Advanced Fuel Cycle Cost Basis Report: L Modules Geologic Disposal

Nuclear Fuel Cycle and Supply Chain

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ACKNOWLEDGEMENT

This latest version of the Module L Geologic Disposal is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report (AFC-CBR). It is not possible to identify and acknowledge all those contributions to the AFC-CBR and this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.

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CONTENTS

FIGURES

TABLES

ACRONYMS

AFC	Advanced Fuel Cycle
bgs	below ground surface
CH	Contact handled
DOE	Department of Energy
EM	Environmental Management
EIS	Environmental Impact Statement
EPRI	Electric Power Research Institute
FCR&D	Fuel Cycle Research and Development
FP	fission products
GTCC LLRW	Greater Than Class Low-level Radioactive Waste
HLW	high-level waste
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
NTS	Nevada Test Site
MTHM	metric tons of heavy metal
MTiHM	metric tons of initial heavy metal
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
O&M	Operation and Maintenance
ORR	Oak Ridge Research Reactor, ORNL
RH	remote handled
SNF	spent nuclear fuel
SRS	Savannah River Site
TRU	transuranic
TSLCC	Total System Life Cycle Cost
WIPP	Waste Isolation Pilot Plant
WIT	What-It-Takes
YMP	Yucca Mountain Project

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Module L1

Geologic Disposal of SNF and HLW

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L1 REVISION LOG

<table>
<tr><th>Rev.</th><th>Date</th><th>Affected Pages</th><th>Revision Description</th></tr>
<tr><td></td><td>2004</td><td>L1-All</td><td>Version of AFC-CBR in which Module first appeared: 2004. Disposal of GTCC was added in 2012 and the Module was split into L1 (SNF and HLW) and L2 (GTCC including borehole disposition.)</td></tr>
<tr><td></td><td>2012</td><td>L1-All</td><td>Version of module in which new technical data was used to establish “what-it-takes” unit cost ranges: 2012
• 2012 data was escalated to 2017$ for this latest revision (9% increase in unit cost)</td></tr>
<tr><td></td><td></td><td>L1-All</td><td>New technical/cost data which has recently become available and will benefit next revision:
• After issuance of 2012 version of CBR another organization at DOE-NE prepared another Repository Fee Adequacy report which included all anticipated life cycle costs for the Yucca Mountain Project.
• The successor organization to the Yucca Mountain Project, the DOE-NE Used Fuel Campaign continues to produce reports on the costs and schedules for repository and temporary storage options for SNF (now called Used Nuclear Fuel or UNF). Some of these reports may be publically available. Reference (ORNL 2016) in Module I is one such study.
• DOE continues to update data on repositories which might be sited in geologies other than Yucca Mountain-type volcanic tuff.
• DOE has begun a borehole R&D program with possible disposal of some types of defense HLW as a goal. Some cost information is available. A separate repository for the bulk of the defense-related HLW is under consideration.
• Canada, Sweden, and Finland have made progress on their geologic disposal programs and may have new data.</td></tr>
<tr><td></td><td>2021</td><td>All</td><td>Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.</td></tr>
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Module L1
Geologic Disposal of SNF and HLW

L1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 Update:** FY21
- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only from last time values underwent technical assessment (2012 AFC-CBR)
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this FY21 update was escalated:** For SNF and HLW data was developed from Life Cycle Cost Assessments periodically prepared by the Yucca Mountain Project.

L1-1. BASIC INFORMATION

This module has been updated to reflect the most recent cost analysis available for seven repository concepts currently seen as viable disposal options[a]. The most recent cost analysis conducted for the Fuel Cycle Research and Development program (FCR&D) is the *Repository Reference Disposal Concepts and Thermal Analysis* (Hardin et al 2012). This is a comprehensive study that performed detailed analyses of the first five options below and then incorporated previously developed cost information for Hard Rock Unsaturated (Yucca Mountain Project) and Deep Borehole disposal options. Any costs included from previous studies have been escalated to reflect 2012 values.

1. **Crystalline (enclosed) -** Vertical borehole emplacement is used with a copper waste package (e.g., Swedish KBS-3 concept) with a clay buffer installed at emplacement. Access drifts are backfilled with low-permeability clay-based backfill at closure.
2. **Generic Salt Repository (enclosed)** – A repository in bedded salt in which carbon steel waste packages are placed on the floor in drifts or alcoves, and immediately covered (backfilled) with run-of-mine salt.
3. **Clay/Shale (enclosed)** – SNF or HLW is emplaced in blind, steel-lined horizontal borings constructed from access drifts. SNF is emplaced in carbon steel packages with a clay buffer. HLW glass is emplaced in stainless steel pour canisters, within a steel liner.
4. **Shale Unbackfilled (open)** – A repository in a thick shale formation constructed so that ventilation is maintained for at least 50 to 100 years after waste emplacement. Emplacement drifts are not backfilled at closure, but all other openings are backfilled to provide waste isolation.
5. **Sedimentary Backfilled (open) –** Constructed in sedimentary rock so that ventilation is maintained for at least 50 to 100 years after waste emplacement. All waste emplacement and other openings are backfilled with low-permeability clay-based backfill prior to repository closure.
6. **Hard Rock Unsaturated (open)** – Constructed in competent, indurated rock (e.g., igneous or metamorphic) using in-drift emplacement, and forced ventilation for at least 50 to 100 years after waste emplacement. The setting is unsaturated so emplacement drifts need not be backfilled at closure, but other engineered barriers may be installed.

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a. The reader is referred to the 2009 edition of the Advanced Fuel Cycle Cost Basis report for background and cost information for the Yucca Mountain Project.

7. **Deep Borehole (enclosed) –** Ongoing studies are assessing the feasibility of drilling large-diameter holes to 5 km in crystalline basement rock (Sandia National Laboratories, 2014). Waste packages would contain single fuel assemblies and be stacked in the lower 2 km of each hole. The upper section would be sealed.

This update incorporates cost estimates for the Deep Borehole concept previously described in Module M1. The remaining two disposal options previously discussed in Modules M2 and M3, Seabed Disposal and Extraterrestrial Disposal, have long since been abandoned as viable disposal options for SNF and HLW. Seabed disposal was prohibited under the United Nations Convention on Law of the Sea and the London Convention and Protocol (Rechard et al. 2011) A National Academy of Science (NAS 2001) study summarizes the extraterrestrial disposal option as not currently feasible because of the scientific, technical, and economic challenges. NAS further notes that “Disposal in space is not expected ever to be practicable, safe technology” (NAS 2001, p. 27). Therefore, Modules M2 and M3 have been removed in total from this revision of the cost estimate.

L1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

The life cycle costs for geologic disposal typically consist of three major types of activities: (1) the repository itself, (2) transportation, and (3) management and oversight. The function of Module L1 is to indicate the costs for geologic disposal of spent nuclear fuel (SNF) and high-level waste (HLW). Module L1 does not include waste conditioning and packaging or transportation; however, those costs are relevant to Module G (HLW Conditioning, Storage, and Packaging) and Module O (SNF/HLW Transportation). Transportation costs are specifically excluded as they are dependent on the specifics of the repository location, shipping routes, and SNF and HLW storage locations.

