	8.00E-04
D	4.29E-03	4.00E-04	4.29E-03	4.00E-04	4.29E-03	4.00E-04
E1	3.75E-03	3.82E-04	2.08E-03	2.65E-04	2.08E-03	3.82E-04
E2	7.49E-05	9.00E-06	3.74E-04	6.75E-05	3.74E-04	9.00E-06
E3	7.49E-05	9.00E-06	3.74E-04	6.75E-05	3.74E-04	9.00E-06
E4	2.66E-04	0.00E+00	1.33E-03	0.00E+00	1.33E-03	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.33E-02	0.00E+00	2.33E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.17E-02	0.00E+00	2.17E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.58E-03	0.00E+00	1.58E-03	0.00E+00

Table D-4. Results: Sensitivity to the likelihood of breaching a waste package while trying to remove it.

	Initial results		S3a		S3b		S3c	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**		**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	96.81%	99.22%	96.81%	99.22%	96.81%	99.22%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics								
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	42.0	22.9	42.0	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.8	433.7	430.0	433.7	429.8	433.7
Probability of radiation release	1.29E-04	7.04E-03	1.29E-05	7.04E-03	4.29E-04	7.04E-03	1.29E-04	7.05E-03
Outcome probabilities								
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.29E-05	7.04E-03	4.29E-04	7.04E-03	1.29E-04	7.05E-03
A1	1.16E-04	0.00E+00	1.16E-05	0.00E+00	3.86E-04	0.00E+00	1.16E-04	5.73E-06
A2	2.32E-06	0.00E+00	2.32E-07	0.00E+00	7.72E-06	0.00E+00	2.32E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.32E-07	0.00E+00	7.72E-06	0.00E+00	2.32E-06	2.70E-07
B1	0.00E+00	7.04E-03	0.00E+00	7.04E-03	0.00E+00	7.04E-03	0.00E+00	7.04E-03
B2	8.24E-06	0.00E+00	8.24E-07	0.00E+00	2.75E-05	0.00E+00	8.24E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.57E-03	8.00E-04	8.15E-03	8.00E-04	8.45E-03	7.88E-04
D	4.29E-03	4.00E-04	4.29E-03	4.00E-04	4.29E-03	4.00E-04	4.29E-03	3.94E-04
E1	3.75E-03	3.82E-04	3.85E-03	3.82E-04	3.48E-03	3.82E-04	3.75E-03	3.76E-04
E2	7.49E-05	9.00E-06	7.69E-05	9.00E-06	6.95E-05	9.00E-06	7.49E-05	8.86E-06
E3	7.49E-05	9.00E-06	7.69E-05	9.00E-06	6.95E-05	9.00E-06	7.49E-05	8.86E-06
E4	2.66E-04	0.00E+00	2.74E-04	0.00E+00	2.47E-04	0.00E+00	2.66E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.33E-02	0.00E+00	2.33E-02	0.00E+00	2.33E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.17E-02	0.00E+00	2.17E-02	0.00E+00	2.17E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.58E-03	0.00E+00	1.58E-03	0.00E+00	1.58E-03	0.00E+00

Table D-5. Results: Sensitivity to the likelihood that dropped waste package(s) breach.

