Appendix E
FCT Document Cover Sheet

Name/Title of Deliverable/Milestone	Repository Reference Disposal Concepts and Thermal Analysis (FCRD-UFD-2012-00219 Rev. 2)
Work Package Title and Number	FT-13SN080403 Disposal Research – Design Concepts & Thermal Load Management
Work Package WBS Number	1.2.08.04
Milestone Number	M2FT-13SN0804031

Responsible Work Package Manager
Ernest Hardin *EHardin* 15Nov2012
(Name/Signature) (Date Submitted)

Quality Rigor Level for Deliverable/Milestone	☐ QRL-3	☒ QRL-2	☐ QRL-1 ☐ Nuclear Data	☐ N/A*

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)
Review Documentation Provided
☐ Signed TR Report, or
TR Report No.:
☐ Signed TR Concurrence Sheet (attached), or
☐ Signature of TR Reviewer(s) below

Peer Review (PR)
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☐ Signed PR Concurrence Sheet (attached), or
☒ Signature of PR Reviewers below

Name and Signature of Reviewers

(Name/Signature)	(Date)
Michael Voegele *M N Voegele*	*11-9-2012*
William Halsey *William G. Halsey*	*Nov. 6, 2012*

*Note: 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 do
cumentation, 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. QRL for such milestones may also be marked N/A in the work package provided the work package clearly specifies the requirement to use the Document Cover Sheet and provide supporting documentation.

Repository Reference Disposal Concepts and Thermal Load Management Analysis

Fuel Cycle Research & Development

Prepared for:
U.S. Department of Energy
Office of Used Fuel Disposition

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November 2012
FCRD-UFD-2012-000219 Rev. 2

Revision History

Rev. 0, August 2012	Original submittal for milestone M3FT-12SN0804032 (Sandia programmatic and classification review)
Rev. 1, September 2012	Corrected transposition errors in costing tables; recalculated stainless steel overpacks to be carbon steel; corrected various editorial problems. (SAND2012-7979P)
Rev. 2, November 2012	Performed peer review and retitled. Submittal for milestone M2FT-13SN0804031 (formerly milestone M2FT-12SN0804031) (SAND2012-9737P)

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Repository Reference Disposal Concepts and Thermal Load Management Analysis

FCRD-UFD-2012-00219 Rev. 2
Work Package: FT-13SN080403
November, 2012

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Executive Summary

This report is part of a 2-year work package to identify reference geologic disposal concepts for generic studies in the Used Fuel Disposition R&D Campaign. An initial report (Hardin et al. 2011) described reference "enclosed" emplacement modes which were adopted from international experience and past work in the U.S. This report summarizes the work on both enclosed and open modes, which has been expanded to include thermal analysis of open modes, a range of spent nuclear fuel (SNF) burnup, additional disposal system description, and cost estimation.

Thermal management for geologic disposal is used to limit various temperatures inside and outside the waste package. The chief constraint is controlling degradation of clay-based buffer or backfill materials in close proximity to the waste package. Further away, or for concepts that do not have buffer or backfill, the next constraint is limiting thermal damage to the host rock caused by processes such as desiccation and thermal expansion of solids or pore fluids. Waste package and waste form materials can resist temperatures at least 100 C° hotter than can the materials surrounding waste packages, but their performance at such temperatures (e.g., 200 to 300°C) depends on other, concept-specific aspects of the disposal environment such as exposure to moisture or air. Other thermal management constraints were identified but not evaluated by this study, including large-scale effects from thermal expansion, and brine migration in salt. Measures available to limit these effects include selecting host rock with superior heat dissipation properties, decay storage or preclosure repository ventilation, smaller waste packages, larger waste package and drift spacings, waste segregation in different parts of a repository, and reliance on far-field barriers that are not thermally degraded. Deep borehole

disposal has been evaluated in parallel studies, and all thermal limits considered in this study would be met because of small package size, large spacings, and reliance on far-field barriers.

This study identified two major categories for waste package emplacement modes: “open” where extended ventilation can remove heat for many years following waste emplacement underground; and “enclosed” modes for clay/shale and salt media. For the enclosed modes, waste packages are emplaced in direct or close contact with natural or engineered materials which may have temperature limits that constrain thermal loading. All disposal concepts developed internationally and in this report fit into one of these two categories. Enclosed modes include backfilled alcoves, vertical and horizontal borehole emplacement in borings constructed from underground, and deep boreholes drilled from the surface. In-drift emplacement can be open or enclosed depending on whether buffer and/or backfill is installed around waste packages at emplacement. Emplacement drifts may be kept open for ventilation, then backfilled or isolated by seals prior to closure.

Reference Disposal Concepts

A disposal concept consists of three parts: waste inventory, geologic setting, and the engineering concept of operations. For inventory, a total of seven waste types (four spent fuel and three HLW types) were selected for this study based on assessment of wastes that could originate from three scenarios: 1) direct disposal of light-water reactor (LWR) fuel with average or high burnup, 2) reprocessing of LWR fuel to produce Pu-metal oxide (MOX) fuel for once-through use and direct disposal, and 3) reprocessing of LWR fuel to feed continuous actinide recycling in sodium-cooled, metal-fueled fast reactors with electrochemical reprocessing. These are examples of nuclear fuel cycles that are related to the current inventory of LWR SNF, and thus could be used as transitional strategies. Irradiated Pu-MOX fuel is a relatively hot waste type that could result from current or transitional activities in the nuclear power industry, or from Pu disposition activities, but may never be generated in large quantities (i.e., more than a few hundred metric tons). In addition, Pu-MOX is a useful representative for a range of higher heat-load waste streams from fuel cycles that are not yet well understood, and some of those waste streams could be hotter than Pu-MOX as used here.

Geologic settings selected for use in reference disposal concepts are: crystalline rock (including granite), clay/shale, bedded salt, massive soft shale, other sedimentary rock (e.g., alluvium) with favorable characteristics, and unsaturated hard rock (e.g., crystalline rock or volcanic tuff). Bedded salt is preferred to domal to accommodate a repository with large capacity. These selections include types of host media being investigated internationally (e.g., granite, clay, and shale—geologic conditions vary). Choosing such media and emphasizing advanced international programs, lets the U.S. program benefit from decades of R&D they have produced.

The reference mined disposal concepts developed in this study are:

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

Each of these concepts has associated constraints on SNF age and burnup and waste package size, that are cited by, or developed in this report. The Crystalline (enclosed) and Clay/Shale (enclosed) concepts follow those developed by Sweden, Finland, France, and other countries. The Generic Salt Repository concept was developed originally for disposal of HLW glass from reprocessing of commercial SNF in the U.S. (Carter et al. 2011b). The Hard Rock Unsaturated open concept is represented by the recently completed license application for a repository in volcanic tuff (DOE 2008b). The Deep Borehole enclosed concept is the subject of parallel studies (Brady et al. 2009; Arnold et al. 2011). Without including the Hard Rock Unsaturated or Deep Borehole concepts, which are analyzed elsewhere, five distinct concepts were analyzed in this study (1 through 5 in the above list).

Thermal Analysis – Enclosed Modes

An important result of this work is that the reference Crystalline (enclosed) and Clay/Shale (enclosed) concepts would need to use relatively small packages for SNF (4-PWR/9-BWR) to limit peak buffer temperatures. The packages are significantly smaller than the transport-aging-disposal (TAD) containers developed previously (DOE 2008b) and much smaller than the dry-storage containers currently being loaded by U.S. nuclear utilities.

Clay-based buffers are part of the Crystalline (enclosed) concept for SNF and HLW, and the Clay/Shale (enclosed) concept for SNF. Various temperature limits for buffers containing swelling clay have been proposed, for example, the Swedish program has used a peak temperature of 100°C. Higher limits have been developed as technical possibilities, but not developed in disposal system safety strategies. In the current analysis the target maximum buffer temperature is 100°C, and the same target of 100°C is used for clay or shale host media that contain similar minerals. These limits may be adjusted in the future when additional information is available, but such adjustments could be small. Adjustments in EBS temperatures can be accommodated with changes in the maximum heat output of waste packages at emplacement, which in turn can be managed using decay storage.

Thermal results are presented for waste package sizes given as capacity for PWR assemblies, but BWR assemblies can also be disposed in quantities that are larger per package because the assemblies have smaller cross-sections (Section 2.2.1). If all existing commercial reactors in the U.S. are operated to 60-yr lifetime, the resulting inventory will include approximately 49,000 MT as BWR SNF, and 91,000 MT as PWR SNF (Table E-1).

Thermal results for Crystalline (enclosed) and Clay/Shale (enclosed) concepts are similar because of the use of clay-based buffers, and the similarity of clay or shale host media to clay buffers. The following results are obtained (Table 3.1-2):

- Existing LWR SNF with average burnup (40 GW-d/MT) could be emplaced in 4-PWR waste packages (or equivalent), after 50 to 75 years of surface decay storage.
- High-burnup (60 GW-d/MT) LWR SNF could be emplaced in 4-PWR waste packages (or equivalent), after approximately 100 years of surface decay storage.
- Waste packages containing a single high-burnup LWR SNF assembly could be emplaced after approximately 10 years of surface decay storage.
- Waste packages containing a single Pu-MOX assembly would require more than 200 years of decay storage.
- HLW generated by reprocessing LWR UOX fuel, and containing both short- and long-lived fission products, could be emplaced after 50 to 100 years of decay storage, depending on the disposal concept and waste characteristics. Other reprocessing wastes (e.g. from the capture and treatment of volatile radionuclides) could be emplaced after fewer than 50 years.

Larger waste packages could be used but would require significantly increased decay storage to meet target temperatures.

For salt a target value of 200°C for the peak salt temperature is used although higher temperatures may be possible (BMWI 2008). The following results are obtained:

- LWR SNF could be emplaced in 4-PWR waste packages (or equivalent) after approximately 10 years of decay storage, regardless of burnup (up to 60 GW-d/MT). Also, 12-PWR packages could be emplaced after approximately 50 years.
- Pu-MOX SNF could be emplaced in 4-PWR waste packages after approximately 110 years of decay storage.
- HLW generated by reprocessing LWR UOX fuel could be emplaced after approximately 10 to 50 years of decay storage, depending on the type of HLW (see Section 1.2 for description of HLW types considered in this study).

Salt has advantageous thermal characteristics and does not require open emplacement mode design to accommodate larger, hotter waste packages. Preliminary finite-element calculations show that 21-PWR size packages containing commercial SNF with 40 GW-d/MT burnup, could be emplaced after 50 years of decay storage. The calculations suggest that larger packages, or higher burnup SNF, can be emplaced at fewer than 100 years.

Thermal Analysis – Open Modes

This study identified three open emplacement mode concepts for disposal of 21-PWR packages, with ventilation requirements ranging from 50 years (Hard Rock Unsaturated concept) to 250 years (Sedimentary Backfilled open mode). Thermal analysis is presented for the Shale Unbackfilled and Sedimentary Backfilled open concepts; the Hard Rock Unsaturated concept has been evaluated by Bechtel-SAIC Company (BSC 2008b) and others. The 21-PWR package size was selected for these modes, for comparison to the transport, aging and disposal (TAD) canister-based system studied previously (DOE 2008b). A set of nominal case results was generated for a range of waste types and ages, then a series of sensitivity analyses evaluated the effectiveness of different measures for limiting peak temperatures. Finally, a "design test case" was developed to show how open-mode disposal of 21-PWR size packages might be used with 100 years or less storage/ventilation.

- **Nominal-Case Results –** Even with 250 years of forced ventilation, peak temperatures exceed 100°C for 21-PWR size (and larger) packages. The entire repository horizon heats up over hundreds of years, and heat generated by the intermediate half-life actinide content of the waste (after decay of short-lived fission products) can sustain buffer or rock-wall temperatures above 100°C after closure. However, sensitivity studies described below show that the open emplacement concepts can be adjusted to manage these temperatures through selection of host media, drift spacing, etc. Comparing the Clay/Shale enclosed concept with the Sedimentary Backfilled open concept assuming shale properties (i.e., comparing enclosed and open concepts in shale), the enclosed concept requires roughly twice the repository footprint for the same inventory. For the ventilated open modes, the repository can open 50 years earlier, and importantly, the last time the waste packages are handled for the open modes would be at approximately 50 years out-of-reactor, addressing concerns about deterioration of SNF during storage that could make transport, handling, and disposal more difficult.

- **Decay Storage/Ventilation Duration –** There are diminishing returns on decay storage or ventilation duration, especially at long ventilation times (e.g., greater than 200 years). Additional sensitivity cases explored whether higher temperatures due to shorter ventilation can be compensated by greater drift spacing. Doubling the drift spacing has an effect on peak temperature that is similar to doubling the ventilation time, so waste package spacing (repository footprint) is a key parameter for open concepts.

- **Drift Spacing –** Increasing drift spacing lowers peak temperatures, and is increasingly effective when peak temperatures occur at later times (e.g., with emplacement of older fuel or with extended repository ventilation). This is because although increased spacing tends to extend the temperature peaks in time, the heat source strength is decreasing at the same time. In the open modes heat removal by ventilation delays the peak temperatures until after ventilation is terminated. This allows time for the few local heat sources (waste packages nearby in the same drift or borehole) to decay, and makes the contributions from adjacent drifts (representing many packages) the dominant contribution to peak temperatures. Drift spacing is increased from 30 to 60 m in the "design test case" described below.

- **Host Rock Thermal Conductivity –** Uncertainty analysis showed this to be a key parameter for thermal management. For 21-PWR or larger waste packages, host rock thermal conductivity of at least 3 to 4 W/m-K is needed to limit near-field host rock (and buffer/backfill) temperatures to 100°C even after 300 years of combined decay storage and repository ventilation. Such values are found in certain media (e.g., salt, some types of crystalline rock) but are significantly higher than other media considered.

- **Backfill Thermal Conductivity –** Backfill does not affect host rock wall temperature, but it has a significant influence on peak waste package temperature. Increasing the buffer/backfill thermal conductivity decreases the temperature difference from the host rock to the waste package. For long term performance of the order of 100 years, the temperature rise in the host rock may be larger, thus transferring control of the waste package peak temperature to the host rock. Once this point in time is reached, further ventilation times may not be effective in lowering the package temperature.

Temperature constraints in the host rock surrounding the drifts are limiting, for open disposal concepts in shale or other clastic sedimentary rock types, with 21-PWR or larger packages, with or without backfill. Thus, for these open modes the focus of peak temperature reduction should be on the heat source (waste package heat output and ventilation duration) or heat dissipation in the host rock (conductivity and drift spacing).

A survey of literature data was used to develop ranges for key parameters of heat transfer through buffer or backfill, and dissipation in the host rock (Appendix D). Host rock thermal conductivity was found to have the greatest relative importance among the parameters analyzed. Within $\pm 1\sigma$ variation of host rock thermal conductivity around the mean of reported values for each geologic medium, peak temperatures shift by approximately +33% (for lower conductivity) and -10% (higher conductivity). These are relatively small variations in temperature, meaning that the general conclusions of this report can be applied to geologic media with different thermal properties, or to natural variation within geologic units, if thermal loading can be adjusted (-33%, +10%) to accommodate these variations.

Open Mode Design Test Case

A combination of parameters was selected to optimize a strategy for disposing of 21-PWR size packages containing SNF with 40 GW-d/MT burnup, while limiting ventilation duration to 100 years. This capability was demonstrated for salt (at 50 years out-of-reactor) using finite-element calculations, and the design test case is intended to show how it might be demonstrated for open emplacement mode disposal in shale or other clastic sedimentary rock. This case evaluated several key ideas: 1) sensitivity to waste package spacing within drifts; 2) effect of no backfill; and 3) the effect of extending the temperature limit boundary 3 m into the rock wall. The latter idea is based on the possibility of heating the near-field host rock above 100°C, in a massive shale formation (low permeability, unfractured). The results show that with drift spacing set to 60 m, the host rock temperature at a distance of 3 m into the wall could be kept below 100°C even after only 50 years ventilation (and 50 years decay storage), for 21-PWR packages containing SNF with 40 GW-d/MT burnup. The design test case is a reasonable solution that was used for cost estimation, subject to confirmation of the performance consequences of over-heating the near-field host rock.

Development and thermal analysis of open reference concepts has defined the important coupling between decay storage/ventilation duration, and temperature limits for clay-based buffer or host rock materials (particularly those materials with a 100°C limit). For open modes in shale or other clastic sedimentary rock, backfilling around large waste packages (e.g., 21-PWR size or larger) requires hundreds of years of decay storage and/or repository ventilation.

Cost Estimation

An evaluation of cost factors for the disposal concepts is provided to show how design features and thermal management strategies affect relative costs. Application of these cost results beyond this purpose should be avoided for several reasons: 1) simplifying assumptions are used in this evaluation and in describing the alternative disposal concepts; 2) key factors such as siting, characterization, and licensing for repository facilities are not included; 3) "upstream" waste management costs such as storage, canisterization, and transportation are not included; and 4) costs associated with delay in the waste management program, which are potentially greater for some concepts than others, are not included.

Each disposal concept is described in sufficient detail to support cost estimation, including construction sequence, shafts, ramps, underground openings, ground support, invert features, and the types of equipment to be used for waste transport and emplacement underground. No bare fuel handling was included, rather, this study assumes that SNF will be received from central storage or a repackaging facility, in sealed stainless steel canisters. Disposal overpacks would be fabricated and inspected off site, and transported to the repository, and are included in the cost estimates. Overpacks would be of carbon steel or copper, with welded closures. Surface facilities are scoped for throughput of 3,000 MT per year but would be developed on a modular basis to meet any disposal schedule. Limited lag storage capacity is provided to buffer throughput, or to cool limited amounts of SNF.

Costs and the associated schedules for all concepts were developed using the same phases and durations derived for two previous salt repository studies (Carter et al. 2011, 2012c). For this generic study, the waste emplacement operations phase of 47 years is determined by the waste inventory (140,000 MT is assumed, based on the total fuel discharges from all existing or shutdown reactors) and the assumed waste emplacement rate of 3,000 MT per year. Cost estimates do not include site selection or characterization (see DOE 1986 for estimates of these costs), at-reactor packaging, centralized storage (if adopted), re-packaging to meet disposal requirements, and waste transport to the repository.

The team also used the same cost models developed for prior salt repository studies (Carter et al. 2011, 2012c) which in turn are tied to another study (DOE 2008c). The mining estimate was significantly improved with the addition of new unit cost data for mining in clay/shale, sedimentary and crystalline rock. Unit costs were also developed for backfilling with host rock or a mixture of host rock and clay.

The cost for permanent disposal of 140,000 MT of commercial SNF ranges from approximately \$24 B to \$81 B in 2012 dollars (Table 5-1) including the range of low to high contingency (+5% to +30%). The lowest cost estimates are for the Generic Salt Repository and the Shale Unbackfilled concepts, and the highest are for the Clay/Shale and Crystalline concepts. This range reflects the different strategies for relying on engineered and natural barriers (i.e., natural barriers cost less). A geologic setting in relatively poor quality shale (e.g., indurated, with fracture permeability) is better suited technically to the Clay/Shale (enclosed) reference concept which uses short (40 m) horizontal emplacement borings, small waste packages, and multiple engineered barriers (buffer, plugs, and seals). By contrast, the Shale Unbackfilled concept is intended for a higher quality, relatively unfractured, low-permeability host rock. It can accept larger waste packages and does not require backfill in emplacement drifts (although backfilling remains an option until repository closure).

It is important to note that the cost estimates in this report are for repositories with relatively simple surface facilities that handle only canistered commercial SNF, or HLW from various sources, that arrives already in waste package-size containers. The costs associated with fabricating SNF canisters of the correct size for waste disposal, including internal structures and materials for heat transfer, criticality control, etc., and the costs associated with repackaging the ever-growing inventory of SNF that is stored in sealed, dual-purpose canisters (DPCs) are not included. Facilities, equipment, and personnel required to support these additional necessary operations will increase the costs all of the repository concepts analyzed.

Recommendations

R&D to Revise Thermal Constraints to Allow Higher Temperatures – This study shows that disposal concepts favoring larger waste packages and smaller repository footprints may offer economic advantages. Tradeoffs and optimization on waste package size and subsurface layouts are generally limited by the assumed thermal constraints imposed on the near field environment. Thermal constraints used in establishing the reference disposal concepts are based on previous experience and international precedent, but are not necessarily fixed limits. The greatest uncertainties associated with calculating near-field temperature histories are the hydration state of clay-based engineered materials, and thermal responses of natural materials (e.g., host rock) in the disposal environment. Complex coupled-process models are needed for explicit simulations (e.g., of the type reported by Weetjens and Sillen 2005). Even with application of such models there are likely to be important uncertainties that should be carefully studied. Repository designers and safety analysts use thermal constraints for several reasons: 1) to mitigate the impact of, or exclude, certain FEPs; 2) to limit the R&D needed to support safety evaluations; or 3) in response to regulatory input. Investment in R&D on thermal limits benefits responses to all these needs. The fidelity of FEP analysis and performance models needs to be optimized to support the use of larger waste packages and smaller repository footprints. Current efforts in EBS and near-field materials research and model development should be sustained.

Engineering Development of Disposal Concepts –The reference disposal concepts are developed sufficiently to allow for thermal analysis and initial cost estimation. Additional engineering studies will be needed to ensure the dimensions and other attributes of the proposed waste packages are adequate, and that the underground layouts, ground support, conveyances, and other design details are appropriate. Some of these details will depend on site-specific information, and some may increase estimated costs substantially (e.g., disposal overpack materials, and the cost for shaft hoists for payloads greater than approximately 45 MT).

Evaluate Reference Concepts in Iterative Performance Assessments – Disposal concepts presented here use previous U.S. and international experience as a starting point and also include significant departures from previous designs. Although the concepts are expected to meet potential postclosure safety standards, they are new concepts and their postclosure safety performance has not been evaluated using a formal performance assessment methodology. Therefore, the reference concepts should be evaluated in iterative postclosure performance assessments. This includes FEP screening and evaluation, subsystem and total system model development, and subsystem and system performance assessments. This work will help identify: 1) where more design detail is needed; 2) where EBS and near-field environment models need to be developed or require additional capabilities; and 3) where data should be collected to support model development or reduce model uncertainties.

High-Fidelity Coupled Thermal Analysis – Additional coupled multi-physics numerical simulations for the Generic Salt Repository (an enclosed mode) and for the open mode concepts, are needed to evaluate thermal constraints on emplacement of larger packages (e.g., 32-PWR size). This study evaluated disposal of 21-PWR size packages with open concepts in shale or other clastic sedimentary rock, and found host medium thermal constraints to be limiting unless decay storage or ventilation is extended to 200 years or longer. More simulations are needed to better understand the need for such long storage/ventilation duration. For salt, the importance of direct contact for heat transfer between waste packages and intact salt needs to be evaluated, and large-scale thermally driven processes need to be evaluated. For shale and sedimentary rock more definitive, multi-physics simulations are needed as guidance on whether a region of the near-field host rock could be overheated, consistent with a reasonable safety case.

Use of Reference Concepts in Site Screening – Reference disposal concepts are developed in this report to support discussions on waste management policy, and provide context for R&D activities. They are not intended to constrain future site screening activities to consider only sites where these reference concepts can be implemented. To include variations on the reference concepts developed here, site screening should consider a comprehensive catalog of possible settings and repository features (Hardin et al. 2011, Appendix I).

Natural Variability in Thermal Properties for Potential Host Media – Based on analysis and literature review, host rock thermal conductivity is the most important thermal parameter for geologic disposal of any waste stream. Screening activities should emphasize thermal conductivity, and identify variation of mean thermal conductivity between formations, or variability within formations, especially if thermal conductivity lies outside the $\mu \pm 1\sigma$ range estimated in Appendix D.

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List of Acronyms

ABR	Advanced Burner Reactor
AFCI	Advanced Fuel Cycle Initiative
ANL	Argonne National Laboratory
BSC	Bechtel-SAIC Company
BWR	Boiling-Water Reactor
CH	Contact Handled
CLAB	Centralized Used-Fuel Storage Facility (Sweden)
Co-Extraction	Co-Extraction Process
CR	Conversion Ratio
DOE	U.S. Department of Energy
EBS	Engineered Barrier System
EC, E-Chem	Electrochemical
EDZ	Excavation Damage Zone
FA	Fuel Assembly
FC	Fuel Cycle
FCR&D	Fuel Cycle Research and Development
FCT	Fuel Cycle Technology
FEP	Features, Events and Processes
FY	Fiscal Year
GTCC	Greater Than Class C
GW-d	Gigawatt-Days
GW-d/t	Gigawatt-Days per Metric Ton (also GW-d/MT)
GWe	Gigawatts-Electrical
GWt	Gigawatts-Thermal
HEPA	High Efficiency Particulate Air
HIC	High Integrity Container
HLW	High Level (Radioactive) Waste
HM	Heavy Metal
HTGR	High Temperature Gas Reactor
IC/MC/OC	Inner Core/Middle Core/Outer Core
LLNL	Lawrence Livermore National Laboratory
LLW	Low Level Waste
LWR	Light Water Reactor
MOX	Mixed Oxide Reactor Fuel
MPa	Megapascals

MT	Metric Ton
MTHM	Metric Tons of Heavy Metal
MTIHM	Metric Tons of Initial Heavy Metal
MTU	Metric Tons of Uranium
MW-d	Megawatt-Days
MW_{th}	Megawatts-Thermal
NEA	Nuclear Energy Agency
NGNP	Next Generation Nuclear Plant
NE	DOE-Nuclear Energy
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Act Amendment
OCRWM	Office of Civilian Radioactive Waste Management (DOE)
ORNL	Oak Ridge National Laboratory
PUREX	Plutonium-Uranium Extraction Process
PWR	Pressurized Water Reactors
R&D	Research and Development
RH	Remote Handled
RW	Radioactive Waste
SAIC	Science Applications International Company
SFR	Sodium Fast Reactor
SNF	Spent Nuclear Fuel
SNFA	Spent Nuclear Fuel Assemblies
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SWB	Standard Waste Box
TAD	Transport/Aging/Disposal
TALSPEAK	Trivalent Actinide Lanthanide Separation by Phosphorus-based Aqueous [K]omplexes
TBM	Tunnel Boring Machine
Tc	Technetium
THM	Thermal-Hydrologic-Mechanical
THMC	Thermal-Hydrologic-Mechanical-Chemical
TRISO	Tri-Isotropic Coated Fuel Particles
TRU	Transuranic
TRUEX	Transuranic Extraction
UDS	Undissolved Solids
UFD	Used Fuel Disposition
UFDC	Used Fuel Disposition Campaign

UNF	Used Nuclear Fuel
UOX	Uranium Oxide Fuel
UREX	Uranium Extraction
VHTR	Very High Temperature Gas Reactor
W	Waste
WP	Waste Package
WIPP	Waste Isolation Pilot Plant
YM	Yucca Mountain
WF_count	Waste Form Count

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Repository Reference Disposal Concepts and Thermal Load Management Analysis

1. Introduction

The safety case for any radioactive waste repository includes a disposal concept: a description of the repository design including the engineered barriers, the geologic setting and its stability, how both engineered and natural barriers are expected to evolve over time, and how they are expected to provide safety. For this purpose the Used Fuel Disposition (UFD) campaign is developing generic disposal concepts (i.e., not site-specific) for a range of geologic settings. The UFD campaign is investigating ways to improve repository safety or the demonstration of future safety, and many of the scientific questions depend on specification of generic disposal concepts for possible host media.

In addition, fuel cycle scenarios under consideration by the U.S. Department of Energy (DOE) Fuel Cycle Technology (FCT) program would generate waste streams and waste forms having different characteristics, such as radionuclide inventory and decay heat output, volume, mass, and chemical form. In order to generate disposal-related metrics for system analysis and system engineering activities that evaluate alternative fuel cycles, the disposal of these wastes needs to be considered for different repository design concepts.

In this report, the UFD campaign presents a set of disposal concepts (also called design concepts, although the program has not initiated a formal design process) for light water reactor (LWR) spent nuclear fuel (SNF) as well as a range of waste forms that could potentially be generated in advanced nuclear fuel cycles. Mature disposal concepts have been developed in other countries for spent nuclear fuel from light water reactor and high-level waste (HLW) from reprocessing, and these serve as starting points for concept development here. Additional repository details (e.g., host media, ramp vs. shaft access, etc.) and engineered barrier system (EBS) concepts (e.g., emplacement mode, buffer prefabrication, etc.) are then considered.

Disposal concepts described here will support the capability of the UFD campaign to contribute to discussions on waste management policy, locations for nuclear fuel cycle facilities, and disposal options. In addition, the reference concepts described here will provide context for R&D activities that seek to advance confidence in models of repository system performance.

Assumed Performance Objectives and Evaluation Methodology

In 1995 the National Research Council of the National Academies of Science and Engineering recommended using dose as the primary measure of harm from a repository. The International Commission on Radiation Protection (ICRP) made a similar recommendation in 1997 (ICRP 1997), and the International Atomic Energy Agency model standard (IAEA 2006) uses a dose measure for deep geologic disposal. Accordingly, this report assumes dose is the primary hazard indicator for radioactive waste disposal.

A performance objective on expected annual dose of 0.15 mSv/yr (15 mrem/yr) before 10^4 yr, and 1 mSv/yr (100 mrem/yr) between 10^4 and 10^6 yr, to a reasonably maximally exposed individual is assumed to be applicable to disposal concepts discussed here. The latter limit is consistent with the ICRP and IAEA recommendations. These performance objectives are not critical to the identification of the reference disposal concepts reported here, except for certain aspects as discussed below.

Other details of the performance assessment framework, including screening criteria for potentially relevant features, events, and processes (FEPs), guidance on inadvertent human intrusion, and retrievability requirements, are assumed to be similar to past repository performance assessments performed in the United States. All the concepts presented are expected to meet the postclosure performance objectives, but specific comparisons will depend on site-specific details.

If all generic disposal concepts meet the postclosure performance objectives, then those objectives may not be useful for selecting one concept over another. However, key parts of this regulatory discussion are potentially important to concept development: 1) the dose standard, 2) 10^6-yr performance period, 3) 10^4 year FEP evaluation horizon, and 4) retrievability for some specified time during repository operations (assumed to be at least 50 yr here). Use of a dose standard means that barrier features can be selected to isolate those radionuclides that contribute most to dose, which typically results in isolation of other radionuclides as well. The 10^6-yr performance period leads to emphasis on performance of natural barriers, and the 10^4-yr horizon for most FEPs limits the impact of increased uncertainty in longer evaluations. The 50-yr retrievability objective is considered in the selection of container materials and dimensions.

The analyses in this report are based on an assumption that key aspects of future regulations governing permanent disposal of SNF and HLW in the U.S. will be similar to the analogous requirements of 40 CFR Part 197 and 10 CFR Part 63. If current regulatory requirements specified in 40 CFR Part 191 and 10 CFR Part 60 remain in effect at the time a repository is licensed, some aspects of these analyses may not be applicable. Anticipation of such future changes in repository regulations is consistent with recent regulatory information (Kokajko 2011; McCartin 2012, p. 144).

Other **Assumptions**

The waste management mission considered here is primarily the disposal of 140,000 MT of spent uranium oxide (UOX) fuel, consisting of all past and future discharges from existing LWRs (Section 1.2). This is a generic study and as such is not constrained by the 70,000 MT limit on the first repository that is prescribed by the Nuclear Waste Policy Act (NWPA). Disposal concepts such as those presented in this report may eventually be implemented, assuming legislative changes to the NWPA as amended, to allow construction of a single repository for all the SNF produced by commercial reactors in the U.S., and also to allow other fuel management facilities such as centralized storage (Sections 1.4.3 and 4).

Disposal of reprocessing wastes (glass, ceramic, and metallic HLW) is also considered, considering disposal concepts (Section 1.4.5) and thermal analysis, without cost estimation or any assumption of total quantity. This study uses a selection of representative HLW types from possible future nuclear fuel cycles (Section 1.2 and Appendix E).

The capability to retrieve waste is assumed to be only needed during the period of repository operations (pre-closure operations). Retrievability is the capability, in principle, to recover waste once it has been emplaced in the repository. There is no expectation that retrieval operations must be exactly the reverse of emplacement operation or that repository designs be optimized for possible retrieval. During repository operations, retrievability is facilitated by the confinement and containment of the waste in substantially intact waste packages in a limited volume (NEA 2011). Having access from the surface to the repository emplacement level also facilitates retrievability. The repository concepts presented here are intended to have waste packages that substantially maintain their integrity during pre-closure operations and have access ramps or shafts that are open and maintained throughout pre-closure operations. Some of the concepts include backfilling either immediately after emplacement or as part of repository closure operations. Although the use of backfill and the timing of its placement add complexity to retrievability, it does not preclude retrievability.

Disposal costs are estimated for commercial SNF, which is the largest part of the waste management mission, assuming there is no future commitment of this material to reprocessing. Previous estimates for HLW disposal cost in salt (Carter et al. 2011; 2012c) indicate that costs are less than SNF, even when expressed on a normalized basis (e.g., per MT initial heavy metal) because handling and packaging costs are smaller. For this study, the normalized cost for HLW disposal is assumed to be less than or equal to the normalize cost for disposal of equivalent quantities of commercial SNF.

A number of assumptions are used in thermal analyses, and are identified in Section 3 and Appendix A. One important assumption made for all thermal analyses is that significant heat-generating waste types are segregated in different parts or panels of the repository. This is more than a convenience; for the large quantities of waste considered, panels will be optimized with different drift spacings, ventilation parameters, etc. Also, the plugs and seals that isolate individual panels may vary according to the contents or capacity of the panel (e.g., total inventory in a panel, including low-level or greater-than-Class-C waste). So waste segregation is assumed in order to preserve flexibility in design and operations.

The remainder of Section 1 presents a summary of the FY11 report (Hardin et al. 2011), including information on international concepts, geologic settings, thermal management options, and selection of enclosed emplacement mode disposal concepts. Section 1.5 presents a similar discussion, with a systematic analysis leading to selection of three open emplacement mode concepts.

1.1 Published Disposal Concepts from the U.S. and Other Countries

This section summarizes disposal concepts that are currently under development internationally, or have been considered in the past. No geologic repository for used fuel or high-level waste presently exists. This summary emphasizes system concepts, while Section 1.3 focuses more on geologic settings.

U.S.A., Germany – Salt

Disposal of radioactive wastes in domal or bedded salt formations has been studied for more than 50 years, tracing to a recommendation by the U.S. National Academy Science (NAS 1957). Former salt mines Asse II and Morsleben were used for disposal of intermediate and low-level wastes in Germany beginning in the 1960’s. Disposal of transuranic wastes in bedded salt is currently being implemented at the Waste Isolation Pilot Project in southern New Mexico. Disposal of high-level waste and SNF in salt in the U.S. has been studied extensively in the past, with recently renewed interest. Salt offers a number of positive characteristics for a geologic repository, including:

- Relatively easy mining,
- Reconsolidation and creep cause entombment of waste packages with time,

- High thermal conductivity (e.g., 4 W/m-K at 100°C; see Appendix D) compared to many other potential host media for geologic disposal,
- Temperature limit of 200°C or higher,
- Very low permeability in the intact and reconsolidated states, and
- Salt formations are found in the U.S. in regions with stable geologic conditions, where they have existed for long geologic time periods, and will remain stable over the period of repository performance.

As envisioned in the U.S. in the 1980's, a salt repository could be placed into a halite layer approximately 250 feet thick (with some interbedding of other salts or clay), in a bedded salt sequence approximately 2500 feet below the surface (Figure 1.1-1). This arrangement was determined by the geologic stratigraphy at the sites that were evaluated at the time, and by the need for sufficient depth to ensure isolation and promote closure of openings in salt. The lateral extent of bedded salt suitable for repository development would be determined from site-specific information. Waste packages could be emplaced either horizontally in emplacement drifts, or horizontally in boreholes or alcoves constructed off of access tunnels, or vertically in boreholes drilled into the floor of access tunnels.

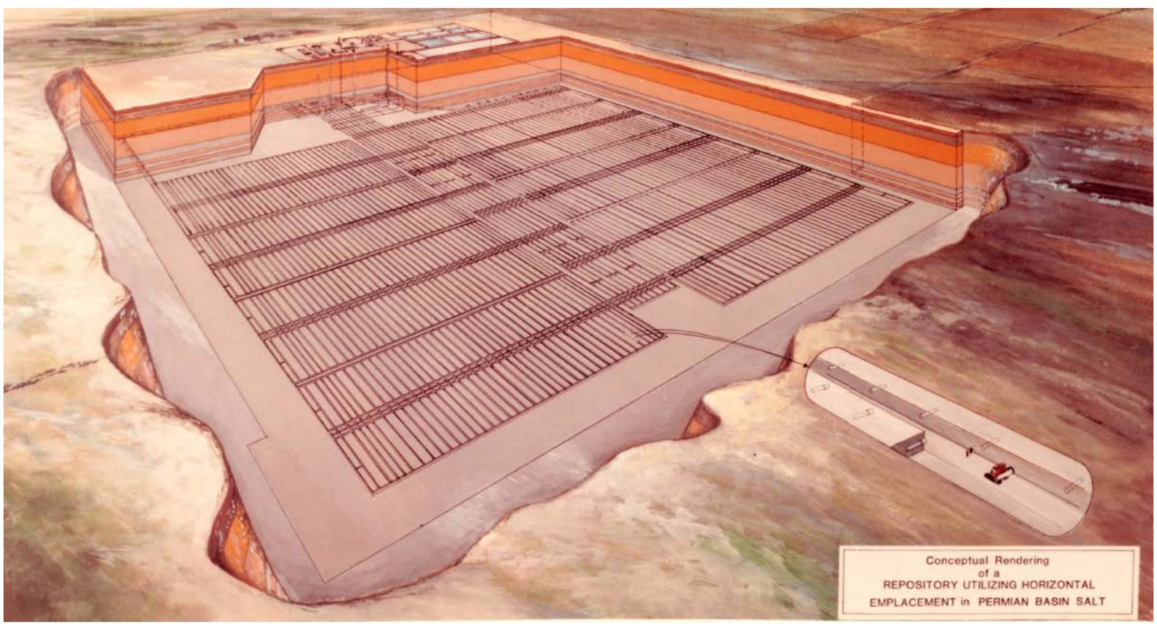

Figure 1.1-1 Schematic of Developed Repository in Bedded Salt (DOE 1987a)

Access to the repository horizon would be via vertical shafts, possibly limiting the maximum waste package size due to hoisting weight constraints. These shafts and the ends of the emplacement tunnels would be closed with multiple plugs and seals to prevent inadvertent intrusion and to eliminate paths for radionuclide migration. Ramp access to a repository in bedded salt has not been proposed because shaft access is more direct, and construction and sealing of shafts is probably more feasible. The feasibility of ramp construction would depend on site-specific factors such as the geomechanical stratigraphy, but shafts were selected for the facility at Gorleben, Germany, and for the proposed salt repository in the U.S. (DOE 1987a). Ramp access is considered for open modes that could accommodate larger packages (Section 1.5).

In the 1987 salt repository concept, waste packages contained either 4-PWR (pressurized-water reactor) or 9-BWR (boiling-water reactor) fuel assemblies, or larger numbers of assemblies in consolidated fuel bundles. The SNF was to be sealed in canisters of carbon steel, approximately 14 feet long and several feet in diameter, and placed into carbon steel disposal overpack containers (DOE 1987a).

Belgium, France, Switzerland – Clay

Disposal of SNF and HLW in clay or soft shale has been investigated principally by Belgium, France, and Switzerland (Figures 1-2 and 1-3). Like salt, clay is relatively easy to excavate. All types of clay and soft shale media can be expected to eventually deform and entomb the waste packages. The more plastic clay media such as the Boom Clay, which has been extensively studied in Belgium, will completely seal around the waste packages. The effective thermal conductivity of clay is less than 2 W/m-K (Appendix D) and clay media are associated with temperature limits of approximately 100°C (Section 1.4.1), leading to lower limits on thermal loading. The European programs have addressed this temperature limit by limiting thermal output of the waste packages, although the Belgian program has also considered boosting the thermal conductivity of clay in the vicinity of the waste package by the addition of graphite (Jobmann and Buntebarth 2009). Maximum waste package heat output ranges from 188 W/package for disposal of UOX fuel in the Boom Clay, to ~1,600 W/package for SNF disposal in the Callovo-Oxfordian shale facies proposed for a French repository. The Belgian program has proposed canisters of stainless steel, nickel, or titanium, while the French and Swiss programs have selected carbon steel. Emplacement would be horizontal, steel-lined drifts or borings constructed from access drifts. Package emplacement systems, and additional barriers of clay and other materials around the packages, have been demonstrated by the European programs.

Access to the repository horizon would be via ramps or vertical shafts and the repository would be placed 250 to 500 m below ground, depending on local stratigraphy and hydrogeology. Repository openings would be backfilled, and plugs and seals installed to limit hydraulic conductivity to that of the surrounding, undisturbed formation.

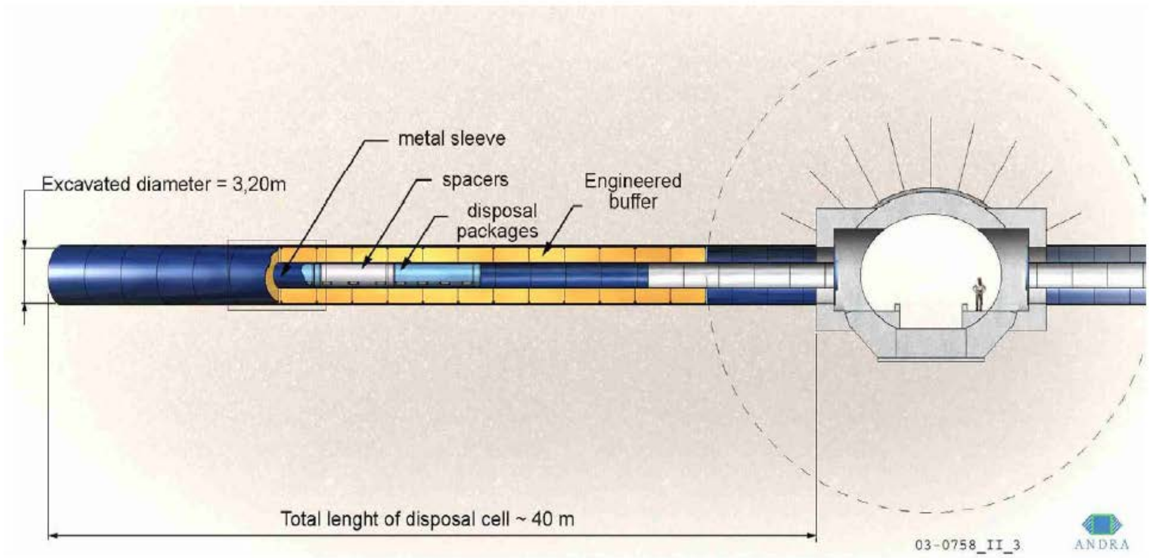

Figure 1.1-2 Schematic of Horizontal Borehole/Drift Emplacement of Spent Fuel Waste Packages (Bosgiraud et al. 2008)

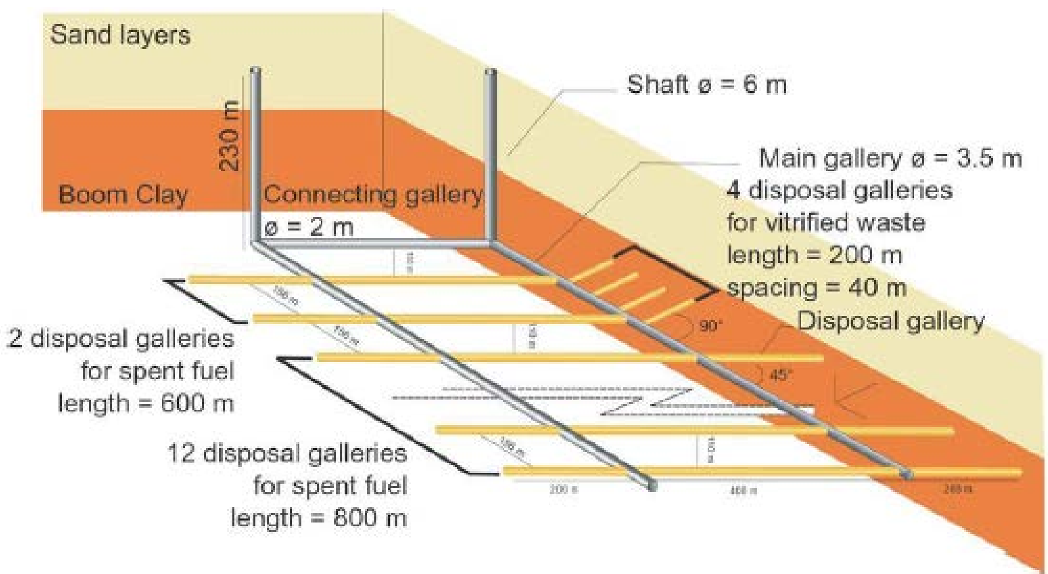

Figure 1.1-3 Schematic of Disposal Galleries for Spent Fuel and Vitrified HLW in a Repository in the Boom Clay (ONDRAF/NIRAS 2001)

Sweden, Finland, Japan – Crystalline Rock

The most advanced crystalline rock repository programs are in Sweden and Finland, and are based on the KBS-3 disposal concept first proposed in 1983 (SKB 2006). Crystalline rock has also been evaluated by France, Switzerland, the U.S., and other countries (Rechard et al. 2010).

The terms “crystalline” and “granite” are often used interchangeably in discussions of repository concepts. As stated in the Dossier 2005 Granite report (Andra 2005b):

> “Granite is a hard rock with very low porosity and permeability. It can be excavated without the need for significant ground supports over volumes compatible with the dimensions and depth of a repository. It consists of quartz (crystallized silica) and feldspars (alumina silicates), where quartz contributes to the generally high thermal conductivity of the rock. Unfortunately, a granite massif is traversed by fractures of various sizes. Minor fractures, of one to tens of meters, are far more numerous than major fractures, extending from one to several kilometers. Minor fractures, which may be more or less connected, generally conduct very little water. Therefore, major fractures, or faults, are the principal vectors of water circulation in granite. The aim is to emplace the waste in the granite rock where it has no fractures or only minor fracturing conducting little or no water. Studies in Sweden anticipate a rejection rate of approximately 10% of the locations investigated for spent fuel disposal.”

In the KBS-3 concept, the repository horizon would be at a depth of approximately 500 m which allows sufficient in situ stress to close many fractures, limits hydraulic gradients, and is below much of the influence of future glaciation. The repository would be accessed by both shafts and ramps, with ramps used for construction and waste transport. Waste packages can be emplaced either horizontally or vertically (Figures 1.1-4 and 1.1-5).

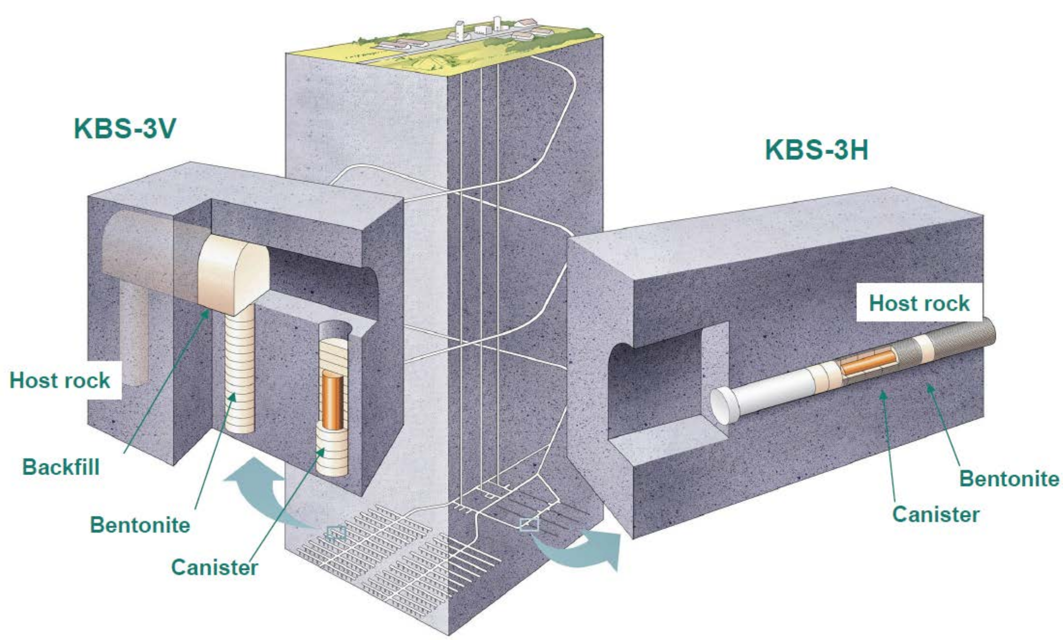

Figure 1.1-4 Schematic of the KBS-3 Vertical and Horizontal Disposal Concepts (Posiva 2010)

The Swedish 2010 license application describes disposal of SNF canisters in vertical borings spaced approximately 6 m apart along the floor of access drifts spaced 20 m apart. Horizontal emplacement would be more efficient with respect to the extent of excavation and backfilling, and has been investigated in collaboration between the Swedish and Finnish programs. One challenge that has been identified is characterizing the suitability of rock conditions over the entire length of every horizontal boring.

The Swedish concept calls for waste packages to be fabricated from copper, with a nodular (ductile) cast iron insert to support the fuel assemblies. Copper corrodes very slowly, if at all, in the reducing conditions present inside the clay buffer, in the selected host rock. Waste packages would be emplaced vertically, surrounded by at least 35 cm of swelling clay in a dehydrated, compacted state. Hydration of the buffer will produce swelling pressure on the order of 6 MPa, ensuring that the buffer has low permeability and resistance to microbial activity and other influences. Access drifts would be backfilled with a mixture of swelling clay and sand or crushed rock. A prefabrication concept is being studied that would enclose the copper canister and compacted clay buffer in a perforated steel shell, for handling and emplacement (Figure 1.1-6).

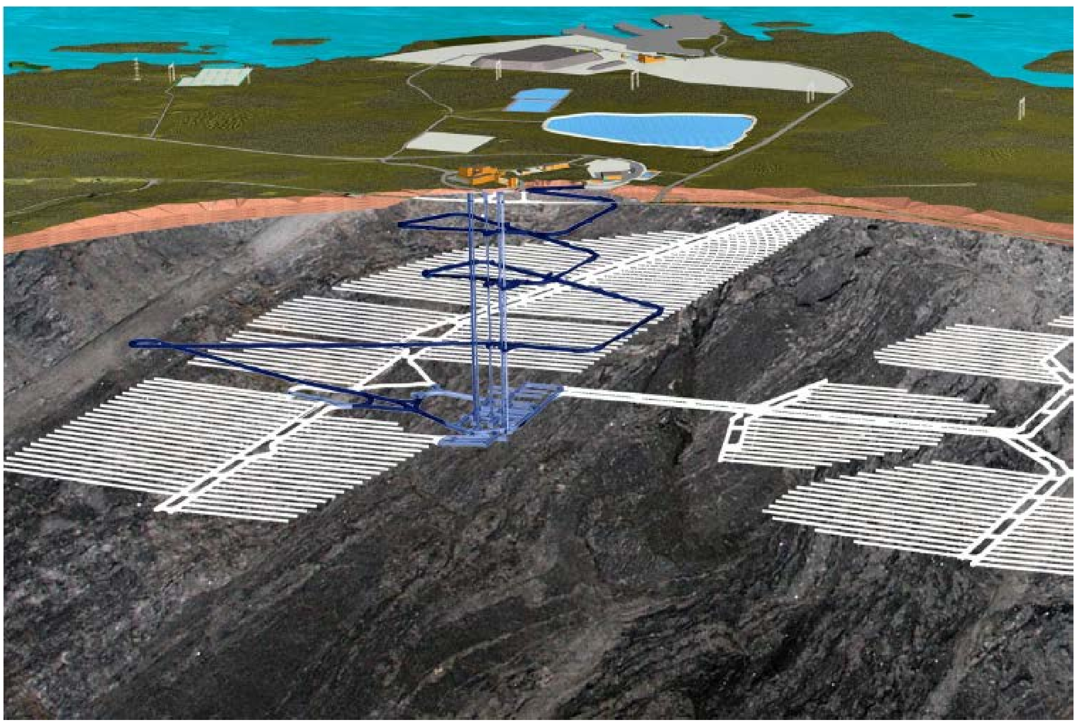

Figure 1.1-5 Schematic of the Facility for Final Disposal of SNF, Finland (Petrakka 2010)

Thermal loading would be limited to about 1,700 W/package at emplacement (SKB 2011, Section 5.2.1) primarily to limit alteration of the clay buffer. Depending on the time out-of-reactor (see Section 3), this generally limits the number of fuel assemblies per package to 4 PWR assemblies or 12 BWR assemblies. For advanced waste forms such as spent MOX fuel, fewer assemblies and/or longer decay storage would be needed.

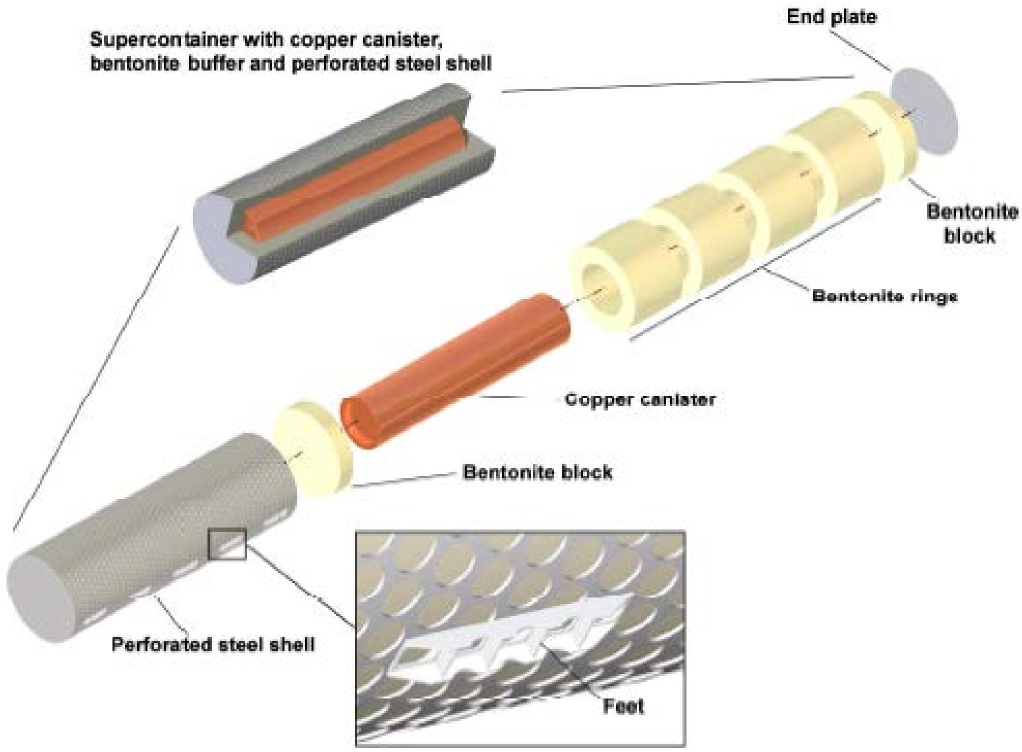

Figure 1.1-6 Schematic of the Prefabricated EBS Concept for Waste Package and Buffer Emplacement in Long Horizontal Boreholes (not to scale; Posiva Oy 2010)

USA, Sweden - Deep Borehole

Deep borehole disposal of SNF and HLW is currently being evaluated in the U.S. (Arnold et al. 2011; Brady et al. 2009; Anderson 2004; SKB 1992) and has been evaluated by others in the past. The following description is extracted from a Swedish alternative study for their KBS-3 repository (SKB 1992). The Deep Borehole concept would involve a number of holes drilled vertically from the ground surface down to great depth in bedrock. The SNF would be encapsulated in canisters with outside diameter of 0.5 m and length of approximately 5 m. The canisters would be lowered into the holes and stacked on top of one another, between 2 km and 4 km (or total depth). The diameter of each borehole would be at least 1 m down to 2 km and 0.8 m where the canisters are emplaced.

Favorable host rock would be geologically stable, crystalline “basement” rock with very slow groundwater circulation as indicated by its salinity and apparent isotopic age. In the Swedish concept canisters would be surrounded by a buffer of engineered, clay-based material. The canisters would not be expected to remain intact over the performance lifetime of a repository (e.g., 10^6 years) and would not contribute significantly to isolation of radionuclides. However, the host rock is expected to maintain isolation because of static groundwater conditions. The upper 2 km of the hole would be sealed with a combination of swelling clay, asphalt, and concrete (Figure 1.1-7), and the sealing system could function well beyond 10^6 years.

A Sandia National Laboratories report (Brady et al. 2009) concluded that a smaller borehole could be acceptable for disposal of canisters containing a single BWR or PWR assembly.

Borehole diameter at emplacement depth could be approximately 17.5-inch (445 mm) with 16-inch (406 mm) casing without consolidation of fuel rods. With consolidation of fuel rods into bundles, the canister size and required borehole size could be much smaller than for the Swedish deep-borehole proposal (see Section 1.4.5.4). Nevertheless, drilling of large diameter, deep deposition holes would be a technical challenge. Larger diameter increases the risk of borehole collapse, and increases the incidence and extent of damage from breakouts caused by in situ stress at depth. Larger diameter also requires much heavier casings and increases costs.

Additional study, including a drilling demonstration project, may be needed to determine if deep borehole disposal of SNF or HLW is technically and economically feasible.

Summary

This short review of previously proposed disposal concepts forms the basis for further discussion of geologic settings (Section 1.3) and reference disposal concepts (Sections 1.4 and 1.5). To support thermal analysis in Section 3, limiting thermal loads and temperatures associated with the concepts discussed above, are tabulated (Table 1.1-1).

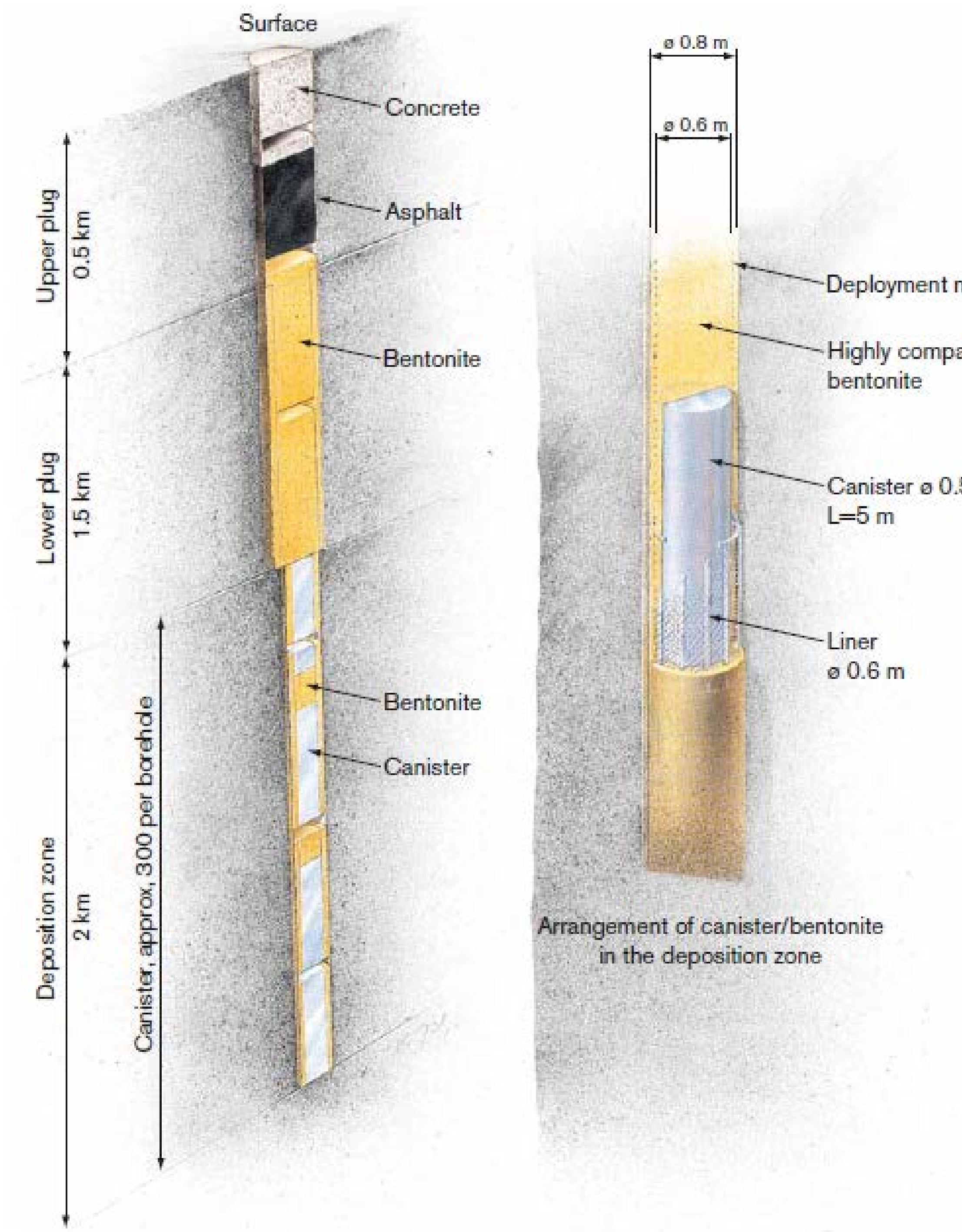

Figure 1.1-7 Schematic of the Deep Borehole Disposal Concept (not to scale; after KASAM 2007)

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Table 1-1 Thermal Constraints Associated with Previously Proposed Disposal Concepts.

Country	Repository Type	Thermal Conductivity	Drift Spacing	Canister Spacing	Temperature Constraint	Maximum Heat Output	Reference
USA	Salt			40 feet	Salt 200°C max. HLW glass 500°C max.	4.2 kW HLW	Ref. 1
			HLW: 120 ft. SNF: 170 ft.	HLW: 8.7 ft. SNF: 10 to 42 ft.	Fuel cladding 375°C max. Salt 250°C max. HLW glass 500°C max.	6.6 kW/canister (consolidated PWR SNF) 1.6 to 5.4 kW BWR/PWR	Ref. 2
		3.09 W/m-K @ 100°C, 3.37 W/m-K @ 29°C	HLW: 120 ft. SNF: 170 ft.	SNF: 28 to 85 ft. Defense HLW glass: 10 ft.	Fuel cladding 375°C max. Salt 250°C max. HLW glass 500°C max.	2.2 to 4.4 kW Intact PWR 6.6 kW consolidated PWR 0.42 kW DHLW glass	Ref. 3
		4.7 W/m-K @ 110°C		7.5 m	Fuel cladding 375°C max. Salt 250°C max.	6.6 kW PWR	Ref. 4
Germany	Salt				Salt 200°C max.		Ref. 5
Belgium	Clay	1.7 W/m-K horizontal, 1.25 W/m-K vertical	HLW: 40 m SNF: 110 m	HLW: 1.6 m SNF: 3 m	Backfill 100°C max. HLW glass 400°C max. SNF 350°C max.	188 W/pkg. UOX 905 W/pkg. MOX	Ref. 6
France	Clay	1.9 to 2.7 W/m-K parallel, 1.3 to 1.9 W/m-K perpendicular	8.5 to 13.5 m	2.5 to 4 m	Argillaceous host rock 100°C max.	1,600 W (4-PWR UOX), 1,100 W (1-PWR MOX)	Ref. 7
Switzerland	Clay	1.8 W/m-K	40 m	3 m	Clay-based buffer 125°C max.	1,500 W/canister	Ref. 8
Sweden	Granite	3.4 to 4 W/m-K 2.45 to 2.9 W/m-K	40 m	6 m 7.2 m	Clay-based buffer 100°C max.	1,700 W/canister	Ref. 9
France	Granite	2.4 to 3.8 W/m-K	25 m	HLW: 8 m SNF: 12 to 15 m	Canister surface 100°C max.	1,600 W (4-PWR UOX) 1,100 W (1-PWR MOX)	Ref. 10
Finland	Granite	2.3 to 3.2 W/m-K		11 m	Clay-based buffer 100°C max.	1,700 W/canister	Ref. 11
USA	Tuff	0.99 to 2.07 W/m-K			Between tunnel temperature <96°C Tunnel Wall temperature <200°C	1,500 W/Canister (DHLW) 18 kW (intact 21-PWR)	Refs. 12, 13 & 15

Notes:
1. Clay-based buffer material has thermal conductivity of approximately 0.4 W/m-K in dry compacted form, 1.35 W/m-K saturated (Ref. 14)

Country	Repository Type	Thermal Conductivity	Drift Spacing	Canister Spacing	Temperature Constraint	Maximum Heat Output	Reference

References:
1. Clayton & Gable 2009. *3-D Thermal Analyses of High-Level Waste Emplaced in a Generic Salt Repository*.
2. DOE 1987a. *Site Characterization Plan Conceptual Design Report for a High-Level Nuclear Waste Repository in Salt, Vertical Emplacement Mode*.
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4. ONWI 1985. *Waste Package/Repository Impact Study Final Report, Conceptual Design of a High-Level Nuclear Waste Repository in Salt*.
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6. ONDRAF/NIRAS 2001.*Technical Overview of the SAFIR 2 Report*.
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9. SKB 2006. *Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar – a First Evaluation*. TR-06-09.
10. Andra 2005b*. Dossier 2005 Granite – Architecture and Management of a Geological Repository*.
11. Posiva Oy 2010, *Interim Summary Report of the Safety Case 2009*, Posiva Oy 2010-02, March 2010.
12. DOE 2008a. *Civilian Radioactive Waste Management System, Waste Acceptance Systems Requirements Document*.
13. Davison, D., et al. 2006. "Benefits of an Integrated Fuel Cycle on Repository Effective Capacity," Waste Management '06 Conference.
14. NAGRA 2002. *Project Opalinus Clay Safety Report*. NTB-02-05.
15. DOE 2008b. *Yucca Mountain Repository License Application for Construction Authorization*. Section 1.3.1.2.5.

1.2 Inventory

Inventory is important to this study for three reasons: 1) to determine how much commercial SNF would need to be disposed of in a repository; 2) to provide the heat generation characteristics of various waste types; and 3) to provide consistent radionuclide inventory data for use in future performance assessments for the disposal concepts documented here. Information on the quantity of SNF is used mainly in Sections 4 and 5 of this report, which include cost estimation for alternative concepts. Inventory projections are obtained from Carter et al. (2012b, Table 2-1). The projections are based on assumptions that the 104 currently operating reactors receive license extensions that extend to 60 years, and the burnup continues to increase (at 1.3% per year, limited by 5% enrichment) for PWRs and BWRs, up to projected burnup limits. The total quantity of SNF produced under these assumptions is approximately 140,000 MT, with the last reactor shutting down permanently in 2055. This “no replacement” estimate results in a reasonable lower bound on the total SNF inventory to be disposed. Projected burnup limits are 54 and 56 GW-d/MT for BWRs and PWRs, respectively, so 60 GW-d/MT is selected as a bounding value for thermal analysis in this study, and as a case for future performance assessments.

This study analyzes repository thermal response for waste from several possible fuel cycles, which were selected because the wastes they generate would be reasonably representative of the qualitative range of waste types that could be disposed in a repository implemented in the next few decades (Appendix E):

1. Current-generation LWRs operating in a once-through cycle with 40 GW-d/MT burnup.
2. Generation-III or upgraded current LWRs operating in a once-through cycle with 60 GW-d/MT burnup.
3. Reprocessing of LWR UOX fuel to produce plutonium-mixed oxide reactor fuel (Pu-MOX, or simply MOX) which is also used in LWRs, and disposed of directly. This is a modified-open cycle that produces a thermally hotter SNF waste type (irradiated MOX). As discussed in Appendix E (Section E-2) this case is included here because it would result from a likely transitional nuclear fuel cycle that is being implemented in the international nuclear industry, and because spent Pu-MOX fuel is a relatively hot waste form.
4. A full-recycle strategy that uses metal-fueled fast reactors operating in a transuranic (TRU) burning configuration with additional TRU material derived from recycling LWR UOX fuel.

The waste types identified for this study are summarized in Table 1.2-1. The lower burnup SNF (40 GW-d/MT) was incorporated following recommendations from previous work (Hardin et al. 2011), to represent the current used fuel inventory. This value corresponds to a projected average of all commercial SNF, to be reached sometime in the next few years. Sources for heat generation and inventory data for the waste types listed above are given in Appendix E. Note that the methodology in this report can be applied to other fuel cycles with hotter waste or larger waste packages.

Table 1.2-1 Summary of Waste Types Selected for Thermal Analysis

Strategy Sampled [A]	Fuel Cycle Description [A]	Waste Types [A]	Example Sources
Once-Through	Direct disposal of high-burnup (40 and 60 GW-d/MTHM) LWR UOX SNF	• UOX SNF (40 and 60 GW-d/MT burnup)	• Commercial LWR fleet • Generation III+ LWRs
Modified- Open	Reprocessing LWR UOX used fuel (51 GW-d/MTHM) to produce MOX fuel that is used once (50 GW-d/MTHM) then directly disposed	• MOX SNF • Co-Extraction HLW borosilicate glass	• "Transitional" variation of the French strategy with direct disposal of MOX SNF • Irradiated MOX from weapons Pu disposition (~500 MTHM total)
Closed	Reprocessing LWR UOX used fuel (51 GW-d/MTHM) to produce U-TRU metal fuel for SFRs (CR = 0.75), and repeated recycle of SFR used fuel (99.6 GW-d/MTHM) [B]	• "New-Extraction" borosilicate glass • Electrochemical ceramic HLW • Electrochemical fission-product metal HLW	• "Transitional" fast-spectrum burner strategy with TRU recycling

[A] See Appendix E for details on fuel cycle justification and waste types.
[B] SFR = sodium-cooled fast reactor; CR = conversion ratio

1.3 Geologic Settings and Host Media

The forty-eight contiguous U.S. states contain many geologic settings likely to be technically suitable for deep geologic disposal of nuclear waste. Given suitable repository concepts of operation, there is substantial confidence that compliance with regulatory standards for human and environmental protection can be demonstrated for various rock types including salt, clay, shale, volcanic rock, granite, and deep borehole settings (crystalline basement). The following discussion is based on reviews by Hansen et al. (2011) and Rechard et al. (2011) each of which cites some of the extensive, previous work done internationally and in the U.S. to investigate potential geologic host media.

Consideration of alternative disposal concepts in the 1970s and 1980s included deep borehole, sub-seabed, shallow alluvium, rock melt, direct injection, and ice-sheet disposal, in addition to mined geologic disposal (Rechard et al. 2011). Hydrogeologic settings that have been considered include saturated, unsaturated, coastal, stable interior, and islands (Rechard et al. 2011). Mined geologic disposal was selected for development in the U.S. and other countries, based on the extent of R&D that would be required, constraints from treaties and international law, and other considerations. Sub-seabed and deep borehole disposal concepts were identified as potentially promising alternatives. Deep borehole disposal has been further investigated more recently (SKB 1992; Brady et al. 2009; Arnold et al. 2011) and remains the leading alternative to mined geologic disposal.

The U.S. pursued deep geologic repository programs in granite, shale, salt, and volcanic rock in the years leading up to the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (Rechard et al. 2011). Crystalline rock investigations included a full-scale emplacement demonstration from 1978-1983 at the Climax Stock on the Nevada Test Site (Patrick 1986), investigations at the Colorado School of Mines experimental mine in the 1980's (Hardin et al. 1982), and an underground laboratory in welded tuff at G-Tunnel at the Nevada Test Site (Zimmerman et al. 1984). Shale programs were supported by laboratory testing and limited field testing (Lappin et al. 1981; Krumhansl 1983), but no underground research laboratory was developed nor was any disposal demonstration conducted in the U.S. Full-scale underground disposal demonstrations and/or underground research laboratories were undertaken at salt sites including near Lyons, Kansas, at Avery Island in Louisiana, and near Carlsbad, New Mexico.

The disposal option in unsaturated, hard rock has been extensively studied (DOE 2008b). Additional work on unsaturated, hard rock settings (including volcanic tuff) is not needed for the present generic study because much has already been learned. Further discussion of the Hard Rock Unsaturated open emplacement mode is provided in Section 1.5.

To summarize, mined geologic disposal of SNF and HLW was selected in the 1980s by the U.S. and other countries, as the most promising approach compared with various alternatives. Selection of clay/shale, salt, and crystalline media for reference disposal concepts in this study is consistent with international progress since the 1980's, and previous work in the U.S. Reference disposal concepts are selected for these media and for deep borehole disposal, in Sections 1.4 and 1.5.

Suitable geologic formations typically exhibit favorable depth, thickness, tectonic stability, and other key geologic characteristics that limit waste dissolution and radionuclide transport (Hansen et al. 2011):

- **Depth –** The disposal horizon should be determined based on site-specific conditions. Geologic isolation is attained by ensuring significant separation between the repository and the biosphere, which would provide extensive zones for robust seal systems. Rock strength characteristics would also determine a practical and functional mining depth. For the Deep Borehole concept, proposed disposal zone depths are 2 to 5 km.

- **Thickness –** Maximal thickness of the isolation medium is desired to ensure radionuclide migration does not exceed regulatory criteria or boundaries. Various "minimal" thicknesses have been put forward, generally of the order of 100 m. However, the thickness of the formation is less important than its uniformity and structure.

- **Uniformity and Structure –** The potential repository interval and surrounding rock should be reasonably homogeneous both vertically and horizontally. The related benefits are simpler and more transparent characterization and performance assessments and safer repository mining and operations.

- **Seismicity –**Seismically quiescent regions favor simpler repository design and operations, and long term performance.

Key geologic and hydrologic attributes of the host rock should also include:

- **Hydrogeology –** Low hydraulic conductivity (~10^{-12} m/sec or lower).

- **Self-Sealing –** Rocks with plastic deformation characteristics tend to reestablish diffusion-dominated transport after excavation effects and damage.
- **Hydrogeochemistry –** Reducing chemical conditions minimize degradation rates for engineered barriers and waste forms, reduce the solubilities for most radionuclides, and improve sorption. Oxidizing environments are also technically feasible but would require low hydraulic flux as found in desert environments.

Other considerations that could be important in a siting process include the potential for disruption by natural processes such as seismicity, inadvertent human intrusion, and sociopolitical issues such as proximity to population centers.

Sandia National Laboratories has recently published in-depth technical reports on the performance of used fuel/HLW repositories in generic clay/shale, salt, crystalline rock, and deep borehole settings (Hansen et al. 2010; Hansen and Leigh 2011; Mariner et al. 2011; Brady et al. 2009). These reports contain maps, originally developed by others, that illustrate the occurrence of granite, shale, and salt. The following paragraphs briefly review the basis for including these geologic settings in this study. These settings exist in the U.S., with background information available showing that geologic conditions are suitable for waste disposal.

Crystalline Rock Formations

The 48 conterminous states have an abundance of crystalline rock formations (Hansen et al. 2011). Several countries have determined that crystalline rock (also called "granite") formations are adequate for mined geologic disposal. Prior to and following enactment of the NWPA in 1982, the U.S. had an active second-repository program that evaluated crystalline rock formations. The NWPAA in 1987 ended the crystalline repository program in the U.S., but R&D programs for waste disposal in crystalline rock continued in Canada, Finland, Sweden, and Switzerland. Mined repositories in crystalline rock are currently scheduled to open in 2020 in Finland and 2025 in Sweden. Crystalline rock is also considered as a possible host medium by several other countries including China, Japan, and the United Kingdom.

Salt Formations

The conterminous U.S.A has many large salt formations, including bedded and domal salt (Hansen et al. 2011; Johnson and Gonzales, 1978). Four major regions of the U.S. where salt formations are found include: 1) Gulf Coast; 2) Permian Basin; 3) Michigan-Appalachian Region; and 4) Williston Basin. Domal salts are found in the Gulf Coast region and Paradox Basin (a Permian feature), and bedded salts are present and accessible in the other three of these major regions. In 1985, the Secretary of Energy nominated three salt sites for further consideration, and the President subsequently approved one of these three sites to fully characterize. Like the crystalline repository program, the salt repository program was ended by the 1987 enactment of the NWPAA.

Clay or Shale Formations

Shale formations meeting the general guidelines for depth, thickness, and other criteria summarized above are also common in the U.S. (Hansen et al. 2010; Gonzales and Johnson 1984). There are potentially significant differences in rock characteristics included in this category of sedimentary rock, as discussed in this recent study of the performance of shale repositories for HLW in the U.S. Shale includes a spectrum of rocks with different characteristics grading from unconsolidated claystone, to lightly indurated mudstone having shale texture and composition, to a compact form of argillaceous rock (can be referred to as argillite). Because high clay content is needed to ensure low permeability and plasticity, the term "argillaceous rock" is also appropriate for this general rock type.

Gonzales and Johnson (1984) concluded that the most desirable host rocks should be between 300 and 900 m below ground level, at least 75 m thick, relatively homogeneous in composition, and in an area of low seismicity and favorable hydrology that is not likely to be intensively exploited for subsurface resources.

Some characterization of shale as a host medium for waste disposal in U.S. has been undertaken. From the 1970s until the mid 1980s Oak Ridge National Laboratory (ORNL) led the U.S. R&D effort in this area, directing limited programs to characterize a few shale formations. Until such time as the U.S. repository program investigates specific shale formations in the U.S., international collaborations with France and Switzerland may be the most important sources of information.

Deep Crystalline Basement

Deep borehole disposal in generic crystalline basement rock could be situated virtually anywhere that geologically old (e.g., hundreds of millions of years) basement rock is within about 2 km of the ground surface. Deep borehole disposal is potentially favorable in part due to the incidence of crystalline basement rock at appropriate depth in the lower 48 states (Hansen et al. 2010, Figure 4). Though the elevated temperature and salinity of deep fluids could accelerate corrosion of steel pipes, fuel assemblies, and the waste itself, the associated low permeability, high salinity, and geochemically reducing conditions at many locations in the deep crystalline basement would limit significant fluid flow and radionuclide transport.

Other Geologic Media

In addition to clay and shale, carbonate rock may prove to be suitable for hosting a HLW repository. Sedimentary carbonates (e.g., chalk and limestone) would provide abundant pH buffering capacity, and they are thought to have favorable physical adsorption and chemical fixation characteristics, and moderate resistance to thermal damage. Carbonate rock is commonly subject to dissolution processes, especially if fractured or otherwise permeable to groundwater, and suitability would depend on site-specific formation characteristics. Although not much repository concept development has been done to date with respect to carbonate formations, the Ontario Power Generation company of Canada has proposed to build a repository for low-level radioactive waste (LLW) and intermediate level waste (ILW) in limestone at a depth of 680 m (Rechard et al. 2011).

Summary

Previous investigations in the U.S. studied various geologic media at particular locations, prior to designation of Yucca Mountain in 1987 as the single site for detailed characterization (Lomenick 1996). The forty-eight conterminous states contain many geologic formations that could be technically suitable for deep geologic disposal of nuclear waste. These include crystalline rock, clay/shale media, bedded salt, and crystalline basement rock, which are considered further in developing reference disposal concepts (Sections 1.4 and 1.5). Given appropriate repository designs, it is likely that a geologic disposal system could be implemented in any of these settings, so as to meet technical performance objectives described in Section 1 above.

1.4 Concepts of Operation

This section describes thermal limits as they might be used in a wide range of repository systems, and the design features or operational limits that are available to achieve such limits. It then develops reference concepts of operation (also called design concepts) for the host media identified in Section 1.3. The design feature discussion here focuses on thermal management, but there are many other aspects such as waste handling, storage, packaging, and emplacement details, repository construction and operations details, and sealing, closure, and monitoring, that make up that overall concept of operations. These are beyond the scope of this study, but some are being studied separately (e.g., storage) or are included in generic R&D studies (Jove-Colon 2010). Some of these details such as waste handling and packaging involve technologies that are not specific to the geologic host medium, while others such as sealing, closure, and monitoring are likely site specific and could be deferred to a later phase in the waste management program. A catalog that includes many of these alternatives was developed for this study (Hardin et al. 2011, Appendix I).

1.4.1 Concepts of Operation: Thermal Management

Experience with disposal concepts for heat-generating nuclear waste has demonstrated that thermal management is important because it constrains such key elements as repository layout, waste package size, design of other EBS components, and operations. Thermal constraints may be imposed as limiting temperatures, or limiting results (minimal or maximal) for thermally driven processes. Such constraints may be imposed for the host rock (or other natural features) or for engineered systems.

Far-Field Thermal Constraints

1. Limit thermally induced stresses or displacements in the host rock or other units, at some distance from the repository, to limit formation of new hydrologic flow paths, or to limit degradation of boreholes and mined openings. For some disposal concepts such as mined disposal in salt or clay/shale, large rock deformations are desirable because they close openings and seal the repository to fluid movement.
2. Limit large-scale thermal expansion, to limit or prevent induced fracturing or displacement along faults or fractures. For example, thermoelastic expansion throughout the repository host rock and other units will produce thermal stresses on faults and other discontinuities where potentially important displacements may occur.

While some thermal constraints pertain to the far-field, most pertain to the near field where temperatures are greater. Constraining temperature history in the near-field effectively constrains temperatures in the far-field. The U.S. repository concept for unsaturated, volcanic tuff is unique in constraining far-field temperature separately, because its peak temperatures are well above the boiling point for water or brine, while the host medium supports hydrologic flow (which is assured in the far field by limiting temperature to below boiling). Other concepts as discussed in this report, have found near-field temperature limits to be sufficient.

Near-Field/Engineered Barrier System Thermal Constraints

1. Limit alteration of clay in buffers, for example by illitization or cementation. Alteration generally involves dissolution, aqueous transport, and precipitation. Alteration products typically include silica (as a precipitate). Clay alteration generally degrades swelling pressure, increases rigidity promoting fracture, and potentially decreases sorption. For

example, the Swedish program has adopted a peak buffer temperature of 100°C (after swelling; SKB 2011, Section 5.5.1). Variations on clay buffer limits have been proposed, for example, limiting an outer portion of the buffer cross section to 125°C (NAGRA 2003). This study uses a target maximum temperature of 100°C for clay buffers.

2. Limit thermally induced micro-cracking in the less ductile crystalline rock types (e.g., crystalline, igneous or metamorphic), to avoid degradation of in situ mechanical properties or creation of flow paths. For example, a limit of 200°C based on laboratory studies, has been used to limit thermal degradation of in situ rock characteristics (Hardin et al. 1997). Crystalline rock could exhibit this mode of degradation, but with the use of clay buffers (as in this study) the clay temperature limit is controlling.

3. Limit temperature of the host medium to control uncertainty in performance models. For salt, a more ductile material, a target value of 200°C has been proposed for the maximum temperature, to limit uncertainty in performance assessments, although higher peak temperatures may be possible if supported by test data (BMWI 2008). The Environmental Assessment for disposal of SNF and HLW at the Deaf Smith County, Texas site indicates that maximum allowable repository temperature is 250°C (DOE 1987a). This study uses a target maximum temperature of 200°C for salt media. For the Deep Borehole disposal concept no near-field temperature limits have been recognized because no performance credit is taken for the near-field host rock, and the boreholes would be spaced far enough apart to preserve the far-field natural barrier function (Brady et al. 2009). Also, the borehole geometry, and thermal loading limited to one PWR SNF assembly (or equivalent) per waste package, serve to limit peak temperatures.

4. Limit the temperature of argillaceous host media to avoid mineralogical changes (e.g., cementation) and thermally driven coupled processes (THM, THMC). Natural clay or shale formations typically contain more impurities such as potassium, which can react with clay minerals, thus temperature limits will be similar to, and possibly lower than for clay buffers. The French authority Andra has proposed a 90°C limit for the argillaceous material surrounding waste packages, in the proposed repository in Callovo-Oxfordian shale (Andra 2005a, Section 1.2.3.4). This study uses a target maximum temperature of 100°C for argillaceous clay/shale media, by analogy to the maximum temperature adopted above for clay-based buffers.

5. Limit the migration of brine-filled fluid inclusions in salt, up the thermal gradient towards heat-generating waste. The rate of brine migration depends on the salt temperature and its gradient, and could be a threshold effect. For example, earlier studies suggested no migration below a temperature on the order of 50°C, or below a gradient of roughly 0.1 C°/cm (levels consistent with Jenks and Claiborne 1981).

6. Limit the waste package surface temperature. Temperature at the waste package surface is used in this study to represent the peak temperature anywhere outside the waste package. For enclosed disposal concepts, the waste package surface temperature is the maximum temperature of the buffer, backfill, or host rock.

7. Limit waste package material temperature

8. Limit cladding temperature to 400°C for normal conditions of storage and short-term pre-closure operations (NRC 2003). During loading operations, repeated thermal cycling

(repeated heatup/cooldown cycles) may occur but should be limited to less than 10 cycles, with cladding temperature variations that are less than 65°C each (NRC 2003).

9. Limit cladding temperature to 350°C during permanent disposal (SNL 2008).
10. Limit the peak centerline temperature of borosilicate glass waste forms below 500°C at all times, to avoid devitrification or crystallization. Similar limits have been established by the French program (450°C; Andra 2005a), the Swiss program (500°C; NAGRA 2002, 2003), and the former salt repository program in the U.S. (500°C; DOE 1987a, Appendix A). Preliminary temperature limits for lanthanide glass, glass-bonded zeolite, and metal alloy wastes from electrochemical processing have also been developed (Carter et al. 2012a).

The higher temperature limits for cladding, glass waste forms, and other waste types are not limiting in the sense that other limits, particularly 100°C for clay-based buffers or host media, control system thermal loading. Temperature differences between the inside and outside of SNF waste packages were evaluated by BSC (2008b) and found to be on the order of 50 C° or less depending on heat generation rate.

Note that in saturated settings where the repository is situated at depths of hundreds of meters, the local boiling temperature for water may be well over 200°C. The EBS may not be saturated when peak temperatures occur soon after emplacement, especially in low-permeability host media and in repository openings that are initially unsaturated or dehydrated, and have been backfilled, plugged, and/or sealed to inhibit water ingress. Thus, boiling could occur locally within the EBS with temperatures near 100°C, and the European programs have adopted corresponding temperature limits. Thus, temporary unsaturated environments could exist during the thermal period (and hydration phase) for Crystalline (enclosed) and Clay/Shale (enclosed) concepts where dehydrated clay-based buffer/backfill materials are used, and in other settings with low-permeability host media that become dewatered in the near field, such as shale and salt.

There are two types of temperature limits that may be applied: peak temperature and temperature-time exposure. Peak temperature limits are appropriate to prevent relatively rapid processes that exhibit temperature threshold-like behavior (e.g., cementation in clay buffers). Engineered materials may exhibit temperature-time dependent degradation, whereby the time above a threshold temperature, or the integration of degradation as a function of both time and temperature, is more important (e.g., metal de-alloying). Examples are the potential thermal sensitization of stainless steel and carbon steel (Fox and McCright 1983; Farmer et al. 1988) and de-alloying of Alloy 22 (BSC 2008c). Other degradation processes may have rates that are functions of temperature and mechanical load (e.g. high temperature creep).