Repository costs can be divided into capital and operating categories. The repository may be constructed in a staged fashion, so that some construction continues after operations begin. Repository capital costs include development of the license application and licensing support network; engineering, procurement, and construction of the required surface facilities (e.g., canister receipt and closure, wet handling, initial handling, receipt facility) and subsurface facilities needed for initial operations (e.g., main access tunnels and emplacement drifts, if a traditional geologic repository); design and procurement of the waste container; physical security systems; and program management. Operating costs may be further divided into three time and activity-based phases of repository operation. These include emplacement during which the waste is received, packaged into the waste containers, and emplaced in the repository; monitoring, in which the repository and its contained waste packages are monitored to ensure adequate performance during the period of higher heat generation; and closure. The approximate time spans estimated for YMP were (1) Development and Construction (1983 to 2023); (2) Emplacement (2017 to 2047); (3) Monitoring (2048 to 2112); and (4) Closure (2113 to 2126). This encompasses a total time period of 144 years. Figure L1-1 is a simple diagram of the functional flow (Hardin et al. 2012) for Module L1.

The *Repository Reference Disposal Concepts and Thermal Analysis* report (Hardin et al 2012) arrived at similar total time periods, with timelines for the concepts ranging from 130 years up to 181 years. In all cases, the first phase to make the repositories operational spanned 24 years and included site selection, characterization, design, and construction. Similarly, the operational phase for all concepts assumed emplacement of 3,000MTHM per year over 47 years to fulfill the design capacity of 140,000MTHM. For the three “enclosed” concepts, the closure phase lasts 10 years followed by 50 years of site monitoring for a total of approximately 130 years. For the two “open” repository concepts, active ventilation and monitoring is estimated at 100 years. Ten years of closure activities then follows, for a total of 181 years.

L1-3. PICTURES AND DIAGRAMS

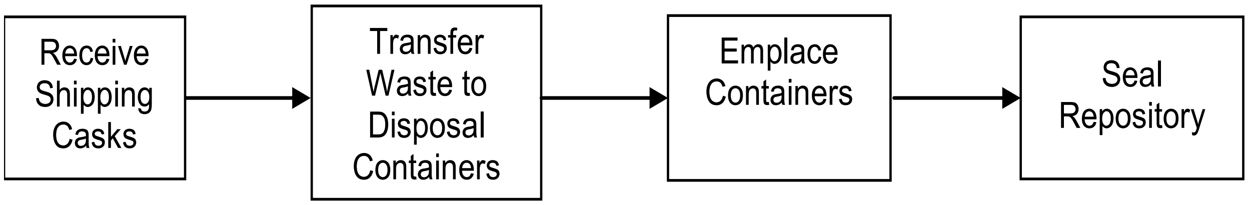

Figure L1-1. Functional block diagram for geologic repository waste disposal.

L1-4. MODULE INTERFACES

This module receives SNF and HLW from Module O (SNF/HLW Transportation) and retains the SNF/HLW in perpetuity. Some waste management schemes include using the geologic repository for interim storage of the SNF until the used fuel is removed for recycling. The additional costs (storage pads, waste handling, repackaging, etc.) to use the repository as an interim storage facility are not included in this module and would need to be separately estimated.

L1-5. SCALING CONSIDERATIONS

There have been several studies that have tried to define the basic scaling relationships between cost and the size of the repository. Costs have been estimated for repositories of two sizes at Yucca Mountain: 97,000 metric ton of heavy metal (MTHM) (DOE 2001; Gillespie 2001) and most recently 122,100 MTHM (DOE 2008). The primary driver for the 2007 Total System Life Cycle Cost (TSLCC) increase of 38% from the comparable May 2001 TSLCC estimate is the 26% increase in waste quantity. The cost increases were due to multiple factors including an extended waste transportation period and emplacement period, increase in required waste packages, and transportation shipments. Another important factor in the cost increase was the refinement and specificity of the system design. The cost increase for only the repository portion was 25% (excluding transportation and balance of program costs). This cost increase could imply a nearly direct relationship between costs and facility capacity of about 1:1 (25%/26%= ~1.0).

The Electric Power Research Institute (EPRI) performed a study in 2006 that considered possible expansion of Yucca Mountain (from 70,000 MTHM to 260,000 MTHM and 570,000 MTHM) and the estimated costs for the expanded capacities (EPRI 2006). One of the difficulties that EPRI had in this analysis was understanding how much of the YMP costs are fixed costs (not tied to repository capacity) and what percent were variable costs (that is, dependent upon the amount of waste capacity). EPRI was able through a 1998 Viability Assessment (Bodvarsson and Bandurranga, 1997) and additional DOE documentation, to estimate the percentage of fixed costs and variable costs in each cost category. The EPRI results concluded that the waste emplacement phase dominated the costs estimates and that those costs increase significantly as a function of repository capacity.

Total costs increased from $72B (2007 $) for a 70,000 MTHM repository (Case 3, $1029/kgHM) to $150B (2007 $) for a 260,000 MTHM repository (Case 4, $577/kgHM) and up to $338B for 570,000MTHM (Case 5, $593/kgHM). Figure L1-2 provides a comparison of the projected repository costs for three sizes of repositories. The costs rose by approximately 200% for an increase in capacity of almost 400%, or a relationship between costs and capacity size of about 1:2 (200%/400%= 0.5). Assuming a relationship: (Cost/Base Cost) = (Capacity/Base Capacity)^n, the EPRI 70 kT and 260kT data points give a value for the exponent n of 0.56. In the EPRI study, when the 260kT capacity is reached, the fixed costs have been amortized. With estimates of $577/kgHM and $593/kgHM for Cases 4 and 5, respectively, the EPRI report also shows a direct cost to capacity ratio of approximately 1:1 for large repositories. This supports their conclusion that the variable costs, such as mining and waste emplacement, become dominant as repository size continues to increase.