	Initial results		S4a		S4b	
	Wireline	Drill string	Wireline	Drill string	Wireline	Drill string
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	96.81%	99.22%	96.81%	99.22%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.9	41.9	23.1	41.2
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	430.0	433.3	430.4	432.1
Probability of radiation release	1.29E-04	7.04E-03	3.26E-04	6.46E-03	1.23E-03	4.08E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	3.26E-04	6.46E-03	1.23E-03	4.08E-03
A1	1.16E-04	0.00E+00	1.16E-04	0.00E+00	1.16E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.32E-06	0.00E+00	2.32E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.32E-06	0.00E+00	2.32E-06	0.00E+00
B1	0.00E+00	7.04E-03	1.95E-04	6.46E-03	1.08E-03	4.08E-03
B2	8.24E-06	0.00E+00	1.06E-05	0.00E+00	2.16E-05	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.45E-03	8.00E-04	8.44E-03	8.00E-04
D	4.29E-03	4.00E-04	4.29E-03	4.00E-04	4.29E-03	4.00E-04
E1	3.75E-03	3.82E-04	3.75E-03	3.82E-04	3.75E-03	3.82E-04
E2	7.49E-05	9.00E-06	7.49E-05	9.00E-06	7.49E-05	9.00E-06
E3	7.49E-05	9.00E-06	7.49E-05	9.00E-06	7.49E-05	9.00E-06
E4	2.66E-04	0.00E+00	2.64E-04	0.00E+00	2.53E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.31E-02	5.80E-04	2.22E-02	2.97E-03
C1	2.17E-02	0.00E+00	2.15E-02	5.66E-04	2.06E-02	2.83E-03
C2	1.58E-03	0.00E+00	1.58E-03	1.38E-05	1.58E-03	1.38E-04

D.2 Sensitivity to Failure Probabilities

Seven sets of sensitivity analyses were run to explore the effect of changes in the basic event failure probabilities used in the fault trees calculations. Tables D-6 and D-7 show the probabilities used for each of the basic events that were subject to sensitivity analyses, for wireline and drill string emplacement. In Table D-6, the first column lists the basic events in each fault tree for wireline emplacement, the second column lists the initial probability for each, and the third column lists the probabilities used in sensitivity analyses. The fifth column shows the results of a "one-off" sensitivity analysis for each event: to conduct these analyses the basic event probabilities were changed one at a time and new top-level failure probability was calculated.

One-off sensitivity analyses such as these are useful primarily in identifying the driving event(s) for each top-level failure; information that was already available and discussed with the initial fault trees in Appendix B. Table D-7 follows the same format for drill string emplacement, but without the one-off sensitivity studies (which were not done).

Of more interest are sensitivity analyses that explore changes that would affect multiple fault trees simultaneously, in a logically consistent way. Seven sets of sensitivity analyses were defined to explore the effects of these kinds of broad changes to basic event probabilities. The last columns of Tables D-6 and D-7 include a reference to the sensitivity case relevant to those basic event probabilities. Several of the cases involved changing probabilities in both sets of event trees simultaneously (for example S-F2 changes all the human error probabilities for both emplacement modes, "S-F2" appears multiple times in both Tables D-6 and Table D-7.

The sensitivity cases and their rationales are described below. Detailed results for each set of sensitivity analyses are shown in Tables D-8 through D-14. Light green or light orange shading is used to highlight changes that might be important in each case. Discussion of the implications of each set of sensitivity analyses is included in Section 5.6.

- **Sensitivity Analysis S-F1 – Sensitivity to the conditional probability that an error or mistake leads to a failure (i.e., a dropped or stuck package or string)**. The initial probabilities are based on a "conservative" assumption that there is a high probability that an error results in a failure: for example, if a misassembled cable head is in use, there is a 10% chance that it will fail are release the WP while tripping in. In this set of sensitivity analyses, both higher and lower conditional probabilities of failure given the initial error are explored.
- **Sensitivity Analysis S-F2 – Sensitivity to the frequency of human errors.** Human errors play an important role in all the fault trees. As described in Sections 5.5 and 5.6, 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.
- **Sensitivity Analysis 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, that 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 assumes that operational change is made and the probability a dynamic overtension failure decreases by a factor of 10.
- **Sensitivity Analysis S-F4 – Sensitivity to the effectiveness of the 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^{-4} to 10^{-2}. This set of sensitivity analyses explores both ends of this range.
- **Sensitivity Analysis S-F5 – Sensitivity to the likelihood WP(s) are 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 explores the impacts of reducing those basic event probabilities by a factor of 10, and also explores the impact of assuming higher probabilities that a single WP gets stuck by debris than that a WP string gets stuck by debris.