It is important to note that thermal constraints are considered here for the purposes of advancing repository design concepts, establishing reference configurations, and generating cost estimates for alternative disposal concepts. Ultimately, thermal constraints will be considered in the context of FEP screening, supported by performance assessment and risk-based consequence analyses. In other words, constraints discussed here likely do not describe all thermal limits that may be imposed. Repository designers may choose to use thermal limits as a basis for limiting or excluding FEP, or to limit the amount of R&D needed to support FEP analysis, or in response to regulatory input. With that said, however, the limits considered here address some major FEPs, and the limits needed for further FEP analysis are likely to fall within those discussed here.

1.4.2 Thermal Management Options

Host Rock Heat Dissipation

The geologic setting (including groundwater and surface processes) is the immediate sink for heat generated in the repository. Host rock thermal conductivity determines the temperature increase from the far field, up the thermal gradient to the waste packages, for any particular repository heat input. Geologic media have different thermal conductivities, ranging from relatively porous, unsaturated, low-conductivity media, to high-conductivity media such as certain salt formations (see Section 5 and Appendix D of this report). As shown in Section 5, selecting a high-conductivity medium can lower peak temperatures (other factors held constant) and thereby provide greater flexibility in repository design and loading strategy.

Other host rock attributes that can affect heat dissipation include repository burial depth, and change in boundary conditions such as surface erosion, glaciation, etc. Changes imposed at greater distance L affect repository temperature at later times Δt, according to the relationship $\Delta t \propto L^2 / \kappa$ where κ is thermal diffusivity. (The proportionality indicates that Δt depends on time-dependent changes in heat output, and on the relative magnitude of temperature change.) The time at which an effect is felt varies as L^2, which means that future changes at the ground surface would influence the repository well after the peak waste package temperature occurs.

Waste Package Size

The size of a waste package controls the amount of heat-generating waste that it contains, and the associated heat output. As demonstrated in Appendix D, waste package instantaneous heat output is a better predictor of peak temperature than waste package diameter. Other factors held constant, smaller and therefore cooler waste packages produce significantly lower temperatures in the repository near field, while the number of packages, number of handling operations, and repository footprint are increased relative to concepts with larger packages. Smaller waste packages can facilitate shorter duration of decay storage, and therefore earlier emplacement in a repository. The smallest SNF waste packages for reference concepts described in this study are for the single-assembly Deep Borehole concept (Section 1.4.5.4) while the largest (21-PWR or equivalent) are considered for open modes (Section 1.5).

Blending of Waste Types, and Sequencing of Emplacement

Where the nuclear fuel cycle produces wastes that differ with respect to heat output because of inventory, age, or other characteristics, co-disposal within individual packages can serve as a thermal management tool. Thus, high-burnup SNF assemblies can be combined with low-burnup assemblies, or with other cooler waste types. High-output HLW can be combined with cooler waste of different types in the same packages. For enclosed, mined emplacement modes described in this report the maximum temperatures are expressed locally and depend heavily on the heat output of individual packages. Thus, blending within waste packages could have an important impact on thermal management. Such blending would not occur at the repository, but at an upstream consolidated storage facility or repackaging facility that could be co-located with either a storage facility or the repository. Blending of different packages with different heat output characteristics is also an alternative, although segregation of similar waste types in different areas of the repository could be more efficient and simpler to analyze.

Waste Package Spacing

Waste package spacing can vary from end-to-end emplacement, or “line loading”, to a “point loading” approach that separates the packages. Line-loading produces more uniform temperatures in the near-field host rock, and maximizes the repository loading density for in-drift emplacement, while point-loading enhances the spreading and dissipation of heat.

The thermal influence from adjacent waste packages is expressed from a few years to hundreds of years after emplacement. The relative contributions to waste package temperature from the immediate package, its neighbors in the same drift, and from adjacent drifts, are investigated in Section 3 of this report. For enclosed modes the peak contribution from neighboring packages generally occurs well after the peak temperature, especially for younger SNF or HLW, so waste package spacing has limited value for controlling peak temperature. For open modes the waste is older at closure (with more slowly changing heat output), and peak temperature occurs later, so adjacent packages (and drifts) have relatively greater effect.

Emplacement Drift, Alcove, and Borehole Spacing

The spacing between adjacent emplacement drifts, alcoves, or boreholes has a similar effect to the in-drift waste package spacing discussed above. Within adjacent drifts, alcoves, or boreholes, line-loading or point-loading may be used. Drift, alcove, or borehole spacing can be used to limit far-field host rock temperatures (SNL 2008).

A multi-level repository layout could be another way to achieve cooler repository temperatures. In the 1980’s, when there were nine sites still under consideration in the United States, multi-level repository layouts were considered for the Richton Salt Dome site in Mississippi and the Cypress Creek and Vacherie Salt Dome sites in Louisiana. This was appropriate because salt has high thermal diffusivity (Appendix D and Section 3) and domal salt typically has great depth extent. By contrast, bedded salt typically limits repository extent except parallel to bedding. Multi-level waste package arrays can increase repository capacity while meeting peak temperature limits within only a few years after emplacement. However, over tens to hundreds of years (e.g., for open modes) they produce average or peak temperatures in the host rock that may be significantly greater than for single-layer layouts (DOE 1999).

Aging

Aging the SNF or HLW incidental to storage, or deliberate aging as part of repository staging and operations, can substantially reduce the thermal power emitted by the waste during repository operations and after permanent closure. The effectiveness of aging, also called decay storage, as a thermal management strategy will vary by waste form, and is generally limited to short-lived radionuclides (e.g., half-lives less than 100 yr). The simplest effect of aging is to allow decay of short lived fission products Cs-137 and Sr-90, which are present in SNF and many types of HLW, and produce the majority of decay heat for 30 years or longer (after SNF has cooled in reactor pools). Aging also allows decay of short-lived actinides such as Pu-241 and Am-241, which are present in SNF and TRU-containing waste forms. In many waste forms including those described in Appendix E (for example, Table E-2 and Figure E-1) peak temperatures at the waste package are caused by short-lived fission products, while post-peak temperatures, and the maximum average host rock temperature, are more strongly associated with decay of certain actinides (e.g., Am-241) with somewhat longer half-lives.

Over periods longer than approximately 100 years, alpha decay of various actinides—principally Pu and Am—dominates the decreased heat output of UOX SNF. The actinides account for the majority of the cumulative heat that is generated after decay of short-lived fission products, during the first l,000 years after reactor discharge.

The effectiveness of aging for MOX SNF will differ from UOX SNF. The heat output of irradiated Pu-MOX fuel (Table E-9 and Figure E-4) is dominated by an abundance of relatively long-lived TRU elements rather than short-lived fission products, for any time period relevant to practical storage or repository operations. Because of the longer half lives of the TRU elements, and their relatively abundance, aging of MOX SNF is not as effective at reducing heat output as aging of UOX SNF.

Repository Ventilation

Removal of heat by forced or natural convection during an operational period of sufficient duration to lower peak repository temperatures. Typically this period is on the order of 50 to 100 yr, but extends to 250 yr or longer in some concepts (Section 3.2). Ventilation used with in-drift emplacement readily removes up to 80% or more of heat generated by waste packages (BSC 2004). At the same time it dries out the disposal environment, which may not recover moisture to hydrate clay-based materials, or transport radionuclides, for thousands of years (based on processes discussed by Jove-Colon et al. 2012).

Backfill or Buffer Thermal Conductivity

Where the limiting temperature is within the buffer or backfill (or at the inner boundary), thermal management goals could be achieved by using admixtures to increase thermal conductivity of the buffer or backfill material. While this might work in the long term, buffer and backfill materials are generally emplaced in dry, compacted form, and may remain dry throughput the period of maximum temperatures (i.e., hundreds or thousands of years). Hence, relying on hydrated properties may not be appropriate, but buffer material could be protected from damage at temperatures greater than 100°C, in its dehydrated form (Hardin and Sassani 2011).

Segregated Disposal of Waste Forms

Another proposal for reducing the heat output of waste forms to be emplaced in a repository, is to separate the short-lived fission products (e.g., chemical separation of Cs and Sr, thus including all the isotopes of each element), and segregate them from other wastes in a different part of the repository. The segregated Cs and Sr (containing mostly short-lived, heat-generating Cs-137 and Sr-90) could overheat the part of the repository where they are emplaced, with limited impact on the overall repository performance because these radionuclides (and their short-lived daughters) decay to stable nuclides. The other fraction of the waste containing actinides and longer-lived fission products, would be emplaced elsewhere in the repository in a lower temperature environment. This proposal could allow more dense loading of the long-lived waste in a different part of the repository if: 1) separation of all other long-lived radioelements is essentially complete, and 2) Cs-135 (half-life 2.3 million years, a fission product with more long-lived radiotoxicity) is separated from Cs-137, or is sufficiently immobile in the disposal environment. Segregation of Cs and Sr could be an effective thermal management tool, without compromising waste isolation, if the disposal environment effectively traps Cs-135 by chemical sorption.

Reactor transmutation of separated Cs (containing Cs-135) in targets has been proposed as a way to minimize the contribution of Cs-135 to radiotoxicity of a segregated waste form, but transmutation of fission products was determined to be relatively ineffective by a previous system study (Sevougian et al. 2011). Instead, a more feasible strategy may be to separate Cs and Sr, age the waste form for 50 to 100 years for cooling, and then dispose with other cooler waste forms in a geologic repository. Such a strategy could be incorporated into any of the HLW disposal concepts presented in this report.

1.4.3 Waste Package Design Considerations

This section summarizes how different waste types, including SNF, HLW glass and other refractory waste types, and LLW, would be packaged for disposal in a geologic repository. A fundamental distinction is made between HLW and SNF canisters, and overpacks for storage, transport, and disposal. Together the canister and disposal overpack comprise the waste package. A waste canister is generally sealed permanently at the point of origin, thereby avoiding any further direct handling or exposure of the waste during successive operations. Overpacks provide economical means to meet different requirements such as heat dissipation, impact damage limits, and corrosion resistance. Overpacks for storage and transport would be re-useable, whereas those for disposal would become permanent parts of the EBS at emplacement.

Waste Packages for SNF and HLW

Canisters for SNF provide structural integrity and support to the fuel, criticality control, heat dissipation, containment during handling and repackaging, and may provide containment after permanent disposal. These functions are met using internal features such as the basket, thermal shunts, moderator exclusion features, neutron absorbers, flux traps, and inserts or fillers. To be included, these internal features must be engineered “up front” for all storage, transport, and disposal functions, for the containers to be permanently sealed at the point of origin.

Typical SNF canisters are thin-walled (e.g., 15 mm) stainless steel structures, with internal stainless steel features to hold fuel assemblies and provide strength and rigidity. Canisters may have external features such as flanges, rings, trunnions, or skirts to facilitate handling. Neutron absorbing structures can be made from borated stainless steel, or other materials with protective coatings. Moderator exclusion can be addressed in container design by incorporating filler materials, or simply limiting the size of the containers and the quantities of SNF they contain. Canisters are sealed by welding (bolted closures receive less credit in transportation safety analyses, and require more frequent inspection).

A previously designed, multi-purpose transport/aging/disposal (TAD) canister for SNF incorporated a range of features (DOE 2008b). The TAD canister design was unique among disposal containers proposed internationally because of the relatively large quantity of SNF that it could hold. A canister similar to the TAD design is envisioned for “open” emplacement modes such as the Hard Rock Unsaturated open mode discussed in Section 1.5.

Pour canisters for HLW glass, or other refractory waste forms, are typically made from stainless steel to resist corrosion in air at elevated temperature, and from radiolysis during storage. Pour canisters are simple, thin-walled vessels with welded closures, and are designed to have low mass and to cool quickly. The same canister design may be used for other waste forms such as compacted hulls and hardware, or immobilized process waste.

Disposal overpacks have been proposed for repository projects in the U.S. and internationally. For the TAD canister discussed above, the overpack consisted of an additional, structural layer of stainless steel, enclosed by an outer corrosion-resistant layer (DOE 2008b). For SNF this overpack just fit over the TAD container, while for HLW it was configured with an internal rack to hold HLW pour canisters and stainless canisters containing defense SNF. Disposal overpacks typically provide structural support, and may provide no corrosion performance, or relatively short corrosion lifetime for limited waste containment (e.g., using corrosion allowance materials with lifetimes of thousands of years), or long corrosion lifetime for waste containment (e.g., using corrosion resistant materials).

For other projects in the U.S., disposal overpacks of carbon steel and stainless steel have been proposed (e.g., ONWI 1985, ONWI 1987a,b). Carbon steel corrosion occurs by well understood mechanisms making it suitable as a "corrosion allowance" material in applications where waste containment is required for only a few hundred to a few thousand years (DOE 1998). Thick-walled carbon steel overpacks facilitate waste handling and ensure package integrity during repository operations. Overpacks of titanium have been proposed for use in crystalline rock (discussed below) where a need for long containment lifetime is indicated.

For the Swedish KBS-3 disposal concept, a thick-walled package of pure copper has been proposed (SKB 2011). Copper has a very small rate of corrosion in the chemically reducing conditions present within the clay buffer, in the proposed host rock. The package would contain a nodular cast iron insert, designed to support the SNF and resist external swelling pressure, and to corrode slowly while consuming oxygen once waste package breach occurs. As proposed, the SNF waste will not be sealed in a stainless steel container, so dry handling may be used in an "encapsulation" facility.

For the French (Andra) disposal system in shale, HLW canisters of stainless steel are proposed, with direct disposal in boreholes lined with carbon steel (Andra 2005a). Used fuel would also be canistered in stainless steel, with a steel overpack, and emplaced in a clay buffer. A Swiss (NAGRA) proposal would embed HLW canisters in cast ductile-iron waste packages, to be emplaced in a clay buffer (NAGRA 2003). The Belgian approach envisions an engineered barrier consisting of stainless steel canisters holding HLW inside a carbon steel overpack surrounded by thick concrete (Hansen et al. 2010).

Storage and transportation overpacks are beyond the scope of this report. The following sections summarize some key selections that would be made in designing waste canisters and disposal overpacks for a geologic repository.

Geometrical Constraints

The number of used fuel assemblies per waste package (assuming no rod consolidation) is a consideration when choosing the size and other design details for SNF containers and packages. The goals are efficient arrangement in a round package configuration, heat transfer from the inner fuel assemblies, and the overall maximum heat output requirements for storage, transport, and disposal. Desirable arrangements typically use ¼ or ½ symmetry to allow for a simple and more readily manufactured arrangements. The cells for individual fuel assemblies are arranged in rows, and junctions between neighboring cells form cross-shapes rather than T-shapes. (T-shaped intersections may be structurally inferior due to the increased possibility of buckling of the cell walls.) Using these geometric constraints, a limited number of SNF waste package configurations is possible without de-rating the capacity.

Previous studies have quantitatively evaluated SNF waste package arrangements by calculating packing efficiency by various measures. In general, larger waste packages make significantly more efficient use of materials and enclosed volume. However, efficiency in terms of wasted space is not linear with respect to the number of assemblies accommodated, and there are optimum arrangements that tend to bracket large, medium, and small waste package sizes. Configurations commonly considered for SNF canisters include: 24-PWR/45-BWR, 21-PWR/44-BWR, 12-PWR/24-BWR, 9-PWR/21-BWR, and 5-PWR/12-BWR.

For the enclosed emplacement modes for clay/shale and crystalline media in this study, the 4-PWR/9-BWR configuration is relied on because it is nearly as space-efficient as a 5-PWR configuration, is being considered in other repository concepts internationally, and serves to limit temperatures as discussed in Section 3. A single-PWR assembly waste package is selected for the Deep Borehole concept, possibly with rod consolidation.

Waste package diameters were selected based on international accounts, and previous conceptual design studies in the U.S. (Table 1.4-1). The 4-PWR package diameter selected for this study is smaller than previous concepts (SKB 2006; NAGRA 2003, Figure 7). A smaller diameter is possible with thinner basket and overpack, and represents a minimum size with a 5-cm overpack wall thickness. The 12-PWR package diameter is based on the original salt repository project conceptual design (DOE 1987a) and the 12-PWR-long waste package design (DOE 2001, Table 2). The 21-PWR size is selected for comparison with the transport, aging and disposal (TAD) canister-based system previously proposed for commercial SNF (DOE 2008b). The SNF canister is assumed to have the same dimensions as the TAD, with a 5-cm overpack thickness. The 32-PWR package size is based on a bounding envelope for existing dual-purpose canisters, plus a 5-cm disposal overpack. The 32-PWR size is used in sensitivity analysis (Section 3.2.2.4) and finite-element thermal analysis for salt (Appendix C) but is not included in the reference concepts presented in this report (Sections 1.4.5 and 1.5). Waste package sizes in Table 1.4-1 were used in reference concept development, thermal analysis, and cost estimation. Small differences in diameters used for thermal analysis are discussed in Section 3.1.1.1.

The inclusion of open emplacement mode disposal concepts in this study extends the range of reference repository concepts to include some that could accept larger (21-PWR/44-BWR) waste packages. Efforts to find disposal solutions that could accommodate even larger dual purpose (storage and transportation) canisters is part of ongoing Used Fuel Disposition Campaign work.

Table 1.4-1 Waste Package Outer Dimensions

Waste Package	Diameter (m)	Length (m)
4-PWR/9-BWR assemblies	0.82	5.0
12-PWR/24-BWR assemblies	1.29	5.0
21-PWR/44-BWR assemblies	1.60	5.0
32-PWR/64-BWR assemblies	2.0	5.0

Integration with Surface Facilities and Storage and Transportation Systems

As reactor operators run out of space in spent fuel pools, UNF is being loaded into a range of dry storage and dual-purpose casks. Current trends in UNF storage and transportation indicate a preference for larger capacity containers. For example, cask vendors have been issued regulatory approval (10 CFR Part 72 certificates) for 32-PWR/64-BWR storage casks (NWTRB 2010), and larger canisters (e.g., 37-PWR) are being deployed. These trends are driven by cost savings in materials, handling, and packaging efficiency. Loading more UNF assemblies into a single canister decreases the total number of operations needed to off-load fuel from pools (e.g., canister preparation, drying, sealing, and transfer). The same economics also apply to disposal waste packages, such that higher capacity packages are associated with lower total cost and fewer operations such as lifts and transfers. On the other hand, smaller waste packages are inherently cooler and allow less decay storage time prior to emplacement, for some disposal concepts (Section 3.1.2.5). A reduction in waste package capacity by a factor of four results in an a four-fold increase in the number of operations at the surface and underground, including welding, inspection, handling, transport into the repository, and emplacement.

Hence, the establishment of centralized interim storage capability for UNF involves tradeoffs between the economics of storage and fuel handling at the reactor plants, vs. the requirements of disposal (considering whether UNF will eventually be directly disposed or reprocessed). The reference enclosed emplacement concepts selected in this report (Section 1.4.5) for mined disposal would use waste packages that are significantly smaller than the storage containers currently being loaded by U.S. nuclear utilities, to accommodate thermal limits. Thus, there is the opportunity to optimize the storage and disposal systems, to extend the range of efficient disposal solutions available in the future.

Waste Package Material Selection

The most common materials considered for reducing environments are carbon steel, stainless steel, copper, and titanium (Shoesmith 2006; Rebak and McCright 2006). Corrosion performance of waste package materials will also be a function of temperature, ionic strength, pH, and concentrations of halide ions.

Steel has a number of attributes that might make it a suitable candidate as a canister for SNF and HLW disposal. It is widely available at relatively low cost, and is relatively easy to weld. Carbon steel and low-alloy steels have been extensively tested in ground water environments for several decades. Researchers in the Swedish repository program have studied the anoxic corrosion behavior of carbon steel and cast iron in ground water at 50°C and 85°C and the impact of the presence of copper on the type and the mechanical properties of the films formed on the iron alloys (Smart et al. 2001). Andra has specified the use of carbon steel for SNF container overpacks, in the Callovo-Oxfordian argillite formation (Andra 2005a). NAGRA has identified carbon steel as the primary candidate waste package material for the Swiss repository concept in Opalinus Clay (NAGRA 2009).

The waste package conceptual design for both vertical and horizontal emplacement concepts in the proposed salt repository at Deaf Smith, Texas was a heavy-walled container made of low-carbon steel. These containers were sized to contain 4-PWR/12-BWR fuel assemblies. As an alternative for cooler SNF, the containers could be configured for consolidated SNF rods from 12-PWR/30-BWR assemblies (ONWI 1987b). Carbon steel and cast ductile-iron have been identified as candidate waste package materials for salt repositories in Germany (Weber et al. 2011). Note that performance assessment models may take no significant containment credit for steel containers, particularly for long-term (i.e., $>10^5$ years) assessments.

Copper can be a suitable waste package material because it is thermodynamically stable under anoxic conditions and it has a tendency to undergo slow, uniform corrosion rather than localized corrosion in reducing environments. The SNF waste package planned for use in Sweden will consist of a nominally 50-mm thick layer of copper over an insert of cast nodular iron which will provide mechanical strength (SKB 2010a). Copper is also the identified waste package material for the Finnish repository concept, and is identified as an alternative to steel in the Swiss repository concept (NAGRA 2003).

As alternatives to active (corrosion allowance) canister materials such as copper and carbon steel, passive alloys of nickel and titanium, and stainless steel, have been considered as waste package materials. These materials form a passive, stable oxide film on the surface in most chemical environments, and the physical properties and chemical inertness of this film limit the general corrosion rate. Passive materials may undergo localized corrosion (e.g., pitting or crevice corrosion) if the oxide film breaks down locally. The behavior of stainless steel has been studied in the Boom Clay, and it was identified as a candidate material for the Belgium repository concept (Kursten et al. 2004).

Titanium alloys have also been studied as candidate waste package materials in Canada, Japan, and Germany. Titanium alloys were selected as potential alternatives because of their excellent performance in more aggressive brine solutions compared, for example, to stainless steels (Kursten et al. 2004; Rebak 2007).

Amorphous metal and ceramic thermal spray coatings have been developed with excellent corrosion resistance and neutron absorption. These coatings, with further development, could be cost-effective options to enhance the corrosion resistance of waste packages and other EBS components, and to limit nuclear criticality in canisters for transportation, aging, and disposal of SNF. Iron-based amorphous metal formulations with chromium, molybdenum, and tungsten have shown corrosion resistant properties. Rare earth additions enable very low critical cooling rates to be achieved. The possible boron content of these materials and their stability at high neutron doses enable them to serve as high efficiency neutron absorbers for criticality control. Another corrosion resistant option, ceramic coatings, may provide even greater corrosion resistance for EBS applications, although the boron-containing amorphous metals are still favored for criticality control. These amorphous metal and ceramic materials have been produced as gas-atomized powders and applied as nonporous coatings with nearly full density, using the high-velocity oxy-fuel process. Blink et al. (2009) summarize the performance of these coatings as corrosion-resistant barriers and as neutron absorbers, and also present a simple cost model to quantify the economic benefits possible with these new materials.

Waste Packages for LLW

A range of different types of secondary containers or package is in use or has been proposed for LLW disposal, and could be used for co-disposal of LLW with HLW or SNF in a mined geologic repository. These include standard 55-gallon drums, shielded drums, standard waste boxes (SWBs), and high-integrity containers (HICs). Whereas LLW can generally be disposed in near-surface facilities licensed for the purpose, this study considers the option to use otherwise uncommitted volume within a mined repository. For repositories in salt, and possibly in clay/shale, this means that access and main drifts or tunnels could be completely filled with LLW, similar to the disposal rooms at WIPP. Packages for LLW would be the same in this application as for near-surface disposal. Low-level waste could also be used to fill extra volume in a repository in crystalline rock, but with the addition of low-permeability buffer or backfill material between the rock and the LLW. Greater-than-Class-C (GTCC) waste, which has more activity than LLW, could be disposed of in similar packages such as the SWB or HIC, or variations as required to establish a licensed capability.

1.4.4 Emplacement Mode Considerations

Emplacement modes influence repository layout, construction, waste package handling operations, and waste package sizes. The emplacement mode may also influence occupational exposures, facility inspections and monitoring (e.g., performance confirmation activities, and retrievability concepts.)

Enclosed vs. Open Emplacement Modes

An important categorization of emplacement concepts is to consider whether or not a concept calls for waste packages to be in direct contact with any surrounding medium such as buffer, backfill, or host geology. This impacts thermal management because it determines if there is air space around the waste packages, in which heat can be dispersed principally by thermal radiation, and natural or forced convection. Section 1.4.5 of this report identifies reference enclosed emplacement modes, while Section 1.5 identifies reference open modes. Open emplacement concepts are amenable to rock types where excavated openings persist for long time periods (e.g., for decades or longer) either because of the inherent stability of the opening or reliance on long-lived ground support. In saturated host media, open emplacement concepts require backfilling or plugging/sealing of emplacement drifts prior to closure, so that the openings do not serve as conduits for groundwater flow that degrades long-term waste isolation performance (discussed further in Section 1.5).

Note that low-permeability media, particularly plastic clay or shale, and salt media, retain low permeability because of plastic deformation. Where such permanent deformation occurs underground openings cannot be maintained for decades, and the applicable emplacement modes are enclosed, not open. Importantly, enclosed modes are typically less efficient at transmitting heat away from waste packages, and produce higher near-field temperatures (other thermal loading details held constant). The higher temperatures can be offset by aging the waste before disposal, by smaller waste packages, and to a limited degree, by wider spacing between waste packages.

Forsberg and Dole (2011) pointed out that emplacement mode choices can influence the complexity and cost of retrieval at some future time. In general, enclosed emplacement modes are associated with more complex retrieval operations. This can be at least partly addressed in self-sealing clay/shale or salt media with use of appropriate ground support and/or liners for emplacement openings, until the end of repository operations.

In-Drift-Emplacement Mode

The in-drift emplacement mode concept consists of waste packages placed horizontally along or parallel to the axis of an emplacement drift. For normal loading operations, waste packages are placed sequentially in each drift. This is considered to be an open emplacement mode unless combined immediately with backfill or a buffer material. Advantages are constructability and simplicity of operations. This emplacement mode does not provide any shielding features. Disadvantages for in-drift emplacement with enclosed systems include potentially large amounts of backfill, and emplacement of backfill remotely, in a hazardous radiological environment. Disadvantages for in-drift emplacement with open systems may include rockfall damage to the EBS, or other damage caused by seismic ground motion.

Vertical Borehole Emplacement Mode

For this mode waste packages are emplaced in vertical boreholes drilled into the floor of access drifts (Figure 1.4-1). The depth of each vertical borehole is sufficient to accommodate a waste package, sealing or buffer materials, and possibly a shield plug. A liner may be installed in each vertical borehole, except where not needed for borehole stability and/or waste package alignment, or where access to the borehole wall is required for characterization. If a buffer around the waste package is part of the disposal design concept, the borehole is sized accordingly. Vertical borehole emplacement is considered an enclosed emplacement mode. Advantages of vertical emplacement include the ability to characterize the near-field rock exposed in the boreholes, and shielding to facilitate access after emplacement. Disadvantages include the complexity and cost of drilling many vertical boreholes. Waste packages would likely be transported underground in a horizontal attitude, then rotated into vertical orientation for emplacement. Similar steps would be taken at the surface to install canistered fuel into disposal overpacks, so the steps are feasible but would need to be adapted to underground operations.

Horizontal Borehole Emplacement Mode

One or more waste packages can be emplaced in horizontal boreholes drilled into the walls of emplacement access drifts or rooms (Figure 1.4-3). For some concepts such as the KBS-3H, the boreholes may be long enough for many packages. Advantages include efficient use of repository area, particularly if multiple waste packages are emplaced in each borehole. Another advantage is the possibility that waste packages will never be handled underground in the vertical orientation. Disadvantages include the complexity and cost of drilling many horizontal boreholes. Also, horizontal boreholes in the host medium may need to be lined, depending on rock characteristics, to ensure rock stability during operations and to facilitate sliding of packages into final position. Sliding can be facilitated using metal rails or skids (Posiva 2007; IAEA 2003a) or a pallet with rollers (Graf et al. 2012).

Backfilled Alcove Emplacement Mode

Waste packages are placed on the floor in small alcoves, and covered in crushed salt or other granular material derived from the host formation (Figure 1.4-2; Carter et al. 2011). Advantages include simplicity and low cost, use of shielding from crushed rock, and the result that drifts are backfilled. Disadvantages may include inefficient heat transfer through the crushed rock backfill.

Deep Borehole Emplacement Mode

Potentially acceptable low-permeability, crystalline basement rock is reasonably common in the U.S. at depths of 2 to 5 km. A vertical borehole with a minimum diameter of approximately 45 cm is drilled into crystalline basement rock to a total depth of approximately 5 km (starting at the surface with a larger diameter; Arnold et al. 2011). The borehole is assessed for stress conditions, mechanical stability, and other properties, including water chemistry, hydraulic conductivity of the wall rock, and geothermal gradient. If conditions are acceptable, then oilfield casing is grouted in place in the disposal interval, ensuring stable borehole conditions for emplacement operations. A linear array of waste containers is then placed in the lower 2 km of the borehole. Canisters are surrounded by clay-based slurry, and the upper (unlined) 3 km of the borehole is sealed by a combination of compacted clay or other sealing elements, and concrete plugs (Figure 1.4-4).

The advantages of the Deep Borehole disposal concept are: enhanced reliance on natural barrier performance, and potentially low cost and flexible siting. Transport pathways to the biosphere are long, at least several kilometers, and transport velocities are demonstrably slow. The natural phenomena indicative of potential natural barrier performance, including flow permeability, hydraulic head, and geochemical and isotopic tracers, are relatively easy to measure and interpret. Disadvantages center on drilling feasibility and waste retrieval capability.

1.4.5 Selection of Enclosed Emplacement Mode Disposal Concepts

Enclosed emplacement modes are defined to include disposal concepts that call for waste packages to be in direct contact with any surrounding solid medium such as buffer material, backfill, or host geology. For enclosed modes the direct contact begins immediately at emplacement or shortly thereafter, so that contact influences peak near-field temperature.

Previous Studies

A review of geologic disposal concepts was undertaken for the nuclear waste management authority in the United Kingdom (Baldwin et al. 2008). The approach included an identification phase similar to this study, and an evaluation exercise that scored 12 alternative concepts. The concepts identified can be compared directly to concepts presented in this report, with a few exceptions. Specifically, the major similarities and differences are:

- In-drift emplacement is used in both studies, with both corrosion allowance (e.g., carbon steel) and corrosion resistant waste packages.
- Borehole emplacement, accessed from underground tunnels, is used in both studies.
- This report does not consider backfilling drifts with cement or depleted uranium.
- Super-containers are regarded in this report as the result of engineering optimization for implementing other concepts, i.e., they are not identified as distinct concepts.
- A steel multi-purpose canister with clay-based backfill is used in both studies.
- The mined deep matrix idea is not pursued in this report based a large rock fractured mass sufficiently characterized in three dimensions, with large diameter boreholes throughout, for a repository containing large amounts of waste (e.g., 140,000 MT) would be prohibitive.
- The hydraulic cage concept is not pursued in this report because it would also be prohibitive for a large repository (as stated by Baldwin et al. 2008).
- Very deep boreholes are used in both approaches.

The Baldwin et al. (2008) study also recognized that multiple approaches may be applicable to a particular geologic setting, that approaches may have variants, and that a repository may combine different approaches (e.g., for different waste types). Like the current UFD campaign, they indicate that multiple approaches should be maintained as reference concepts, without selection or specification until actual site conditions are identified. They indicate that non-nuclear impacts from geologic disposal are minor, and that wide differences exist in projected costs for different concepts.

Recent U.S. reviews of international progress in geologic disposal have been conducted by the Electric Power Research Institute (Sowder 2010) and the U.S. Nuclear Waste Technical Review

Board (NWTRB 2011). These reviews show the influence of the more advanced programs such as those in Sweden and France, on repository development in other countries. The leading concepts attributed to each country are consistent with reference concepts presented here.

The geologic settings (Section 1.3) selected for reference mined, enclosed-mode disposal concepts are crystalline rock (including granite), clay/shale, and bedded salt. Bedded salt is preferred to salt domes, to accommodate a repository with large areal extent. These are reasonably representative of host media being investigated internationally (although geologic conditions vary). Choosing such media and emphasizing advanced international programs, lets the U.S. program benefit from decades of R&D they have produced.

The enclosed mode reference disposal concepts described below (Table 1.4-2) follow those developed by Sweden and France for the crystalline and clay/shale settings, respectively, and the generic repository concept developed by the U.S. (Carter et al. 2011).

An important result of this work is that the enclosed reference mined, enclosed disposal concepts selected in this report (Section 1.4.5) would use relatively small packages for SNF (4-PWR/9-BWR for the Clay/Shale and Crystalline concepts and 12-PWR/24-BWR for the bedded salt concepts) to limit peak temperatures (Section 3.1). These waste package size selections are consistent with current international repository concepts in Sweden, France, and elsewhere, but smaller than the canisters currently used for dry storage (Section 1.5).

1.4.5.1 Crystalline Disposal Concept (enclosed)

As noted previously, Sweden, Finland and Japan have advanced concepts for disposal of LWR SNF in crystalline rock (Sections 1.1 and 1.3). The Swedish KBS-3 disposal concept is currently accepted worldwide as a reference. Note also that Sweden has deployed interim storage at a centralized used-fuel storage facility (CLAB) which limits waste heat output at the time of emplacement in the repository, and is a basic component of their disposal system. Canada has also investigated granite repository concepts (Rechard et al. 2011). The reference generic mined granite repository design concept presented here draws heavily from these concepts. The proposed depths for crystalline repositories range from 420 m (Finland; Posiva Oy 2010) to 500 m (Sweden, SKB 2006). For consistency with those concepts and to facilitate future comparisons of analysis results, the reference mined crystalline repository concept is assumed to be nominally 500 m below the surface in hydrologically saturated, low-permeability granitic host rock in which hydraulic gradients are very small. These conditions are expected to result in very slow groundwater flow typical of the Canadian Shield, which may be corroborated by the presence of saline groundwater with great apparent age. The host rock chemical environment is expected to be reducing, which may be indicated by the presence of minerals such as pyrite.

The subsurface layout and arrangement of waste packages is similar to the KBS-3V design (see Section 1.1; Figure 1.1-4). The initial subsurface layout selected for thermal analyses consists of parallel emplacement drifts, with waste packages emplaced in vertical boreholes drilled into the floor from these emplacement drifts (Figure 1.1-4). Waste packages for SNF are thick-walled, made from copper or carbon steel (a choice to be made at some future time, based on economics and performance assessment), with welded closures. Waste packages for HLW are thick-walled carbon steel. The space between the canister and the emplacement borehole wall (approximately 35 cm on the radius) is filled with a low-permeability buffer material consisting of swelling clay (e.g., Wyoming bentonite) emplaced initially in its dry, compacted form, that swells on contact with groundwater (swelling pressure on the order of 6 MPa is readily resisted by the minimum in situ stress). Specific dimensions of the features discussed here are given in Table 1.4-2, and in the thermal analysis (Section 3). Construction may be expedited by use of prefabricated assemblies consisting of a single waste package and the surrounding clay buffer in compacted dry form, held together by a steel envelope (McKinley et al. 2006).

Access drifts have 6.5 m height to provide overhead clearance for drilling equipment and waste package transport, and are spaced 20 m apart (equivalent to the KBS-3 concept). This is a point-loading configuration with a single 4-PWR/9-BWR waste package or a single HLW waste package in each vertical emplacement borehole. Vertical emplacement boreholes are spaced approximately 10 m apart. This dimension is greater than the 6-m spacing published for the KBS-3 concept, but a wider spacing allows somewhat hotter waste packages (the KBS-3 documentation acknowledges the possibility of different spacings).

Excavation could be drill-and-blast or by tunnel boring machine (TBM). In either case the openings will be stable, requiring minimal ground support during operations. An excavation damage zone (EDZ) will form around the mined openings. Backfill, plugs, and seals will ensure that: 1) drift backfill has lower permeability than the host rock; and 2) axial flow in the EDZ along backfilled openings, if it occurs, will be dispersed by plugs and seals. Swelling pressure in the clay buffer around waste packages, and in the emplacement drift backfill (which also contains swelling clay), will exert a compressive stress on the surrounding EDZ that tends to confine and close fractures.

Fuel assemblies are positioned inside the canister by an insert made of nodular cast iron. This material is an economical choice, and provides structural support (e.g., resisting swelling pressure from the clay buffer, on the waste package). It also provides a sink for oxygen in the disposal environment, and a source of corrosion products that can readily sorb radionuclides released from the waste form.

The Crystalline concept has relatively large additional repository volume in access drifts, to accommodate LLW and greater-than-Class-C (GTCC) waste (Table 1.4-3). Much of the additional volume could be available for enclosing the LLW in low-permeability buffer or backfill material.

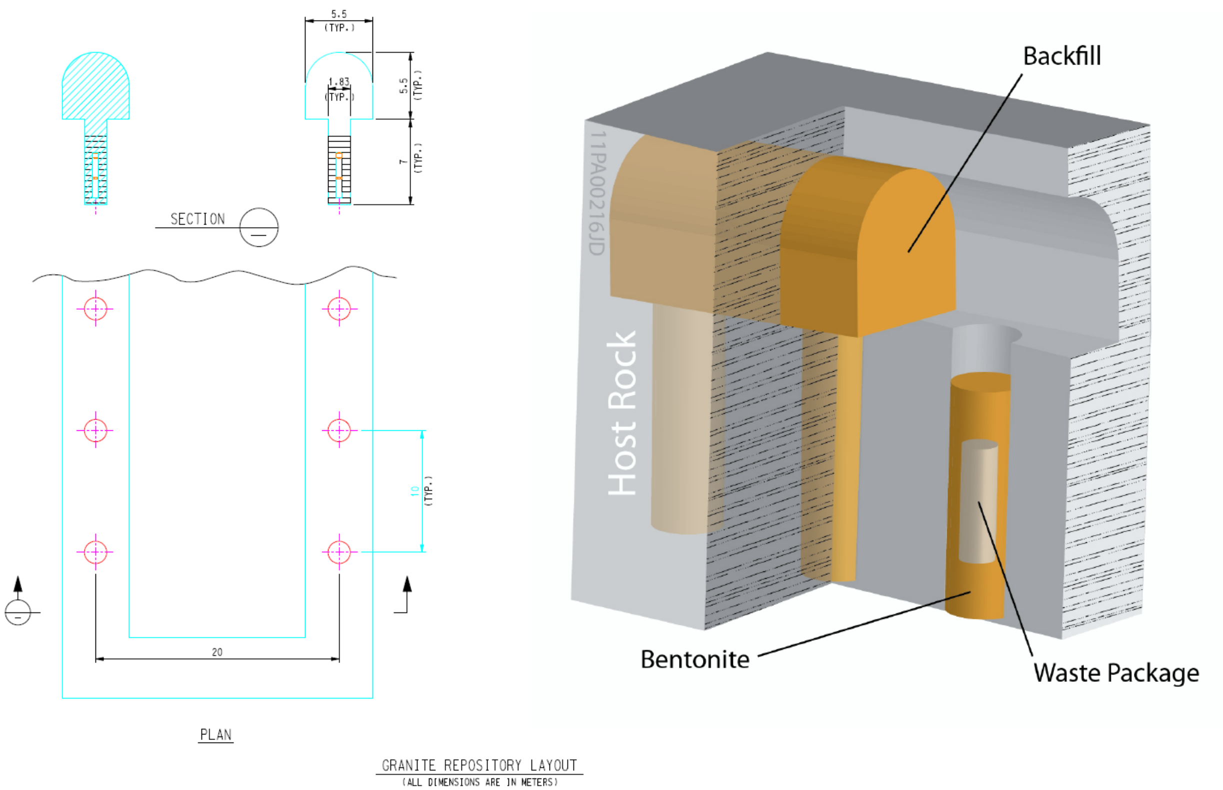

Figure 1.4-1 Schematic of the Reference (enclosed) Disposal Concept for Crystalline Host Media

1.4.5.2 Generic Salt Repository (enclosed)

A recent conceptual salt repository study for HLW advanced a disposal concept based on lessons learned from the WIPP and other salt excavations (Carter et al. 2011). The conceptual mining layout was developed for a high thermal load salt repository in bedded salt, based on experience and mining observations. Contributors to the Generic Salt Repository study generated some basic operational and structural conclusions, including: 1) bedded salt is preferred over domal salt because it generally has much greater lateral extent; 2) rubber-tire vehicles should be used for construction and disposal operations; 3) large diameter, pre-drilled emplacement holes should be avoided; 4) shielded containers are not needed for disposal; and 5) narrow room widths can be used to improve mining efficiency and structural stability. Although previous conceptual designs for HLW repositories in salt called for disposal of canisters in vertical or horizontal boreholes (DOE 1987a,b), a simpler disposal scheme was selected whereby canisters would be placed on the floor of a mined alcove, using rubber-tire equipment (Figure 1.4-2). Canisters for both SNF and HLW have carbon steel overpacks. Specific dimensions are given in Table 1.4-2, and in the thermal analysis (Section 3). Canisters are immediately covered with crushed salt from repository excavation, and the drift openings backfilled, for radiation shielding and to promote reconsolidation. Note that borehole emplacement as proposed for the Deaf Smith repository remains an alternative that could be adopted, for example, if needed to promote heat transfer with the intact salt.

For thermal calculations in this report the drift spacing is set to 40 m, so that heat-generating packages placed in each alcove, are on a 20-m grid. This somewhat larger than the ranges of spacings used by Carter et al. (2011), but accommodates larger waste packages containing more HLW or SNF, and can be adjusted during repository development for specific waste types. Non-heat generating packages could also be emplaced in the alcoves as depicted in Figure 1.4-2.

Height and width dimensions for the main access drifts and alcoves are selected accounting for waste package dimensions and the use of readily available mining equipment. Access drifts are approximately 3 m high and 6 m wide to provide clearance for nominally 5-m long waste packages. Alcoves are mined from both sides of the access drifts. This is a point-loading arrangement where a single waste package is placed at the end of each alcove, with the result that waste packages are situated on a 20-m grid. The original authors suggested that additional, non-heat generating waste could also be emplaced in the same alcoves, thus increasing the waste loading of the repository (Carter et al. 2011).

The alcove disposal concept uses mine-run crushed salt placed over the waste canisters for radiological shielding and to promote reconsolidation. The operation of placing crushed salt over the waste would involve remote controlled, low-haul-dump equipment similar to that used commonly in mining. Minimal ground support is required in a salt repository.

A larger waste package containing 12 PWR or 24 BWR assemblies is selected as the reference case (Table 1.4-2) supported by FEM calculations (Appendix C) showing that commercial SNF with either 40 or 60 GW-d/MT burnup could be emplaced after 50 yr or less decay storage, without exceeding the peak salt temperature limit of 200°C (Table C-4). A ventilated, enclosed "hybrid" salt concept is also evaluated in Appendix C, as a variant of the Generic Salt Repository that would allow earlier emplacement in lieu of longer decay storage at the surface.

The reference disposal concept for salt has sufficient additional repository volume in access drifts, to accommodate LLW and GTCC waste (Table 1.4-3). Additional drifts could be constructed between emplacement openings, to provide any needed additional volume.

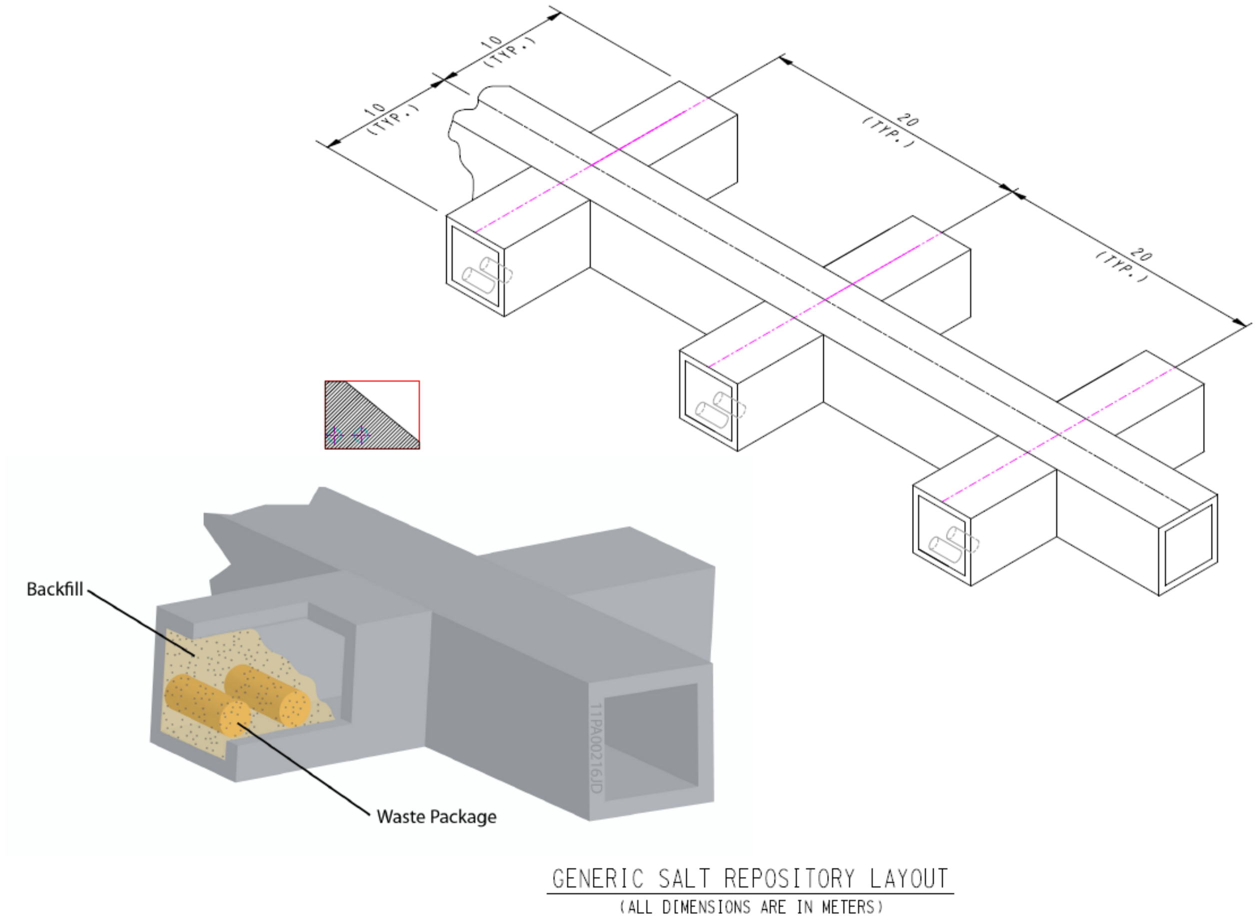

Figure 1.4-2 Schematic of the Reference (enclosed) Disposal Concept for HLW and SNF in Bedded Salt

1.4.5.3 Clay/Shale Disposal Concept (enclosed)

The French nuclear waste authority Andra has an advanced concept for a repository in the Callovo-Oxfordian argillite, and their experience is used to inform the generic reference design concept. The French program has narrowed the candidate repository site to be within an area of approximately 200 km^2 situated near Bure, in eastern France. The candidate rock unit is 130 m thick, centered at 500 m depth (Andra 2005a). For consistency with the French concept and to facilitate future comparisons of analysis results among the generic mined disposal concepts, the reference mined Clay/Shale concept is assumed to be nominally 500 m below the surface in hydrologically saturated host rock with very small hydraulic flux.

While sedimentary basins may have broad spatial extent, suitable repository host rock may be found in layers of limited thickness, situated within a sequence of argillaceous, evaporite, and/or carbonate sediments. For the reference disposal concept, low-permeability clay/shale sediments with total thickness of 150 m are assumed to exist between the repository and the ground surface (similar to the stratigraphy evident at the Bure location).

The clay or shale stratigraphy may be limited spatially, and constrain repository development. For example, the repository elevation may need to follow the host rock stratum, with the same inclination. Tunnels and drifts will be excavated using mechanized mining equipment. Horizontal emplacement boreholes are preferred over vertical ones, even short ones as in the KBS-3V concept for crystalline rock, to accommodate limited stratigraphic thickness. Accordingly, the reference clay/shale repository concept presented here will make use of horizontal emplacement boreholes, or emplacement directly in horizontal drifts.

The need for and amount of ground support in the emplacement openings and access drifts depends on the mechanical properties of the clay. Clay can be described as either plastic (soft) or indurated (hard), with widely varying mechanical properties. Soft clays (e.g., Boom Clay) with relatively high water content tend to behave plastically, rapidly filling underground openings, and may present challenges for supporting those openings during repository operations. More indurated clay rocks (e.g., clay shale, claystone or argillite) have less porosity and smaller water content, and greater strength and rigidity. Fractures can form in such media and may be evident in surface pits or quarry excavations, but are generally closed at depth (Arnould 2006). Regardless, ground support that ensures operational safety during construction, waste emplacement, and monitoring activities can be provided by steel sets and shotcrete.

Pour canisters containing HLW are placed into carbon steel overpacks with welded closures. These waste packages will be emplaced in horizontal, steel-lined boreholes with approximately 0.75 m diameter (Figure 1.4-3). Stainless steel containers with SNF will be inserted into carbon steel overpacks, and will be installed using the in-drift emplacement mode in horizontal, steel-lined tunnels with diameter of 2.64 m, surrounded by clay-based bluffer material. Emplacement of SNF waste packages is thus basically similar to HLW packages, except that emplacement drifts are larger and potentially longer than boreholes, and completely filled with clay buffer and backfill materials. Specific dimensions of the features discussed here are given in Table 1.4-2, and in the thermal analysis (Section 3). For the reference concept described here, the waste package spacing is 10 m for in-drift emplacement of SNF (packages nominally 5 m long), and 6 m for borehole emplacement of HLW canisters (4.57 m long). Borehole and emplacement drift spacings are 30 m. These dimensions are comparable to those proposed for the clay/shale repository in France (Andra 2005a) but with larger inter-package spacings to allow for hotter SNF and HLW. Access drifts have nominal 5.5-m diameter to provide clearance for drilling equipment and waste package transport, and are spaced approximately 50 m apart for HLW (to accommodate 40-m emplacement boreholes, following the French concept). A similar geometry is assumed here for SNF disposal (also following the French concept).

As in the French concept, plugs and seals at the collar of each HLW emplacement borehole and SNF emplacement tunnel will limit desiccation during repository operations, provide radiation shielding after emplacement, and inhibit movement of radionuclides into the access drift openings after repository closure. Access drift openings with sufficient dimensions for construction and waste handling equipment, will be backfilled at closure using mined clay/shale material processed for low-permeability and swelling potential on hydration in situ.

The Clay/Shale concept has some additional repository volume in access drifts, to accommodate LLW and GTCC waste (Table 1.4-3). Some of this additional volume could be needed to enclose the LLW in low-permeability buffer or backfill material. This is attributable to the use of boreholes and in-drift emplacement (with drifts completely filled with buffer material).

Additional drifts or alcoves could be constructed between HLW/SNF alcoves to provide any needed additional volume.

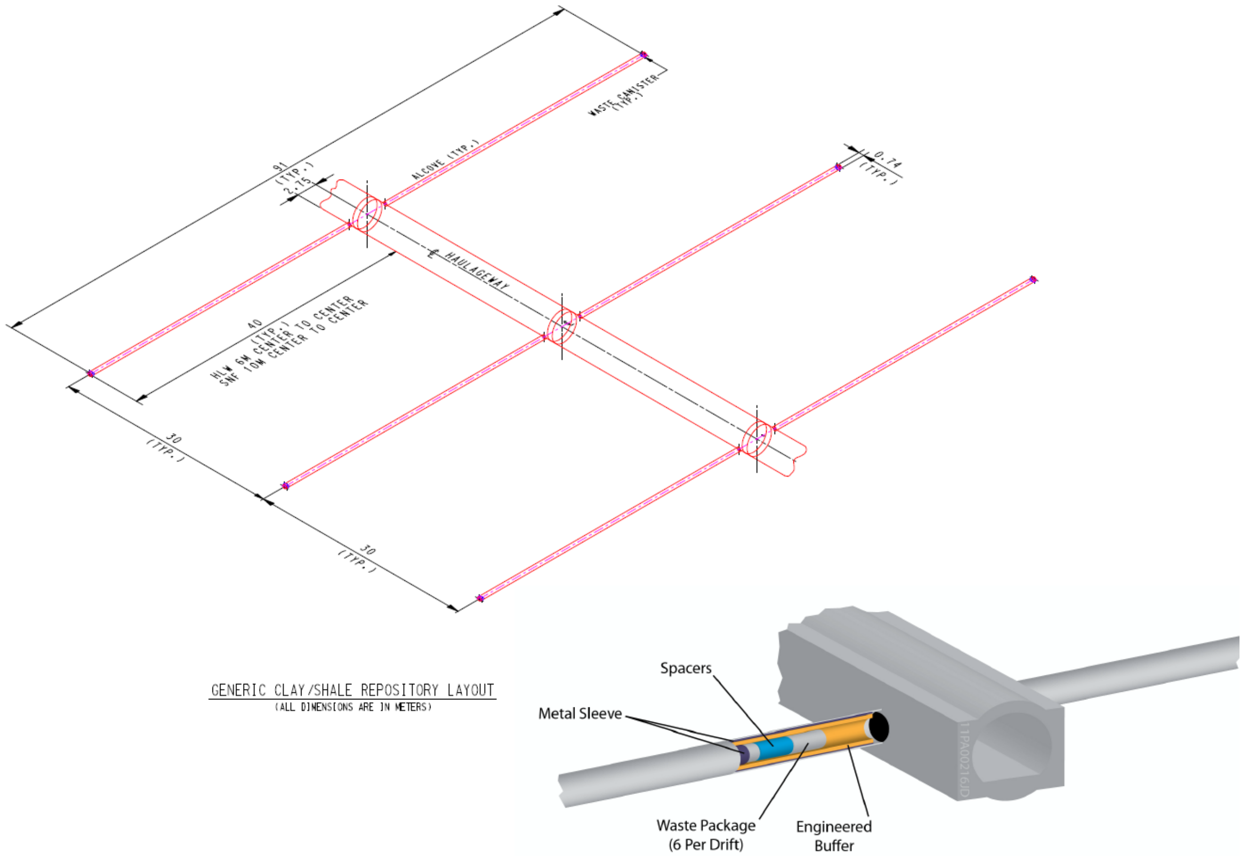

Figure 1.4-3 Schematic of the Reference (enclosed) Disposal Concept for HLW in Clay/Shale Media

1.4.5.4 Deep Borehole Disposal Concept (enclosed)

Nuclear waste disposal in very deep boreholes has been investigated in the U.S. and internationally for many years. Direct injection of liquid waste into deep boreholes was considered favorably in the 1957 review by the U.S. National Academy of Science (NAS 1957). Deep hole disposal was considered in a waste management environmental impact study (DOE 1980) supported by technical feasibility analysis (O'Brien et al. 1979). In 2000 the Swedish program conducted a feasibility study of deep drilling technology that would be used, including design details for well completions and waste canisters (SKB 2000). A more recent review of drilling technology was performed for the British waste program (Gibb 2010). Both these reviews concluded that the required large-diameter holes could be drilled, but would technologically challenge the drilling industry.

Recent work has concluded that deep borehole disposal could more effectively isolate solid waste forms (SNF or HLW glass) than some mined disposal concepts (Brady et al. 2009). Deep borehole disposal could also have the advantage of less constraining thermal management requirements because emplacement boreholes would be situated hundreds of meters apart. Also, waste packages would be small and contain only one PWR fuel assembly, or a limited quantity of HLW. As discussed previously, groundwater boiling will not occur in the near field because of the hydrostatic pressure. Isolation performance is provided predominantly by the far-field host medium and the long sealing system emplaced in the borehole above the waste, such that thermally driven changes to the waste form or the near-field host rock would not be significant. Suitability of the host medium can be determined using established methods for geophysical, geochemical, and hydrologic measurements in wells. The waste package for deep borehole disposal is simple and relatively cheap, since it has no containment longevity function after emplacement. Borehole arrays could scale in number and cost, directly to the inventory of waste for disposal.

Crystalline basement rock, possibly covered by as much as 2 km of sedimentary overburden, is readily available in the U.S. Distributed, regional disposal facilities could be constructed to share the burden of disposal, and to decrease the number and extent of waste shipments. Drilling technology would be a significant challenge, but drilling cost could be much less than for the corresponding activities to construct and operate a mined repository and associated surface facilities (Brady et al. 2009). Hence, disposal of SNF and solid HLW is included in this study as a reference concept, with recognition that additional R&D is needed to establish the technical basis to a degree comparable with mined repository concepts.

The Deep Borehole disposal concept is described by Arnold et al. (2010) as follows:

> "…consists of drilling a borehole into crystalline basement rock (typically granite) to a depth of about 5000 m, emplacing waste canisters containing spent nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2000 m of the borehole, and sealing the upper 3000 m of the borehole….
>
> "The viability and safety of the deep borehole disposal concept are supported by several factors. Crystalline basement rocks are relatively common at depths of 2000 to 5000 m in the United States and many other countries, suggesting that numerous appropriate sites exist. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources, which is the most likely pathway for human exposure. The density stratification of groundwater would also oppose thermally induced groundwater convection from the waste to the shallow subsurface….Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides in the waste, leading to limited mobility.
>
> "Preliminary estimates for deep borehole disposal of the entire projected waste inventory through 2030 from the current U. S. fleet of nuclear reactors suggest a need for a total of about 950 boreholes, with a total cost that could be less than a mined repository disposal system at Yucca Mountain."

Deep disposal boreholes would be spaced approximately 200 m apart to limit thermal interaction between boreholes and to allow for some borehole deviation (Figure 1.4-4). Specific dimensions of the waste packages, buffer, and liner for SNF and HLW disposal are given in Table 1.4-2 and in the thermal analysis (Section 3). The reference concept indicates no solid buffer material would be used between the waste packages and the borehole liner (Table 1.4-2), and the thermal calculations assume the properties of water, although an earlier study proposes to use a water-clay slurry or "deployment mud" (Brady et al. 2009). Thermal properties of slurry and water are reasonably close and the annular thickness is small which limits the thermal resistance.

Waste packages or containers can be made from sections of standard oilfield casing 5 m in length, with inner diameter of 32 cm and outer diameter of 34 cm. Each such canister could hold one PWR fuel assembly, or one BWR assembly with extra space (Brady et al. 2009). One canister could hold the contents of multiple assemblies with rod consolidation (or the canister diameter could be decreased to fit in a smaller diameter borehole). Welded end-caps seal the canisters. The disposal canister is strong enough to prevent radionuclide release during the waste emplacement phase, including recovery operations for canisters that become stuck or damaged in the wellbore. Canisters can be emplaced individually or as part of strings with as many as 10 to 20 canisters each. Crushing of underlying canisters during emplacement is prevented by installation of bridge plugs in the borehole.

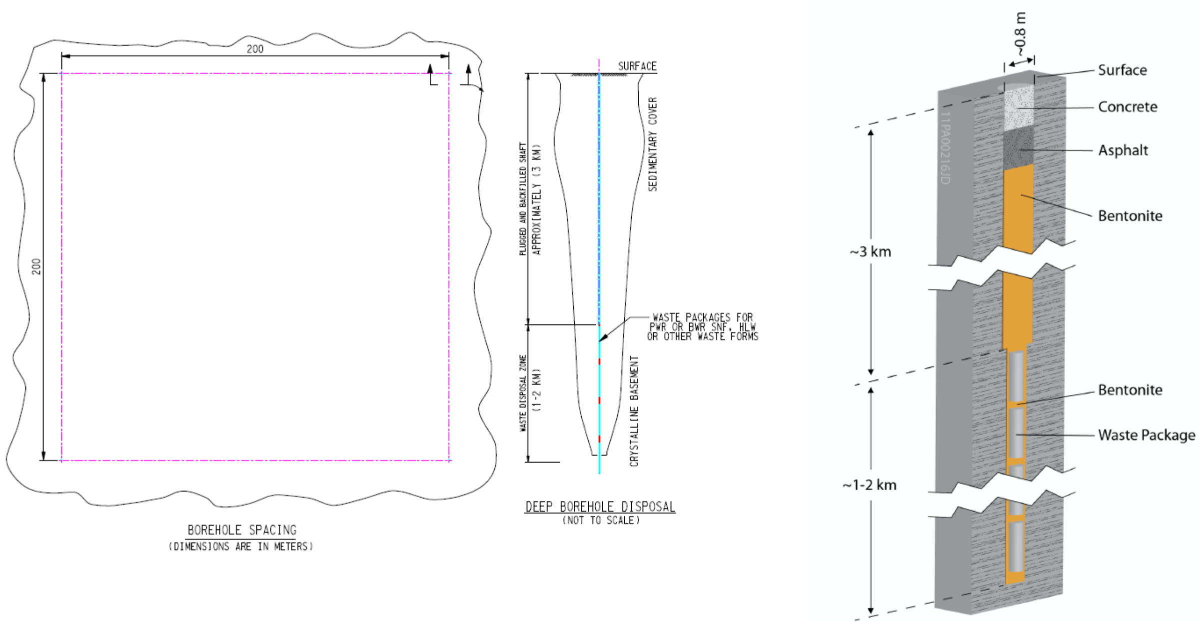

Figure 1.4-4 Schematic of the Reference Deep Borehole Disposal Concept

Table 1.4-2 Summary of Characteristics for Reference Repository Design Concepts

Geologic Media/Concept	Mined Crystalline	Mined Clay/Shale	Mined Bedded Salt	Deep Borehole
Repository depth	~500 m	~500 m	~500 m	>3000 m
Hydrologic setting	Saturated	Saturated	Saturated	Saturated
Ground support material	Rockbolts, wire cloth & shotcrete	Steel sets & shotcrete	Rockbolts	Not used
Seals and plugs	Shaft & tunnel plugs and seals	Shaft & tunnel plugs and seals	Shaft & tunnel plugs and seals	Borehole seals
Normalized Areal Loading (GWe-yr/acre)	1 to 10	1 to 10	1 to 10	<1
SNF Emplacement Mode	Vertical emplacement boreholes in floor	Horizontal in-drift emplacement	Horizontal emplacement in alcoves containing single packages	Vertical emplacement, stacked
WP configuration	4-PWR	4-PWR	12-PWR	1 PWR assembly (rod consolidation)
Overpack material	Copper or steel [B]	Steel [B]	Steel [B]	Steel [B]
Package dimensions	0.82 m D x 5.0 m L	0.82 m D x 5.0 m L	1.29 m D x 5.0 m L	0.34 m D x 5.0 m L
Drift/borehole dia.	1.66 m (boreholes)	2.64 m (drifts)	5 m (nominal; alcoves)	45 cm (boreholes)
Drift/borehole spacing	20 m (drifts) 10 m (boreholes)	30 m (drifts) 10 m (packages)	40 m (drifts) 20 m (alcoves) Result: packages on 20-m grid	>100 m (boreholes)
Borehole liner material	NA	Steel [B]	NA	Steel [B]
Buffer material	Clay-based	Clay-based	NA	Clay-based
Backfill material	Clay/sand mixture	Crushed clay/shale	Crushed salt	NA
Line or point loading	Point	Point	Point	Line
HLW Emplacement Mode	Vertical emplacement boreholes in floor	Horizontal parallel boreholes containing multiple packages	Horizontal emplacement in alcoves containing single packages	Vertical emplacement, stacked
Overpack material	Steel [B]	Steel [B]	Steel [B]	Steel [B]
Drift/borehole dia.	1.52 m	0.75 m (boreholes)	5 m (nominal; alcoves)	>45 cm (boreholes)
Drift/borehole spacing	20 m (drifts) 10 m (boreholes)	30 m (boreholes) 6 m (packages)	40 m (drifts) 20 m (alcoves) Result: packages on 20-m grid	>100 m (boreholes)
Package dimensions				
Modified-Open Borosilicate Glass	0.82 m D x 4.7 m L	0.72 m D x 4.7 m L	0.61 m D x 4.7 m L	~0.34 m D x 4.7 m L [A]
Closed Cycle Borosilicate glass	0.82 m D x 4.7 m L	0.72 m D x 4.7 m L	0.61 m D x 4.7 m L	~0.34 m D x 4.7 m L [A]

Geologic Media/Concept	Mined Crystalline	Mined Clay/Shale	Mined Bedded Salt	Deep Borehole
Closed Cycle E-Chem zeolite	0.82 m D x 4.7 m L	0.72 m D x 4.7 m L	0.61 m D x 4.7 m L	~0.34 m D x 4.7 m L [A]
Closed Cycle La-glass (3)	0.82 m D x 1.7 m L	0.72 m D x 1.7 m L	0.61 m D x 1.7 m L	~0.34 m D x 1.8 m L [A]
Closed Cycle Metal alloy	0.82 m D x 3.3 m L	0.72 m D x 3.3 m L	0.61 m D x 3.3 m L	~0.34 m D x 4.7 m L [A]
Borehole liner material	NA	Steel [B]	NA	Steel [B]
Buffer material	Clay-based	NA	NA	Clay-based
Backfill material	Clay/sand mixture	Crushed clay/shale	Crushed salt	NA
Line or point loading	Point	Line	Point	Line
Non-Heat Generating	Stacked in access tunnels	Stacked in access tunnels	Stacked in access tunnels	Assume near-surface disposal
Package construction	Steel or cement [B]	Steel or cement [B]	Steel or cement [B]	NA
Drift/borehole dia.	NA	NA	NA	NA
Borehole liner material	NA	NA	NA	NA
Buffer material	NA	NA	NA	NA
Radiation shielding	Backfill	Backfill	Backfill	NA
Backfill material	Clay/sand mixture	Clay/sand mixture	Crushed salt	NA

Notes:

[A] Smaller diameter, and possibly shorter HLW pour canisters would be used for deep borehole applications.

[B] The types of materials to be used in these applications, such as the types of steel, are to-be-determined but for this study they are considered to be readily available and relatively low-cost.

Table 1.4-3 Comparison of Available Additional Repository Volume With LLW and GTCC Waste Production

Available Volume					
	Drift Diameter (m)	Drift Length per "Cell" (m)	# Pkgs. per "Cell"	Available Drift (m^3/Pkg.)	
Crystalline					
HLW	5.5	10	1	237	
SNF	5.5	10	1	237	
Clay/Shale					
HLW	5.5	30	10	71	
SNF	5.5	30	10	71	
Salt					
HLW	4.4	20	2	150	Diameter is equivalent circle for a 5 x 3 m opening.
SNF	4.4	20	2	150	

LLW+GTCC Waste Volume						
	MTHM per Pkg.	Reprocessing Waste (m^3/MTHM)	Fuel Fab. Waste (m^3/MTHM)	Repository Waste (m^3/MTHM)	Total LLW+GTCC (m^3/Pkg.)	
Once-Through						
UOX SNF	1.88	0	0	1	1.9	
Modified-Open						
HLW (Co-Extraction)	5.26	10	0	1	57.9	Approximate value representing contributions from Table 2-10.
Pu MOX SNF	1.88	0	5	1	11.3	Approximate value representing contributions from Table 2-11.
Closed						
HLW (New Extr.)	9	12	0	1	117	Approximate value representing contributions from Table 2-25.
HLW (E-Chem)	1 to 10	12	0	1	13 to 130	Assume LLW+GTCC is similar to New Extr.; range is for different E-Chem waste types.

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1.5 Open Emplacement Modes

This section refines the definitions for enclosed and open emplacement modes in mined geologic disposal, and offers several reasons why open reference concepts are important. It then develops a systematic description of possible open (and enclosed) emplacement modes, and recommends three open disposal concepts for use by the Used Fuel Disposition (UFD) R&D program. Whereas the enclosed modes described in Section 1.4 are based on international experience and previous work in the U.S., the additional use of a systematic approach is appropriate for open modes because they are new concepts intended specifically for the U.S. program.

This section expands on previous work (DOE 2008b) by identifying additional concepts that allow heat removal from the repository by forced ventilation, applicable to any geologic formation in which underground openings can persist with minimal maintenance for at least a few decades. The previous work is extended to host media that are not strongly indurated, and are hydrologically saturated, provided that repository openings are appropriately backfilled, plugged, and/or sealed at closure. Although open modes could in principle be used for thermal management of HLW glass, this discussion focuses on SNF for which larger, hotter waste packages represent a greater technical challenge.

Open modes offer the possibility of emplacing larger waste packages containing more SNF, while meeting repository temperature limits. The FY11 study showed that small waste packages (e.g., 4-PWR) would be needed for disposal concepts such as the Crystalline or Clay/Shale concepts proposed for Sweden and France, respectively. By comparison, SNF is currently being loaded at commercial nuclear power plants into dry cask storage systems containing 32 or more PWR assemblies (or equivalent BWR assemblies). Going a step further, open emplacement modes could help facilitate direct disposal of dual-purpose canisters (DPCs). Previous thermal analyses suggest that direct disposal is possible, for example, Kessler and others (2008) showed that direct disposal of existing DPCs containing 32 intact PWR assemblies could meet published temperature limits.

The approach taken here identifies possible concepts using combinations of four key attributes of open (or enclosed) emplacement modes: competent/plastic host rock, high/low permeability host rock, saturated/unsaturated hydrogeologic setting, and whether a low-permeability backfill/buffer is installed prior to closure. These are used to describe all possible open or enclosed modes in a generic sense. More attributes could be selected, however, this would increase the complexity of the analysis. A hierarchal framework for depicting the attributes of open (and enclosed) modes is referred to here as a “taxonomy” (Figures 1.5-1 and 1.5-2). The key to useful taxonomic descriptions is to identify the important discriminating attributes to discern alternative system concepts.

To support the selection of key attributes, a catalog of disposal system features (Hardin et al. 2011, Appendix I) has identified four types of settings for geologic disposal: geologic, hydrogeologic, geomechanical, and geochemical. The selected attributes provide simple, generic coverage of the range of settings available, with recognition that some settings are particular to certain locations or regions, and that some disposal concepts may depend on site-specific characteristics.

Geologic Settings – The geologic settings available from the catalog include hard rock and soft rock choices. These are included in the open mode selections with further choices based on the following rationale:

- **Hard rock –** This designation includes rock types (e.g., granite, volcanic tuff, basalt, and the crystalline basement) that have relatively high strength contributing to long-term stability of underground openings. While it is conceivable that geologically young granites could be relatively free of fractures, this is unlikely because of igneous cooling effects, tectonic processes, and excavation damage, so low-permeability, unfractured granite is not considered further here. Instead, hard rock is assumed to be fractured, with moderate to high permeability. Deeply buried crystalline rock may have closed fractures, with lower bulk permeability, but such conditions are likely to be saturated, presenting an open mode choice that is rejected in the following discussion.
- **Soft rock –** This designation includes rock types (e.g., clay, shale, salt, carbonates, chalk, marl, alluvium) for which engineered ground support would be an important part of any open emplacement mode. For argillaceous media (e.g., shale) and other sedimentary media containing clay minerals, a moisture barrier would be needed as part of ground support, to limit desiccation during repository ventilation. For this discussion clay is replaced by shale, recognizing that shale is plentiful in the U.S., while robust and expensive ground support would be needed to keep drifts open in plastic clay. Alluvium is included in addition to shale, to represent a variety of hydrogeologic settings. Other possibilities (e.g., carbonates, chalk, marl) are potentially viable disposal media but are less widely distributed than shale. For salt heated in a mined repository, there is no practical way to keep emplacement boreholes, alcoves, or drifts open with ground support.

The remaining geologic settings from the catalog (e.g., seabed and isolation by non-host units) are limited by treaty or are beyond the scope of generic options considered in this report (see additional discussion in Hardin et al. 2011).

Hydrogeologic Settings – These consist of saturated and unsaturated host media, and the local and regional boundary conditions that control groundwater pressure gradients and fluxes (Hardin et al. 2011, Appendix I). The key difference between saturated and unsaturated settings is that open modes in saturated settings would generally require backfilling, plugging, and/or sealing of emplacement openings prior to permanent closure, to limit preferential groundwater flow and advection of released radionuclides through the repository. For open modes in saturated settings (including many shale formations) performance could likely be improved with the addition of low-permeability backfill or emplacement drift plugs and seals (or both) to isolate waste packages.

Unsaturated settings could also benefit from backfilling or plugging at closure (Figure 1.5-1). Given the long performance periods for geologic repositories (assumed to be 10^6 yr; see Section 1) even a small, preferential flow along repository openings in an unsaturated, low-permeability host medium could result in significant advection of released radionuclides without backfilling or plugging control measures. Whereas high permeability, unsaturated host rock may be free draining so that backfilling and plugging/sealing of emplacements drifts are not needed to control groundwater flow, other possible unsaturated host media such as shale have lower permeability so that such drainage may not exist.

Low-permeability host media generally act as confining units in hydrogeologic systems, whether saturated or unsaturated, so that groundwater flow rates are small and/or insignificant. One consequence is that pre-closure ventilation tends to remove all moisture influx by evaporation. After closure, this study uses the conservative assumption that low-permeability host media such as shales have widely spaced, large-scale hydrologic discontinuities such as faults, which are capable of conducting groundwater flow into one or more repository drifts. For such conditions, backfilling or plugging/sealing control measures (or both) are needed. This assumption should be re-evaluated when site-specific data are available.

This study has identified emplacement modes that could likely be implemented in sedimentary basins (shale, alluvium) and unsaturated hard rock. For open modes in saturated settings, only low-permeability media are recommended here. This avoids the situation where waste isolation performance in the presence of saturated flow depends critically on one or more engineered barriers around each waste package (e.g., buffer or backfill) that cannot be installed until after all waste packages are emplaced, and must be installed in a radiological environment.

The host media discussed above as candidates for open emplacement modes could perform in arid, semi-arid, or temperate hydrogeologic settings. Other hydrogeologic settings identified in the catalog (e.g., island, archipelago, hydraulic sump, isolation by non-host units, lacustrine/marine, glacial, alpine) represent local conditions that would be evaluated during site screening or selection.

Geomechanical Settings – Open modes require that emplacement openings remain open for heat removal for up to 100 yr, or until the thermal limits for the disposal system are met. The basic distinction used in this study is therefore whether the host medium is “plastic” (self-sealing and prone to collapse) or “competent” (fracture permeability persists, and unlikely to collapse) on this time scale. Other distinctions such as the type of in situ stress condition and its magnitude, the extent of excavation damage, potential for rockburst, etc. are included within the functional definitions for “plastic” and “competent” media. In other words, these are working definitions that include combinations of rock characteristics that determine the feasibility of open modes. The other geomechanical processes identified in the catalog (Hardin et al. 2011, Appendix I) are site-specific external boundary conditions (e.g., ground motion, faulting, erosion, isostasy) that are beyond the scope of this report.

Geochemical Settings – Oxidizing and reducing conditions are generally associated with unsaturated media, and saturated low-permeability media, respectively. Unsaturated settings generally communicate to the atmosphere through interconnected, gas-filled porosity. Many rock types contain minerals or organic matter that can react with oxygen and thereby maintain reducing conditions over geologic time scales if the permeability is low enough to limit the rate of such activity, i.e., the rate of fresh oxygenated groundwater inflow. Hence, a range of reducing and oxidizing settings is implicit in the selection of saturated, low permeability media (e.g., shale) and unsaturated media (e.g., alluvium or hard rock) for open emplacement modes. Sorption behavior can be expected in all host media to some extent, but is more pronounced in reducing media (represented by low permeability). Saline conditions are assumed to be limited to salt media and deep crystalline rock (an assumption that should be re-evaluated when site-specific data are available).

Summary of Open Mode Attributes – Based on this discussion, the following attributes are selected for an open-mode taxonomy (Figure 1.5-1):

- Plastic vs. competent host rock (persistence of fracture permeability, and stability of underground openings in heated rock on time scales up to 100 years)
- Low-permeability vs. higher permeability host rock (the importance of host rock performance vs. engineered material performance, to the isolation performance of the disposal system)
- Saturated vs. unsaturated (concerning the types of barriers needed to isolate waste from groundwater, and the potential for saturated flowpaths within the repository, particularly after permanent closure)
- Open after closure vs. installation of low-permeability backfill at closure, i.e., whether low-permeability backfill throughout emplacement areas of the repository is needed to control groundwater flow after permanent closure

These attributes are used in Figures 1.5-1 and 1.5-2, and Table 1.5-1, in the selection of reference concepts. They are also used in the discussion below of combinations of attributes that were not selected. They comprise a simple set that is well suited to guiding a generic R&D program, and enabling site evaluation and selection for a broad range of geologic, hydrogeologic, geomechanical, and geochemical settings.

Open Mode Taxonomy – Most branches of the open mode taxonomy (Figure 1.5-1) are covered by the selected reference concepts including the Hard Rock Unsaturated open concept. A notable exception is:

- **High-permeability, saturated media** – In-drift emplacement was not selected by the Swedish program for waste disposal in fractured, crystalline rock, even with low permeability backfill. A clay buffer was selected instead (an enclosed mode) with associated thermal limits. As discussed above, for open emplacement modes in saturated settings, only low-permeability media are recommended here.

To be clear, the foregoing discussion allows the possibility for open modes in saturated or unsaturated, low-permeability host rock (e.g., shale) without using low-permeability backfill. A plugging/sealing strategy to compartmentalize emplacement, could be used instead of (or in addition to) low-permeability backfill throughout the emplacement areas. The validity of using plugging/sealing to compartmentalize the repository in lieu of installing low-permeability backfill in every drift is subject to confirmation by testing and modeling using site-specific information. Importantly, the repository can be designed and initially constructed to allow either closure strategy, leaving open the option for both, with final selection benefitting from many years of site-specific investigation.

Comparable Results for Enclosed Modes – A similar taxonomy is presented for enclosed modes (Figure 1.5-2) using the same attributes used for open modes. This taxonomy captures the crystalline, clay/shale, and salt disposal concepts selected previously (Hardin et al. 2011, Section 4). Exceptions are:

- **High permeability, unsaturated media with low-permeability buffer** – A clay buffer could contribute significantly to performance in unsaturated systems because of less buffer erosion (Hardin and Sassani 2011). This benefit to waste isolation could be offset by the influence of oxidizing formation conditions on radionuclide transport in the far field. Regardless, unsaturated, competent rock is well represented in this discussion by the Sedimentary Backfilled open concept, and past repository design studies for unsaturated volcanic tuff (DOE 1999).

- **Enclosed modes in plastic media without low-permeability backfill –** As discussed above for open modes, clay or shale media span the range between competent and plastic, corresponding to media requiring low-permeability backfill or drift plugs to compartmentalize emplacement areas, or not. This study conservatively assumes that low-permeability backfill or a plugging/sealing strategy would be required for emplacement in shale media, whether saturated or unsaturated, and whether the emplacement mode is open or enclosed.

This remainder of this section recommends and describes open disposal concepts in sedimentary rock, shale, and hard rock (Table 1.5-2). Shale may be more or less competent (depending on the geologic age and/or degree of induration) and potentially provides low permeability even in saturated settings. The sedimentary context for the backfilled open mode is conceptualized as competent for excavation, unsaturated or saturated, relatively unfractured, and with hydrologic properties that are much more uniform than fractured rock. The hard rock, unsaturated concept has been widely studied (DOE 2008b) and does not require backfilling at closure. These three recommended concepts are discussed in more detail below.

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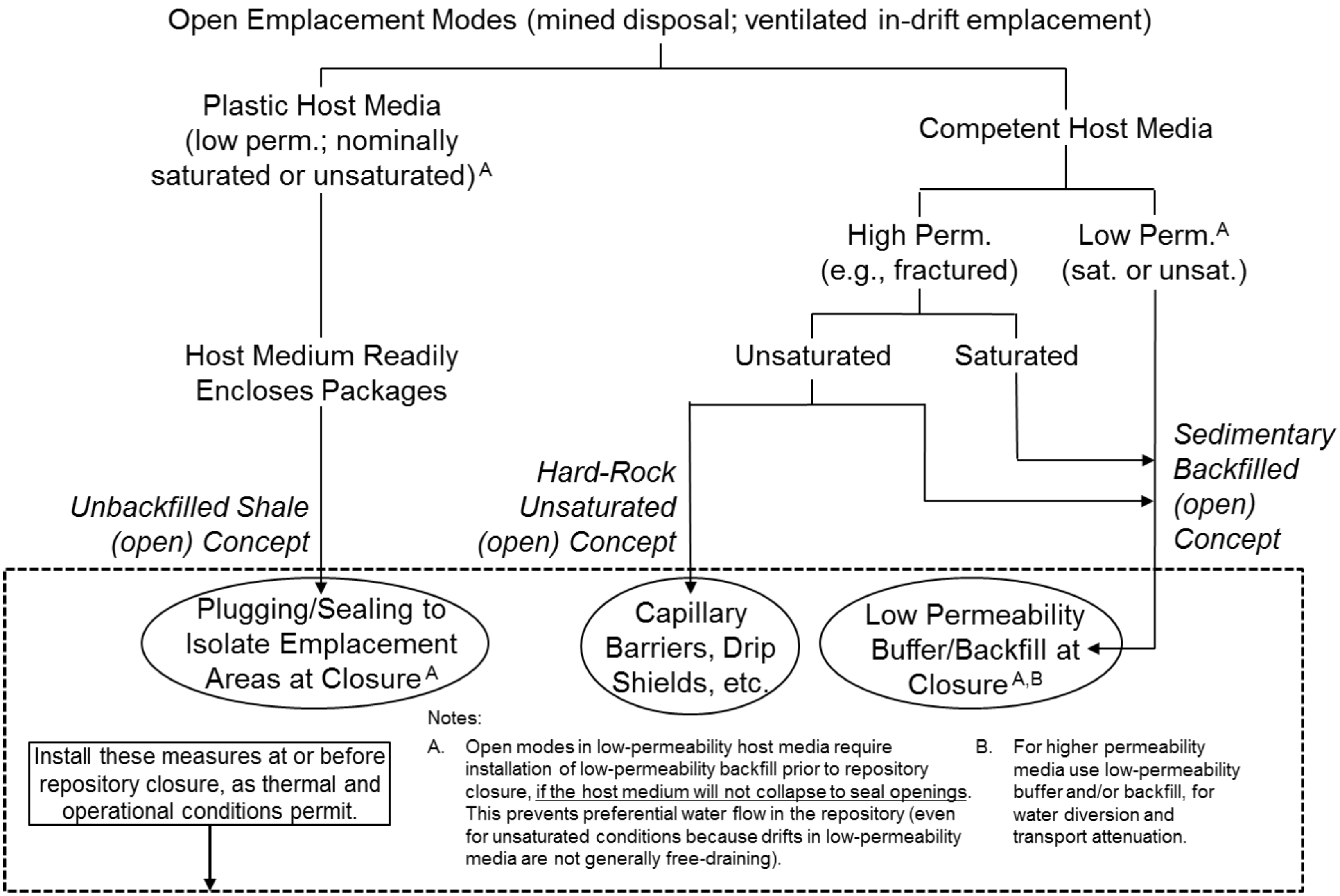

Figure 1.5-1 Open Emplacement Mode Taxonomy

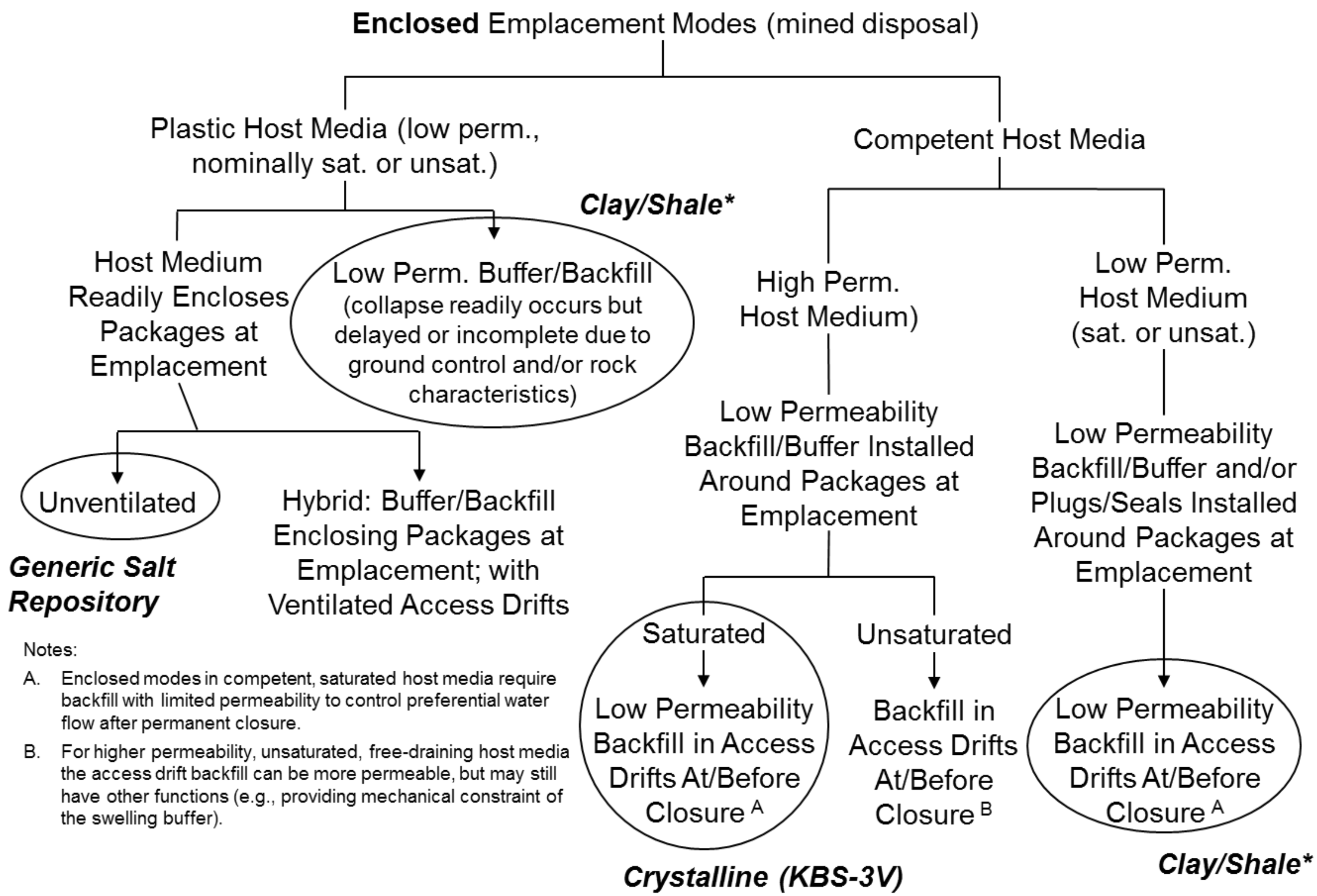

Figure 1.5-2 Enclosed Emplacement Mode Taxonomy

Table 1.5-1 Enclosed and Open Emplacement Mined Emplacement Mode Taxonomy and Reference Concepts

Medium Type	Permeability	Saturated vs. Unsaturated	Buffer/Backfill Around WPs	Comments (Use in Reference Concepts)
Enclosed Emplacement Modes				
Plastic	Low k	Either saturated or unsaturated	No	Host rock readily collapses around and seals waste packages. (Generic Salt Repository enclosed reference concept; crushed salt backfill is highly permeable initially but readily consolidates)
			Yes	Collapse readily occurs but is delayed or incomplete; buffer/backfill is used to ensure that waste packages are enclosed, and to control transport pathways. (Clay/Shale enclosed reference concept as applied to more plastic host media)
Competent	Low k	Either saturated or unsaturated	Yes	Collapse does not readily occur; buffer/backfill is needed to enclose waste packages and control transport pathways. (Clay/Shale enclosed reference concept as applied to more competent host media)
	Low to high k	Unsaturated	Yes	Buffer/backfill is used to enclose waste packages and control transport pathways. (Hydrogeologic setting is more amenable to open modes; see below)
		Saturated	Yes	Buffer/backfill is used to enclose waste packages and control transport pathways; KBS-3 concept. (Crystalline rock reference concept)
Open Emplacement Modes				
Plastic	Low k	Either saturated or unsaturated	No	Host rock readily collapses around waste packages regardless of ground support, interfering with ventilation for heat removal.
			No	Collapse occurs after ventilation but may be delayed or incomplete. (Shale Unbackfilled open reference concept; each emplacement drift segment is isolated by plugs/seals)
Competent	Low k	Either saturated or unsaturated	Yes	Emplacement drifts are backfilled after ventilation and before permanent closure. Saturated, high-k media are not recommended for open modes (see text). (Sedimentary Backfilled open reference concept; emplacement drifts backfilled at closure; e.g., unsaturated alluvium)
	High k	Saturated		
		Unsaturated		
		Unsaturated	No	Capillary barriers, drip shields, etc. are used to limit waste contact with groundwater (Hard Rock Unsaturated open reference disposal concept)

1.5.1 Shale Unbackfilled Open Mode

The reference open emplacement mode concept for SNF disposal in shale (Figure 1.5-3) is similar to the clay/shale enclosed mode for SNF, with plugs and seals installed after the ventilation period and prior to repository closure, to isolate emplacement drift segments. The liner (e.g., shotcrete and steel supports) would have sufficient longevity to stabilize the opening throughout the ventilation period. Pre-closure ventilation could be used throughout the operational period, or it could be used for each drift only for as long as needed. Opening stability and protection of the shale medium from desiccation would be controlled using a liner. A system of shotcrete with steel reinforcement is assumed for this study, but other methods could be used such as pre-cast concrete liner blocks. Performance of the liner, and corresponding changes to the host rock behind the liner during heating, depend on site-specific factors and are subject to confirmation by testing.