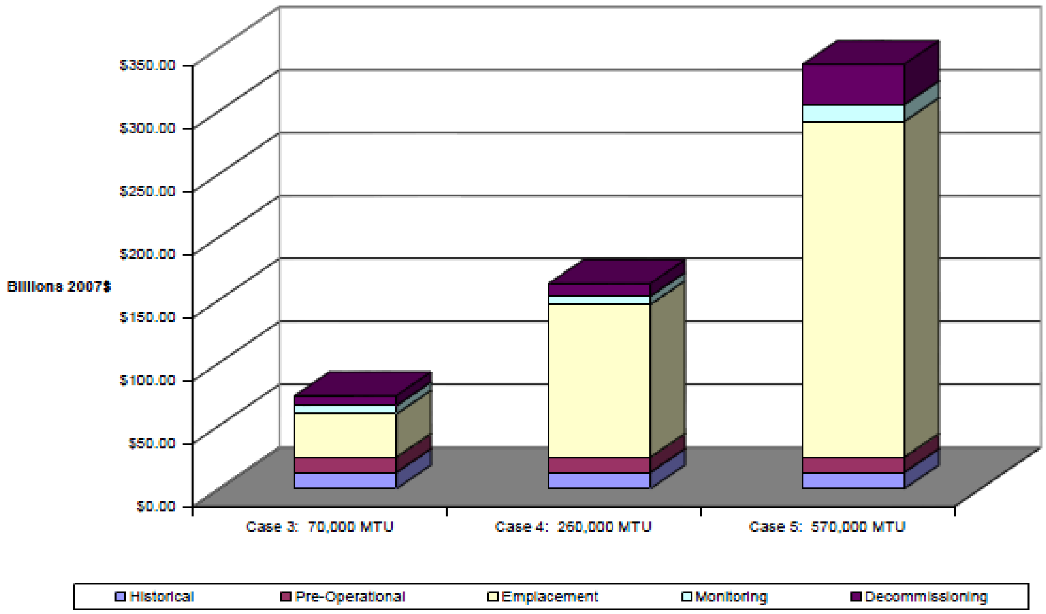

Figure L1-2. Comparison of projected repository costs for 70,000 MTHM, 260,000 MTHM, and 570,000 MTHM repositories (EPRI 2006).

The Nuclear Energy Agency (NEA) prepared an international review of cost estimates for disposing of SNF and HLW in deep geologic repositories in 1993 (NEA 1993). The NEA report evaluated the impact of the economy of scale on disposal costs. They concluded that though there is considerable variability in the estimated costs, and there is a general trend that disposing larger quantities of waste result in lower normalized disposal costs. They found that “a substantial investment will be relatively constant,” irrespective of how much waste will be disposed of. This investment is primarily related to constructing facilities that would need to be in place regardless of the size of the repository and includes access shafts/ramps, ventilation systems, lifting equipment, service supply, and communication equipment. The 1993 NEA report points out studies that show cost of increasing repository capacity is smaller than the cost of developing a second repository. This general finding would appear in agreement with the EPRI study as repositories with small or moderate capacities grow in size. The beneficial effects seem to diminish as repository capacity approaches and exceeds 100,000 MTHM.

If a country chose to use multiple, small scale disposal facilities rather than a centralized repository then the fixed costs for siting, site characterization, design, and construction of some facilities would have to be repeated at several sites. The advantage of a single repository concept where an existing facility would continue to be used (or expanded as necessary) to dispose of SNF/HLW is that the fixed costs would have already been incurred with only variable costs increasing with the size of the facility.

Based on the experience of the Yucca Mountain Project, it is evident that the fixed costs of site selection, site characterization, facility design and construction of the surface facilities is substantial. For small repositories, the burden is substantial on a per kilogram basis if the fixed costs are amortized over a small volume of waste. From the DOE 2008 and the EPRI 2006 studies discussed above, as the repository size approaches 100,000MTHM or greater, the variable operational costs of mining, packaging, and emplacement become dominant.

Some small economy of scale may still exist if the site was originally characterized to provide for future expansion, there is no major change to the waste stream (e.g., from SNF to cycled products in HLW) or packaging concepts (transportation and disposal canister repackaging), and the facility receiving throughput remains the same. Under these conditions, any improvements on a unit cost basis appear to be minimal so a scaling factor of approximately 0.8–1.0 would seem appropriate for large repository concepts.

With current US forecast needs for disposal of a minimum of 140,000 MTHM of SNF from the domestic fleet of reactors, a single repository would seem to be advantageous over building two or more smaller facilities. If the capacity is available for growth, incremental increases in the SNF forecast would best be accommodated in this one repository. If it becomes evident that the power industry will replace, and potentially grow, the existing reactor fleet with new nuclear generating capacity, a second large scale repository of greater than 100,000 MTHM could become viable without negatively impacting the normalized cost of SNF disposal.

L1-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The most recent cost estimates for large United States repositories are based on recent analyses in *Repository Reference Disposal Concepts and Thermal Analysis* (Hardin 2012). To be consistent with earlier analyses for based on previous Yucca Mountain Project and Deep Borehole, and more accurately estimate the TSLCC for disposal for all repository concepts, these cost estimates have been adjusted as follows for purposes of this report. Note that any cost estimates that are adjusted to 2012 $'s used the values in the Nuclear Projects column from the table in "Escalation Rate Assumptions for DOE Projects (November 27, 2009)" (http://www.cfo.doe.gov/cf70/escalation.pdf) (DOE 2009).

First the High Range values have been adjusted to include a more conservative use of stainless steel for the waste packages versus the carbon steel evaluated in (Hardin et al 2012 Carter 2012). Since the Crystalline (enclosed) already provided copper disposal overpacks in the original estimate, there is no increase in the High Range. These costs are noted in the "Adjusted Costs for SS Overpack" column in Table L1-1 below. Then to provide a consistent TSLCC bases across all seven domestic repository estimates, $10B for site selection and characterization as estimated for Deep Borehole (Brady 2009) plus $2.8B for "Benefits, Payments Equal to Taxes, Outreach and Institutional (i.e., Set-Asides)" have been added (DOE 2008) These additional costs add approximately $91/kgHM to the total disposal costs in each of the five 140,000 MTHM repositories. Table L1-1 compares these Total Adjusted Costs.

Table L1-1. Adjustments to Normalized Costs from *Repository Reference Disposal Concepts and Thermal Analysis* (Hardin et al 2012).

Repository Concept	Disposal Capacity (MTHM)	Cost Normalized to Mass ($/kg)	Adjusted Costs for SS Overpack Normalized to Mass ($/kgHM)	Total Adjusted Costs Normalized to Mass ($/kgHM)
Crystalline (enclosed)	140,000	439 to 579	439 to 579	530 to 670
Generic Salt Repository (SNF, enclosed)	140,000	174 to 232	174 to 281	265 to 373
Clay/Shale (enclosed)	140,000	428 to 571	428 to 710	520 to 801
Shale Unbackfilled (open)	140,000	182 to 242	182 to 277	273 to 368
Sedimentary Backfilled (open)	140,000	231 to 309	231 to 344	322 to 435

The latest TSLCC for the Yucca Mountain Project (Hard Rock Unsaturated) was estimated at $97.0B. This accommodated 109,300 MTHM of SNF and 12,800 MTHM of Defense HLW and included $20.3B in transportation costs. Twenty percent of the YMP cost is attributed to Defense Waste disposal (DOE 2008). Subtracting out the transportation costs and 20% of the project costs for Defense Wastes leaves $61.4B for the SNF disposal. This equates to a normalized cost for SNF of $561 per kgHM. Escalated to 2012 $s, the cost actually decreases to $554/kgHM because of a large drop in steel prices from reduced demand and high production rates in 2009 and 2010.