- **Sensitivity Analysis S-F6 – Sensitivity to the likelihood of rigging failure while assembling a WP string**. As discussed in Appendix B the probability of rigging failure leading to a drop for lifts in nuclear facilities could be as high as 10^{-4} per lift. In this analysis, that assumption would lead to a probability of dropping a WP that is unrealistically high compared to drilling rig experience. Accordingly, the expert panel adopted a probability of 10^{-5}. This sensitivity study demonstrates the level of risk that would be assumed if rigging failure has a likelihood of 10^{-4} per lift.
- **Sensitivity Analysis 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 as a result of the length of time required to assemble a string of 40 waste packages. The set of sensitivity analyses explores the effect of both higher and lower frequencies for casing collapse.

Table D-6. Failure basic event probabilities for wireline emplacement and values explored in sensitivity analyses.

Basic Event	Initial Probability	Sensitivity Probabilities	--->	Failure Probability of Top Event (for a single event sensitivity)	Sensitivity case
Surface Drop: Initial Failure probability = 1.12E-07					
Blind ram door left open	1.00E-03	1.00E-04			S-F2
Attempt to open blind ram door at wrong time	1.00E-03	1.00E-04	--->	1.11E-07	S-F2
Attempt to open shipping cask door at wrong time	1.00E-03	1.00E-04	--->	1.10E-07	S-F2
Attempt to operate winch in the wrong direction	1.00E-03	1.00E-04	--->	2.20E-08	S-F2
Door Interlock Failure	1.00E-03	1.00E-02	--->	1.30E-07	S-F4
		1.00E-04	--->	1.10E-07	
System Interlock Failure	1.00E-04	1.00E-02	--->	1.00E-05	S-F4
		1.00E-03	--->	1.01E-06	
		1.00E-05	--->	2.20E-08	
Trip-in Drop: Initial Failure Probability = 5.50E-05					
Attempt to close shipping cask door at wrong time	1.00E-03	1.00E-04	--->	5.41E-05	S-F2
Attempt to close blind ram at wrong time	1.00E-03	1.00E-04	--->	5.41E-05	S-F2
Wireline damage not detected	1.00E-02	1.00E-03	--->	5.41E-05	S-F2
Attempt to release WP at wrong time	1.00E-03	1.00E-04	--->	5.50E-05	S-F2
Misdiagnose WP connection	1.00E-02	1.00E-03	--->	5.41E-05	S-F2
Human misassembles WP connection	1.00E-03	1.00E-04	--->	5.41E-05	S-F2
Attempt to release cablehead from cable	1.00E-03	1.00E-04	--->	5.50E-05	S-F2
Misdiagnose cablehead connection	1.00E-03	1.00E-04	--->	5.41E-05	S-F2
Human misassembles cablehead	1.00E-03	1.00E-04	--->	5.41E-05	S-F2
Door Interlock Failure	1.00E-03	1.00E-02	--->	7.30E-05	S-F4
		1.00E-04	--->	5.32E-05	
Wireline damage and fatigue sufficient to break	1.00E-04	1.00E-03	--->	6.40E-05	S-F1
		1.00E-05	--->	5.41E-05	
WP drop while attached is sufficient to break wireline	1.00E-03	1.00E-04	--->	1.00E-05	S-F3
Mechanism fails to recognize WP load	1.00E-05	1.00E-04	--->	5.51E-05	
Misassembling sufficient to lead to release	1.00E-01	1	--->	6.40E-05	S-F1
		1.00E-02	--->	5.41E-05	
Mechanism fails to recognize cablehead load	1.00E-05	1.00E-04	--->	5.51E-05	
		1.00E-06	--->	5.50E-05	
Stuck: Initial Failure Probability = 2.18E-05					
Debris not noticed or reported	1.00E-02	1.00E-03	--->	2.17E-05	S-F2
Human fails to correctly run caliper log before emplacement	1.00E-03	1.00E-04	--->	2.18E-05	S-F2
Debris falls into borehole from worker activity	1.00E-05	1.00E-04	--->	2.27E-05	S-F5
		1.00E-06	--->	2.17E-05	
Gauge ring fails to catch concrete debris	1.00E-05	1.00E-04	--->	1.12E-04	S-F5
		1.00E-06	--->	1.28E-05	
Other Debris	1.00E-05	1.00E-04	--->	1.12E-04	S-F5
		1.00E-06	--->	1.28E-05	
Casing Collapse (1.15E-06 per hour)	1.71E-06	3.45E-06	--->	2.36E-05	S-F7
	1.37E-05	2.76E-05	--->		
Casing Collapse (5.70E-08 per hour)	1.71E-06	1.71E-07	--->	2.03E-05	S-F7
	1.37E-05	1.37E-06	--->		
Caliper log fails to detect casing collapse	1.00E-04				
Trip-out Drop: Initial Failure Probability = 4.01E-6					
Attempt to close shipping cask door at wrong time	1.00E-03	1.00E-04	--->	3.11E-06	S-F2
Attempt to close blind ram at wrong time	1.00E-03	1.00E-04	--->	3.11E-06	S-F2
Wireline damage not detected	1.00E-02	1.00E-03	--->	3.11E-06	S-F2
Attempt to release cablehead from cable	1.00E-03	1.00E-04	--->	4.00E-06	S-F2
Misdiagnose cablehead connection	1.00E-02	1.00E-03	--->	3.11E-06	S-F2
Human misassembles cablehead	1.00E-03	1.00E-04	--->	3.11E-06	S-F2
Door Interlock Failure	1.00E-03	1.00E-02	--->	2.20E-05	S-F4
		1.00E-04	--->	2.21E-06	
Wireline damage and fatigue sufficient to break	1.00E-04	1.00E-03	--->	1.30E-05	S-F1
		1.00E-05	--->	3.11E-06	
Mechanism fails to recognize cablehead load	1.00E-05	1.00E-04	--->	4.10E-06	
		1.00E-06	--->	4.00E-06	
Misassembling sufficient to lead to release	1.00E-01	1	--->	1.30E-05	S-F1
		1.00E-02	--->	3.11E-06	