Use of emplacement drift plugs and seals without complete backfilling is a variation suggested by the repository compartmentalization proposed by the French program (Andra 2005, Section 2.3.1), and by the characteristics of current generic performance assessment models (Vaughn et al. 2011). The models for clay/shale repository performance rely principally on the host rock and other natural barriers for waste isolation (i.e., no performance credit is taken for engineered barriers other than a slowly degrading waste form). Each package is considered independently with respect to release and transport of radionuclides, and the radionuclide transport mass flux along each transport pathway depends initially on the source concentration and not the mass of radionuclides available at the source (although some radionuclides can eventually be depleted at the source by transport). For such models the calculation produces similar results whether a drift is backfilled or not, if certain processes such as advective transport in the host rock are limited. For models of this type, and even more detailed, site-specific models that could be developed for a repository safety case, reasonable waste isolation performance could be assured without the additional expense and uncertainty associated with backfilling emplacement drifts at closure. Backfilling of emplacement drifts remains an option until repository closure, and could be implemented if necessary to assure waste isolation.

Emplacement drifts would be short, with drift segments accommodating only a few waste packages. The short segments would remain open, but gradually fill with rubble after closure, while isolated from the rest of the repository by engineered plugs and seals. Plugs and seals at the ends of each emplacement drift segment could be engineered and partially constructed before waste emplacement to minimize construction activities at closure. If the compartmentalization approach is shown to provide satisfactory waste isolation performance, it would mean that the feasibility of backfill emplacement in emplacement areas at repository closure would not be as important a factor in selecting the disposal concept for a particular site.

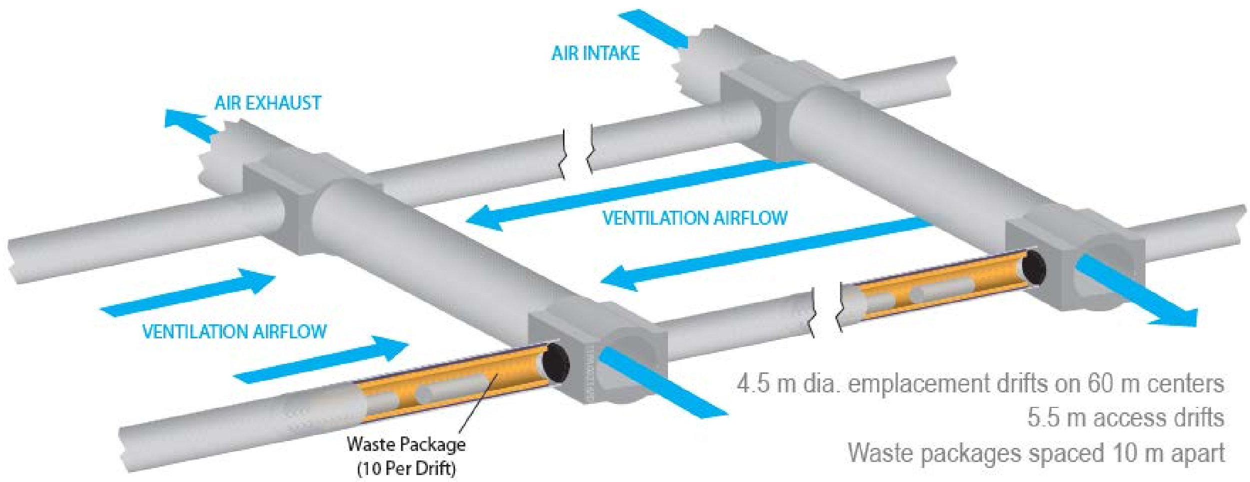

Figure 1.5-3 Schematic of Shale Unbackfilled Open Disposal Concept

1.5.2 Sedimentary Backfilled Open Mode

The repository concept of operations (Figure 1.5-4) uses in-drift emplacement, with capability for backfilling at or prior to permanent closure using remote operations. The description here and in Section 4 assumes the host medium is a soft sedimentary rock such as alluvium (Appendix B) or shale. Ground support consists of rock bolts and shotcrete, with steel reinforcing elements as needed (DOT/FHA 2009; for indurated sedimentary rock at reasonable depth). Additional layers or coatings could be used for support, and to prevent desiccation of the rock if needed. The underground repository would be accessed with vertical shafts, and an inclined ramp for waste handling (facilitated by relatively shallow repository depth). The layout schematic (Figure 1.5-4) includes short emplacement segments to facilitate backfilling, bulkheads or labyrinths for shielding during backfilling operations, and turnouts at the drift ends to enhance shielding. Repository openings would be backfilled before closure, with low permeability backfill material engineered to impose a diffusion-dominated, sorptive barrier to radionuclide transport

In low-permeability, reducing host media the required waste isolation performance would be provided by the natural setting and the low-permeability backfill. For higher permeability and/or oxidizing host media such as alluvium, the waste package would be constructed with a corrosion resistant outer barrier to ensure long-term integrity in an oxidizing environment, supplementing the performance of the low-permeability backfill (Table 1.5-2).

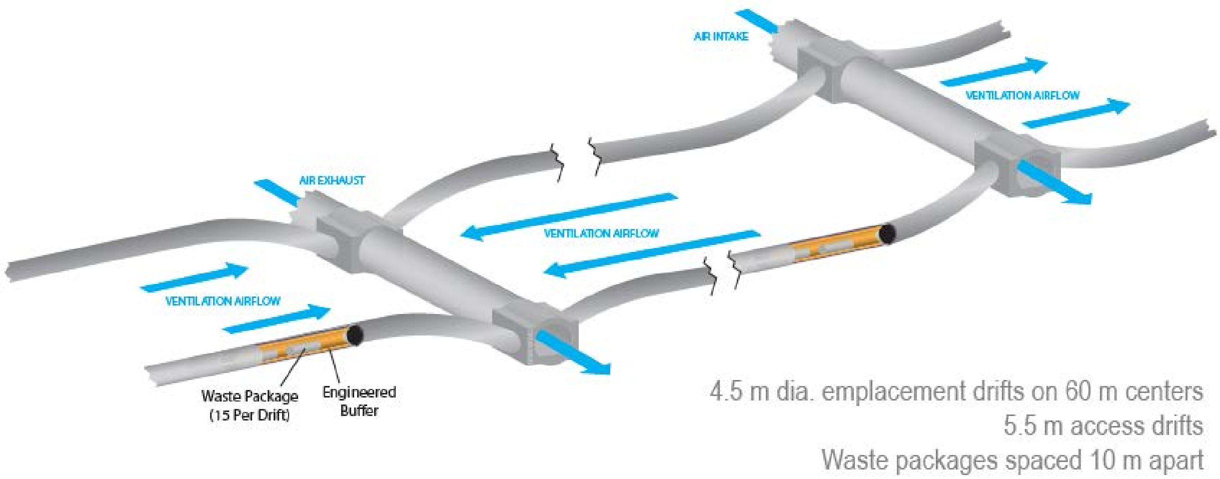

Figure 1.5-4 Schematic of Sedimentary Backfilled Open Concept

1.5.3 Hard Rock Unsaturated Open Mode

The Hard Rock Unsaturated open concept was developed previously as the result of a comprehensive design study (OCRWM 1999). The concept involves packaging canistered SNF into corrosion-resistant overpacks, and placing the packages onto pedestals in open, ventilated drifts. Ventilation is forced by suction fans located at the ground surface, aided by the chimney effect of warm air rising in exhaust shafts. Other, corrosion resistant EBS components such as drip shields could be installed at repository closure. After closure heat continues to be dissipated to the drift walls by thermal radiation and natural convection.

The previous design responded to requirements of the Nuclear Waste Policy Act (NWPA). Long-term surface decay storage was not included in the strategy because of the timetable for waste disposal, and other constraints. The timetable (e.g., NWPA Section 302(a)(5)(B)) was consistent with the conclusions of the Interagency Review Group (1979) on timely disposal for inter-generational equity. In this concept, heat output from commercial SNF would be managed by preclosure ventilation for at least 50 years, and all the design alternatives considered in the referenced study included this feature. Extending the duration of preclosure ventilation beyond 50 years is an important option to achieve a cooler repository, that can be implemented as needed later, long after emplacement.

This concept represents the possibility for extended (100 yr or longer) preclosure ventilation without the need for complete backfilling at closure, in a rock type that exhibits long-term opening stability to peak temperatures of 200°C. Thus, the concept combines the temperature resistance of salt (although with smaller thermal diffusivity) with the mechanical stability of granite.

Table 1.5-2 Details of Reference Open Emplacement Modes

Host Geologic Media/Concept >>>	Shale Unbackfilled Open	Sedimentary Backfilled Open	Hard Rock Unsaturated Open
Repository depth	~500 m	200 to 300 m	300 to 500 m
Hydrologic setting	Saturated	Saturated or Unsaturated	Unsaturated
Ground support material	Shotcrete; steel supports as needed	Rockbolts, wire cloth & shotcrete; steel supports as needed	Rockbolts
Seals and plugs	Emplacement drift plugs and seals Shaft & ramp plugs and seals	Shaft & ramp plugs and seals	Shaft & ramp plugs and seals
Normalized Areal Loading (GWe-yr/acre)	1 to 10	1 to 10	1 to 10
SNF Emplacement Mode	Horizontal in-drift emplacement	Horizontal in-drift emplacement	Horizontal in-drift emplacement
WP configuration	21-PWR	21-PWR	21-PWR
Overpack material	Steel [B]	Steel [B] or corrosion resistant (see text)	Corrosion resistant
Package dimensions	≤2 m D x 5 m L	≤2 m D x 5 m L (typ.)	≤2 m D x 5 m L
Drift/borehole dia.	4.5 m (drifts)	4.5 m (drifts)	5.5 m (drifts)
Drift/borehole spacing	60 m (drifts) 10 m (packages)	60 m (drifts) 10 m (packages)	60 m (drifts) 6 m (packages)
Borehole liner material	NA	NA	NA
Buffer material	NA	NA	NA
Backfill material	In crossing drifts only: crushed, conditioned shale with swelling clay added	In all drifts: crushed, conditioned shale with swelling clay added	No backfill
Line or point loading	Point	Point	Line

The corresponding concept for saturated hard rock would require complete backfilling at closure to limit groundwater movement through the repository. The plugging/sealing strategy discussed in Section 1.5.1 would not be effective in saturated hard rock because the waste packages would not be protected by low permeability host rock, or a clay buffer (Section 1.4.5.1). Accordingly, a low-permeability backfill would be needed to limit advective transport from potentially large numbers of waste packages.

1.6 Design Flexibility

The design concepts described here are intended to be part of an overall waste management system that is flexible and can adapt to various construction and operational conditions. In this report, the phrase "flexibility in design" refers to capabilities built into the repository design to accommodate changing conditions, such as unanticipated underground conditions and new design requirements. The need for flexibility in the repository design evolves from operational requirements, such as:

- Disposal of a wide range of radioactive waste forms and container sizes, with the understanding that not all details are yet known on waste receipt and delivery schedules.
- Preserving the capability to retrieve one or all waste packages (this is an assumed requirement).
- Maintaining the ability to monitor the facilities and surrounding environment over a period of decades and possibly centuries before committing to closure.
- Designing a subsurface ventilation system that can achieve the selected repository thermal goals and accommodate concurrent underground construction and waste emplacement.

Flexibility in design affords the capability to adapt to different waste receipt and operational scenarios and to unanticipated underground conditions encountered during construction. Examples of flexibility in design of subsurface facilities include modularity of emplacement panels, alternative routing of waste handling and other traffic, prefabrication of engineered barrier components, etc. Systems for waste packaging, transport, and emplacement will be designed to accept different size waste canisters and different waste types, to the extent practical. Whereas specialized equipment may be needed for inspection, lifting, welding, and related operations for each canister type and disposal overpack design, the facilities that house these operations can be designed for flexibility.

Three key aspects of design flexibility are: 1) the capacity of the repository to support a range of thermal management strategies; 2) the capability to expand or modify the repository design; and 3) the capability to accommodate a range of waste types and throughput scenarios.

1.6.1 Sequential and Modular Repository Development

A waste management system that is flexible and can adapt to future changes would likely include a modular approach to surface and subsurface construction. Modular or sequential implementation allows for decisions concerning repository design, development, operation, and closure to be made in a stepwise manner: at each step in the process, a decision whether to proceed would be made based on the licensing and regulatory requirements, funding profile, and operating experience. The next stage of construction would proceed informed by the experience gained from the previous stage.

The possible benefits of a modular or stepwise approach range from incorporation of lessons learned after each stage of construction to leveling annual construction costs.

1.6.2 Potential Benefits

Ability to Adapt and Improve the System

Sequential development provides opportunities to apply lessons learned from the construction of one module can be applied to other modules. The ability to refine designs based on pilot-scale testing of first-of-a-kind waste packaging and underground emplacement equipment could help ensure that the system will perform reliably and economically.

Increased Confidence in Meeting Schedule Expectations for Waste Receipt and Disposal

By reducing not only the investment but also the time required to construct a spent fuel repository's initial disposal capability, sequential and modular development can enhance confidence that the schedule for the start of repository operations could be met despite funding uncertainties. This development approach also offers the flexibility to adapt to unanticipated policy and budget changes and to unexpected developments during operation with fewer impacts on schedule and cost.

Potential Impacts

Sequential and modular repository development could increase the estimated total cost of the repository by extending operating periods and foregoing some economies of scale in design and construction. However, the impact on the discounted value of disposal costs may be smaller. If a sequential and modular implementation concept is adopted, the overall approach to licensing a repository would not necessarily have to change. The license application to the NRC could describe the sequential and modular construction and operation plan, and could contain a safety analysis for a fully developed and loaded repository. The compliance analysis could be based on the entire expected inventory and the complete repository system and facilities.

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2. General Description of Facilities Common to Disposal Concepts

2.1 Waste Packaging

As noted in Section 1.4.3 above, there are numerous considerations that go into the design and selection of waste packages and many of those considerations are coupled to the repository host geologic media, subsurface design, layout and concept of operations, requirements for preclosure handling and safety and postclosure performance.

2.1.1 Canistered Commercial Spent Nuclear Fuel

This study assumes that commercial SNF is delivered to the repository surface facilities in sealed stainless steel canisters or containers; no bare fuel handling will be performed at the repository. This does not preclude the capability to age and blend SNF into disposal canisters elsewhere, such as a consolidated storage facility or repackaging facility. Aging and blending functions could be co-located with either a storage facility or the repository, or both. This is consistent with system architecture studies (Nutt et al. 2012).

The SNF canisters will be placed in disposal overpacks at the repository surface facilities. There is a distinction between waste canisters, or waste containers, and overpacks for storage, transport, and disposal. Together the canister/container and disposal overpack are referred to as a waste package. A waste canister/container is generally sealed permanently at the point of origin, thereby avoiding any further exposure of the waste during successive handling, packaging, and transport operations. Overpacks provide economical means to meet different requirements such as heat dissipation, impact damage limits, and corrosion resistance. Overpacks for storage and transport may be re-useable, whereas those for disposal would become permanent parts of the engineered barrier system at emplacement.

Containers for SNF provide structural integrity and support to the used fuel, criticality control, heat dissipation, containment during handling and repackaging, and possibly some containment after permanent disposal. These functions are met using a sealed metal right circular cylinder and internal features such as baskets for fuel support, thermal shunts, moderator exclusion features (potentially), neutron absorbers, flux traps, and inserts, spacers, or fillers. These internal features must be engineered “up front” for all storage, transport, and disposal functions, in order for the containers to be permanently sealed at the point of origin.

Containers for SNF are typically loaded in fuel pools and accordingly, are fabricated from materials such as stainless steel that do not react rapidly with borated water, limit corrosion, and do not disperse particles or other products of corrosion into the pools. Carbon steel could possibly be used and is a cost-effective alternative, but must be completely and effectively coated to prevent interaction with water and boric acid in fuel pools (NRC 1999). Stainless steels also provide more resistance to radiolytic corrosion during storage when high gamma fields exist, and traces of moisture, along with air, are present on the container surface. For this reason, the spent nuclear fuel containers that are shipped to the repository are assumed to be fabricated from stainless steel.

The containers for SNF have smooth stainless steel walls, with internal stainless steel baskets to hold fuel assemblies and provide strength and rigidity. Containers are assumed to have an integral external feature that does not protrude from the external wall to facilitate handling and to allow for future insertion into a waste package overpack. Neutron absorbing structures can be made from borated stainless steel, or other materials with protective coatings. The containers are assumed to be sealed by welding at the packaging/repacking facility prior to transfer to the repository. During the sealing operation the water must be drained, residual moisture removed by evacuation, and the containers charged with inert gas (helium for its heat transfer properties, or argon if needed to maintain the replacement atmosphere during welding). Costs associated with fabricating, loading, and sealing the commercial spent nuclear fuel canisters are not included in the waste package cost estimate.

2.1.2 Waste Package Size

The size of the canisters and associated waste package overpack as well as the materials of construction for the overpack are selected for the disposal concept. The Crystalline (enclosed) and Clay/Shale (enclosed) repository concepts described in Sections 1.4.5.1 and 1.4.5.3, respectively, use waste packages that can accommodate 4-PWR or 9-BWR assemblies in order to address assumed thermal constraints imposed on the buffer materials and near field geologic media. The Generic Salt Repository (Section 1.4.5.2) uses a waste package that can accommodate 12-PWR or 24-BWR assemblies because of the higher temperature tolerance and thermal conductivity typical of salt. The open emplacement mode concepts described in Section 1.5 use a waste package that can accommodate 21-PWR or 44-BWR assemblies. The waste package relative sizes are depicted in Figure 2.1-1.

Table 2.1-1 Numbers of Different Size Waste Packages for a 140,000 MT SNF Repository

	4-PWR/9-BWR	12-PWR/24-BWR	21-PWR/44-BWR
PWR	52,250	17,417	9,952
BWR	30,333	11,375	6,205
Total	82,583	28,792	16,157

All commercial SNF canisters are assumed to have a nominal length of 5.0 meters for the purposes of developing subsurface layouts and waste package overpack cost estimates. A nominal overpack length of 5 m supports most, but not all (e.g. South Texas) canistered SNF. Spacers and spread rings or similar features can be used to hold SNF canisters in place inside disposal overpacks that have extra length.

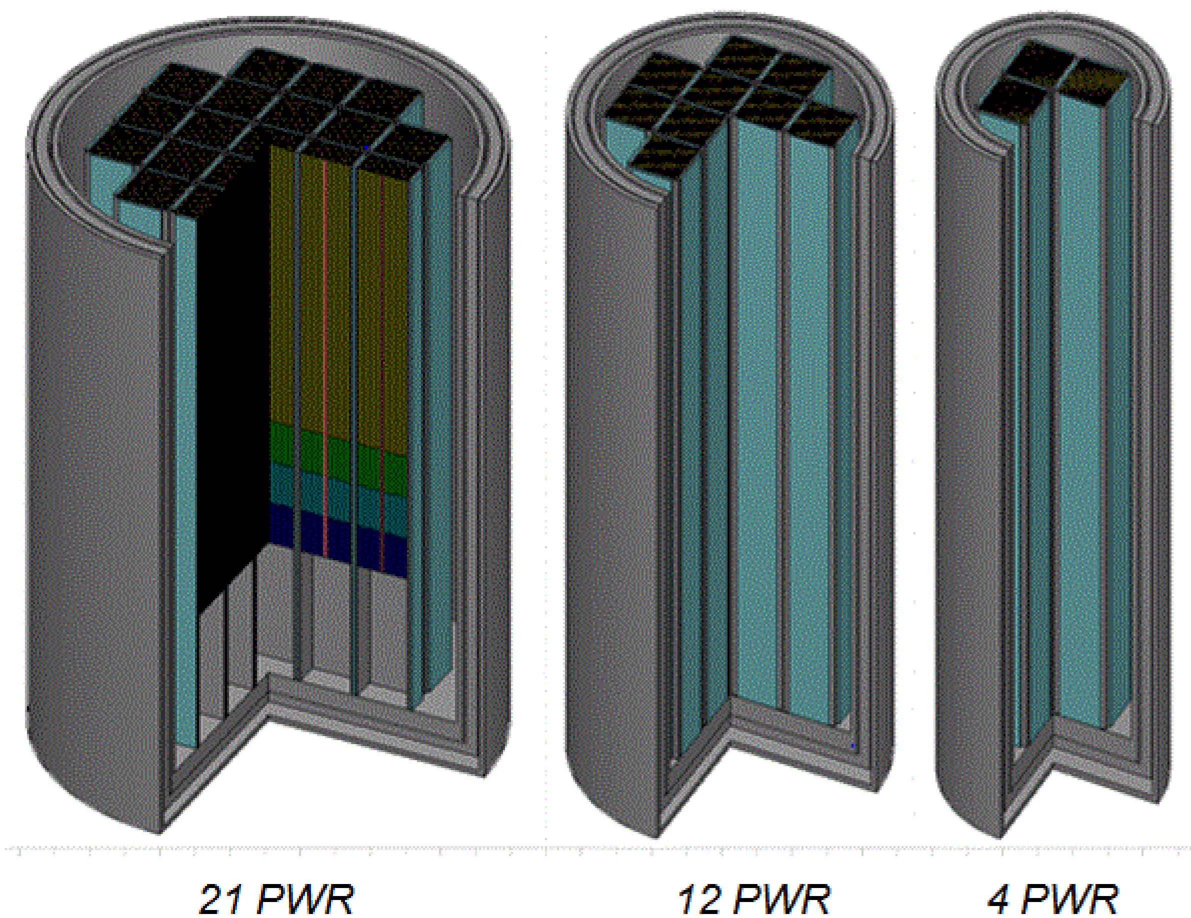


Figure 2.1-1 Relative Waste Package Sizes

2.1.3 Overpack Materials of Construction

As noted in Section 1.4.5.1 above, a copper canister overpack has been selected for the Crystalline (enclosed) concept largely based on the Swedish KBS-3 concept (SKB 2011). The other enclosed-mode disposal concepts described in Section 1.4.5 use carbon steel overpacks that provide the needed performance in a cost-efficient manner. Outer diameters of the different size waste packages considered in this study are shown in Table 1.4-1. Overpacks for the various reference concepts are described in Section 4, and costs are estimated in Section 5. Overpack unit costs from this effort are summarized in Table 5.3-1.

2.1.4 Other Considerations –Shielding

The concepts discussed above generally do not include radiological shielding integral to the waste package and therefore this potential design feature is not included in the cost estimates. The absence of shield plugs in either the canister or overpack design will necessitate the use of remote welding as described in Section 2.2.

The need for shielding would arise if human activity is required in the immediate disposal environment, for example, to inspect waste packages or other EBS features, or to facilitate the placement of backfill materials at repository closure. Gamma radiation is the principal concern, so shielding would involve the use of metallic or other high-density materials. If required, shielding could be provided as a separate structure, as an integral part of the waste package, or a combination of both. If shielding is provided as in integral part of the waste package it will increase the package size and weight. The open disposal concepts described in Section 1.5 could require personnel access to drifts that intersect emplacement areas, for backfilling operations. Some form of shielding would be needed, while minimizing any associated construction activities. This leads to a possibility that shielding could be constructed prior to waste emplacement, then used tens to hundreds of years later. Some preliminary investigations of shielding provided as a separate structure, as an integral part of the waste package, and as a combination of both are presented in Appendix F. The results show that reasonable dose rates can be achieved, but shielding concepts will be the subject of future investigations.

2.2 Surface Facilities

Operation of a geologic repository will involve a number of distinct but interrelated waste handling activities and functions that are performed on the surface; the major ones include receiving, handling, and packaging. These functions are needed for any geologic setting and subsurface concept. This section describes the surface facilities for a potential repository for SNF and HLW, based on these activities and functions. This description assumes that bare fuel packaging operations and opening, unpacking and repackaging the contents of existing dual purpose canisters is done at a packaging and repackaging facility separate from, but possibly directly adjacent to or co-located with, the repository operations area. *Importantly, it assumes that the repository operations area receives only canistered SNF and HLW, and does not have the ability to handle bare fuel under normal operating conditions.*

The surface facilities will be located in a Repository Operations Area, a Development Area, and one or more areas for surface shaft or ramp facilities (where the ventilation shafts and fans could be located).

The Repository Operations Area is logically segregated into the Radiologically Controlled Area, the balance-of-plant area, and the site services area. The Radiologically Controlled Area comprises all facilities necessary to receive, package, and emplace waste in the repository. The balance-of-plant area comprises general infrastructure facilities such as administration, emergency management (medical and fire), and motor pool and fleet services. The site services area comprises general parking and possibly a visitor center.

The Development Area will support continuing construction of the repository, even as the Repository Operations Area accepts and prepares waste for underground emplacement.

The following sections describe the movement of SNF and HLW through the Repository Operations Area. It presents the interrelationship of the systems, equipment, and facilities for receiving, preparing, packaging (overpacks if required), and ultimately transporting these waste forms to the underground. It also provides information on how the waste will arrive at the repository, how the systems for handling the waste forms will operate, and how secondary low-level radioactive waste will be handled.

2.2.1 Waste Receiving Operations

Spent nuclear fuel and HLW arriving at the repository will be in solid form, but in a variety of types and sizes. Hence, the materials will arrive in a variety of transportation casks, all certified for use by the NRC. The commercial SNF is assumed to arrive in a 1.6 cm (5/8 inch) welded stainless steel, waste package sized, sealed canister which has been placed in a transportation cask loaded on a trailer or railcar. The canistered commercial SNF could come from a packaging/repackaging facility or directly from reactor sites. For the various reference disposal concepts, the canister could hold 4-PWR/9-BWR, 12-PWR/24-BWR, or 21-PWR/44-BWR assemblies, depending on the geologic setting and other disposal system attributes described in this report. Repackaging of commercial SNF in larger dry storage canisters, would be done at the upstream packaging/repackaging facility. The waste will be transported by rail or road to the Repository Operations Area security station, where personnel will verify the shipping manifests, then inspect and survey the cask and its carrier. Following receipt inspections, loaded transportation casks may be placed in the Lag Storage Parking Area (LSPA) or delivered directly to the SNF Receipt Bay for unloading, depending on operations priorities for waste receipts at any time. If delivered to the LSPA they will subsequently be brought to the Waste Handling Building (WHB) for unloading, based on operations priorities. When left in the staging areas, shipping casks will have their impact limiters removed and will be placed on stand-offs for interim storage. Up to six months of lag storage is assumed.

2.2.2 Carrier Preparation Functions and the SNF Receipt Bay

A Carrier Preparation area and SNF receipt bay will support preparation of the waste transportation casks before they enter the other waste handling modules. This could be a one-story, high-bay steel framed structure enclosed with insulated steel roof and wall panels. It could be either a free standing building or it could be integral to the other waste handling building modules. For the purpose of cost estimating it is assumed to be included in the square footage of the Waste Handling Facility described in Section 2.2.6. The interior framing will be of light-gauge steel and easily decontaminated panels. The foundations will consist of reinforced concrete spread footings, to support the facility’s columns, and continuous reinforced concrete mat foundations, to support the railroad tracks. To mitigate vibrations from carrier movement, the spread footings will be separated from the mat foundations. The facility’s columns will support bridge cranes running the length of the facility, each of which will span a gantry crane for servicing the tracks. The transportation carriers will enter and exit the facility through remotely operated roll-up doors (CRWMS M&O 2000a, Attachment II, Section 1.3).

2.2.2.1 Carrier Preparation Area and SNF Receipt Bay: Material Handling System

The material handling system in the Carrier Preparation Area and SNF Receipt Bay will receive and inspect shipping casks from the carrier/cask transport system, then prepare the casks for unloading. Parallel tracks/roadways will permit the passage of both truck and rail carriers. Outer tracks/roadways will serve incoming carriers from the rail yard or truck-parking area, and inner tracks/roadways will serve outgoing carriers (CRWMS M&O 2000a, Attachment II, Sections 1.3.2.1, 1.3.1.3.1).

Receiving operations will include:

- Performing a radiation survey of the carrier and the transportation cask
- Removing or retracting the personnel barrier(s)
- Sampling the cask exterior for contamination
- Measuring the cask temperature

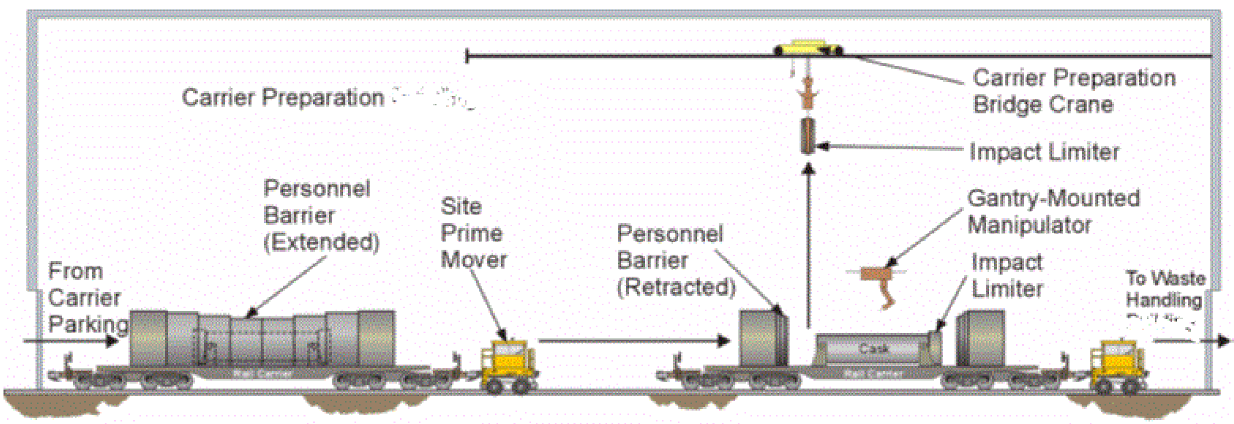
- Removing or retracting the cask impact limiters
- Installing the cask's lifting attachments (if any)

Shipping operations for carriers/casks leaving the repository will include:

- Installing the cask trunnions (if required)
- Checking the cask tie-downs
- Installing the cask impact limiters
- Performing another radiation survey of the cask

An overhead bridge crane and a remotely operated manipulator will serve the preparation lines. The facility support equipment will include tools and fixtures for removing and installing personnel barriers, impact limiters, cask lifting attachments, and cask tie-downs (CRWMS M&O 2000a, Attachment II, Section 1.3).

If the used fuel packaging and re-packaging facility is co-located near the repository, then canisters will be transferred from the packaging and repackaging facility using a site transporter. The SNF receipt operations can be bypassed in this case.



Note: The materials handling system uses manual and remote equipment to prepare incoming road and rail transportation casks for offloading in the Waste Handling facility. The same system could be used for preparing outgoing empty transportation casks.

Figure 2.2-1 Concept for Operations in the Carrier Preparation Area /SNF Receipt Bay

2.2.3 Waste Receipt and Transfer Facility (WRTF) Modules

Waste Receipt and Transfer Facility modules are assumed to be multi-building, concrete and steel structures made of noncombustible materials. The exterior walls will be mainly concrete; walls that do not provide shielding for radiation protection will be constructed of metal siding panels with insulation.

Personnel will enter the facility through a security portal in the administrative area. Staff who work in contaminated or potentially contaminated areas will change into protective clothing in the change rooms before proceeding to workstations through entrance/exit corridors. All operations levels will be accessible by corridors and stairwells. To meet functional and safety requirements, the access corridors will be located outside the transfer cells. Access corridors are shielded areas where operators can safely and remotely observe and control operations. Shielding walls, windows, and doors will protect staff operating and maintaining the primary waste handling systems.

The WRTF modules will integrate the primary systems that receive, lift, unload, handle, and place canistered SNF and high-level radioactive waste into waste package overpacks and deliver sealed waste packages to subsurface waste handling systems.

The primary systems in the facility are:

- Carrier/cask handling system
- Canister transfer system
- Disposal container (overpack) handling system

Each transfer line will contain:

- A cask preparation and decontamination area
- A disposal container loading cell
- A disposal container decontamination cell

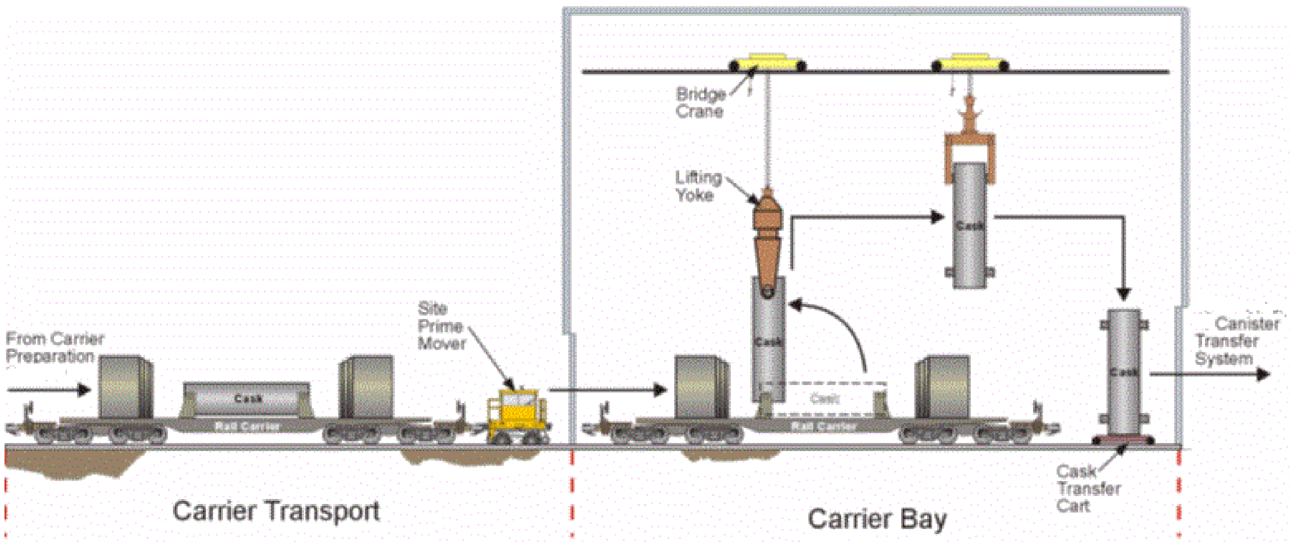
The Waste Receipt and Transfer Facility will be sized to accommodate the equipment and operations described below.

A number of systems and structural features will support these waste handling operations. An area will be designated for preparing empty disposal containers, and a holding area will provide room for loaded and sealed waste packages waiting for emplacement. A maintenance bay will be available to maintain the handling cranes. The facility will also have shops to repair and maintain instruments, robotic welders, and other equipment, along with storage areas for all necessary tools, maintenance materials, high-efficiency air particulate filters, and gas bottles.

2.2.4 Waste Receipt and Transfer Facility: Carrier/Cask Handling System

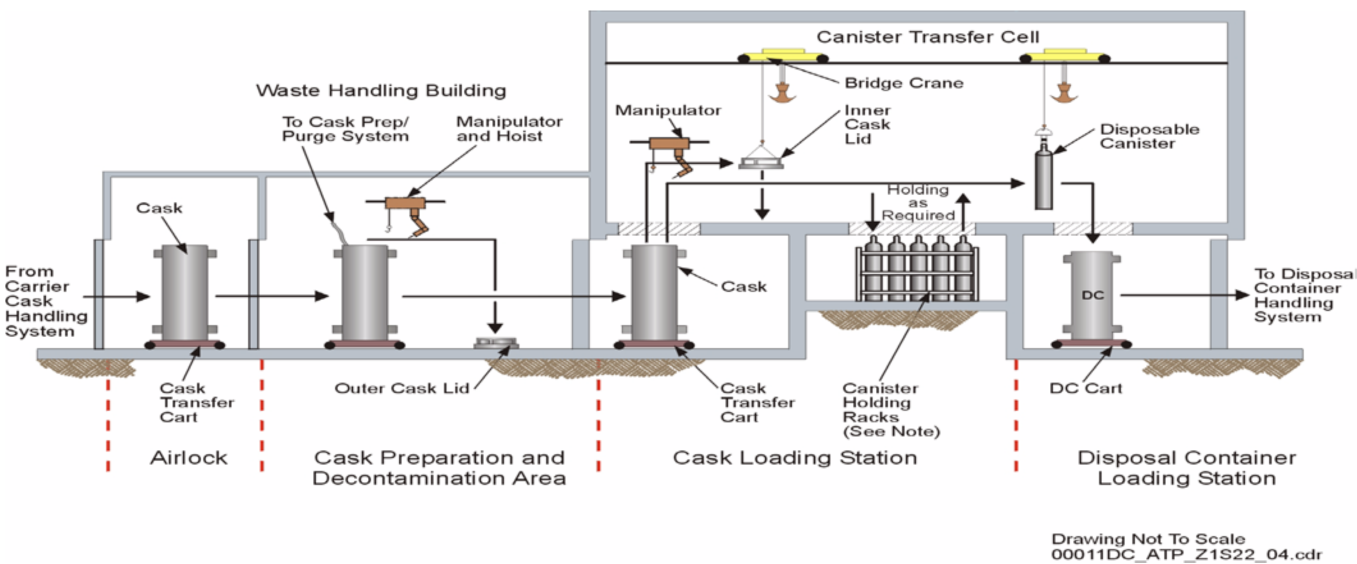
The carrier/cask handling system will be housed in the SNF Receipt Bay of the WRTF. Figure 2.2-2 provides a mechanical flow diagram of handling system operations (CRWMS M&O 2000a, Attachment II, Section 1.1.3.1).

A site prime mover will tow the truck carrier or railcar into the carrier bay loading area. After removal of the cask tie-downs, a bridge crane will lift the cask off the carrier and place it onto a cask transfer cart for delivery to the canister transfer system, as appropriate. After the cask is unloaded and decontaminated, it will be returned to the carrier/cask handling system for shipment offsite.



Note: Transportation casks containing canistered SNF and HLW are off-loaded from road/rail carriers in the carrier bay (SNF Receipt Bay) of the WRTF. The cart is the means by which loaded and emptied transportation casks are moved about within the WRTF. The transportation casks remain closed while in the carrier bay.

Figure 2.2-2 Carrier/Cask Handling System Concept



Note: The transportation cask outer lid is removed and the internal gas is sampled using a purge system and remote manipulator. If necessary, the gas is filtered prior to release. The cask transfer cart moves the cask into the canister transfer cell, where the inner cask lid is removed and the canister is removed from the transportation cask and inserted directly into a disposal container. Canister holding racks are not in the direct transfer path from the loading station to the disposal station.. The disposal container is moved and positioned using a seismically restrained transfer cart similar to the one used for moving the transportation cask. DC = disposal container.

Figure 2.2-3 Canister Transfer System Concept

2.2.5 WRTF Canister Transfer System

The WRTF will house the canister transfer system, which will receive rail and truck transportation casks from the carrier/cask handling system and empty disposal containers from the disposal container handling system. The canister transfer system is located in the shielded hot cell.

Figure 2.2-3 provides a mechanical flow diagram for the operations of the canister transfer system. The line will be configured to handle disposable canisters of HLW or SNF, ultimately loading them into disposal containers. The canister transfer line will also have:

- A below grade transfer tunnel or alternatively an air lock
- A cask preparation and decontamination area
- A canister transfer cell

Additional space could also be provided for an off-normal canister handling cell and a transfer tunnel connecting the canister transfer and off-normal canister handling cells if those functions are not available in a packaging/repackaging facility co-located with the repository surface facilities. The off-normal canister handling cell is not included in the cost estimate for the repository surface facilities.

A transportation cask containing canisters of SNF or HLW will be unloaded in the SNF Transfer Bay, then transferred to a cask transfer cart and secured against overturning. The cask transfer cart will move through a transfer tunnel or into a canister transfer system air lock, either of which would have isolation doors to maintain a lower air pressure in the canister transfer work areas than in the SNF Receipt Bay (Carrier Bay) (CRWMSM&O 2000a, Attachment II, Section 1.1.2.1).

The cask preparation area remote handling equipment will consist of a cask transfer cart, cask preparation manipulator, and the tools required to perform cask unbolting, venting, lid removal, and decontamination. Workers preparing a cask will:

- Sample the cask vent ports
- Vent the cask and purge the cavity gas, if required, to the atmosphere through a high efficiency particulate air filtration system
- Loosen the outer lid bolts
- Secure a lifting fixture to the outer lid
- Remove the outer lid and stage it in the cask preparation area

Once the canisters are removed from the transportation cask, the empty cask will be prepared for shipment back to the transportation system for reuse.

All canister transfer operations will be performed remotely in shielded canister transfer handling cells. The canister transfer cell will consist of:

- A cask unloading port
- A disposal container loading port where canisters will be loaded
- A canister holding area

- A crane maintenance area

The canister transfer system will then deliver the loaded disposal containers to the disposal container handling system (CRWMS M&O 2000a, Attachment II, Section 1.1.2.1).

The hot cell will areas for:

- Unloading transportation casks
- Loading disposal containers
- A canister holding area

The canisters will be removed from a transportation cask by remote equipment and placed in a disposal container and taken to the holding area. Remote handling equipment in the transfer cell will include an electromechanical manipulator, and a suite of small canister-lifting fixtures. The remote equipment will be designed to facilitate in-cell operations, maintenance, and recovery from off-normal events. A maintenance bay inside the cell will facilitate in-cell maintenance.

Interchangeable components will facilitate maintenance, repair, and replacement of equipment. Lay-down areas will be provided, as required, for fixtures, tooling, and canister grapples. If in-cell equipment fails, the crane and manipulator can be remotely withdrawn to the maintenance bay by using off-normal and recovery operations. Once a disposal container has been loaded, it will be moved to the disposal container handling system (CRWMS M&O 2000a, Attachment II, Section 1.1.2.1).

2.2.6 WRTF Disposal Container (Overpack) Handling System

Disposal container overpacks and lids are assumed to be fabricated at off-site fabrication facilities and shipped to the repository. The disposal container (overpack) arrives without any waste inside. After waste is loaded, the disposal container design provides some radiation shielding for operating personnel, but not enough to keep occupational exposures within allowable limits. Therefore, all loaded disposal container operations will be done remotely.

Loading and closing operations on disposal containers will be performed in shielded cells. Once the disposal container is loaded and its top lid(s) are welded, inspected, and accepted, the disposal container is called a waste package.

Figure 2.2-4 provides a mechanical flow diagram for the operations of the disposal container handling system. The system receives loaded disposal containers from the canister transfer systems.

The system includes areas for:

- Preparing empty disposal containers
- Welding disposal container lids
- Holding loaded disposal containers
- Docking and loading the waste package transporter
- Maintaining equipment used in handling the disposal containers/waste packages

The empty disposal container is assumed to be fabricated at a separate facility and shipped, with the appropriate closure lid(s), to the WRTF for loading. The disposal container handling system will receive and prepare the empty container for loading, then deliver it to either the assembly or canister transfer systems for loading.

Once loaded, the container will be returned to the disposal container handling cell for welding. A number of welding stations will be provided to receive loaded containers from the assembly or canister transfer system lines. The welding operations include:

- Removing temporary lid sealing devices
- Installing and welding the lids
- Conducting nondestructive examination
- Performing in-process weld stress relief

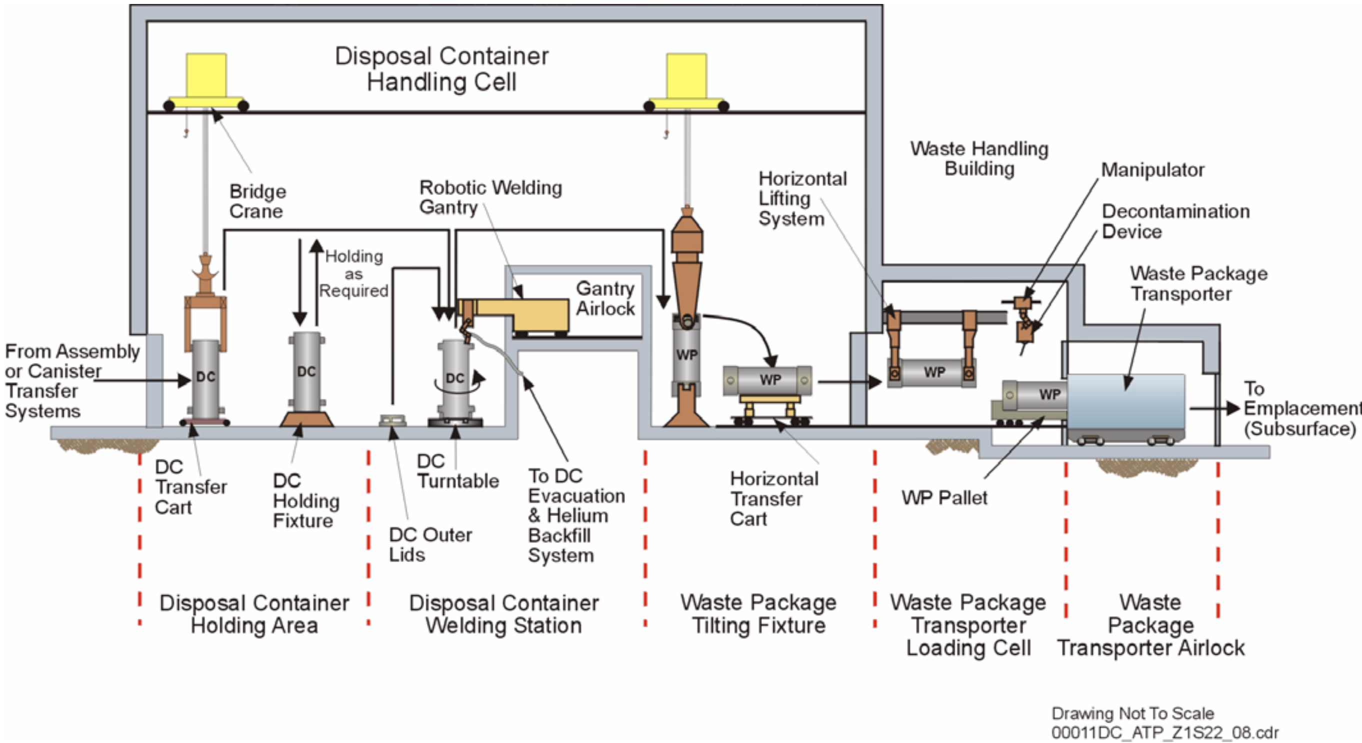
Following the nondestructive examination and acceptance of the weld, the container will be certified as a waste package and transferred to a tilting station for transport to the underground repository. Any disposal container that does not meet the weld examination criteria will be transferred to the waste package remediation system for repair or corrective action. A suite of handling fixtures, including yokes, lift beams, collars, grapples, and attachments, will support the operations of the disposal container handling system. The remote equipment will be designed to facilitate decontamination, maintenance, and use of interchangeable components, where appropriate. Set-aside areas will be included, as required, for fixtures and tooling to support off-normal and recovery operations. Semiautomatic, remote, manual, and backup control methods will be used to support normal, maintenance, and recovery operations. The interfaces of the WRTF will provide the facility, utility, maintenance, safety, and auxiliary systems required to support operations and radiation protection activities.

Following examination and certification of the welds, the waste package will be prepared for transport underground to the repository. A completed waste package will be moved either to the holding area for loaded disposal containers, or to the waste package tilting area, where the waste package will be rotated to a horizontal position resting on a horizontal transfer cart. This cart will transfer the waste package to the transporter loading cell.

Equipment for the disposal container handling system (Figure 2.2-4) will be designed to facilitate remote retrieval for manual decontamination, maintenance, and component replacement, as required. All handling operations will be supported by a variety of remote handling fixtures, including:

- Disposal container lifting and base collars
- Lifting trunnions
- Lifting yokes
- Lifting beams
- Tilting fixtures
- Holding fixtures
- Lid sealing devices

A crane maintenance bay at the far end of the handling cell will allow for contact maintenance and testing of the cranes in the cell.



Note: Loaded disposal containers are received from the canister transfer systems. An overhead bridge crane lifts the disposal container from the transfer cart and places it onto the disposal container welding station, where the disposal container is permanently sealed) and the interior backfilled with helium to promote efficient heat transfer from the inner portion of the container to the outer walls. After remote inspection and acceptance of the welds, the disposal container is termed a waste package. The waste package is moved to a horizontal position in preparation for loading into the waste package transporter, which will be used in moving the waste package underground to the emplacement drifts. DC = disposal container; WP = waste package.

Figure 2.2-4 Disposal Container Handling System Concept

Waste Package Transporter Loading

The final handling sequence for the surface facilities involves:

- Repositioning the waste package to a horizontal position
- Transferring the waste package to a decontamination and transporter loading cell
- Loading the waste package onto the waste package transporter Decontaminating the waste packages (final)
- Inspecting the waste packages (final)
- Certifying and tagging waste packages.

These operations will be performed using:

- A remotely operated horizontal transfer cart
- A waste package horizontal lifting machine
- Decontamination and inspection manipulators
- The waste package transporter.

The waste package, once it is moved into the transporter loading cell from the disposal container handling cell, will be lifted off the horizontal transfer cart by the lifting collar, the base collar, and the horizontal lifting machine. While suspended, the waste package will be decontaminated, inspected, and certified. Data needed for repository record keeping will be recorded. The mobile pallet of the transporter will then move into the cell, and the waste package will be lowered onto the pallet. The handling collars will then be remotely removed and taken out of the waste package transporter loading cell for reuse. Any contamination picked up during disposal container sealing will be manually removed in rooms for equipment contamination before the collars are transferred to the empty disposal container preparation area for reuse.

A transporter air lock will be provided at the exit of the transporter loading line so the waste package transporter vehicle may enter and be docked for loading. The air lock will prevent movement of air between the transporter loading cell and the outside atmosphere. In the final surface waste handling steps, the transporter shield doors will be closed, and the waste package transporter will be disengaged from the loading cell dock. Then the waste package will be transported to the subsurface repository via the waste shaft or ramp facilities.

2.2.7 Facility Size Estimates

The Waste Handling Facility Modules will have multiple transfer lines dependent upon throughput requirements. Each line will operate independently to handle waste throughput and support maintenance operations.

Figure 2.2-5 reflects a WHB RH Complex area associated with receipt and transfer of SNF packages. The same or similar facilities could be used for the receipt and transfer of canistered DOE HLW.

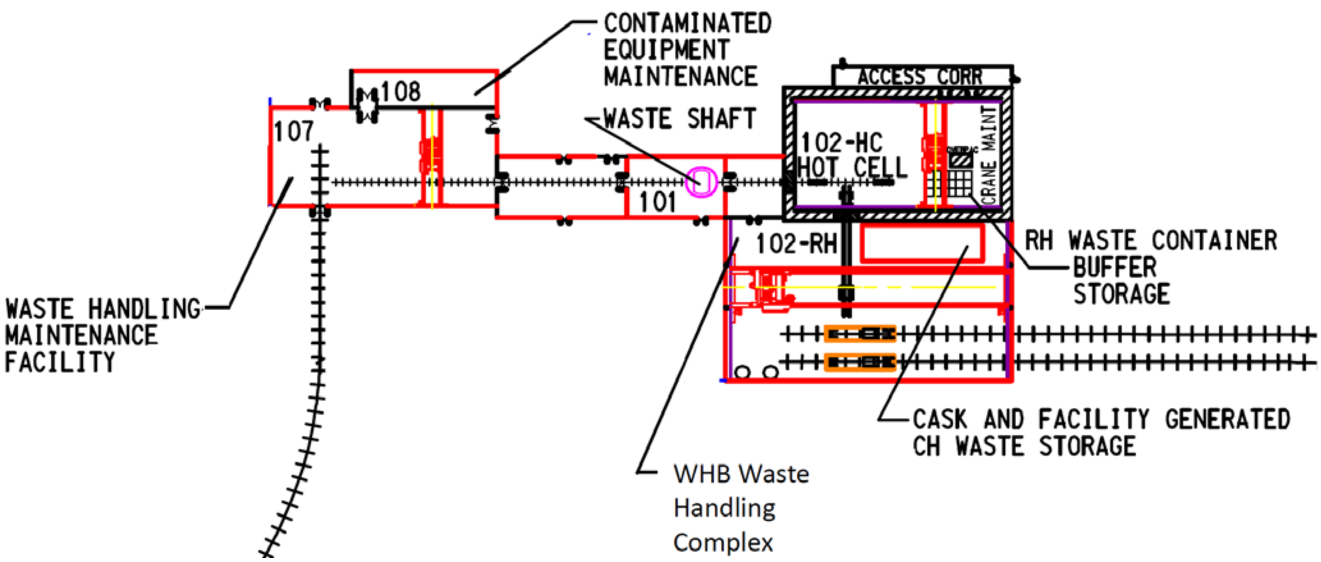
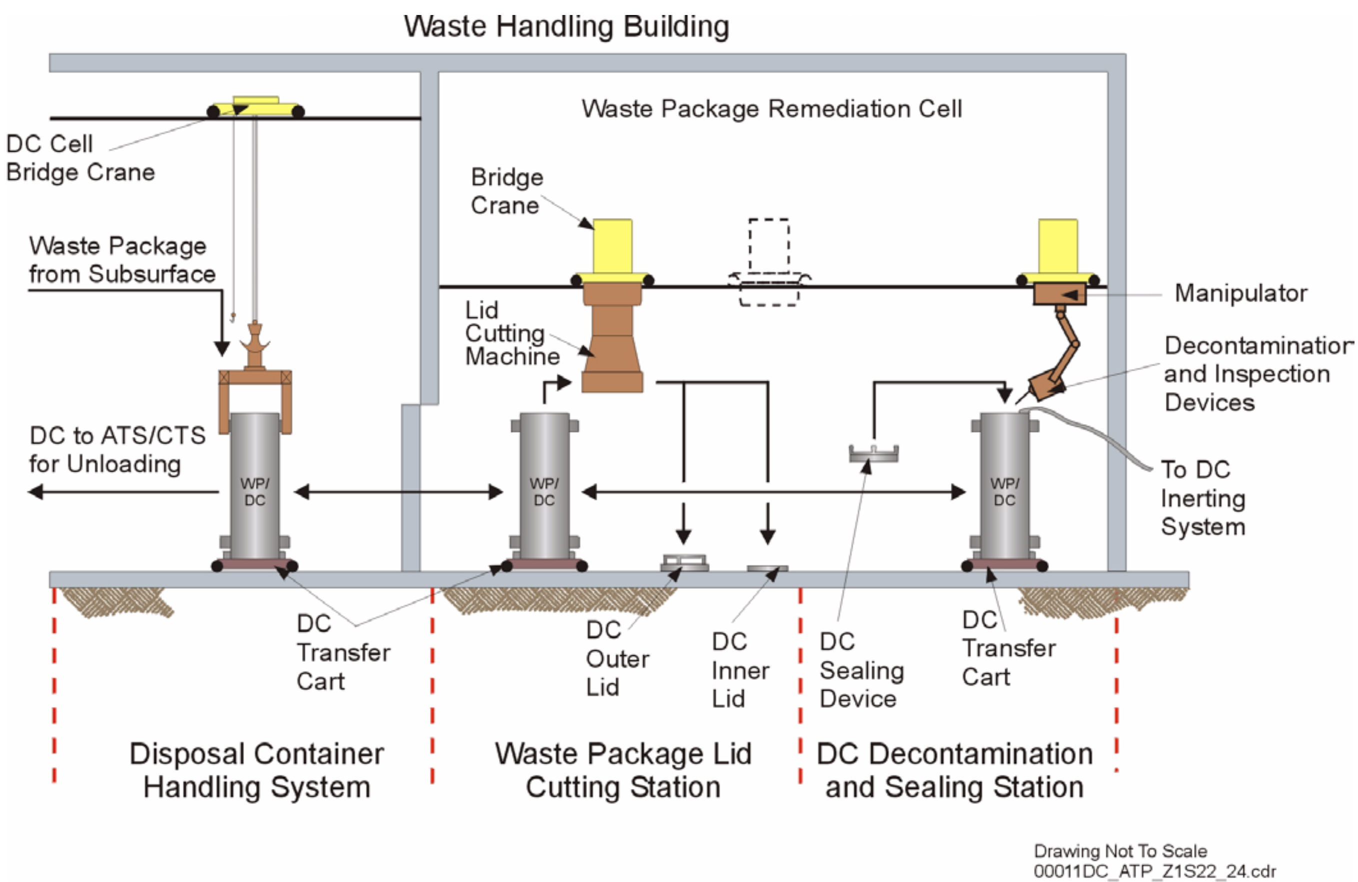


Figure 2.2-5 Waste Handling Facility Configuration for a Single Waste Package Line

The module configuration above has a capacity of approximately 550 waste packages per year (subsystems are scaled to handle waste packages of specified sizes). This estimate is based on an overall cycle time of about 20 hours total to conduct the steps described on each SNF canister receipt. About half of the operations are performed in the shielded hot cell and the remaining steps are performed in the receipt bay support structure. Therefore a single waste package can be processed in a 10 hour shift. Assuming two 10-hour shifts per day and a 75% utilization of the hot cell, 550 waste packages can be processed in a year.

To support annual waste package processing greater than 550 waste packages per year, the number of hot cells is increased. As configured in Figure 2.2-1 the receipt bay support structure can support up to two hot cell facilities. The number of receipt bay support structures is increased as the number of hot cells is increased. The associated costs estimates for these facilities and operations are described in Section 4 below.



Note: The waste package remediation system can be used to repair minor defects in disposal containers and waste packages. The system will be used to remedy weld defects and unload waste packages for the purpose of performance confirmation activities. A lid cutting machine will be used to open the waste packages. DC = disposal container; WP= waste package.

Figure 2.2-6 Waste Package Remediation System

2.2.8 Additional Systems

Waste Package Remediation

When a waste package is found to be abnormal or damaged it will need to be remediated. Although not included in the cost estimate for the repository, it could be included in the WTRF or if a packaging/repackaging facility is co-located next to the repository, it could be part of those systems., Figure 2.2-6 provides a mechanical flow diagram for the system's operations. (CRWMS M&O 2000a, Attachment II, Section 1.1.4.1).

The waste package remediation system will receive disposal containers and waste packages that:

- Are defective or abnormal
- Have failed the weld inspection processes
- Have been selected for retrieval from the repository for performance confirmation examinations.

If inspections of the closure weld reveal an unacceptable but repairable welding defect, the disposal container will be prepared for rewelding, which may include complete weld removal. Correction of rejected closure welds will require removal of the defect in such a way that the disposal container can be returned to the disposal container handling system to complete the closure welding process. If examination of the closure weld shows the defect or damage to be irreparable, the container will be opened. If a waste package is retrieved from the repository for any reason—suspected damage, known failure, or planned performance confirmation examinations—it will be opened in the waste package remediation system (CRWMS M&O 2000a, Attachment II, Section 1.1.4.1).

The remediation system will use a variety of remotely operated equipment, including an overhead bridge crane, an in-cell multipurpose manipulator, a lid-cutting machine, and closed circuit television viewing systems. System operations will all be performed remotely, using equipment designed to facilitate decontamination, maintenance, and replacement of interchangeable components, as required (CRWMS M&O 2000a, Attachment II, Section 1.1.4.2.4).

The remediation system will also interface with the performance confirmation data acquisition/monitoring system to gather data needed to support the performance confirmation program.

Treatment of Low-Level Radioactive Waste from Repository Operations

Operations at a repository, i.e., receiving, handling, and packaging commercial SNF and HLW into disposal overpacks, will generate secondary LLW. Most of it will be generated in the Waste Handling Facility; smaller quantities may be produced in the Waste Treatment Facility, where secondary low-level waste is processed.

Regulations at 40 CFR Part 261, promulgated under the authority of the Resource Conservation and Recovery Act of 1976 (42 U.S.C. 6901 et seq.), define hazardous wastes as: “wastes that exhibit one of more of the characteristics of toxicity, corrosivity, reactivity, or ignitability, or are wastes from specific sources, wastes from nonspecific sources, or are specified discarded commercial chemical products.” Administrative controls will be used to minimize generation of hazardous wastes.

Hazardous wastes that are not mixed wastes will also be packaged for shipment off site to an approved disposal facility. Wet, solid LLW (e.g., spent ion exchange resins and filtration materials if used to treat liquid LLW generated from cask washdowns) generated in the Waste Handling facility will be collected and packaged for disposal. Then it will be transferred in containers to the Waste Handling Facility for staging until disposal. Any other solid LLW generated in the Waste Handling Facility that does not exceed the radioactivity limit for the Waste Treatment facility will be collected at its point of origin and transferred to the Waste Treatment Facility to be processed and packaged for disposal at an approved low-level radioactive waste facility (which could be the same facility as the repository. Solid waste that exceeds Waste Treatment Facility administrative activity limits will be packaged at the source of generation for shipment and disposal off the repository site.

Mixed Waste Management System

The term “mixed waste” refers to materials that contain a combination of radioactive waste and hazardous chemicals. Since administrative controls designed into a monitored geologic repository will generally restrict the use of hazardous materials, operating a repository should not generate a significant amount of mixed waste. If mixed waste is generated, however, it will be collected and repackaged for disposal at the point of generation. During packaging, samples will be collected for analysis. The packaged mixed waste will then be transferred to the Waste Treatment Facility for holding before being transported to a suitable disposal facility (CRWMS M&O 2000a, Attachment II, Section 1.5.5).

2.3 Shaft and Ramp Access

The following high-level information is provided as a basis for cost estimation, for the mined geologic disposal concepts. Shafts will be used for men and materials, waste rock removal, radioactive waste handling, ventilation intake, and ventilation exhaust. Emergency egress ladders or elevators will be built into the men & materials shaft, the waste rock removal shaft, and other shafts as appropriate (e.g., ventilation shafts). The numbers of shafts used in a repository is sufficient that dedicated emergency egress shafts are not required.

The first shaft to be excavated in all concepts will be for men-and-materials. It will be excavated using drill-and-blast methods, and will likely be lined with nonreinforced concrete. This shaft will be circular, with a small diameter (approximately 5 m finished). The liner thickness will be nominally 30 cm, but may be adjusted to accommodate ground conditions. Most of the disposal concepts are situated in sedimentary rock which may be sensitive (e.g., clay or shale) or squeezing (e.g., clay or evaporites at a few hundred meters depth). Where long term creep deformation is expected the ground support will consist of rockbolts, steel sets, and welded steel lagging (steel sets and lagging are more readily maintained than concrete). In sensitive media shotcrete will be used to anchor the lagging and seal exposed areas of rock. Reinforced, cast-in-place concrete will be used at shaft collars and stations, possibly in conjunction with steel ground support and shotcrete in low-quality rock. Various ground support options are available to shaft designers and may be changed during construction in response to local ground conditions. This discussion assumes that water inflow is not significant; where shafts penetrate aquifers more complicated measures would be taken for shaft construction and lining (e.g., as described by DOE 1987a). The men & materials shaft will be equipped with a counterweighted drum-wind hoist, and an emergency egress ladder or elevator. Intake air for ventilation will be forced through a duct by a fan at the surface.

The waste rock removal shaft will be excavated next, using a raise-boring method, following a large-diameter pilot hole drilled from the surface. The method used to drill pilot holes will be compatible with the host geology, e.g., air foam or brine may be used as drilling fluids. If squeezing ground is known to exist (e.g., based on experience with the first shaft) all shafts will be excavated by drill-and-blast from the surface. Waste rock from the raise bore will be removed up the men-and-materials shaft, but for all subsequent raise bores the waste rock shaft will be used. This shaft will also be circular, with a relatively small-diameter shaft (approximately 5 m finished diameter) consistent with size limitations for available raise-boring equipment. Ground support will be installed after completion of the bore, working down from the collar using a galloway or other staging system. The waste rock removal shaft will be equipped with a drum wind, counter-weighted or two-bucket hoist, and an emergency egress ladder or elevator. Intake air for ventilation will be forced through a duct by a fan at the surface.

The remaining shafts or ramps can be constructed in any order. A ventilation intake shaft will be excavated using the same raise-boring method, with the same diameter and ground support discussed above. This shaft will be fitted with an intake fan at the surface to enhance and control airflow during repository construction, but the capacity of this fan (e.g., up to approximately 250,000 cfm) will be less than for exhaust fans used in open repository designs as discussed below. Additional ventilation intake shafts will be excavated as multiple emplacement panels are developed, as discussed below for each concept.

A ventilation exhaust shaft will be excavated using drill-and-blast methods, because of its larger diameter (e.g., 8 m) but with the same ground support discussed above. Greater capacity is indicated for exhaust shafts because the ventilation design for the repository will focus airflow downstream from the emplacement drifts, to fewer and fewer openings, to limit the need for worker access to downstream drifts. Larger shafts and higher capacity fans will realize economy of scale, and limit use of plan area for shaft pillars. Exhaust shafts will have the same internals and ground support configuration as intake shafts, with extraction fans located at the collar. An emergency egress elevator or ladder will be installed.

The numbers of shafts needed to dispose of 140,000 MT of SNF vary according to whether ventilation is used to remove heat (open modes), or merely to maintain drifts available for human access after emplacement (crystalline and shale enclosed modes), or only for construction and emplacement operations (salt). For the open modes, previous studies have shown that airflow of 15 m^3/sec is sufficient to achieve 75% or greater ventilation heat removal efficiency (DOE 2008b) even for 21-PWR size packages with heat output up to 18 kW. This rate (15 m^3/sec) can also be applied for construction (e.g., TBM operation) and for construction and emplacement in salt. For maintaining human access to access drifts in crystalline rock or shale, a smaller airflow rate is needed, decreasing the fresh air residence time gradually (increasing residence time from a few minutes to hours, depending on temperature and air quality requirements such as radon control).

The largest exhaust shafts are capable of approximately 500,000 cfm (250 m^3/sec), and can therefore serve approximately 16 open emplacement drifts, or several hundred drifts in the crystalline and shale concepts. The ventilation system can be operated in a combined push-pull mode to ensure that working areas are always at higher pressure than emplacement areas.

Waste Handling Shafts vs. Ramps

A dedicated shaft or ramp will be excavated for waste handling. The principal factors in selecting shaft vs. ramp access are the required payload, excavation size, the extent of rock available for construction, and the technical feasibility of sealing at repository closure.

Waste packages (including overpack) weigh approximately 25 to 50 MT depending on capacity, e.g., from 4-PWR to 21-PWR size, and are approximately 5 m long. Transporters have some shielding, adding 25 to 70 MT or more to the weight to be transported. A modular arrangement can be used for conveyance so that ancillary equipment such as apparatus for waste package transfer, lifting, or up-ending can be separated and does not add to the conveyance payload. For shafts the resulting hoist payload capacity ranges from approximately 50 MT (4-PWR package with shielding and carriage) to approximately 150 MT for 21-PWR packages, to 175 MT or greater for multi-purpose canisters containing 32 or more PWR assemblies (or equivalent). For this study shafts are specified for reference concepts using 4-PWR and 12-PWR size (or equivalent) waste packages. Hoists large enough to handle the 4-PWR size are in use at WIPP and at the Gorleben site in Germany. The 12-PWR size packages could be hoisted by the larger, 85-MT payload hoist concept tested at Gorleben (Biurrun et al. 2009). Larger packages (i.e., 21-PWR) are assumed in this study to be conveyed using ramps (Section 4.7.3).

Waste packages will be transported horizontally to limit the size of underground openings, and limit the number of up-ending operations underground. Shaft diameter (finished) must be at least 7.5 m (to accommodate 5-m waste packages in shielded transporters). A waste package transfer station is needed underground, where packages are loaded into an emplacement vehicle (or "deposition machine") for final emplacement. Specialized emplacement vehicles will be used for different concepts, as discussed below.

Shaft hoists are of two types: drum and friction. Drum hoists are more common, and simply wind the cable onto a large, spiral-grooved drum at the surface in a separate building from the shaft headframe. Two or more cables attached to separate hoist cars ("skips") can be counter-wound on different ends of the same drum (with opposite grooving) for balance. Friction hoists use continuous cable loops fed over large sheaves at the surface and the shaft bottom, driven by motors connected to the upper sheaves. A single, large hoist car would be used to accommodate large payloads, and it would be counterbalanced with approximately half the weight of a fully loaded car. The continuous cable is self-balancing.

The largest hoists suitable for mine shafts are of the friction type. The friction hoist at the WIPP has a payload capacity of 41 MT and a depth of 650 m, and was the largest in the world when built in 1986. A friction hoist test system was built at Gorleben, Germany in the early 1990's and operated repeatedly with a payload of 85 MT, to demonstrate the capability to hoist POLLUX casks weighing approximately 65 MT. The reference concept for a repository in clay at Mol, Belgium will involve lowering of self-shielding super-containers weighing approximately 65 MT, to a depth of 225 m. At the Bruce site in Ontario, Canada, a proposed ILW and LLW repository would involve lowering waste containers of similar weight (with shielding) to a depth of 680 m. Larger friction hoists are proposed based on the same technology but using equipment of increased size, with payload capacity up to 175 MT (Graf et al. 2012).

Waste handling ramps can have grades up to approximately 2.5% for rail, up to approximately 10% to 15% for rubber-tire equipment, or 20% or more for funicular systems. The experience base includes existing railways and highways, ramps constructed at Yucca Mountain and Äspö, Sweden, and many ramps constructed underground for mining. The need for ramp access is greatest for heavy waste packages (e.g., 21-PWR size or larger) for which the needed shaft hoist payload capacity exceeds that of currently available equipment.

There currently exists equipment for conveying heavy waste packages down ramps ("declines") with grades of 10% or more. The SKB authority in Sweden recently (in 2010) purchased a transporter from the Italian company Cometto (6/4/2,43 module) with 24 rubber tires on 12 independently steerable axles, a deck height of 1.5 m, and a payload capacity of 90 MT for ramp operation (Figure 2.3-1). This self-powered diesel-hydraulic transporter was tested in the ramp at Äspö. Additional capacity can be obtained with more axles, driven by a more powerful engine. Other solutions are currently in use for shipbuilding and construction, and hauling nuclear fuel (e.g., in the U.S. Wheelift® systems transport Transnuclear NUHOMS® transfer casks containing dry storage canisters).

Whereas safe construction and operation of shafts and ramps has been demonstrated in various geologic media for mining and highway applications, challenges for waste handling include: 1) demonstrating operational safety requirements are met; 2) managing groundwater inflow; 3) sealing ramp openings at closure; and 4) maintaining ramp stability in soft sedimentary rock. Operational safety analysis has shown that hoisting and ramp conveyance accidents can represent low risk (Dennis et al. 1985; Engelmann et al. 1992). However, licensing a conveyance system of either type for waste transport in the U.S. would likely involve complex analysis of multiple accident types. Controlling groundwater inflow, and sealing at closure, are inter-related challenges. For thick shales both could likely be readily met because of low host rock permeability and the scarcity of flowing groundwater. For bedded host-rock strata underlying permeable aquifers the shaft geometry gives a clear advantage for controlling stability, water inflow, and sealing because of the reduced surface area of the excavation exposed to such aquifers. An approach for shaft excavation through aquifers was developed for the proposed Deaf Smith salt repository (DOE 1987a). The approach involves water-tight multi-layer reinforced concrete and steel lining installed throughout water bearing strata. Extending these measures to ramp completion would greatly expand the scope and cost of construction.

For estimation purposes (Section 4) waste handling ramps for rubber-tire transporters are assumed for the Hard Rock Unsaturated open mode and for the enclosed and open emplacement modes in shale. For unsaturated hard rock the terrain may permit access by short ramps with grade low enough for rail. In a massive shale formation it is assumed that there would be abundant room to build a waste handling ramp (linear or spiral decline to a depth of 500 m at a grade of 10%). Thus, ramp access will be available for larger waste packages in the open emplacement modes (21-PWR size). For emplacement of 12-PWR sized packages in salt (the Generic Salt Repository reference concept) a friction hoist with capacity similar to the waste hoist at Gorleben is assumed (85 MT).

Figure 2.3-1 Diesel Powered Cometto-Built Transporter at Äspö

2.4 Underground Conveyance Concepts

Equipment used to transport waste packages underground will generally be different from that used for final emplacement. The enclosed concepts for mined disposal (crystalline, clay/shale, and salt) will use specialized equipment to align and position the packages. For the Crystalline concept, this equipment will transport packages, up-end them into emplacement boreholes, and complete the installation of buffer and shield plugs. For the Clay/Shale concept this equipment will align the packages with horizontal emplacement borings, and push them into place followed by buffer and shield plugs. With shielded equipment these borehole emplacements can be manned. For the Generic Salt Repository specialized, remotely operated equipment will handle packages transversely (within a shield) and deposit them onto the floor in salt alcoves.

All the other disposal concepts discussed in this report use in-drift emplacement. Remotely operated equipment would transport waste packages into position, lower them onto the floor, and then withdraw from the emplacement drift. For transport throughout the repository, including shafts or ramps, all systems would be shielded. Only at the point of emplacement will the waste package (canister + disposal overpack) be removed from its shielded transfer cask.

The specialized emplacement equipment is not optimal for waste package transport from the surface. In the case of shaft access, it adds weight to shaft hoist payloads. For ramp access, the extra equipment would add bulk to systems that are already large. Hence, a handling station is needed underground to reconfigure waste packages from transfer vehicles to emplacement vehicles. The only exception noted is the Transport-Emplacement-Vehicle (DOE 2008b), a shielded transporter design that would operate on rails and bring waste packages from the surface directly into emplacement drifts.

Two alternatives are available for underground conveyances: rail or rubber-tire. Rail systems have the advantages of inherent alignment, lower motive power requirements, use of rails as electrical feeds, and potentially smaller turning radius (as little as 20 m; Filbert et al. 2010). However, they are expensive because loads are high requiring heavy structural support, whereas rubber tires spread bearing loads over larger areas. Thus, rubber-tire vehicles can run on lightly reinforced or non-reinforced concrete, or rock floors, whereas rail installation requires more material and labor. Rubber-tire transport on non-reinforced concrete or rock floors is assumed for all surface and subsurface repository construction, waste handling, emplacement, and operating functions in this study. High traffic, non-emplacement areas can be paved with reinforced concrete as needed. This assumption means that certain rubber-tire equipment will need the capability for precision alignment (e.g., for aligning waste packages with emplacement boreholes). It also means that the safety case must account for the presence of cementitious materials (in addition to ground support) in the disposal environment. Whereas concrete floors in emplacement areas could be removed at closure (SKB 2010b, Section 2.3.1) this study assumes that all floors are permanent, and that supporting performance analysis will be available.

Alternative design solutions to certain aspects of underground conveyance were identified in this study. In lieu of rail or concrete floors, rubber-tire equipment could be developed to run on compacted rock ballast, or directly on the rock wall (e.g., in circular tunnels). The capabilities of heavy vehicles with independently powered and steerable, load-bearing wheel sets have probably not been fully recognized in the repository engineering community. Another alternative concerns the method for powering underground transporters. Whereas diesel equipment is self-contained, it is subject to accidents initiated by fire. Electrical equipment can run on batteries, energized rails, or overhead wires (i.e., with a pantograph). This study assumes that the most reliable alternative will be selected for remotely operated equipment, but that other, shielded equipment could be used in non-radiation environments.

3. Thermal Analysis

The semi-analytical method is based on the approach developed in FY11 specifically for enclosed emplacement modes, supplemented by new features to represent open modes and the associated effects from ventilation, backfill, package size, etc. In the following section, the methodology and results for enclosed and open modes are presented separately. Additional detail is provided in Appendix A, and for enclosed modes only, in the FY11 report and its appendices (Hardin et al. 2011).

3.1 Thermal Analysis of Enclosed Emplacement Modes

3.1.1 Analysis Approach – Enclosed Emplacement Modes

The modeling tools generated in MathCAD 15®, Microsoft Excel® 2007, and MatLab® Version 7.3 were used to calculate the temperature histories for combinations of disposal concept and waste type, assuming a particular emplacement layout for each concept (Sutton et al. 2011a; Greenberg et al. 2012a). Numerical finite element methods used in this study are discussed in Appendix C, and were used only to increase confidence in peak temperature estimates for the Generic Salt Repository concept.

0Two types of SNF assemblies were considered, namely UOX (40 and 60 GW-d/MT burnup) and Pu-MOX SNF (50 GW-d/MT; see Section 1.2). For thermal analysis of open modes, only the UOX SNF was considered (Section 3.1.2). MOX SNF is not envisioned to be available in sufficient quantity, or in packages of sufficient capacity, to warrant specific analysis in open disposal concepts.

Four types of HLW packages were considered, containing borosilicate glass from the Co-Extraction and New Extraction aqueous methods, and the ceramic and metallic waste forms from electrochemical reprocessing (EC-C and EC-M, respectively). As a simplification of the analysis, HLW disposal was not analyzed for open disposal concepts because typical HLW packages do not have size or heat output (after decay storage) comparable to larger SNF packages.

Thermal responses for these waste forms were investigated for reference disposal concepts in four generic host media (crystalline rock, clay/shale, bedded salt, and crystalline basement rock for deep borehole emplacement). The number of assemblies per waste package, in packages of corresponding size, was varied in a sensitivity study to inform the trade-off with decay storage duration, with respect to peak temperature at the waste package wall.

The reference disposal concepts (Section 1.4.5) were based on representative international concepts for mined disposal in crystalline, clay/shale, and salt media (Andra 2005 and 2005b, European Commission 2010, SRNL 2011) and used recent work on deep borehole disposal by SNL and others (Brady et al. 2009).

The thermal analysis presented here calculates: 1) temperature history at or near the interface between the EBS and the host medium, and 2) temperature history at selected locations within the EBS. For the EBS interface, the model assumes a homogeneous medium with the EBS simply replaced by the geologic media, and with the heat source being a combination of a finite line for the central waste package, point sources for nearby packages, and infinite line sources for neighboring drifts. For selected locations within the EBS, a steady-state calculation was performed at each point in time, propagating the thermal power through annular regions around the waste package, with appropriate thermal properties for each region, and using the interface solution as the time-varying, outer temperature boundary condition. This is an approximate solution that tends to slightly overestimate temperatures by neglecting heat storage in the EBS, and tends to slightly underestimate temperatures around the central package by neglecting low-conductivity EBS materials present at the waste package ends.

3.1.1.1 Calculation Approach

Other details of the physical and mathematical basis for the calculation approaches used in this report are described in detail in Appendix A. The general approach is based on heat transfer by conduction only, neglecting convection and thermal radiation. These simplifications are appropriate for low permeability media and enclosed emplacement modes (Section 1.4).

Two mathematical/computational modeling methods can be applied: the first is based on analytical models, and the second uses numerical simulation (e.g., finite element method). The analysis presented in this report is limited to analytical models implemented in MathCAD 15®, Microsoft Excel® 2007, and MatLab® Version 7.3.

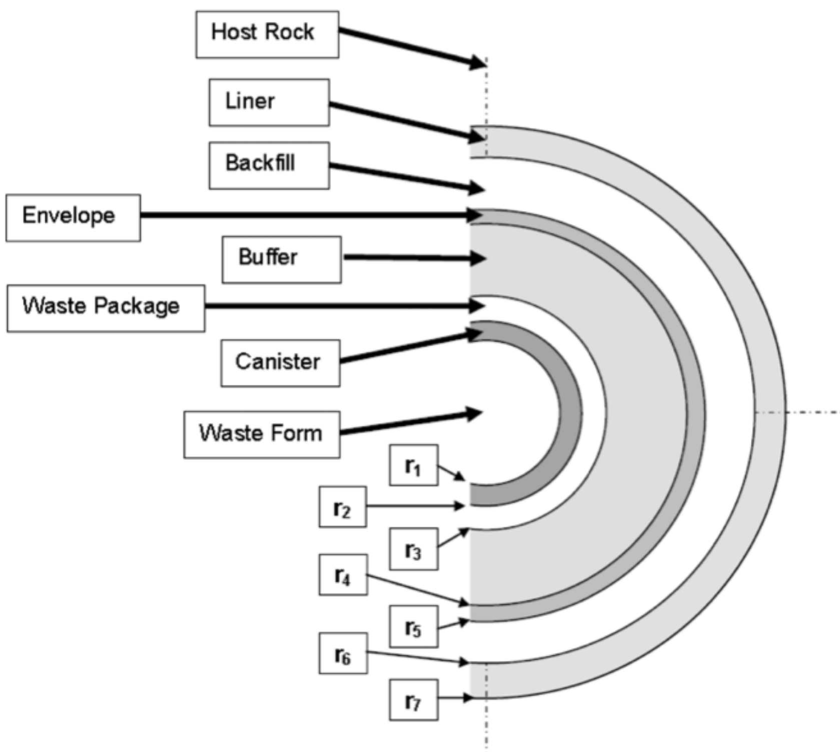


Figure 3.1-1 Illustration of Terminology for EBS Regions, from Waste Canister to Host Rock

A waste package layout was selected for each disposal concept (Section 1.4.5). Figure 3.1-1 shows a generic EBS, with labels for the EBS regions adopted for this report. These labels may differ slightly from those found in the technical literature for various design concepts, but are intended to be general and inclusive. Figure 3.1-2 is a generic repository layout that defines the dimensions. The waste package axis may be horizontal or vertical. For disposal in salt the axial direction is a line of alcoves, whereas for HLW disposal in clay/shale it is an array of parallel emplacement boreholes. The lateral direction is the separation of emplacement boreholes, or emplacement drifts, or linear arrays of alcoves containing waste packages.

The calculation approach is implemented in two steps. The first calculates the temperature at the host rock boundary, or more generally at a calculation radius at or within the host rock, due to a central finite-length waste package plus arrays of nearby packages in the same drift, and in neighboring drifts. The second step uses the steady state approximation to calculate temperature differences across annular EBS regions, starting at the calculation radius and working back toward the waste package. The sum of the temperature at the calculation radius plus the temperature increase at the waste package wall, is the principal temperature estimate used in this study.

The calculation radius for most cases is at the host rock wall (except for the Generic Salt Repository discussed below). Recognizing that for mined disposal the outer dimensions of UOX and MOX SNF waste packages are the same, and the dimensions of HLW glass canisters are the same, two general EBS configurations, for SNF and HLW, were developed for each geologic setting. Using descriptions of the reference disposal concepts, the inner radius and thickness of each engineered barrier component was tabulated, summing outward to the rock wall radius (Figures 3.1-3 through 3.1-6).

Waste package dimensions are shown in Table 1.4-1, except for outer diameters used for the 4-PWR and 12-PWR sizes. For the 4-PWR package an outer diameter of 0.96 m is used in thermal analysis for the Crystalline (enclose) concept, and 0.98 m for the Clay/Shale (enclosed) concept. These sizes were retained from previous fiscal year calculations (Hardin et al. 2011, Table 4-1). For thermal sensitivity studies a 1-PWR assembly waste package was assumed with outer diameter of 0.48 m (half the 4-PWR diameter) and the same 5-cm wall thickness. The reference package size for the Generic Salt Repository (enclosed) concept was increased from 4-PWR (Hardin et al. 2011) to 12-PWR in this study, with an outer diameter of 1.17 m to represent a more compact configuration (and potentially greater peak temperature). Small differences in package diameter were found to be associated with small differences in peak package surface temperature (limited to a few percent; Greenberg et al. 2012c, Section 5.2.4). Waste package dimensions used in the analysis of open concepts are discussed in Section 3.2.