For the Deep Borehole disposal concept Brady et al. (2009) produced a rough estimate of $71B (2007 dollars) for disposal of 109,300 MT of commercial SNF. This estimate included $10B for transportation costs. Module O is defining the transportation costs; therefore this has been backed out of the total. In addition, the cost for drilling a single deep borehole was updated from $20M to $27M by Arnold et al. (2011). With these adjustments and escalating costs to 2012 $'s, the TSLCC value for Deep Borehole disposal remains at $71B and $650/kgHM.

The cost basis for geologic disposal was drawn from domestic studies and Table L1-2 summarizes the latest adjusted cost estimates. The table also includes cost data from international studies for purposes of comparison. The international estimates span the range of low and high estimates presented in this report, but closer comparison is unwarranted because the various estimates likely include different facilities and activities.

Table L1-2 Unit SNF Disposal Cost Comparison (2012 $s).

Estimate	Disposal Capacity (MTHM)	Cost Normalized to Mass ($/kg)	References[1]
United States			
Crystalline (enclosed)	140,000	530 to 670	Hardin 2012
Generic Salt Repository (SNF, enclosed)	140,000	265 to 373	
Clay/Shale (enclosed)	140,000	520 to 801	
Shale Unbackfilled (open)	140,000	273 to 368	
Sedimentary Backfilled (open)	140,000	322 to 435	
Hard Rock Unsaturated (open)	109,300	554	DOE 2008
Deep Borehole	109,300	650	Hardin 2012
NEA	109,300	356 to 710	NEA 2003[2]
Canada	96,000	147	IAEA 2002[2]
Belgium (2000 estimate)	4,900	368	ONDRAF/NIRAS 2000[2]
Czech Republic	3,724	457	IAEA 2002[2]
Finland (2007 estimate)	5,500	714	www.posiva.fi[2]
Hungary	1,320	1036	IAEA 2002[2]
Sweden	12,000	521	SKB 2003[2]

1. Updated international repository values provided by Mark Nutt, ANL in 2012 $s. (Nutt 2009)

2. Basis of estimates may include repository site selection or characterization, at-reactor packaging, centralized storage, re-packaging to meet disposal requirements, and waste transport to the repository, and may therefore be only roughly comparable to values developed in this study.

L1-7. DATA LIMITATIONS

The Nuclear Waste Policy Act (DOE 2004) places a limit of 70,000 MTHM on the first geologic repository, so scenarios considering higher capacities are contingent on legislation to modify this restriction. The Secretary of Energy has recommended removal of the 70,000 metric ton limitation (DOE 2009). Note also that lawsuits and delays have already caused substantial expenditures for YMP and could well incur additional costs in the future. Such costs are included in the existing contingency estimates to some extent, but possibly could be even higher.

The technology readiness could probably be considered pilot-feasible. While no HLW repository has yet been built, portions of the Yucca Mountain repository have been constructed as part of the testing activities, and the WIPP is an operating geologic repository for transuranic waste. The data quality is categorized as a scoping assessment with a common basis/approach.

L1-8. COST SUMMARIES

With the high degree of uncertainty of repository plans, concepts, locations and their associated costs, the authors recommend that a broad uncertainty range of costs be used for any fuel cycle economic analysis. Cost summaries are provided for SNF disposal (Table L1-3) and HLW disposal of recycled SNF (Table L1-4).

The module cost information is summarized in the Advanced Fuel Cycle (AFC) What-It-Takes (WIT) Tables L1-3 and L1-4. The summaries shows the normalized reference costs (constant year dollars), reference contingency factors (if known), and the cost analyst's judgment of the potential upsides (reductions to the costs from the reference case), downsides (additions to cost from the reference base), and selected values (i.e., expected costs based on the reference cost, contingency, upsides, and downsides). These values are preliminary and will be updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to report Section 2.6 for additional details on the cost estimation approach used to construct the WIT table. Note that contingency estimates to measure uncertainty are not available. The "project" contingencies have been included in the estimates for the individual line items.

The triangular distribution for the SNF disposal costs from the WIT Table L1-3 is shown in Figure L1-3. The distribution is skewed toward the high costs due to the current uncertainties in geologic disposal and waste management policies.

Per unit of energy produced, the cost for disposal of recycled SNF is expected to be less than from unprocessed SNF. By reprocessing the SNF, many of the heat-producing radionuclides can be removed, allowing for more efficient disposal. A study by Wigeland & Bauer (Wigeland et al. 2007) determined that uranium, plutonium, americium, and neptunium, along with fission products cesium and strontium were responsible for limiting loading in a repository based on volumetric and thermal constraints.

Table L1-3. Cost summary 'What-It-Takes' (WIT) table for Domestic SNF disposal (Module L1) in a geologic repository.

2012 $				
Reference Cost and Related Capacity	Low Cost $/kgHM (SNF)	Mode Cost $/kgHM (SNF)	Mean Cost $/kgHM (SNF)	High Cost $/kgHM (SNF)
TSLCC $96.18B (122,100 MTHM) (DOE 2008)	$265	$550		$801
2017 $				
	$289	$600	$587	$873
	Use of bedded salt utilizes experience/cost data from WIPP.	Based on average of High Range of most recent US cost estimates for large domestic facilities with good economies of scale.		Most expensive design due to long-term active ventilation and enclosed design.
2020 Escalation from 2012 to 20200 1.134	$300	$623	$611	$908

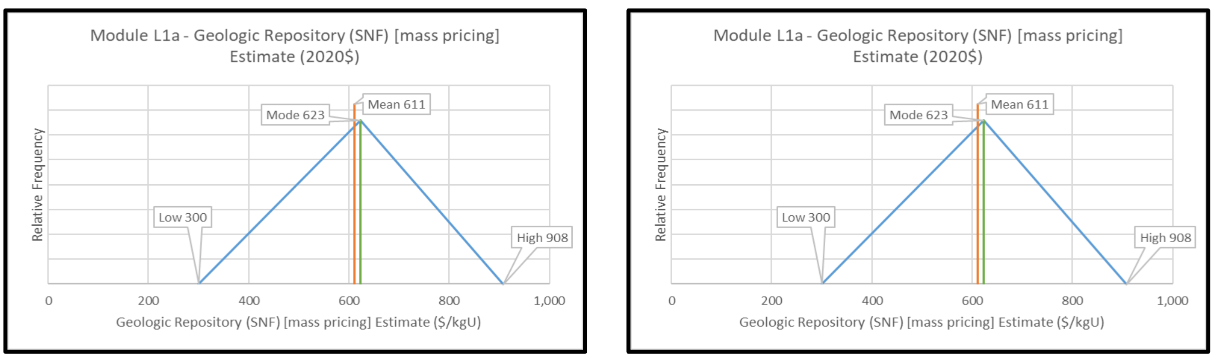

Figure L1-3. Geologic repository for SNF estimated cost frequency distribution.