Table D-7. Failure basic event probabilities for drill string emplacement and values explored in sensitivity analyses.

Basic Event	Initial Probability	Sensitivity Probability	--->	Failure Probability of Top Event (for a single event sensitivity)	Sensitivity Category
Surface Drop: Initial Failure probability = 4.084E-04					
Basement slips inadvertent opening	1.00E-03	1.00E-04	--->	4.08E-04	S-F2
Elevator ram inadvertent opening	1.00E-03	1.00E-04	--->	4.08E-04	S-F2
System interlock failure	1.00E-03	1.00E-04	--->	4.08E-04	S-F4
Rigging Failure	1.00E-05	1.00E-04	--->	4.01E-03	S-F6
		1.00E-06	--->	4.84E-05	
WP joint under-torqued such that it will fail immediately	1.00E-04	1.00E-03	--->	4.44E-04	S-F1
		1.00E-05	--->	4.08E-04	
Interlock system fails to detect under torqued joint	1.00E-03	1.00E-02	--->	4.44E-04	S-F4
		1.00E-04	--->	4.08E-04	
WP joint cross-threaded such that it will fail immediately	1.00E-04	1.00E-03	--->	4.44E-04	S-F1
		1.00E-05	--->	4.08E-04	
Interlock system fails to detect cross-threaded joint	1.00E-03	1.00E-02	--->	4.44E-04	S-F4
		1.00E-04	--->	4.08E-04	
Drop Trip-in: Initial Failure Probability = 1.599E-04					
Interlock system fails to detect under torqued joints	1.00E-03	1.00E-02	--->		S-F4
		1.00E-04	--->		
Interlock system fails to detect cross threaded joint	1.00E-03	1.00E-02	--->		S-F4
		1.00E-04	--->		
Under torqued joint between WPs sufficient to fail	1.00E-04	1.00E-03	--->		S-F1
		1.00E-05	--->		
Under torqued joint undetected during surface preparation	1.00E-03	1.00E-02	--->		S-F4
		1.00E-04	--->		
Cross threaded joint between WPs sufficient to fail	1.00E-04	1.00E-03	--->		S-F1
		1.00E-05	--->		
Cross threaded joint undedetected during surface preparation	1.00E-03	1.00E-02	--->		S-F4
		1.00E-04	--->		
Rig slips inadvertnet opening	1.00E-05		--->		S-F2
Pipe ram inadvertent opening	1.00E-05		--->		S-F2
System interlock failure	1.00E-03	1.00E-02	--->		S-F4
		1.00E-04	--->		
Get Stuck: Initial Failure Probability = 8.029E-5					
Debris falls into borehole from worker activity	1.00E-05	1.00E-04			S-F5
		1.00E-06			
Debris not noticed or detected	1.00E-02	1.00E-03			S-F2
Gauge ring fails to catch concrete debris	1.00E-05	1.00E-04			S-F5
		1.00E-06			
Other debris	1.00E-05	1.00E-04			S-F5
		1.00E-06			
Casing collapse after caliper, before/during lowering of WP	5.47E-04	1.10E-03			S-F7
		5.47E-05			
Lead Package doesn't detect collapse (telemetry failure)	1.00E-01	1.00E-02			S-F1
Failure to respond to detected collapse	1.00E-02	1.00E-03			S-F2
Drop Trip Out: Initial Failure Probability = 1.394E-4					
Rig Slips inadvertent opening	1.00E-05				
Pipe ram inadvertent opening	1.00E-05				
System interlock failure	1.00E-03	1.00E-02			S-F4
		1.00E-04			