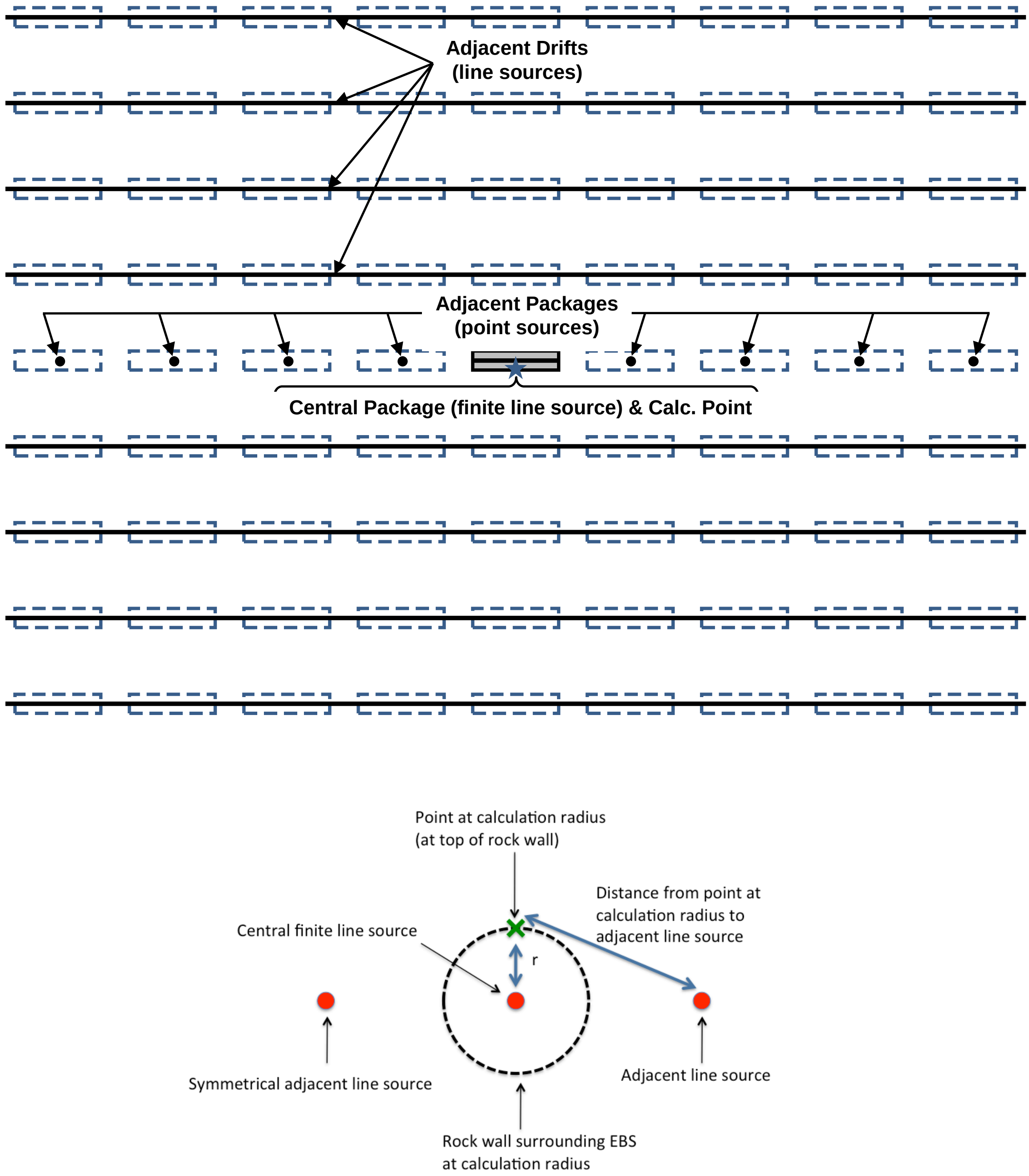
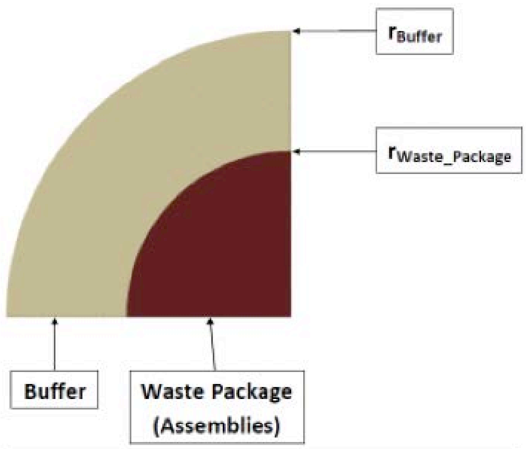


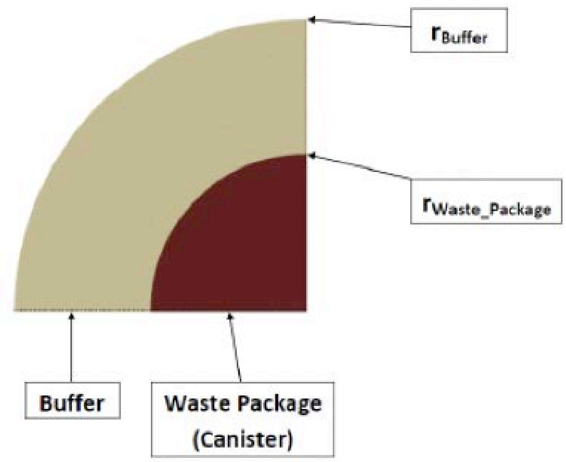
Figure 3.1-2 Layout of Waste Packages for Thermal Analysis (plan and elevation views)

3.1.1.2 Geometry and Thermal Properties

The EBS regions and their dimensions are specific to each disposal concept and waste type (Figures 3.1-3 through 3.1-6). For the Crystalline concept (Figure 3.1-3) waste packages of both types are emplaced individually in vertical emplacement boreholes, encapsulated in swelling clay-based buffer material. Emplacement drifts can be filled with LLW or other non-heat generating material prior to repository closure, but this does not significantly affect the thermal calculations presented here. The central package is modeled as a finite line source that is horizontal, rather than vertical, to conform to the uniform modeling approach, but this does not significantly affect the calculated temperatures. Finally, four adjacent emplacement drifts on either side of the central drift are modeled as parallel, infinite line sources separated by 20 m lateral distance.



Key	Region	Material		Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	4-PWR Waste Package	Copper	366.9	0.48
			Steel	46	
	Buffer	Bentonite	Wet	0.85	0.83
			Dry	0.60	



Key	Region	Material		Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	Carbon Steel		53	0.41
	Buffer	Bentonite	Wet	0.85	0.76
			Dry	0.60	

Source: Hardin et al. (2011).

Figure 3.1-3 Graphical Representation of EBS Configuration for the Crystalline (enclosed) Reference Disposal Concept, for SNF (left) and HLW (right)

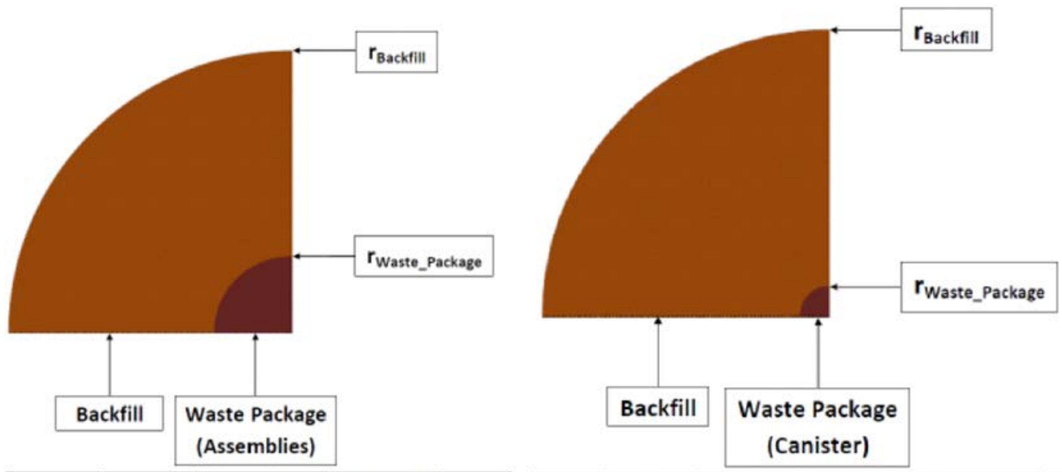
For most thermal analysis presented in this report, where clay-based buffer material (or backfill) is used, it is initially dry, in compacted form, and remains so during the period of peak EBS temperature. Note that clay-based buffers are used only for the crystalline (enclosed, SNF and HLW) and clay/shale (enclosed, SNF only) concepts. Compacted, dry clay-based buffer material is represented by thermal conductivity of 0.6 W/m-K. With this approximation the thermal resistance of the buffer can be 2 to 4 times that of the host rock (Hardin et al. 2011, Appendix G, Figure G.4-1).

The European (ONDRAF-NIRAS 2001, ONDRAF-NIRAS 2010), Japanese (JAEA 2000), and Korean (Choi and Choi 2008) disposal concepts include other engineered buffer materials. The JNC (2000) EBS buffer includes approximately 30% silica sand. European studies have included clay mixtures with graphite and sand. A Korean study (Choi and Choi 2008) combined graphite in compacted clay blocks to increase thermal conductivity up to 2.0 W/m-K. Further discussion of buffer mixtures and thermal conductivity is provided in Appendix A.

Figure 3.1-4 shows the EBS regions representing the Generic Salt Repository concept. Waste packages are emplaced on the floor at the back of mined alcoves, and covered with crushed salt. As a simplification, the axis of each waste package is assumed to be parallel to the access drift axis. The central WP is represented as a finite line source, and eight neighboring WPs (four on either side, in adjacent alcoves) are represented as point sources spaced 20 m apart. Finally, four adjacent lines of waste packages on both sides of the central WP and its neighbors, are modeled as infinite line sources separated by 20 m lateral spacing. The backfill of crushed salt is expected to consolidate into intact salt in a few years, but not before the peak waste package temperature for hotter waste types. Because the thermal conductivity of crushed salt is several times less than for intact salt, the calculation radius for the homogeneous calculation is set at 4 m, somewhat farther than the 3.048 m radius if the backfill is converted, volumetrically, to a cylindrical geometry. Thus, EBS temperatures are calculated based on a region of intact salt extending inward from 4 m to 3.048 m, and either intact or crushed salt inward from that point (two sensitivity cases). Also, heat-generating waste packages would be placed into semi-cylindrical cavities milled in the alcove floor to improve heat transfer to the intact salt (see Section 4.2 for additional discussion). Thus, at least half of the waste package circumference is in close contact with intact salt, so a third case (selected as the reference) uses intact salt properties from 4 m inward to the waste package, but with only 75% of the periphery available to transfer heat. The combination of half the package surface in contact with intact salt, and half with backfill, is represented by 75% in contact with intact salt. This approximation and others related to temperature-dependent thermal conductivity, are tested by comparison with finite element calculations (Appendix A, Section A.4).

EBS regions for the Clay/Shale (enclosed) concept follow the French concepts (Andra 2005a). SNF waste packages are surrounded by a thick clay-based buffer, but HLW packages are not (Figure 3.1-5). The EBS for SNF disposal consists of a carbon steel envelope enclosing a compacted clay buffer, and a carbon steel disposal overpack around each SNF canister. The EBS for HLW disposal consists of horizontal, steel-lined boreholes into which HLW canisters are emplaced directly. SNF and HLW disposal are modeled with six to nine WPs per drift or borehole (this number may deviate from published concepts but does not significantly affect calculated temperatures at the central package). The central WP is modeled as a finite line source, and the eight neighboring WPs are modeled as point sources 30 meters apart (axial distance). Finally, four adjacent emplacement boreholes on either side of the central borehole are modeled as parallel, infinite line sources separate by 40 m lateral distance.

EBS regions for the deep borehole calculations are shown in Figure 3.1-6. The deep borehole waste package contains one fuel assembly, while the HLW packages are limited by the borehole diameter and contain only 29% of the waste volume for the standard HLW packages used in other disposal concepts. The waste packages are emplaced in deep vertical boreholes drilled from the surface, with nine packages per borehole for thermal calculations (this number is less than used in published descriptions of deep borehole disposal, but does not significantly affect the calculated temperature at the central waste package). The central waste package is represented as a finite line source, and the eight neighboring packages are represented as point sources with axial spacing of 6 meters. Finally, four adjacent emplacement boreholes on each side of the central borehole are represented as infinite line sources, at a distance of 200 m (this is fewer neighboring boreholes than used in published studies with lateral spacing of 200 m, but the large borehole spacing means that there will be little effect on peak temperature at the central waste package).



Key	Region	Material	Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	4-PWR Waste Package, Carbon Steel	53	0.41
	Backfill	75% Intact Salt	2.41	3.048

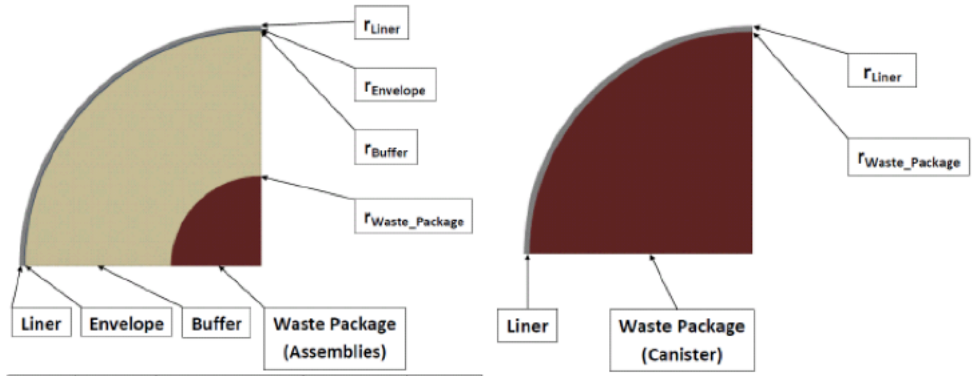
Key	Region	Material	Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	12-PWR Waste Package, Carbon Steel	53	0.585
	Backfill	75% Intact Salt	2.41	3.048

Key	Region	Material	Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	Steel	46	0.305
	Backfill	75% Intact Salt	2.41	3.048

Source: Greenberg et al. (2012c).

Note: Backfill thermal conductivity is 75% of the intact salt conductivity at 200°C (see Appendix D).

Figure 3.1-4 Graphical Representation of EBS Configuration for the Generic Salt Repository (enclosed) Reference Disposal Concept, for SNF (left) and HLW (right).

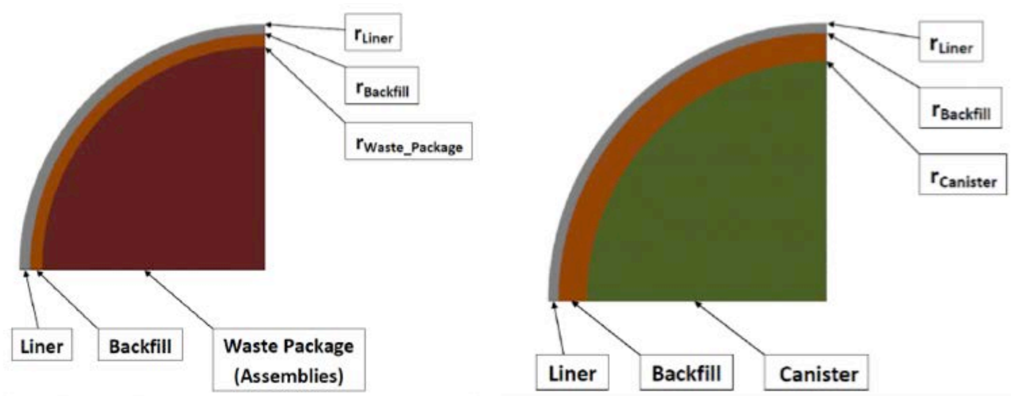


Key	Region	Material		Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	4-PWR Waste Package, Carbon Steel		53	0.49
	Buffer	Bentonite	Wet	0.85	1.29
			Dry	0.60	
	Envelope	Carbon Steel		53	1.296
	Liner	Steel		46	1.321

Key	Region	Material	Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	Carbon Steel	53	0.36
	Liner	Steel	46	0.37

Source: Hardin et al. (2011).

Figure 3.1-5 Graphical Representation of EBS Configuration for the Clay/Shale (enclosed) Reference Disposal Concept, for SNF (left) and HLW (right)



Key	Region	Material	Thermal Conductivity (W/m-K)	Radius (m)
	Waste Package	1-PWR Waste Package, Carbon Steel	53	0.17
	Backfill	Water	0.68	0.18
	Liner	Steel (Drill Casing)	46	0.188

Key	Region	Material	Thermal Conductivity (W/m-K)	Radius (m)
	Canister	Carbon Steel	53	0.17
	Backfill	Water	0.68	0.19
	Liner	Steel (Drill Casing)	46	0.198

Note: Region labeled “Backfill” is assigned properties for water at 100°C. Source: Hardin et al. (2011).

Figure 3.1-6 Graphical Representation of the Deep Borehole Disposal Concept, for SNF (left) and HLW (right).

For each disposal concept and waste type, time-dependent temperature calculations were performed: 1) for the interface of the EBS and the geologic medium, and 2) within the EBS. The central drift consists of one finite line source representing the central waste package, and eight point sources representing the four axial neighboring waste packages on each side, with nominal waste package center-to-center spacing (Figure 3.1-2). There are four adjacent lines of waste packages on each side of the central waste package and its immediate neighbors, represented by infinite line sources. The relative contributions to peak temperature from the central waste package, its axial neighbors, and the adjacent lines of packages, can provide insight into the effects of increasing or decreasing the waste package spacing or drift spacing. Hence, these three contributions to the temperature are tracked individually in the calculations.

3.1.1.3 Input Data and Assumptions

Decay heat curves for the waste forms evaluated in this study are provided in Appendix E, in Figures 3.1-7 and 3.1-8, and supporting references (Carter et al. 2012a). Curves for the Deep Borehole concept (Figure 3.1-8) are scaled down to one fuel assembly per waste package, or 29% of the inventory of a standard HLW canister of the same length.

Ambient average ground surface temperature of 15°C, and a natural geothermal gradient of 25°C/km, were assumed to calculate the background temperature at the repository horizon. Host rock property data (Figures 3.1-3 through 3.1-6, and Appendix D) were developed by comparison to published data (Andra 2005a; European Commission 2010; SRNL 2011; Brady et al. 2009). Whereas thermal conductivity can be temperature dependent especially in salt, rock properties for this comparative analysis were evaluated for 100°C, except for salt thermal conductivity which was evaluated at 200°C (i.e., at the assumed temperature limit).

At any point in time the low thermal mass of EBS components compared to the host rock, means that temperature variation within the EBS, and heat transfer between EBS components and the near-field host rock, can be approximated as steady state processes using the instantaneous time-varying heat output of the waste.

3.1.2 Results Summary – Enclosed Emplacement Modes

3.1.2.1 Host Rock and Waste Package Temperatures

Host rock temperature was calculated for all combinations of the four enclosed disposal concepts and six waste forms considered in this study. In addition, for UOX and MOX waste forms, the host rock temperature was evaluated as a function of the number of assemblies per waste package (1, 2, 3, 4 and 12 per package). Waste package length and thermal output, EBS geometry, rock properties, and the axial and lateral spacing of waste packages are discussed in Section 3.1.1.

As examples, Figures 3.1-9 and 3.1-10 plot the temperature transient at the host rock calculation radius after surface decay storage times of 10, 50, and 100 years, for a repository in crystalline rock, for waste packages containing four UOX assemblies, and four MOX assemblies, respectively. The MOX SNF waste form is the hottest among those evaluated for this report, while the UOX SNF calculation is more typical. A full set of plots for all disposal concepts and waste types is available (Hardin et al. 2011, Appendix G).

Calculated temperature results from three contributions: the central waste package (finite line source), axially adjacent waste packages (point sources), and laterally adjacent emplacement arrays (infinite line sources). Waste package spacing (axial) and drift spacing (lateral) are discussed in Section 5.1. As examples, Figures 3.1-11 and 3.1-12 plot these three components at the host rock calculation radius after surface decay storage of 10 years, for a repository in crystalline rock, for waste packages containing four UOX assemblies, and four MOX assemblies, respectively.

Table 3.1-1 summarizes the host rock peak temperature and the corresponding time out-of-reactor when the peak occurs. For all cases except salt, the calculation radius corresponds to the wall of emplacement borehole or drift (for salt it is within the host rock), so this radius is correlated with peak temperature. For the Deep Borehole concept, where the adjacent lines of packages are widely spaced (200 m), the temperature peaks sooner than for the other concepts. In the other media the temperature peaks after a few decades or more. Note that the time from emplacement to the peak temperature increases with decay storage, because after decay of the short-lived fission products the waste heat output decreases more slowly.

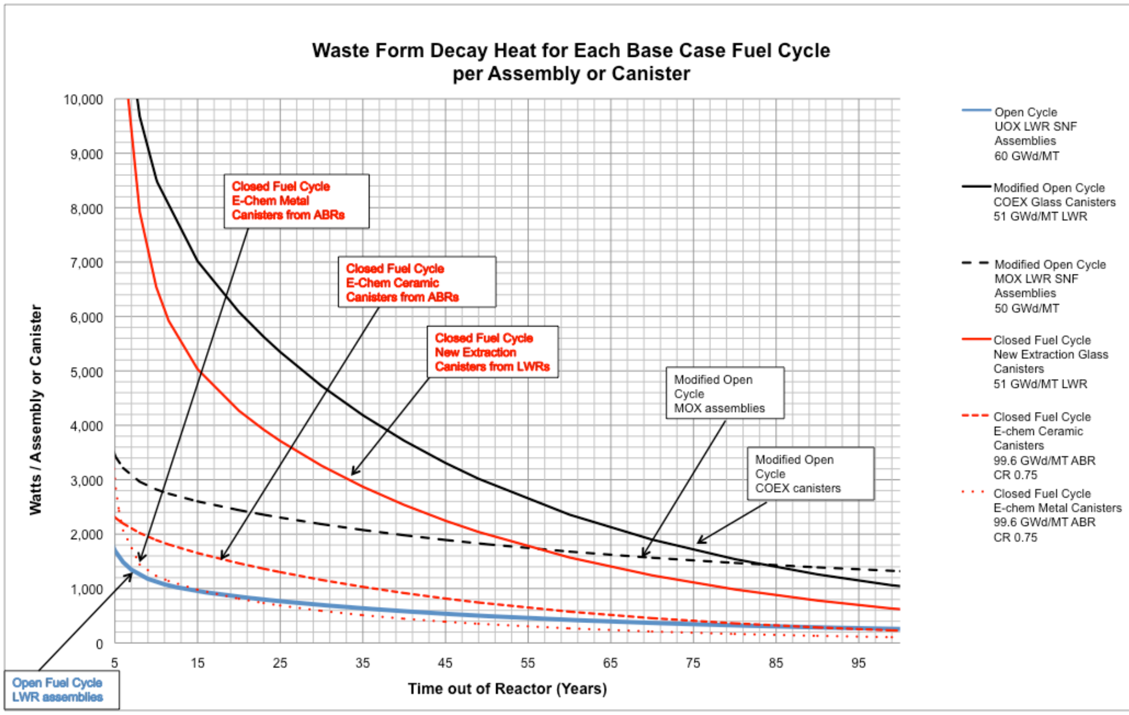


Figure 3.1-7 Decay Heat Curves for Individual SNF Assemblies (UOX and MOX) and Pour-Canisters of HLW (Co-Extraction, New Extraction, EC-Ceramic, and EC-Metal Waste Types)

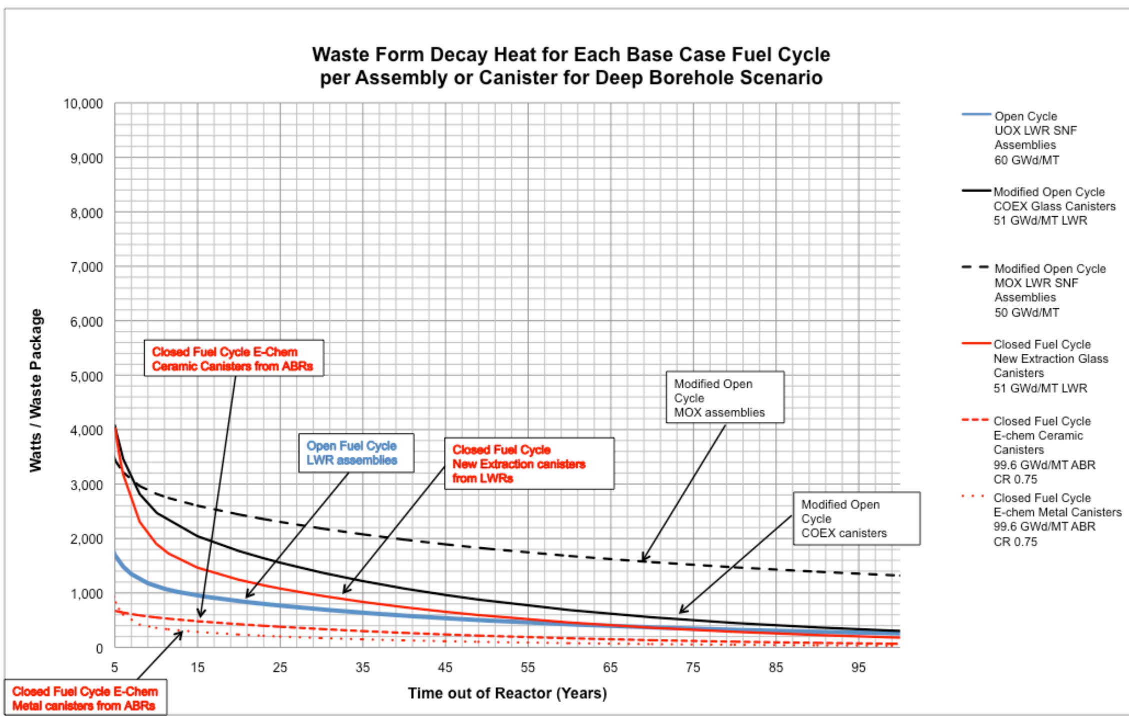
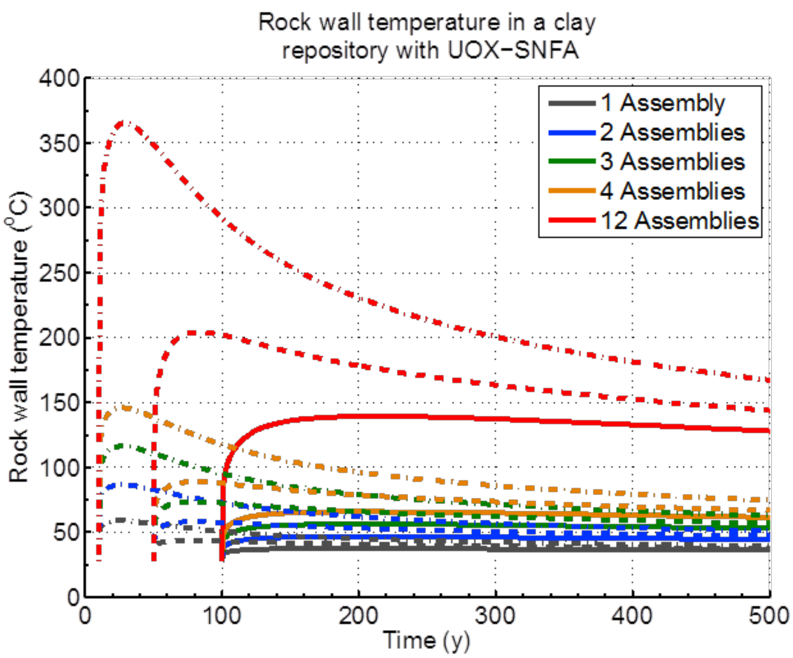


Figure 3.1-8 Decay Heat Curves for 1 UOX or MOX Assembly and 0.291 Co-Extraction, New Extraction, EC-Ceramic or EC-Metal Canisters per Waste Package (deep borehole)

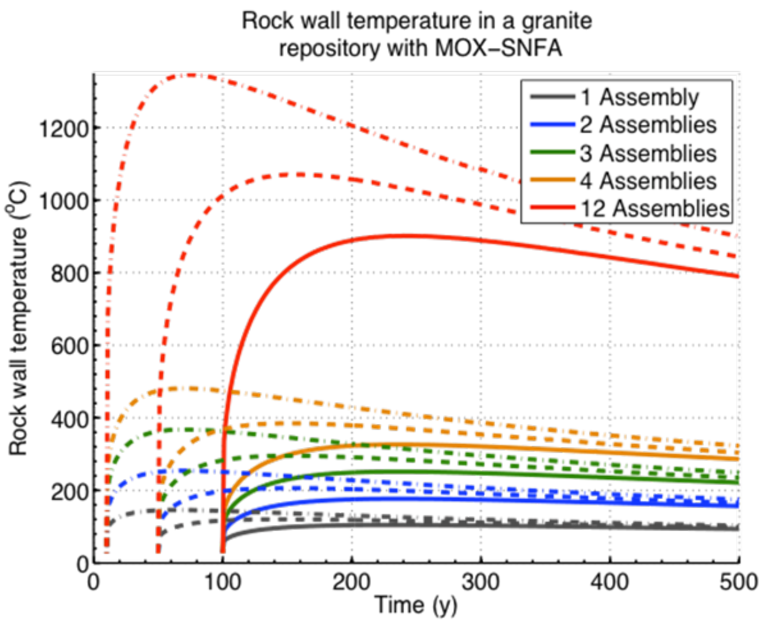
The limiting temperatures (target maximum temperatures from Section 1.4.1) considered in this study depend on the design concept and host medium, and for enclosed modes they are defined at the waste package surface in contact with sensitive buffer or host media. The waste package surface temperature is always greater than the rock temperature at the calculation radius. However, even without calculating temperatures at the waste package surface or elsewhere in the EBS, the rock temperatures summarized in Table 3.1-1 support some conclusions:

- A waste package containing four UOX assemblies requires surface storage of approximately 50 years before emplacement in crystalline or clay/shale media, and fewer than 10 years in salt.
- In crystalline rock even a single MOX assembly package requires more than 100 years storage, whereas a single UOX assembly package may be emplaced in crystalline, clay/shale, or salt media within 10 years out-of-reactor.
- Co-Extraction glass, the hottest of the HLW forms, requires more than 50 years storage before emplacement in crystalline rock or clay/shale media.



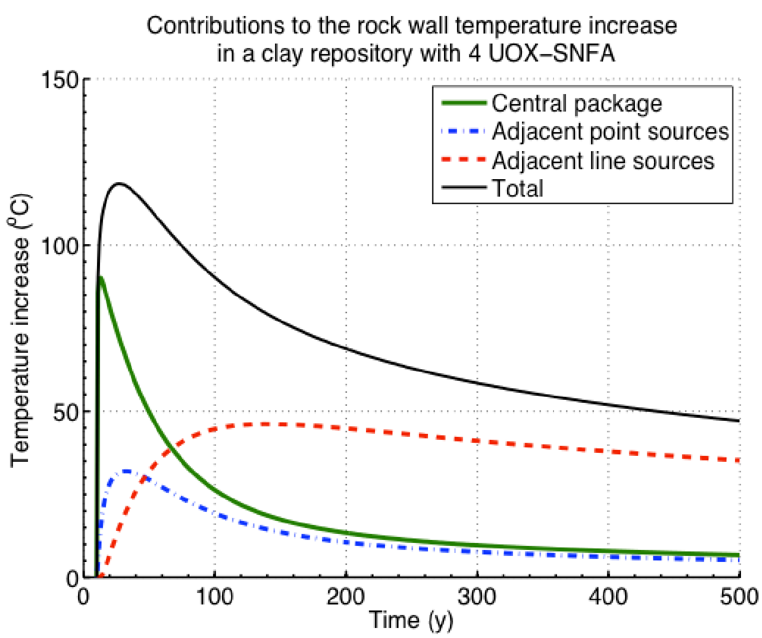
Note: Dash-dot lines are for 10 yr, dashed lines are for 50 yr, and solid lines are for 100 yr decay storage. Source: Hardin et al. (2011).

Figure 3.1-9 Temperature Histories at the Calculation Radius After Decay Storage of 10, 50 and 100 yr for Waste Packages Containing 1, 2, 3, 4 and 12 UOX Assemblies, for a Repository in Clay/Shale Media



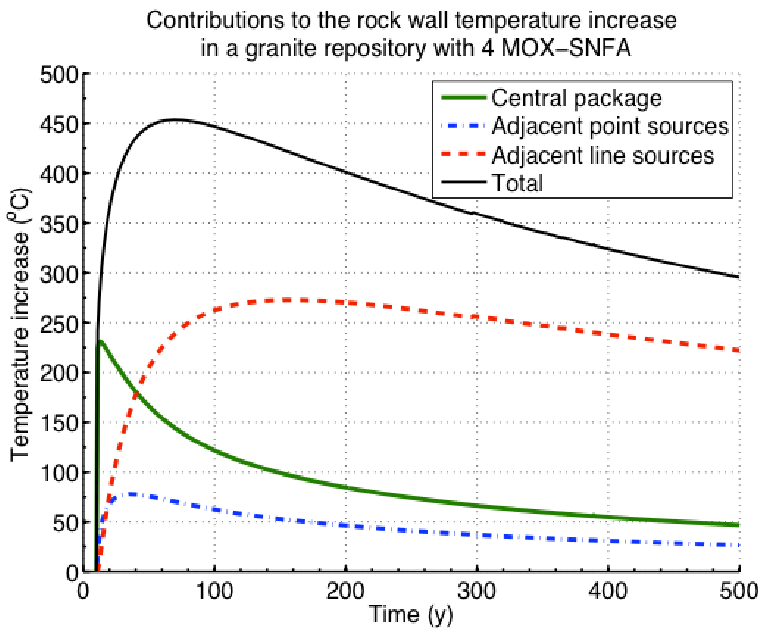
Note: Dash-dot lines are for 10 yr, dashed lines are for 50 yr, and solid lines are for 100 yr decay storage. Source: Hardin et al. (2011).

Figure 3.1-10 Temperature Histories at the Calculation Radius After Decay Storage of 10, 50 and 100 yr, for Packages Containing 1, 2, 3, 4 and 12 MOX Assemblies, in Crystalline Rock



Source: Hardin et al. (2011).

Figure 3.1-11 Contributions to Temperature at the Calculation Radius from the Central Package, Adjacent Packages, and Neighboring Drifts for a Waste Package Containing 4 UOX Assemblies (60 GW-d/MT) in Clay/Shale Media (10 yr Decay Storage)



Source: Hardin et al. (2011).

Figure 3.1-12 Contributions to Temperature at the Calculation Radius from the Central Package, Adjacent Packages, and Neighboring Drifts for a Waste Package Containing 4 MOX Assemblies in Crystalline Rock (10 yr Decay Storage)

Table 3.1-1 Peak Temperature at the Calculation Radius and Corresponding Time of the Peak for Four Disposal Concepts, Six Waste Types and Four Decay Storage Periods

Disposal Scenarios				10 Year Storage Peak Values		50 Year Storage Peak Values		100 Year Storage Peak Values		200 Year Storage Peak Values	
Geology	**Waste Type**	**Assemblies per WP**	**Calculation Radius (m)**	**Peak Temp (°C)**	**Time of Peak (yr)**	**Peak Temp (°C)**	**Time of Peak (yr)**	**Peak Temp (°C)**	**Time of Peak (yr)**	**Peak Temp (°C)**	**Time of Peak (yr)**
Granite	4-UOX-60-SNFA	4	0.83	165.8	35	100.7	87	73.0	172	58.7	389
	4-UOX-40-SNFA	4	0.83	113.4	37	76.1	93	60.3	197	52.6	389
	1-UOX-60-SNFA	1	0.64	64.2	31	46.8	83	39.4	166	35.6	351
	1-UOX-40-SNFA	1	0.64	50.2	35	40.3	88	36.0	186	34.0	395
	4-MOX-50-SNFA	4	0.83	481.2	69	384.9	154	326.5	229	263.4	389
	1-MOX-50-SNFA	1	0.64	146.0	63	120.3	146	104.9	229	88.2	372
	Co-Extraction	1	0.76	279.9	26	126.0	69	64.9	126	43.4	372
	New Extraction Glass	1	0.76	205.2	24	92.7	67	47.9	118	29.6	217
	EC-Ceramic	1	0.76	88.3	28	51.4	67	34.9	117	28.2	217
	EC-Metal	1	0.76	65.5	17	39.7	64	31.2	115	27.9	215
Clay	4-UOX-60-SNFA	4	1.32	146.0	27	88.9	80	65.8	201	55.5	477
	4-UOX-40-SNFA	4	1.32	100.6	31	68.1	86	56.0	299	50.3	493
	1-UOX-60-SNFA	1	1.13	59.1	24	43.7	76	37.4	186	34.7	452
	1-UOX-40-SNFA	1	1.13	46.9	28	38.2	83	34.8	281	33.3	493
	4-MOX-50-SNFA	4	1.32	406.5	76	335.8	211	291.0	299	239.7	477
	1-MOX-50-SNFA	1	1.13	126.2	69	106.9	201	95.2	299	81.9	461
	Co-Extraction	1	0.37	477.9	15	197.3	59	89.5	111	52.3	447
	New Extraction Glass	1	0.37	354.9	13	141.1	57	62.9	108	31.1	208
	EC-Ceramic	1	0.37	133.5	17	69.0	57	40.4	108	28.8	208
	EC-Metal	1	0.37	105.0	13	50.8	55	34.6	106	28.2	206
Salt 200°C K_{th}	1-UOX-40-SNFA	1	4.00	34.1	47	31.3	102	30.1	203	29.5	412
	2-UOX-60-SNFA	2	4.00	48.7	44	38.9	95	34.7	176	32.4	403
	2-UOX-40-SNFA	2	4.00	40.7	47	35.1	102	32.7	208	31.5	412
	3-UOX-60-SNFA	3	4.00	59.2	44	44.6	95	38.3	176	34.9	351
	3-UOX-40-SNFA	3	4.00	47.3	47	38.9	102	35.3	204	33.4	412
	4-UOX-40-SNFA	4	4.00	53.9	47	42.7	102	37.9	201	35.4	401
	12-UOX-60-SNFA	12	4.00	154.4	44	95.9	95	70.6	176	56.9	351
	12-UOX-40-SNFA	12	4.00	106.8	47	73.1	102	58.6	204	51.2	401
	2-MOX-50-SNFA	2	4.00	98.9	79	83.9	161	74.7	240	64.5	390
	3-MOX-50-SNFA	3	4.00	134.6	79	112.1	161	98.2	240	83.0	390
	12-MOX-50-SNFA	12	4.00	456.0	79	366.0	161	310.4	240	249.6	390
Salt 100°C K_{th}	1-UOX-60-SNFA	1	4.00	38.1	44	33.2	95	31.1	176	30.0	403
	4-UOX-60-SNFA	4	4.00	69.8	44	50.3	95	41.9	176	37.3	351
	1-MOX-50-SNFA	1	4.00	63.2	79	55.7	161	51.1	240	46.0	390
	4-MOX-50-SNFA	4	4.00	170.3	79	140.3	161	121.8	240	101.5	390
	Co-Extraction	1	4.00	99.6	36	56.1	80	38.6	139	32.4	405
	New Extraction Glass	1	4.00	77.9	35	46.2	76	33.4	128	28.1	230
	EC-Ceramic	1	4.00	45.0	38	34.4	76	29.6	128	27.7	229

Disposal Scenarios				10 Year Storage Peak Values		50 Year Storage Peak Values		100 Year Storage Peak Values		200 Year Storage Peak Values	
Geology	Waste Type	Assemblies per WP	Calculation Radius (m)	Peak Temp (°C)	Time of Peak (yr)	Peak Temp (°C)	Time of Peak (yr)	Peak Temp (°C)	Time of Peak (yr)	Peak Temp (°C)	Time of Peak (yr)
Salt, cont.	EC-Metal	1	4.00	36.9	32	30.7	77	28.5	127	27.6	229
Deep Borehole	1-UOX-60-SNFA	1	0.19	71.2	13	48.2	55	38.6	107	33.4	214
	1-UOX-40-SNFA	1	0.19	53.8	14	40.9	56	35.1	108	32.0	216
	1-MOX-50-SNFA	1	0.19	257.6	16	219.5	59	199.5	113	182.3	218
	Co-Extraction	0.291	0.20	238.2	13	176.0	54	152.9	105	143.8	210
	New Extraction Glass	0.291	0.20	212.5	12	164.2	54	147.5	104	140.8	204
	EC-Ceramic	0.291	0.20	162.7	14	148.9	54	142.8	104	140.3	204
	EC-Metal	0.291	0.20	157.6	12	145.2	53	141.6	103	140.2	204

Notes:
1. Salt thermal conductivity at 200°C used in the analysis.
2. Source: Greenberg et al. (2012c).

3.1.2.2 Waste Package and EBS Peak Temperatures

As discussed in Section 3.1.1, for each point in time a transient solution for a homogeneous domain (the host rock) was used to evaluate temperature at a selected calculation radius from the waste package (typically, the drift wall). A steady-state “snap-shot” calculation was then used to increase this temperature value, representing the steady-state temperature difference across each annular layer of the EBS between the calculation radius and the waste package surface. The approximation of steady-state heat flow across the EBS is reasonable because heat output of the packages varies slowly so that EBS temperatures maintain a quasi-steady state.

Table 3.1-2 presents peak temperatures at the waste package surface for the Crystalline, Clay/Shale, and Deep Borehole disposal concepts (salt is presented later). For some cases, particularly with the EC-C and EC-M waste types and longer storage times, the difference in temperature at the waste package surface and the calculation radius is only a fraction of a degree. For hotter and/or younger waste types, the use of a clay buffer, and the relatively low thermal conductivity of clay/shale media, produce greater temperature differences.

A target maximum temperature of 100°C for clay-based buffer materials or clay/shale media is used here for comparative purposes. Also, note that clay-based buffer material starts out dry with low conductivity, and gradually hydrates. An intermediate value for thermal conductivity (half way between dry-compacted and hydrated values) is used in these enclosed-mode calculations, and is subject to verification.

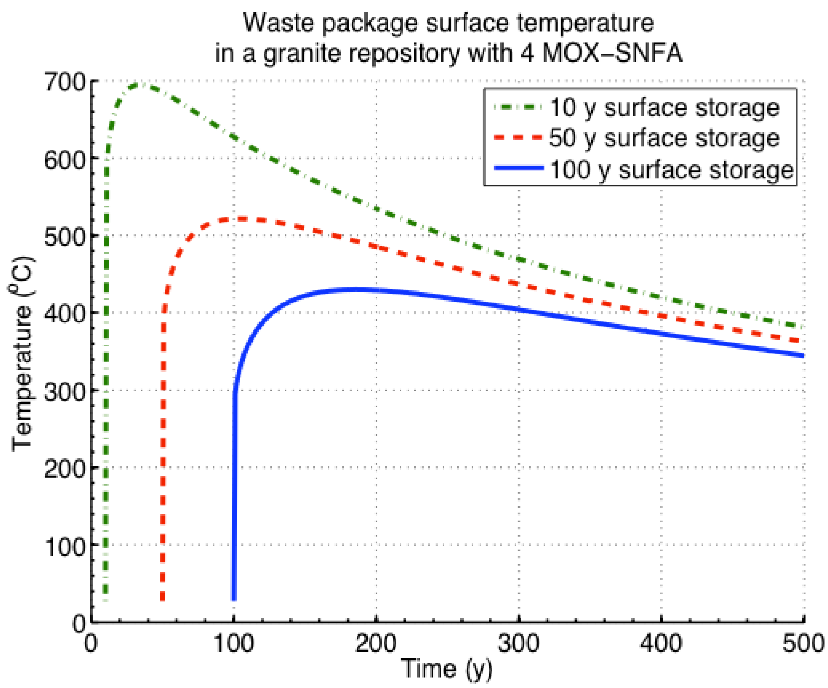


Figure 3.1-13 Calculated Waste Package Temperature After Decay Storage of 10, 50 and 100 yr, for Packages Containing 4 MOX Assemblies, for a Repository in Crystalline Rock

With these caveats, the results from Table 3.1-2 can be summarized for crystalline and clay/shale disposal concepts:

- LWR UOX waste packages containing one assembly (1-PWR) could be emplaced in a crystalline or clay/shale (enclosed) repository after approximately 10 to 50 years of decay storage, whereas packages containing a single MOX assembly would require more than 200 years decay storage
- LWR UOX waste packages containing four assemblies (4-PWR) could be emplaced in a crystalline or shale repository after approximately 100 years of decay storage (similar to SNF management practices being implemented by the Swedish program)
- MOX SNF must be disposed in single-assembly packages to avoid hundreds of years of decay storage
- Co-Extraction and New Extraction glass waste types could be emplaced after approximately 50 to 100 years of decay storage
- EC-C and EC-M waste types can be emplaced after fewer than 50 years, and approximately 10 years, respectively, of surface decay storage

Table 3.1-2 Peak Waste Package Surface Temperature and the Time When the Peak Occurs

Disposal Scenarios			Storage Time, Yr							
			10		50		100		200	
Geology	Waste Type	Assemblies per WP	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)
Granite	4-UOX-60-SNFA	4	256.9	17	141.2	65	92.8	134	68.9	299
	4-UOX-40-SNFA	4	167.0	19	101.8	67	73.3	144	60.3	351
	1-UOX-60-SNFA	1	100.5	17	62.6	59	47.0	122	39.4	273
	1-UOX-40-SNFA	1	71.4	14	50.3	61	41.1	129	36.9	299
	4-MOX-50-SNFA	4	694.6	35	521.7	104	430.1	186	337.1	324
	1-MOX-50-SNFA	1	229.8	25	172.9	88	144.0	166	116.2	299
	Co-Extraction	1	521.2	12	209.9	56	93.6	108	49.8	273
	New Extraction Glass	1	396.6	11	149.9	55	65.6	105	31.3	206
	EC-Ceramic	1	142.0	15	72.2	55	41.4	105	28.9	206
	EC-Metal	1	124.8	11	55.7	53	36.0	103	28.3	203
Clay	4-UOX-60-SNFA	4	341.9	12	174.0	55	106.4	111	72.9	273
	4-UOX-40-SNFA	4	216.2	12	122.1	55	81.7	113	63.3	323
	1-UOX-60-SNFA	1	127.1	11	73.5	53	52.0	107	41.0	241
	1-UOX-40-SNFA	1	87.2	12	57.2	54	44.3	108	38.0	277
	4-MOX-50-SNFA	4	860.7	16	600.1	67	474.2	148	366.1	299
	1-MOX-50-SNFA	1	288.6	13	203.4	64	161.8	130	126.8	273
	Co-Extraction	1	478.0	15	197.3	59	89.5	111	52.4	447
	New Extraction Glass	1	355.0	13	141.1	57	62.9	108	31.1	208
	EC-Ceramic	1	133.6	17	69.1	57	40.4	108	28.8	208
	EC-Metal	1	105.0	13	50.8	55	34.6	106	28.2	206
Salt 200°C K_{th}	1-UOX-60-SNFA	1	71.2	12	47.8	54	38.4	111	33.7	239
	1-UOX-40-SNFA	1	53.8	12	40.6	55	35.0	113	32.3	255
	2-UOX-60-SNFA	2	97.9	12	60.6	57	45.6	115	38.0	252
	2-UOX-40-SNFA	2	69.7	12	48.9	58	40.0	120	35.7	270
	3-UOX-60-SNFA	3	133.1	12	77.1	57	54.7	116	43.3	252
	3-UOX-40-SNFA	3	90.9	12	59.7	58	46.3	120	39.8	270
	4-UOX-60-SNFA	4	168.3	12	93.7	57	63.8	116	48.6	252
	4-UOX-40-SNFA	4	112.0	12	70.4	58	52.5	119	43.9	270
	12-UOX-60-SNFA	12	391.2	12	201.5	59	124.1	120	84.8	262
	12-UOX-40-SNFA	12	246.1	13	140.5	61	94.5	125	72.1	282
	1-MOX-50-SNFA	1	142.8	16	106.8	68	88.8	135	72.7	258
	2-MOX-50-SNFA	2	216.9	20	160.4	76	131.7	144	105.1	270
	3-MOX-50-SNFA	3	311.7	20	226.9	76	183.8	144	144.0	270
	4-MOX-50-SNFA	4	406.4	20	293.4	76	235.9	144	182.8	270
	12-MOX-60-SNFA	12	1031.4	24	741.8	81	592.3	152	451.2	282
	Co-Extraction	1	346.1	12	142.6	52	68.6	103	39.8	225
	New Extraction Glass	1	263.3	12	105.1	52	51.6	102	29.9	202
	EC-Ceramic	1	100.4	12	55.8	52	36.3	102	28.4	202
	EC-Metal	1	93.3	12	46.8	52	33.3	102	28.1	201

Disposal Scenarios			Storage Time, Yr							
			10		50		100		200	
Geology	Waste Type	Assemblies per WP	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)
Deep Borehole	1-UOX-60-SNFA	1	73.9	13	49.4	55	39.2	107	33.8	214
	1-UOX-40-SNFA	1	55.4	13	41.6	56	35.5	108	32.2	215
	1-MOX-50-SNFA	1	264.5	16	224.1	59	202.9	112	184.7	217
	Co-Extraction	0.291	250.8	12	180.5	54	154.5	104	144.2	209
	New Extraction Glass	0.291	222.1	12	167.2	54	148.5	104	140.9	204
	EC-Ceramic	0.291	165.6	13	150.0	54	143.1	104	140.3	203
	EC-Metal	0.291	160.4	12	146.0	53	141.8	103	140.2	203

Notes:
1. See Notes 2 and 3 from Table 3.1-1.
2. Source: Greenberg et al. (2012c).

For the Deep Borehole concept water or hydrated clay will fill the space between the borehole casing and the waste package (a representative thermal conductivity for water at 100°C is used in the analysis). The borehole size, rather than any potential temperature limit, will likely drive the design. The borehole size limits the UOX and MOX waste forms to one assembly per waste package, and for HLW the borehole diameter limits the canister cross-sectional area to 29.1% of that of a standard (2-ft diameter) canister. Importantly, no temperature limit or need for one has been identified for the deep borehole disposal. For deep borehole disposal, the results in Table 3.1-2 are consistent with thermal calculations reported previously (Brady et al. 2009).

3.1.2.3 Waste Package Surface Peak Temperature for Salt

The steady-state temperature solution calculates temperature offsets in the EBS layers from the calculation radius (4 m for salt) inward to the waste package. At the time of emplacement, part of the salt around the package is crushed and has thermal conductivity and other characteristics that are significantly different from intact salt. Over a few decades the crushed salt reconsolidates under the influence of heat and pressure. For this study, the calculation methods are not amenable to time- or temperature-dependent backfill properties. However, cases were run using three different assumptions for salt backfill conductivity to bracket the potential results:

- Intact salt reconsolidates immediately
- Crushed salt retains its low conductivity, from the package surface out to 3.05 m radius, with intact salt to 4 m
- Intact salt, but with the package contact area limited to 75% of the available surface. This 75% represents thermally intimate association of the waste package with the back wall and floor of the emplacement alcove. The other 25% of the package surface contacts crushed salt within the alcove, and no heat transfer credit is taken in this quadrant.

Table 3.1-3 Peak Waste Package Surface Temperature and the Time When the Peak Occurs, for the Salt Disposal Concept, Investigating Alternative Calculation Methods

Disposal Scenario:			Storage Time, Yr							
Salt, WP temperature			10		50		100		200	
Model	Waste Form	Assemblies per WP	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)	Peak Temp. (°C)	Peak Time (yr)
Intact salt	4-UOX-60-SNFA	4	120.4	17	73.5	65	53.8	129	43.6	277
	1-UOX-60-SNFA	1	55.3	13	40.9	61	35.0	123	32.0	266
	4-MOX-50-SNFA	4	296.9	32	224.3	93	185.8	165	147.6	299
	1-MOX-50-SNFA	1	105.3	27	83.3	84	71.9	156	60.9	288
	Co-Extraction	1	230	12	102.2	56	54.5	108	36.4	252
	New Extraction Glass	1	179.6	11	77.7	55	43.1	105	29.1	205
	EC-Ceramic	1	74.4	15	45.8	55	33.2	105	28.1	204
	EC-Metal	1	69.2	11	39.5	52	31.1	103	27.9	202
Crushed salt to 3.048 m (all times)	4-UOX-60-SNFA	4	534.4	11	256.4	51	147.2	101	89.3	208
	1-UOX-60-SNFA	1	191.7	11	101.7	51	66.3	101	47.4	204
	4-MOX-50-SNFA	4	1329.7	11	874.7	52	649.9	106	466.6	215
	1-MOX-50-SNFA	1	449.3	11	301.6	51	228.0	103	167.9	210
	Co-Extraction	1	1217.1	11	449.5	51	177.1	101	68.8	202
	New Extraction Glass	1	921.2	11	312.2	51	116.0	101	36.3	201
	EC-Ceramic	1	296.2	11	131.4	51	59.9	101	30.6	201
	EC-Metal	1	281.9	11	100.5	51	49.5	101	29.6	201
75% contact with intact salt, 25% crushed salt with 100°C properties	4-UOX-60-SNFA	4	139.9	13	81.8	61	57.9	122	45.7	267
	1-UOX-60-SNFA	1	62.1	11	43.8	57	36.4	117	32.7	255
	4-MOX-50-SNFA	4	341.8	26	252.8	84	206.4	156	162.2	284
	1-MOX-50-SNFA	1	120.8	21	93.1	76	79.0	144	65.9	273
	Co-Extraction	1	281.5	11	119.1	54	60.4	105	37.8	236
	New Extraction Glass	1	218.4	11	89.2	53	46.7	103	29.4	204
	EC-Ceramic	1	85.3	13	50.0	53	34.5	103	28.2	204
	EC-Metal	1	80.3	11	42.6	51	32.1	102	27.9	202
75% contact with intact salt, 25% crushed salt with 200°C properties	4-UOX-60-SNFA	4	168.5	11	93.7	57	63.7	116	48.6	252
	4-UOX-40-SNFA	4	132.4	11	79.5	55	57.3	113	46.4	256
	1-UOX-60-SNFA	1	71.6	11	47.8	54	38.4	111	33.7	239
	1-UOX-40-SNFA	1	53.7	11	40.5	55	35.0	113	32.2	256
	4-MOX-50-SNFA	4	401.8	21	290.5	76	233.7	144	181.3	270
	1-MOX-50-SNFA	1	142.8	16	106.7	67	88.7	135	72.7	258
	Co-Extraction	1	343.1	11	140.0	52	67.7	104	39.6	226
	New Extraction Glass	1	260.0	11	101.9	52	50.6	102	29.8	202
	EC-Ceramic	1	97.4	12	54.7	52	36.0	102	28.3	202
	EC-Metal	1	93.6	11	46.4	51	33.2	101	28.1	201

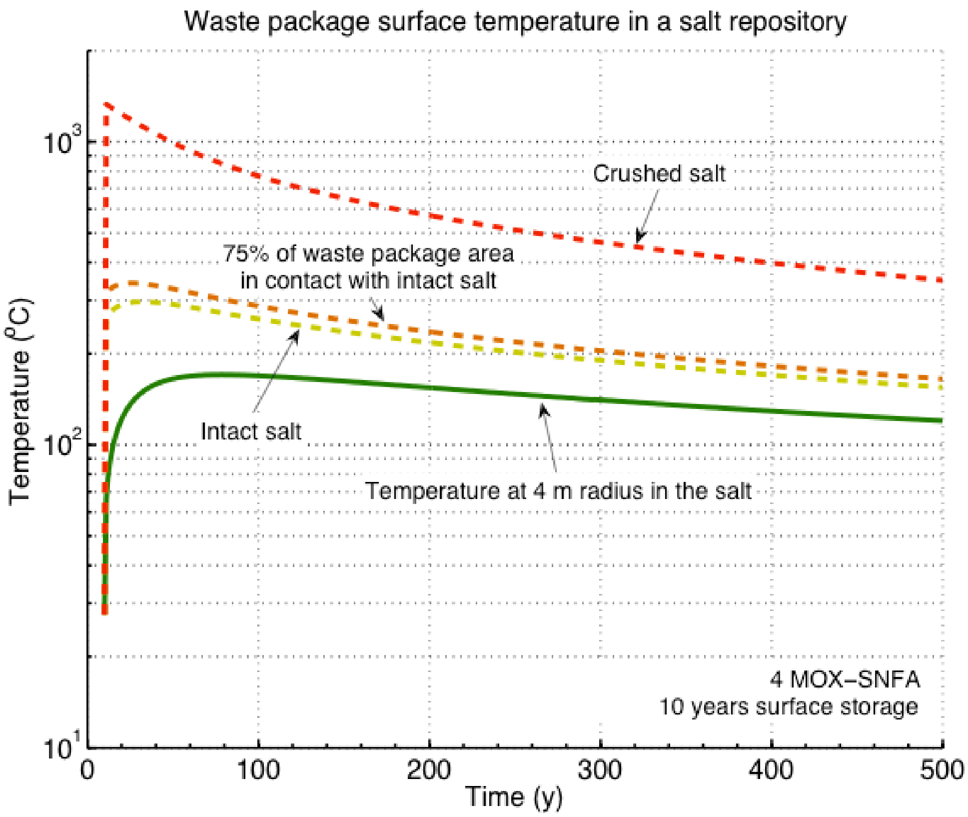


Figure 3.1-14 Calculated Waste Package Temperature After 10 yr Decay Storage, for Waste Packages Containing 4 MOX Assemblies, for the Salt Disposal Concept, and Assuming that Backfill has the Thermal Conductivity of Crushed, Intact, or 75% of Intact Salt

Because thermal conductivity for crushed salt (initially 0.57 W/m-K) is less than that of intact salt (4.2 W/m-K at 100°C), the temperature rise for the second case is large, particularly for waste packages containing four MOX assemblies (Figure 3.1-14). For the third case (75% contact), the waste package peak temperature is limited to less than approximately 250°C with 100 years of decay storage (Table 3.1-2). This latter case provides intermediate results that represent the effect of low-conductivity backfill and of coupling with the intact salt, and is used for peak salt temperature calculations in the remainder of this report. Importantly, this analysis emphasizes the likely importance for the Generic Salt Repository concept for SNF, of preparing a semi-cylindrical cavity in the floor to facilitate heat transfer to the intact salt.

3.1.2.4 Peak Temperature as a Function of Decay Storage and Package Capacity

An additional parametric study was done for UOX and MOX SNF disposal in crystalline, clay/shale, and salt media with enclosed emplacement modes, to discern the relationship between the number of assemblies per waste package and the surface storage time, for a given temperature limit. For crystalline and clay/shale media a target value of 100°C was used for the maximum waste package temperature, based on potential degradation of clay-based buffer material or clay/shale host rock. For salt the target maximum temperature was 200°C, although salt may withstand higher temperatures (Section 1.4.1).

Five options were considered: one, two, three, four and 12 PWR assemblies per package. With two, three, and four assemblies, package size was held constant (i.e., the 4-PWR configuration with one or two positions not used). For one and 12 assemblies the engineering barrier thicknesses were kept the same as in the reference model, while the waste form radius was adjusted. The inner radius for a single-assembly package was assumed to be half of that of the 4-PWR package. The 12-PWR waste package radius (0.625 m) was determined previously (DOE 2001). The storage time was varied from 10 to 300 years.

The minimum storage times need to meet these maximum temperatures were interpolated from the peak temperature data above. The results are shown in Figure 3.1-15 for UOX and MOX SNF, for the 100°C (clay-based materials) and 200°C (salt) limits. For crystalline and clay/shale media, approximately 100 years of surface decay storage will limit clay buffer temperature to 100°C, for up to 4 UOX assemblies per package. In salt, which has higher thermal conductivity, only 5 years (minimum time considered in the analysis) are needed to cool the 4-PWR configuration. For a 12 UOX assembly package, approximately 50 years of decay storage are needed in salt, whereas more than 300 years would be needed for crystalline and clay/shale media. The results for MOX are qualitatively similar, but longer decay storage durations are needed (Figure 3.1-15). For crystalline and clay/shale media, approximately 300 or more years of decay storage are needed to emplace the single-assembly MOX package. For salt, a package containing four MOX assemblies needs fewer than 100 years of surface storage, while a single-assembly MOX package could be emplaced in approximately 5 years (minimum time considered in the analysis).

3.1.2.5 Sensitivity to Maximum Buffer or Backfill Temperature

Required decay storage time as a function of waste package capacity, was recalculated for alternative temperature limits (Figure 3.1-15). Temperature limits for clay-based buffers or host rock material (nominally 100°C) and for salt (200°C) were increased as shown (Sutton et al. (2011b). The results (Figure 3.1-15) show that sensitivity to temperature limits is not as important as the difference between salt and the other media. Extending the temperature limit for clay-based buffers to 125°C or 150°C could decrease the required decay storage time by hundreds of years, but the require storage times for packages containing more then 4-PWR assemblies (or equivalent) are still well in excess of 100 yr (Greenberg et al. 2012b). Thus, extension of temperature limits addresses, but does not resolve, the need to repackage SNF in small canisters (e.g., 4-PWR size) and/or for decay storage much greater than 100 yr.

The non-linearity observed at 4-PWR waste package size (particularly for UOX fuel and the clay/shale and crystalline concepts) is caused by waste package size and declining heat production at the time of emplacement coupled with finite drift spacing. For waste packages containing 2, 3 or 4 PWR assemblies, the same waste package radius is used (de-rating the nominal 4-PWR package), whereas a 12-PWR waste package naturally has a larger radius. For 12-PWR and larger packages, the longer storage times result in waste emplacement when heat production is further along the decay curve, when the rate of change in heat production is smaller, and the time (after emplacement) to the peak temperature is longer. Thus the temperature results for larger packages reflect greater contributions from adjacent drifts.

Recalculate Salt Sensitivity to Maximum Backfill Temperature

As noted in Appendix A, single values of thermal conductivity are used in this analysis for host media, although some media exhibit temperature dependence. The dependence is notable in salt, for which thermal conductivity decreases by approximately 40% from 25 to 200°C (see constitutive equations in Appendix C). The assumed temperature limit for salt is 200°C, so the initial calculations using the 100°C value for intact thermal conductivity were repeated with the 200°C value (Figure 3.1-16). Results for both 40 and 60 GW-d/MT commercial SNF show that the smaller conductivity at 200°C decreases (Greenberg et al. 2012c) but does not fundamentally change the differences between salt and other media. Note that finite element calculations were performed (Appendix C) that explicitly accounted for temperature dependence in conductivity for both the intact and crushed salt. The FEM calculations more accurately accounted for heat coupling to the backfill, and produced slightly cooler results than the analytical approximation. Correlation of peak salt temperature with initial waste package heat output power, based on FEM simulations and on analytical solutions, is discussed in Appendix D.

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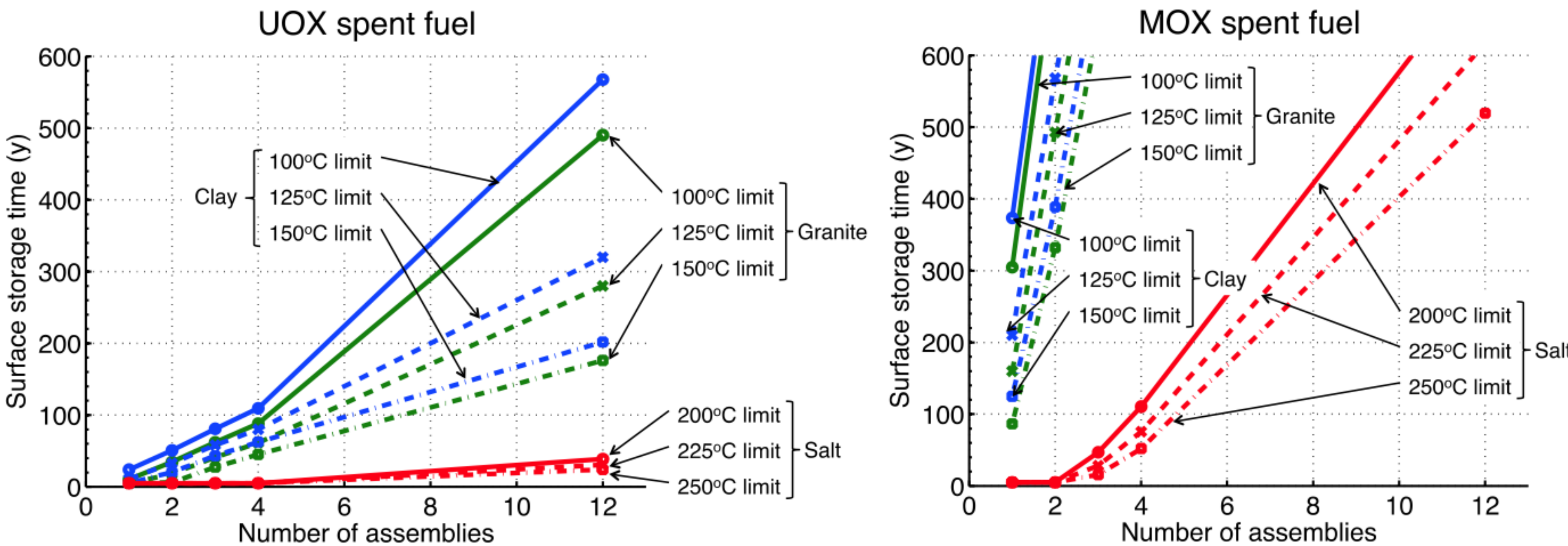
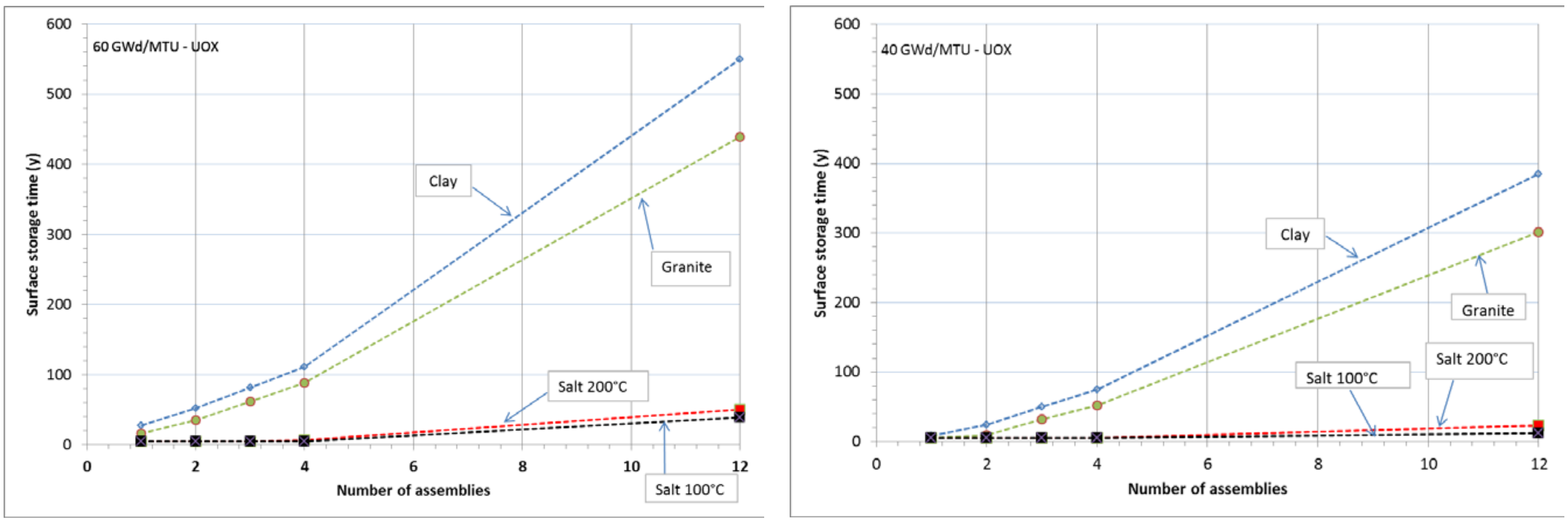


Source: Greenberg et al. (2012b). Calculated using thermal conductivity values for all media at 100°C.

Figure 3.1-15 Minimum Decay Storage Duration to Limit Peak Waste Package Temperature to 100°C (for clay buffer or clay/shale media) or 200°C (for salt) as a Function of UOX or MOX Assemblies, Showing Sensitivity to Temperature Limits



Source: Greenberg et al. (2012c).

Figure 3.1-16 Minimum Decay Storage Needed to Meet Temperature Limits as Shown, for 40 and 60 GW-d/MT Commercial SNF, Using Thermal Conductivity Values for Crystalline Rock (granite, at 100°C), Clay/Shale (at 100°C), and Salt (at 100 and 200°C)

3.2 Thermal Analysis for Open Emplacement Modes

Open emplacement modes were developed for commercial SNF, and disposal concepts for HLW are limited to the enclosed modes (Sections 1.4 and 3.1). The following sections describe thermal analysis for disposal of commercial SNF in open drifts in shale or other sedimentary rock types. All the options involve ventilation for heat removal, which is functionally equivalent to surface decay storage, but allows earlier development of the repository and emplacement of waste.

3.2.1 Analysis Approach – Open Emplacement Modes

For many open-mode thermal results reported here, SNF is emplaced in the repository at 50 or 100 yr out-of-reactor, then forced ventilation ensues for the next 200 to 250 yr, and closure commences when the fuel is 300 years out-of-reactor This long ventilation period helped to determine how temperature limits (e.g., 100°C in clay or shale) could be met. At closure it is assumed that the ventilation heat removal stops, and closure operations (e.g., backfilling) begin and take 10 yr, before backfill is installed. From 300 to 310 yr the air gap continues to exist in the open emplacement drifts, with radiative heat transfer to the walls, but no heat removal by forced ventilation. Backfilled conditions are assumed to commence at 310 years, as a step function. Sensitivity analyses for ventilation efficiency and duration, backfill thermal conductivity, and host rock thermal conductivity are reported in Appendix A. For some sensitivity cases discussed in Section 3.2.2 the duration of underground ventilation is limited to 50 or 100 yr, retaining the 10 yr period for closure operations.

3.2.1.1 Geometry and Thermal Properties

In the open mode design concepts evaluated in this report, the buffer, envelope, and backfill layers are all replaced with an air gap to allow operation of a ventilation system prior to closure. At closure, the air gap becomes a contiguous backfill layer. In Figure 3.1-1, the numbered radii r_1, r_2, r_3, and r_4 represent outer radii for the liner, backfill, envelope, and buffer layers respectively. In the open-mode analyses, the air gap, and subsequently the backfill, occupy the region bounded by r_2 and r_{WP}. Waste packages dimensions for open mode analysis are presented in Table 1.4-1.

Host rock properties used for the Shale Unbackfilled concept and the Sedimentary Backfilled concept (represented by alluvium) are discussed in Appendix D. Alluvium has significantly lower thermal conductivity (average of 1.06 W/m-K compared to 1.73 W/m-K for shale).

Thermal analysis for the Sedimentary Backfilled open concept assumes backfilling of the emplacement drifts at closure. For the Sedimentary Backfilled open concept, EBS temperature at the waste package surface is limiting after backfill is installed (protecting swelling clay used in the backfill mixture).

Thermal analysis for the Shale Unbackfilled concept assumes an open drift around waste packages after closure. However, this concept can also be represented by the backfill approach described above for the Sedimentary Backfilled concept, because: 1) partial or complete drift collapse is expected to occur after closure, and the backfill calculations provide a reasonable upper bound on waste package temperature under collapse rubble; and 2) the host shale formation temperature is expected to be limiting for this concept, not the waste package temperature, and since the host formation temperature is not sensitive to the imposition of backfill in the model, useful results can be obtained from the backfill calculations.

For cost estimation and to limit ventilation time to 100 yr, a “design case” was developed based on the Sedimentary Backfill Open concept using shale properties for the host rock. Sensitivity analysis for that case included three values for backfill thermal conductivity: 0.6 W/m-K (dry compacted clay-based buffer material), 1.2 W/m-K (hydrated mixture of 70% clay and 30% sand), and 2.0 W/m-K (hydrated mixture of clay, sand, and graphite).

Specific details of the ventilation system for open modes are not addressed here, but the methodology for achieving a given ventilation efficiency is straightforward. For the current analysis, a constant ventilation system thermal efficiency for heat removal is assumed. When the ventilation system is turned off, 100% of the heat generation goes into the rock.

For the enclosed disposal concepts, the components and dimensions of the EBS are tailored to each geologic medium. However, the Shale Unbackfilled and Sedimentary Backfilled open concepts use in-drift waste package emplacement, in drifts with diameter of 4.5 m, lined with shotcrete and steel reinforcement. (The Hard Rock Unsaturated open concept uses a similar arrangement.) The only geometric parameter that is varied as the size of the waste package changes (i.e., for packages containing 4, 12, or 21 PWR assemblies), is the thickness of the air gap between the outside of the waste package and the inside of the liner required to keep the host rock opening diameter at 4.5 m.

The methodology and approach are the same as described in Section 3.1.1, but with EBS simplification for open modes. The EBS consists only of a bare waste package and a shotcrete/steel liner inside the emplacement drifts in shale or other sedimentary media. For simulations of the Sedimentary Backfilled open concept, thermal properties of alluvium (Appendix B, D) or shale (Appendix D) were used.

Conduction, radiation, and convection are included in different parts of this analysis, with simplifications. A thermal radiation calculation is used during ventilation and prior to backfilling, to calculate the waste package temperature from the rock wall temperature. Convection is neglected except for the impact of forced ventilation, which is treated using a modeling approach developed and validated previously (BSC 2004). Buoyancy affects ventilation airflow during forced ventilation, but the model considers the overall effect of ventilation on heat transfer without representing the specifics of airflow. During the 10 yr assumed for closure operations, natural convection would occur in addition to radiative coupling, so waste package temperatures would be slightly less than calculated. A previous study concluded that during such heating conditions, thermal radiation would be the dominant mode of heat transfer (BSC 2005).

3.2.1.2 Input Data and Assumptions

The decay heat curves for UOX SNF with burnup of 40 and 60 GWd/MT (Appendix E) show significant differences between generation rates for surface decay storage times of 50 and 100 years. Thermal analysis calculates corresponding differences in rock wall and waste package surface temperatures for enclosed mode repository design concepts. That is because for the enclosed modes near-field temperatures peak shortly after emplacement, and are therefore sensitive to instantaneous heat output which is greatest (and changes the most) at early time. By contrast, for the open modes 75% of that heat is removed by ventilation, and the peak temperatures don’t develop until after ventilation is turned off (as late as 300 years out-of-reactor). As a result, differences in peak temperatures between the 40 and 60 GWd/MT cases are not as significant for the open emplacement mode concepts as for the enclosed mode concepts.

3.2.2 Results Summary – Open Emplacement Modes

This section includes summary tables and plots, presenting the rock wall and waste package peak temperatures for the various cases and sensitivity analyses. The following paragraphs present sensitivity studies performed for the Shale Unbackfilled and Sedimentary Backfilled open concepts:

- Nominal-case results (shale properties, 30 m drift spacing, 21-PWR packages, 40 GW-d/MT burnup, 75% ventilation efficiency, 50 yr decay storage, 250 yr ventilation)
- Sensitivity to ventilation efficiency: 50, 60, 70, 80, and 90%.
- Sensitivity to ventilation duration: 250, 200, 150, 100, and 50 yr.
- Sensitivity to drift spacing: 30, 40, 50, 60, and 70 m (consider both 21 and 32-PWR packages and ventilation efficiency 90%).
- Sensitivity to host rock thermal conductivity: 1, 2, 3, 4, and 5 W/m-K (consider 21-PWR packages with 40 and 60 GWd/MT burnup).
- Sensitivity to backfill thermal conductivity: 1, 2, 3, 4, and 5 W/m-K.

In addition, this section includes a study evaluating the range of uncertainty for host rock thermal conductivity in shale and alluvium (Appendix D) assuming a mean value ± 1 and 2 standard deviations.

The results presented here are summarized from the report of Greenberg et al. (2012a) where one can find temperature histories for all cases, whereas only peak temperatures are tabulated in this report.

3.2.2.1 Nominal-Case Thermal Analysis Results

Figure 3.2-1 presents a summary of peak host rock wall and waste package temperatures for 30-m drift spacing, 50 and 100 yr decay storage, 40 and 60 GW-d/MT burnup, and thermal properties for shale and alluvium. Alluvium properties are selected for the Sedimentary Backfilled concept. The backfill calculations apply to both the Shale Unbackfilled and Sedimentary Backfilled open concepts as discussed in Section 3.2.1.1. The nominal-case results for peak temperatures are summarized in Table 3.2-1, and temperature history plots for these cases are provided by Greenberg et al. (2012a). All cases in this table assume 75% ventilation efficiency, with repository closure starting when the SNF is 300 yr out-of-reactor. Backfill emplacement starts at 300 yr, with assumed thermal conductivity of 1.2 W/m-K (an optimistically high value that is selected for evaluating thermal trends). Backfilling operations are completed in 10 years. Thus, heat transfer from the surface of the waste package to the drift/borehole liner switches from radiation to conduction through the backfill at 310 years.

The results summarized in Table 3.2-1 show that even with 250 yr of forced ventilation, peak temperatures exceed 100°C for 21-PWR size and larger packages. There are several reasons why these cases are slow to cool down: 1) the 30-m drift spacing allows the entire repository horizon to heat up over hundreds of years; 2) the waste cools slowly after decay of short-lived fission products (90% decay in the first 100 yr); and 3) the large SNF capacity of 21-PWR size packages means more heat output that pushes up the peak postclosure temperature regardless of package size, according to the correlations developed in Appendix D (Section D.5).

Waste package temperatures are incrementally hotter than the rock wall. Clay-based buffer temperatures in the shale cases are lower than for alluvium because of the lower host rock thermal conductivity. The effect of storage time is minimal because the conceptual model replaces reduced storage time with additional ventilation time (removing 75% of the heat in that period). Burnup is a significant factor, particularly for large WPs.

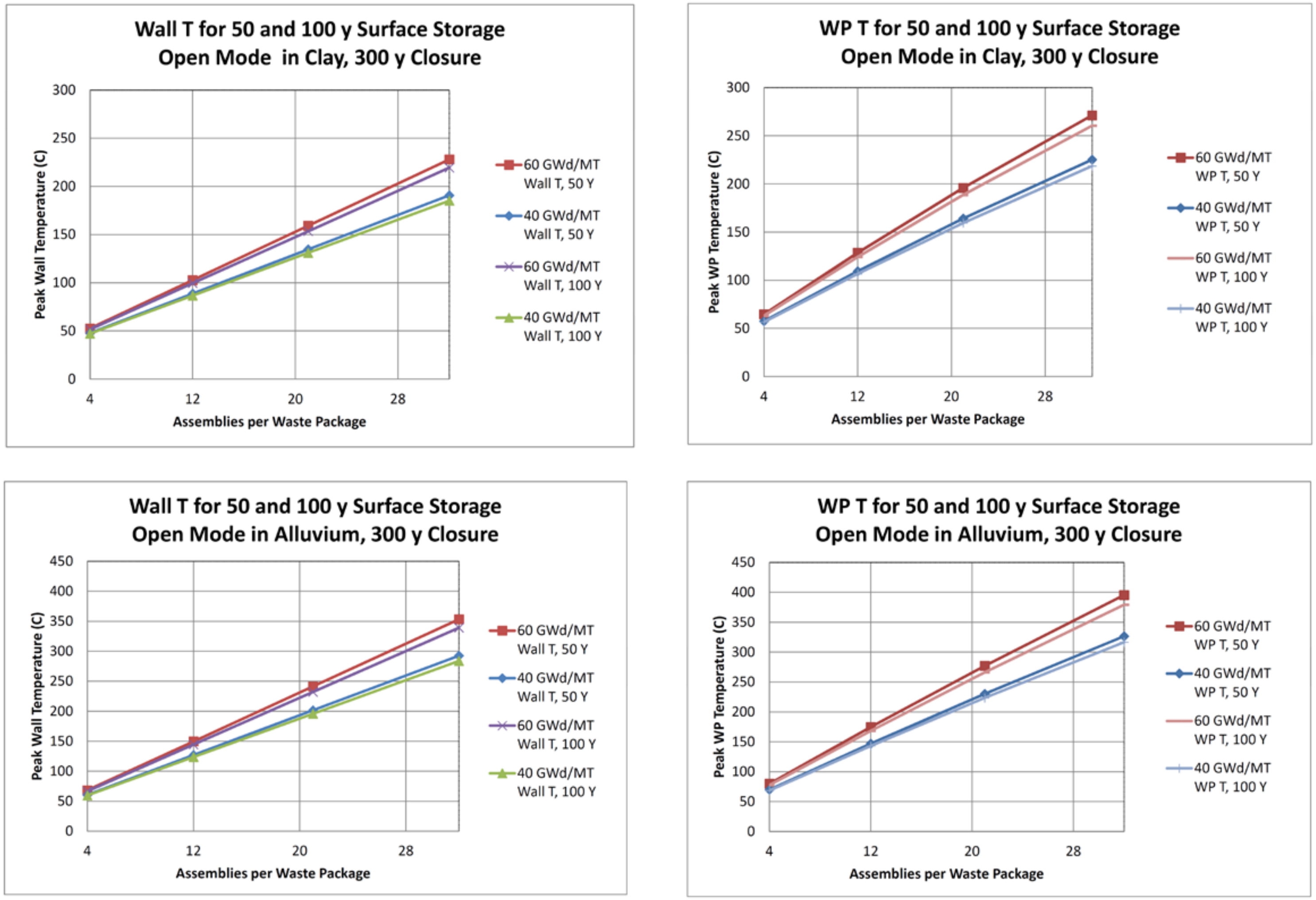


Figure 3.2-1 Nominal-Case Peak Rock Wall and Waste Package Temperatures (30-m drift spacing, 50 and 100 yr decay storage, 40 and 60 GWd/MT burnup, shale and alluvium properties)

Table 3.2-1 Summary of Nominal Thermal Results for Peak Rock Wall and Waste Package Temperatures (50 and 100 yr decay storage, 40 and 60 GWd/MT burnup, shale and alluvium properties)

		Surface Storage = 50 yr				Surface Storage = 100 yr			
Host Medium	**WP Size/ Burnup (GWd/MT)**	**Peak Rock Temp (°C)**	**Peak Time (yr)**	**WP Surface Temp (°C)**	**Peak Time (yr)**	**Peak Rock Temp (°C)**	**Peak Time (yr)**	**WP Surface Temp (°C)**	**Peak Time (yr)**
Shale	4-PWR/40	47.8	593	57.6	442	47.2	624	56.6	455
	4-PWR/60	52.6	567	64.7	410	51.5	628	63.1	423
	12--PWR/40	88.7	593	109.4	488	86.6	628	106.7	489
	12--PWR/60	102.7	567	128.5	442	99.5	628	124.2	470
	21--PWR/40	134.6	593	164.1	488	131.0	624	159.5	515
	21--PWR/60	159.1	567	195.8	468	153.4	628	188.6	496
	32--PWR/40	190.7	593	225.2	516	185.2	628	218.6	536
	32--PWR/60	228.0	567	271.2	487	219.4	628	260.5	496
Alluvium	4--PWR/40	60.6	593	70.0	488	59.5	628	68.6	515
	4--PWR/60	68.2	567	79.9	458	66.5	628	77.6	482
	12--PWR/40	126.9	593	147.0	515	123.6	628	143.0	530
	12--PWR/60	149.6	567	174.7	482	144.4	628	168.3	515
	21--PWR/40	201.5	593	230.3	521	195.7	628	223.5	544
	21--PWR/60	241.2	567	277.0	493	232.1	628	266.2	515
	32--PWR/40	292.6	593	326.5	541	283.8	628	316.6	577
	32--PWR/60	353.2	567	395.5	515	339.2	628	379.3	536

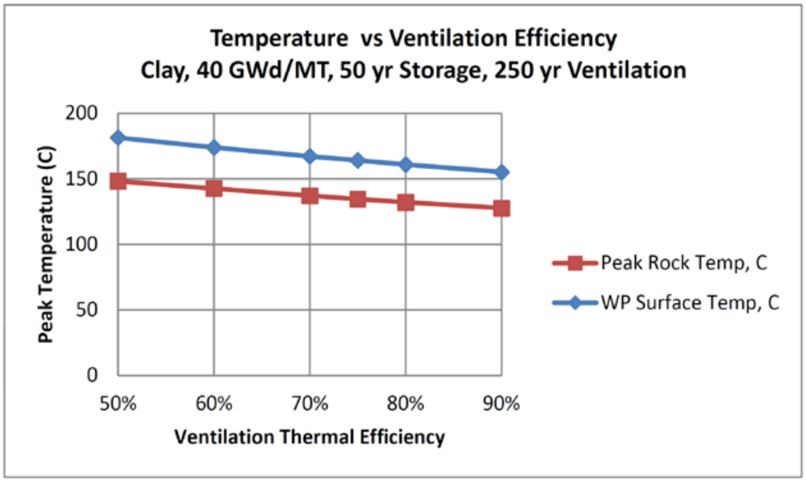
3.2.2.2 Sensitivity to Ventilation Efficiency

Table 3.2-2 presents sensitivity to ventilation thermal efficiency with 30-m drift spacing, 21-PWR size packages, 40 GW-d/MT burnup, 50-yr decay storage, 250-yr ventilation, and shale properties. Temperature histories for these cases are available from Greenberg et al. (2012).

Figure 3.2-2 summarizes the results for the ventilation efficiency sensitivity cases. Ventilation efficiency has enough of an effect on temperature that it should be included in cost/performance trade studies. The top pane shows the effect of ventilation thermal efficiency on peak wall and WP temperatures for one repository design. The bottom pane shows the transient rock wall and WP temperatures for six ventilation thermal efficiencies. The peak temperature from each curve is a data point on the red curve of the top plot.

Table 3.2-2 Sensitivity of Peak Temperatures to Ventilation Efficiency (shale properties)

Ventilation Efficiency	Peak Rock Temp (°C)	Peak Time (yr)	Peak WP Surface Temp (°C)	Peak Time (yr)
50%	148.2	491	181.5	410
60%	142.7	545	174.0	442
70%	137.1	567	167.2	468
75%	134.6	593	164.1	488
80%	132.2	608	161.0	516
90%	127.6	659	155.2	539



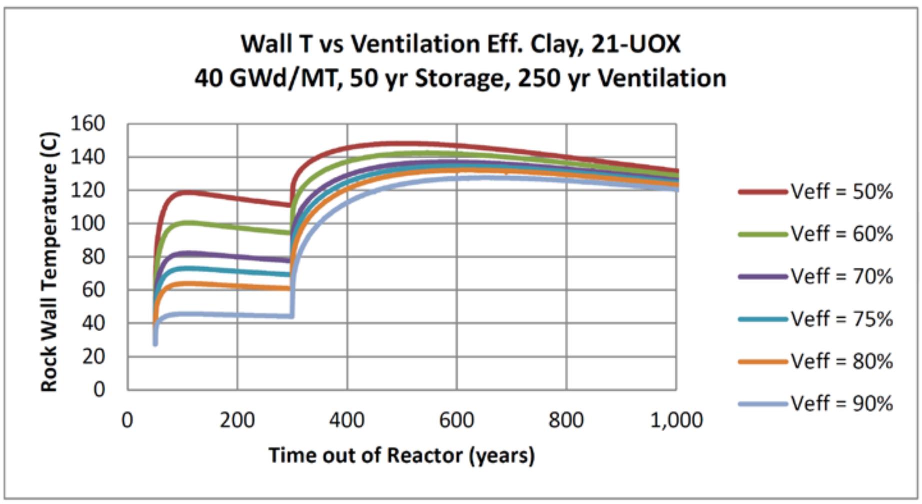


Figure 3.2-2 Effect from Ventilation Efficiency on Peak Temperatures, and Histories for Rock Wall Temperature

3.2.2.3 Sensitivity to Ventilation Duration

Table 3.2-3 and Figure 3.2-3 show the results of the cases analyzed. There are diminishing returns on ventilation duration, especially at long ventilation times (e.g., greater than 200 yr). The lower right figure shows details around the time of closure, with the initial steep rise at the cessation of ventilation, then another steep rise when the insulating backfill replaces more efficient radiative heat transfer.