However, when transuranic elements are recycled and short-lived fission products (Cs, Sr) are placed in separate decay storage, then there could be an increased utilization of space as indicated by the allowable linear loading in repository drifts (tunnels). The results further showed that limited recycling in thermal reactors would provide only a fraction of the benefit that could be achieved with repeated processing and recycling, as is possible in fast neutron reactors.

Ultimately, the disposal efficiency will depend on the partitioning efficiency in the separations process and on the "loading" of HLW in the vitrified end product. A simple rule of thumb applicable to all nuclear reactors consuming uranium or plutonium is that energy production of 1 GWd_t consumes 1 kg of fuel and therefore produces 1 kg of fission products. A 1 GWe plant operating with a capacity factor of 0.9 and a thermal efficiency of 33% therefore discharges 20 MT/year of SNF but produces approximately 1 MT of fission products per year. This corresponds to a fuel discharge exposure of approximately 50 GWD/MT. If the fission product waste loading in the vitrified glass is 12%, then the vitrified HLW equivalent to the SNF output will be 8 MT/yr (a waste mass reduction of 60%). If the fission product loading and partitioning efficiency are such that 1 MT of vitrified HLW (with a higher fission product loading) can be emplaced in the same space as 1 MT of SNF, then the cost to emplace 1 MT of vitrified HLW will be the same as the cost to emplace 1 MT of SNF. In terms of the amount of original SNF represented by the fission product content of the HLW, this will increase the disposal efficiency to 250% of that for SNF.

Note that this result applies to light-water reactor fuel with performance characteristics that are a small "stretch" compared to those attainable today. If, for example, the discharge exposure were increased to 100 GWD/MTHM, twice as much vitrified HLW would be generated from each tonne of SNF. Since only half as much of that SNF would be discharged annually, the annual production of HLW would remain the same as would the annual cost. If 1 MTHM of such SNF could be emplaced in the same space as 1 MTiHM of SNF discharged at 50 GWD/MTHM, the disposal costs for SNF would be halved. Consequently, the disposal cost for HLW, in terms of its equivalent SNF, would be doubled. In the case of fast reactor SNF, with discharge exposures possibly exceeding 200 GWD/MTiHM, the disposal efficiency for such material, either as SNF or HLW, is more uncertain and requires further evaluation.

The costs for disposal of recycled SNF are derived using the nominal cost of SNF disposition at $550/kg HM (or $13,750/kg fission products (FP) based on an average FP composition of 4% of initial heavy metal). The waste loading of the HLW is estimated to be improved by a factor of 2x to 10x, with a nominal loading of 2.5x. Therefore, the related HLW disposition costs are estimated to range from $1,377/kg FP to $6,880/kg FP, with a nominal cost of $5,500/kg FP. Since these costs are tied to the defined nominal cost of SNF, the costs should be re-calculated if the conditions defined for the upsides or downsides better represent the geologic repository estimating assumptions.

Table L1-4. Cost summary table for HLW disposal in a geologic repository.

What-It-Takes Table (2012 $)				
Reference Cost and Related Capacity	Upsides (Low Unit Cost)	Downsides (High Unit Cost)	Mean Value	Selected Values (Mode Cost)
$550/kgHM (SNF) Average High Range TSLCC from Table L1-3.	$1,377/kg FP (HLW) Nominal SNF cost with a FP waste loading of 10x.	$6,880/kg FP (HLW) Nominal SNF cost with a FP waste loading of 2x.	$4586/kg FP (HLW)	$5,500/kg FP (HLW) Nominal SNF cost with a FP waste loading of 2.5x.
Escalated to 2017$>> 9% from 2012	$1500/kg FP (HLW)	$7500/kg FP (HLW)		$6000/kg FP (HLW)
Escalated to 2020 from 2012 at 1.134	$1561	$7799	$5198	$6235

The triangular distribution for the HLW disposal costs from the WIT Table L1-4 is shown in Figure L1-4. The distribution is skewed toward the high costs due to the greater probability of achieving a waste form loading (glass, ceramic, etc.) in the 2x–4x range.

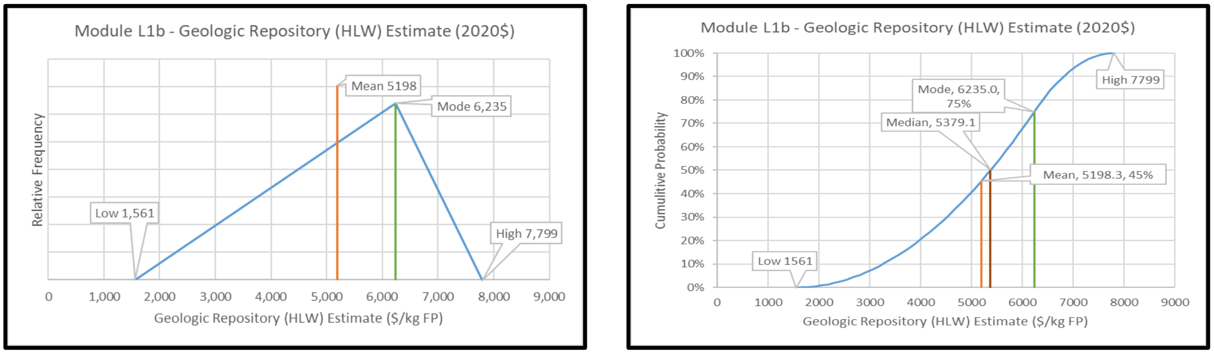

Figure L1-4. Geologic repository for HLW estimated cost frequency distribution.

L1-9. SENSITIVITY AND UNCERTAINTY ANALYSES

No sensitivity analyses were conducted in the preparation of this information. The reader is referred to the references for examples of sensitivity and uncertainty analyses for the SNF/HLW disposal function.

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Module L2

Disposal of GTCC Waste

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L2 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2012	L2-All	**Version of AFC-CBR in which Module first appeared: 2012.** Disposal of GTCC was added in 2012 and the Module was split into L1 (SNF and HLW) and L2 (GTCC including borehole disposition.). No unit cost data appeared in the 2012 version. Unit costs were calculated in 2015 update.
	2015	L2-All	**Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges:** 2015 2015 unit cost data was escalated to 2017$ for this latest revision (3% increase in unit cost)
		L2-All	**New technical/cost data which has recently become available and will benefit next revision:** DOE may have new information on the costs of borehole disposition. It is being considered for small amounts of some highly radioactive wastes from site D&D projects.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module L2

Disposal of GTCC Waste

L2-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only from last time values underwent technical assessment (2015 AFC-CBR)
- **Estimating Methodology for latest (2015 AFC-CBR) technical update from which this 2017 update was escalated:** Data was developed from estimates prepared by DOE's Office of Environmental Management for waste disposal projects at various Government sites.

L2-1. BASIC INFORMATION

This Section of Module L discusses Greater Than Class Low-level Radioactive Waste (GTCC LLRW) and GTCC-Like Waste. GTCC LLRW refers to LLRW that has radionuclide concentrations that exceed the limits for Class C LLRW given in 10 CFR 61.55. This waste is generated by activities licensed by the Nuclear Regulatory Commission (NRC) and Agreement State licensees, and it cannot be disposed of in currently licensed commercial LLRW disposal facilities.