Table D-8. Results: Sensitivity to conditional probability that error leads to failure.

	Initial results		SF1a		SF1b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	95.09%	99.13%	96.99%	99.28%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.9	42.4	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.5	434.4	429.9	433.6
Probability of radiation release	1.29E-04	7.04E-03	1.28E-04	8.46E-03	1.29E-04	6.91E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.28E-04	8.46E-03	1.29E-04	6.91E-03
A1	1.16E-04	0.00E+00	1.15E-04	0.00E+00	1.16E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.29E-06	0.00E+00	2.32E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.29E-06	0.00E+00	2.32E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	8.46E-03	0.00E+00	6.91E-03
B2	8.24E-06	0.00E+00	8.17E-06	0.00E+00	8.25E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.38E-03	2.17E-04	8.46E-03	3.09E-04
D	4.29E-03	4.00E-04	4.25E-03	1.08E-04	4.29E-03	1.55E-04
E1	3.75E-03	3.82E-04	3.71E-03	1.04E-04	3.75E-03	1.49E-04
E2	7.49E-05	9.00E-06	7.42E-05	2.44E-06	7.49E-05	2.86E-06
E3	7.49E-05	9.00E-06	7.42E-05	2.44E-06	7.49E-05	2.86E-06
E4	2.66E-04	0.00E+00	2.64E-04	0.00E+00	2.67E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	4.06E-02	0.00E+00	2.15E-02	0.00E+00
C1	2.17E-02	0.00E+00	3.20E-02	0.00E+00	2.06E-02	0.00E+00
C2	1.58E-03	0.00E+00	8.58E-03	0.00E+00	8.71E-04	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)						
Drop one or more WP from top	4.41E-05	4.07E-03	4.37E-05	4.79E-03	4.41E-05	4.00E-03
Drop one or more WP during trip in	2.16E-02	1.59E-03	3.20E-02	2.29E-03	2.06E-02	1.52E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	8.58E-03	1.38E-03	8.71E-04	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	8.52E-03	8.00E-04	8.60E-03	3.09E-04

Table D-9. Results: Sensitivity to frequency of human errors.