The last three cases in Table 3.2-3 explore whether higher temperatures due to shorter ventilation can be compensated by greater drift spacing. Doubling the drift spacing has an effect on peak temperature that is similar to doubling the ventilation time, which is consistent with the general heat transfer behavior discussed in Section 1.4.2

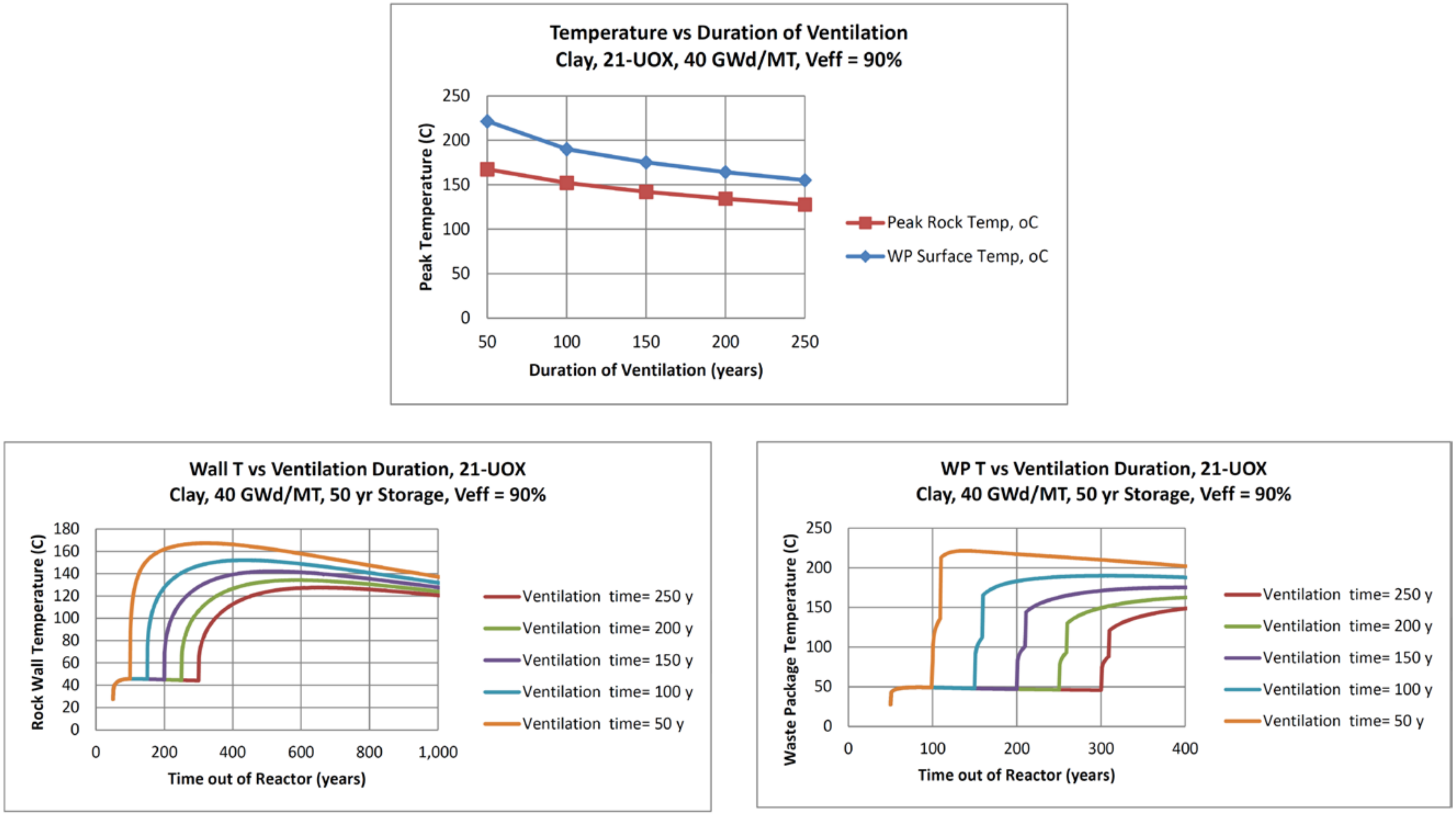


Figure 3.2-3 Effect of Ventilation Duration on Peak Rock Wall and Waste Package Temperatures

Table 3.2-3 Sensitivity of Peak Temperatures to Ventilation Duration, Combined with Drift Spacing

Ventilation Period (yr)	Drift Spacing (m)	Peak Rock Temp (°C)	Peak Time (yr)	Peak WP Surface Temp (°C)	Peak Time (yr)
250	30	127.6	659	155.2	539
200	30	134.3	602	164.3	479
150	30	142.0	518	175.3	417
100	30	152.0	424	190.1	314
50	30	167.4	322	221.4	139
50	40	141.3	349	207.5	118
50	50	124.2	322	203.3	111

3.2.2.4 Sensitivity to Emplacement Drift Spacing

Table 3.2-4 and Figure 3.2-4 summarize the peak temperature results for drift spacing. These calculations are perturbations of the nominal cases presented previously (40 GWd/MT burnup, 50-yr decay storage, 250-yr ventilation, and ventilation efficiency 75%).

Increasing drift spacing will lower peak temperatures, and is increasingly effective at later time. This is because although increased spacing tends to extend the temperature peaks, the heat source strength is decreasing with time. Increasing spacing to 50 m or beyond, appears to push the peak response beyond the decay envelope. Drift spacing is adjusted in the “design test case” described at the end of this section.

Table 3.2-4 Sensitivity of Peak Temperatures to Drift Spacing, for Large Packages (shale properties)

Drift Spacing (m)	Peak Rock Wall Temp (^{o}C)	Peak Time (yr)	Peak WP Surface Temp (^{o}C)	Peak Time (yr)
21-PWR Waste Package				
30	134.6	593	164.1	488
40	116.1	641	145.3	470
50	103.2	641	133.6	432
60	94.0	641	126.6	378
70	87.4	567	122.4	355
32-PWR Waste Package				
30	190.7	593	225.2	516
40	162.4	641	196.5	514
50	142.9	641	178.0	468
60	128.8	641	166.3	410
70	118.7	567	159.3	374

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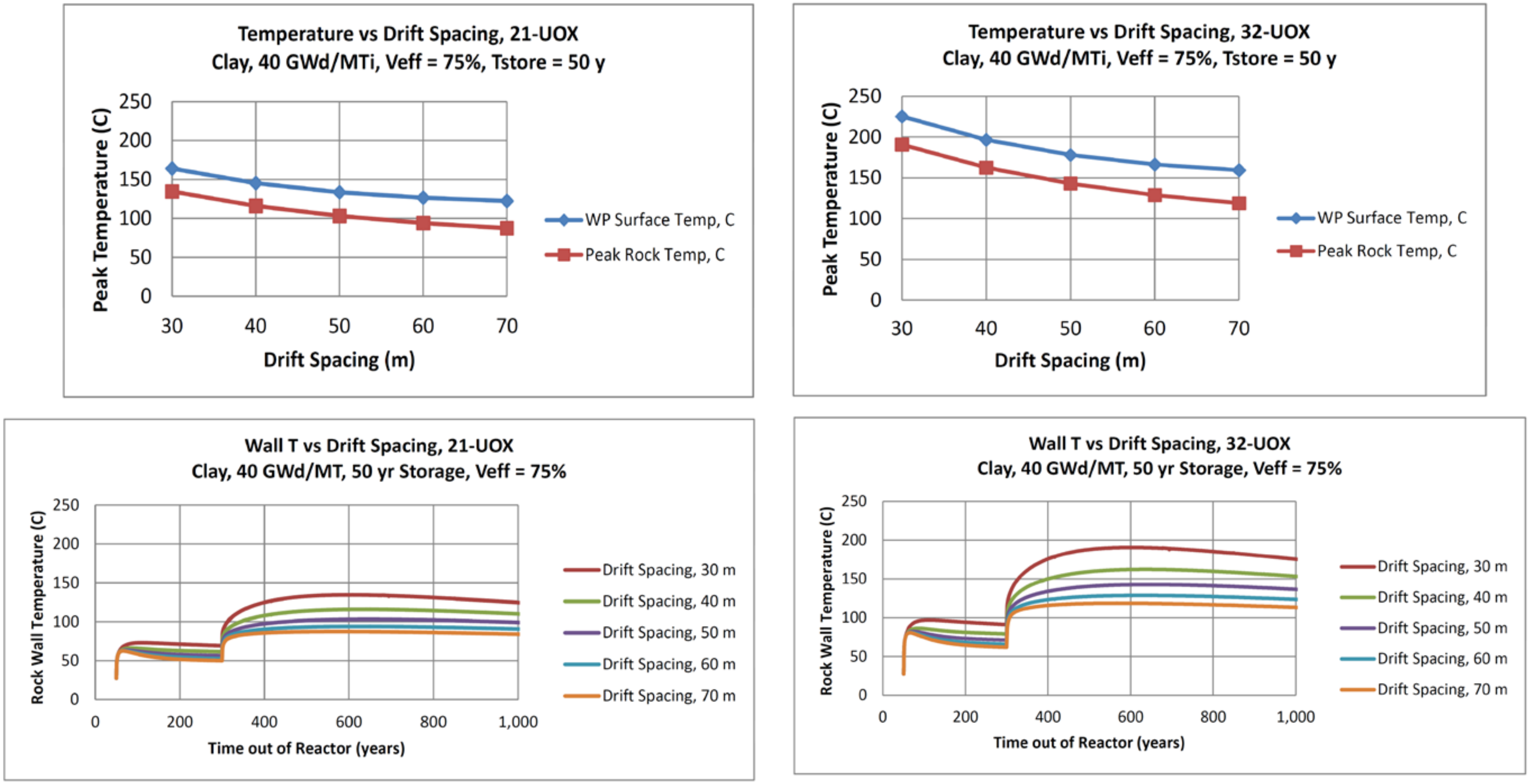

Figure 3.2-4 Effect of Drift Spacing on Peak Rock Wall and Waste Package Temperatures, for Large Packages (shale properties)

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3.2.2.5 Sensitivity to Host Rock Thermal Conductivity

Table 3.2-5 and Figure 3.2-5 summarize the peak temperature information for sensitivity to host rock thermal conductivity. Shale heat capacity is used, with 40 and 60 GW-d/MT burnup SNF in 21-PWR packages, also 50-yr decay storage, 250-yr ventilation duration, and 75% ventilation efficiency.

Host rock thermal conductivity (and diffusivity) is identified as a key parameter in the uncertainty analysis of Appendix D. Temperature reduction is inversely related (to a first approximation) to the square root of diffusivity (and therefore of conductivity because heat capacity varies little in sedimentary rocks). This behavior is apparent from calculated results (Table 3.2-5) particularly if the background temperature is subtracted from the peak temperature values.

These results suggest that for open modes with large waste packages (e.g., 21-PWR size or larger) the focus of near-field temperature reduction should be on the heat source (waste package loading and ventilation duration) or heat dissipation in the host rock (conductivity and drift spacing).

Table 3.2-5 Sensitivity of Peak Temperatures to Rock Thermal Conductivity

Burnup (GWd/MT)	Thermal Conductivity (W/m-K)	Peak Rock Temp. (°C)	Peak Time (yr)	Peak WP Surface Temp. (°C)	Peak Time (yr)
40	1	182.4	641	209.9	547
40	2	125.8	604	155.3	488
40	3	101.4	567	132.8	442
40	4	87.8	526	120.3	417
40	5	78.9	526	112.2	405
60	1	217.7	624	252.0	515
60	2	147.7	567	185.1	439
60	3	118.4	518	157.8	410
60	4	101.8	495	142.5	393
60	5	90.6	491	132.6	370

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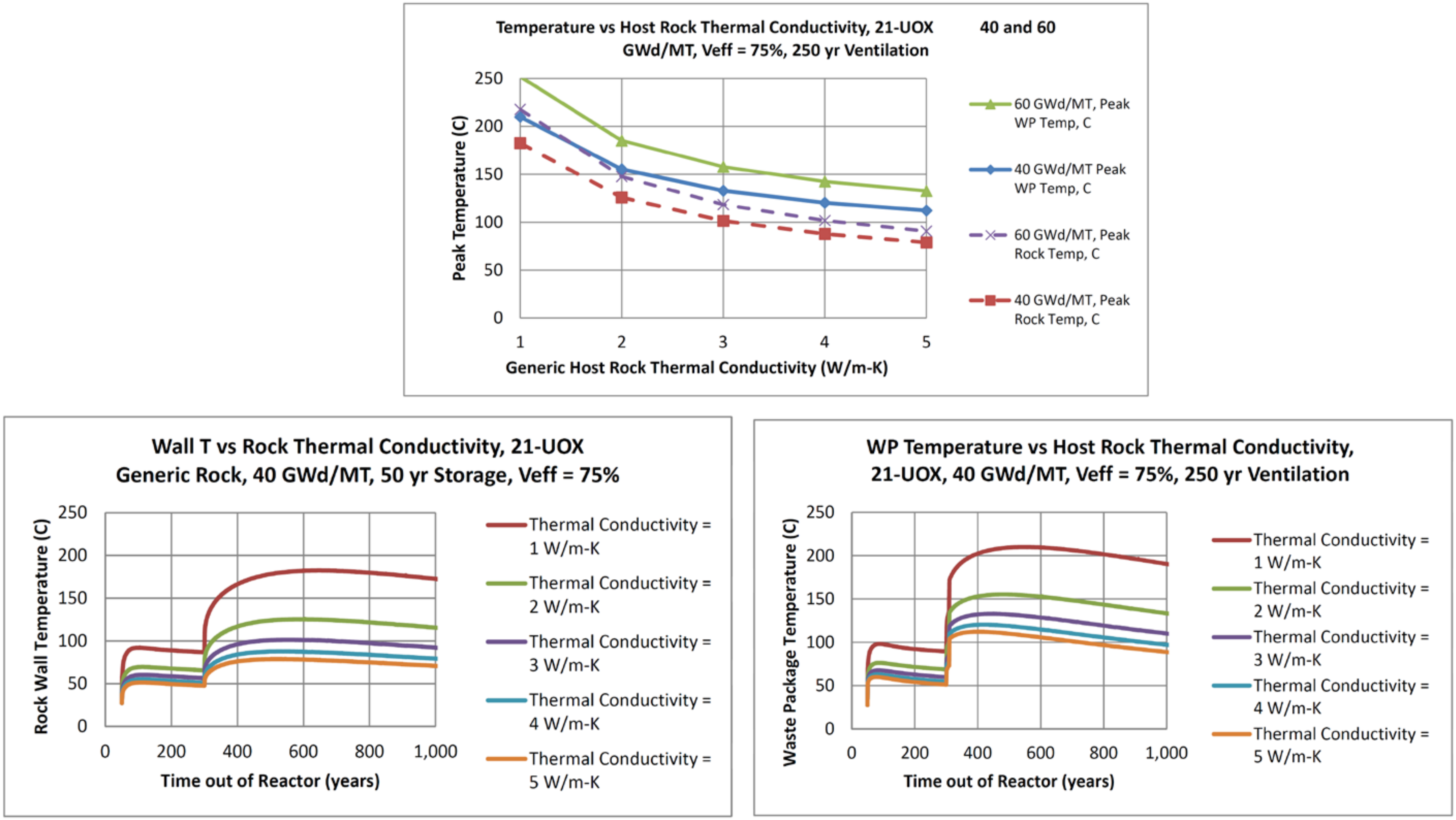

Figure 3.2-5 Sensitivity of Peak Temperatures to Generic Host Rock Thermal Conductivity

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3.2.2.6 Sensitivity to Backfill Thermal Conductivity

Table 3.2-6 and Figure 3.2-6 summarize the peak temperature information for generic backfill with thermal conductivity ranging from 1 to 5 W/m-K, and nominal-case settings for other variables (30-m drift spacing, 40 GW-d/MT burnup SNF in 21-PWR size packages, 50-yr decay storage, 250-yr ventilation, 75% ventilation efficiency). Values for backfill thermal conductivity are discussed in Appendix A (Section 3.2.1) and Appendix D. Backfill does not affect rock wall temperature, and has only a moderate influence on peak waste package temperature (lowering the buffer/backfill resistance transfers control of the package temperature to the rock wall).

Table 3.2-6 Sensitivity of Peak Temperatures to Backfill Thermal Conductivity

Burnup (GWd/MT)	Backfill Thermal Conductivity (W/m-K)	Peak Rock Temp. (°C)	Peak Time (yr)	Peak WP Surface Temp. (°C)	Peak Time (yr)
40	1	134.6	593	170.4	488
40	2	134.6	593	151.8	535
40	3	134.6	593	145.9	554
40	4	134.6	593	143.0	567
40	5	134.6	593	141.3	567

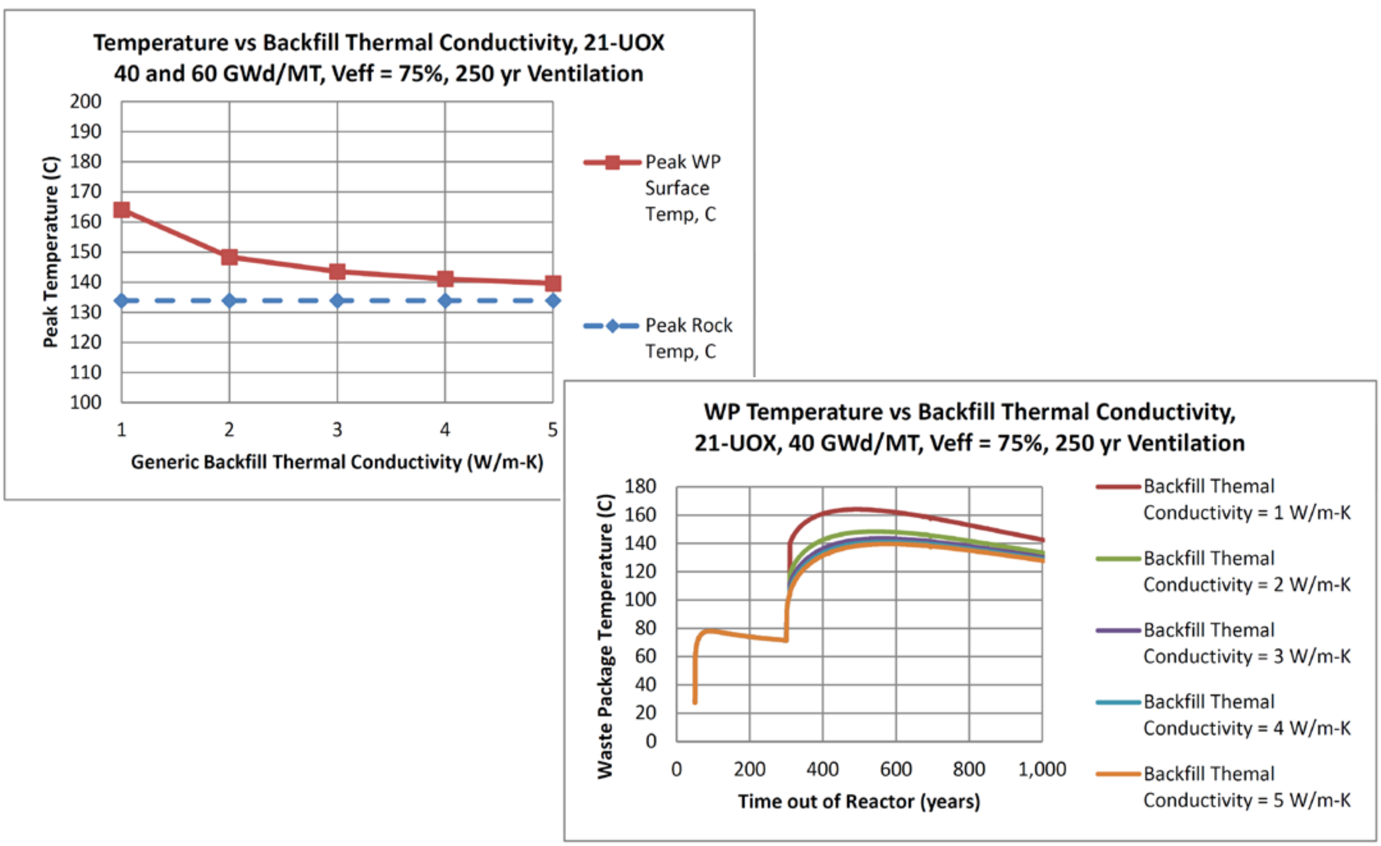

Figure 3.2-6 Sensitivity of Peak Temperatures to Generic Backfill Thermal Conductivity

3.2.2.7 Uncertainty Analysis for Host Rock Thermal Conductivity

One and two standard deviations in thermal conductivity were calculated for shale and alluvium properties, using data from Appendix D (Table D-1). Analysis in the appendix establishes host rock thermal conductivity as the most important parameter of peak waste package surface temperature. The developed ranges in thermal conductivity actually include three factors: variation between sites or host formations, spatial variation within a site, and measurement uncertainty. Results are summarized in Table 3.2-7, and show that considerable variation in peak temperatures is possible within the reported range of thermal conductivity (30-m drift spacing, 40 GW-d/MT burnup SNF in 21-PWR size packages, 50-yr decay storage, 250-yr ventilation, and 75% ventilation efficiency).

Within $\pm 1\sigma$ variation of thermal conductivity around the mean values, peak temperatures shift by approximately +33% (for lower Kth) and -10% (for higher Kth). The general conclusions of this report can be applied to geologic media with different thermal properties, or for natural variability of properties within geologic units, if thermal loading can be adjusted (-33%, +10%) to accommodate these variations. Geologic settings with very low thermal conductivity (μ-2σ) could be screened out or otherwise addressed during repository design by adjusting drift spacing, decay storage, ventilation duration, etc.

Table 3.2-7 Sensitivity of Peak Temperatures to Uncertainty in Rock Thermal Conductivity

Medium	# of Std. Deviations from the Mean	Thermal Conductivity (W/m-K)	Peak Rock Temp. (°C)	Peak Time (yr)	Peak WP Surface Temp. (°C)	Peak Time (yr)
Shale	-2	0.51	265.2	675	291.2	593
Shale	-1	1.12	172.1	648	200.0	536
Shale	Mean	1.73	134.6	593	164.1	488
Shale	+1	2.34	115.6	592	146.2	464
Shale	+2	2.95	102.5	567	133.9	442
Alluvium	-2	0.84	238.5	611	266.5	544
Alluvium	-1	0.95	222.0	606	250.5	515
Alluvium	Mean	1.06	201.5	593	230.3	521
Alluvium	+1	1.17	196.3	592	225.4	521
Alluvium	+2	1.28	186.2	592	215.6	515

3.3 “Design Test Case” for Cost Estimation

Using the insight gained from sensitivity studies presented above, a combination of parameters was selected as a strategy for disposing of 21-PWR packages containing SNF with 40 GW-d/MT burnup, while limiting ventilation duration to 50 or 100 yr. Backfill thermal conductivity is varied across a wide range representing what may be possible (see discussion in Appendix A), including no backfill (radiative transfer). Table 3.3-1 presents a summary of peak temperature information, and Figure 3.3-1 presents the corresponding temperature histories graphically. This study evaluates several key ideas not explored in Section 3.2: 1) sensitivity to waste package spacing within drifts; 2) effect of no backfill; and 3) the effect of extending the temperature compliance boundary 3 m into the rock wall. The latter idea is based on the possibility of heating the near-field host rock above 100°C, in a massive soft shale formation (low permeability, unfractured). The r_{DW} = 5.25 m cases explore the feasibility of restricting temperatures in excess of 100°C to a small region around each drift.

These calculations use 50-yr storage time, and either 50 or 100 years of ventilation at 75% efficiency, as well as the post-ventilation 10-yr backfill installation period. They use the same nominal waste package spacing (10 m center-to-center) but an extended drift spacing of 60 m, selected to help moderate peak temperature response. Backfill thermal conductivity is varied across the full range used in Section 3.2 (except for cases with no backfill, or those for which the temperature limit boundary is extended into the host rock).

Another sensitivity analysis evaluates the effect of varying axial waste package spacing (10, 15, and 20 m). In each case, the drift spacing is 60 m, with 21-PWR size packages, 40 GW-d/MT burnup, ventilation duration 50 yr, ventilation efficiency 75%, and backfill thermal conductivity 1.2 W/m-K. Results for these cases are summarized in Table 3.3-2. The effect is similar to varying the drift spacing, and reinforces the conclusion drawn above that limiting near-field peak temperature requires attention to the heat source, or heat dissipation in the host rock.

Table 3.3-1 Peak Temperature Information for the "Design Test Case" [A]

Host Medium	Description	Decay Storage (yr)	Time to Closure (yr)	Peak Rock Temp. (°C)	Peak Time (yr)	Peak WP Surface Temp. (°C)	Peak Time (yr)
Shale	No backfill	50	100	121.3	129	135.2	121
Shale	backfill Kth=2	50	100	121.3	129	172.6	113
Shale	backfill Kth=1.2	50	100	121.3	129	208.9	110
Shale	backfill Kth=0.6	50	100	121.3	129	300.0	110
Shale	r_{DW} = 5.25 m [B]	50	100	100.9	470	[B]	[B]
Shale	No backfill	50	150	107.3	384	115.7	210
Shale	backfill Kth=2	50	150	107.3	384	139.0	177
Shale	backfill Kth=1.2	50	150	107.3	384	164.0	166
Shale	backfill Kth=0.6	50	150	107.3	384	228.8	160
Shale	r_{DW} = 5.25 m [B]	50	150	95.1	562	[B]	[B]

[A] Drift diameter 4.5 m, drift spacing 60 m, 21-PWR sized packages, 40 GW-d/MT, 50 and 100 yr of ventilation, and varying backfill thermal conductivity.

[B] Host rock temperature transient at 3 m depth into the host rock is independent of the backfill properties and other aspects of EBS configuration

Table 3.3-2 Sensitivity of "Design Test Case" Peak Temperature to Waste Package Axial Spacing (10, 15, and 20 m)

Host Medium	Waste Package Spacing (m)	Backfill Thermal K_{th} (W/m-K)	Decay Storage (yr)	Time to Closure (yr)	Peak Rock Temp. (°C)	Peak Time (yr)	Peak WP Surface Temp. (°C)	Peak Time (yr)
Shale	10	1.2	50	100	121.3	129	208.9	110
Shale	15	1.2	50	100	101.7	123	191.2	110
Shale	20	1.2	50	100	92.9	116	183.6	110

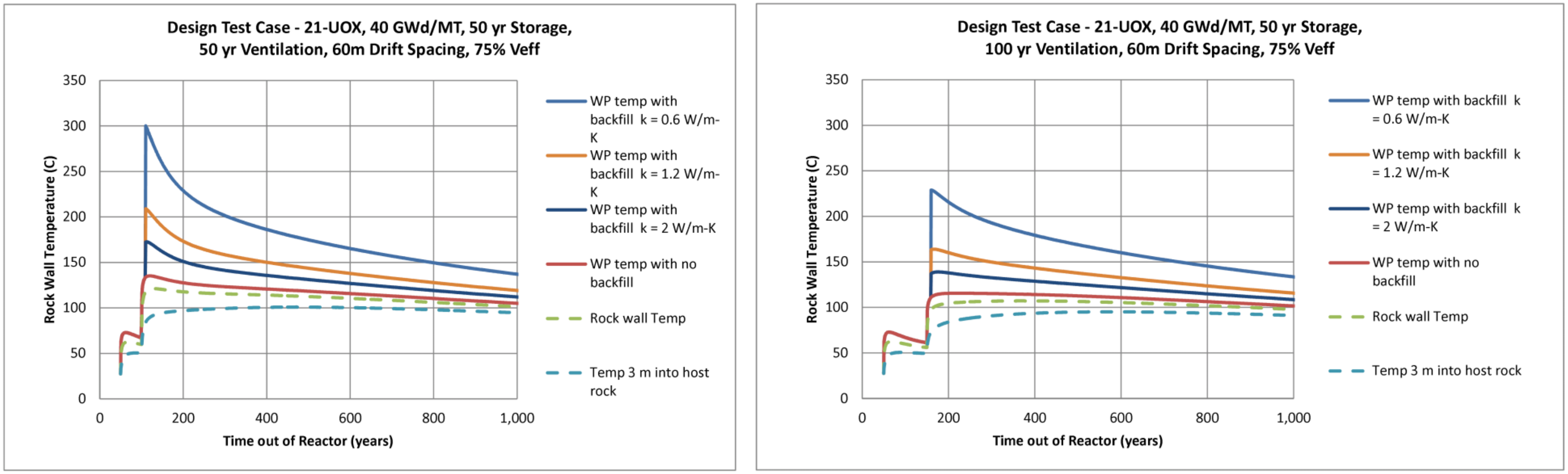

Figure 3.3-1 Temperature Histories for "Design Test Case," for 50- and 100-yr Ventilation Periods

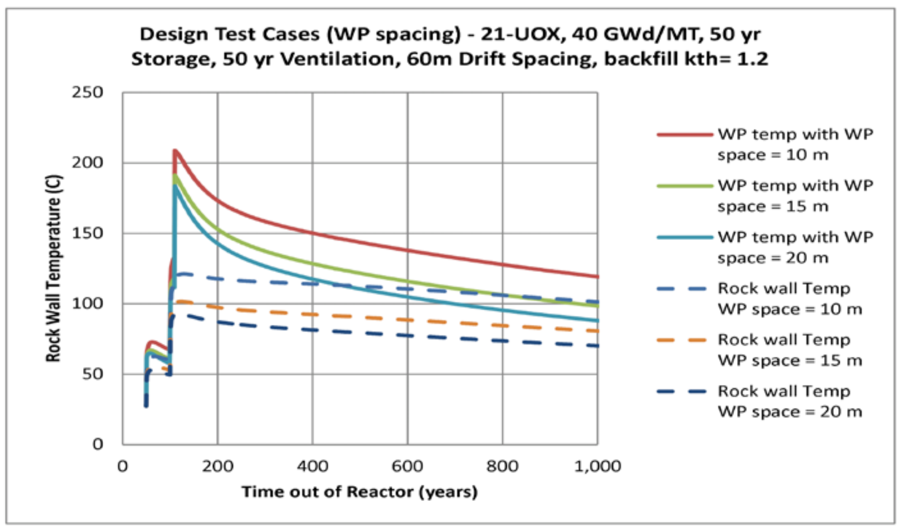

Figure 3.3-2 Design Test Case for Cost Analyses: Sensitivity to Axial Waste Package Spacing

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4. Concept Description Information for Cost Estimates

The engineering description and cost estimation portions of this study (Sections 4 and 5) address only the first five of the seven generic disposal concepts discussed so far and listed below:

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 (Section 1.4.5.1).
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 (Section 1.4.5.2).
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 (Section 1.4.5.3).
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 (Section 1.5.1).
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 (Section 1.5.2).
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 drifts need not be backfilled, but other engineered barriers may be installed (Section 1.5.3).
7. **Deep Borehole (enclosed) –** Ongoing studies are assessing the feasibility of drilling large-diameter holes to 5 km in crystalline basement rock. Waste packages would contain single fuel assemblies, and be stacked in the lower 2 km of each hole. The upper section would be sealed.

The Deep Borehole disposal concept (Section 1.4.5.4) and the Hard Rock Unsaturated open concept (Section 1.5.3) are described and estimated elsewhere. The details and rough-order-of-magnitude cost for deep borehole disposal are described by Brady et al. (2009) and Arnold et al. (2011). The hard rock unsaturated concept is represented by the recently completed license application for a repository in volcanic tuff, although the same concept could be implemented in other, similar hydrogeologic settings. As such, previously published information is available for typical details (DOE 2008b) and cost estimates (DOE 2008c).

The open modes listed above and in Section 1.5 are intended for SNF. HLW glass is typically available in pour canisters with smaller diameter (e.g., 2 ft.) determined by the minimum cooling rate needed to avoid crystallization of the borosilicate glass waste form. The heat output of HLW glass from reprocessing commercial fuel could be high (see Carter et al. 2011b) but decreases significantly over a few decades of surface decay storage. The heat output of HLW glass from defense activities (DOE HLW) is already low (Carter et al. 2012c) partly because of decay storage and partly because the DOE borosilicate glass is limited in waste loading by interactions with non-radioactive chemical constituents (e.g., aluminum). Multiple HLW canisters can be loaded in larger waste packages, and the resulting heat output depends on the type of HLW.

Basis for Estimation

A repository capacity of 140,000 MT of commercial SNF is assumed for this generic study. Implementation of such a facility would require changes in the Nuclear Waste Policy Act and implementing regulations (see Section 1). The repository receives SNF in sealed stainless steel canisters that are in the configuration needed for disposal, and are not re-opened. As discussed below, surface facilities (Section 2.2) are needed to package these canisters into disposal overpacks that are specific to each disposal concept.

Each of the five concepts (Sections 4.1 through 4.5) required description of the repository layout, emplacement mode, and waste packaging. Concepts were developed considering thermal management (among other factors) using typical heat transfer characteristics for each generic geologic setting (Section 3).

This study assumes a total SNF emplacement of 140,000 MT at an annual emplacement rate of 3,000 MT per year, which will require approximately 47 years for disposal of the total inventory (Sections 1 and 1.2). The 140,000 MT capacity is based on operating the existing 104 commercial U.S. nuclear reactors for 60 years each. The cost estimation methodology developed in Sections 4.6 and 5 is modular to allow cost studies for multiple repositories although only the results for a single repository are presented.

Major aspects of the description, based on Sections 4.1 through 4.5, are summarized in Tables 4-1 through 4-3. Table 4-1 summarizes the waste package configuration, total and annual numbers of waste packages for disposal, and the materials of construction. The annual numbers of waste packages would be processed by modular facilities as discussed in Section 2.2.7.

Repository layouts were developed as modular panels for each concept, which is important because the scale or volume of excavation is one of the principal differences among alternatives (Table 4-2). These modular panels (e.g., Figure 4.1-1) were then multiplied to accommodate the total SNF inventory of 140,000 MT.

Shafts connect the surface and underground facilities to provide men-and-materials access, ventilation, waste rock removal, and waste transfer. Waste package transport is by shaft hoist system for two concepts, and by ramp for the other three. Shaft/ramp selection is discussed in more detail for each concept in the following sections. The numbers of ventilation intake and exhaust shafts vary according to whether ventilation is used to remove heat (open modes), or merely to maintain drifts available for human access after emplacement (crystalline and shale enclosed modes), or only for construction and emplacement operations (salt). The ventilation needed to support various operations, and the ventilation capacity for shafts and ramps, are discussed in Section 2.3. The basic approach is to support a flow rate of 15 m^3/sec per drift for construction or waste heat removal. For all other openings ventilation is scoped to provide air turnover times of a few hours. Intake and exhaust shafts are scoped to maintain maximum air velocity of approximately 10 m/sec. Table 4-3 summarizes the number of shafts assumed for each concept, for disposal of 140,000 MT SNF.

Repository surface facilities provide the infrastructure to: receive inbound waste in sealed canisters, unload the canisters in a radiologically shielded area, provide interim lag storage as needed, transfer the canisters to disposal overpacks, and transfer the loaded waste packages to the underground in shielded casks. This scope does not include repackaging SNF from storage canisters (e.g., dual-purpose canisters containing 32 or more PWR assemblies), into the waste package configurations described in Table 4-2. The cost of such repackaging depends on other variables such as the interim storage configuration (e.g., dry storage or as bare fuel in pools). This study assumes that such packaging or repackaging is performed at a centralized fuel storage facility (Section 2.1.1).

Note that evaluation of cost factors is provided here and in Section 5, to show how design features and thermal management strategies affect relative costs. Application of these cost results beyond this purpose should be avoided.

Table 4-1 Summary of Waste Package Numbers for 5 Disposal Concepts

	Package Capacity (PWR/BWR)	140,000 MT Repository		Disposal Overpack
		Total Waste Packages	Annual Waste Packages	Material
Crystalline (enclosed)	4/9	82,583	1,757	Copper
Generic Salt Repository (enclosed)	12/24	28,792	616	Carbon Steel
Clay/Shale (enclosed)	4/9	82,583	1,757	Carbon Steel
Shale Unbackfilled (open)	21/44	16,157	344	Carbon Steel
Sedimentary Backfilled (open)	21/44	16,157	344	Carbon Steel

Table 4-2 Summary of Mined Opening Length and Volume for 5 Disposal Concepts

	Access Drift		Disposal Drifts/ Borings		Service Drift		Repository Total	
	Length (m)	Volume (m^3)	Length (m)	Volume (m^3)	Length (m)	Volume (m^3)	Length (m)	Volume (m^3)
Crystalline (enclosed)	8.3E5	2.7E7	8.3E5	1.8E6	2.3E5	7.7E6	1.9E6	3.7E7
Generic Salt Repository (enclosed)	3.1E5	1.7E7	3.5E5	4.4E6	1.3E5	7.2E6	7.9E5	2.9E7
Clay/Shale (enclosed)	3.9E5	9.2E6	8.3E5	4.6E6	3.7E5	8.7E6	1.6E6	2.3E7
Shale Unbackfilled (open)	7.7E4	2.2E6	1.4E5	2.3E6	9.3E4	2.2E6	3.1E5	6.7E6
Sedimentary Backfilled (open)	8.5E4	2.0E6	2.2E5	3.5E6	5.8E4	1.4E6	3.6E5	6.9E6

Table 4-3 Summary of Shaft and Ramp Quantities for a 140,000 MT SNF Repository

	Air Intake	Rock Waste	Ventilation Exhaust	Waste Emplacement	
				Shafts	Ramps
Crystalline (enclosed)	1	1	2	1	0
Generic Salt Repository (enclosed)	1	1	2	1	0
Clay/Shale (enclosed)	1	1	2	0	1
Shale Unbackfilled (open)	8	1	4	0	1
Sedimentary Backfilled (open)	10	1	5	0	1

4.1 Crystalline (enclosed)

The repository is assumed to be nominally 500 meters below the surface in hydrologically saturated, low-permeability granitic host rock. The subsurface layout is similar to the KBS-3 vertical concept (Section 1.4.5.1) except that where the KBS-3V concept uses “blind” access drifts to limit groundwater flow, this study assumes that these drifts would be connected to the layout at both ends to facilitate excavation by tunnel boring machine. This additional efficiency is reasonable because of the large excavation volume needed for this concept. The underground layout selected for estimation and thermal analysis consists of parallel 6.5-m diameter access drifts 1,000 m in length, spaced 20 m apart on centers (Figure 4.1-1). Individual waste packages are emplaced in vertical, 1.66-m diameter emplacement borings drilled into the floor, 10 m apart. Drift diameter is sufficient for waste package handling equipment that rotates each package into a vertical position over its emplacement borehole. Smaller emplacement boring spacing may be possible with cooler waste, and access drifts with smaller diameter may be possible with smaller packages. The choices used here would accommodate high-burnup SNF in large packages (at least 5.0 m length).

For estimation, the repository will require approximately 60 panels of 12 access drifts (each 1,000 m) plus ventilated service drifts totaling a fraction of the access drift length. The total repository ventilation airflow requirement is therefore approximately 500 m^3/sec with allowance for construction activities, additional cooling, etc. This requires 2 exhaust shafts and 3 intake openings (waste rock, waste handling, and ventilation intake shafts). The exhaust shafts will be widely separated to support repository development in different directions.

Waste packages consist of a stainless steel SNF canister containing 4-PWR/9-BWR assemblies, within a disposal overpack made of copper with a 5-cm wall thickness, and welded closures. The annulus between the canister and the emplacement borehole wall (approximately 35 cm on the radius) is filled with a low-permeability buffer material consisting of swelling clay (e.g., Wyoming bentonite) emplaced initially in its dry, compacted form. Fuel assemblies are positioned inside the canister by an insert made of nodular cast iron, which provides structural support, is a sink for oxygen in the disposal environment, and is a source of corrosion products that can readily sorb radionuclides released from the waste form. Note that use of cast iron may require dry handling at the packaging facility. Prefabricated assemblies may be used, containing a waste package surrounded by compacted bentonite, held together by a steel shell (adapting a concept from McKinley et al. 2006). Further details of emplacement are discussed in Section 1.4.5.1.

Access to the repository horizon (500 meters below the surface) will be by shaft (see Section 2.3) because this could permit consideration of a broader range of granite bodies suitable for repository development in the U.S. Shaft access could allow for use of smaller granite bodies, including those bounded by features that might not be well suited for construction of 5-km spiral decline ramp from the surface. Also, the small size of waste packages for this disposal concept means that hoist payloads are within the capabilities of currently operating or available shaft hoists.

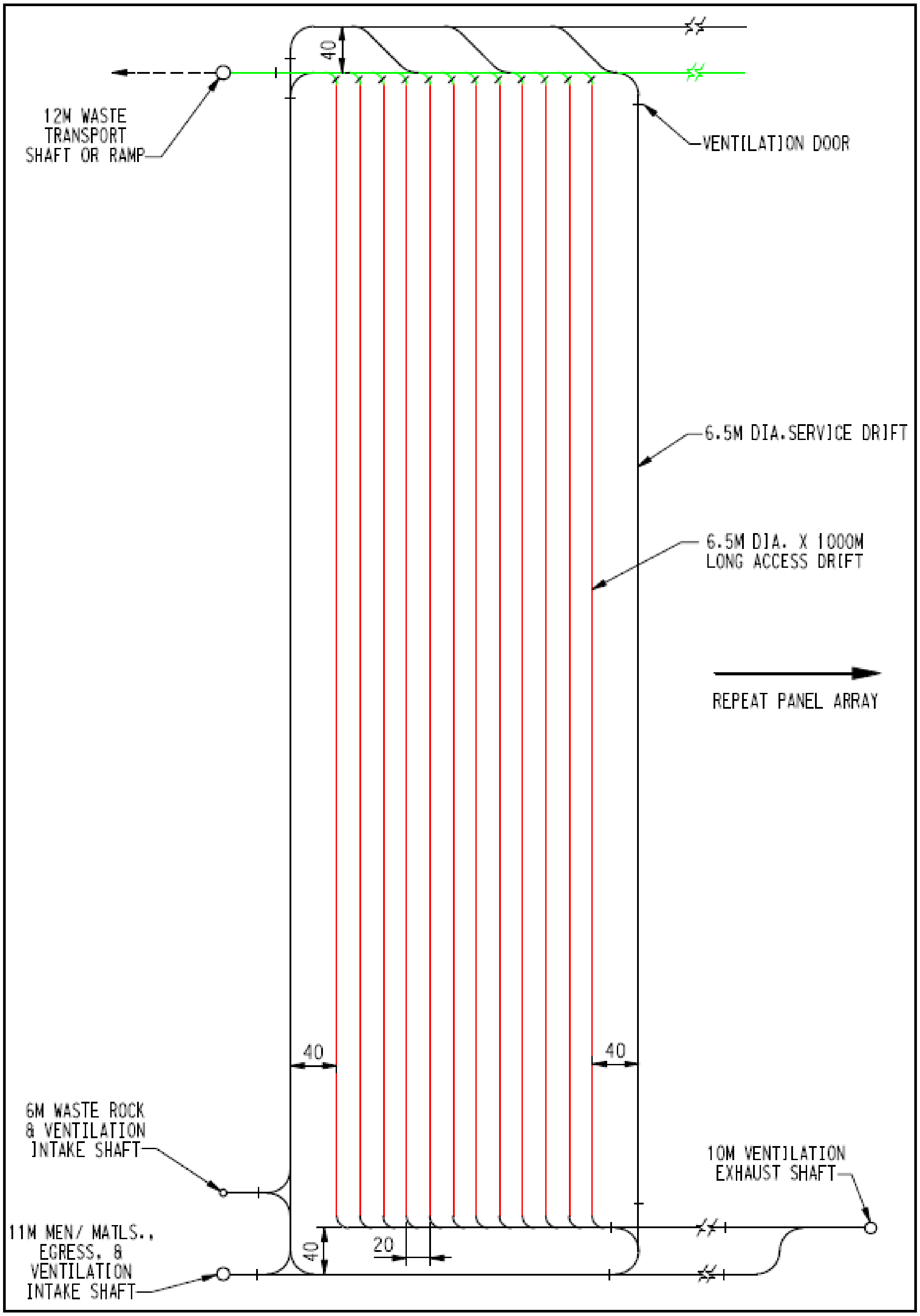

Figure 4.1-1 Crystalline (enclosed) Concept Repository Panel Schematic for Cost Estimation

The repository will be mostly excavated using tunnel boring machines, with a small amount of drill-and-blast excavation. Vertical emplacement boreholes will be excavated from the access drifts to a depth of approximately 8 m using a micro-boring machine. All floors will be reinforced concrete, with the extent of steel reinforcement depending on load analysis and the amount of traffic. The lightest reinforcement will be in the access drifts, to limit the total quantity of reinforcing steel and to facilitate removal of the floors at closure if required. Alternatives to concrete floors include: a flat floor milled directly on the host rock, crushed rock ballast, or pre-cast fiber-reinforced concrete floor panels. Some of these would have the advantage that they could be readily removed, and even reused as successive drifts are constructed and filled with waste.

Ground support will be minimal in high-quality rock; consisting of 2-m fully grouted rockbolts, wire cloth, and 3 cm of shotcrete with 270° coverage around the opening perimeter. Concrete used in floors, and shotcrete formulations, will be selected to limit leachate alkalinity (e.g., pH 11 or lower) and to limit permeability. Limited permeability will help ensure that cast-in-place floors and shotcrete liners do not become conduits for groundwater moving through the facility.

Tables 4.1-1 and 4.1-2 present crystalline (enclosed) repository drift and waste package details used to develop ROM estimates (Section 5).

Table 4.1-1 Crystalline (enclosed) Repository Drift Panel Detail Summary

Drift/Boring Function	Diameter (m)	Length (m)	Number (per panel)	Total Length (m)	Spacing (m)	Closure
Waste Emplacement	1.66	10	1,200	12,000	10	Bentonite clay backfilled at emplacement and shield plug installed
Access Drifts	6.5	1000	12	12,000	20	Backfilled with 30% bentonite clay and 70% crushed rock
Service Drifts	5.5	326 1100	4 2	3,352	N/A	Backfilled with 30% bentonite clay and 70% crushed rock
Panel Total				27,352		

Table 4.1-2 Crystalline (enclosed) Concept Repository Waste Emplacement Details

Emplacement Mode	PWR/BWR Package Size	Waste Package Spacing (m)	Waste Packages per Emplacement Drift	Waste Packages Per Panel	Waste Package Description
Vertical Borehole	4/9	10	100 WP per 1,000 m segment	1200	Stainless steel SNF canister with 5 cm thick copper overpack

4.2 Generic Salt Repository

The repository is assumed to be nominally 500 meters below the surface in bedded salt. The concept (Section 1.4.5.2) draws from experience at the WIPP and other salt excavations (Carter et al. 2011). A simple disposal scheme is selected in which each canister is placed on the floor, at the back of a mined alcove, using rubber-tire equipment.

Waste canisters (thin-walled stainless steel canisters containing SNF in a 5-cm thick carbon steel overpack) would be configured for 12-PWR or 24-BWR LWR fuel assemblies. This is a departure from the 4-PWR package size proposed by Hardin et al. (2011), supported by FEM thermal calculations (Appendix C). The overpack thickness allows some flexibility for structural and containment integrity for a period of hundreds to potentially thousands of years after emplacement. After being placed on the floor, packages would be immediately covered with crushed salt from repository excavation, to provide radiation shielding, and to eventually facilitate reconsolidation of the host rock. This waste package was selected based on previous thermal modeling results (Hardin et al. 2011) which showed that a 12-PWR size waste package could be disposed of in salt after as few as 50 yr of decay storage, with 60 GW-d/MT burnup (Table 3.1-2).

Height and width for the access drifts and alcoves are selected to accommodate waste package dimensions and the use of readily available mining equipment. Service drifts are approximately 6 m high and 9 m wide to provide clearance for mining and waste emplacement equipment. Emplacement drifts (alcoves) are assigned dimensions of 3 m high, 6 m wide (nominal), and 12 m deep, oriented 45 degrees to the access drifts. Emplacement drifts (alcoves) are mined from both sides of access drifts, and are spaced every 11.25 m along the 210 m long access drift (room). The access drift (room) spacing is set to 24.4 m to accommodate the two emplacement drifts back to back. Shaft access would be used for all functions (Figure 4.2-1), for flexibility in excavating, maintaining, and closing these openings in all types of soft sedimentary rock that could be encountered. Rubber-tire equipment would be used for construction, waste emplacement, and backfilling, running on floors cut directly in the host rock as is the practice at the WIPP and in salt mines.

All excavations will be mined using a boom-type roadheader, which has proven to be efficient at WIPP and other salt excavations. A representative disposal panel concept is shown in Figure 4.2-1. A total of 236 heat-generating waste packages can be emplaced in one panel as shown. Cooler waste or non-heat generating waste can also be emplaced as second packages in the same alcoves, as suggested by the original study authors (Carter et al. 2011). The original study stated without elaboration that repository closure would involve “backfilling and closing underground areas” (Carter et al. 2011, Section 7.2.9). The access and service drifts could be: 1) used for disposal of non-heat generating waste, and backfilled; 2) backfilled without such waste; or 3) left in the unbackfilled condition at closure, without such waste. For this study the simplest alternative was selected, to leave these openings in the unbackfilled condition. If backfilling of these openings is determined to be necessary during design or licensing, the addition would raise the cost of the Generic Salt Repository slightly (Table 5-1).

For hotter waste packages, a semi-cylindrical cavity with the same diameter as a waste package, can be milled in the alcove floor to improve heat transfer (numerical simulations in Appendix C were set up with semi-cylindrical cavities). All of the alcoves accessed from one access drift would be constructed before waste emplacement, then the furthest package would be emplaced and backfilled, then successive packages would be emplaced, retreating toward the drift entry.

The alcove disposal concept uses mine-run crushed salt as backfill placed over the waste packages. Excavation and waste emplacement operations can proceed concurrently in adjacent access drifts or panels, so that much of the crushed salt can be used as backfill (without hauling it to the surface). The operation of placing crushed salt over the waste would involve remote controlled, low-haul-dump equipment. Minimal ground support is required in a salt repository, consisting of rock bolts in the roof for high-traffic drifts, combined with steel braces or wire cloth where rockfall is evident.

As successive access drifts comprising a panel are constructed and filled with waste, ventilation would be adjusted so that the access to emplaced waste are always at lower pressure (i.e., closer to exhaust mains) than construction areas. As development proceeds ventilation airflow requirements do not change because only active construction areas and high-traffic main drifts are ventilated. Two widely separated exhaust shafts are required because the repository will consist of approximately 100 panels spread out over 30 square kilometers. The total length of service drifts will be on the order of 200 km or less, requiring airflow of less than 100 m^3/sec. Therefore smaller exhaust shafts (e.g., 5.5 m) would be used with ample additional capacity for construction and operations. Three intake openings (waste rock, waste handling, and ventilation intake shafts) are needed.

Tables 4.2-1 and 4.2-2 present Generic Salt Repository drift and waste package details used to develop ROM cost estimates (Section 5).

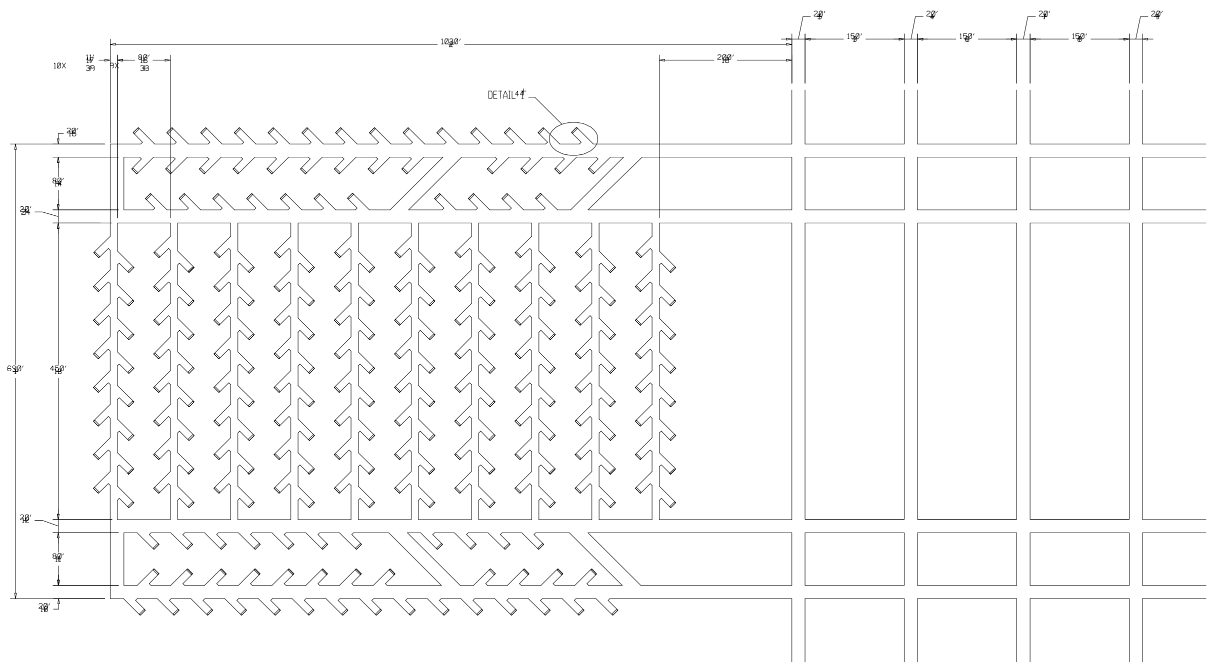

Figure 4.2-1 Enclosed Salt Repository Panel Concept Layout

Table 4.2-1 Generic Salt Repository (enclosed) Drift Panel Detail Summary

Drift/Boring Function	Diameter (m)	Length (m)	Number (per panel)	Total Length (m)	Spacing (m)	Closure
Waste Emplacement	3 × 6	12	236	2,832	11.25	Alcoves backfilled with mine-run salt
Access Drifts	6	253 210 24 36	4 10 6 2	2,577	24.4	See text.
Service Drifts	6	142 260	4 2	1,087	n/a	See text.
Panel Total				6,496		

Table 4.2-2 Generic Salt Repository (enclosed) Waste Emplacement Details

Emplacement Mode	PWR/BWR Package Size	Waste Package Spacing (m)	Waste Packages per Emplacement Drift	Waste Packages Per Panel	Waste Package Description
Alcove	12/24	n/a	1 WP per alcove	236	Stainless steel SNF canister in a 5-cm thick carbon steel overpack

4.3 Clay/Shale (enclosed)

As discussed in Section 1.4.5.3 the French program has narrowed the candidate repository site to be within an area of approximately 200 km^2 situated near Bure, in eastern France. For consistency with the French concept and to facilitate future comparisons of analysis results among the generic mined disposal concepts, the reference mined Clay/Shale concept is assumed to be nominally 500 meters below the surface in a thick shale unit that is hydrologically saturated.

The repository will require approximately 100 panels of four access drifts (each 630 m) plus ventilated service drifts slightly exceeding the access drift length (a single panel is shown in Figure 4.3-1). The total ventilation airflow requirement for the repository is approximately 300 m^3/sec with allowance for construction activities, additional cooling, etc. This requires two exhaust shafts and three intake openings (waste rock and ventilation intake shafts, and waste handling ramp). The exhaust shafts will be widely separated to support repository development in different directions. Selection of a ramp for waste handling is appropriate because shale formations tend to be extensive, i.e., uniform in horizontal and vertical directions, with low permeability throughout the geologic interval so that water inflow can be readily controlled and plugging/sealing can be readily accomplished at closure.

A reference panel concept (Figure 4.3-1) has been developed based on the proposed disposal concept for SNF in clay/shale media (Section 1.4.5.3). Emplacement openings are blind drifts excavated using automated equipment both for efficiency and because of the relatively small size. Other openings (access and service drifts) would be excavated mechanically using a boom-type roadheader appropriate for the soft-rock lithology.

As in the French concept, plugs and seals at the collar of each SNF emplacement drift will limit desiccation during repository operations, provide radiation shielding after emplacement, and inhibit movement of radionuclides into the access drift openings after repository closure. Use of radiation shield plugs allows construction and waste emplacement to occur essentially concurrently during the repository development sequence. Access drift openings with sufficient dimensions for construction and waste handling equipment, would be excavated first, then emplacement drifts would be excavated and completed as needed. Access and service drifts would be backfilled at closure using mined clay/shale material processed for low-permeability and swelling potential on hydration in situ.

The need for and amount of ground support in the emplacement openings and access drifts depends on the mechanical properties of the clay. Clay can be described as either plastic (soft) or indurated (hard), with widely varying mechanical properties. Plastic clay requires full structural lining. The Belgian program has used both pre-fabricated cast ductile-iron liner segments and concrete liner segments at the Mol laboratory (Verstricht et al. 1999) and proposes pre-cast concrete liner segments for repository drifts (ONDRAF/NIRAS 2001). More indurated clay rocks (e.g., clay shale, claystone or argillite) can be lined with shotcrete, reinforced with steel sets and lagging, as used in the underground laboratory at Bure (Delay et al. 2010). A more indurated shale is assumed for estimation.

Emplacement openings for HLW and SNF will be small (Section 1.4.5.3) and will be lined with a steel liner tube installed in segments. Access drifts will have a full lining of shotcrete with steel reinforcement, and a cast-in-place reinforced concrete floor. The floor is designed for high traffic with heavy rubber-tire equipment. Alternative floor or invert designs are limited because the shale may have low bearing strength, and because of the need to prevent slaking. The clay/shale (enclosed) disposal concept is intended for any clay or shale lithology regardless of rock quality, because emplacement openings are fully lined and SNF packages are surrounded by a clay-based buffer in addition to the surrounding host medium.

Waste packages for SNF are 4-PWR/9-BWR size, selected based on the thermal analysis conducted in FY11 (Hardin et al. 2011) which showed these packages could be emplaced after as few as 50 years of decay storage. Waste package spacing is 10 m (center-center) for in-drift emplacement of packages nominally 5 meters long (this spacing could be decreased for cooler waste). Emplacement drift spacing is 30 m. These dimensions are comparable to those proposed for the clay/shale repository in France (Andra 2005a) but with larger inter-package spacing to allow for hotter SNF. Access drifts have nominal 5.5-m diameter to provide clearance for drilling equipment and waste package transport, and are spaced approximately 110 meters apart (Figure 4.3-1). This arrangement accommodates 40-m emplacement boreholes with 30-m separation. Note that the collar of each emplacement drift is built out, increasing the effective width of the access drift to facilitate construction of the liner, pre-fabricated buffer, and shield plug, as well as handling of waste packages.

An annular buffer would be constructed in each emplacement drift from compacted bentonite blocks, before any waste is emplaced. A smaller, thinner steel liner tube would then be inserted, in segments, to line the cavity within the buffer. Waste packages would be inserted into that smaller tube, alternating with cylindrical spacers of compacted buffer material. Packages and spacers would slide into place on a steel form or pallet, which would then be withdrawn, using specialized handling equipment.

Tables 4.3-1 and 4.3-2 present the clay/shale (enclosed) repository drift and waste package details used to develop ROM cost estimates (Section 5).

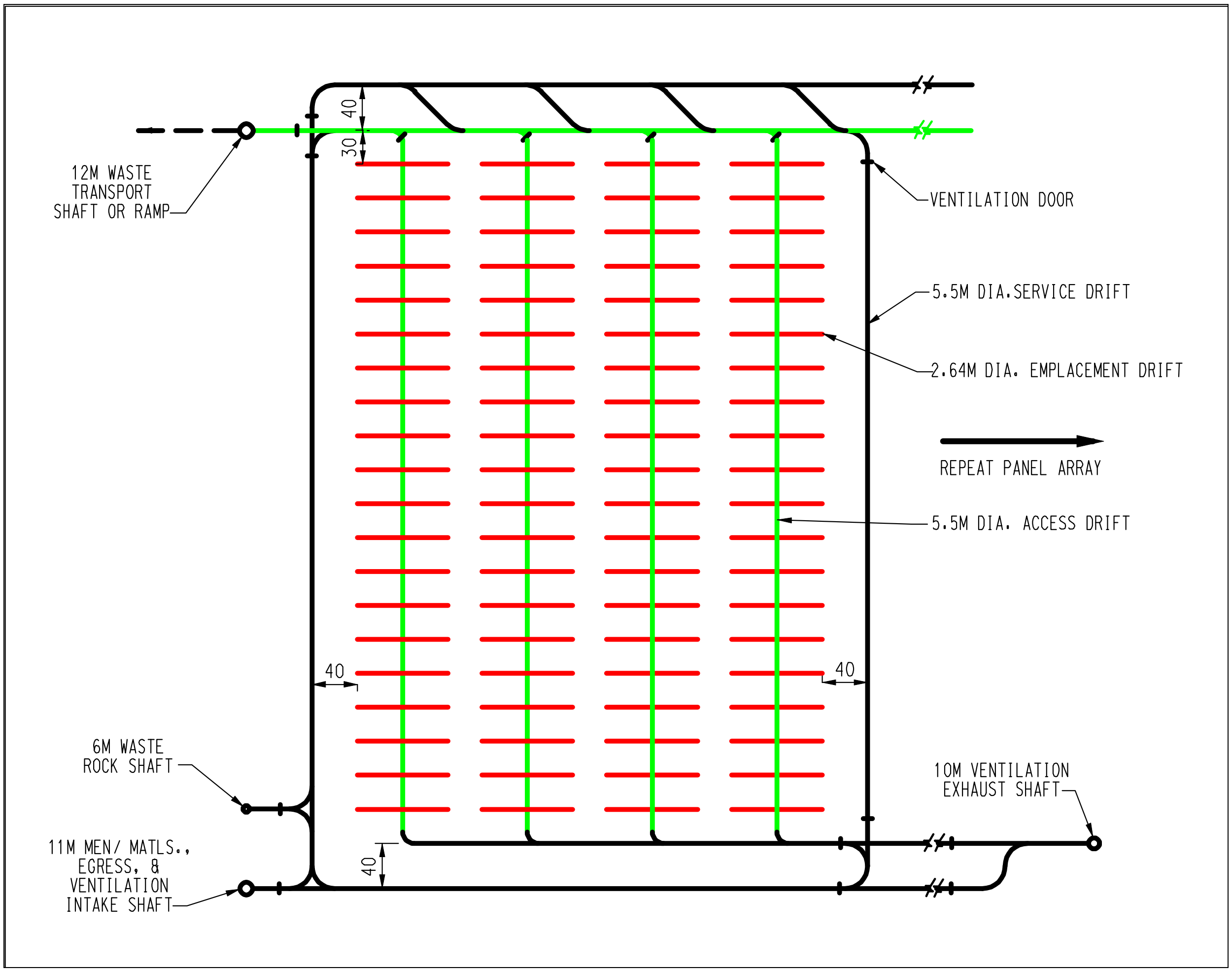

Figure 4.3-1 Clay/Shale (enclosed) Concept Panel Concept Layout

Table 4.3-1 Clay/Shale (enclosed) Concept Drift Panel Detail Summary

Drift/Boring Function	Diameter (m)	Length (m)	Number (per panel)	Total Length (m)	Spacing (m)	Closure
Waste Emplacement	2.64	40	160	6,400	30	Backfilled at emplacement, with prefabricated bentonite clay rings and plugs and concrete shield plug
Access Drifts	5.5	470 630	1 4	2,990	110	Backfilled with conditioned host rock
Service Drifts	5.5	470 710	3 2	2,830	N/A	Backfilled with conditioned host rock
Panel Total				12,220		

Table 4.3-2 Clay/Shale (enclosed) Concept Waste Emplacement Details

Emplacement Mode	PWR/BWR Package Size	Waste Package Spacing (m)	Waste Packages per Emplacement Drift	Waste Packages Per Panel	Waste Package Description
Linear in-drift	4/9	10	4 WP per 40m segment	640	Stainless steel SNF canister in a 5-cm thick carbon steel overpack

4.4 Shale Unbackfilled Open Concept

The unbackfilled, open emplacement mode concept for SNF disposal in shale is similar to the clay/shale (enclosed) mode, but with important differences. In-drift emplacement would be used for potentially much larger waste packages, and forced ventilation would remove heat for decades prior to closure. At closure, emplacement drift segments containing approximately 10 waste packages would be isolated from one another by seals. Low-permeability backfill with swelling properties would be installed in the service and access drifts only. Ventilation would be adjusted during seals installation and backfilling operations to provide a fresh-air, temperature-controlled working environment. Backfilling of cross-drifts would serve to seal off adjacent emplacement drift segments from each other. No backfill would be installed within the drift segments where waste packages are emplaced. As stated previously, backfilling of these emplacement drift segments remains an option until repository closure, if determined to be necessary to assure waste isolation.

A representative panel layout is shown in Figure 4.4-1. Construction details would be similar to the Clay/Shale concept (Section 4.3) with use of shotcrete and concrete floors to limit damage to the host rock. The layout in Figure 4.4-1 is configured for excavation using a tunnel boring machine, although other methods could be used and excavation by roadheader is assumed for estimation. Waste would be transported underground using a dedicated ramp as discussed in Section 4.3. Ramp access is especially appropriate for the larger, hotter SNF waste packages intended for this concept, assuming that ramp construction and eventual sealing in the overlying strata are demonstrated to be feasible. Emplacement drifts would be short (8 segments of 88 m, comprising each 700-m emplacement drift) with drift segments accommodating only a few (approximately 10) waste packages. Waste packages would be configured for 21-PWR or 44-BWR fuel assemblies, the largest waste package envisioned by this study. Forced ventilation would remove 75% of the decay heat away from the host rock. Drift spacing of 60 m would help to limit peak postclosure temperatures as discussed in Section 3.

The repository would require approximately 16 panels of 12 emplacement drifts, requiring a total of approximately 2,000 m^3/sec (at 10 m^3/sec per drift). However, repository development will be protracted over decades, and the airflow demand for each drift diminishes with time as the SNF generates less heat. Assuming a service factor of 50% to reflect thermal decay over time, a total of 1,000 m^3/sec airflow would be needed, which could be met using four large-diameter exhaust shafts. A larger number of smaller intake shafts (approximately 8), together with the waste rock shaft and waste handling ramp, would accommodate this airflow rate. Positioning of the intake shafts focuses airflow toward the exhausts. Ventilation of access drifts not used for primary ventilation, would add only a small airflow.

Ground support and protection of the shale medium from desiccation would be controlled by the liner (nominally shotcrete with steel sets and lagging). This concept is intended for indurated shale formations in which appropriately supported drifts can remain open for decades (the concept would be very challenging in plastic clay). In the access and service drifts, the liner would have sufficient longevity to stabilize the opening throughout the ventilation period and until installation of the backfill, with minimal maintenance. No maintenance or reentry of any kind would be planned in the emplacement drifts; rockfall or even collapse of drift segments would not be expected to significantly impact ventilation or waste isolation performance (subject to confirmation by analysis and testing).

The short segments would remain open and gradually fill with rubble after closure, while isolated from the rest of the repository by engineered backfill. Shield plugs or labyrinths (Appendix F) at both ends of each emplacement drift would be engineered and pre-constructed before waste emplacement to minimize construction activities and worker dose during backfilling operations at closure. For estimation a mixture of 30% bentonite clay and 70% host rock is assumed as a backfill material for the service and access drifts.

Spent fuel waste would be packaged in thin-walled stainless steel canisters, within carbon steel overpacks with 5-cm thickness. Carbon steel is a corrosion allowance material that would provide structural integrity and containment during preclosure ventilation.

Tables 4.4-1 and 4.4-2 present the Shale Unbackfilled open disposal concept drift and waste package details used to develop ROM cost estimates (Section 5).

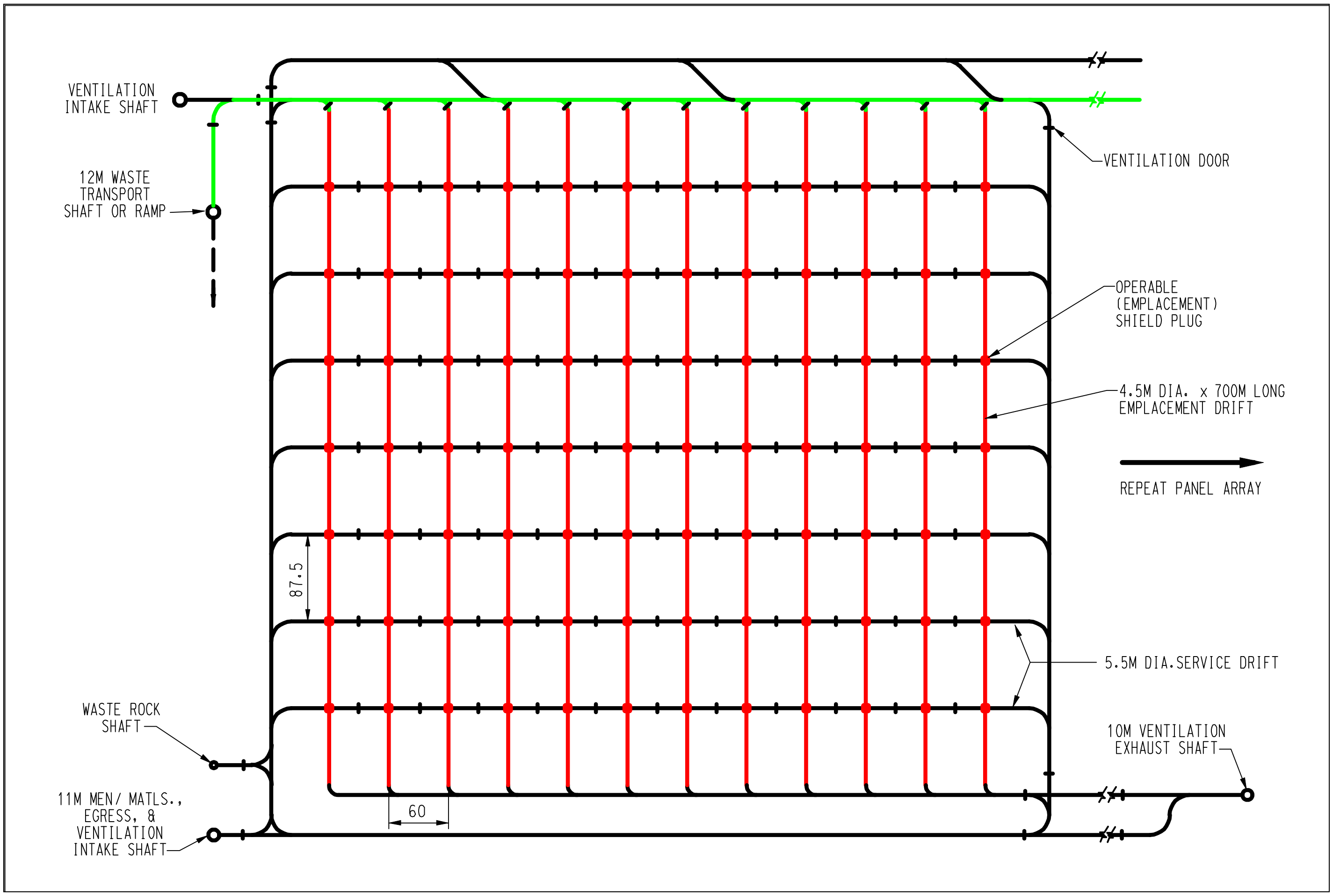

Figure 4.4-1 Shale Unbackfilled Open Concept Repository Panel Layout

Table 4.4-1 Shale Unbackfilled Open Concept Drift Panel Detail Summary

Drift/Boring Function	Diameter (m)	Length (m)	Number (per panel)	Total Length (m)	Spacing (m)	Closure
Waste Emplacement	4.5	700	12	8,400	60	Open, sealed at ends.
Access Drifts	5.5	360 700	4 2	4,520	N/A	Backfilled with conditioned host rock
Service Drifts	5.5	450	7	5,460	N/A	Backfilled with conditioned host rock
Panel Total				18,380		

Table 4.4-2 Shale Unbackfilled Open Concept Waste Emplacement Details

Emplacement Mode	PWR/BWR Package Size	Waste Package Spacing (m)	Waste Packages per Emplacement Drift	Waste Packages Per Panel	Waste Package Description
Linear in-drift	21/44	10	10 WP per 90 m segment; 8 segments per 700-m emplacement drift	960	SNF in a stainless steel canister in a 5 cm thick carbon steel overpack on a pallet suitable for in drift emplacement

4.5 Sedimentary Backfilled Open Concept

For the Sedimentary Backfilled open concept, the repository is assumed to be at a depth of 500 m, however, it could be as shallow as 200 m depending on local stratigraphy and the potential for long-term erosion, glaciation, and other disruptive processes (for example, see Appendix B for a description of alluvium formations). Shallower depth could reduce overburden loads and thereby promote long stand-up times for emplacement openings.

A representative panel layout is provided in Figure 4.5-1 and is similar to the Shale Unbackfilled open concept, which also uses in-drift emplacement. Construction details would be similar to the Clay/Shale concepts (Sections 4.3 and 4.4) with use of shotcrete and concrete floors to limit damage to the host rock. The layout in Figure 4.5-1 is configured for excavation using a tunnel boring machine, although other methods could be used and excavation by roadheader is assumed for estimation. As discussed in Section 1.5.2, ground support would consist of rock bolts and shotcrete, with steel reinforcing elements as needed (DOT/FHA 2009; for indurated sedimentary rock at reasonable depth).

The underground repository would be accessed with vertical shafts, and a ramp for waste handling (facilitated by the relatively shallow repository depth). The layout schematic (Figure 4.5-1) includes short emplacement segments (200 m) to facilitate backfilling, shield plugs to protect workers during backfilling operations, and curved accesses ("turnouts") at the drift ends to enhance shielding for backfilling operations at closure. Each panel would consist of twelve 4-sgement emplacement panels. Waste packages would be on 10 m spacing (center-center). Each segment would contain 15 waste packages or 720 waste packages per panel.

The repository will require approximately 20 panels of 48 emplacement drift segments (each 200 m), requiring a total ventilation airflow of approximately 3,000 m^3/sec (at 3 m^3/sec per drift). However, repository development will be protracted over decades, and the airflow demand for each drift diminishes with time. Assuming a service factor of 50% to reflect thermal decay over time, a total of 1,500 m^3/sec airflow is needed, which can be met using 5 large-diameter exhaust shafts. A larger number (approximately 10) of smaller intake shafts, together with the waste rock shaft and waste handling ramp, will accommodate this airflow rate. Positioning of the intake shafts will focus airflow toward the exhausts. Ventilation of access drifts not used for primary ventilation, will add only a small airflow.

Repository openings would be backfilled before closure, with low permeability backfill material engineered to impose a diffusion dominated, sorptive barrier to radionuclide transport. Ventilation would be adjusted during backfilling operations to provide a fresh air, temperature limited working environment.

SNF would be packaged in thin-walled stainless steel canisters, inside disposal 5-cm thick overpacks made from corrosion allowance or corrosion resistant material depending on chemical transport conditions in the host medium. For oxidizing conditions such as exist in unsaturated, permeable sediments overpacks would be constructed from corrosion resistant materials such as nickel alloys to promote long-term containment integrity. Such packages would be placed on an appropriate pedestal so it is not resting directly on the concrete floor. For reducing conditions, e.g., low-permeability shales containing organic matter and pyrite, overpacks would be made from a corrosion allowance material such as carbon steel. The choice of carbon steel would ensure structural integrity and containment until repository closure, with the possibility of waste retrieval for a reasonable duration. Note that the hydrated, low-permeability clay-based backfill would limit ingress of oxygen and water that support corrosion processes.

Tables 4.5-1 and 4.5-2 present the Sedimentary Backfilled open disposal concept drift and waste package details used to develop ROM cost estimates (Section 5).

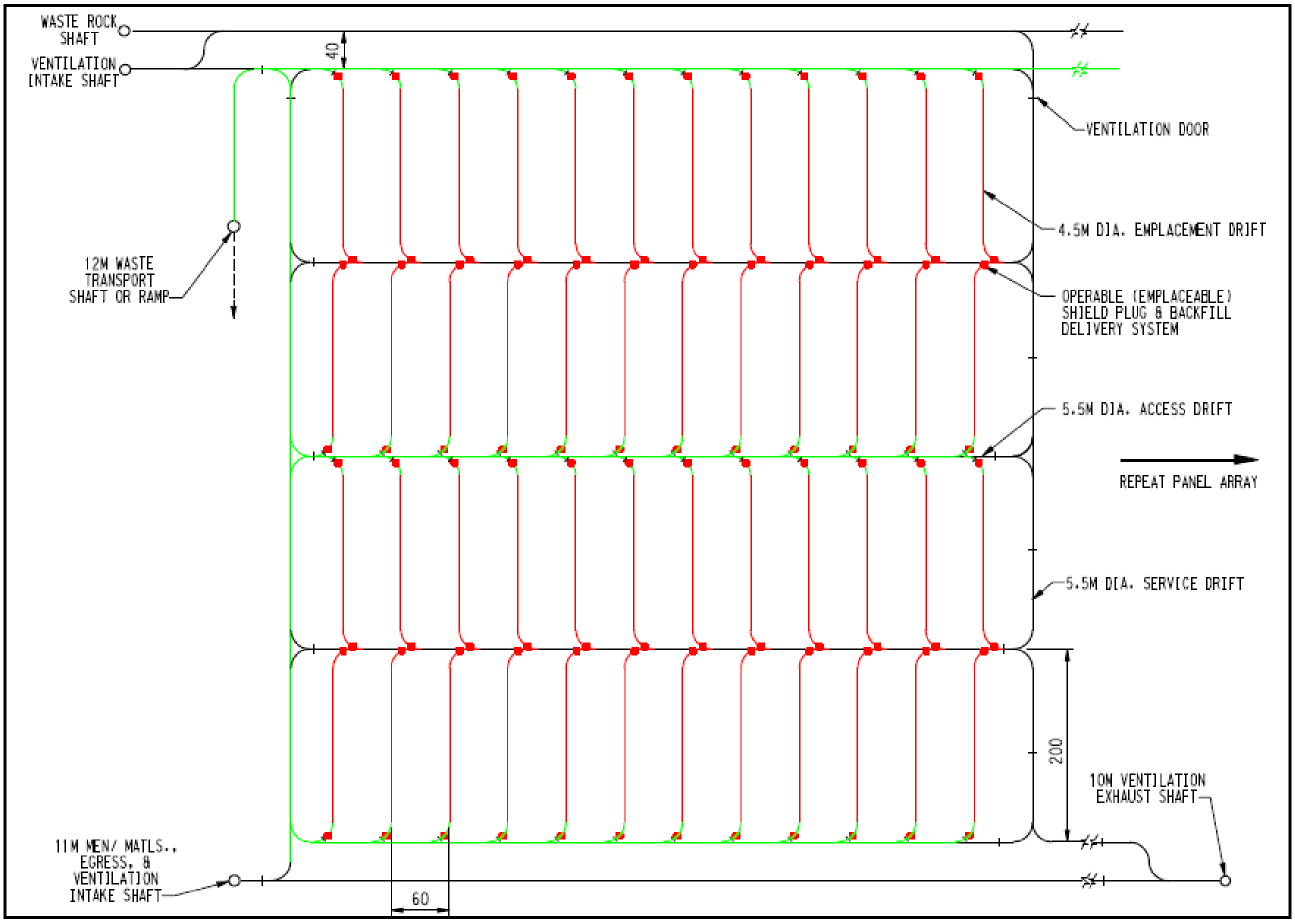

Figure 4.5-1 Sedimentary Backfilled Open Concept Repository Panel Layout

Table 4.5-1 Sedimentary Backfilled Open Concept Drift Panel Detail Summary

Drift/Boring Function	Diameter (m)	Length (m)	Number (per panel)	Total Length (m)	Spacing (m)	Closure
Waste Emplacement	4.5	200	48	9,600	60	Backfilled remotely with mixture of 30% bentonite clay and 70% conditioned host rock
Access Drifts	5.5	410 900	2 2	3,700	N/A	Backfilled remotely with mixture of 30% bentonite clay and 70% conditioned host rock
Service Drifts	5.5	410	5	2,520	200	Backfilled remotely with mixture of 30% bentonite clay and 70% conditioned host rock
Panel Total				15,820		

Table 4.5-2 Sedimentary Backfilled Open Concept Waste Emplacement Details

Emplacement Mode	PWR/BWR Package Size	Waste Package Spacing (m)	Waste Packages per Emplacement Drift	Waste Packages Per Panel	Waste Package Description
Linear in drift	21/44	10	15 WP per 200-m segment	720	SNF in a stainless steel canister in a 5-cm thick carbon steel overpack

4.6 Underground Configurations Summary

A modular approach is used for estimation, that is applicable to repositories with 70,000 MT or 140,000 MT capacity, or to separate repositories. Modularity and phasing of repository development are reasonable and cost effective attributes, and all facilities do not have to be replicated (for example, the waste handling shaft or ramp). For information on disposal costs for HLW, the reader is referred to studies for disposal in salt (Carter et al. 2011, 2012c).

Based on the panel configurations described in Sections 4.1 to 4.5, Table 4.6-1 summarizes the total lineal feet of different drift types, for each disposal concept, on a per-panel basis. The volume of excavation is also calculated. Table 4.6-2 summarizes the number of panels that would be needed to accommodate 140,000 MT of SNF for each disposal concept, taking into concept-specific differences in panel design, waste package capacity, and other aspects. Table 4.6-3 summarizes the total lineal feet of different drift types for each disposal concept (similar to Table 4.6-1) on a per-repository basis. The total excavated drift length varies by more than a factor of 6, from 310,000 m to 1,900,000 m across the five concepts evaluated. The quantities in Tables 4.6-1 through 4.6-3 are used as basic inputs for cost estimation (Section 5).

Table 4.6-4 summarizes the total decay heat per panel and maximum (initial) areal thermal loading as a function of the panel configurations and decay storage time. The thermal loads are based on the waste package configuration proposed for each geologic setting and the bounding decay heat from a 60 GWd/MT PWR fuel assembly as discussed in Section 1.2. Waste emplacement operations have been proposed to begin after decay storage of various durations, based on concept-specific thermal management considerations.

Table 4.6-1 Drift Requirements for Each Panel and Disposal Concept

Dimensions per Panel	Access Drift			Disposal Drift			Service Drift			Panel Total	
	Dia-meter (m)	Length per panel (m)	Volume Per panel (m^3)	Dia-meter (m)	Length per panel (m)	Volume Per panel (m^3)	Dia-meter (m)	Length per panel (m)	Volume Per panel (m^3)	Drift Length Per Panel (m)	Total Volume Per Panel (m^3)
Crystalline (enclosed)	6.5	12,000	398,197	1.66	12,000	25,971	6.5	3,352	111,230	27,352	535,397
Generic Salt Repository (enclosed)	6×9.1	2,577	140,711	3×6	2,832	36,000	6×9.1	1,087	59,354	6,496	236,065
Clay/Shale (enclosed)	5.5	2,990	71,037	2.64	6,400	35,033	5.5	2,830	67,236	12,220	173,306
Shale Unbackfilled (open)	5.5	4,520	129,720	4.5	8,400	133,596	5.5	5,460	129,720	18,380	393,037
Sedimentary Backfilled (open)	5.5	3,700	87,906	4.5	9,600	152,681	5.5	2,520	59,871	15,820	300,458

Table 4.6-2 Panel Requirements for Each Disposal Concept

	Waste Package Configuration (PWR/BWR assemblies)	Waste Packages per Panel	140,000 MT Repository	
			Total Waste Packages	Total Panels
Crystalline (enclosed)	4/9	1,200	82,583	69
Generic Salt Repository (enclosed)	12/24	236	28,792	122
Clay/Shale (enclosed)	4/9	640	82,583	130
Shale Unbackfilled (open)	21/44	960	16,157	17
Sedimentary Backfilled (open)	21/44	720	16,157	23

Table 4.6-3 Mining Requirements for a 140,000 MT Repository for Each Disposal Concept

	Access Drift		Disposal Drift		Service Drift		Repository Total	
	Length (m)	Total Volume (m^3)	Length (m)	Total Volume (m^3)	Length (m)	Total Volume (m^3)	Total Drift Length (m)	Total Volume (m^3)
Crystalline (enclosed)	828,000	2.7E7	828,000	1.8E6	231,288	7.7E6	1.9E6	3.7E7
Generic Salt Repository (enclosed)	314,409	1.7E7	345,504	4.4E6	132,623	7.2E6	7.9E5	2.9E7
Clay/Shale (enclosed)	388,700	9.2E6	832,000	4.6E6	367,900	8.7E6	1.6E6	2.3E7
Shale Unbackfilled (open)	76,840	2.2E6	142,800	2.3E6	92,820	2.2E6	3.1E5	6.7E6
Sedimentary Backfilled (open)	85,100	2.0E6	220,800	3.5E6	57,960	1.4E6	3.6E5	6.9E6

Table 4.6-4 Areal Thermal Density as a Function of Time and Disposal Concept

			Time (years out-of-reactor)			
			30	50	70	100
Decay Heat (watts/MT)			1,458	1,036	773	541
Decay Heat (watts per assembly)			635	451	337	236
			Waste Package Decay Heat (W per WP)			
Crystalline (enclosed)			2,539	1,804	1,346	942
Generic Salt Repository (enclosed)			7,618	5,413	4,039	2,827
Clay/Shale (enclosed)			2,539	1,804	1,346	942
Shale Unbackfilled (open)			13,331	9,473	7,068	4,947
Sedimentary Backfilled (open)			13,331	9,473	7,068	4,947
			Total Panel Decay Heat (W per panel)			
Crystalline (enclosed)			3.0E6	2.2E6	1.6E6	1.1E6
Generic Salt Repository (enclosed)			1.8E6	1.3E6	9,5E5	6.7E5
Clay/Shale (enclosed)			1.6E6	1.2E6	8.6E5	6.0E5
Shale Unbackfilled (open)			12.8E6	9.1E6	6.8E6	4.7E6
Sedimentary Backfilled (open)			9.6E6	6.8E6	5.1E6	3.6E6
	Panel Dimensions					
	Length	**Width**	**Panel Max. Areal Thermal Areal Load (W/m^2)**			
Crystalline (enclosed)	1,100	260	10.7	7.6	5.6	4.0
Generic Salt Repository (enclosed)	227	270	29.3	20.8	15.5	10.9
Clay/Shale (enclosed)	730	470	4.7	3.4	2.5	1.8
Shale Unbackfilled (open)	800	820	19.5	13.9	10.3	7.2
Sedimentary Backfilled (open)	800	780	13.7	9.7	7.2	5.1

4.7 Estimating Surface and Underground Support Facilities

This section describes the surface facilities needed to support each of the five disposal concepts. The greatest factor in determining the scope of surface and underground support facilities is the annual repository emplacement rate (“throughput”). This study selected a throughput rate of 3,000 MT SNF per year; at this rate the assumed 140,000 MT inventory will be emplaced in 47 yr. Table 4.7-1 (similar to Table 2.1-2) summarizes the total and annual waste package counts for the five concepts.