GTCC-like waste refers to radioactive waste that is owned and generated by DOE and has characteristics sufficiently similar to GTCC LLRW such that a common disposal approach may be appropriate. GTCC-like waste consists of high activity LLRW and potential non-defense-related TRU waste that has no identified path for disposal. The use of the term "GTCC-like" does not have the effect of creating a new DOE classification of radioactive waste. The DOE is responsible for developing a disposal capability for GTCC LLRW. DOE recently drafted an Environmental Impact Statement (EIS) which describes the planning basis for GTCC waste disposal (DOE 2011).

For the purposes of analysis in the DOE EIS, GTCC LLRW and GTCC-like waste are categorized as being one of three waste types: activated metal, sealed sources, or Other Waste. The waste inventory being addressed in the EIS includes both stored inventory (wastes that were already generated and are in storage) and projected inventory (wastes that are expected to be generated in the future). The stored inventory includes waste in storage at sites licensed by the NRC (GTCC LLRW) or by Agreement States and at certain DOE sites (GTCC-like waste) and consists of all three waste types (activated metal, sealed sources, and Other Waste).

The three waste types fall into two groups on the basis of uncertainties associated with their generation for analysis in the DOE EIS. Group 1 consists of wastes from current operating facilities that are either already in storage or are expected to be generated from these facilities (such as commercial nuclear power plants). All stored GTCC LLRW and GTCC-like wastes are included in Group 1.

Group 2 consists of projected wastes from proposed actions or planned facilities not yet in operation. These actions include those proposed by DOE and those to be conducted by commercial entities (including electric utilities) for an assumed number of new (i.e., still to be licensed or constructed) nuclear power plants. Some or all of the Group 2 waste may never be generated, depending on the outcome of the proposed actions that are independent of the DOE EIS. No stored GTCC LLRW and GTCC-like wastes are included in Group 2. The inventory considered in the DOE EIS does not include future waste from commercial spent nuclear fuel reprocessing activities; however, the unit cost disposal costs are considered to be valid for this waste source.

This module is dedicated to those wastes that contain sufficient long or short-lived radionuclides to be classified GTCC and are:

> "Waste that is not generally acceptable for near-surface disposal is waste for which form and disposal methods must be different, and in general more stringent, than those specified for Class C waste. In the absence of specific requirements in this part, such waste must be disposed of in a geologic repository as defined in part 60 or 63 of this chapter unless proposals for disposal of such waste in a disposal site licensed pursuant to this part are approved by the Commission." (40 CFR 61)

L2-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

GTCC wastes may require specialized containment/shielding/waste forms/storage canisters/storage that may be a hybrid of low-level, transuranic, and High Level Waste (HLW), depending on the alpha or beta/gamma radiation prevalence. In general, the beta/gamma radiation from these wastes will require some shielding or special handling that may not be necessary for Class A/B/C wastes. Also, depending on the nature of the waste matrix and the treatment technology, wastes that are not transuranic (TRU) (>100 nCi/g), but that contain appreciable TRU contamination, may also require alpha containment similar to TRU wastes. Refer to LLW and TRU waste modules in the 2009 AFC-CBR (Modules J and B-5) for more detail.

DOE-EM (Environmental Management) developed the four action alternatives after careful consideration of the waste inventory, disposal technologies, and comments received during the public scoping period for the EIS. The WIPP repository is evaluated to determine the feasibility of the disposal of GTCC waste at a geologic repository, which is a disposal method acceptable to the NRC for GTCC LLRW given in 10 CFR Part 61. The proposed land disposal methods (i.e., borehole, trench, and vault) are being evaluated because NRC regulations allow other methods of disposal to be proposed for NRC approval and state that there might be some instances when GTCC LLRW would be acceptable for near-surface disposal with special processing or design. The alternatives are discussed as follows.

- Alternative 1: No Action
- Alternative 2: Disposal at the WIPP geologic repository,
- Alternative 3: Disposal in a new borehole disposal facility,
- Alternative 4: Disposal in a new trench disposal facility, and
- Alternative 5: Disposal in a new vault disposal facility.

Alternative 1: No Action

Under the No Action Alternative, current practices for storing GTCC LLRW and GTCC like waste would continue. The GTCC LLRW generated by the operation of commercial nuclear reactors (mainly activated metal waste) would continue to be stored at the various nuclear reactor sites that generated this waste or at other reactors owned by the same utility. Sealed sources would continue to be stored at interim storage and generator sites. Other Waste would also remain stored and managed at the generator or interim storage sites. In a similar manner, all stored and projected GTCC-like waste would remain at current DOE storage and generator locations. Under this alternative, DOE would take no further action to develop disposal capability for these wastes, and current practices for managing these wastes would continue into the future. National security concerns over the lack of a disposal capability for GTCC sealed sources wound not be addressed.

Alternative 2: Disposal at WIPP

This alternative involves the disposal of GTCC LLRW and GTCC-like waste at WIPP. The current operation at WIPP involves disposal of TRU waste generated by atomic energy defense activities by emplacement in underground disposal rooms that are mined as part of a panel and an access drift. Each mined panel consists of seven rooms. Contact handled (CH) TRU waste containers are emplaced on disposal room floors, and remote handled (RH) TRU waste containers are currently emplaced in horizontal boreholes in disposal room wall spaces. However, DOE has submitted a planned change request to use shielded containers for safe emplacement of selected RH TRU waste streams on the floor of the repository. The use of the shielded containers will enable DOE to significantly increase the efficiency of transportation and disposal operations for RH TRU waste at the WIPP. Consistent with this planned change request, the DOE EIS assumes all activated metal waste and Other Waste-RH would be packaged in shielded containers that would be emplaced on the floor of the mined panel rooms in a manner similar to that used for the emplacement of CH waste.

The analysis discussed in the DOE EIS assumes that current disposal procedures and practices at WIPP would continue, except for the emplacement of activated metal and Other Waste-RH on room floors (not in wall spaces as is the current procedure). It is also assumed that all above ground support facilities would be available for the disposal of GTCC LLRW and GTCC like waste and that construction of additional above ground facilities would not be required.

Alternative 3: Disposal in a New Intermediate-Depth Borehole Disposal Facility

Alternative 3 involves the construction, operations, and post-closure of a new borehole facility for the GTCC LLRW and GTCC-like waste inventory. Reference locations at the following five sites are evaluated for this alternative: the Hanford Site, INL, LANL, NTS, and the WIPP Vicinity. Because of the shallow depth to groundwater at ORR and SRS, this alternative is not evaluated for these two sites. Of the four NRC regions considered for the generic commercial facility, only NRC Region IV (generally, the western U.S. and plains states, excluding ID, MT, WY, and SD) was analyzed in the EIS as the depth to groundwater at the other three regions is considered too shallow for application of this method. A cross section of a conceptual borehole design is shown in Figure L2-1. For purposes of the Draft EIS analysis, a borehole with a depth of 40 m (130 ft) was evaluated.