	Initial results		SF2	
	Wireline	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	97.15%	99.22%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics				
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.9	433.7
Probability of radiation release	1.29E-04	7.04E-03	1.28E-04	7.05E-03
Outcome probabilities				
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.28E-04	7.05E-03
A1	1.16E-04	0.00E+00	1.15E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.31E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.31E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	7.05E-03
B2	8.24E-06	0.00E+00	8.22E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.43E-03	7.50E-04
D	4.29E-03	4.00E-04	4.28E-03	3.75E-04
E1	3.75E-03	3.82E-04	3.73E-03	3.58E-04
E2	7.49E-05	9.00E-06	7.46E-05	8.38E-06
E3	7.49E-05	9.00E-06	7.46E-05	8.38E-06
E4	2.66E-04	0.00E+00	2.66E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.00E-02	0.00E+00
C1	2.17E-02	0.00E+00	1.98E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.23E-04	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)				
Drop one or more WP from top	4.41E-05	4.07E-03	7.89E-06	4.07E-03
Drop one or more WP during trip in	2.16E-02	1.59E-03	1.98E-02	1.59E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	1.23E-04	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	8.56E-03	7.50E-04

Table D-10. Results: Sensitivity to specific operational and design changes.

	Initial results		SF3	
	Wireline	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	98.57%	99.22%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics				
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	430.2	433.7
Probability of radiation release	1.29E-04	7.04E-03	1.30E-04	7.04E-03
Outcome probabilities				
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.30E-04	7.04E-03
A1	1.16E-04	0.00E+00	1.17E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.34E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.34E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	7.04E-03
B2	8.24E-06	0.00E+00	8.31E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.53E-03	8.00E-04
D	4.29E-03	4.00E-04	4.33E-03	4.00E-04
E1	3.75E-03	3.82E-04	3.78E-03	3.82E-04
E2	7.49E-05	9.00E-06	7.55E-05	9.00E-06
E3	7.49E-05	9.00E-06	7.55E-05	9.00E-06
E4	2.66E-04	0.00E+00	2.69E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	5.61E-03	0.00E+00
C1	2.17E-02	0.00E+00	4.02E-03	0.00E+00
C2	1.58E-03	0.00E+00	1.59E-03	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)				
Drop one or more WP from top	4.41E-05	4.07E-03	4.45E-05	4.07E-03
Drop one or more WP during trip in	2.16E-02	1.59E-03	3.97E-03	1.59E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	1.59E-03	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	8.67E-03	8.00E-04

Table D-11. Results: Sensitivity to effectiveness of the interlock systems.

	Initial results		SF4a		SF4b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	95.40%	99.11%	96.96%	99.23%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.9	42.5	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.5	434.5	429.9	433.6
Probability of radiation release	1.29E-04	7.04E-03	1.28E-04	8.71E-03	1.29E-04	6.88E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.28E-04	8.71E-03	1.29E-04	6.88E-03
A1	1.16E-04	0.00E+00	1.15E-04	0.00E+00	1.16E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.30E-06	0.00E+00	2.32E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.30E-06	0.00E+00	2.32E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	8.71E-03	0.00E+00	6.88E-03
B2	8.24E-06	0.00E+00	8.18E-06	0.00E+00	8.25E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.39E-03	2.17E-04	8.46E-03	8.00E-04
D	4.29E-03	4.00E-04	4.26E-03	1.08E-04	4.29E-03	4.00E-04
E1	3.75E-03	3.82E-04	3.72E-03	1.04E-04	3.75E-03	3.82E-04
E2	7.49E-05	9.00E-06	7.43E-05	2.44E-06	7.49E-05	9.00E-06
E3	7.49E-05	9.00E-06	7.43E-05	2.44E-06	7.49E-05	9.00E-06
E4	2.66E-04	0.00E+00	2.64E-04	0.00E+00	2.67E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	3.75E-02	0.00E+00	2.18E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.89E-02	0.00E+00	2.10E-02	0.00E+00
C2	1.58E-03	0.00E+00	8.60E-03	0.00E+00	8.70E-04	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)						
Drop one or more WP from top	4.41E-05	4.07E-03	4.02E-04	4.79E-03	7.96E-06	4.00E-03
Drop one or more WP during trip in	2.16E-02	1.59E-03	2.85E-02	2.54E-03	2.10E-02	1.50E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	8.60E-03	1.38E-03	8.71E-04	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	8.53E-03	8.00E-04	8.60E-03	8.00E-04

Table D-12. Results: Sensitivity to likelihood that WP(s) are stuck by debris in the borehole.