4.7.1 Surface Facility Scope

The surface complex provides the infrastructure to receive inbound waste transportation packages containing sealed SNF canisters, unload the transportation casks, provide interim lag storage of the canisters as needed, transfer the canisters to disposal overpacks, and transfer the loaded SNF waste packages to the shielded repository transfer system for transport underground.

Surface facilities also support repository functions not directly related to waste handling. These facilities include mine shaft and hosting facilities, ramp portals, ventilation fans and filters, waste rock disposal, material storage and handling, and personnel support. Waste package transfer to the underground is by shaft hoist system in two of the concepts and by ramp in heavy wheeled transporters for three (Section 2.3).

Table 4.7-1 Cumulative and Annual Waste Packages for 3,000 MT/yr Throughput

	Waste Package Configuration (PWR/BWR assemblies)	140,000 MT Repository	
		Total Waste Packages	Annual Waste Packages
Crystalline (enclosed)	4/9	82,583	1,757
Generic Salt Repository (enclosed)	12/24	28,792	616
Clay/Shale (enclosed)	4/9	82,583	1,757
Shale Unbackfilled (open)	21/44	16,157	344
Sedimentary Backfilled (open)	21/44	16,157	344

4.7.2 Surface Facilities for Waste Package Handling

SNF waste canisters are thin-walled (nominally 5/8 inch) welded stainless steel containers. They arrive at the repository in Type B shipping/transportation casks from the central storage/repackaging facility, by rail or truck carrier. It is assumed that shipping casks are used to transport SNF canisters one at a time, either with a single cask on a legal-weight truck trailer for the smaller 4-PWR/9-BWR size canisters, or on a rail car for the larger waste ones. For this study, the received SNF waste canisters are assumed to be packaged or re-packaged to the correct size and sealed, prior to transport and receipt at the repository.

Upon arrival, the loaded shipping casks can be stored in a lag storage pad area (LSPA), adjacent to the waste handling building (WHB). The LSPA will have the capacity for up to 6 months of shipments.

Waste Handling Building (WHB)

The WHB includes the remote-handling (RH) elements for receiving waste canisters from offsite and preparing them for disposal in the underground. Remotely operated equipment is used to extract each canister, inspect it, and place it into the disposal overpack. The combined SNF canister/overpack is then placed in the repository transfer system for transfer underground. A more detailed description follows.

Upon arrival at the gate, following receipt inspections, loaded transportation casks are placed in the LSPA or delivered directly to the WHB for unloading, depending on operations priorities. If delivered to the LSPA they are later brought to the WHB for unloading. When left in the staging areas, shipping casks will have their impact limiters removed and will be placed on stand-offs for interim storage.

When ready for unloading, the transport cask and shuttle trailer or railcar are moved into the WHB or temporarily held in the staging area prior to transfer into the WHB. Figure 2.2-6 reflects a WHB RH Complex area associated with receipt and transfer of SNF packages.

The waste handling process begins in the SNF Receipt Bay where the impact limiters are removed from the transport cask if they have not already been removed in the LSPA. The cask is unloaded from the transport vehicle using the SNF Receipt Bay Facility Overhead Bridge Crane and placed on the SNF Transport Cask Transfer Car, where it is moved to an adjacent work stand or cask inspection station. The outer head of the cask is removed and inner bolts are loosened.

The SNF Transport Cask Transfer Car then moves the transport cask to the Cask Unloading Room within the waste receipt transfer facility (WRTF) hot cell.

The inner lid is then removed to provide access to the SNF canister. Using the remotely-operated cranes in the SNF Cask Unloading Room, the canister is pulled from the transport cask, inspected remotely, and placed vertically into the waste disposal overpack (Section 2.1). The disposal overpack is placed horizontally into a SNF Facility Shielded Cask. Once secured in the SNF Facility Shielded Cask, the DHLW Facility Shielded Cask is closed.

When ready for transfer to the underground, the SNF Facility Cask Transfer Car moves the loaded shielded cask from the hot cell and onto the waste hoist conveyance, or to the ramp entrance for transfer underground.

The WRTF described above has a capacity of approximately 550 waste packages per year. This estimate is based on an overall cycle time of about 20 hours total to conduct the steps described above on each SNF canister received. About half of the WRTF operations are performed in the shielded hot cell and the remaining steps are performed in the receipt bay support structure. Therefore a single waste package can be processed in a 10-hour shift. Assuming two 10-hour shifts per day and a 75% utility of the hot cell, 550 waste packages can be processed in a year.

To support annual throughput greater than 550 waste packages per year, the number of hot cells can be increased. The receipt bay support structure can support up to 2 hot cell facilities. The number of receipt bay support structures can be increased as the number of hot cells is further increased.

4.7.3 Underground Access Shafts and Ramps

Shaft construction, diameter, ground support, and facilities are described in Section 2.3 for men-and-materials, ventilation intake, waste rock removal, waste handling, and ventilation exhaust shafts.

A single waste shaft is capable of transferring up to three waste packages per 10-hour shift (or six waste packages per day) to the repository horizon, and a single waste shaft is capable of handling a 3,000 MT per year emplacement rate. Future studies utilizing higher emplacement rates may require additional waste handling shafts.

The design operating life for shafts is 50 years. Shaft liners will be designed to meet the site geological and hydrological conditions. Head frames, hoist houses, and related facilities will be designed to withstand site-related design-basis seismic and weather loadings.

Three disposal concepts use ramps for waste handling instead of shafts. In particular, ramps are used to transport the larger waste packages (e.g., 21-PWR/44-BWR) that are too heavy for existing shaft hoists. Ramps are assumed to be 5.5-m diameter tunnels with 10% slope, with reinforced concrete floor 4 m wide. Heavy rubber-tire vehicles would be used to transport waste packages underground. For scoping ramp and shaft costs, the repository depth is assumed to be 500 m, so the ramps are approximately 5,000 m long. Table 4.7-2 presents shaft and ramp details used for ROM cost estimates (Section 5). Shafts are assumed to be lined with 30 cm of non-reinforced concrete, which assumes rock conditions favorable to long-term stability and minimal water inflow. Thicker concrete, or other lining methods such as reinforced concrete, or steel lining, could be required depending on site conditions. Also, control of water in overlying strata could be addressed by freezing or grouting, and use of impermeable barriers embedded in a concrete liner (for example, see DOE 1987a).

As discussed in Section 2.3, the numbers of shafts needed to dispose of 140,000 MT of SNF vary according to whether ventilation is used to remove heat (open modes), or to maintain drifts available for human access after emplacement (crystalline and shale enclosed modes), or only for construction and emplacement operations (salt). For the open modes, airflow of 15 m^3/sec is sufficient to achieve needed ventilation heat removal efficiency. This rate (15 m^3/sec) is also used for construction (e.g., TBM operation) and for construction and emplacement in salt. For maintaining human access to access drifts in crystalline rock or shale, a much smaller airflow rate is needed.

The largest exhaust shafts are capable of approximately 500,000 cfm (250 m^3/sec), and can therefore serve approximately 16 open emplacement drifts, or several hundred drifts in the crystalline and shale concepts. For the salt concept construction, emplacement, and backfilling operations proceed together so the ventilation requirement is minimal, and most capacity will be used for access drifts. Table 4.7-3 summarizes the numbers of shafts needed for each concept to accommodate 140,000 MT of SNF.

Table 4.7-2 Shaft and Ramp Support Details

Shaft/Ramp Type	Construction Type	Ground Support	Finished Diameter (m)
Men-and-Materials, or Ventilation Intake	Raise bore or drill-and-blast	Cast in place concrete (non-reinforced)	5
Ventilation Exhaust	Drill-and-blast	Cast in place concrete (non-reinforced)	8
Waste Rock Removal	Raise bore	Cast in place concrete (non-reinforced)	5
Waste Emplacement	Drill-and-blast	Cast in place concrete (non-reinforced)	8
Waste Emplacement	10% ramp, mechanized excavator	Shotcrete, with rock bolts and/or steel sets and lagging as needed. Ramp floors are reinforced concrete approximately 4 m wide	5.5

Table 4.7-3 Shaft and Ramp Numbers for Each Concept

	Air Intake	Rock Waste	Ventilation Exhaust	Waste Emplacement	
				Shafts	Ramps
Crystalline (enclosed)	1	1	2	1	0
Generic Salt Repository (enclosed)	1	1	2	1	0
Clay/Shale (enclosed)	1	1	2	0	1
Shale Unbackfilled (open)	8	1	4	0	1
Sedimentary Backfilled (open)	10	1	5	0	1

4.7.4 Balance of Surface Facilities

The following list summarizes the balance of the surface facilities required:

- Shaft/Ramp Support – Structures and facilities (hoist buildings, power transmission, headframes, etc.) to serve the shafts and ramps discussed in Section 4.7.3
- Lag Storage Pad Area – Provide storage for up to six months SNF throughput
- Waste Receipt Support Facility – provides facility waste handling support staff office, locker room, break areas, showers and meeting space.
- Waste Handling Maintenance Building – Inspection and maintenance of waste handling equipment, casks and seals etc.
- Contaminated Equipment Maintenance Facility – Maintenance of contaminated or potentially contaminated equipment
- Entry Control Facilities and Gatehouse – Control physical access to the site
- Guard and Security Building – House the facility security personnel, and communications equipment necessary for them to perform their duties; auditorium and cafeteria
- Central Control Facility – Centralized communication and site-wide monitoring and control systems, central alarm system, and data acquisition
- Central Engineering and Administration – Administrative staff, engineering support staff, training, quality assurance, procurement, and records
- Warehouses and Central Receiving – Central receiving and warehousing for all non-waste materials, consumables, bulk materials, engineered/procured items, overpacks, chemicals, and geologic samples
- Telephone and Communications Buildings – Interface with landlines and cellular and microwave towers
- Central Maintenance and Craft Shops – Primary maintenance services
- Equipment and Materials Storage Yards – Outdoor laydown areas for materials not requiring environmental control
- Emergency and Standby Diesel Generators
- Compressor Building – Compressed air for surface and underground equipment
- Chilled Water Services and Cooling Tower – Support facility heating, ventilation, and air conditioning (HVAC) and other needs
- Railroad Operations Facility – Central rail operations facility control for the WRTF
- Rail Staging Area – Central rail yard local to the WRTF, for staging inbound and outbound rail carriers
- Truck Staging Area – Manage trucks and empty casks being sent back to generator sites
- Vehicle Maintenance and Motor Pool
- Heavy Equipment Maintenance Facility

- Electrical Utility System – Includes normal and backup power, switchgear, transmission, lighting, grounding, lightning protection
- Fuel and Diesel Oil Storage and Fueling Station – Store and dispense gasoline and diesel for vehicles both at the surface and underground, and standby generators
- Oil and Grease Storage – Store fresh oil and grease for onsite use
- Compressed Gas Bottle Storage – Specialty storage area for compressed bottled gases
- Hazardous Materials Storage Area – Bulk quantities of unused chemicals and other materials considered hazardous
- Water Treatment Facility – Process effluent from oil/water separators, and other activities
- Evaporation Ponds – Manage non-hazardous water collected from underground, the ventilation system, groundwater sampling, and other non-specific waters
- Stormwater Retention/Detention Ponds – Capture runoff from paved areas and roofs to allow sampling prior to discharge
- Firewater Facility – Storage of sufficient water to fight/extinguish facility fires
- Sanitary Waste Treatment Facility – Treatment facility and associated effluent ponds
- Waste Rock Storage – Approximately 250 acres to store mined rock in piles up to 20 feet high, with impermeable liner and attached runoff evaporation ponds
- Topsoil Storage Area – Retain topsoil removed during site development to be used for reclamation
- Meteorological Station – Onsite meteorological data collection for environmental compliance
- Repository Performance Demonstration Facility – House the personnel and equipment for a performance confirmation program
- LLW Facility – Manage small amounts of LLW generated by the repository activities, to be disposed of at an approved offsite LLW facility
- Sample Management Facility – Store geologic and environmental samples under controlled conditions
- Safety, Emergency Response & Medical Building – Surface emergency response vehicles (fire truck, rescue truck, ambulance), health services (first aid), emergency response center, industrial safety, environmental monitoring, and radiological protection
- Fire Protection System
- Miscellaneous – Fencing, landscaping, concrete and gravel staging areas, temporary structures, visitor center

These additional elements are included in cost estimates described in the next section.

5. Cost Estimation

This section provides an evaluation of cost factors for the five disposal concepts described in Section 4. This information is provided to show how design features and thermal management strategies affect relative costs. Application of these cost results beyond this purpose should be avoided for several reasons: 1) simplifying assumptions are used in this evaluation and in describing the alternative disposal concepts; 2) key factors such as siting, characterization, and licensing for repository facilities are not included; 3) "upstream" waste management costs such as storage, canisterization, and transportation are not included; and 4) costs associated with delay in the waste management program, which are potentially greater for some concepts than others, are not included.

Results Summary

Estimates for design, construction start-up, operations, closure and monitoring costs (lumped together as the DCSOCMC) are determined using four schedule phases (Carter et al. 2012b). Table 5-1 summarizes the design, construction, start-up, operations, closure and monitoring cost (DCSOCMC) range for each of the five disposal concepts, for 140,000 MT of commercial SNF. The assumption of 140,000 MT repository capacity, and the modularity of cost estimates, are discussed in Sections 1 and 4.6, respectively. Estimates for DCSOCMC do not include activities associated with site selection or characterization, at-reactor packaging, centralized storage (if adopted), re-packaging to meet disposal requirements, and waste transport to the repository.

The results summary shows that the cost of a repository for permanent disposal of 140,000 MT of SNF ranges from (approximately) $24 B to $81 B in 2012 dollars, including the range of low to high contingency discussed below. The lowest cost estimates are for the Generic Salt Repository and the Shale Unbackfilled concepts, and the highest are for the Crystalline and Clay/Shale enclosed concepts.

The range (about a factor of 3) reflects many factors, notably the differences in numbers of waste packages, which range from approximately 16,000 to 83,000 (a factor of 5). Mining costs vary by a factor of 6 based on the extent of tunneling required (Table 4.6-3). These examples are lumped with other costs in the Operations & Maintenance category (Table 5-1).

The range in DCSOCMC reflects different strategies for relying on engineered and natural barriers (i.e., natural barriers cost less). A geologic setting in relatively poor quality shale (e.g., indurated, with fracture permeability) is better suited technically to an enclosed emplacement concept with additional engineered barrier elements; and the Clay/Shale (enclosed) reference concept uses short (40 m) horizontal emplacement borings, small waste packages, and multiple engineered barriers (buffer, plugs, and seals). By contrast, the Shale Unbackfilled concept is intended for a higher quality, relatively unfractured lithology. It can accept larger waste packages and does not require backfill in the emplacement drifts (although backfilling remains an option until repository closure).

The costs and schedules for all cases were developed using the collective experience of the task team. They used the same durations developed in two previous salt repository studies (Carter et al. 2011, 2012c) for the conceptual design, preliminary design, final design, construction, and start-up periods. The operational or waste emplacement phase of 47 years is determined by the waste inventory (140,000 MT) and the assumed waste emplacement rate of 3,000 MT per year.

Schedules presented in this section do not reflect the activities that are not included in the estimates as discussed above.

Table 5-1 Summary of Costs for Design, Construction, Start-up, Operations, Closure and Monitoring for a 140,000 MT SNF Repository

Costs in $Millions	Crystalline (enclosed)		Generic Salt Repository (enclosed)		Clay/Shale (enclosed)		Shale Unbackfilled (open)		Sedimentary Backfilled (open)	
Element	**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**	**Low Range**	**High Range**
Facility Design, Construction, Startup	3,754	5,495	3,896	5,595	6,872	10,064	3,303	4,711	5,410	7,599
Operations & Maintenance	17,545	22,475	7,947	10,259	26,884	34,525	9,702	12,408	9,614	12,264
Closure	9,563	13,704	832	1,363	5,556	8,334	1,622	2,515	2,263	3,558
Waste Packages	17,489	21,647	3,998	4,950	7,542	9,337	2,882	3,569	2,882	3,569
Regulatory & Licensing	424	441	368	379	414	429	417	421	668	679
Monitoring	10,685	14,571	4,580	6,246	9,021	12,302	3,395	4,629	3,775	5,148
Performance Confirmation	411	561	567	773	758	1,034	423	576	798	1,088
Program Integration	1,575	2,142	2,136	2,907	2,914	3,965	3,732	5,084	6,878	9,370
DCSOCMC	**$61,450**	**$81,040**	**$24,330**	**$32,480**	**$59,970**	**$79,990**	**$25,480**	**$33,920**	**$32,290**	**$43,280**
DCSOCMC in $ per kg SNF	**$439**	**$579**	**$174**	**$232**	**$428**	**$571**	**$182**	**$242**	**$231**	**$309**

The team also used the same cost estimate models developed for the prior salt repository studies (Carter et al. 2011, 2012c) which in turn were based on a previous study (DOE 2008c). The mining estimate was significantly improved with the addition of new unit cost data for mining in clay/shale, sedimentary and crystalline rock. Unit costs were also developed for backfilling with host rock or a mixture of host rock and bentonite clay (Section 5.2.2).

Comparison to Previous Cost Estimates

A survey of cost estimates for international programs was compiled by Nutt (2009). Some of the data reported are presented in Table 5-2, for comparison to the reference disposal concepts developed here (Table 5-1). The estimates in Table 5-2 are expressed in either 2009 or 2012 dollars (differing by approximately 10% due to escalation, which is well within the accuracy of the estimates). 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.

For the Deep Borehole disposal concept Brady et al. (2009) produced a rough estimate of $71B (2007 dollars) for disposal of 109,000 MT of commercial SNF. Escalating by 10% and dividing by the inventory, yields an equivalent cost of $715/kg. In addition, the cost for drilling a single deep borehole was updated from $20M to $40M by Arnold et al. (2011), which could represent a significant increase in cost for deep borehole disposal.

Table 5-2 Unit SNF Disposal Cost Comparison with International Estimates (Nutt 2009)

Estimate	Disposal Capacity (MTHM)	Cost Normalized to Mass ($/kg)	References (Note 1)
United States			
Crystalline (enclosed)	140,000	464 to 609	Presented in this report
Generic Salt Repository (SNF, enclosed)	140,000	176 to 236	
Clay/Shale (enclosed)	140,000	439 to 584	
Shale Unbackfilled (open)	140,000	184 to 245	
Sedimentary Backfilled (open)	140,000	233 to 312	
Hard Rock Unsaturated (open)	109,300	450 to 550	DOE 2008c (Note 2)
NEA	N/A	340 to 675	NEA 2003 (Note 2)
Canada	96,000	140	IAEA 2002 (Note 2)
Belgium (2000 estimate)	4,900	361	ONDRAF/NIRAS 2000 (Note 2)
Czech Republic	3,724	437	IAEA 2002 (Note 2)
Finland (2007 estimate)	5,600	800	www.posiva.fi (Note 2)
Hungary	1,320	984	IAEA 2002 (Note 2)
Sweden	9,740	350	SKB 2003 (Note 2)

Notes:
1. Values shown were reported by Nutt (2009) based on the references in this column.
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 may be only roughly comparable to values developed in this study.

Contingency

Contingency was estimated using engineering judgment and some general guidelines (Table 5-3). These guidelines were evaluated for each element of the cost estimate and adjusted as appropriate for the range of uncertainty as determined by the study authors. Application of the contingency estimates generated the high and low ranges of the DCSOCMC estimates.

Table 5-3 DCSOCMC Estimate Contingency Guidelines (%)

Facility	Contingency (Scope/pricing uncertainty)		Technical Risk (T&PRA) (Process/equipment uncertainty)		Total Contingency (%)	
	Low	High	Low	High	Low	High
Infrastructure & Balance of Plant						
Similar facilities/estimates model	5	30	0	0	5	30
R.S. Means	5	30	0	0	5	30
Uncertainties in size/layout/conditions:	5 to 20	50	0	0	5 to 20	50
Site Infrastructure actual average:			0	0		
Process Facilities/Buildings, Waste Packages						
First-of-a-kind, hardened/shielded/high-rad	20	50	0	25	20	75
Nth-of-a-kind, hardened/shielded/high-rad	10	40	0	0	10	40
Nth-of-a-kind, low rad	5	30	0	0	5	30
Other Processes						
Mining	5	30	30	70	35	100

Schedule Range

The schedule was developed for four major phases: 1) design and construction (which includes conceptual, preliminary, and final design, construction and start-up activities), 2) operations, 3) closure and 4) postclosure monitoring (Carter et al. 2012b). The schedule was developed as a point estimate for a generic location, and the team applied uncertainty based on engineering judgment, resulting in the schedule ranges presented in Table 5-4. A duration of 15 to 25 yr is estimated for design and construction activities following siting and site characterization.

Table 5-4 Repository Schedule Estimates

Phase	Duration Range (yr)
Design and Construction:	
Conceptual Design	3 to 9
Preliminary Design	1.5 to 2
Final Design	4 to 5.5
Construction and Start-up	6.5 to 8
Total Design and Construction	15 to 24.5
Operations	47
Ventilation (concept dependent)	0 to 100
Closure	9 to 12
Post Closure Monitoring	50 to 75

5.1 Facilities Design and Construction Cost

A summary of the facilities design and construction cost for the surface and sub-surface facilities for the five SNF disposal concepts considered in this study is presented in Table 5.1-1. The surface facilities are described in Section 2.2.

The facilities design and construction cost was estimated by developing a facilities list that includes a description and size of the building. The surface facilities are similar to those developed for a Generic Salt Repository for the disposition of HLW from reprocessing (Carter et al. 2011) with respect to base facility sizes and costs. For each facility the anticipated hazard category was used to select a cost model for the individual structures. The cost model derives from recent Follow-on Engineering Alternatives Studies estimates for the recycling facility. Table 5.1-2 provides this base facility size and cost.

Table 5.1-2 also extends the base facility to the five disposal concepts, or "cases" for study, based on the differences in annual waste package capacity required (shaded light blue) or the number of access shafts (shaded in light green). The "Case" columns in Table 5.1-2 provide the scaling factor used for each surface facility to establish the point estimate for each case. Low and high contingencies were assessed for each facility based on their complexity and relative degree of uncertainty.

Table 5.1-1 Facilities Design and Construction Costs for Disposal Concepts

Costs in $Millions (2012)	Crystalline (enclosed)		Generic Salt Repository (enclosed)		Clay/Shale (enclosed)		Shale Unbackfilled (open)		Sedimentary Backfilled (open)	
	Low Range	High Range	Low Range	High Range	Low Range	High Range	Low Range	High Range	Low Range	High Range
Major Surface Facilities	693	875	1,258	1,592	1,761	2,233	693	875	1,823	2,310
Balance of Plant and Support Surface Facilities	498	617	503	624	503	624	623	772	698	865
Subsurface Facilities	19,098	29,434	7,071	10,931	37,467	57,750	4,074	6,296	4,394	6,828
Major Equipment	96	96	96	96	200	200	52	52	125	125
Total Facilities Construction Cost	**20,384**	**31,021**	**8,929**	**13,243**	**39,932**	**60,806**	**5,442**	**7,995**	**7,041**	**10,127**

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Table 5.1-2 Surface Facility Base Size, Base Cost and Scaling Factor

ID	Facility	Base Size						Base Cost				Case				
		Base Footprint	UOM	Total Size	UOM	Other Size	UOM	Unit Cost	per UOM	Total Cost		1	2	3	4	5
SF102-RH	102-RH	36500	SF	53050	SF			$ 6,174	per SF	$ 344,900	-	1	2	3	1	3
SF102HC	102HC	18225	SF	14100	SF			$ 6,174	per SF	$ 112,600	-	1	2	3	1	3
SF102-CH	CH Receipt & Transfer Facility {102-CH}	42840	SF	42840	SF			$ 2,818	per SF	$ 129,800	-	0	0	0	0	0
SF109	109 - Rail Staging	38500	SF	38500	SF			$ 99	per SF	$ 3,900	-	0.5	1	1	0.5	1.5
SF110	110 - Truck Staging	22500	SF	22500	SF			$ 99	per SF	$ 2,300	-	0.5	1	1	0.5	1.5
SF600	Low Level Waste (LLW) Facility {600}	2000	SF	2000	SF			$ 206	per SF	$ 500	-	0.5	1	1	0.5	1.5
SF700A	Central Control Facility { 700A}	8100	SF	12500	SF			$ 485	per SF	$ 6,100	-	1	1	1	1	1
SF107	Waste Handling Maintenance Bldg 107	20000	SF	28000	SF			$ 2,818	per SF	$ 79,000	-	0.5	1	1	0.5	1.5
SF108	Cont. Equipment Maintenance Facility 108	2500	SF	2500	SF			$ 2,818	per SF	$ 7,100	-	0.5	1	1	0.5	1.5
SF1005	Heavy Equipment Maintenance Facility {10	22500	SF	22500	SF			$ 250	per SF	$ 5,700	-	0.5	1	1	0.5	1.5
SF1000	Warehouse & Central Receiving {1000}	12800	SF	12800	SF			$ 206	per SF	$ 2,700	-	1	1	1	1	1
SF500	Analytical Support Facility {500}	16000	SF	32000	SF			$ 587	per SF	$ 18,800	-	0.5	1	1	0.5	1.5
SF816	Emergency Diesel Generator Facility { 81	5000	SF	5000	SF			$ 4,495	per SF	$ 112,400	-	1	1	1	1	1
SF74	Cask Transportation Pkg Lag Storage Area	150	EA	150	EA	8.25	AC	$ 1,400	per EA/AC	$ 1,000	-	0.5	1	1	0.5	1.5
SF802	Compressor Building {802}	2500	SF	2500	SF			$ 172	per SF	$ 500	-	1	1	1	1	1
SF803	Chilled Water Services and Cooling Tower	7000	SF	7000	SF	2950	LF	$ 1,803	per SF	$ 13,200	-	1	1	1	1	1
SF809	Evaporation Pond(s) {809}	61650	SF	61650	SF			$ 6	per SF	$ 400	-	1	1	1	1	1
SF810	Standby Diesel Generator Facility { 810	3750	SF	3750	SF			$ 785	per SF	$ 3,000	-	1	1	1	1	1
SF1004	Fuel & Diesel Oil Storage and Fueling St	14000	SF	14000	SF			$ 1,002	per SF	$ 14,100	-	1	1	1	1	1
SF812	Switchyard (Offsite power) {812}	70000	SF	70000	SF			$ 364	per SF	$ 25,500	-	1	1	1	1	1
SF813	Offsite Power Switchgear Facility {813}	15500	SF	15500	SF	31000	LF	$ 785	per SF	$ 26,800	-	1	1	1	1	1
SF815	Fire Water Facility {815-E and 815-W}	3150	SF	3150	SF	7320	LF	$ 3,069	per SF	$ 24,000	-	1	1	1	1	1
SF700B	Central Security Station {700B}	3050	SF	3050	SF			$ 8,207	per SF	$ 25,100	-	1	1	1	1	1
SF705	Package Receipt Security Station {705}	3750	SF	3750	SF			$ 539	per SF	$ 2,100	-	0.5	1	1	0.5	1.5
SF808	Stormwater Retention Pond {808}	27500	SF	27500	SF	7000	LF	$ 6	per SF	$ 800	-	1	1	1	1	1
SF1001	Central Maintenance and Craft Shops {100	10000	SF	10000	SF			$ 417	per SF	$ 4,200	-	0.5	1	1	0.5	1.5
SF202	Exhaust filter building {202}	13500	SF	13500	SF			$ 4,400	per SF	$ 59,400	-	2	2	2	4	5
SF817	Generic and Excavated Rock Tailings Sur	2178000	SF	2178000	SF	50	AC	$ 6	per SF	$ 13,100	-	0.823529412	0.823529412	0.823529412	0.823529412	0.823529412
SF701	Emergency Response & Medical {701} (3 l	10000	SF	30000	SF			$ 461	per SF	$ 13,900	-	1	1	1	1	1
SF703	Entry Control Facilities {703}	1250	SF	1250	SF			$ 539	per SF	$ 700	-	1	1	1	1	1
SF704	Gate House {704}	5000	SF	5000	SF			$ 135	per SF	$ 1,400	-	1	1	1	1	1
SF1003	Equipment and Materials/Yard Storage {1	15000	SF	15000	SF			$ 4	per SF	$ 100	-	1	1	1	1	1
SF900	Central Engineering and Administration F	50000	SF	100000	SF			$ 181	per SF	$ 18,100	-	1	1	1	1	1
SF1006	Vehicle Maintenance & Motor Pool {1006}	12800	SF	12800	SF			$ 417	per SF	$ 5,400	-	1	1	1	1	1
SF	Parking	219001	SF	219001	SF			$ 9	per SF	$ 2,000	-	1	1	1	1	1
SF	Paved Roads	N/A	SF	N/A	SF	53948.444	SY	$ 56	per SY	$ 3,030	-	1.6666	1.6666	1.6666	1.6666	1.6666
SF	Gravel Roads	N/A	SF	N/A	SF	81724	SY	$ 13	per SY	$ 1,070	-	1	1	1	1	1
SF	Railroads	N/A	SF	N/A	SF	14798	LF	$ 335	per LF	$ 4,960	-	0.5	1	1	0.5	1.5
SF804	Potable and non-potable water systems {	10000	SF	10000	SF	5115	LF	$ 1,158	per SF	$ 13,100	-	1	1	1	1	1
SF805	Sanitary Waste Treatment {805}	30100	SF	30100	SF	5000	LF	$ 380	per SF	$ 13,830	-	1	1	1	1	1
SF806	Grey Water Pond 1 {806}	13240	SF	13240	SF	250	LF	$ 5	per SF	$ 140	-	1	1	1	1	1
SF807	Grey Water Pond 2 {807}	17912	SF	17912	SF	250	LF	$ 5	per SF	$ 170	-	1	1	1	1	1
SF503	Sample Management Facility {503}	10000	SF	10000	SF			$ 206	per SF	$ 2,100	-	1	1	1	1	1
SF504	Repository Performance Confirmation Faci	15000	SF	15000	SF			$ 587	per SF	$ 8,900	-	1	1	1	1	1
SF1008	Rail Operations Facility {1008}	25000	SF	25000	SF			$ 604	per SF	$ 15,100	-	1	1	1	1	1
SF401	Ai r Intake Shaft Hoist Building {401}	1600	SF	1600	SF			$ 99	per SF	$ 200	-	1	1	1	1	1
SF402	Ai r Intake Shaft Winch Building {402}	800	SF	800	SF			$ 99	per SF	$ 100	-	1	1	1	1	1
SF105	Auxiliary Air Intake {105}	1000	SF	1000	SF	1	EA	$ 99	per EA	$ 100	-	1	1	1	1	1
SF301	Rock Handling Shaft Hoist Building {301	4500	SF	4500	SF			$ 99	per SF	$ 500	-	1	1	1	1	1
SF303	Rock Handling Shaft Operations {303}	1000	SF	1000	SF			$ 266	per SF	$ 300	-	1	1	1	1	1
SF203	Exhaust Shafts Monitoring Stations {203}	N/A	SF	N/A	SF	1	EA	$334,300	per EA	$ 400	-	2	2	2	4	5
SF403	Air Intake Shaft Head Frame {403}	1900	SF	1900	SF	1	EA	$ 99	per EA	$ 200	-	1	1	1	1	1
SF302	Rock Shaft Head Frame {302}	1900	SF	1900	SF	1	EA	$ 99	per EA	$ 200	-	1	1	1	1	1
SF811	Telephone & Communications Interface {811}	3750	SF	3750	SF			$ 160	per SF	$ 750	-	1	1	1	1	1
SF	Running Track	29145	SF	29145	SF			$ 44	per SF	$ 1,280	-	1	1	1	1	1
SF1009	Oil & Grease Storage Bldg. {1009}	1250	SF	1250	SF			$ 124	per SF	$ 200	-	1	1	1	1	1
SF1010	Compressed Gas bottle Storage Bldg. {1010}	5000	SF	5000	SF			$ 178	per SF	$ 900	-	1	1	1	1	1
SF1002	Tailings Vehicle Shelter {1002}	12000	SF	12000	SF			$ 99	per SF	$ 1,200	-	1	1	1	1	1
SF581	Meterological Stations {581}	1500	SF	1500	SF			$ 160	per EA	$ 320	-	1	1	1	1	1
SF505	Waste Receipt Support Facility {505}	22750	SF	22750	SF			$ 266	per SF	$ 6,100	-	1	1	1	1	1
SF908	Visitor Center {908}	8000	SF	8000	SF			$ 138	per SF	$ 1,100	-	1	1	1	1	1
SF1015	Recyclables Yard {1015}	10000	SF	10000	SF			$ 4	per SF	$ 100	-	1	1	1	1	1
SF820	Topsoil Stockpile {Area 820}	161200	SF	161200	SF	3.7	AC	$ 1	per SF	$ 300	-	1	1	1	1	1
SF63	Site Clearing and Grading	4225400	SF	4225400	SF	97	AC	$ 1	per SF	$ 5,600	-	1	1	1	1	1
SF64	Security Fence	N/A	SF	N/A	SF	17135	LF	$ 52	per LF	$ 900	-	1.25	1.25	1.25	1.25	1.25
SF65	Landscaping (including sidewalks	N/A	SF	N/A	SF	41104.411	SY	$ 54	per SY	$ 2,340	-	1	1	1	1	1
SF66	Construction Temporary Facilities	150000	SF	150000	SF			$ 206	per SF	$ 30,900	-	1	1	1	1	1
SF67	Substations (QTY)	5000	SF	5000	SF			$ 785	per SF	$ 15,700	-	1	1	1	1	1
SF68	Hazardous Waste Staging Facility (601)	1250	SF	1250	SF			$ 124	per SF	$ 200	-	1	1	1	1	1
SF69	Hazardous Material Storage Facility (101	2500	SF	2500	SF			$ 143	per SF	$ 400	-	1	1	1	1	1
SF70	Rock Water Evaporation Pond	57500	SF	57500	SF			$ 6	per SF	$ 400	-	0	0	0	0	0
SF71	Misc Equipment	N/A	SF	N/A	SF	525	EA	$ 60,080	per EA	$ 31,600	-	1	1	1	1	1
SF72	Concrete Staging Area	240000	SF	240000	SF			$ 56	per SY	$ 1,500	-	1	1	1	1	1
SF73	Gravel Staging Area	105000	SF	105000	SF			$ 13	per SY	$ 200	-	1	1	1	1	1

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Mining Estimate

FERMILAB Tunnels Cost Estimate Models developed in 2001 were utilized for developing parametric quantities and costs for portions of the current Generic Repository Estimates. The Cost Models were used in conjunction with industry standard rock classification guidelines for determining quality of rock and modified to account for the dimensions and equipment needed for the generic repository. Using DOE Escalation data, the 2001 FERMILAB Tunnels Cost Estimate Models were escalated to bring the cost current as of 2012. From there a current unit cost was developed per unit length.

The cost per linear foot for construction of the access, service and emplacement drifts is developed in Appendix G (Tables G-1 to G-6). Table 5.1-3 summarizes mining costs on a lineal foot basis. Table 5.1-4 summarizes the costs of backfill operations at closure.

Table 5.1-3 Access, Service and Emplacement Drift Unit Cost

	Crystalline (enclosed)	Generic Salt (enclosed)	Clay/Shale (enclosed)	Shale Unbackfilled Open	Sedimentary Backfilled Open
Service, Access and Emplacement Drifts ($ per lineal foot) [A]	2,353	2,043	2,384	2,540	2,384
Steel Lined Shale Emplacement Drift ($ per lineal foot)			8,308		

[A] For the clay/shale (enclosed) mode this unit cost does not include emplacement drifts, which are tabulated in the next row.

Table 5.1-4 Repository Backfill Unit Costs

	Unit Cost ($/Cubic Yard)
Backfilling Operations with 30/70 Bentonite/Crushed Rock	150
Backfilling Operations Mine Muck Only	111

5.2 Operations and Maintenance Cost

Operations and maintenance cost are provided for each disposal concept in Table 5.2-1. Annual O&M costs are presented in Figures 5.2-1 to 5.2-5, illustrating the cash flow requirements. The schedule input to this calculation is discussed above. The annual O&M cost ranges from about $150 million to $800 million per year. The O&M costs were developed based on the full time equivalent (FTE) employees necessary to support on-going mining and waste emplacement operations. Manpower estimates reflect the extent of mining from Table 4.6-3 and the number of waste disposal packages in Table 4-1. Further projections of overall manpower and annual staffing levels are provided by Carter et al. (2012b).

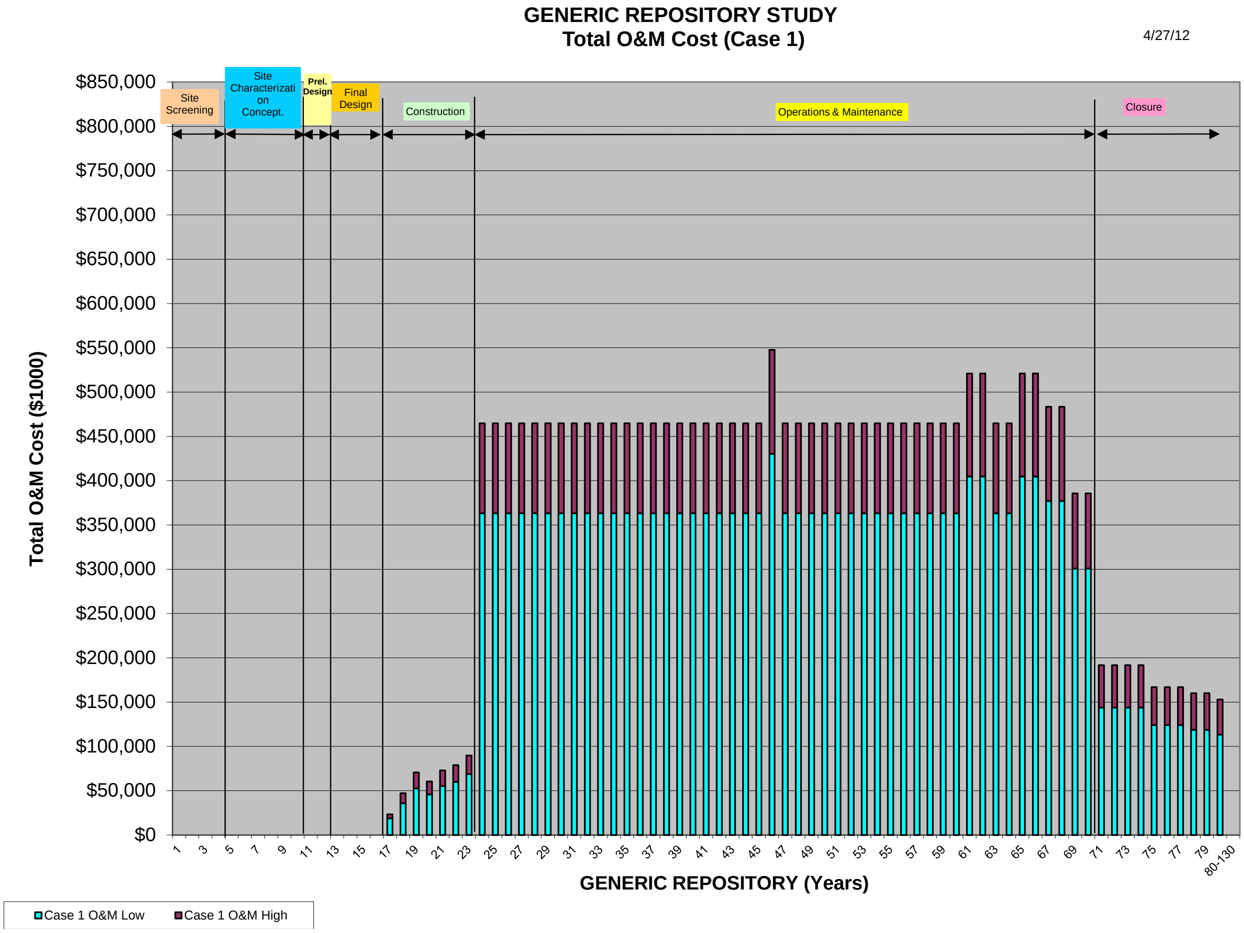

Figure 5.2-1 Annual O&M Costs for the Crystalline (enclosed) Concept (Case 1)

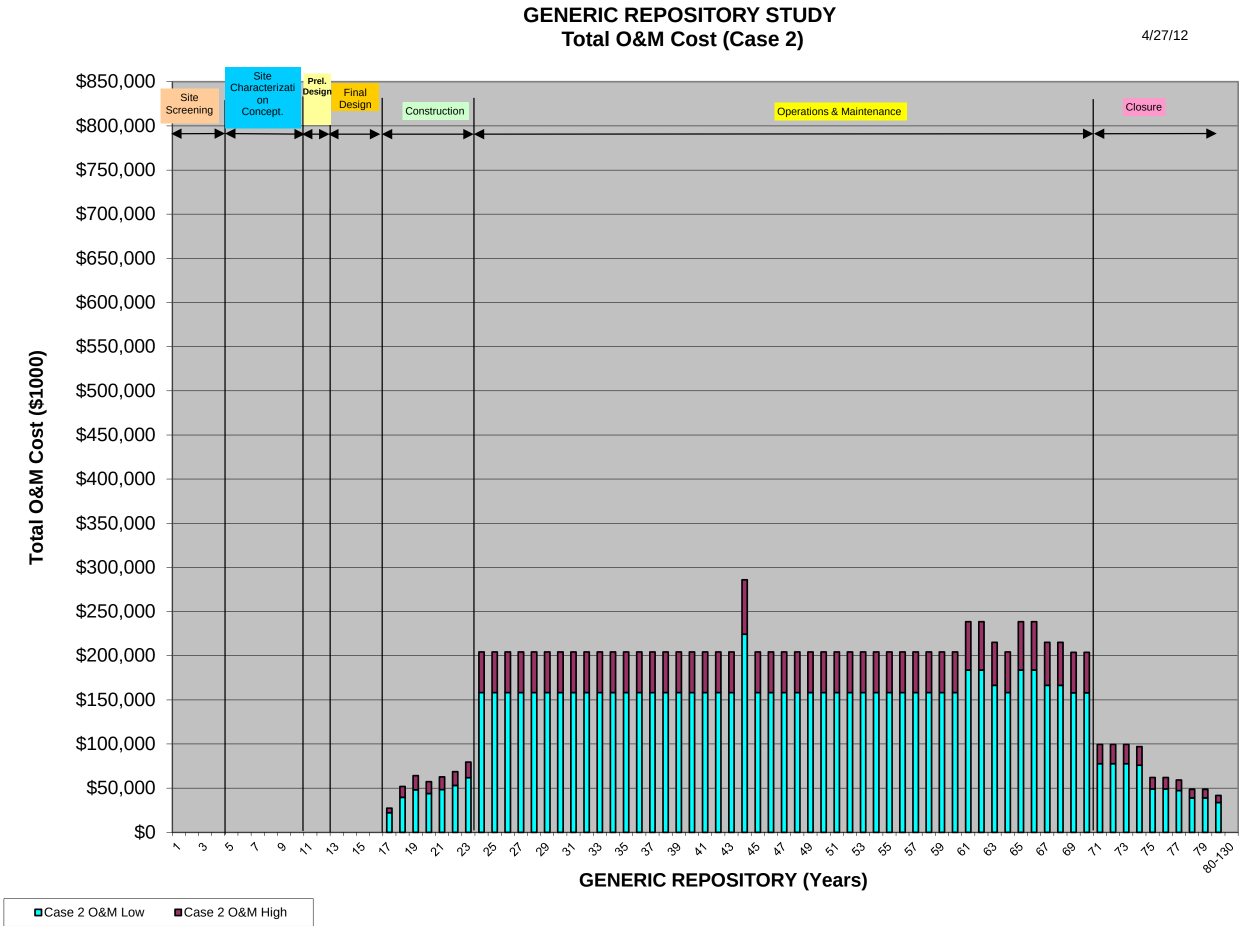

Figure 5.2-2 Annual O&M Costs for the Generic Salt Concept (Case 2)

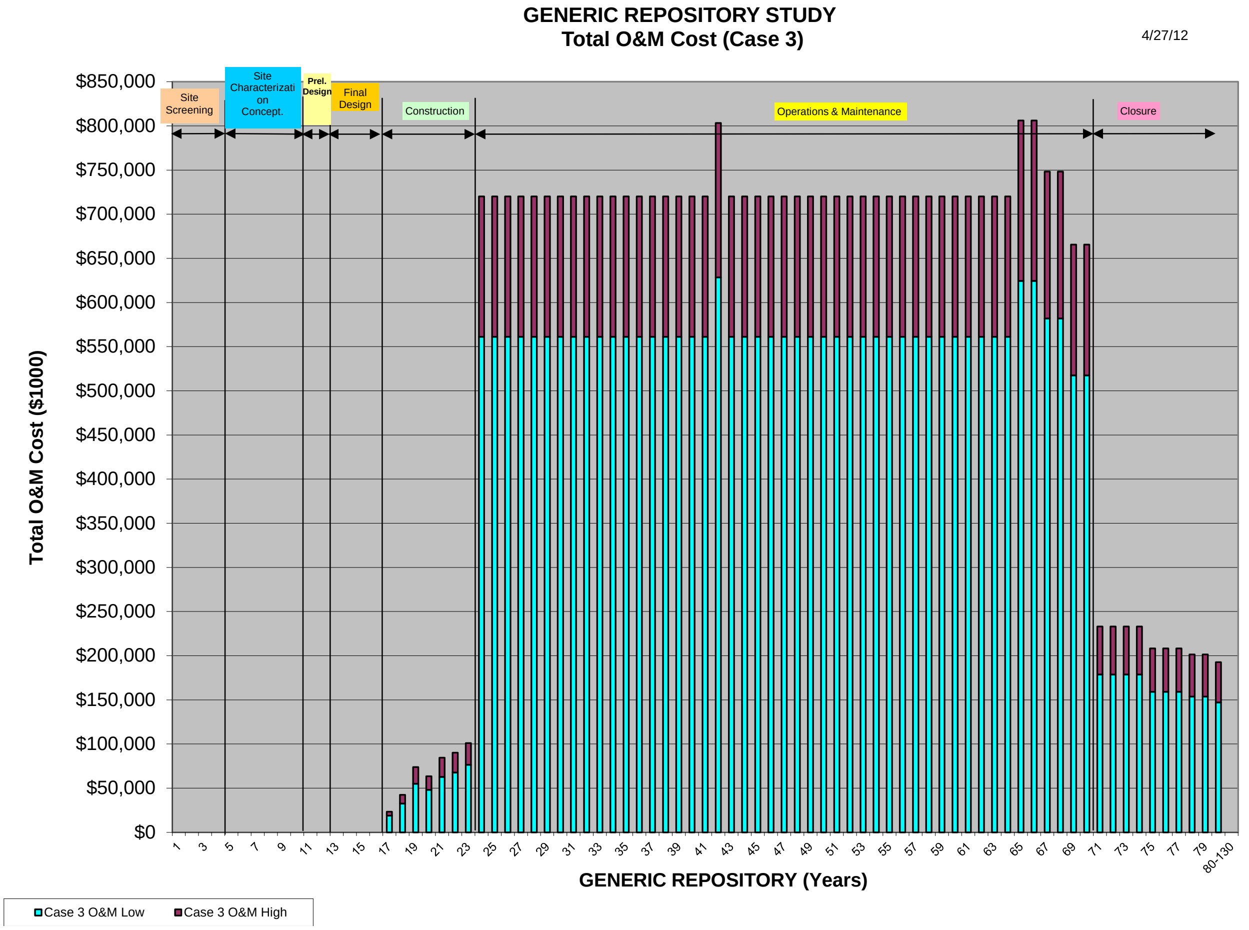

Figure 5.2-3 Annual O&M Costs for the Clay/Shale (enclosed) Concept (Case 3)

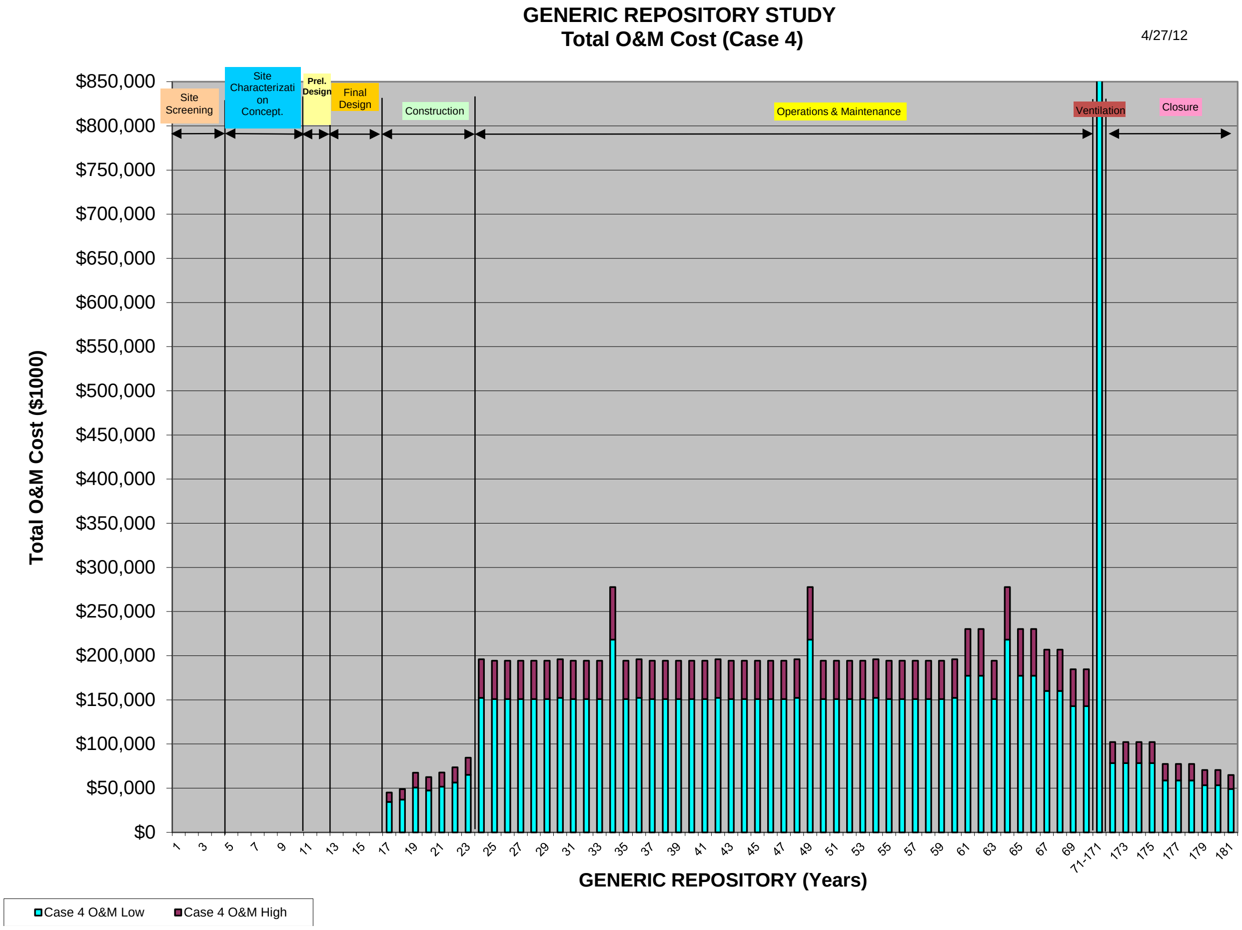

Figure 5.2-4 Annual O&M Costs for the Shale Unbackfilled Open Concept (Case 4)

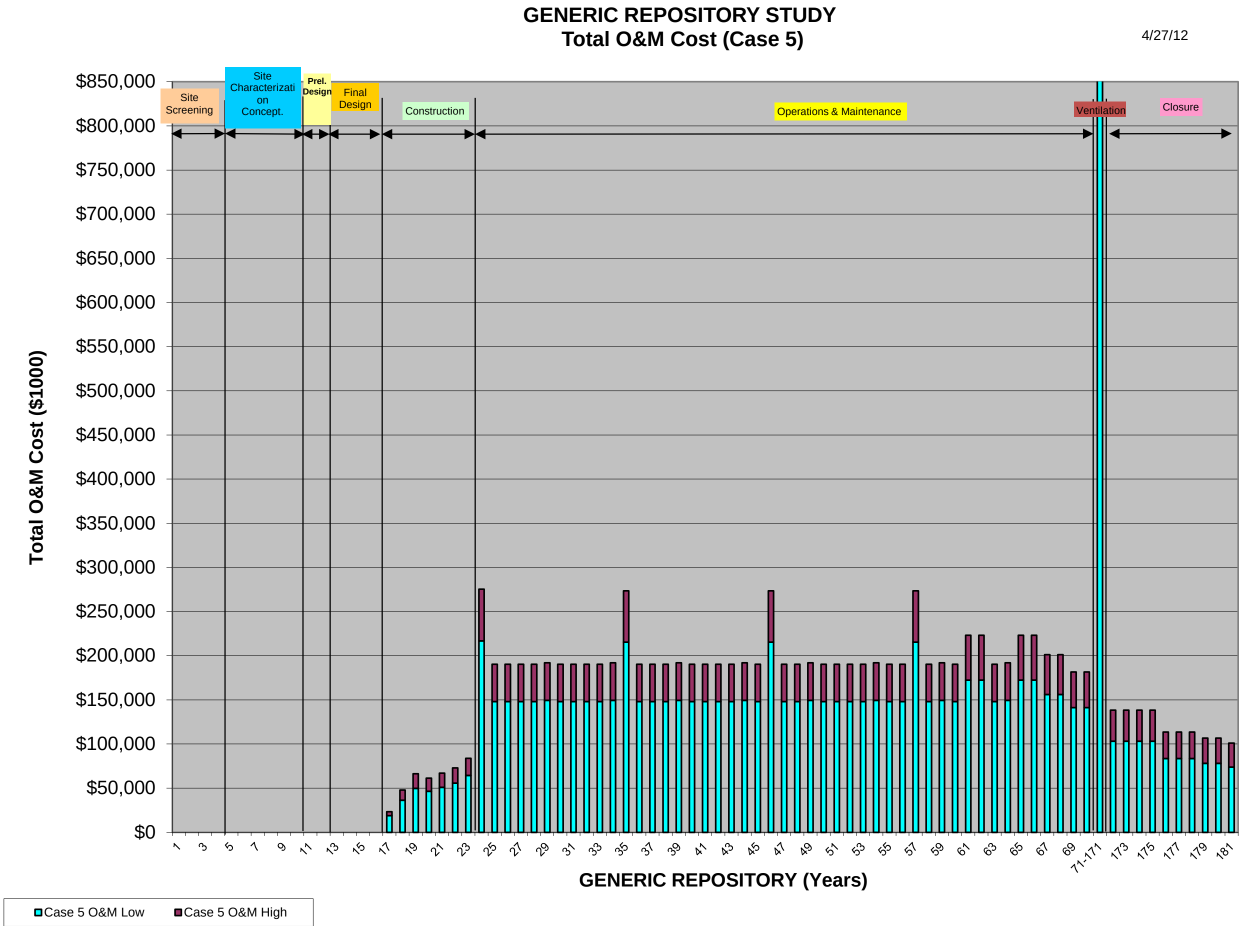

Figure 5.2-5 Annual O&M Costs for the Sedimentary Backfilled Open Concept (Case 5)

Waste Handling Staffing

The estimate of the staffing needs for waste handling operations is derived from the experience with the WIPP. The WIPP repository for defense transuranic (TRU) waste has established similar operations for the receipt and transfer of waste packages via shafts to a deep geologic repository. The following assumptions were used in developing this estimate:

- Waste handling will occur on two shifts per day, with up to two crews on each shift. Typical RH crew size is 10 including supervisory personnel. One RH package is emplaced each shift. One additional crew is included to accommodate vacations and training periods.
- RADCON occurs during the day shift and whenever waste handling is underway
- Quality Assurance staff is available whenever waste handling is underway
- Information Technology provides waste data base administrators whenever waste handling is underway

Support Staffing Bases

The support staffing is derived from the experience with the WIPP. The following assumptions were used in developing this estimate:

- Hoisting is available for three shifts per day
- RADCON occurs during the day shift and whenever waste handling is underway
- Surface and underground maintenance occur on one shift per day
- Engineering occurs during one shift per day
- Security is available 24 hours per day
- Emergency response is available 24 hours per day
- All other functions are single shift

Since some support staffing is population dependent, appropriate increases were made for which have higher waste package handling requirements.

Standard Savannah River Site labor, overhead and fee costs were used to convert the estimated operations and maintenance staffing into estimates of annual operating cost for each case. Allowances were added for additional costs which are applicable (e.g., replacement of mining machines, other small projects and materials), as well as utility costs. 5% contingency (30% for mining and security) was then added to these calculated costs to establish the low range estimate, and 30% contingency (100% for mining and security) was added to them for the high range estimate.

5.3 Waste Package Costs

Spent fuel waste is received at the repository in thin-walled stainless steel canisters, which are placed inside heavier overpacks for disposal. Overpack unit costs have been estimated for the various repository concepts (Table 5.2-1). This cost category also includes standard waste boxes for packaging the repository generated waste.

Table 5.3-1 Disposal Overpack Unit Costs

	Waste Package Configuration (PWR/BWR assemblies)	140,000 MT Repository		Disposal Overpack	
		Total Waste Packages	Annual Waste Packages	Materials of Construction	Cost ($ each) *
Crystalline (enclosed)	4/9	82,583	1,757	Copper	241,175
Generic Salt Repository (enclosed)	12/24	28,792	616	Carbon Steel	145,943
Clay/Shale (enclosed)	4/9	82,583	1,757	Carbon Steel	104,010
Shale Unbackfilled (open)	21/44	16,157	344	Carbon Steel	187,382
Sedimentary Backfilled (open)	21/44	16,157	344	Carbon Steel	187,382

These costs range from ~$6.7 billion to ~$21.6 billion depending on the waste disposal overpack and including contingency over the life of the repository. Contingency of 5% (low range) to 30% (high range) is included.

5.4 Regulatory and Licensing

Regulatory and licensing costs are a part of the existing cost estimating model and have been included in Tables 5-1 and 5-3 above.

This category includes the preparation of environmental assessments, site characterization studies and federal and state regulator support. This category does not include costs associated with developing or changing laws and regulations, or siting.

5.5 Monitoring

This category captures costs during design, construction, and operations, and after closure, associated with laboratory and field testing activities that support performance confirmation, and that also support monitoring during a 75-yr time period after repository closure. The range in part reflects the extent of underground excavation (Tables 5-1 and 5-3).

5.6 Performance Confirmation

Performance confirmation costs including low contingency ranges from $411 million to ~ $1,100 million (Tables 5-1 and 5-3). The cost methodology reflects variation in the facility design and construction costs between the cases.

5.7 Program Integration

Program integration costs are includes these components:

- Owner cost
- Program manager integrator cost
- Program independent quality assurance cost

These cost ramp up over the conceptual design period and remains at this level through the closure time period. The cost methodology reflects variation in the facility design and construction costs between the cases (Tables 5-1 and 5-3). Contingency is then added from 10% (low range) to 50% (high range).

5.8 Repository Closure

Repository closure will include backfilling and closing underground areas, shaft and ramp sealing and backfilling, surface facilities decontamination, as necessary, demolition and removal of surface structures, and site reclamation and restoration (Tables 5-1 and 5-3). It is expected that detailed planning and preparation for closure would commence before the end of the operations period and that actual closure activities would require approximately ten years.

Closure costs include the backfill material (Table G-6) and the mining staff required for installing the backfill closure period. Capital projects for active and passive institutional controls are estimated by using 15% of the facility design and construction point estimate. Contingency of 10% (low range) and 50% (high range) was applied.

6. Summary, Conclusions and Recommendations

This report is part of finalizing a multi-year work package to identify reference disposal concepts for generic studies in the Used Fuel Disposition R&D Campaign. An initial report (Hardin et al. 2011) described reference "enclosed" emplacement modes which were adopted from international experience and past work in the U.S. That report made several recommendations that were pursued in FY12, including developing a small set of disposal concepts with "open" emplacement modes. This report summarizes the work on both enclosed and open modes, which has been expanded to include additional inventory options, thermal analysis of open modes, disposal system description, and cost estimation. This section provides a summary of all results, and the insights from two years of study of reference disposal concepts.

Identification of Thermal Constraints and Measures for Thermal Management

The following thermal constraints are associated with far-field processes in the host rock or other units (Section 1.4.1):

- Limit thermally induced stresses or displacements in the host rock or other units
- Limit large-scale thermal expansion
- Limit thermally driven coupled processes in the host rock
- Limit the migration of brine-filled fluid inclusions in salt

These constraints pertain to the near field where temperatures and gradients are greatest. Constraining temperature in the near-field effectively constrains temperatures in the far-field, for all the disposal concepts considered here. International disposal concepts discussed in Section 1 have found near-field temperature limits to be sufficient. The following thermal constraints are associated with near-field processes in the host rock and/or the EBS (Section 1.4.1):

- Limit physical and/or chemical changes to clay buffers (see discussion below)
- Limit thermally induced micro-cracking in the less ductile rock types (see discussion below)
- Limit temperature of the host medium to control uncertainty in performance models
- Limit the temperature of argillaceous host media
- Limit the waste package surface temperature, to represent peak temperature anywhere in the disposal system outside the waste package
- Limit cladding temperature to 400°C for normal conditions of storage and short-term operations. Also limit 10 thermal cycles, and maximum temperature during off-normal and accident conditions.
- Limit cladding temperature to 350°C during permanent disposal
- Limit the peak centerline temperature of borosilicate glass waste forms below 500°C

Thermal management measures to meet the constraints above are available to repository designers and operators, and include the following (Section 1.4.2):

- Select host rock with strong conductive heat dissipation properties

- Use smaller waste packages to improve heat transfer and limit peak temperature
- Blend different waste types, ages, etc. within waste packages to decrease heat output. Also, sequence hotter and cooler packages in adjacent emplacement locations.
- Increase waste package spacing (emplacement drift, alcove, or borehole spacing to limit long-term and peak temperatures, particularly for waste types such as Pu-MOX SNF that contain minor actinides with intermediate half-lives.
- Surface decay storage (aging) of waste types prior to emplacement in the repository
- Separate heat-generating radionuclides in waste, and segregate disposal of the hottest waste forms in the repository. Degradation or increased uncertainty in repository waste isolation performance caused by heating, can thus be limited to a particular waste type and location.

Emplacement Modes

This study identified two major categories for waste package emplacement modes: “open” where extended ventilation can remove heat for many years after waste emplacement underground; and “enclosed” modes for clay/shale and salt media, and deep boreholes. For the enclosed modes, waste packages are emplaced in direct or close contact with natural or engineered materials which may have temperature limits that constrain thermal loading. All disposal concepts proposed internationally and in this report fit into one of these two categories (Section 1.4.4). Enclosed modes include backfilled alcoves, vertical and horizontal borehole emplacement in borings constructed from underground, and deep boreholes drilled from the surface. In-drift emplacement can be open or enclosed depending on whether buffer and/or backfill is installed around waste packages at emplacement. Emplacement drifts may be kept open for ventilation, then backfilled or isolated by seals prior to closure.

Selection of Disposal Concepts

As discussed in Section 1, a disposal concept consists of three parts: waste inventory, geologic setting, and the concept of operations. Waste inventory for this study (Section 2) consists of six waste types that could originate from three scenarios:

- Direct disposal of existing (40 GW-d/MT burnup) or future high-burnup (60 GW-d/MT) LWR UOX SNF.
- Reprocessing of LWR UOX UNF (51 GW-d/MT) to produce Pu-MOX fuel and HLW from reprocessing, then direct disposal of the HLW and irradiated MOX SNF (without further reprocessing).
- Aqueous reprocessing of LWR UOX UNF to produce U-TRU metal fuel for SFRs, and reprocessing HLW. The SFR UNF is continuously recycled using an electrochemical process, producing glass, ceramic, and metallic HLW forms.

These scenarios were selected as examples of once-through, modified-open, and full recycle strategies that are related to the current inventory of LWR UOX SNF (and thus these are transitional strategies). This study considers Pu-MOX to be a particularly hot waste type that could result from current or transitional activities in the nuclear power industry, without considering the quantity that could be generated.

The geologic settings (Section 1.3) selected for reference mined, enclosed and open disposal concepts are: crystalline rock (including granite), clay/shale, bedded salt, massive soft shale, and other sedimentary rock (e.g., alluvium) with favorable characteristics. Bedded salt is preferred to domal to accommodate a repository with large areal extent. These selections are reasonably representative of host media being investigated internationally (geologic conditions vary). Choosing such media and emphasizing advanced international programs, lets the U.S. program benefit from decades of R&D they have produced.

The reference mined disposal concepts proposed in this study are:

1. **Crystalline (enclosed)** - A repository in crystalline rock (also referred to here as granite). Vertical borehole emplacement is used with a copper waste package (e.g., Swedish KBS-3 concept) with a clay buffer installed at emplacement. Access and service drifts are backfilled with low-permeability clay-based swelling backfill at closure. Access shafts are sealed at closure (Section 1.4.5.1).
2. **Generic Salt Repository (enclosed)** – A repository in bedded salt in which individual, carbon steel waste packages are placed on the floor in drifts or alcoves, and immediately covered (backfilled) with run-of-mine salt. All repository openings are backfilled at closure, and shafts are sealed (Section 1.4.5.2).
3. **Clay/Shale (enclosed)** – Spent fuel or HLW is emplaced in blind, steel-lined horizontal borings constructed from horizontal access drifts. Spent fuel is emplaced in carbon steel packages with a clay buffer. HLW glass is emplaced in stainless steel pour canisters, within a steel liner. Access and service drifts are backfilled with low permeability clay-based backfill at closure, access shafts and ramps are sealed (Section 1.4.5.3).
4. **Shale Unbackfilled (open)** – A repository in a clay/shale environment constructed such that ventilation is maintained for at least 50 to 100 years after waste emplacement and before the repository is closed. At repository closure, the access and service drifts (shafts) are backfilled, but not the disposal drift segments where waste packages are emplaced (Section 1.5.1).
5. **Sedimentary Backfilled (open)** – A repository in unsaturated soft rock constructed such that ventilation is maintained for at least 50 to 100 years after waste emplacement and before the repository is closed. The waste emplacement, access, and service drifts are backfilled at the time of repository closure (Section 1.5.2).
6. **Hard Rock, Unsaturated (open)** – A repository in competent, indurated rock (e.g., igneous or metamorphic) using in-drift emplacement, and forced ventilation for 50 to 100 yr after waste emplacement. The hydrologic setting is unsaturated so the emplacement drifts are not backfilled at closure, but other engineered barriers may be installed such as corrosion resistant metallic barriers to water movement.
7. **Deep Borehole (enclosed)** – As discussed previously, ongoing studies are assessing the feasibility of drilling large-diameter holes to 5 km in impermeable crystalline basement rock. Waste packages would contain single SNF assemblies, or reduced quantities of HLW glass, and would be stacked in the lower 2 km of each hole. The upper section would be sealed.

The reference Crystalline (enclosed) and Clay/Shale (enclosed) disposal concepts follow those developed by Sweden, France, and others for these media (Section 1.4.5). The Generic Salt

Repository concept was developed for implementation in the U.S. (Carter et al. 2011b). The Hard Rock Unsaturated open concept is represented by the recently completed license application for a repository in volcanic tuff (DOE 2008b). The Deep Borehole (enclosed) concept is the subject of parallel studies (Brady et al. 2009; Arnold et al. 2011). Although not evaluated in this report, some results pertain and are included below. Without including the Hard Rock Unsaturated or Deep Borehole concepts, there are five distinct concepts analyzed (1 through 5 in the above list): three enclosed and two open.

6.1 Thermal Analysis Results Summary – Enclosed Emplacement Mode Concepts

6.1.1 Waste Package Size/Capacity Limitations for Enclosed Emplacement Modes

An important result of this work is that the reference Crystalline and Clay/Shale enclosed-mode mined disposal concepts would use relatively small packages for SNF (4-PWR/9-BWR) to limit peak temperatures (Section 3.1.2). Peak temperatures calculated for the various disposal concepts and waste types are summarized below. These waste package size selections are consistent with current international repository concepts in Sweden, France, and elsewhere. The packages are significantly smaller than the transport-aging-disposal (TAD) containers described in DOE 2008b, and much smaller than the dry-storage containers currently being loaded by U.S. nuclear utilities (typically 32-PWR/68-BWR size or larger; EPRI 2010, Table 2-2). Implementing disposal using an enclosed emplacement mode would therefore require re-packaging thousands of dry-storage canisters, and as many as 82,583 waste packages (Table 4-1). The possibility for disposing of SNF in larger containers is discussed below in reference to open modes.

6.1.2 Thermal Management for Reference Crystalline and Clay/Shale Disposal Concepts

A clay-based buffer is part of the Crystalline (enclosed) concept for SNF and HLW, and part of the Clay/Shale (enclosed) concept for SNF. As discuss in Section 1.4.1, various temperature limits for buffers containing swelling clay have been proposed. In the current analysis a target value for the maximum temperature of the clay buffer is assumed to be 100°C, and the same target is used for clay/shale host media because of mineralogical similarity to buffer materials.

Thermal results for crystalline and clay/shale disposal concepts are similar because of the use of the clay-based buffer, and the similarity of the clay/shale host medium. Where used, the clay-based buffer constitutes the dominant thermal resistance in the EBS outside the waste package. The following results are obtained in Section 3.1.2:

- High-burnup (60 GW-d/MT) LWR SNF could be emplaced in 4-PWR waste packages (or equivalent), after approximately 100 yr of surface decay storage, without the outer package temperature exceeding the 100°C target. This result is similar to SNF management practices being implemented by the Swedish program.
- Waste packages containing a single high-burnup LWR SNF assembly could be emplaced after approximately 10 yr of surface decay storage.
- Waste packages containing a single Pu-MOX assembly would require more than 200 yr decay storage to meet the target maximum temperature of 100°C.
- HLW generated by reprocessing LWR UOX fuel by either method considered here, could be emplaced after approximately 50 to 100 yr of decay storage

- Other waste types from electrochemical reprocessing of SFR metal fuel can be emplaced after fewer than 50 years of surface decay storage

Larger waste packages could be used but would require additional decay storage, to maintain target values for maximum temperature in the clay buffer or clay/shale host medium.

6.1.3 Thermal Management for the Reference Generic Salt Repository Concept

For salt a target value of 200°C for the maximum salt temperature is used here, although higher peak temperatures may be possible if supported by test data (BMWI 2008). The Environmental Assessment for disposal of SNF and HLW at the Deaf Smith County, Texas site suggested a maximum salt temperature of 250°C could be imposed (DOE 1987a). In more recent studies (Clayton and Gable 2009, and Carter et al. 2011b) a limit of 200°C was discussed. In the current analyses a target value of 200°C for the maximum temperature is used for comparative evaluations of surface decay storage time and waste package size/capacity. The following results are obtained in Section 3.1.2:

- High-burnup (60 GW-d/MT) LWR SNF could be emplaced in 4-PWR waste packages (or equivalent), after approximately 10 yr of decay storage, without exceeding 200°C at the waste package – host rock interface. In addition, 12-PWR packages could possibly be emplaced after approximately 40 years of decay storage without exceeding 200°C.
- Waste packages containing Pu-MOX SNF in the 4-PWR configuration would require approximately 110 years of decay storage to meet the 200°C target temperature.
- HLW generated by reprocessing LWR UOX fuel by either method considered here, could be emplaced after approximately 10 to 50 years of decay storage, without exceeding 200°C.

Salt has advantageous thermal characteristics and does not require open emplacement mode design to accommodate larger, hotter waste packages. Preliminary FEM calculations (Appendix C, Table C-4) show that 21-PWR size packages containing commercial SNF with 40 GW-d/MT burnup, can be emplaced in a Generic Salt Repository at 50 yr out-of-reactor. The calculations suggest but do not directly show that larger packages, or higher burnup SNF, can be emplaced at fewer than 100 yr out-of-reactor. Importantly, the thermal analysis in Section 3.1 emphasizes the likely importance for the Generic Salt Repository for SNF, of milling a semi-cylindrical cavity in the floor to facilitate heat transfer to the intact salt.

6.1.4 Thermal Management for the Deep Borehole Disposal Concept

For the Deep Borehole disposal concept no near-field temperature limits have been recognized because no performance credit is taken for the near-field host rock, and the borehole seal interval extends well beyond the thermal near field. Also, the boreholes would be spaced far enough apart to preserve the far-field natural barrier function (Brady et al. 2009).

6.1.5 Disposal of Non-Heat Generating Waste in Geologic Repositories

Waste volume, including non-heat generating or secondary waste (Appendix E) is generally comparable to, or less than the total volume available in repository access drifts (Table 1.4-3). Adequate volume (without additional mining) is available for the reference concepts in crystalline rock and salt. In crystalline rock, the volume is sufficient that LLW could be emplaced in access drifts and isolated from the host rock by an additional layer of low-permeability buffer or backfill material. This additional material would not be needed for salt (as demonstrated by disposal of TRU waste in the WIPP repository). For the Clay/Shale concept, limited volume is available for LLW, which could be isolated by a layer of low-permeability buffer or backfill, or emplaced directly if backfill does not serve a function to control water movement. For all mined disposal concepts, additional drifts or alcoves for emplacement of non-heat generating waste, could be easily incorporated without major changes to the layouts proposed here (Section 1.4.5).

6.2 Thermal Analysis Results Summary – Open Emplacement Mode Concepts

This study demonstrated a systematic approach to identifying enclosed and open disposal concept options, based on four key attributes: plastic vs. competent host rock, low vs. high permeability, saturated vs. unsaturated hydrologic setting, and whether the waste packages are surrounded by backfill or buffer material (Section 1.4). The approach identified three concepts for disposal of 21-PWR packages, with ventilation requirements ranging from 50 yr (Hard Rock Unsaturated open concept), to 250 yr (Sedimentary Backfilled open concept).

The selection of open reference concepts has defined the important coupling between decay storage or ventilation duration, and temperature limits for clay-based buffer or host rock materials (particularly those materials with a 100°C limit). For open modes, backfilling around large waste packages (e.g., 21-PWR size or larger) at closure, requires hundreds of years of decay storage and/or repository ventilation.

The open modes evaluation and supporting work in Appendices C and D, support the FY11 conclusions of this study that smaller waste packages (e.g., 4-PWR size) are needed to meet temperature limits in the Crystalline and Clay/Shale enclosed modes. For salt, the superior thermal conductivity and greater tolerance to elevated temperature (up to 200°C or possibly higher), allow use of larger waste packages less decay storage, and no additional engineered barriers, all at lower cost. More specifically, 12-PWR size packages are included in the Generic Salt Repository reference concept, with thermal results summarized in Section 6.1, while larger packages could be emplaced in salt as shown in Appendix C).

6.2.1 Nominal-Case Results

The results summarized in Table 3.2-1 show that even with 250 yr of forced ventilation, peak temperatures exceed 100°C for 21-PWR size packages and larger. There are several reasons why these cases are slow to cool down: 1) the 30-m drift spacing allows the entire repository horizon to heat up over hundreds of years; 2) the waste cools slowly after decay of short-lived fission products (90% decay in the first 100 yr); and 3) the large SNF capacity of 21-PWR size packages means more heat output that pushes up the peak (backfilled) temperature regardless of package size, according to the correlations developed in Appendix D (Section D.5).

Based on the nominal case a number of sensitivity studies were run to examine effects from ventilation efficiency and duration, drift spacing, host-rock thermal conductivity, and backfill thermal conductivity. A limited evaluation of waste package spacing was also included in the design test case (Section 3.3).

Comparing the Clay/Shale enclosed concept with the Sedimentary Backfilled open concept assuming shale properties (i.e., comparing enclosed and open concepts in shale) demonstrates:

- The enclosed concept (4-PWR, 60 GW-d/MT, emplaced at 100 yr) requires roughly twice the footprint of an equivalent open mode design (approximately 8-PWR, 60 GW-d/MT, emplaced at 50 yr, and backfilled at 310 yr) for the same inventory. Or, a given repository footprint can dispose of twice the waste if the open mode design is used.
- Surface decay storage for the enclosed mode is twice as long (e.g., 100 yr) as for the open mode (50 yr), offset by the 250 yr of preclosure ventilation needed to meet a 100°C temperature limit.
- The repository can open 50 yr earlier for the open mode in this case, and the last time the waste packages are handled is at 50 yr out-of-reactor, addressing concerns about deterioration of SNF that could impact waste isolation performance and make transport, handling, and emplacement more difficult.

6.2.2 Ventilation Duration

There are diminishing returns on ventilation duration, especially at long ventilation times (e.g., greater than 200 yr). Additional sensitivity cases (Table 3.2-3) explored whether higher temperatures due to shorter ventilation can be compensated by greater drift spacing. Doubling the drift spacing has an effect on peak temperature that is similar to doubling the ventilation time, which is consistent with the general heat transfer behavior discussed in Section 1.4.2.

6.2.3 Drift Spacing

Increasing drift spacing will lower peak temperatures, and is increasingly effective at later times. This is because although increased spacing tends to extend the temperature peaks, the heat source strength is decreasing with time. Increasing spacing to 50 m or beyond, appears to push the peak response beyond the decay envelope. Drift spacing is increased from 30 to 60 m in the "design test case" (Section 3.3).

6.2.4 Host Rock Thermal Conductivity

Host rock thermal conductivity (and diffusivity) is identified as a key parameter in the uncertainty analysis of Appendix D. Peak temperature is inversely related (to a first approximation) to the square root of diffusivity (and therefore of conductivity because heat capacity varies little in sedimentary rocks). This behavior is apparent from calculated results (Table 3.2-5) particularly if the background temperature is subtracted from the peak temperature values. For larger waste packages, host rock thermal conductivity of at least 3 to 4 W/m-K is needed to limit near-field temperatures to 100°C even after 300 yr of combined decay storage and repository ventilation. Such values are typical of salt but higher than other media considered (Appendix D).

6.2.5 Backfill Thermal Conductivity

Backfill does not affect host rock wall temperature, but it has a significant influence on peak waste package temperature (increasing the buffer/backfill thermal conductivity transfers control of the package temperature to the rock wall). The effect of increasing the backfill thermal conductivity from 0.6 W/m-K to 2.0 W/m-K can be seen in the Design Test Case (Section 3.3.1) discussed below.

Considering near field temperature constraints in the host rock, for open modes with large waste packages (e.g., 21-PWR size or larger), the focus of peak near-field temperature reduction should be on the heat source (waste package loading and ventilation duration) or heat dissipation in the host rock (conductivity and drift spacing).

6.2.6 Uncertainty of Host Rock Thermal Conductivity

Within $\pm 1\sigma$ variation of thermal conductivity around the mean values, peak temperature differences shift by approximately +33% (for lower conductivity) and -10% (for higher conductivity). The general conclusions of this report can be applied to geologic media with different thermal properties, or for natural variability of properties within geologic units, if thermal loading can be adjusted (-33%, +10%) to accommodate these variations. Geologic settings with very low thermal conductivity (μ-2σ) could be screened out or otherwise addressed during repository design by adjusting drift spacing, decay storage, ventilation duration, etc.

6.2.7 Design Test Case

A combination of parameters was selected to optimize a strategy for disposing of 21-PWR size packages containing SNF with 40 GW-d/MT burnup, while limiting ventilation duration to 50 or 100 yr. This study evaluated several key ideas: 1) sensitivity to waste package spacing within drifts; 2) effect of no backfill; and 3) the effect of extending the temperature limit boundary 3 m into the rock wall. The latter idea is based on the possibility of heating the near-field host rock above 100°C, in a massive shale formation (low permeability, unfractured). Drift spacing was increased to 60 m. Sensitivity studies varied backfill thermal conductivity across a wide range representing what may be possible for engineered bulk material (Appendix A). The no-backfill cases (relying only on radiative transfer) represent the Shale Unbackfilled open concept after permanent closure and cessation of ventilation, but before significant drift collapse, during the peak thermal period.

The results showed that host rock temperature at a distance of 3 m into the wall could be kept at or below 100°C even with closure after only 50 yr ventilation (and 50 yr decay storage), for 21-PWR packages containing SNF with 40 GW-d/MT burnup. The effect of increasing the in-drift axial spacing between packages is similar to varying the drift spacing, and reinforces the conclusion drawn above that limiting near-field peak temperature requires attention to the heat source, or to heat dissipation in the host rock. The design test case is a reasonable solution that can be used for cost estimation, subject to confirmation that performance consequences of over-heating the near-field are acceptable.

Finally, the greatest uncertainty associated with calculating near-field temperature histories (and other responses such as groundwater movement) is the hydration state of clay-based engineered and natural materials in the disposal environment. Complex coupled models are needed for explicit simulations (e.g., Weetjens and Sillen 2005), and even with application of such models there still may be important uncertainties.

6.3 System Description and Cost Estimation

Evaluation of cost factors for the disposal concepts is provided to show how design features and thermal management strategies affect relative costs. Application of these cost results beyond this purpose should be avoided for several reasons: 1) simplifying assumptions are used in this evaluation and in describing the alternative disposal concepts; 2) key factors such as siting, characterization, and licensing for repository facilities are not included; 3) “upstream” waste management costs such as storage, canisterization, and transportation are not included; and

4) costs associated with delay in the waste management program, which are potentially greater for some concepts than others, are not included.

Reference disposal concepts are described in sufficient detail to support cost estimation (Sections 2 and 4). Only five of the seven identified reference concepts are evaluated, because the others are addressed elsewhere as discussed in Section 4. The evaluation addresses construction sequence, shafts, ramps, underground openings, ground support, invert features, and the types of equipment to be used for waste transport and emplacement underground.

No bare fuel handling is included, rather, this study assumes that SNF will be received from central storage or a repackaging facility, in sealed stainless steel canisters. Disposal overpacks would be fabricated and inspected off site, and transported to the repository. Overpacks would be of materials such as carbon steel or copper, with welded closures. Surface facilities are scoped for throughput of 3,000 MT per year but would be developed on a modular basis to meet the ramp-up in a disposal schedule. Limited lag storage capacity is provided to buffer throughput, or possibly for decay storage of limited amounts of SNF. Facility descriptions (Sections 2 and 4) are reasonably consistent with the cost estimation (Section 5).

Costs and the associated schedules for all concepts were developed using the same durations derived in two previous salt repository studies (Carter et al. 2011, 2012c) for the conceptual design, preliminary design, final design, construction, and start-up periods. The waste emplacement operations phase of 47 years is determined by the waste inventory (140,000 MT) and the assumed waste emplacement rate of 3,000 MT per year. Cost estimates do not include site selection or characterization (see DOE 1986 for estimates of these costs), at-reactor packaging, centralized storage (if adopted), re-packaging to meet disposal requirements, and waste transport to the repository.

The team also used the same cost models developed for prior salt repository studies (Carter et al. 2011, 2012c) which in turn were tied to another study (DOE 2008c). The mining estimate was significantly improved with the addition of new unit cost data for mining in clay/shale, sedimentary and crystalline rock (Appendix G). Unit costs were also developed for backfilling with host rock or a mixture of host rock and bentonite clay (Section 5.2.2).

The cost for permanent disposal of 140,000 MT of commercial SNF ranges from approximately \$24 B to \$81 B in 2012 dollars (Table 5-1) including the range of low to high contingency (+5% to +30%; see Section 5). The lowest cost estimates are for the Generic Salt Repository and the Shale Unbackfilled concepts, and the highest are for the Clay/Shale and the Crystalline concepts. This range reflects different strategies for relying on engineered and natural barriers (i.e., natural barriers cost less). A geologic setting in relatively poor quality shale (e.g., indurated, with fracture permeability) is better suited technically to an enclosed emplacement concept, i.e., the Clay/Shale reference concept which uses short (40 m) horizontal emplacement borings, small waste packages, and multiple engineered barriers (buffer, plugs, and seals). By contrast, the Shale Unbackfilled concept is intended for a higher quality, relatively unfractured lithology. It can accept larger waste packages and does not require backfill in the emplacement drifts (although backfilling remains an option until repository closure).

It is important to note that the cost estimates in this report are for repositories with relatively simple surface facilities that handle only canistered commercial SNF, or HLW from various sources, that arrives already in waste package-size containers. The costs associated with fabricating waste package size canisters, including internal structures and materials for heat transfer, criticality control, etc., and the costs associated with repackaging the ever-growing inventory of SNF that is stored in sealed, dual-purpose canisters (DPCs) is not included. Facilities, equipment, and personnel required to support these additional necessary operations will increase the costs all of the repository concepts presented here.

6.4 Recommendations

R&D to Revise Thermal Constraints to Allow Higher Temperatures – This study shows that disposal concepts favoring larger waste packages and smaller repository footprints offer significant economic advantages. Tradeoffs and optimization on waste package size and subsurface layouts are generally limited by the assumed thermal constraints imposed on the near field environment. Thermal constraints used in establishing the reference disposal concepts are based on previous experience and international precedent, but are not necessarily fixed limits. The greatest uncertainties associated with calculating near-field temperature histories are the hydration state of clay-based engineered materials, and thermal responses of natural materials (e.g., host rock) in the disposal environment. Current efforts in EBS and near-field materials research and model development should be sustained. Repository designers and safety analysts use thermal constraints for several reasons: 1) to mitigate the impact of, or exclude, certain FEPs; 2) to limit the R&D needed to support safety evaluations; or 3) in response to regulatory input. Investment in R&D on thermal limits responds to all these needs.

Complex coupled-process models are needed for explicit simulations (e.g., of the type reported be Weetjens and Sillen 2005). Even with application of such models there are likely to be important uncertainties that should be carefully studied. For example, the FEM analysis for salt needs to be extended to include temperature-dependent fluid dynamical interactions, to evaluate whether large displacements of hot waste packages can occur.

The fidelity of FEP analysis and performance models needs to be optimized to support the use of larger waste packages and smaller repository footprints. Investigations are needed to evaluate the feasibility of direct disposal of DPCs, including current systems designed to receive 37 or more PWR assemblies (or equivalent). These investigations need to consider waste package handling, transport, and emplacement in addition to thermal performance.