To dispose of the entire inventory of GTCC LLRW and GTCC-like waste, the conceptual design indicates that about 44 ha (110 ac) of land would be required for the 930 boreholes needed to accommodate the waste packages of GTCC LLRW and GTCC-like waste. This acreage would include land required for supporting infrastructure, such as facilities or buildings for receiving and handling waste packages or containers, and space for a storm water retention pond. Less acreage and fewer boreholes would be required if a decision were made to only dispose of certain GTCC waste types in a borehole facility. The borehole method entails emplacement of waste in boreholes at depths below 30 m (100 ft) but above 300 m (1,000 ft) below ground surface (bgs). Boreholes can vary widely in diameter (from 0.3 to 3.7 m [1 to 12 ft]), and the proximity of one borehole to another can vary depending on the design of the facility. After placement of the wastes in the borehole, a reinforced concrete barrier would be added above the disposal containers to deter inadvertent drilling into the isolated waste during the post-closure period, and backfill would be added to the surface level.

Alternative 4: Disposal in a New Enhanced Near-Surface Trench Disposal Facility

Alternative 4 involves the construction, operations, and post-closure performance of a new trench disposal facility. This alternative is evaluated for the Hanford Site, INL, LANL, NTS, SRS, and the WIPP

Vicinity. The conceptual design of the trench is shown in Figure L2-2. With regard to ORR, Alternative 4, like Alternative 3, is not evaluated because of the shallow depth to groundwater at that site. Alternative 4 is evaluated for the generic commercial location in NRC Regions II and IV in order to allow for a comparison with the federal sites in these two regions. A commercial trench facility could also be considered in Regions I and III.

To dispose of the entire inventory of GTCC LLRW and GTCC-like waste, the conceptual design for the trench method includes 29 trenches occupying a footprint of about 20 ha (50 ac). This acreage includes land required for supporting infrastructure, such as facilities or buildings for receiving and handling waste packages or containers, and space for a storm water retention pond. Each trench would be approximately 3 m (10 ft) wide, 11 m (36 ft) deep, and 100 m (330 ft) long. After wastes were placed in the trench, a concrete layer would be placed on top, and backfill would be added to the surface level. The additional concrete layer would provide additional shielding during the operational period, and at some sites where the material through which drilling would be done is typically soft (e.g., sand or clay), the layer could deter inadvertent drilling into the buried waste during the post-closure period. Measures would be included in the designs of the facilities to reduce the likelihood for future inadvertent human intrusion. In addition to the concrete cover noted above, the conceptual design for the trench is deeper and narrower than conventional near surface LLRW disposal facilities to minimize this potential intrusion during the post-closure period. Additional intruder barriers would also be adopted for those sites in hard rock settings. Protecting against an inadvertent human intruder will be a key feature of the final facility design.

Alternative 5: Disposal in a New Above-Grade Vault Disposal Facility

Alternative 5 involves the construction, operations, and post-closure performance of a new vault disposal facility at the Hanford Site, INL, LANL, NTS, ORR, SRS, and the WIPP Vicinity. The conceptual design of the vault is shown Figure L2-3. Alternative 5 is evaluated for the generic commercial location in all four NRC regions. The conceptual design for the vault disposal employs a reinforced concrete vault constructed near grade level, with the footings and floors of the vault situated in a slight excavation just below grade.

The vault disposal facility to emplace the entire GTCC waste inventory would consist of 12 vaults (each with 11 vault cells) and occupy a footprint of about 24 ha (60 ac). Each vault would be about 11 m (36 ft) wide, 94 m (310 ft) long, and 7.9 m (26 ft) tall, with 12 vaults situated in a linear array. The interior cell would be 8.2 m (27 ft) wide, 7.5 m (25 ft) long, and 5.5 m (18 ft) high, with an internal volume of 340 m3 (12,000 ft3) per cell. Double interior walls with an expansion joint would be included after every second cell. The thick concrete walls and earthen cover would minimize inadvertent intrusion into the vault.

L2-3. PICTURES AND DIAGRAMS

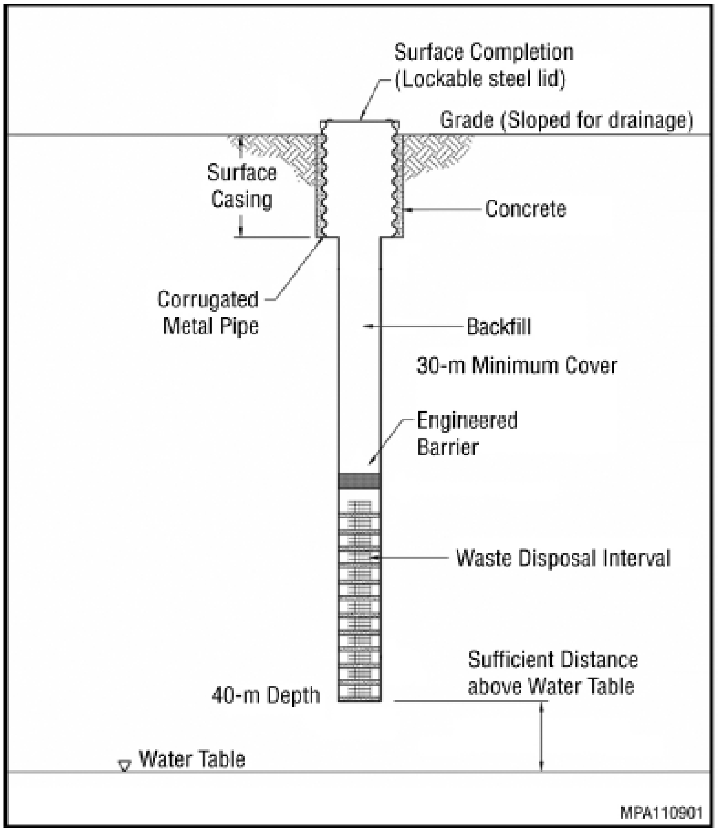

Figure L2-1. Cross Section of the Conceptual Design for an Intermediate-Depth Borehole.