	Initial results		SF5a		SF5b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	90.05%	99.04%	97.52%	99.23%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	24.0	42.1	22.7	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	432.6	433.7	429.6	433.7
Probability of radiation release	1.29E-04	7.04E-03	1.16E-03	7.04E-03	2.22E-05	7.04E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.16E-03	7.04E-03	2.22E-05	7.04E-03
A1	1.16E-04	0.00E+00	1.04E-03	0.00E+00	1.99E-05	0.00E+00
A2	2.32E-06	0.00E+00	1.94E-05	0.00E+00	5.40E-07	0.00E+00
A3	2.32E-06	0.00E+00	1.94E-05	0.00E+00	5.40E-07	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	7.04E-03	0.00E+00	7.04E-03
B2	8.24E-06	0.00E+00	7.68E-05	0.00E+00	1.14E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	7.59E-02	2.60E-03	1.46E-03	6.19E-04
D	4.29E-03	4.00E-04	3.85E-02	1.30E-03	7.39E-04	3.10E-04
E1	3.75E-03	3.82E-04	3.37E-02	1.25E-03	6.45E-04	2.94E-04
E2	7.49E-05	9.00E-06	6.28E-04	2.25E-05	1.75E-05	7.64E-06
E3	7.49E-05	9.00E-06	6.28E-04	2.25E-05	1.75E-05	7.64E-06
E4	2.66E-04	0.00E+00	2.48E-03	0.00E+00	3.67E-05	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.25E-02	0.00E+00	2.34E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.09E-02	0.00E+00	2.18E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.52E-03	0.00E+00	1.58E-03	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)						
Drop one or more WP from top	4.41E-05	4.07E-03	4.25E-05	4.06E-03	4.42E-05	4.07E-03
Drop one or more WP during trip in	2.16E-02	1.59E-03	2.09E-02	1.59E-03	2.17E-02	1.59E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	1.52E-03	1.38E-03	1.58E-03	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	7.70E-02	2.60E-03	1.48E-03	6.20E-04

Table D-13. Results: Sensitivity to the likelihood of rigging failure during assembly of WP string.

	Initial results		SF6a		SF6b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	96.81%	95.76%	96.81%	99.57%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	52.0	22.8	41.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.8	451.8	429.8	431.8
Probability of radiation release	1.29E-04	7.04E-03	1.29E-04	4.22E-02	1.29E-04	3.47E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.29E-04	4.22E-02	1.29E-04	3.47E-03
A1	1.16E-04	0.00E+00	1.16E-04	0.00E+00	1.16E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.32E-06	0.00E+00	2.32E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.32E-06	0.00E+00	2.32E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	4.22E-02	0.00E+00	3.47E-03
B2	8.24E-06	0.00E+00	8.24E-06	0.00E+00	8.24E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	8.45E-03	2.13E-04	8.45E-03	8.01E-04
D	4.29E-03	4.00E-04	4.29E-03	1.06E-04	4.29E-03	4.01E-04
E1	3.75E-03	3.82E-04	3.75E-03	1.02E-04	3.75E-03	3.83E-04
E2	7.49E-05	9.00E-06	7.49E-05	2.39E-06	7.49E-05	9.01E-06
E3	7.49E-05	9.00E-06	7.49E-05	2.39E-06	7.49E-05	9.01E-06
E4	2.66E-04	0.00E+00	2.66E-04	0.00E+00	2.66E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.33E-02	0.00E+00	2.33E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.17E-02	0.00E+00	2.17E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.58E-03	0.00E+00	1.58E-03	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)						
Drop one or more WP from top	4.41E-05	4.07E-03	4.41E-05	3.93E-02	4.41E-05	4.83E-04
Drop one or more WP during trip in	2.16E-02	1.59E-03	2.16E-02	1.57E-03	2.16E-02	1.60E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	1.58E-03	1.36E-03	1.58E-03	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	8.59E-03	7.88E-04	8.59E-03	8.01E-04

Table D-14. Results: Sensitivity to the frequency of casing collapse.