Engineering Development of Disposal Concepts –The reference disposal concepts are developed sufficiently to allow for thermal analysis and initial cost estimation. Additional engineering studies will be needed to ensure the dimensions and other attributes of the proposed waste packages are adequate, and that the underground layouts, ground support, conveyances, and other design details are appropriate. Many of the details needed to better understand concept feasibility and the range of disposal costs are generic, so such studies would not require site-specific information. When site-specific information does become available, estimated costs could change substantially (e.g., disposal overpack materials, and the cost for high-capacity shaft hoists).

Reference Concepts Should Be Evaluated in Iterative Performance Assessments – Disposal concepts presented here use previous U.S. and international experience as a starting point and also include significant departures from previous designs. Although the concepts are expected to meet potential postclosure safety standards, they are new concepts and their postclosure safety performance has not been evaluated using a formal performance assessment methodology. Therefore, the reference concepts should be evaluated in iterative postclosure performance assessments. This includes FEP screening and evaluation, subsystem and total system model development, and subsystem and system performance assessments. This work will help identify: 1) where more design detail is needed; 2) where EBS and near-field environment models need to be developed or require additional capabilities; and 3) where data should be collected to support model development or reduce model uncertainties.

High-Fidelity Thermal Analysis – Additional coupled multi-physics numerical simulations for the Generic Salt Repository concept and for the open emplacement mode concepts, are needed to evaluate thermal constraints on emplacement of larger packages (e.g., 32-PWR size). This study evaluated disposal of 21-PWR size packages with open concepts in shale or other clastic sedimentary rock, and found host medium thermal constraints to be limiting unless decay storage or ventilation is extended to 200 years or longer. More simulations are needed to better understand the need for such long storage/ventilation duration. For salt, the importance of direct contact for heat transfer between waste packages and intact salt needs to be evaluated, and large-scale thermally driven processes need to be evaluated. For shale and sedimentary rock more definitive, multi-physics simulations are needed as guidance on whether a region of the near-field host rock could be overheated, consistent with a reasonable safety case.

Use of Reference Concepts in Site Screening – Reference disposal concepts are developed in this report to support the capability of the UFD campaign to contribute to discussions on waste management policy, and provide context for R&D activities that seek to advance confidence in models of repository system performance (Section 1). They are not intended to constrain future site screening activities to consider only sites where these reference concepts can be implemented. For example, a host geologic formation may be isolated hydrologically by adjacent strata, potentially combining advantages in constructability with a hydrogeologic setting favorable to waste isolation. To include variations on the reference concepts developed here, site screening should consider a comprehensive catalog of possible settings and repository features (Hardin et al. 2011, Appendix I).

Natural Variability in Thermal Properties for Potential Host Media – Based on analysis and literature review, host rock thermal conductivity is the most important thermal parameter for geologic disposal of any waste stream. A $\pm 1\sigma$ variation among geologic formations of each type surveyed is associated with a range of -10%, +30% about the mean of peak waste package surface temperature (expressed as a difference from ambient temperature). Accordingly, screening activities should emphasize thermal conductivity, and identify variation of mean thermal conductivity between formations, or variability within formations, especially if thermal conductivity lies outside the $\mu \pm 1\sigma$ range estimated in Appendix D.

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Appendix A – Thermal Analysis for Enclosed and Open Disposal Concepts

A.1 Enclosed Emplacement Modes

There are two general modeling methods that can be applied to the geometry described in Section 3.1 for thermal analysis: analytical solutions and numerical simulation. The analysis presented in this appendix is limited to analytical models implemented in MathCAD 15®, Microsoft Excel® 2007, and MatLab® Version 7.3. Numerical finite element methods used in this study are discussed in Appendix C, and were used only to increase confidence in peak temperature estimates for the Generic Salt Repository concept. Note that coupled THMC processes may also be active, but the effects on temperature would be limited in mined geologic settings with low-permeability materials, and would be evaluated as FEPs in analysis of waste isolation performance.

The following paragraphs describe inputs, the transient analytical heat transfer calculation, and the steady state multi-layer analytical calculation of temperatures at the EBS layer interfaces ending at the waste package surface.

The transient calculation (referred to here as the “external calculation”) is for a homogeneous medium representing the host rock. Homogeneity permits use of linear, superposed analytical solutions for point, infinite line, and finite line sources. The “calculation radius” for the external calculation is generally the interface between the EBS and the host rock, although for salt it is somewhat further away as discussed in the text (Section 3.1).

Temperature histories within the EBS (referred to here as the “internal calculation”) are estimated using an analytical expression for steady heat flow in concentric annular regions, driven by a time-varying boundary condition from the external calculation. The steady-state approximation is equivalent to assuming that the heat flow through the calculation radius at any given time is nearly equal to the heat generation in the waste at any time. This is reasonable except at very early times (e.g., less than a year) when EBS temperature changes may lead the temperature history at the boundary.

Variables Used in the Analytical Models

The input variables in the analytical models are in the form of several vectors and matrices of data, keyed to two index values. The index WF varies from 1 to 6 and represents the waste forms (UOX, Co-Extraction, MOX, new extraction, E-Chem ceramic, and E-Chem metal), and the index RT varies from 1 to 4 and represents repository host rock types (crystalline/granite, clay, salt, and deep borehole/crystalline basement).

For each repository design combination of rock type and waste form, there are specified EBS radii as discussed in Section 3.1. In the transient analytical model in the host rock, only the calculation radius and axial and lateral WP spacing are included from the geometry data. The radial dimensions of the EBS components are used in the internal steady state analytical model that starts at the calculation radius and extends to the surface of the waste package.

Host Rock Property Data

The host rock is represented by a single homogenous set of isotropic properties, with the thermal conductivity value at 100°C assumed for all calculations except salt, for which the 100°C value was used for previous calculations (Hardin et al. 2011), but calculations with the 200°C value are introduced in this report. Host rock and engineered material property data are summarized in

Appendix D. The properties of crushed salt backfill are utilized in the quasi-steady-state model of the EBS, and are listed under EBS material property data discussed below. Thermal conductivity (W/m-K) is designated by K_{th}, and thermal diffusivity (m^2/s) by α:

HOST ROCK PROPERTY DATA

$$\text{Rock\_type} := \begin{pmatrix} \text{"Granite"} \\ \text{"Clay"} \\ \text{"Salt"} \\ \text{"Deep Borehole"} \end{pmatrix} \qquad \text{Kth} := \begin{pmatrix} 2.5 \\ 1.75 \\ 4.2 \\ 3.0 \end{pmatrix} \cdot \frac{W}{m \cdot K} \qquad \alpha := \begin{pmatrix} 1.13 \cdot 10^{-6} \\ 6.45 \cdot 10^{-7} \\ 2.07 \cdot 10^{-6} \\ 1.38 \cdot 10^{-6} \end{pmatrix} \cdot \frac{m^2}{s}$$

Reference Data

Other variables that describe the EBS in thermal analysis include waste package length, emplacement drift spacing, and waste package spacing within each emplacement drift:

Waste Package Length:

SELECT WASTE FORM INPUT DATA

$$\text{WF\_name} := \begin{pmatrix} \text{"UOX"} \\ \text{"COEX"} \\ \text{"MOX"} \\ \text{"New\_Ext"} \\ \text{"E\_CHEM\_C"} \\ \text{"E\_CHEM\_M"} \end{pmatrix} \qquad \text{WF\_type} := \begin{pmatrix} \text{"Assembly"} \\ \text{"Canister"} \\ \text{"Assembly"} \\ \text{"Canister"} \\ \text{"Canister"} \\ \text{"Canister"} \end{pmatrix} \qquad \text{WP\_length} := \begin{pmatrix} 5 \\ 4.572 \\ 5 \\ 4.572 \\ 4.572 \\ 3.048 \end{pmatrix} \cdot m$$

Emplacement Drift Radius ("Calculation Radius"):

The calculation radius is the host rock surface interface with the EBS, and it varies by both waste type and disposal concept. The rows in the matrix below are for UOX SNF, Co-Extraction HLW, MOX SNF, New Extraction HLW, EC-C, and EC-M, while the columns are for Crystalline (enclosed), Clay/Shale (enclosed), Generic Salt Repository, and Deep Borehole concepts. The radius of the deep borehole design is based on an estimate of the maximum feasible drill casing.

The calculation radius also varies with the number of assemblies assumed per waste package. The 4-assembly (UOX or MOX) waste package can also be used with spacers to hold 2, 3 or 4 assemblies, and the calculation radius in the matrix below is consistent with the 4-assembly waste package design. The same model was used with different inputs for the 1-assembly and 12-assembly waste package designs to evaluate sensitivity of the results as a function of the number of assemblies. Calculations for the Deep Borehole concept use a single-assembly package with correspondingly small calculation radius.

$$\text{drift\_r} := \begin{pmatrix} 0.83 & 1.321 & 4 & 0.188 \\ 0.755 & 0.370 & 4 & 0.198 \\ 0.83 & 1.321 & 4 & 0.188 \\ 0.755 & 0.370 & 4 & 0.198 \\ 0.755 & 0.370 & 4 & 0.198 \\ 0.755 & 0.370 & 4 & 0.198 \end{pmatrix} \cdot \text{m}$$

Repository Design – Lateral Spacing, Axial Spacing and Depth:

Lateral spacing is the center-to-center borehole or drift spacing. Axial spacing (perpendicular to the lateral direction) describes the waste package center-to-center spacing within a given emplacement borehole, series of alcoves, or drift, with different values for SNF and HLW. Lateral and axial spacings for the enclosed disposal concepts are given in the following vectors (rows apply to the disposal concepts):

$$\text{Drift\_spacing} := \begin{pmatrix} 20 \\ 30 \\ 20 \\ 200 \end{pmatrix} \cdot \text{m} \qquad \text{WP\_space\_SNF} := \begin{pmatrix} 10 \\ 10 \\ 20 \\ 6 \end{pmatrix} \cdot \text{m} \qquad \text{WP\_space\_HLW} := \begin{pmatrix} 10 \\ 6 \\ 20 \\ 6 \end{pmatrix} \cdot \text{m}$$

Repository Design – EBS Component Data:

Selection of the disposal concept geometry is discussed in Section 3.1. For the steady-state internal calculation, all EBS components are represented by concentric cylindrical shells, and the specific inputs required are shown in Figures 3.1-3 to 3.1-6.

Waste Form Count

The time-dependent decay heat data discussed in Section 3.1 is expressed per SNF assembly or per HLW canister, and is multiplied by the waste form count (WF_count) to obtain the heat source per waste package.

The waste form count for the deep borehole reference repository is based on the fixed maximum diameter of the drill casing. For the SNF waste forms, rod consolidation is assumed, enabling a single assembly to fit within the narrow borehole diameter (WF_count = 1). For the HLW waste forms, the canister diameter is limited by the drill casing, so that only 29.1% of the full-size canister internal cross-sectional area is available. The inventory and heat generation (per length of borehole) are scaled accordingly (WF_count = dbh_cnt).

$$\text{WF\_count} := \begin{pmatrix} 4 & 4 & 4 & 1 \\ 1 & 1 & 1 & \text{dbh\_cnt} \\ 4 & 4 & 4 & 1 \\ 1 & 1 & 1 & \text{dbh\_cnt} \\ 1 & 1 & 1 & \text{dbh\_cnt} \\ 1 & 1 & 1 & \text{dbh\_cnt} \end{pmatrix}$$

Surface Decay Storage

Surface storage times of 10, 50, 100, and 200 years are evaluated for all enclosed emplacement mode cases analyzed, and input as a vector variable T_{store}. The effect of surface decay storage is the same as underground ventilation with 100% heat removal efficiency.

Heat Source Calculation

The analytic model incorporates three types of heat sources:

> Q_{L_wp} = A finite line source representing a single waste package of interest [W/m]
>
> Q_{L_avg} = An infinite line source representing the average line load for each adjacent emplacement drifts or borehole included in the calculation. (as an infinite line source) [W/m]
>
> Q_{wp} = A point source representing a single adjacent waste package, where the source strength is the total heat output for a waste package [W]

The three types of heat sources accounting for the effects of surface storage times are calculated as follows (MathCAD® syntax):

$Veff := 1.00$ Assume 100% efficiency (equivalent to surface storage), where Vdur = Tstore

$$Q_{L\_wp}(t, T_{store}, wf, rt) := \frac{Q(t,wf)\cdot WF\_count_{wf,rt}}{WP\_length_{wf}} \cdot \left[1 - Veff\cdot\left(t \le T_{store}\right)\right]$$

$$Q_{L\_avg}(t, T_{store}, wf, rt) := \frac{Q(t,wf)\cdot WF\_count_{wf,rt}}{WP\_spacing_{rt}} \cdot \left[1 - Veff\cdot\left(t \le T_{store}\right)\right]$$

$$Q_{wp}(t, T_{store}, wf, rt) := Q(t,wf)\, WF\_count_{wf,rt}\cdot\left[1 - Veff\cdot\left(t \le T_{store}\right)\right]$$

where Q(t,wf) is a continuous decay heat source function for one unit of waste (an assembly or HLW canister). Function Q(t,wf) is evaluated in MathCAD® using a cubic spline interpolation function through the tabular data points which are input to the model. The interpolation is stable and provides a good fit for the time period of interest in this calculation. However, when the decay heat values become small in the very long term (>> 1,000 yr) the cubic spline can produce oscillating values, and a different interpolating function (e.g., exponential) would be better.

Host Rock Temperature Transient Analytical Solution

An infinite medium is assumed to represent a given rock type. Rock temperature at the calculation radius is evaluated based on rock properties and an array of superposed, time-dependent heat sources. Three components that together: a finite line source at the middle of the array representing the waste package of interest, eight adjacent, parallel, infinite line sources (four on each side) representing nearby drifts, and eight adjacent, axially arranged point sources (four on each side) representing adjacent waste packages.

The solution for the finite line source is derived from the point source solution as described in Sutton et al. (2011a, Section 8.1.2). The solution for the infinite line source is presented by Carslaw and Jaeger (1959, Section 10.3), and the solution for a point source is based on Carslaw and Jaeger (1959, Section 10.4).

The one-dimensional temperature transient is the sum of the contributions from these terms as a function of radial distance and time, and is evaluated at the calculation radius (drift_r). Note that for the second and third terms, the distance is calculated to a location at the crown of the emplacement borehole or drift (see Figure 3.1-2)

$$\mathrm{DW\_T\_finite\_line}(t, y, T_{store}, wf, rt) := \left[\int_0^t \frac{\mathrm{Q_{L}\_wp}(\tau, T_{store}, wf, rt)}{8\cdot(\pi\cdot Kth_{rt})\cdot(t-\tau)} \cdot e^{\frac{-\left[(\mathrm{drift\_r}_{wf,rt})^2\right]}{4\cdot\alpha_{rt}\cdot(t-\tau)}} \cdot \left[\mathrm{erf}\left[\frac{1}{2}\cdot\frac{\left(y+\frac{\mathrm{WP\_length}_{wf}}{2}\right)}{\sqrt{\alpha_{rt}\cdot(t-\tau)}}\right] - \mathrm{erf}\left[\frac{1}{2}\cdot\frac{\left(y-\frac{\mathrm{WP\_length}_{wf}}{2}\right)}{\sqrt{\alpha_{rt}\cdot(t-\tau)}}\right]\right] d\tau\right]$$

$$\mathrm{DW\_T\_drifts}(t, T_{store}, wf, rt) := 2\left[\sum_{id=1}^{N_{drifts}} \int_0^t \frac{\mathrm{Q_{L}\_avg}(\tau, T_{store}, wf, rt)}{4\cdot(\pi\cdot Kth_{rt})\cdot(t-\tau)} \cdot e^{\frac{-\left[(\mathrm{drift\_r}_{wf,rt})^2 + (id\cdot \mathrm{Drift\_spacing}_{rt})^2\right]}{4\cdot\alpha_{rt}\cdot(t-\tau)}} d\tau\right]$$

$$\mathrm{DW\_T\_adjacent\_pkgs}(t, T_{store}, wf, rt) := 2\left[\sum_{ip=1}^{N_{adj}} \int_0^t \frac{Q_{wp}(\tau, T_{store}, wf, rt)}{8\cdot Kth_{rt}\cdot\sqrt{\alpha_{rt}}\cdot\pi^{1.5}\cdot(t-\tau)^{1.5}} \cdot e^{\frac{-\left[(\mathrm{drift\_r}_{wf,rt})^2 + (ip\cdot \mathrm{WP\_spacing}_{rt})^2\right]}{4\,\alpha_{rt}\cdot(t-\tau)}} d\tau\right]$$

Eqn. A.1-1

EBS Steady-State Temperature Calculation

As described in Section 3.1, it is assumed that at any given point in time, the relatively low thermal mass of the EBS components compared to the essentially infinite geologic medium, can be considered to be at a quasi-steady state condition.

The equation for steady-state conduction in concentric annular regions solution is from Kreith (1966; Section 2-2). In this geometry, the analytical solution is a one-dimensional (radial heat flow) model assuming an infinite line as the heat source. Total heat transfer is defined as

$$Q = U * A_{outside} * (T_{inside} - T_{outside}) \qquad \text{Eqn. A.1-2}$$

Where the conductance, U, is the reciprocal of the sum of the resistances:

$$U = \frac{1}{\frac{r_3}{r_1 \cdot h_i} + \frac{r_3 \ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{r_3 \ln\left(\frac{r_3}{r_2}\right)}{k_2} + \frac{1}{h_o}}$$

Eqn. A.1-3

where r_3 = the outside surface of the insulation

r_2 = the outside surface of the pipe

r_1 = the inside surface of the pipe

The heat flux per exterior unit area is defined as $q_A = Q/A_{outside}$. By conservation of energy at steady state, the temperature at the surface of each layer can be calculated as follows:

$$q_A = \frac{(T_i - T_1)}{R_i} = \frac{(T_1 - T_2)}{R_1} = \frac{(T_2 - T_3)}{R_2} = \frac{(T_3 - T_o)}{R_o}$$

Eqn. A.1-4

where T_i = inside fluid temperature
T_1 = pipe wall internal surface temperature
T_2 = pipe wall external temperature (and at the insulation internal surface)
T_3 = insulation external surface temperature
T_0 = air temperature

Application of this approach to the EBS components drops the convection resistance terms and uses a series of thermal resistance values calculated on the basis of the EBS component radii and thermal conductivities. The following equation shows the thermal resistance terms all the way to the surface of the waste form (calculation results presented in this report stop at the surface of the waste package):

$$U_{overall} = \frac{1}{R_{canister} + R_{waste\_pkg} + R_{buffer} + R_{envelope} + R_{backfill} + R_{liner}}$$

Eqn. A.1-5

The approach is modified for a line load (W/m) instead of an areal heat flux (W/m^2), by substituting $q_L = q_A{*}2\pi r_{outside}$. For example, the outer surface temperature of the backfill is

$$T_{BACKFILL} = T_{DW} + \frac{q_L}{2\cdot\pi\cdot r_{DW}}\cdot R_{LINER}\cdot = T_{DW} + \frac{q_L\cdot r_{DW}\cdot \ln\left(\frac{r_{DW}}{r_{BACKFILL}}\right)}{2\cdot\pi\cdot r_{DW} k_{LINER}} = T_{DW} + \frac{q_L}{2\cdot\pi\cdot k_{LINER}}\cdot \ln\left(\frac{r_{DW}}{r_{BACKFILL}}\right)$$

Eqn. A.1-6

where k_{LINER} is the liner thermal conductivity. The normalized thermal resistance for each layer associated with the calculations for SNF and HLW in the four geologic media are shown in Figure A.1-1.

Potential Improvement

This analysis assumes constant thermal properties for the host rock and EBS, whereas some properties such as conductivity and heat capacity can change with temperature, porosity, or moisture content. This has been addressed for clay-based buffer materials (using an intermediate value; Section 3.1) and for the Generic Salt Repository (comparison to numerical solutions, Appendix C). Clayton and Gable (2009, Section 3.1) provide data addressing the thermal conductivity and diffusivity of intact salt with temperature (Equation 3.1), and of crushed salt with porosity and temperature (Equation 3.4). Figures A.1-2 and A.1-3 are derived from the equations and data in Clayton and Gable (2009, Section 3.1). This information is used in the FEM simulations described in Appendix C.

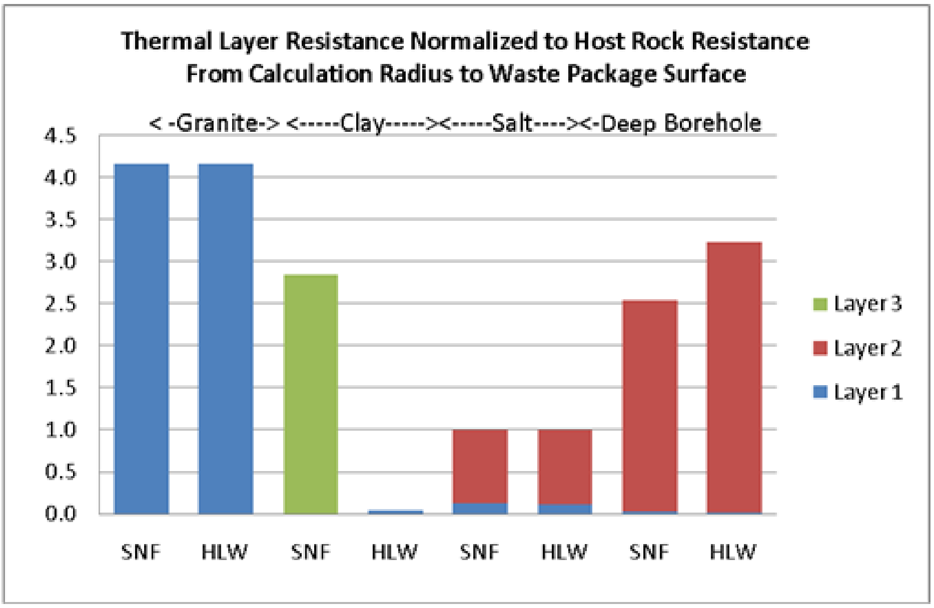

Figure A.1-1 Normalized Thermal Resistance of Each EBS Layer

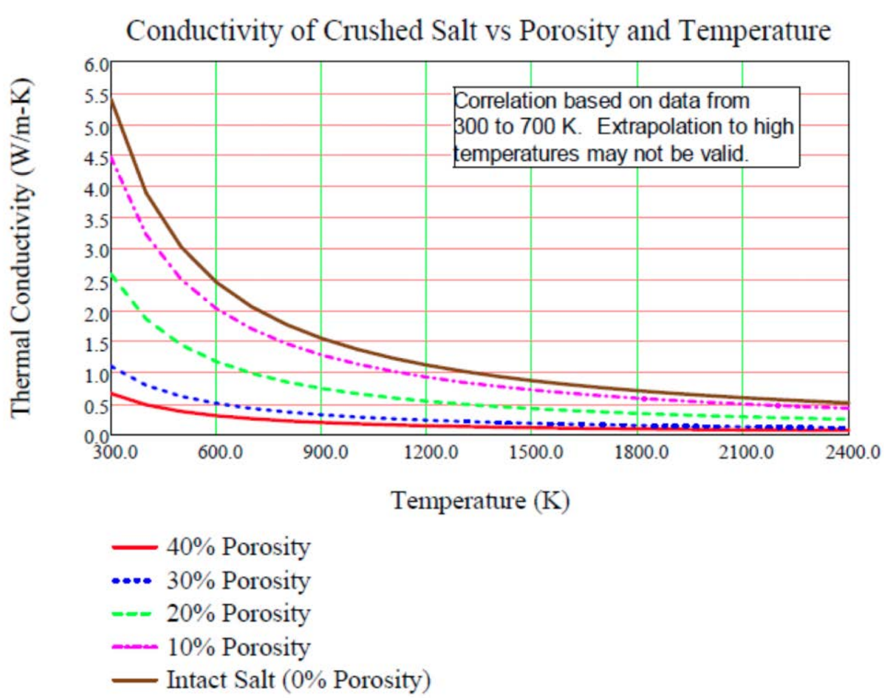

Figure A.1-2 Effects of Porosity and Temperature on Thermal Conductivity of Crushed Salt

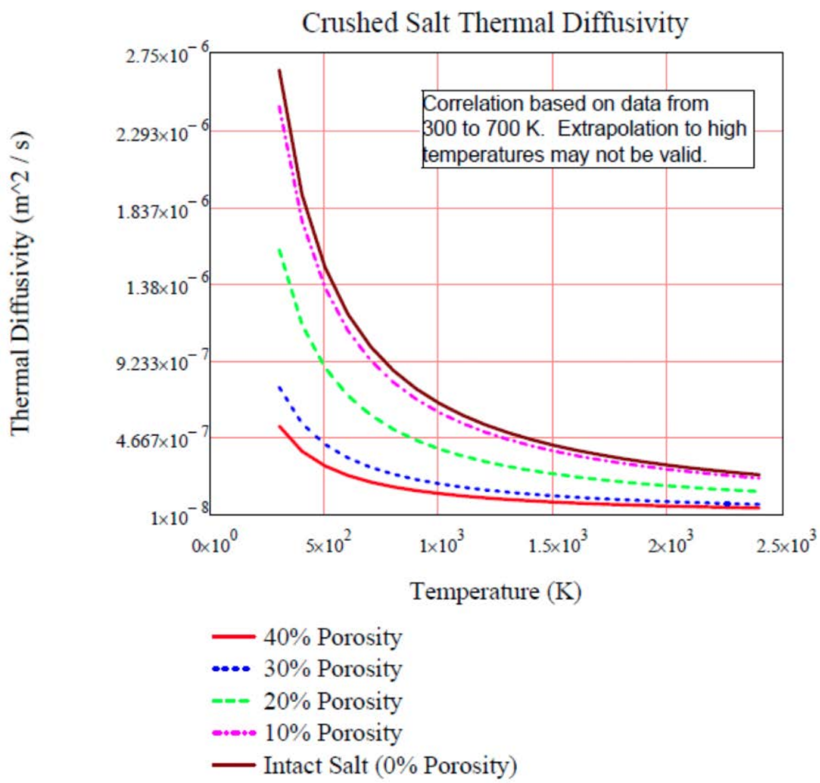

Figure A.1-3 Effects of Porosity and Temperature on Thermal Diffusivity of Crushed Salt

A.2 Open Emplacement Modes

A combination of transient heat transfer analytical solutions for a finite line source, a series of point sources, and a series of parallel infinite line sources are combined with a quasi-steady-state multi-layered cylindrical solution to simulate the temperature response of geologic disposal systems with multi-layered natural and engineered barriers. The original development was documented by Sutton et al. (2011a, Appendix G). Modifications of the original approach to accommodate open emplacement modes include:

- Radiative heat transfer for the open air space between the waste package and the rock wall, prior to backfill and/or closure
- Ventilation with fixed value of heat removal efficiency
- Backfill thermal conduction replacing the radiative heat transfer condition when backfill is installed at closure, for some cases

The feasibility of heat removal by forced ventilation (e.g., 75% heat removal) is based on previous work (BSC 2004) that considered the contribution from natural convection. After cessation of forced ventilation natural convection is neglected with justification, because thermal radiation is the more important mode of heat transfer (BSC 2005, Section 6.2.1). Natural convection would decrease estimates for waste package temperature, and produce non-uniform distribution of temperature at the rock wall. The assumption is a useful simplification that produces results that suit the purpose of this study, a scoping evaluation of alternative disposal concepts.

The host rock thermal transient temperature response contributions from the point sources, finite line sources, and infinite line sources were added by superposition. The analytical solutions must be convolved with the time-varying heat generation function. The convolution integral equations from Sutton et al. (2011a) are:

$$T_{point}(t,r) = \frac{1}{8 \cdot \rho \cdot Cp \cdot (\pi \cdot \alpha)^{\frac{3}{2}}} \cdot \int_0^t \frac{q(t')}{(t-t')^{\frac{3}{2}}} \cdot e^{\frac{-r^2}{4 \cdot \alpha \cdot (t-t')}} \, dt'$$

Eqn. A.2-1

$$T_{line}(t,x,y,z) = \frac{1}{8 \cdot \pi \cdot k} \cdot \int_0^t \frac{q_L(t')}{t-t'} \cdot e^{\frac{-\left(x^2+z^2\right)}{4 \cdot \alpha \cdot (t-t')}} \cdot \left[\operatorname{erf}\left[\frac{1}{2} \cdot \frac{\left(y + \frac{L}{2}\right)}{\sqrt{\alpha \cdot (t-t')}} \right] - \operatorname{erf}\left[\frac{1}{2} \cdot \frac{\left(y - \frac{L}{2}\right)}{\sqrt{\alpha \cdot (t-t')}} \right] \right] dt'$$

Eqn. A.2-2

$$T_{infinite\_line}(t,x,z) = \frac{1}{4 \cdot \pi \cdot k} \cdot \int_0^t \frac{q_L(t')}{t-t'} \cdot e^{\frac{-\left(x^2+z^2\right)}{4 \cdot \alpha \cdot (t-t')}} \, dt'$$

Eqn. A.2-3:

where	α	=	thermal diffusivity, $m^2/s = k/(\rho\text{-}C_p)$
	C_p	=	specific heat, kJ/(kg-K)
	k	=	thermal conductivity, W/(m-K)
	L	=	length of the finite line source, m
	$q_L(t)$	=	heat per unit length (a function of time), W/m
	q	=	heat, W
	r	=	radius, m
	ρ	=	density, kg/m^3

These equations are applied to the repository layout of heat sources shown conceptually in Figure 3.1-2. For the enclosed mode concepts, which are conduction-only cases, the waste package surface and EBS transient temperatures are calculated using the quasi steady-state approach described by Sutton et al. (2011a, Section G.4).

In the current analysis a similar approach is taken, however heat transfer across the air gap (e.g., during preclosure ventilation) is predominantly by thermal radiation instead of conduction. After backfilling at closure, the open-mode temperature calculations revert to conduction-only cases.

Radiative Heat Transfer

Heat transfer is simplified by assuming infinite concentric cylinders because the view factor between nested cylinders is unity. The equation for the radiation heat transfer coefficient h_{rad} is taken from Incropera and DeWitt (1996, Table 13.3) for concentric infinite cylinders (based on the inner surface as the heat source), and is also referenced elsewhere (BSC 2004, p. 6-8). The same modeling approach using infinite concentric cylinders was also applied by Weetjens and Sillen (°5, p. 34).

$$h_{rad\_infinite}(r_i, r_o, \varepsilon_i, \varepsilon_o) := \frac{\sigma}{\frac{1}{\varepsilon_i} + \left(\frac{1-\varepsilon_o}{\varepsilon_o}\right)\cdot\frac{r_i}{r_o}}$$

Eqn. A.2-4

where $h_{rad\_infinite}$ has units of $W/(m^2\text{-}K^4)$, and

ε_i = emissivity of the inner surface (dimensionless)
ε_o = emissivity of the outer surface (dimensionless)
r_i = radius of the inner cylinder, m
r_o = radius of the outer cylinder, m
σ = Stefan Boltzmann constant = 5.670×10^{-8} W/ (m^2-K^4)

The outer surface emissivity (ε_o) is chosen to represent either bare rock, a steel liner, or shotcrete ($\varepsilon_o = \varepsilon_{wall} = 0.9$). The inner surface emissivity is chosen to represent the waste package metal surface in a stable, oxidized condition ($\varepsilon_i = \varepsilon_{WP} = 0.6$), and is chosen to approximate both copper and steel surfaces.

The basis for the wall and waste package emissivity values assumed is from Incropera and DeWitt (1996, Table A-11) which shows a range from 0.88 to 0.93 based on hemispherical emissivity of rock at around 300K. This range is corroborated by *Perry's Chemical Engineers Handbook* (1984, Table 10-17) for normal emissivity of rough silica and rough fused quartz, ranging from 0.8 to 0.93.

The temperature of the waste package, given the transient temperature of the host rock, is represented in Mathcad as:

$$q_{L\_rad\_infinite}(r_i, r_o, \varepsilon_i, \varepsilon_o, T_{cold}, T_{hot}) := h_{rad\_infinite}(r_i, r_o, \varepsilon_i, \varepsilon_o)\cdot(2\cdot\pi\cdot r_i)\left(T_{hot}^{\ 4} - T_{cold}^{\ 4}\right)$$

Eqn. A.2-5

where $q_{L\_rad\_infinite}$ is the linear heat load (W/m), calculated by dividing the waste package heat source by the waste package length, T_{hot} is the waste package surface temperature, and T_{cold} the host rock wall temperature.

Ventilation

Instantaneous ventilation thermal efficiency and integrated ventilation thermal efficiency are defined by BSC (2004; Section 6.3.5). Because the ventilation air temperature increases as the air flows from the inlet of the emplacement drift to the exit into the exhaust main, and the decay heat sources are functions of time, the instantaneous ventilation efficiency is both a function of time and distance from the entrance and is defined by:

$$\eta(t,x) \equiv \frac{Q_{air}(t,x)}{Q_s(t)}$$

Eqn. A.2-6

where $\eta(t,x)$ = instantaneous ventilation efficiency (dimensionless)
Q_{air} = heat transferred by natural and forced convection to the air from the waste package and drift wall surfaces (W/m)
Q_s = heat generated by the waste package (W/m)
t = time since ventilation began
x = distance from the drift entrance (m)

It also defines integrated ventilation efficiency as:

$$\eta_{\text{integrated}} \equiv \frac{\int_0^b \left[\int_0^a Q_{air}(t,x) \cdot dx \right] dt}{x \cdot \int_0^b Q_s(t) \cdot dt}$$

Eqn. A.2-7

where $\eta_{\text{integrated}}$ = integrated ventilation efficiency (dimensionless)
a = limit of integration in terms of the total drift length
b = limit of integration in terms of the total ventilation duration

The integrated ventilation thermal efficiency calculated in BSC (2004) was 86%. The ventilation efficiency assumed in this study (V_{eff}) is also an integrated ventilation efficiency, and is assumed to have a constant value of 75%.

A.3 Backfill Properties and Assumptions

Bentonite is a common name for montmorillonite-rich material mined in Wyoming, U.S.A. Its properties are often used in analyses of European high-level radioactive waste repository concepts because it is widely available, with uniform composition. However, it is not particularly cheap and other, locally derived clay-rich materials are being investigated.

The addition of quartz sand has been considered to provide increased structural strength of bentonite (Pakbaz and Khayat 2004), and to provide increased thermal conductivity (Jobmann and Buntebarth 2009).

The backfill material assumed in the nominal-case calculations for the Sedimentary Backfilled concept and sensitivity studies in this report is a 70% bentonite/30% quartz sand mixture, with hydrated thermal conductivity of 1.2 W/m-K. Note that the experiments reported by Jobmann and Bentebarth (2009) were conducted under confined, hydrated conditions. Calculations of waste package temperature using this value therefore represent best case, cooler results. If hydration of dedicated clay-based buffer or backfill material could not proceed promptly or completely due to scarcity of water, or excessive temperature, thermal conductivity would be closer to the value of 0.6 W/m-K for compacted, dehydrated pure bentonite. For the enclosed-mode calculations described above, an intermediate value of buffer thermal conductivity was used to represent a partially hydrated state that exists during the period of peak temperature less than 100°C.

The results of a sensitivity study of backfill thermal conductivity ranging from 1 to 5 W/m-K are presented in Section 3.2.2.

A.4 Comparison of Analytical Solution Against Finite Element Modeling for Salt

The FEM simulation method described in Appendix C (Table C-4) produced peak salt temperature estimates that can be directly compared to results from the analytical solution method (Section 3.1 and this appendix). The FEM calculations used for this comparison are thermal-only, assuming crushed salt properties at 20% fixed porosity.

Comparison (Table A.4-1 and Figure A.4-1) shows that the analytical solution correlates with the FEM results, with a tendency to over-predict the peak temperature rise by approximately 40% (based on Figure A.4-1). This can be explained because the analytical solution approximated the effect of backfill by taking 75% of the intact salt conductivity (Section 3.1.1.2). Also, for conduction through this reduced area, the solution used intact salt conductivity at 200°C which is less than that at lower temperatures (Table D-1). These results show that the approximation taken in the analytical solution that heat dissipation is equivalent to conduction through intact salt but with only 75% available area, is a conservative approach with respect to predicting peak temperature.

Table A.4-1 Comparison of Analytical Model Results with Finite Element Calculations in Salt

Package Type	Fuel Burnup (GW-d/MT)	Age OoR (yr)	Initial Heat Output (kW)	FEM Peak Salt Temperature (°C) [A]	Analytical Model Peak Salt Temperature (°C) [B]
4-PWR	60	50	2.0	65	93.7
4-PWR	40	10	2.7	75	112.0
12-PWR	40	50	3.8	90	140.5
4-PWR	60	10	4.5	110	168.3
12-PWR	60	50	5.9	130	201.5
12-PWR	40	10	8.0	160	246.1
12-PWR	60	10	13.5	275	391.2

[A] From Table C-4.
[B] From Table 3.1-2 (using salt thermal conductivity at 200°C)

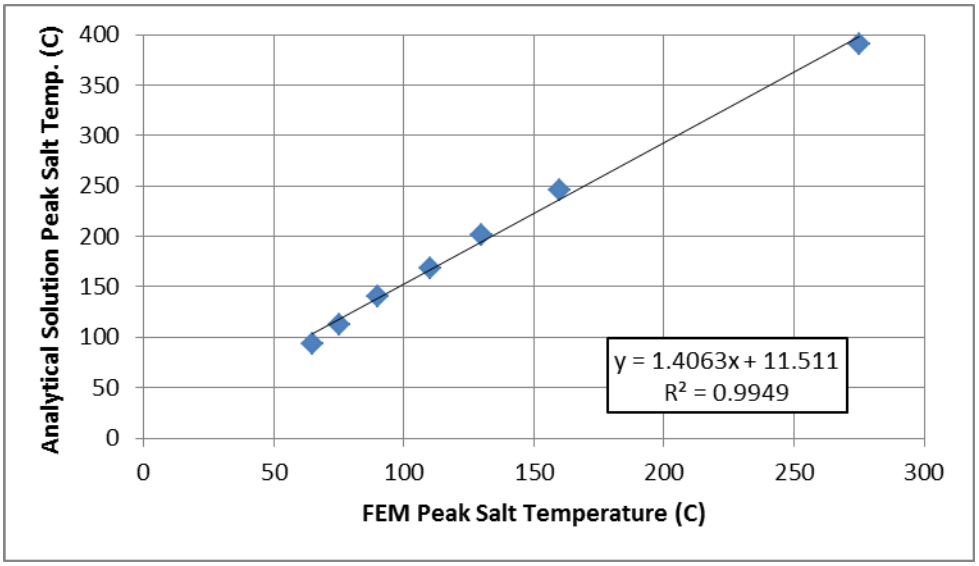

Figure A.4-1 Comparison of Analytical Model Results with Finite Element Calculations in Salt

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Appendix B – Scoping Study of Alluvium as a Potential Geologic Setting

Alluvium has been studied as a possible burial medium for waste isolation for more than 60 years, and was selected for disposal of transuranic (TRU) waste in the Greater Confinement Disposal Boreholes (GCDB) facility for greater-than-Class C (GTCC) waste at the Nevada National Security Site (NNSS; formerly Nevada Test Site). Extensive characterization of unsaturated alluvium has been conducted for waste disposal and for arid zone water resource assessments. Arid alluvium has several favorable characteristics for waste isolation including low water flux, high specific surface area and sorption capacity, and constructability. At several sites, profiles of matric potential, chloride, and stable isotopes have been used to show zero recharge flux for more than 100 kyr. Low flux and slowly changing conditions permit relatively long-term paleohydrologic reconstructions, which in turn allow high quality predictions of future variation at a given site. The low flux combined with the potential sorption capacity of highly porous, fine grained material, suggest that natural barrier performance could be robust, while constructability and relatively shallow depth are favorable to engineering feasibility.

The concept of HLW disposal in unsaturated alluvium was championed by the U.S. Geological Survey throughout the 1970’s and early 1980’s (Winograd 1981; Roseboom 1983). Alluvium hydrology and radionuclide transport have been studied as part of nuclear weapons testing in arid alluvium for the past 50 years. As a result of weapons testing and the GCDB, significant knowledge exists on the mechanical and hydrological properties of arid alluvium (Cochran et al. 2001).

A dry alluvium repository would be placed in an arid setting where depth to groundwater is on the order of 500 m. The mined repository would be placed at or below 200 m in depth, roughly halfway between the surface and the water table providing ample groundwater travel time to the water table. (We note that the depth criterion in 10CFR960 is a favorable condition, applicable to depths of at least 300 m, and not a disqualifying condition.) Placement below 100 m ensures a downward liquid flux due to gravity drainage, below the root zone and a vestige of the last pluvial climate (approximately 100 kyr ago). Downward movement would tend to maximize the travel time to the accessible environment, and ensures significant dilution of radionuclides that reach the water table.

Alluvium is a potential host geologic setting for the Sedimentary Backfilled open concept described in Section 1.4.5. The repository concept of operations would use in-drift emplacement, preclosure ventilation for decades, then backfilling at closure. Ground support would consist of rock bolts and shotcrete as used extensively in the U1a tunnel complex on the NNSS, where large spans with excellent, long-term opening stability are in use (Figure B-1). Additional layers or coatings could be used to prevent desiccation of the alluvium, if needed, and corrosion resistant bolts, mesh and fastenings could be used to enhance longevity. The underground repository would be accessed with vertical shafts, and an inclined ramp for waste handling (facilitated by the relatively shallow repository depth). As discussed for the Sedimentary Backfilled open mode, the layout includes short emplacement segments to facilitate backfilling. Emplacement drift segments would have operable radiation shielding or labyrinths to provide shielding for operations in the access drifts. Repository openings would be backfilled before closure, with low permeability backfill material engineered to impose a diffusion dominated, sorptive barrier to radionuclide transport. The chemical environment in unsaturated alluvium is oxidizing, so attenuation of released radionuclides in the natural system would be limited. To provide compensating additional performance of the engineered barrier system, the waste package would be constructed from a corrosion resistant material, although the hydrated backfill would limit the ingress of oxygen and the availability of water to support corrosion processes.

B.1 Alluvium Geological Setting

Alluvium refers to all detrital materials deposited by running water. Thick alluvial deposits fill the basins adjacent to mountain ranges in the arid southwestern U.S., particularly the Basin and Range province. Valley fill is primarily deposited in large alluvial fan systems which extend outward from mountain ranges. Alluvial fans are controlled by flood deposition during infrequent runoff events, and comprise heterogeneous sediments ranging from clay to large cobbles, with the majority of material as sand and gravel. Alluvial fans grade laterally with coarser material closer to the mountains, generally fining towards the basins (Cochran et al. 2001; Tyler et al. 1996; Smyth et al. 1979).

Alluvial material is derived from the adjacent mountain ranges, and can vary widely in composition. Alluvium in the Basin and Range region is dominated by Paleozoic carbonates and Tertiary silicic volcanic rock (Cochran et al. 2001). The southwestern U.S. has an extensive distribution of alluvial deposits. Two key aspects of this distribution are the local aridity and the depth to groundwater. The extent of alluvial deposits in the United States that receive less than 10 inches/year of rainfall is shown in Figure B-2. Mapped alluvium was extracted from state geological maps (Luddington et al. 2007; Stoeser et al. 2007) and average annual precipitation was derived by the PRISM model for the years 1960-1990 (Daly 2000). The majority of arid alluvium is found in the Basin and Range province in western Utah, Nevada, southeastern California and western Arizona (Figure B-2). A regional water table map for the arid southwest is not available, however, a reasonable coverage exists in the state of Nevada which hosts a large area of arid alluvium. A closer look at the depth to the groundwater table in Nevada is shown in Figure B-3 (Zehner 2012), from which it is apparent that the requirement of a deep water table significantly reduces the availability of potential disposal sites.

B.2 Alluvium Hydrogeologic Setting

Recharge in arid zones has been studied from a water resources perspective and as part of the performance assessment for the GCDB. Most arid soils throughout the southwest United States have experienced little to no recharge or deep infiltration in the past 10,000 yr (Phillips 1994). The amount of deep infiltration depends on the vegetation, with pinion-juniper ecosystems allowing periodic deep infiltration recharge events, grasslands allowing infrequent deep infiltration events, and desert scrub (e.g. creosote) ecosystems allowing zero recharge (Walvoord and Phillips 2004).

At the NNSS where alluvium has been studied extensively, environmental tracers in the valley floor alluvium where the plant community is dominated by creosote, indicate that in many locations recharge has not occurred for the last 100 kyr (Walvoord and Phillips 2004; Kwicklis et al. 2006; Tyler et al. 1996). Water movement in deep arid vadose zones occurs in both the liquid and vapor phases and is still responding to long-term climate changes over the past 100 kyr (Walvoord et al. 2002a). Water movement is accurately described by two-phase porous medium flow. Liquid gravity drainage from the last pluvial climate 100 kyr ago is still occurring at depths greater than ~100 m (Walvoord et al. 2002a; Tyler et al. 1996), and fluid residence times are on the order of 100 kyr. In the upper 100 m there is a net upward movement of water in the liquid and vapor phase. Above depths of around 50 m moisture moves almost entirely in the vapor phase (Walvoord et al. 2002a, 2002b; Cochran et al. 2001) which provides a barrier against the upward transport of liquid-borne radionuclides.

Figure B-1 Shaft Station at the Main Working Level (~300 m depth) in the U1a Underground Facility at the NNSS (photo released for unlimited use)

B.3 Climate Reconstructions

Climate and recharge reconstructions for many sites in the arid southwest have been created using environmental tracers in water contained in alluvium, and in fossilized pack rat middens. For example, extensive surveys (Tyler et al. 1996) and subsequent refinements (Walvoord et al. 2002a; Kwicklis et al. 2006) have produced a reasonably consistent reconstruction at the NNSS for the past 120 kyr. A pluvial climate existed from 120 to 95 kyr ago depending on elevation and latitude. This climate was wet enough to induce deep infiltration and recharge at Yucca Flat, with estimated recharge rates on the order of 5 mm/yr. From 100 kyr to approximately 14 kyr ago, arid conditions existed with zero deep infiltration and recharge. A shift around 14 kyr ago back to pluvial conditions brought about deep infiltration past the root zone at approximately 5 mm/yr. However, a rapid shift back to arid conditions around 10 kyr ago stopped the deep infiltration. The extent of infiltration was not sufficient to cause a recharge event and the downward migration of water from the last pluvial was contained in the upper 100 m of the vadose zone.

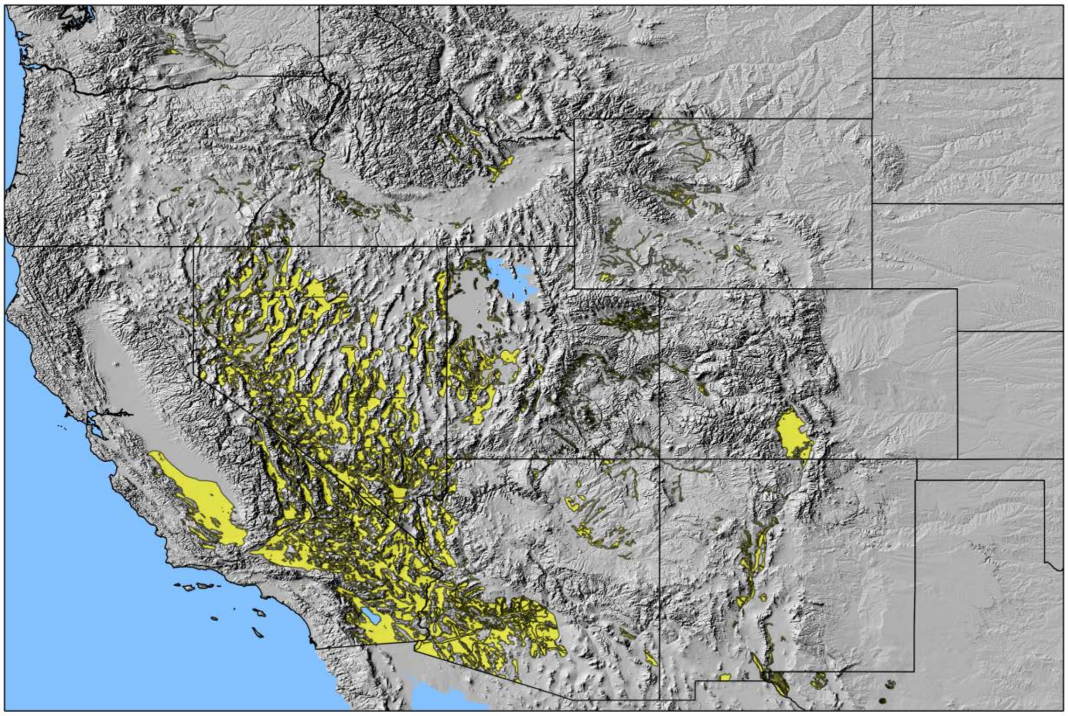

Figure B-2 Extent of Mapped Alluvial Deposits with Average Annual Rainfall of Less Than 10 Inches (yellow areas are mapped alluvium which fall in areas of 10 in. or less average precipitation over the last 100 yr)

For the past 10 kyr arid conditions have persisted with zero infiltration past the root zone. Climatic conditions vary with site-specific elevation and latitude, but this reconstruction provides a first order approximation of climatic conditions across the arid southwest. Even in the event of future pluvial climate conditions, the paleohydrologic evidence at the NNSS shows that downward liquid flux would likely be in the range of 5 to 10 mm/yr, which is much less than the saturated hydraulic conductivity. Thus, the wettest future climate would produce unsaturated conditions for which natural and engineered barrier performance are well understood.

B.4 Alluvium Properties

Well-studied alluvium from the NNSS is assumed here to represent, to a reasonable degree, the general properties of alluvium throughout the region. Alluvium is a heterogeneous mix of clay to cobble sized particles. At the NNSS the typical composition is 20% gravel, 70% sand and less than 8.5% silt/clay with a mean grain size of sand (Cochran et al. 2001). Porosity ranges from 38 – 50% with a mean dry bulk density of 1600 kg/m^3 (Smyth et al. 1979). The mechanical properties are heterogeneous, varying with grain type and depositional facies. Fracture strength for alluvium is less than for tuff; however, fractures are very scarce in underground workings, and alluvium is competent as evidenced by mined openings kept open for more 30 years, on the NNSS. Thermal conductivity of alluvium is low with measured values on re-compacted samples ranging from 0.5 to 0.8 W/m-K, and in situ values in the range 1 to 1.2 W/m-K (summarized by Hardin et al. 2012; estimated from regional heat flow and the existing geothermal gradient by Smyth et al. 1979). Saturated hydraulic permeability ranges from 5.5×10^{-5} to 0.5 m/s (Smyth et al. 1979). Sorption capacity for radionuclides is generally high; for example, the mean retardation coefficient for Np is approximately 110 with coefficient of variation of around 133% (Painter et al. 2006).

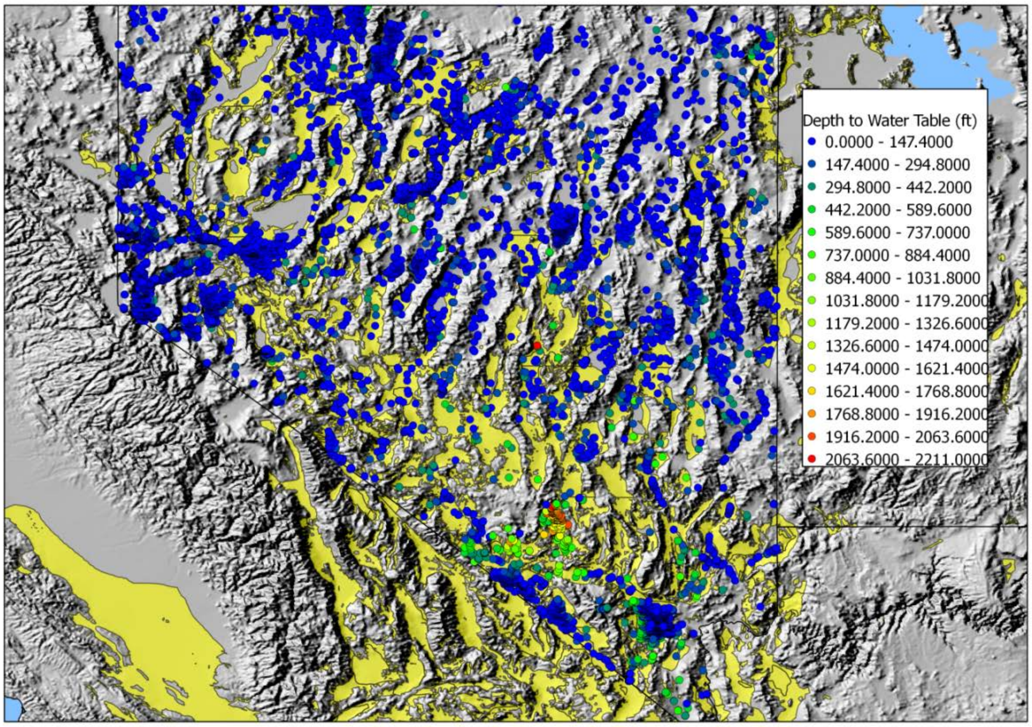

Figure B-3 Depth to the Groundwater Water Table in the Nevada Basin and Range Region

B.5 Summary

Dry alluvium in the arid southwestern United States has a number of favorable characteristics for long-term waste disposal, the principal characteristic being low water flux for time scales up to 100 kyr. Low flux combined with a deep water table and sorptive retardation, could result in very long radionuclide travel times in the vadose zone (and additional travel time in the saturated zone beneath). Low liquid flux through the vadose zone would also give rise to large dilution factors at the water table. Engineered barriers could be configured to isolate waste from downward groundwater flux during future pluvial recharge conditions. Alluvium is readily excavated, and underground openings are stable for several decades at least, especially if protected from desiccation and other possible effects from heating (subject to verification by testing). Performance assessment for alluvium should consider the potential for surface erosion, and future return to pluvial climate conditions.

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Appendix C – Finite Element Analysis for the Generic Salt Repository and a Hybrid Mode

This section describes finite element simulations performed during the first quarter of FY12 for several purposes: 1) to evaluate the potential for emplacing larger, hotter SNF waste packages in the Generic Salt Repository (GSR); 2) to evaluate the extent to which peak salt temperature is affected by backfill consolidation; and 3) to explore the feasibility of a "hybrid" emplacement mode in which the GSR is ventilated for heat removal, but through the access drifts only. The following paragraphs describe the simulation, then summarize the results in a table of peak temperatures.

In this project, a two-way coupled thermomechanical analysis is carried out by loosely coupling thermal and mechanical codes through an interface that allows state variables such as temperature and porosity to be passed from one code to the other. The combined code is executed using output from the thermal code as input to the mechanical code, and vice versa. Two codes developed at Sandia National Laboratories were coupled for these calculations: Aria (a Galerkin finite element based program for solving coupled-physics problems described by systems of partial differential equations) was used for thermal analysis, and Adagio (a Lagrangian mechanical modeling program with special provisions for modeling salt deformation) was used to couple the temperature dependent creep behavior of intact and crushed salt. A third code, Arpeggio, was used to couple the two codes together and control the simulations.

C.1 Simulated Geometry

For this analysis, a GSR is modeled with several different SNF waste package sizes (located at the small circle in Figure C-1) in a 10-m long, 5.5-m wide, 3-m high alcove (dark rectangle in Figure C-1). The different size waste packages are described in Table C-1. The alcove connects to a perpendicular, horizontal, 3-m high, 5-m wide access drift (light colored rectangle in Figure C-1, perpendicular to the page). In this scheme adjacent waste packages are 20 m apart in both horizontal directions. For most cases, the alcove and access drift are filled with crushed, run-of-mine salt, surrounded by intact salt (lightest color in Figure C-1). For cases that include ventilation, the alcove is backfilled but the access drift is not, and a convective boundary condition is applied on the access drift walls to represent ventilation. Because of the GSR geometry (waste packages on a 20-m grid) this ventilation condition is similar to the "hybrid" mode proposed here. Symmetry conditions are imposed on the four vertical boundaries of the model grid so the domain represents an alcove within the interior of the repository.

C.2 Finite Element Grid

The grid is constructed using 3-D hexagonal elements. Representative vertical slices are shown in Figure C-2. The cylindrical waste package is approximated with hexagonal elements to simplify the gridding. The grid is extended 200 m above and below the alcove so that alcove responses are unaffected by the thermal and mechanical boundary conditions applied at the top and bottom boundaries.

Table C-1 Waste Package Outer Dimensions Used in Salt Thermal Analysis

Waste Package	Diameter (m)	Length (m)
4 PWR assemblies	0.82	5.13
12 PWR assemblies	1.29	5.13
21 PWR assemblies	1.60	5.13
32 PWR assemblies	2.0	5.13

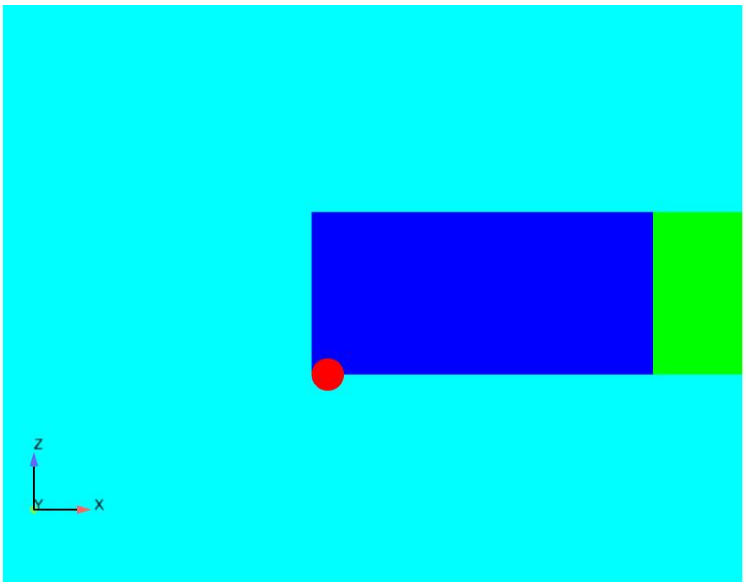


Figure C-1 Representative GSR Geometry

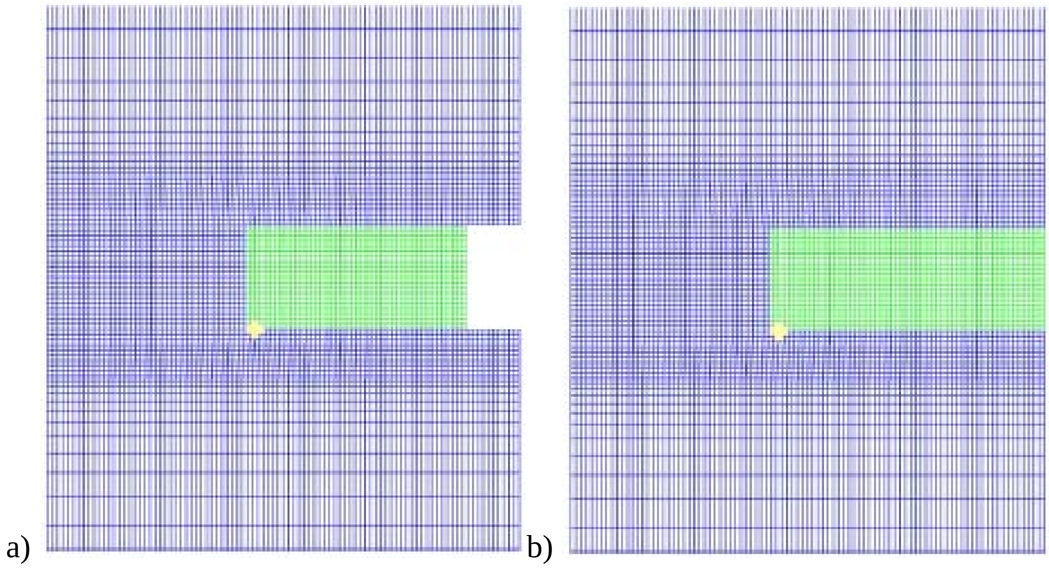


Figure C-2 Near-Field Alcove Grid a) with and b) without Ventilation

C.3 Analysis Input

All the materials are assumed to be initially at 27°C. Spent fuel at two burnup levels, 40 GW-d/MT and 60 GW-d/MT, aged 10 years out-of-reactor (OoR) were analyzed with the thermal decay response for SNF as a function of time shown in Figure C-3. The lower burnup approximates the SNF currently stored in fuel pools and dry cask storage at existing plants, while the higher burnup represents a possible future waste stream from commercial light-water reactors. Complementary cases where the SNF was further aged to 20 or 50 years OoR were also run, and the normalized decay response (Figure C-3) was then shifted in time to correspond to the amount of aging.

The convective boundary condition used for the ventilation cases was derived by using the properties of air at 27°C and the Dittus-Boelter equation (Dittus and Boelter 1930) for internal cooling turbulent flow. Assuming ventilation air mass flow rates of 50 and 5 kg/s, heat transfer coefficients of 9.95 and 1.58 W/m^2/K were calculated and used in the analyses.

The temperature dependent thermal conductivity of intact salt used in the analysis is given in the following equation

$$\lambda_{salt}(T) = \lambda_{300}\left(\frac{300}{T}\right)^{\gamma} \qquad \text{Eqn. C-1}$$

where: λ_{300} = material constant, 5.4 (W/m/K)

γ = material constant, 1.14

T = temperature (K)

The thermal conductivity of crushed salt is based on the BAMBUS II study (Bechthold et al. 2004) in which the thermal conductivity of crushed salt was determined from field experiments.

From this study, a fourth-order polynomial was fit to the field data to describe crushed-salt thermal conductivity as a function of porosity (ϕ)

$$k_{cs}(\phi) = -270\,\phi^4 + 370\,\phi^3 - 136\,\phi^2 + 1.5\,\phi + 5 \qquad \text{Eqn. C-2}$$

This representation is valid for porosities between zero and 40%. When the porosity is zero, Equation C-2 produces a thermal conductivity of 5.0 W/m/K. Therefore, Equation (C-2) is modified by a factor (f) so that the intact salt thermal conductivity of 5.4 W/m/K at ambient temperature is reproduced at zero porosity. Equation C-2 is rewritten as

$$k_{cs}(\phi) = \left(-270\,\phi^4 + 370\,\phi^3 - 136\,\phi^2 + 1.5\,\phi + 5\right) \cdot f \qquad \text{Eqn. C-3}$$

where f is simply (5.4/5.0 or 1.08). For this study, the initial porosity of the crushed salt is assumed to be 20%, which accelerates the numerical analysis but is also consistent with compaction that will occur during transport and emplacement. The temperature-dependent nature of the crushed-salt thermal conductivity is assumed to be the same as for intact salt, so the crushed-salt thermal conductivity is given by

$$\lambda_{c-salt}\left(T\right) = k_{cs}(\phi)\left(\frac{300}{T}\right)^{\gamma} \qquad \text{Eqn. C-4}$$

The density of the crushed salt is calculated as a linear function of porosity. A summary of the thermal material properties assumed for the waste package and its contents, intact salt, and crushed salt is shown in Table C-3.

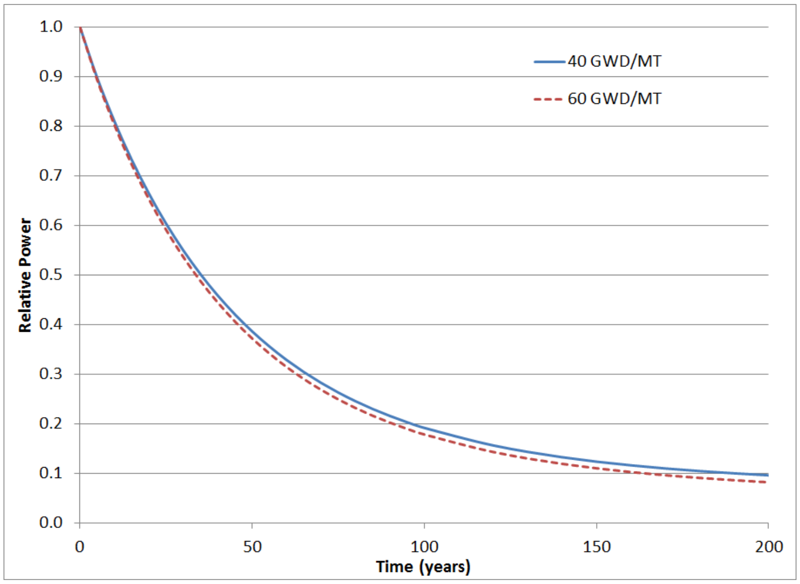


Figure C-3 Normalized Decay Curves Used in the Thermal Analyses

Table C-2 Thermal Properties for Intact Salt, Crushed Salt, and the Waste Package

Material	Thermal Conductivity (W/m/K)	Specific Heat (J/kg/K)	Density (kg/m^3)
Waste	1.0	840	2,220
Intact Salt	Equation C-1	931	2,160 (ρ_0)
Crushed Salt	Equation C-4	931	$\rho_0(1-\varphi)$

Table C-3 Mechanical Properties Used for Waste Package and Contents

Material	Young's Modulus (Pa)	Poisson's Ratio	Thermal Expansion (K^{-1})
Heater	2.0E11	0.3	2.0E-6

For the mechanical analysis, the boundary conditions are set so that horizontal displacements are zero along the vertical boundaries and the bottom of the model grid. The mechanical loads acting on the model consist of an overburden pressure applied to the top of the grid, corresponding to a repository depth of ~600 m. The intact salt is initialized with an isotropic stress condition corresponding to the overburden pressure, while the waste package and crushed salt backfill are initialized with no external loads. The intact salt is modeled using the multimechanism-deformation (M-D) creep model (Munson et al. 1989), the crushed salt was modeled using the crushed salt creep model (Callahan 1999), and the waste was assumed to respond elastically using the properties of steel shown in Table C-3.

C.4 Analysis Results

Each case was run as a thermal-only problem to determine the peak temperature experienced by the intact and crushed salt surrounding the waste package. A summary of the thermal-only cases run, along with the approximate peak salt temperatures, is shown in Table C-4. For thermal-only cases, the alcove and backfill geometry does not change throughout the simulation, and the backfill porosity is maintained at 20%. The peak salt temperature increases with increasing package size and heat output, as shown by comparing the 60 GW-d/MT burnup SNF cases with the complementary 40 GW-d/MT cases. The peak temperatures decrease with increased aging of the fuel. Cases with ventilation show a notable decrease in peak salt temperature compared with the same cases without ventilation, especially for hotter cases in which the peak salt temperature without ventilation is greater than 200°C.

Comparing thermal-only with coupled thermomechanical cases run for 4-PWR and 21-PWR packages (Table C-4), shows that peak salt temperatures are slightly lower, mainly due to consolidation and increased thermal conductivity of the crushed salt backfill around the waste package. This shows that backfill consolidation produces a small but potentially useful decrease in peak salt temperature.

The temperature history for the 4-PWR package case with 40 GW-d/MT SNF, 10 years OoR, and no ventilation is shown in Figure C-4. The corresponding average backfill porosity history for the same case is shown in Figure C-5. Temperatures increase during the simulation reaching a peak near the waste package around 14 years and cool off as the SNF continues to decay. The porosity substantially decreases during the first 40 years and then continues to decrease throughout the remainder of the simulation. This behavior is consistent among all the cases.

A single simulation for larger (32-PWR size) packages suggests that such packages (containing 40 GW-d/MT burnup commercial SNF) could be emplaced in a Generic Salt Repository after fewer than 100 yr of decay storage.

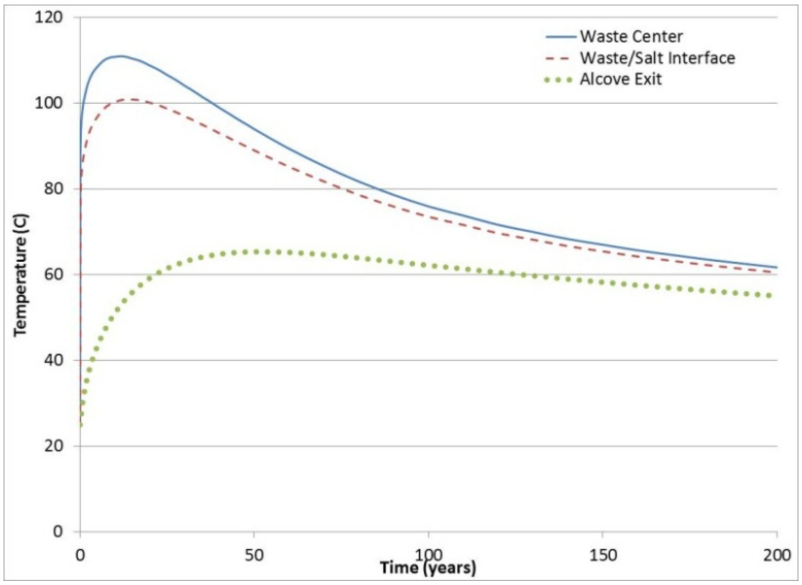


Figure C-4 Temperature History for the 4-PWR Package Case with 40 GW-d/MT Burnup, 10 yr OoR, and without Ventilation

Table C-4 Case Descriptions and Peak Salt (Waste Package Wall) Temperature

Package Type	Fuel Burnup (GW-d/MT)	MTIHM	Age OoR (yr)	Initial Heat Output (kW)	Ventilation	~ Peak Salt Temperature (°C)
WASTE PACKAGE SIZE [A]						
4-PWR	40	1.88	10	2.7	No	75
4-PWR	60	1.88	10	4.5	No	110
12-PWR	40	5.64	10	8.0	No	160
12-PWR	60	5.64	10	13.5	No	275
21-PWR	40	9.87	10	14.1	No	270
AGING STUDY [A]						
4-PWR	40	1.88	50	1.3	No	50
4-PWR	60	1.88	50	2.0	No	65
12-PWR	40	5.64	50	3.8	No	90
12-PWR	60	5.64	50	5.9	No	130
21-PWR	40	9.87	50	6.7	No	145
21-PWR	60	9.87	50	10.4	No	220
32-PWR	40	15.04	50	10.2	No	210
32-PWR	60	15.04	50	15.8	No	330
BACKFILL CONSOLIDATION STUDY [B]						
4-PWR	40	1.88	10	3.7	No	100
4-PWR*	40	1.88	10	3.7	No	100
21-PWR	40	9.87	50	9.0	No	190
21-PWR*	40	9.87	50	9.0	No	185
VENTILATION STUDY [C]						
12-PWR	40	5.64	10	11.2	No	240
12-PWR	40	5.64	10	11.2	5 kg/s	205
12-PWR	60	5.64	10	17.5	No	410
12-PWR	60	5.64	10	17.5	5 kg/s	350
12-PWR	60	5.64	20	14.0	No	315
12-PWR	60	5.64	20	14.0	5 kg/s	265
12-PWR	60	5.64	50	7.8	No	170
12-PWR	60	5.64	50	7.8	5 kg/s	145
21-PWR	40	9.87	10	19.7	No	450
21-PWR	40	9.87	10	19.7	50 kg/s	345
21-PWR	40	9.87	10	19.7	5 kg/s	360
21-PWR	40	9.87	20	15.9	No	345
21-PWR	40	9.87	20	15.9	5 kg/s	280
21-PWR	40	9.87	50	9.0	No	190
21-PWR	40	9.87	50	9.0	5 kg/s	150
21-PWR	60	9.87	50	13.6	No	295
21-PWR	60	9.87	50	13.6	5 kg/s	235

NOTES:

[A] SNF heat generation functions from Carter et al. (2012a).

[B] These runs used heat generation functions approximately 30% hotter than Carter et al. (2012a) and are presented here for relative comparison of backfill consolidation effects. The asterisks denote coupled thermal-mechanical runs, while the others are thermal-only.

[C] These runs also used 30% hotter heat generation functions, and are presented for relative comparison of the effects from ventilation (see text). Peak salt temperature for these runs occurs within a few years after emplacement and the start of ventilation.

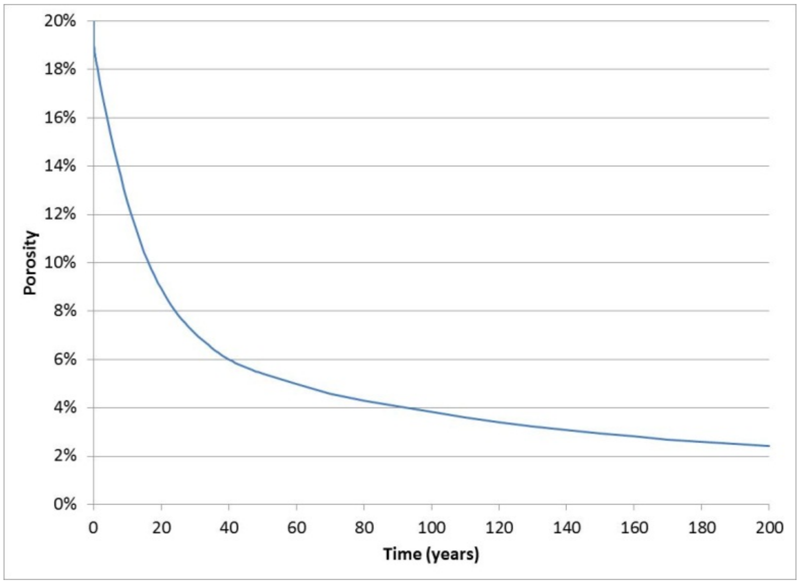


Figure C-5 Crushed Salt Backfill Porosity History for the 4-PWR Package Case with 40 GW-d/MT Burnup, 10 yr OoR, and without Ventilation

C.5 Salt "Hybrid" Concept

The "hybrid" concept for a salt repository is an extension of the Generic Salt Repository with the addition of dedicated drifts to remove heat by forced ventilation. Salt is not suited to open emplacement modes with in-drift emplacement, because the closure of underground openings accelerates at elevated temperature. Accordingly, to stay open for heat removal the ventilated openings must be maintained at close to the ambient salt temperature, which means they must be vigorously ventilated and set apart from the emplacement openings. The "hybrid" reference mode does this with a simple change to the GSR concept by adding parallel ventilation drifts (Figure C-6). The cross-section of the ventilation drifts is selected to maximize stability, and is assumed to be circular (for an isotropic in situ stress state in the salt formation). By comparison, the disposal access drifts and emplacement alcoves would be rectangular as proposed for the original GSR concept (Section 4.3). During ventilation operations the dedicated drifts can be readily maintained because the surrounding rock is kept cool, and radiological shielding is provided by the rock mass. The duration of ventilation could be a few years to several decades, depending on cooling needs for the types of waste emplaced in the adjacent emplacement alcoves.

The results summarized in Table C-4 show that this concept reduces peak temperatures by approximately 50 C° (for temperatures in the range 200 to 300°C) for the lower ventilation rate (5 kg/s), and close to 100 C° for the higher ventilation rate (50 kg/s) and higher temperatures. Temperature rise at the access drift wall is only a few degrees, for ventilation air introduced at the ambient temperature of 27°C.

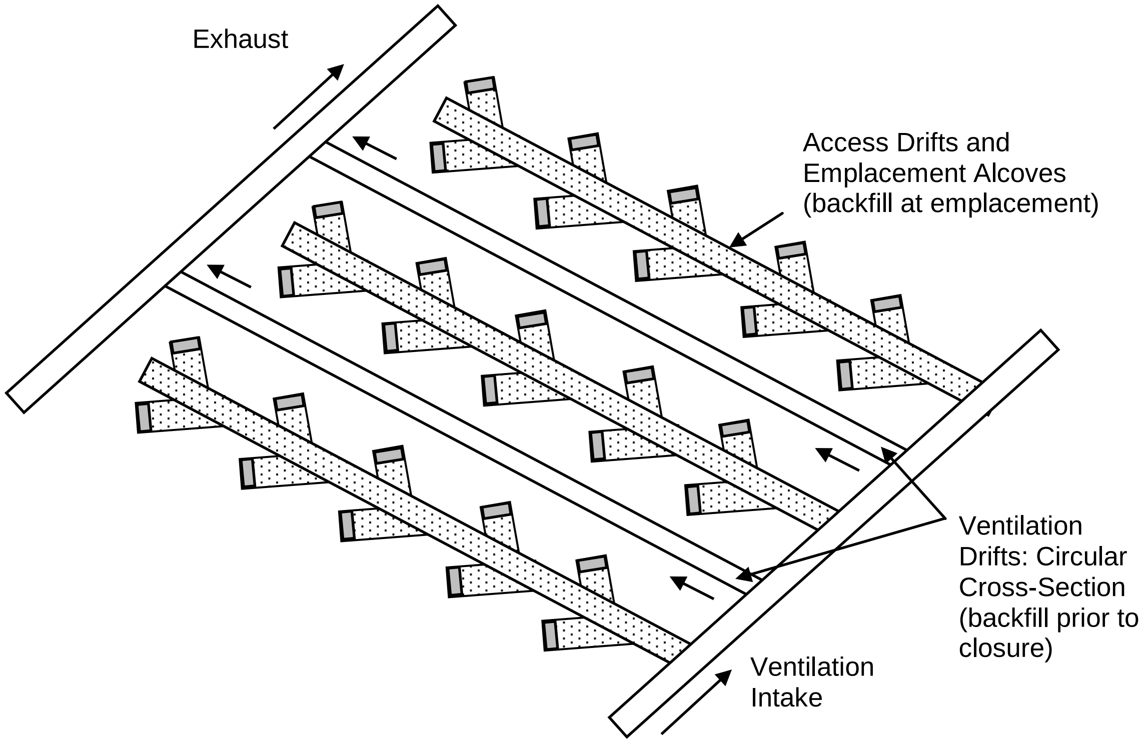


Figure C-6 Schematic of the “Hybrid” Emplacement Mode for Heat Removal in Salt

To be able to provide ventilation, the ventilation drifts must remain open with reasonable maintenance. To evaluate the long-term stability of access drifts, the mechanical response of a circular opening was simulated at various values of the (homogeneous) rock temperature. The opening diameter of 3.75 m corresponds approximately to the hydraulic diameter of the access drifts in previous simulations. Closure histories for the round opening are shown in Figure C-7 for temperatures up to 40°C. The closure rate increases with temperature. For the opening to close by 10% of its original diameter at 25°C would take about 33 years, while that time decreases to 14 years at 40°C. Thus it may be feasible to maintain open ventilation drifts for a few decades, if the ventilation is designed to limit the temperature rise in the rock around those drifts.

These results indicate that a “hybrid” emplacement mode in salt could be effective for a few decades, before maintenance of the ventilation openings becomes intensive (e.g., until closure reaches approximately 10% of original opening diameter). Ventilation for a few decades would effectively limit peak salt temperatures that would otherwise occur in the first 10 to 20 years, and therefore trades directly against additional surface decay storage. Also, an effective limit on temperature rise in the wall rock around the access drifts means that fresh air would be provided to small panels in which each access drift connects to only a few alcoves (e.g., 10 to 20). This is a minor constraint on the repository layout, and might be offset by a different layout optimized for heat removal by ventilation. Finally, note that peak salt temperature is the most stringent test on the effectiveness of heat removal by ventilation, and that ventilation would be much more effective at limiting the average temperature rise across the repository footprint, if that proves to be a more important constraint.

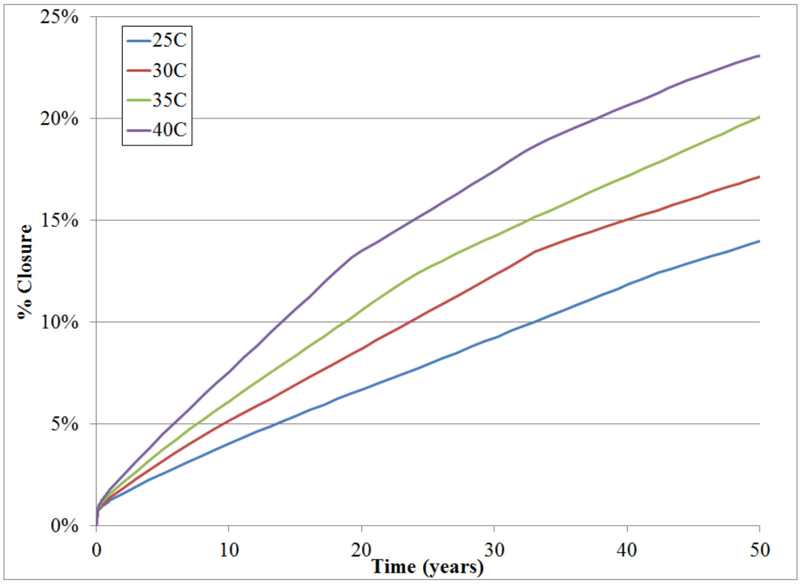


Figure C-7 Closure History for a 3.75 m Diameter Circular Opening vs. Salt Temperature

Appendix D – Parameter Uncertainty for Repository Thermal Analysis

D.1 Introduction

An earlier study of reference geologic disposal concepts (Hardin et al. 2011) concluded that certain disposal concepts would require extended decay storage prior to emplacement, or the use of small waste packages, or both. The study used nominal values for thermal properties of host geologic media and engineered materials, demonstrating the need for uncertainty analysis to support the conclusions. This appendix identifies the input parameters of the maximum temperature calculation, surveys published data on measured values, uses an analytical approach to determine which parameters are most important, and performs an example sensitivity analysis.

The survey of published information on thermal properties of geologic media and engineered materials, is sufficient for use in generic calculations to evaluate the feasibility of reference disposal concepts. A full compendium of literature data is beyond the scope of this report. The term "uncertainty" is used here to represent measurement uncertainty, spatial variability within host geologic units, and variability across units. Uncertainty is then quantified by "variance" in the analysis. For the most important parameters (e.g., buffer thermal conductivity) the extent of literature data surveyed here samples these different contributions.

D.2 Analytical Sensitivity

The purpose of this analysis is to determine the relative contribution of variance in each key parameter to overall variance in temperature, as calculated with an analytical method similar to that used to evaluate reference disposal concepts (Hardin et al. 2011, Section 5). A classical approach is used to evaluate the relative contributions from thermal conductivity, heat capacity, and buffer radius ratio parameters, while a direct approach is used for sensitivity to initial waste heat output. In the classical approach, variance in key parameters and in overall temperature, is evaluated for parameter values in the local vicinity of solutions used to represent each reference disposal concept (i.e., this is a local, not a global variance analysis). This limitation is appropriate because the purpose of this analysis is to gain insight on generic disposal concepts, where each input parameter can be considered separately and the parameters are uncorrelated. For a particular site, other approaches such as Monte Carlo sampling could be used given the availability of more definitive parameter support (e.g., separately quantified spatial variability).

The direct approach is described in Section D.5, and is used to show the correlation between maximum temperature and waste package power at emplacement (taking into account the form of the thermal decay function). Such correlations for SNF disposal in each host medium are developed for use in system studies that impose thermal power limits on SNF packaging, storage, transport, or disposal.

D.2.1 Analytical Derivation of Temperature Sensitivity

A simplified model is used for uncertainty analysis, that represents both the transient and steady-state parts of the analytical model. The transient part is represented using an analytical line-source solution (Hardin et al. 2011, Section G.3) and the steady-state part is represented by adding the same axisymmetric function (Section G.4). This approach departs from the full solution only with respect to the difference between an infinite line source, and a finite line source plus an array of point sources. For this analysis heating from adjacent drifts is less important for peak near-field temperatures that occur in the first few years after waste emplacement (Hardin et al. 2011; comparing the sum of the central package and adjacent package contributions, to the adjacent drift contributions in Figures 5.3-3 and 5.3-4). Whereas the model developed in the FY11 report used multiple annular layers to represent the EBS (Hardin et al. 2011, Figures 5.1-1, and 5.1-3 through 5.1-6), the simplified model used here uses a single annular layer to address the impact of an uncertain thermal resistance, dominated by backfill or a clay buffer, on the total variance for temperature. The simplified model for temperature *T* as a function of radius *r* (with $r = r_2$) and time *t*, to be used for parameter uncertainty analysis, has the form:

$$T(t) = T_{amb} + \frac{Q(t)}{2\pi K_{buf}} \ln\left(\frac{r_2}{r_1}\right) + \int_0^t \frac{Q(\tau)}{4\pi K_{rock}(t-\tau)} e^{\frac{-r_2^2 \rho C_p}{4K_{rock}(t-\tau)}} d\tau \qquad \text{Eqn. D-1}$$

where K_{rock} = rock thermal conductivity (W/m-K)
ρC_p = rock heat capacitance (volumetric heat capacity; J/m^3-K)
K_{buf} = buffer thermal conductivity (W/m-K)
$Q(t)$ = the line source strength (W/m)
r_1 = waste package radius (m)
r_2 = buffer radius (m)
T_{amb} = the ambient (far-field) rock temperature (°C)

The line-source temperature at radius r_2 (outer radius of the buffer, or alternatively, the interface between the EBS and the host rock) represented by the third term on the right-hand side of Equation D-1, is increased by the second term to account for heat conductance across a single annular layer. Additional layers could be added to the engineered barriers between the waste package and the rock, such as a metallic liner or envelope, but metallic layers have little effect on peak waste package surface temperature because they are thin and have high thermal conductivity. The overall variance of T(t) is given by (Hahn and Shapiro (1967, p. 231):

$$\mathrm{Var}\{T(t)\} = \sum_{i=1}^{n} \left(\frac{\partial T}{\partial z_i}\right)^2 \mathrm{Var}\{z_i\} \qquad \text{Eqn. D-2}$$

where there are n parameters z_i. Analytical expressions for $\frac{\partial T}{\partial z_i}$ were symbolically calculated using MathCad14®, with respect to parameters K_{rock}, K_{buf}, ρC_p, and r_2/r_1. The calculation point for maximum temperature is selected as the waste package wall, as it was for the previous analysis. Materials outside the waste package (clay-based buffer, intact clay/shale, crushed salt backfill, intact salt, etc.) have maximum allowable temperatures (e.g., 100°C or possibly higher for clay buffers, 200°C for crushed salt; see Hardin et al. 2011) that are less than the limit on waste package wall temperature associated with package contents. These materials are therefore limiting for management of waste heat after emplacement.

Framing parameter uncertainty as a variance analysis for this model, incorporates not only the functional dependence $\frac{\partial T}{\partial z_i}$ but also the range of variability for key parameters, expressed in $\mathrm{Var}\{z_i\}$. Values for $\mathrm{Var}\{z_i\}$ are estimated in the next section using ranges reported in the literature for similar materials.

With the addition of open modes to the portfolio of reference disposal options, thermal analysis must account for the heat removed by preclosure ventilation, and radiative heat transfer across gaps whenever ventilation is not effective. During ventilation, heat removal decreases the power dissipated to the waste package surroundings by as much as a factor of 6 (BSC 2004) so there is no possibility of exceeding near-field temperature limits for normal operation. (Off-normal operations are beyond the scope of this report.) For heat transfer across gaps, the effect is similar to a high effective thermal conductivity (e.g., see BSC 2004, Equation 6-53).