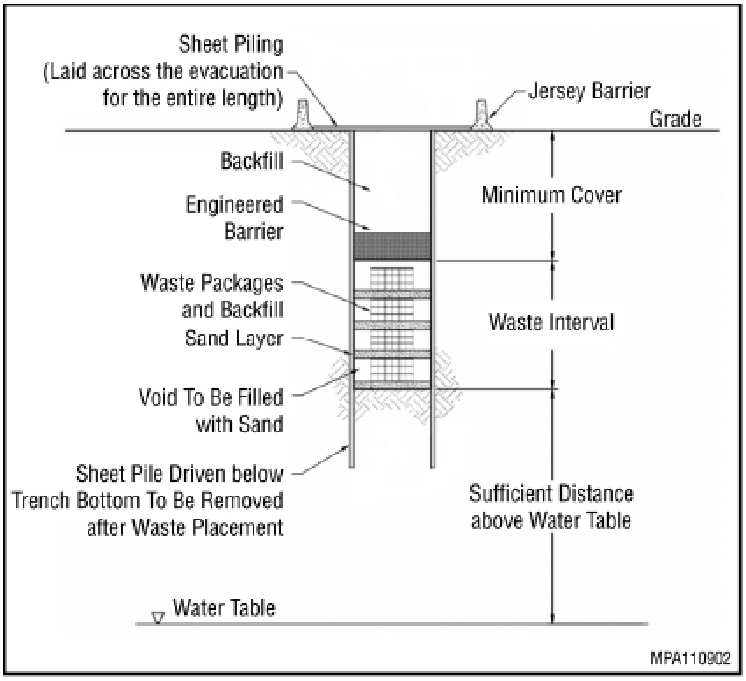

Figure L2-2. Cross Section of the Conceptual Design for a Trench.

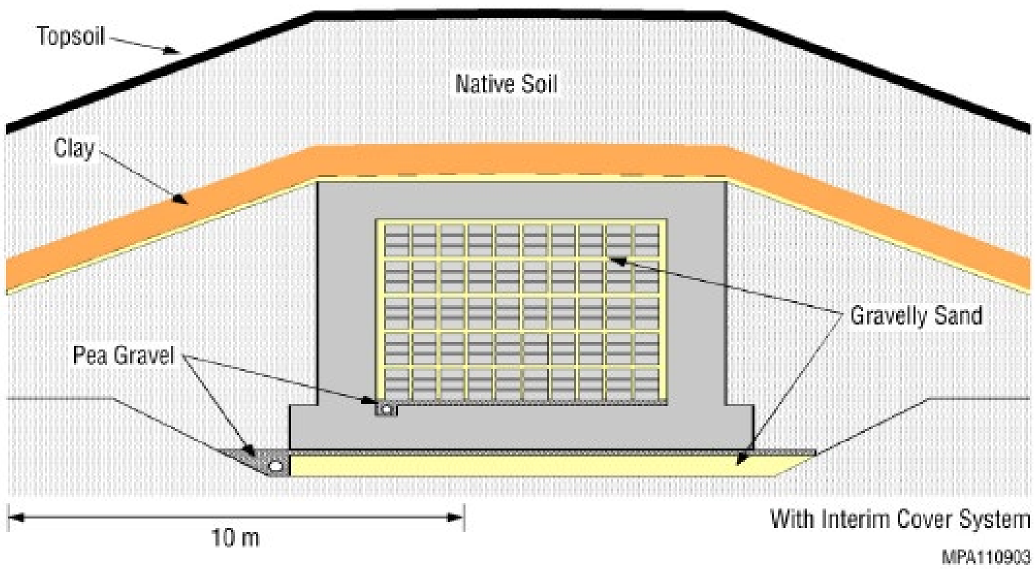

Figure L2-3. Schematic Cross Section of the Conceptual Design for a Vault Cell.

L2-4. MODULE INTERFACES

This module receives GTCC from Module G (Waste Conditioning, Storage, & Packaging) and retains the GTCC in perpetuity.

L2-5. SCALING CONSIDERATIONS

Any non-pilot GTCC disposal facility is assumed to be developed for large-scale operations. The cost estimates in this module are based on this assumption.

L2-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The Draft *Greater than Class C Environmental Impact Statement* (DOE 2011) considered the disposal of approximately 120,000 cubic meters of GTCC waste in three different enhanced confinement type near surface concepts (borehole, trench, and vault) and for the deep geologic disposal in the Waste Isolation Pilot Plant (WIPP). The estimated total cost for each disposal concept and the normalized cost (120,000 m3 of GTCC) are shown in Table L2-1 in year 2011$. The costs of disposal in the WIPP reflect mostly O&M costs that would be incurred by placing GTCC into an already-operating deep geologic facility. The unit costs of disposal in the borehole, trench, and vault concepts reflect the construction and operation of new facilities.

Table L2-1. Estimated total cost for each disposal concept and normalized cost.

GTCC Disposal Alternative	Construction Cost ($M)	Operations Cost ($M)	Total Cost ($M)	Normalized Cost (2011 $/m^3)	2017$ Normalized Cost ($/m3)	2020$ Escalated from 2011 to 2020 at 1.155
WIPP	14	560	574	4783	5320	5526
Borehole	210	120	330	2750	3060	3176
Trench	88	160	248	2067	2300	2388
Vault	360	160	520	4333	4820	5005

A uniform distribution Figure L2-4 which spans the above normalized and escalated unit cost is assumed to cover the uncertainty for this waste type.

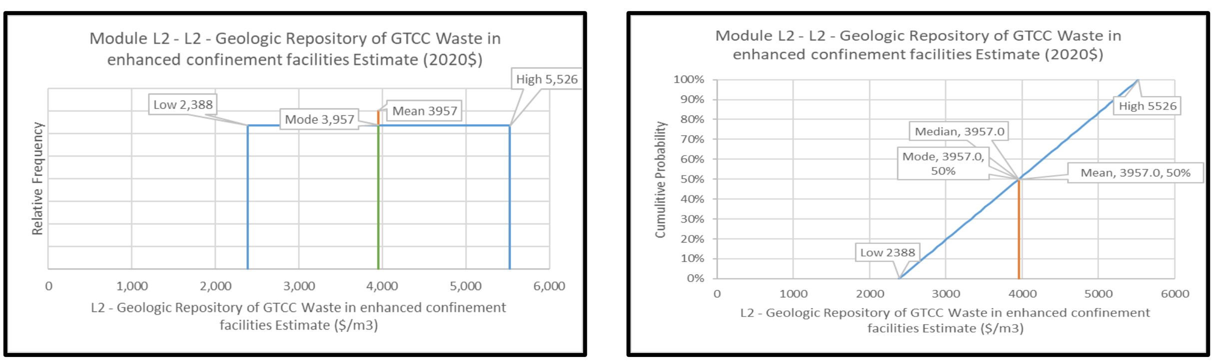

Figure L2-4. Frequency distribution for unit cost of GTCC waste disposal.

L2-7. DATA LIMITATIONS

No GTCC disposal facility has operated in the U.S., so estimated costs are based on designs and not actual experience.

L2-8. COST SUMMARIES

The nominal cost of disposing GTCC in new enhanced confinement facilities will be $3,295/m^3 (average of borehole, trench, and vault cost estimates). If it is preferable to dispose of GTCC in an existing deep geologic repository co-located with SNF or HLW, use the normalized value for WIPP of \$5,165/m^3 (DOE 2011).

L2-9. SENSITIVITY AND UNCERTAINTY ANALYSES

No sensitivity analyses were conducted in the development of this information.

L2-10. REFERENCES

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