	Initial results		SF7a		SF7b	
	Wireline	**Drill string**	**Wireline**	**Drill string**	**Wireline**	**Drill string**
Probability of incident-free emplacement of 400 WP	96.81%	99.22%	96.75%	99.15%	96.87%	99.27%
Approximate total costs if successful ($ million)	22.615	40.015	22.615	40.015	22.615	40.015
Expected performance against the defined performance metrics						
Expected value of costs ($ million), considering both normal and off-normal events	22.8	42.0	22.8	42.0	22.8	42.0
Expected total time of operations (days), considering both normal and off-normal events	429.8	433.7	429.9	433.7	429.8	433.6
Probability of radiation release	1.29E-04	7.04E-03	1.39E-04	7.04E-03	1.20E-04	7.05E-03
Outcome probabilities						
Probability of a failure that leads to radiation release (outcomes A or B)	1.29E-04	7.04E-03	1.39E-04	7.04E-03	1.20E-04	7.05E-03
A1	1.16E-04	0.00E+00	1.25E-04	0.00E+00	1.08E-04	0.00E+00
A2	2.32E-06	0.00E+00	2.66E-06	0.00E+00	2.02E-06	0.00E+00
A3	2.32E-06	0.00E+00	2.66E-06	0.00E+00	2.02E-06	0.00E+00
B1	0.00E+00	7.04E-03	0.00E+00	7.04E-03	0.00E+00	7.05E-03
B2	8.24E-06	0.00E+00	8.60E-06	0.00E+00	7.96E-06	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E)	8.45E-03	8.00E-04	9.15E-03	1.41E-03	7.87E-03	2.60E-04
D	4.29E-03	4.00E-04	4.64E-03	7.07E-04	4.00E-03	1.30E-04
E1	3.75E-03	3.82E-04	4.05E-03	6.74E-04	3.49E-03	1.25E-04
E2	7.49E-05	9.00E-06	8.61E-05	1.67E-05	6.52E-05	2.25E-06
E3	7.49E-05	9.00E-06	8.61E-05	1.67E-05	6.52E-05	2.25E-06
E4	2.66E-04	0.00E+00	2.78E-04	0.00E+00	2.57E-04	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	2.33E-02	0.00E+00	2.33E-02	0.00E+00	2.33E-02	0.00E+00
C1	2.17E-02	0.00E+00	2.17E-02	0.00E+00	2.17E-02	0.00E+00
C2	1.58E-03	0.00E+00	1.58E-03	0.00E+00	1.58E-03	0.00E+00
Top level failure probabilities (likelihood of each of these types of failures occuring before 400 WP are successfully emplaced)						
Drop one or more WP from top	4.41E-05	4.07E-03	4.41E-05	4.06E-03	4.41E-05	4.07E-03
Drop one or more WP during trip in	2.16E-02	1.59E-03	2.16E-02	1.59E-03	2.17E-02	1.59E-03
Drop wireline or drill string on trip out	1.58E-03	1.39E-03	1.58E-03	1.38E-03	1.58E-03	1.39E-03
WP or WP string stuck	8.59E-03	8.00E-04	9.28E-03	1.41E-03	7.98E-03	2.60E-04

References for Appendix D

Gertman, D.I., H.S. Blackman, J.L. Marble, J.C. Byers and C.L. Smith 2005. *The SPAR-H Human Reliability Analysis Method*. NUREG/CR-6883. U.S. Nuclear Regulatory Commission. Idaho Falls, ID.