Selection of the ratio r_2/r_1 is based on the idea that buffer size (r_2) would be selected after waste package size (r_1). For the four key parameters K_{rock}, K_{buf}, ρC_p, and r_2/r_1 of the model (Equation D-1) the partial derivatives comprising the right-hand side of Equation D-2 are:

$$\frac{d}{dKrock}T(t) = \int_0^t \left[\frac{e^{\frac{\rho Cp \cdot (r_2)^2}{4 \cdot Krock \cdot (\tau - t)}} \cdot Q(\tau)}{4 \cdot \pi \cdot Krock^2 \cdot (\tau - t)} + \frac{\rho Cp \cdot (r_2)^2 \cdot e^{\frac{\rho Cp \cdot (r_2)^2}{4 \cdot Krock \cdot (\tau - t)}} \cdot Q(\tau)}{16 \cdot \pi \cdot Krock^3 \cdot (\tau - t)^2} \right] d\tau$$

Eqn. D-3

$$\frac{d}{dKbuff}T(t) = -\frac{\ln\left(\frac{r_2}{r_1}\right) \cdot Q(\tau)}{2 \cdot \pi \cdot Kbuff^2}$$

Eqn. D-4

$$\frac{d}{d\rho Cp}T(t) = \int_0^t -\frac{(r_2)^2 \cdot e^{\frac{\rho Cp \cdot (r_2)^2}{4 \cdot Krock \cdot (\tau - t)}} \cdot Q(\tau)}{16 \cdot \pi \cdot Krock^2 \cdot (\tau - t)^2} \, d\tau$$

Eqn. D-5

$$\frac{d}{dr2r1}T(t) = \frac{Q(\tau)}{2 \cdot \pi \cdot Kbuf \cdot r2r1} + \int_0^t -\frac{(r_2)^2 \cdot \rho Cp \cdot e^{\frac{(r_2)^2 \cdot \rho Cp}{4 \cdot Krock \cdot (\tau - t)}} \cdot Q(\tau)}{8 \cdot \pi \cdot Krock^2 \cdot (\tau - t)^2} \, d\tau$$

Eqn. D-6

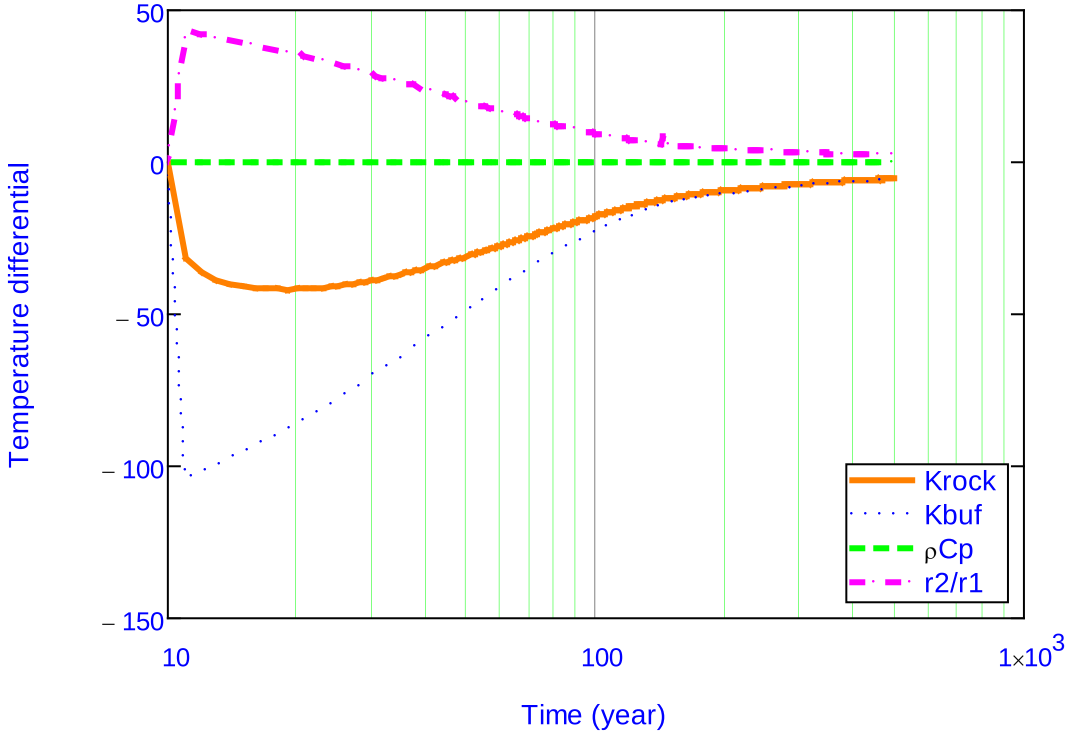
where parameter r2r1 represents r_2/r_1. Note that the derivative expressions above are presented in MathCad® syntax as total derivatives, whereas Equation D-2 is written with partials. The distinction is not meaningful here because the parameters of interest here are essentially independent, uniform (within the domains where they apply), and not time-varying (e.g., K_{buf} is an effective value). Thus, the two types of derivatives are equivalent for this analysis.

Each of the expressions above (Equations D-3 through D-6) contains an integral which is the convolution of the thermal decay function and must be evaluated numerically. The results from applying these derivatives are presented below as the unnormalized magnitudes of the differentials $\frac{\partial T}{\partial z_i}$ (Figure D-1). The differentials with respect to thermal conductivities of the rock and buffer are negative, as expected, while the differential with respect to r_2/r_1 is positive, and that with respect to ρC_p is close to zero. Because these curves are unnormalized and therefore have different dimensions, they cannot be compared directly in magnitude. The variance approach outlined above is used in Section D.4 below to facilitate direct comparison.

The above discussion does not consider uncertainty on the heat input, i.e., the line source strength Q(t). Uncertainty in heat output from SNF or HLW is related to uncertainty in composition, particularly the major heat-producing fission products (Cs-137 and Sr-90) and certain actinides (e.g., Am-241). Whereas uncertainty in heat output of SNF assemblies is possible, it is not treated as parametric uncertainty here because it is relatively small compared to that associated with other parameters such as clay buffer characteristics and host rock thermal conductivity. Also, the uncertainty for a waste package containing multiple assemblies decreases statistically, if the variability among assemblies is uncorrelated. The potential effects of uncertainty in waste package heat output on maximum temperature can be readily visualized using the correlations developed in Section D.5.2.

D.3 Parameter Uncertainty Ranges

This section presents a limited survey of literature data for K_{rock} and ρC_p, specific to crystalline rock, clay/shale media, salt, and alluvium. It also reviews literature data for K_{buf}, for clay buffer materials and other engineered materials. The important result of these reviews is a set of low-high ranges for each parameter, for each host medium. Treating the reported literature data as samples from populations of independent data, the sample mean and sample standard deviation were calculated (Tables D-1 though D-4).



Note: For the case of crystalline host rock, 4-PWR waste packages (0.66 m diameter), 0.35 m buffer thickness, and SNF with 40 GW-d/MT burnup (10 yr out-of-reactor). For buffer thermal conductivity the average of dry and hydrated values was used.

Figure D-1 Unnormalized (dimensional) Partial Derivatives of Temperature at the Waste Package Surface with Respect to Key Model Parameters (K_{rock}, $K_{buf,}$ ρC_p, and r_2/r_1), for the Crystalline Rock SNF Disposal Reference Case

The estimated sample statistics are useful to describe the uncertainty in these key parameters, subject to limitations because the literature data were not all produced the same way, have associated measurement errors or biases, and in some instances the data are sparse. Accordingly, a range selection is also provided, rounding the estimates (mean ± standard deviation) up or down, consistent with qualitative indications of the reproducibility and stability in reported data of each type. The adjusted estimate of the standard deviation is then half the selected range, and the estimated parameter variance for use in this study is the square of the standard deviation.

D.3.1 Host Rock Thermal Conductivity

Thermal conductivity for the different host geologic media are shown in Table D-1, derived from a collection of literature (much of which is related to geologic disposal of heat-generating waste). Some of the sources have provided ranges, and the endpoints are treated as separate estimates thereby assigning twice the weight to these sources.

Granite and other crystalline rocks (metamorphic or igneous) have small porosity, and thermal conductivity is not sensitive to the state of moisture saturation. Hence, the values used here do not distinguish saturation state. The calculated standard deviation of K_{rock} is 0.37, but the selected range (representing $\pm 1\sigma$) has a width of 0.8 allowing for some unknown variations in porosity, saturation, measurement method, spatial variability, etc. The variance Var{K_{rock}}is estimated from the square of the estimated standard deviation ($0.37^2 = 0.14$, units of $(W/m\text{-}K)^2$).

For clay and shale media the range is broader reflecting the incorporation of indurated shales and non-indurated plastic clays. Also, the parallel and perpendicular orientations are lumped together, which is an approximation that can be used as input to a temperature solution for isotropic media (the estimates could be split for anistropy calculations). For in situ or intact measurements on these materials, the moisture content is assumed to be close to undisturbed conditions, so the values here do not distinguish saturation state. The excavation damage zone (EDZ) measurement of Johnson et al. (2002) is included, but falls near the middle of the selected range.

For salt two thermal conductivity ranges are selected, for 100°C and 200°C. Only one value for 200°C is presented here (model based, supported by experimental data) so the standard deviation from the 100°C data is used for the 200°C case. Salt has low porosity and moisture content so thermal conductivity is not sensitive to the state of moisture saturation.

Alluvium has high porosity (on the order of 30% or greater) and volumetric (total) moisture content from approximately 5% to 20% (i.e., moisture saturation up to 70% or greater). Accordingly, two ranges are presented for in situ or unsaturated conditions, and for wet or saturated conditions. Only data for naturally consolidated (not re-consolidated) samples or in situ measurements are presented. The unsaturated data are recommended for use with the unsaturated, sedimentary disposal concept, although the "wet" or saturated data could be used with justification.

Finally, no literature data survey is provided for the crystalline basement host medium. This is a somewhat generic category of rock types so a wide range of igneous and metamorphic rock types is possible. Importantly, the previous analysis (Hardin et al. 2011, Section 5) showed that maximum temperatures for the Deep Borehole concept would be relatively low because of the small diameter and limited waste content of the canisters. Further, no temperature limits were identified, so the uncertainty in basement rock thermal conductivity does not appear to be a significant factor, and no analysis is provided here.

D.3.2 Engineered Material Thermal Conductivity

Thermal conductivity for clay buffer materials described in the geologic disposal literature, and for metals and alloys used in waste packages, are presented in Table D-2. Thermal properties of dry and hydrated bentonite clay-based buffer materials are well studied. Dry and hydrated data are separated in Table D-2, and the modeling strategy should determine the state of the buffer for which maximum temperatures are calculated. An intermediate value was used in previous analysis (Hardin et al. 2011, Section 5.3.2) subject to verification by modeling or experiment.

The results for metals and alloys show that the range of uncertainty is small for all materials except stainless steels, which exhibit variation with differences in type and composition. Regardless, thermal conductivities for all these materials are great enough, and thickness small enough, that they have no significant impact on maximum temperatures (even if used in the engineered barrier system outside of the waste package, such as for liners).

D.3.3 Host Rock Heat Capacity

Heat capacitance (volumetric heat capacity) for the different host geologic media are shown in Table D-3. A somewhat different approach was used for range selection, to allow for additional uncertainty due to saturation and compositional differences, and more direct comparison of the different media. The ranges use the estimated sample mean as the midpoint, and are guided by the calculated standard deviations. For low porosity salt and granite, a ±5% range is selected, while for clay/shale and alluvium, ranges of ±15% and ±20% are selected, respectively. For the crystalline basement (deep borehole) a range of ±10% is assumed.

D.3.4 Waste Package and Buffer Size

The buffer size ratio parameter r_2/r_1 is an engineering detail and not a material physical property. However, it is shown by this report to be an important parameter in the uncertainty of maximum temperature predictions, and a "variance" is estimated to reflect the need for flexibility in the engineering details of disposal concepts. As shown in Table D-4, the variance is approximated using a ±50% range about a nominal buffer thickness ($r_2 - r_1$), for a range of waste package sizes (r_1).

The data for open concepts in Table D-4 are suitable for use in calculations that involve pre-closure ventilation (reducing Q(t)) followed by cessation of forced ventilation at or before repository closure, and either: 1) installation of a backfill around the waste packages, or 2) leaving the air space open around the waste packages. In the first instance, the temperatures after backfilling can be calculated using a model that includes the backfill even during preclosure ventilation, but adjusts Q(t) to account for ventilation heat removal (this is consistent with the model in Equation D-1 because the annular EBS term is steady-state). The point of temperature calculation may be chosen at the waste package surface, to limit the maximum temperature of the engineered backfill. In the second instance, the backfill is replaced by an effective thermal conductivity for the air space throughout the calculation. This is a good approximation because the thermal resistance of an air gap is much lower than backfill or buffer material (effective K_{th} much greater than buffer conductivity K_{buf}). In this second instance the point of temperature calculation may be selected at the rock wall or the waste package depending on which is limiting.

D.3.5 Summary

Key parameters (K_{rock}, K_{buf}, ρC_p, and r_2/r_1) were identified for an analytical solution for repository temperatures, that represents the analysis approach used in the FY11 report (Hardin et al. 2011). Literature data were compiled (Tables D-1 through D-3) and uncertainty ranges selected for different host geologic media and for clay-based buffers. The buffer radius ratio (expressed as r_2/r_1) was similarly described using ±50% variation around the reference values (Table D-4; reference values from Hardin et al. 2011). The results consisting of average and low, high (±1σ) values for each parameter, are intended for use in temperature uncertainty analyses using calculation approaches similar to Equation D-1.

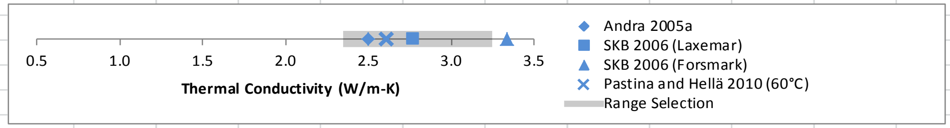
Parameter ranges for K_{rock}, K_{buf}, ρC_p, and r_2/r_1 from Section D.2 are converted to estimates of variance representing for host media, and clay-based buffers, using the range endpoints as estimates of ±1σ values. The sample variance is then estimated from

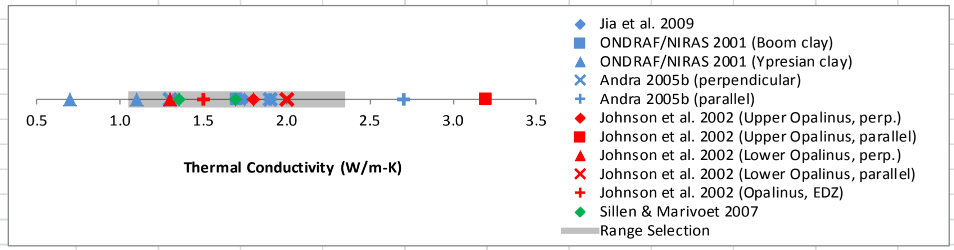
$$\mathrm{Var}\{z_i\} \approx \left[\frac{\left(\mathrm{Range}_{\mathrm{high}} - \mathrm{Range}_{\mathrm{low}}\right)_i}{2} \right]^2 \qquad \text{Eqn. D-7}$$

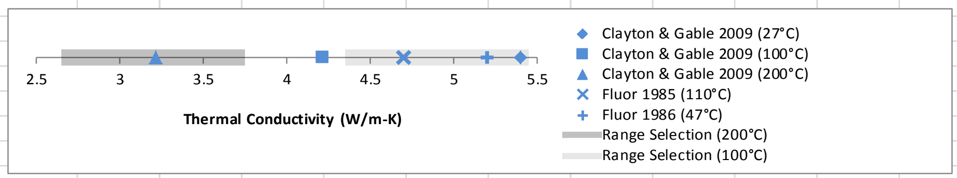
The resulting sample variance estimates for the key parameters K_{rock}, K_{buf}, ρC_p, and r_2/r_1, along with the nominal values of these parameters for reference disposal concepts, are summarized in Table D-5.

Table D-1 Host Rock Thermal Conductivity Ranges and Parameter Variance

Host Rock Thermal Conductivity					
Low	High	Source	Average	Std. Dev.	
Granite					
2.50		Andra 2005a	2.81	0.37	
2.77		SKB 2006 (Laxemar)			
3.34		SKB 2006 (Forsmark)			
2.61		Pastina and Hellä 2010 (60°C)			
2.4	3.2	Range Selection			
Clay/Shale					
1.75		Jia et al. 2009	1.73	0.61	
1.70		ONDRAF/NIRAS 2001 (Boom clay)			
0.70	1.1	ONDRAF/NIRAS 2001 (Ypresian clay)			
1.3	1.9	Andra 2005b (perpendicular)			
1.9	2.7	Andra 2005b (parallel)			
1.8		Johnson et al. 2002 (Upper Opalinus, perp.)			
3.2		Johnson et al. 2002 (Upper Opalinus, parallel)			
1.3		Johnson et al. 2002 (Lower Opalinus, perp.)			
2.0		Johnson et al. 2002 (Lower Opalinus, parallel)			
1.5		Johnson et al. 2002 (Opalinus, EDZ)			
1.35	1.69	Sillen & Marivoet 2007			
1.1	2.3	Range Selection			
Salt					
5.4		Clayton & Gable 2009 (27°C)	4.88	0.53	
4.2		Clayton & Gable 2009 (100°C)			
4.7		Fluor 1985 (110°C)			
5.2		Fluor 1986 (47°C)			
3.2		Clayton & Gable 2009 (200°C)	3.21	0.53	
4.4	5.4	Range Selection (100°C)			
2.7	3.7	Range Selection (200°C)			
Alluvium					
1.05		Wollenberg et al. 1982 (in situ)	1.06	0.11	
0.91	1.14	Wollenberg et al. 1983 (downhole probe)			
1.0	1.2	Smyth et al. 1979 (unsat., consolidated)			
1.0	1.2	Range Selection (unsat., consolidated)			
0.98	1.42	Wollenberg et al. 1982 (wet, consolidated)	1.49	0.34	
1.21	1.81	Wollenberg et al. 1982 (wet, consolidated)			
1.51	2	Wollenberg et al. 1982 (wet, consolidated)			
1.5		Wollenberg et al. 1982 (saturated, consolidated)			
1.2	1.8	Range Selection (saturated, consolidated)			
Crystalline Basement					
3.0		Brady et al. 2009			No temperature limits identified for deep borehole disposal concept (Hardin et al. 2011).







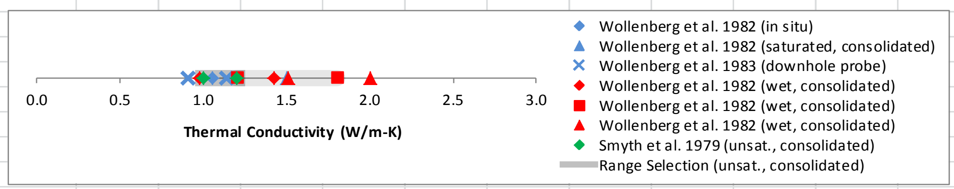
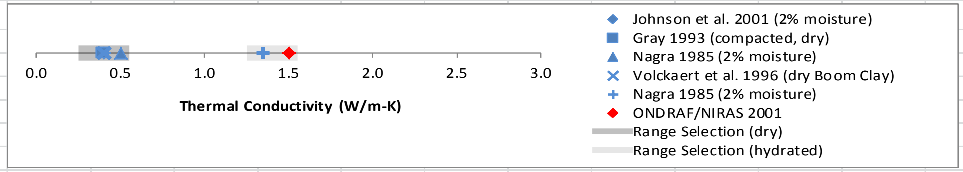
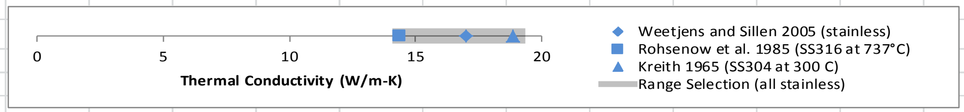
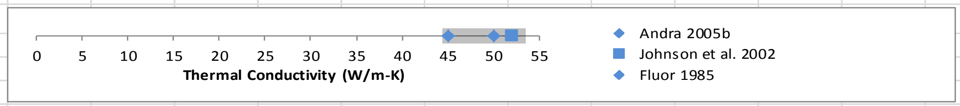


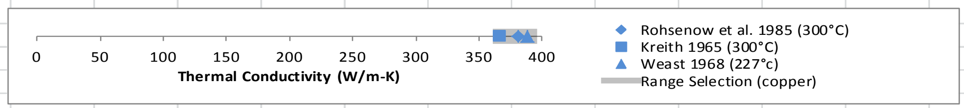
Table D-2 Engineered Material Thermal Conductivity Ranges and Parameter Variance

Engineered Material Thermal Conductivity				
Low	**High**	**Source**	**Average**	**Std. Dev.**
Clay Buffer (compacted)				
0.4		Johnson et al. 2001 (2% moisture)	0.42	0.05
0.39		Gray 1993 (compacted, dry)		
0.5		Nagra 1985 (2% moisture)		
0.4		Volckaert et al. 1996 (dry Boom Clay)		
0.3	0.5	Range Selection (dry)		
1.35		Nagra 1985	1.43	0.11
1.5		ONDRAF/NIRAS 2001		
1.3	1.5	Range Selection (hydrated)		
Stainless Steel				
17.0		Weetjens and Sillen 2005 (stainless)	16.7	2.26
14.4		Rohsenow et al. 1985 (SS316 at 737°C)		
18.9		Kreith 1965 (SS304 at 300 C)		
14.4	19	Range Selection (all stainless)		
Carbon Steel				
50.0		Andra 2005b	49.0	3.61
52.0		Johnson et al. 2002		
45.0		Fluor 1985		
45.4	52.6	Range Selection (carbon steel)		
Copper				
380.9		Rohsenow et al. 1985 (300°C)	378.6	10.73
366.9		Kreith 1965 (300°C)		
388.0		Weast 1968 (227°c)		
367.9	389.3	Range Selection (copper)		
Crushed Salt (partially consolidated)				
0.46		Fluor 1985	0.47	0.01
0.47		Bechtold et al. 2004 (30% porosity, 100°C)		
0.4	0.6	Range Selection (30% porosity, 100°C)		
1.34		Bechtold et al. 2004 (20% porosity, 200°C)	1.34	0.01
1.2	1.4	Range Selection (20% porosity, 200°C)		









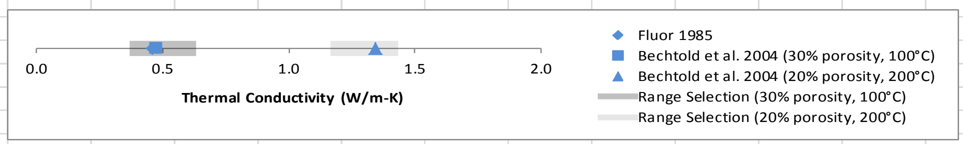
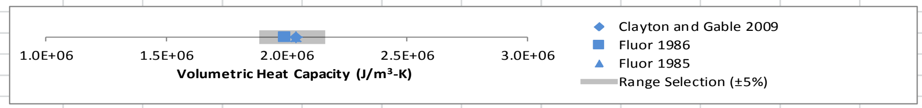
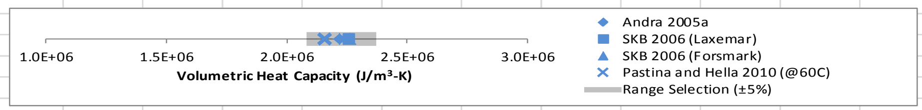
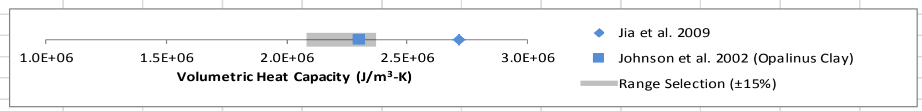


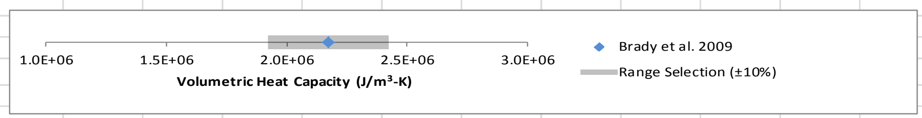
Table D-3 Host Rock Heat Capacitance (Volumetric Heat Capacity) Ranges and Parameter Variance

Gravim. Heat Cap. (J/kg-K)	Dry Bulk Density (kg/m^3)	Volum. Heat Cap. (J/m^3-K)	Host Rock Heat Capacitance	Avg.	Std. Dev.
Salt					
931	2190	2.04E+06	Clayton and Gable 2009	2.02E+06	2.88E+04
920	2162	1.99E+06	Fluor 1986		
931	2190	2.04E+06	Fluor 1985		
			Range Selection (±5%): 1.92E+06 to 2.12E+06		
Granite					
837.5	2650	2.22E+06	Andra 2005a	2.22E+06	5.01E+04
837.5	2700	2.26E+06	SKB 2006 (Laxemar)		
837.5	2700	2.26E+06	SKB 2006 (Forsmark)		
784	2749	2.16E+06	Pastina and Hella 2010 (@60C)		
			Range Selection (±5%): 2.11E+06 to 2.34E+06		
Clay/Shale					
1005	2700	2.71E+06	Jia et al. 2009	2.51E+06	2.92E+05
	2400	2.30E+06	Johnson et al. 2002 (Opalinus Clay)		
			Range Selection (±15%): 2.13E+06 to 2.88E+06		
Deep Borehole (Crystalline Basement)					
790	2750	2.17E+06	Brady et al. 2009	2.17E+06	NA
			Range Selection (±10%): 1.96E+06 to 2.39E+06		
Alluvium					
1000	1700	1.70E+06	Smyth et al. 1979	1.46E+06	2.31E+05
1000	1200	1.20E+06	Smyth et al. 1979		
836	1600	1.34E+06	Wollenberg et al. 1983		
1000	1600	1.60E+06	Wollenberg et al. 1983		
			Range Selection (±20%): 1.17E+06 to 1.75E+06		









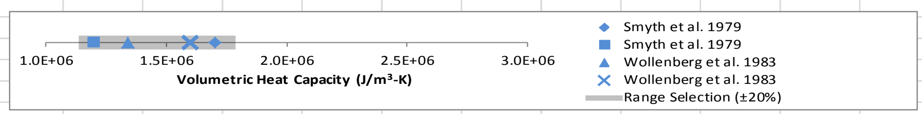


Table D-4 Buffer:Waste Package Radius Ratio Ranges and Parameter Variance

Buffer:Waste Package Radius Ratio								
			Thickness Range Selection		Ratio Range Selection		Std. Dev.	Variance
Waste Package	Radius (m)	Buffer Thickness (m)	-50%	+50%	r2/r1 (-50%)	r2/r1 (+50%)	r2/r1	r2/21
Crystalline Rock (Clay buffer)								
1-PWR	0.17	0.35	0.175	0.525	2.06	4.18	1.06	1.12
4-PWR	0.33	0.35	0.175	0.525	1.53	2.59	0.53	0.28
1-HLW	0.30	0.35	0.175	0.525	1.57	2.72	0.57	0.33
Clay/Shale (Enclosed Mode)								
1-PWR	0.17	0.7	0.35	1.05	3.12	7.36	2.12	4.50
4-PWR	0.33	0.7	0.35	1.05	2.06	4.18	1.06	1.12
1-HLW - no buffer								
Salt (Enclosed Mode) - no buffer								
Deep Borehole - negligible buffer thermal resistance								
Shale Open Mode (backfilled or open at closure)								
4-PWR	0.33	1.82	0.91	2.73	3.76	9.27	2.76	7.60
12-PWR	0.62	1.53	0.765	2.295	2.23	4.70	1.23	1.52
21-PWR	0.90	1.25	0.625	1.875	1.69	3.08	0.69	0.48
32-PWR	1.00	1.15	0.575	1.725	1.58	2.73	0.58	0.33
Sedimentary Open Mode (alluvium, backfilled at closure)								
4-PWR	0.33	1.82	0.91	2.73	3.76	9.27	2.76	7.60
12-PWR	0.62	1.53	0.765	2.295	2.23	4.70	1.23	1.52
21-PWR	0.90	1.25	0.625	1.875	1.69	3.08	0.69	0.48
32-PWR	1.00	1.15	0.575	1.725	1.58	2.73	0.58	0.33

D.4 Variance Estimates for Temperature

Variance estimates from Table D-5 are then used with Equation D-2, to calculate contributions to the overall temperature variance from the variance assigned to each parameter. Figures D-2 through D-4 contributions from key parameters, with and without a buffer. For Figure D-3 the temperature is normalized to temperature using Equations D-1 and D-2:

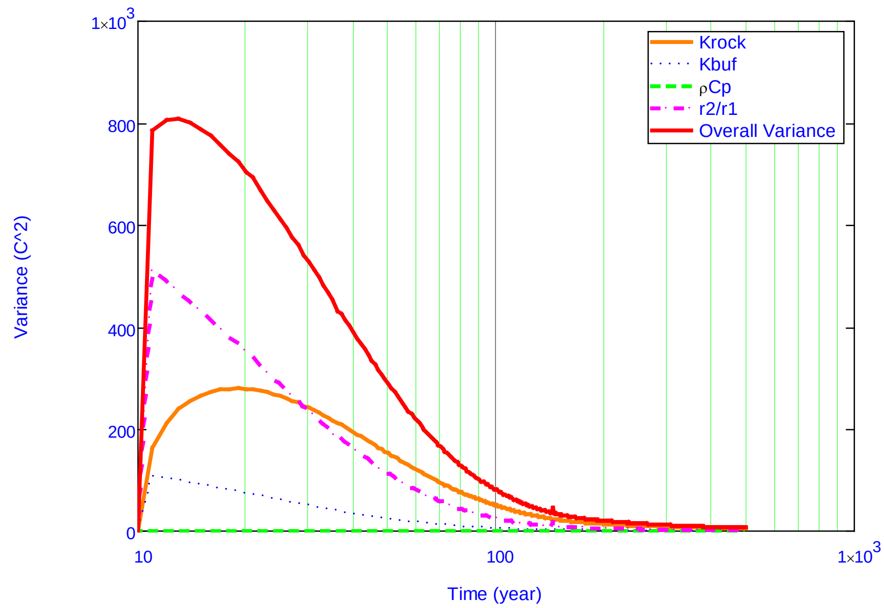
$$\text{Normalized temperature variance} = \frac{\text{Var}\{T(t)\}}{T^2(t)} \qquad \text{Eqn. D-8}$$

The discussion below focuses on the un-normalized, time-varying temperature variance (Figures D-2 and D-4) which applies directly to temperature histories calculated for these cases. (The standard deviation of temperature uncertainty can be estimated by taking the square root of variance in Figures D-2 and D-4.)

Figure D-2 summarizes the results of the analytical sensitivity analysis. The components of variance are summed to generate the overall variance on temperature. The K_{buf} (buffer) curve can be neglected and the overall variance adjusted accordingly, for concepts with no buffer (e.g., Figure D-4). Similarly, the r_2/r_1 curve can be ignored for applications where the waste package and buffer diameters are known.

Table D-5 Parameter Variance Values Used in Analysis

Medium	Range Selection [Low High]	Nominal Value	Std. Deviation	Variance
Host Rock Thermal Conductivity (W/m-K)				
Granite	[2.4 3.2]	2.8	0.37	0.16
Clay/Shale	[1.1 2.3]	1.7	0.61	0.36
Salt (100°C)	[4.4 5.4]	4.9	0.53	0.25
Salt (200°C)	[2.7 3.7]	3.2	0.53	0.25
Alluvium (unsaturated)	[1.0 1.2]	1.1	0.11	0.01
Alluvium (saturated)	[1.2 1.8]	1.5	0.34	0.09
Crystalline Basement	NA	3.0	NA	NA
Engineered Material Thermal Conductivity (W/m-K)				
Clay Buffer (dry)	[0.3 0.5]	0.4	0.05	0.01
Clay Buffer (hydrated)	[1.3 1.5]	1.4	0.11	0.01
Stainless Steel	[14.4 19]	16.7	2.26	5.3
Carbon Steel	[45.4 52.6]	49.0	3.6	13.0
Copper	[367.9 389.3]	378.6	10.7	114.5
Crushed Salt (100°C)	[0.4 0.6]	0.5	0.01	0.01
Crushed salt (200°C)	[1.2 1.4]	1.3	0.01	0.01
Host Rock Heat Capacitance (J/m3-K)				
Granite	[2.11E6 2.34E6]	2.23E6	5.0E4	3.3E9
Clay/Shale	[2.13E6 2.88E6]	2.5E6	2.9E5	1.4E11
Salt	[1.92E6 2.12E6]	2.0E6	2.9E4	1.0E10
Alluvium	[1.17E6 1.75E6]	1.46E6	2.3E5	8.4E10
Crystalline Basement	[1.96E6 2.39E6]	1.18E6	NA	4.6E10
Buffer:Waste Package Radius Ratio				
Granite (enclosed 4-PWR)	[1.53 2.59]	2.06	0.53	0.28
Clay/Shale (enclosed 4-PWR)	[2.06 4.18]	3.12	1.06	1.12
Salt (enclosed all packages)	no buffer			
Alluvium (enclosed 21-PWR)	[1.69 3.08]	2.39	0.69	0.48
Crystalline Basement (enclosed 1-PWR)	negligible thermal resistance			



Note: For the case of crystalline host rock, 4-PWR waste packages (0.66 m diameter), 0.35 m buffer thickness, and SNF with 40 GW-d/MT burnup (10 yr out-of-reactor). For buffer thermal conductivity the average of dry and hydrated values was used. Units of y-axis are (°C)^2.

Figure D-2 Contributions to Overall Un-normalized Variance of Temperature (Equation D-2) at the Waste Package Surface, from Parameters (K_{rock}, K_{buf}, ρC_p, and r_2/r_1) for the Crystalline Rock SNF Disposal Reference Case from Figure D-1

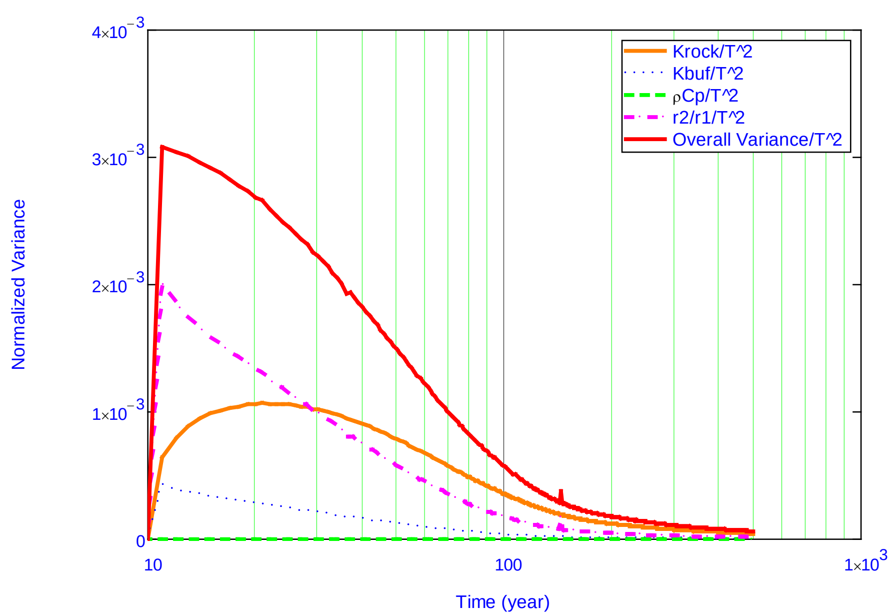
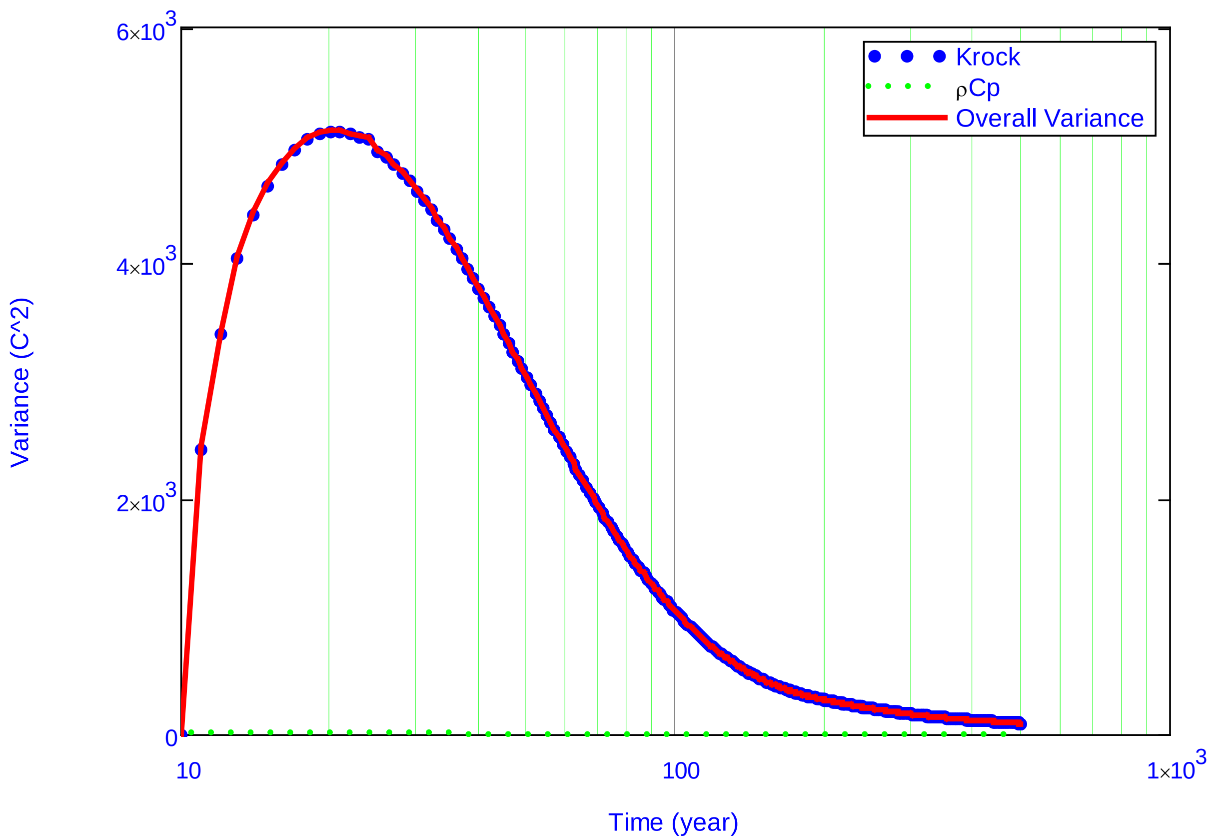


Figure D-3 Normalized Variance of Temperature (Equation D-8) at the Waste Package Surface, for the Crystalline Rock SNF Disposal Reference Case from Figures D-1 and D-2

Uncertainty in heat capacitance (ρC_p) has little or no influence on overall temperature uncertainty at all times (Figures D-2 through D-4) which is expected and consistent with the limited effect and narrow uncertainty ranges for this parameter. Uncertainty in buffer thermal conductivity is less important than the uncertainty in the buffer radius ratio parameter, given the uncertainty ranges assigned to each parameter (Table D-5). Uncertainty in rock thermal conductivity (K_{rock}) becomes most important (Figures D-2 and D-4) after an initial heating period. Similar figures can be generated for other disposal concepts using different waste types and package sizes, but the results are similar to those presented here.

A clay buffer can be a large thermal resistance (combining the effects of K_{buf} and r_2/r_1), and potentially dominate the maximum temperature as shown by the unnormalized derivatives (Figure D-1). Note that the partial derivatives are squared in Equation D-2, so that differences in sign, e.g., between $\partial T/\partial K_{buf}$ and $\partial T/\partial(r_2/r_1)$, do not appear in the overall variance (Figure D-2). Only when the state of knowledge about K_{buf} as represented by Var{K_{buf} } is incorporated, is the variance contribution less than for the host rock (K_{rock}) or buffer radius ratio (r_2/r_1).



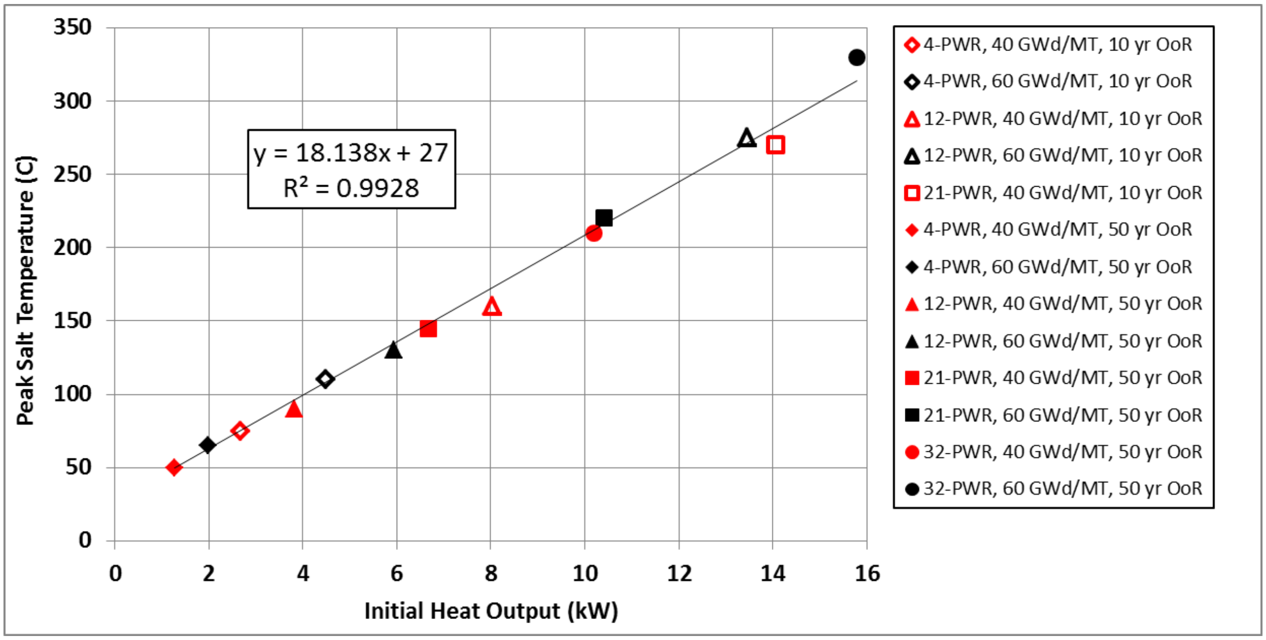
Note: For the case of salt host rock, 21-PWR waste packages (1.80 m diameter), and SNF with 40 GW-d/MT burnup (10 yr out-of-reactor). Thermal conductivity of intact salt at 200 °C was used. The concept does not involve a buffer, so this solution is based on a simple line-source calculation. Units of y-axis are $(°C)^2$

Figure D-4 Contributions to Overall Un-normalized Variance of Temperature (Equation D-2) at the Waste Package Surface, from Parameters (K_{rock} and ρC_p)

D.5 Maximum Temperature Sensitivity

D.5.1 Finite Element Based Correlation for Generic Salt Repository

An earlier study using finite-element (FEM) simulation of the Generic Salt Repository (Appendix C) showed that maximum salt temperature (peak temperature at the waste package surface) is correlated with the initial thermal power of the package at emplacement. The correlation applies over a wide range of package sizes, for a range of SNF burnup (Figure D-5). This result is potentially useful as a thermal-power acceptance criterion for when SNF can be emplaced in a repository, in fuel management system studies. The correlation is further explored in the following section using the analytical solution (Equation D-1) for different geologic host media, waste package sizes, SNF burnup, and decay storage periods.



Note: Calculations combine SNF inventory from Carter and Luptak (2009), with the generic salt disposal concept (Carter et al. 2011), in a series of thermal and thermal-mechanical coupled calculations. See also Appendix C of this report.

Figure D-5 Correlation of Maximum Salt Temperature (Peak Package Surface Temperature) from a Set of Finite Element Simulations of the Generic Salt Repository (calculations described in Appendix C)

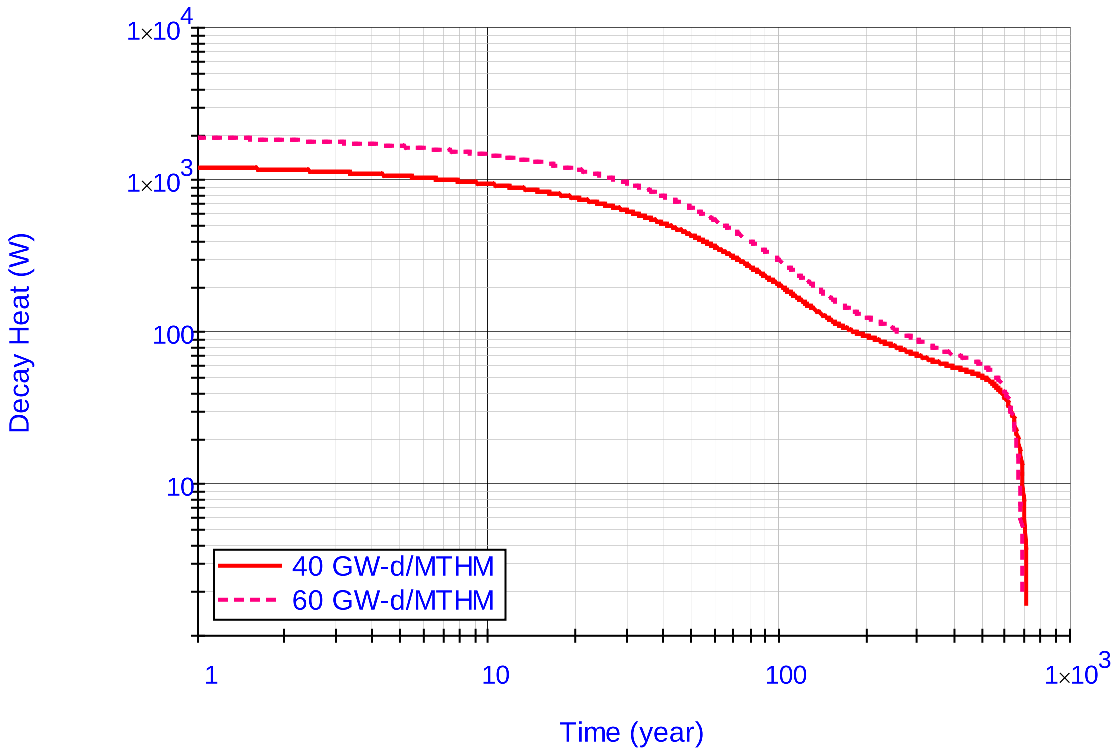
D.5.2 Analytical Line Source Correlations

To corroborate the FEM results for salt, maximum temperatures are calculated for the FY11 reference disposal concepts for SNF using Equation D-1, implemented in MathCad14®. For the salt and deep borehole cases, no buffer is included (i.e., the second term on the right-hand side of Equation D-1 was zero). Input parameters for these calculations include:

- Geologic host media: crystalline (granite), clay/shale, salt, crystalline basement (deep borehole)

- Waste package sizes: 4-, 12- and 21-PWR packages (Hardin et al. 2011)
- Decay heat based on 40 and 60 GW-d/MTHM burnup (Carter and Luptak 2009)
- Surface storage times: 10, 20, 50, 100 years

The calculations are based on a surface temperature of 15°C, a geothermal gradient of 25°C/km, and a depth of 500 m (giving in situ temperature for the disposal depths described by Hardin et al. 2011) except for the deep borehole calculation which is for a depth of 4 km. For this analysis only PWR assemblies (UOX) are considered, and waste package length is 5 m. Figure D-6 shows decay heat for single SNF assemblies with burnup of 40 and 60 GW-d/MTHM.



Note: This figure is based on a curve fit to tabulated data extending up to 500 yr, and was used only to interpolate in the analysis.

Figure D-6 Decay Heat vs. Time Out of Reactor for Individual SNF Assemblies with Burnup of 40 and 60 GW-d/MTHM

The results (Figures D-7 to D-10) show calculated maximum temperatures (peak waste package surface temperatures) for the different disposal concepts, as functions of initial power, waste package size, SNF burnup, and fuel age prior to disposal. The figures show strong correlation between maximum temperature and initial power, with slight shifts due to burnup and age.

For the salt calculation heat dissipation through the crushed salt backfill (comprising 1/4 of the package circumference) is ignored, i.e., the waste heat output is increased by 4/3, and the heat dissipates directly into intact salt. A similar approach was taken for salt in the original calculation (Hardin et al. 2011, Section 5). The calculated maximum temperatures in salt (Figure D-9) are greater than calculated using the FEM (Figure D-4) because of this approximation.

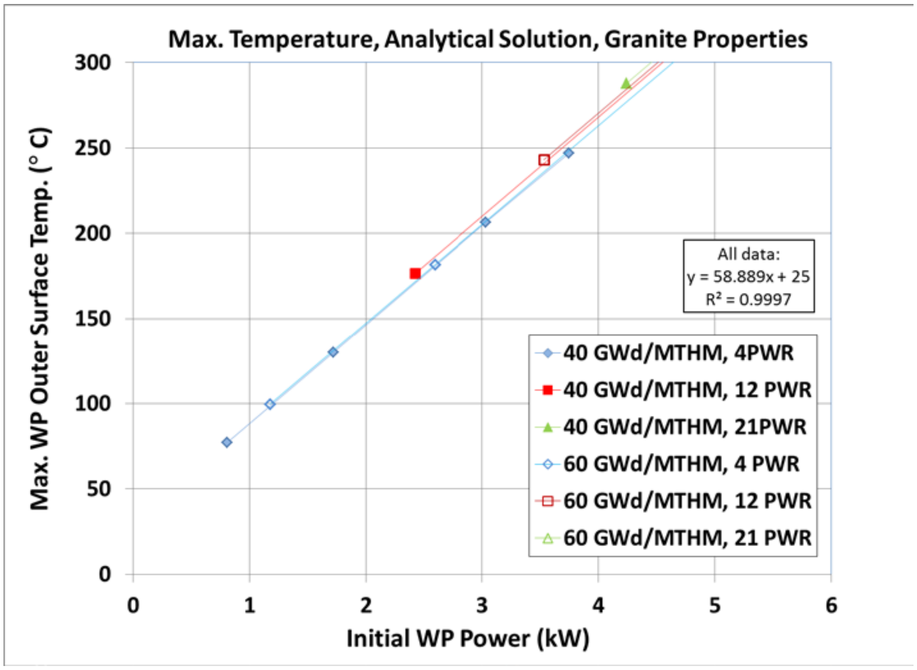


Figure D-7 Maximum Temperature vs. Initial Power for Disposal in Crystalline Rock (with buffer) for Combinations of Waste Package Size, SNF Burnup, and Age

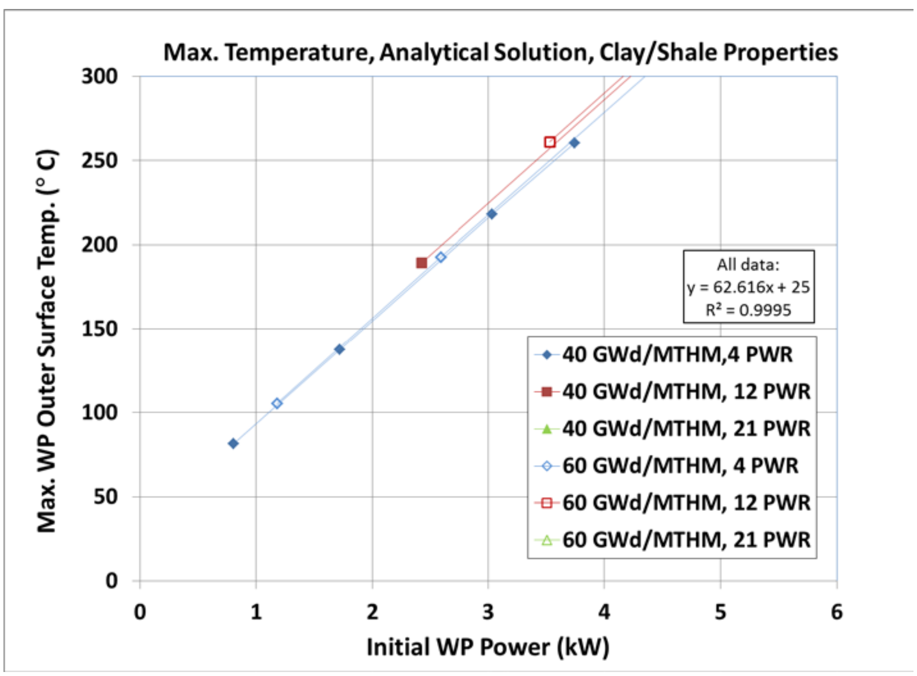


Figure D-8 Maximum Temperature vs. Initial Power for Disposal in Clay/Shale (with buffer) for Combinations of Waste Package Size, SNF Burnup, and Age

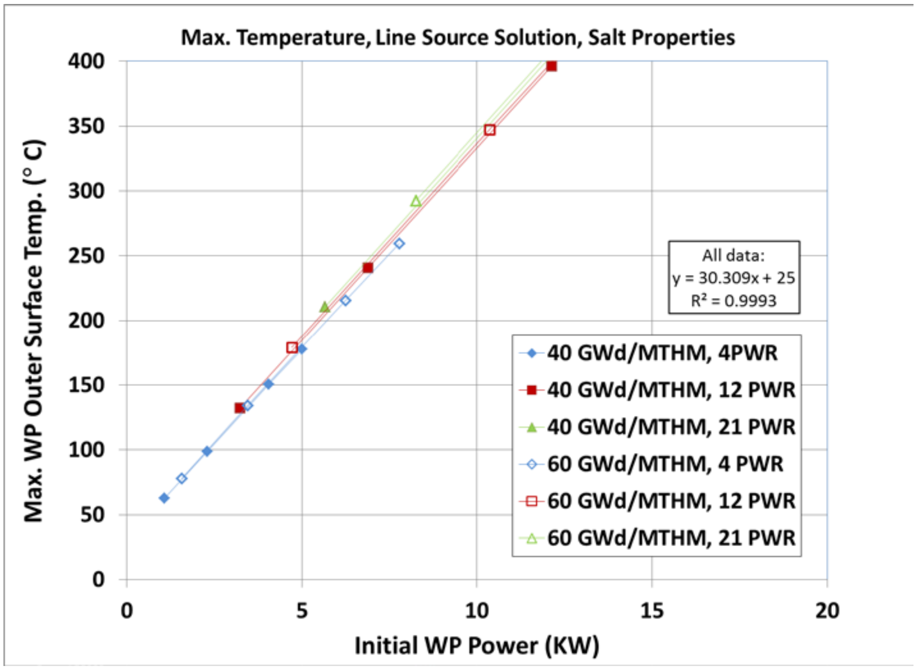


Figure D-9 Maximum Temperature vs. Initial Power for Disposal in Salt (no buffer) for Combinations of Waste Package Size, SNF Burnup, and Age

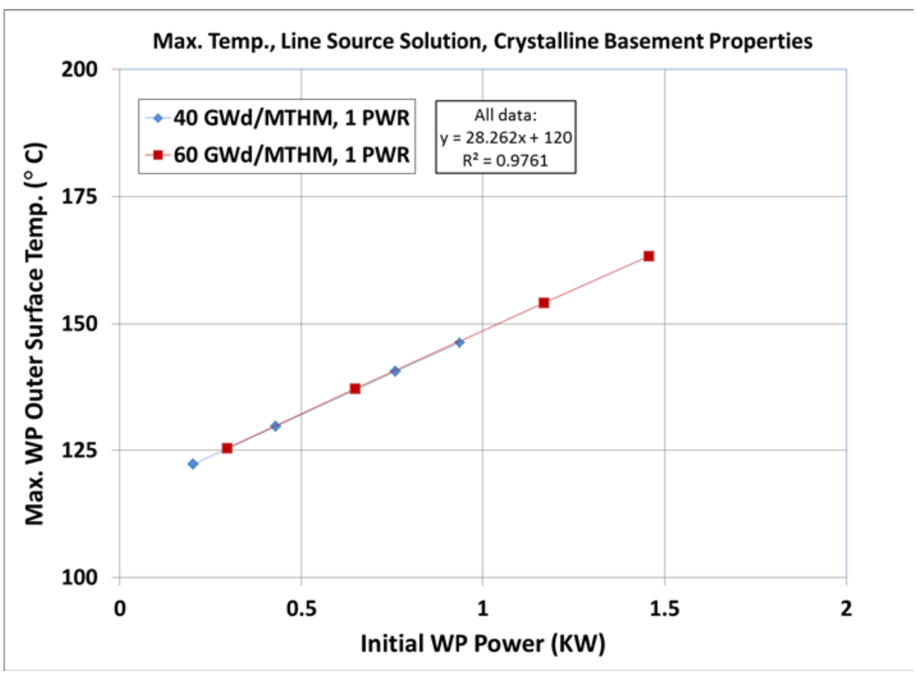


Figure D-10 Maximum Temperature vs. Initial Power for Disposal in the Crystalline Basement (Deep Borehole concept; no buffer) for Combinations of Package Size, SNF Burnup, and Age

D.6 Parameter Uncertainty Summary and Conclusions

This appendix describes three contributions to analysis of uncertainty in maximum repository (peak waste package surface) temperatures:

- Analytical description of overall variance in temperature, as a function of contributions from key parameters of the analytical solution used in previous temperature analyses (Hardin et al. 2011).
- Compilation of literature data on key parameter values, for various geologic host media and clay-based buffer materials, drawing on international work to develop geologic disposal solutions for heat-generating waste.
- Correlation between maximum repository temperature and waste package power at emplacement, without explicit adjustment for waste package size, SNF burnup, or fuel age.

The analytical treatment of temperature variance (Sections D.3 and D.4) uses partial derivatives of temperature with respect to each key parameter (K_{rock}, K_{buf}, ρC_p, and r_2/r_1), and separate variance estimates for the parameters, in a classical approach. The results include the following:

- Temperature at all times is relatively insensitive to heat capacitance (volumetric heat capacity) given the state of knowledge represented by the assigned parameter variance.
- Buffer thermal conductivity is an important parameter in early time (except for disposal concepts that have no buffer), but reported properties for dry and hydrated, clay-based buffer materials are relatively tightly grouped. Hence, the buffer radius ratio (expressed as r_2/r_1) may be a more important parameter depending on how much it is allowed to vary in developing a disposal concept. This implies that disposal concepts that allow partial buffer hydration during the thermal period, are potentially increasing the greatest source of uncertainty in maximum temperature.
- Host rock thermal conductivity is the most important input parameter, especially at later time (e.g., greater than 10 years after emplacement) and where buffers are not used.

Compilation of literature data and selection of uncertainty ranges (Tables D-1 through D-5) provide mean and $\pm 1\sigma$ property values for temperature uncertainty analysis based on the analytical solution (Equation D-1).

Finally, the study of maximum (peak waste package surface) temperature (Section D.5.2) corroborates the earlier finding from FEM simulations of the Generic Salt Repository (Section D.5.1) showing a correlation between peak waste package surface temperature and initial package thermal power. The waste package heat output at emplacement can be used to predict maximum temperature, to a good approximation evident from the linearity in Figures D-7 through D-10, for all host media, waste package sizes, SNF burnup, and decay storage duration cases considered.

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Appendix E – Inventory for Disposal Concept Development

This appendix selects six heat-generating waste types for representative fuel cycles, including wastes from advanced reprocessing of uranium oxide (UOX) used fuel from light-water reactors (LWRs). It then presents isotopic abundance and heat generation rates for these fuels. This information was previously presented (Hardin et al. 2011) and is based on previous work (Carter et al. 2012).

E.1 Once-Through Used Nuclear Fuel Cycle

The U.S. currently uses a once-through fuel cycle where used nuclear fuel (UNF) is stored on-site in either wet pools or in dry storage systems, with ultimate disposal as spent nuclear fuel (SNF) in a deep mined geologic repository envisioned. Commercial nuclear power plants have operated in the United States since about 1960. There are currently 104 operating nuclear power plants. Fuel discharges from commercial reactors up to the present, and those projected from currently operating reactors through 2055, are shown in Table E-1. These projections are based on the assumption that each currently operating reactor receives a license amendment that extends operating life to 60 yr. Future escalation in enrichment and burnup is based on industry estimates, capped for PWR and BWR systems (Carter et al. 2012).

Methods developed for the Nuclear Energy Institute in 2005 were used to estimate the number of assemblies and metric tons (MTs) of uranium (Gutherman 2009). To estimate the average enrichment and burn-up, projections were made by utility companies, as documented in *Calculation Method for the Projection of Future Spent Fuel Discharge*s (DOE 2002). These projections identified a burn-up increase of 2.38% per year for BWR UNF and 1.11% per year for PWR UNF. The enrichment increased at the same rate as burn-up until reaching the current enrichment limit of 5%. Once the 5% enrichment limit is reached, the enrichment and burn-up are assumed to remain constant.

The maximum burn-up achieved in PWRs is approximately 54.2 gigawatt-days (GW-d) per MT and in BWRs is approximately 56.3 GW-d/MT. The current inventory has an average burn-up of approximately 39.6 GW-d/MT for PWRs and 33.3 GW-d/MT for BWRs.

This study uses PWR fuel with 40 and 60 GW-d/MT as reference cases for thermal analysis, representing the current inventory and an upper bound on burn-up, respectively. Table E-2 and Figures E-1 and E-2 show decay heat as a function of time (Carter et al. 2012a, Figures 3-10 and 3-11; detailed isotopic composition in Appendix C).

Secondary Waste From Repository Operations

Secondary wastes associated with the once-through fuel cycle are those generated by the handling and emplacement activities involved in the disposal of UNF at a geologic repository. Sources of secondary waste from repository operations include:

- Cask, facility and equipment decontamination activities
- Pool system skimming and filtration operations
- Used dual purpose canisters
- Tooling and clothing
- Facility ventilation filtration
- Chemical sumps
- Carrier and transporter washings

All of the radioactive waste streams from repository operations are classified as either Class A, B or C low level waste (LLW). No greater than Class C (GTCC) or mixed wastes are anticipated from repository operations.

Secondary waste estimates from repository operations depend on the fraction of the UNF received in disposable canisters that do not require opening at the repository but can be directly placed into a waste package for disposal in the repository. (By handling UNF in canisters that were sealed elsewhere, production of contaminant particles and other fuel residues produced during handling is avoided.) Figure E-3 shows the volume of LLW estimated from repository operations based on the fraction of UNF received in directly disposable containers.

Table E-1 Summary of Projected Fuel Discharge from Existing Reactors

Year	Number of Assemblies [a]			Total Initial Uranium (MTU) [b]			Average Enrichment		Average Burn-up (MWd/MTU) [c]	
	PWR	BWR	Totals	PWR	BWR	Totals	PWR	BWR	PWR	BWR
2010	97,400	128,600	226,000	42,300	23,000	65,200	3.74	3.12	39,600	33,300
2030	165,000	219,200	384,200	72,000	39,200	111,100	4.24	3.87	45,400	42,600
2055	209,000	273,000	483,000	91,000	49,000	140,000	4.40	4.09	47,300	45,300

[a] The estimated number of assemblies has been rounded to the nearest 200 prior to 2050 and nearest 1000 thereafter, totals may not appear to sum correctly

[b] The estimated fuel discharged has been rounded to the nearest 100 MTU prior to 2050 and the nearest 1,000 thereafter, totals may not appear to sum correctly

[c] The burn-up has been rounded to the next 100 MWd/MT

Table E-2 PWR 40 and 60 GW-d/MT Used Fuel Decay Heat

Decay Heat (Watts/MT)	Time (years)							
	1	10	30	50	70	100	300	500
40 GW-d/MT Burnup								
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	2765	1,054	566	354	222	110	1	0
Noble Metals Ag, Pd, Ru, Rh	2,752	11	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	3,593	64	10	2	0	0	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	819	348	332	309	287	258	159	116
Others	515	15	2	1	0	0	0	0
Total	10,444	1,492	910	666	509	368	160	116
60 GW-d/MT Burnup								
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	4,608	1,576	824	516	323	160	1	0
Noble Metals Ag, Pd, Ru, Rh	3,447	14	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	3,843	109	17	3	1	0	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	1,515	785	613	516	449	381	199	139
Others	522	21	3	1	0	0	0	0
Total	13,936	2,505	1,458	1,036	773	541	201	139

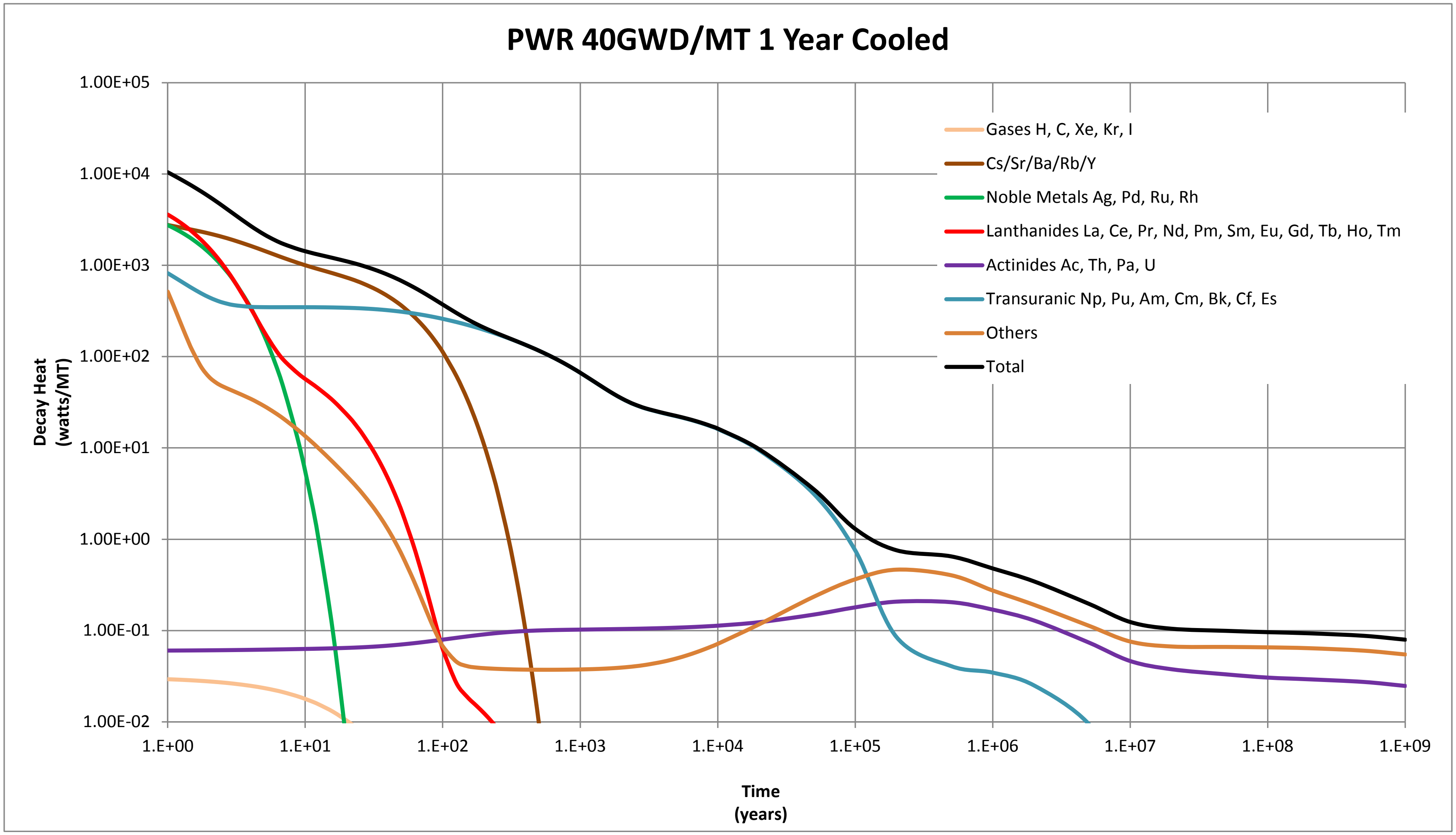

Figure E-1 PWR 40 GW-d/MT Used Fuel Decay Heat

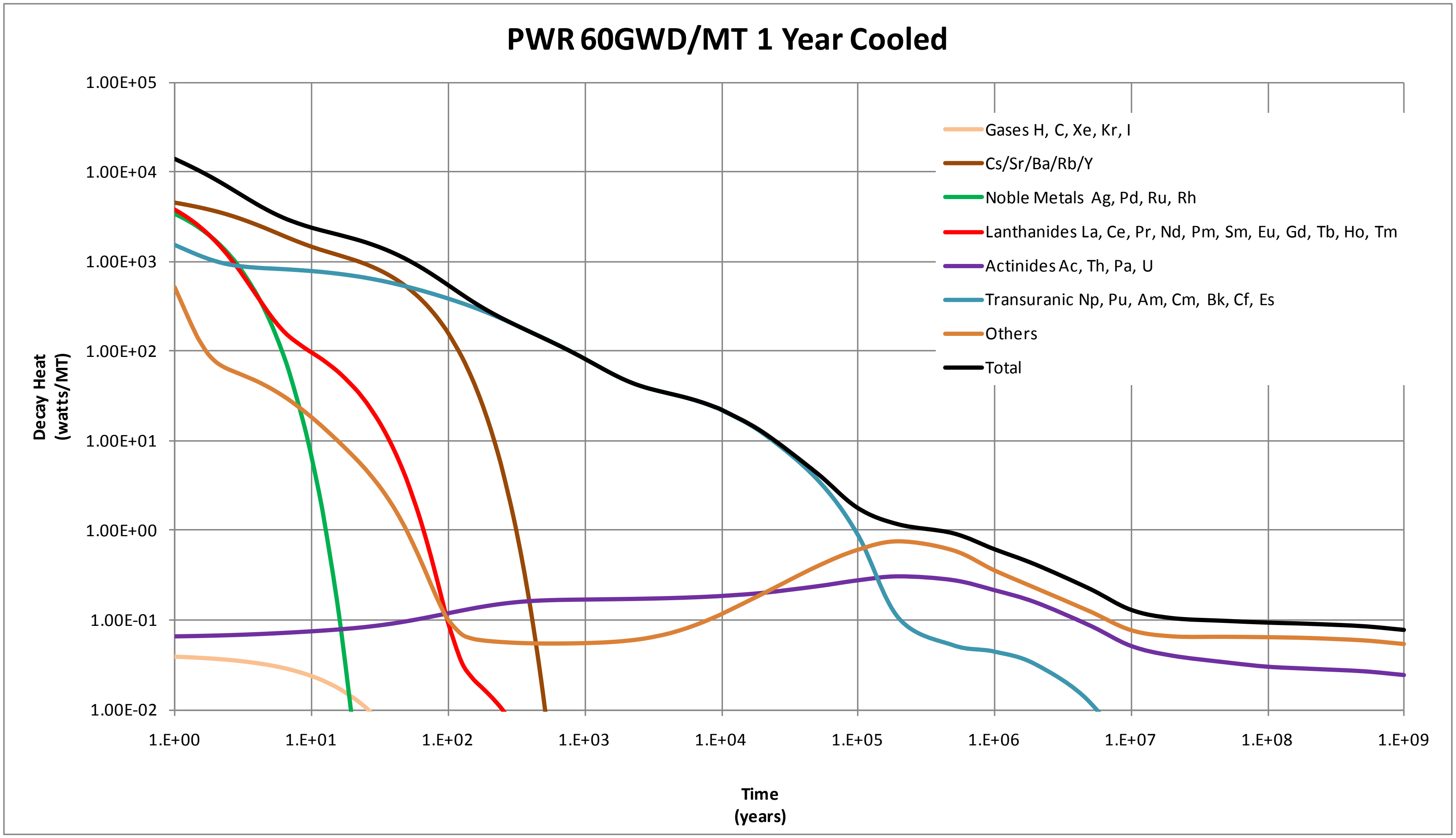

Figure E-2 PWR 60 GW-d/MT Used Fuel Decay Heat

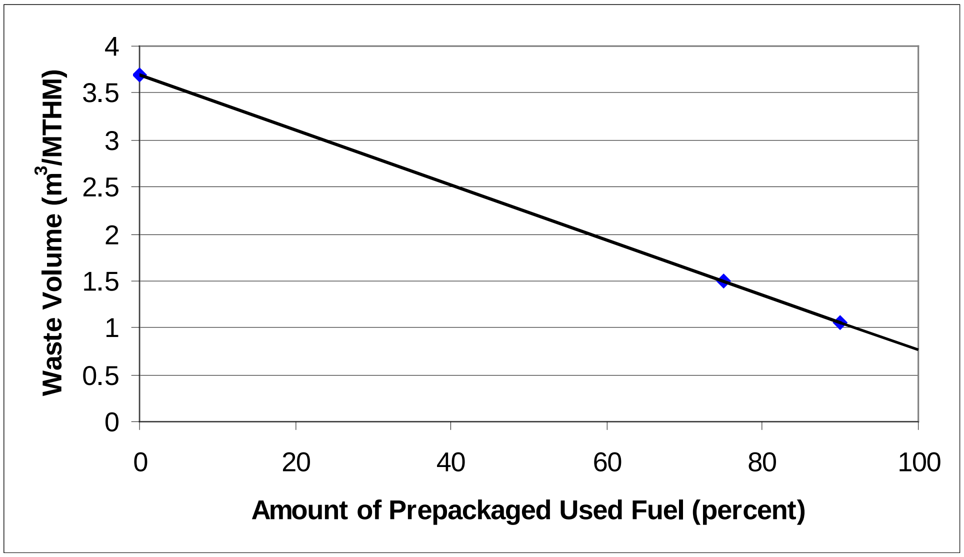

Figure E-3 Low Level Waste Volume From Repository Operations

E.2 Modified Open Cycle

This case is implemented by the recycling of LWR UOX fuel to recover uranium and plutonium (U/Pu). The U/Pu product is converted into a LWR Mixed Oxide reactor fuel (MOX) fuel and burned in conventional LWR reactors to approximately 50 GW-d/MT. This MOX fuel is not recycled but is directly disposed in a geologic repository after a single reactor pass. The waste inventory for this case was estimated by Carter et al. (2012), and all of the associated figures and tables presented here are based on those results.

The *Initial Screening of Fuel Cycle Options* study (Sevougian et al. 2011, Section 4.2.5) recommended that an equilibrium, thermal spectrum, single-stage MOX limited recycle fuel cycle option would be of only minor benefit, but noted that this result is "not indicative of its merit as a transitional fuel cycle." This report does not analyze or recommend nuclear fuel cycles, and considers Pu-MOX only as one waste type that could result from current or transitional activities in the nuclear power industry, or from Pu disposition activities, but may never be generated in large quantities (i.e., more than a few hundred metric tons).

While once-through Pu-MOX is not being pursued as an end-state fuel cycle in the U.S., there are other advanced fuel cycles being evaluated that include Pu-MOX prior to further recycle, and the ability to dispose of this fuel in the event further recycle is not forthcoming is important. In addition, Pu-MOX is a useful representative for a range of higher heat-load waste streams from fuel cycles that are not yet well understood. Note also that some of those higher-heat waste streams could be hotter than Pu-MOX as used here.

E.2.1 Overall Mass Flows for a Modified Open Fuel Cycle

The Fuel Cycle Technologies (FCT) program has previously studied various MOX fuel alternatives (Taiwo et al. 2007). Specifically they studied the scenario in which LWR UOX UNF is burned to 51 GW-d/MT and allowed to cool for 5 years post-irradiation and then partitioned to separate the plutonium from the minor actinides, the other heavy metal (HM) nuclides, and the fission products. Because the Co-Extraction partitioning strategy is assumed, the spent fuel uranium in the LWR UOX SNF is assumed to be the uranium base of the MOX fuel (instead of natural or depleted uranium). This MOX fuel is stored for 2 years prior to introduction into the full MOX core. The delay time results in the build-up of Am-241 in the MOX fuel, which arises from the decay of Pu-241.

The full MOX fuel core is subsequently burned to an average value of 50 GW-d/MT. The burn-up of the MOX core is limited to 50 GW-d/MT because of a constraint on the plutonium content in the MOX fuel. Previous studies (Salvatores et al. 2003) showed that plutonium content less than 12% (Pu in heavy metal) is necessary to ensure a negative void coefficient in a full MOX core; the specific value is actually plutonium isotopic vector dependent, but that dependence was not investigated (Taiwo et al. 2007).

Table E-3 provides a summary of the LWR derived MOX fuel parameters. The average plutonium enrichment is 10.74%. Therefore, each MT of LWR fuel which is reprocessed allows fabrication of 108.9 kg of MOX fuel. Table E-3 includes only the HM portion of the MOX fuel assembly (FA). The hardware (cladding, spacers, etc.) are not included. Estimates of the hardware mass are estimated based on the mass of a PWR assembly of 158 kg per assembly (Carter et al. 2012).

Table E-3 LWR Derived MOX Fuel Summary

LWR UOX fuel burnup (GW-d/t)	51
LWR MOX fuel burnup (GW-d/t)	50
LWR UOX core	
Uranium enrichment (%U-235)	4.21
Pu-239 in 5-yr cooled fuel (% total Pu)	52.7
Fissile Pu (239 & 241) in 5-yr cooled fuel (% total Pu)	64.7
Total Pu in 5-yr cooled fuel (% initial HM))	1.17
Total MA in 5-yr cooled fuel (% initial HM)	0.14
Total Pu in 5-yr cooled (kg/GWt-d)	0.234
Total MA in 5-yr cooled (kg/GWt-d)	0.027
Cycle length (Days)	495
LWR MOX core (Note 1)	
Pu content in initial MOX fuel (%Pu/HM)	10.74
Uranium consumption (%)s	4
Pu consumption (%)	25
Pu-239 consumption (%)	42
Pu fissile consumption (%)	37
Am production (%)	450
Np content in 5-yr cooled fuel (kg / initial ton MOX fuel)	0.89
Cm content in 5-yr cooled fuel (kg / initial ton MOX fuel)	0.99
Cycle length (Days)	495

Notes:

1. Consumption, production, and content data are differences between charge and 5-year post-irradiation states.

E.2.2 Characteristics of Waste Generated by Co-Extraction Reprocessing LWR UOX Fuel

The Co-Extraction method represents the simplest and most technically mature aqueous reprocessing method evaluated. The process envisioned is similar to the current generation of deployed reprocessing technology (e.g., the Rokkasho Reprocessing Facility). Uranium and plutonium are recovered together (no pure plutonium separation). The principal fission product wastes including the minor actinides are combined with the undissolved solids (UDS) and recovered Technetium into a single borosilicate glass waste form.

The gaseous radionuclides I-129 and H-3 released during reprocessing are captured and converted to waste forms suitable for disposal while C-14 and Kr-85 are assumed to be released to the atmosphere.

While this process is similar in function to the industrial Co-Extraction™ process deployed by AREVA, the two processes assume different processing methods and steps and so the product and waste streams cannot be directly compared.

Co-Extraction Baseline Waste Forms

The Global Nuclear Energy Partnership Integrated Waste Management Strategy Baseline Study (Gombert 2007) summarized the state-of-the-art in stabilization concepts for byproduct and waste streams. It recommended a baseline of waste forms for the safe disposition of proposed waste streams from future fuel recycling processes. This baseline has been adopted for this study as applicable to the specific reprocessing method.

Off-Gas Waste Forms

Tritium (H-3) is not captured nor treated with current generation reprocessing methods (aqueous methods practiced commercially). Tritium is currently released to the environment via atmospheric or waste water discharges. This release is assumed to be an unacceptable practice in future domestic reprocessing applications. To prevent the aqueous phases from becoming contaminated with tritium, voloxidation is used to ensure tritium is captured by an off-gas system as tritiated water. The tritiated water is converted to a grout and allowed to cure in 10 liter containers, which are subsequently contained in a double steel box.

I-129 is captured on silver mordenite. The mordenite is then grouted and allowed to cure in 55-gal drums.

Metal Waste Forms

After being separated from the fuel, compacted hulls and hardware, consisting of the assembly hardware (principally stainless steels) and zirconium and stainless steel based cladding, are decontaminated, compacted, and placed inside a HLW canister. Each canister is 2 ft in diameter by 10 ft tall and contains 3,600 kg of waste material.

Principal Fission Product Waste Forms

In the aqueous processes most of the fission products are incorporated into a borosilicate glass. While this waste form is an accepted standard for reprocessing waste disposal, the waste form is limited by a number of attributes which must be considered in this study.

The limits to avoid the formation of multi-phase glasses include:

- Maximum decay heat of 14 kW per 2-ft diameter, 15-ft. long canister to prevent the canister centerline temperature from reaching the transition temperature
- Molybdenum trioxide solubility is limited to 2.5% by weight
- Noble metals (Ag, Pd, Rh, Ru) are limited to 3% by weight

The limit selected for any representative fuel allows the maximum waste loading, and minimum projected waste volume and mass. The glass is cast into 2-ft diameter by 15-ft tall canisters containing 2,900 kg of glass.

Co-Extraction Waste Volumes, Masses and Containers

The potential waste from Co-Extraction reprocessing a 51 GW-d/MT fuel is provided in Tables E-4 through E-7.

Table E-4 Co-Extraction Fuel Reprocessing Off-Gas Waste Summary

	Captured Tritium Grouted				Captured I on Silver Mordenite Grouted		
	Containers: 10 liter poly bottle contained within a double steel box. Each bottle contains 23 kg cured grout				Containers: 55 gallon drum. Each drum contains 460 kg cured grout		
Burn-up (GW-d/MT)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT
51	2.10	0.09	0.09	0.18	11.74	0.19	0.03

Table E-5 Co-Extraction Fuel Reprocessing Metal Waste Summary

	Compacted Metal Containers: 2 ft diameter x 10 ft tall canisters. Each Canister Contains 3,600 kg.		
Burn-up (GW-d/MT)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT
51	300.5	2.62	0.084

Table E-6 Co-Extraction Fuel Reprocessing Fission Product Waste Summary.

	Borosilicate Glass Containers: 2 ft diameter x 15 ft tall canisters. Each Canister Contains 2,900 kg.			
Burn-up (GW-d/MT)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)
51	537.5	8.73	0.19	14,000

Table E-7 Co-Extraction Fuel Reprocessing Recovered Uranium Summary.

	Recovered Uranium (U_2O_3) Containers: 55 gal Drum canisters. Each Canister Contains 400 kg.		
Burn-up (GW-d/MT)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT
51	1,097	20.2	2.74

Co-Extraction Borosilicate Glass Characteristics

The isotopic composition for borosilicate glass, which is the principal heat generating waste from the Co-Extraction process, was decayed using the ORIGEN 2.2 methods and isotopic parameters. Table E-8 and Figure E-5 provide the decay heat as a function of time for the Co-Extraction borosilicate glass. Detailed isotopic composition of the Co-Extraction glass after 5, 30, 100 and 500 years of cooling is available elsewhere (Hardin et al. 2011, Appendix B Table B-1).

E.2.3 Characteristics of Used MOX Fuels

It is important to note the difference in thermal output between UOX spent fuel and MOX spent fuel. The MOX spent fuel is significantly hotter after discharge at the same burn-up, and the thermal output decays more slowly. Whereas a UOX PWR fuel assembly takes approximately 10 to 20 years to drop below 1 kW, a MOX PWR assembly takes 100 to 200 years (Figure E-4).

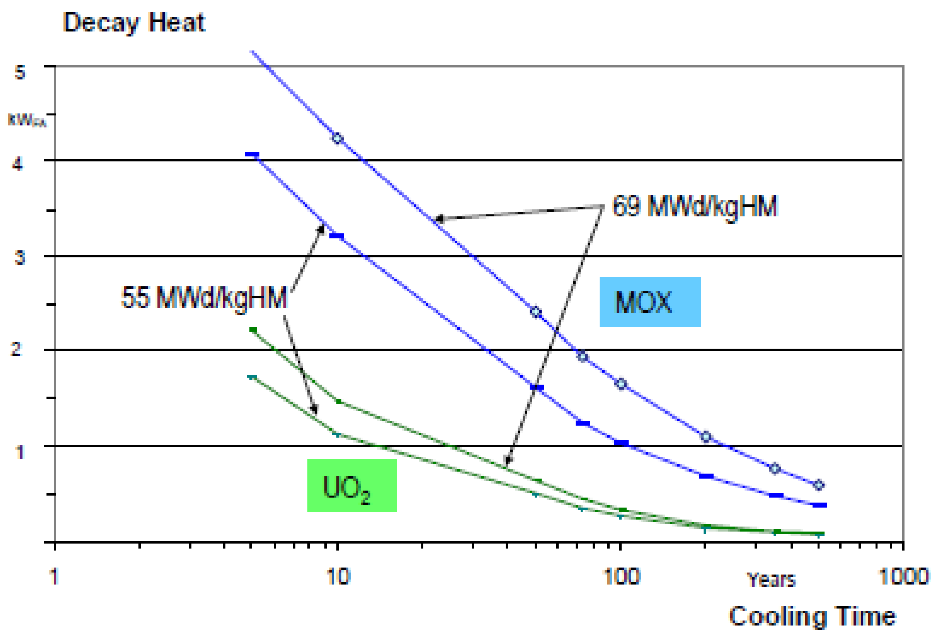

Figure E-4 Decay heat of UOX and MOX Fuel Assemblies Depending on Burnup and Cooling Time for Discharge Burnup of 55 and 69 GW-d/MTHM (after IAEA 2003b).

The difference in the decay heat is primarily that starting with Pu-239 in the MOX results in more Am-241 and Pu-238, which dominate the heat from the MOX.

- At 100 yr, Am-241 is responsible for approximately 30% of the heat in UOX, and 52% of the heat in MOX. The heat contribution from Pu-238 in MOX is approximately 5.5X the contribution in UOX.
- Overall, the thermal contribution from transuranics in MOX is over 7X the contribution in UOX.

The isotopic composition of discharged MOX fuel was obtained from the transmutation library maintained by the Systems Analysis Working Group (Piet 2010, written communication). This discharge composition was decayed using the methods and isotopic parameters in ORIGEN 2.2 by adapting the method to a spreadsheet. Table E-9 and Figure E-6 provide the decay heat of the MOX fuel as a function of time. Detailed isotopic composition of the discharged MOX fuel after 5, 30, 100 and 500 years of cooling is available (Carter et al. 2012a, Appendix I).

Table E-8 Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GW-d/MT 5-year Cooled PWR Fuel

Decay Heat (Watts/Container)	Time (years)							
	Initial Production	10	30	50	70	100	300	500
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	10,156	5,727	3,518	2,201	1,377	682	6	0
Noble Metals Ag, Pd, Ru, Rh	1,186	1	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	1,282	268	52	11	2	0	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	1,376	1,020	615	423	329	266	178	132
Others	7	1	0	0	0	0	0	0
Total	14,008	7,016	4,185	2,635	1,709	949	185	132

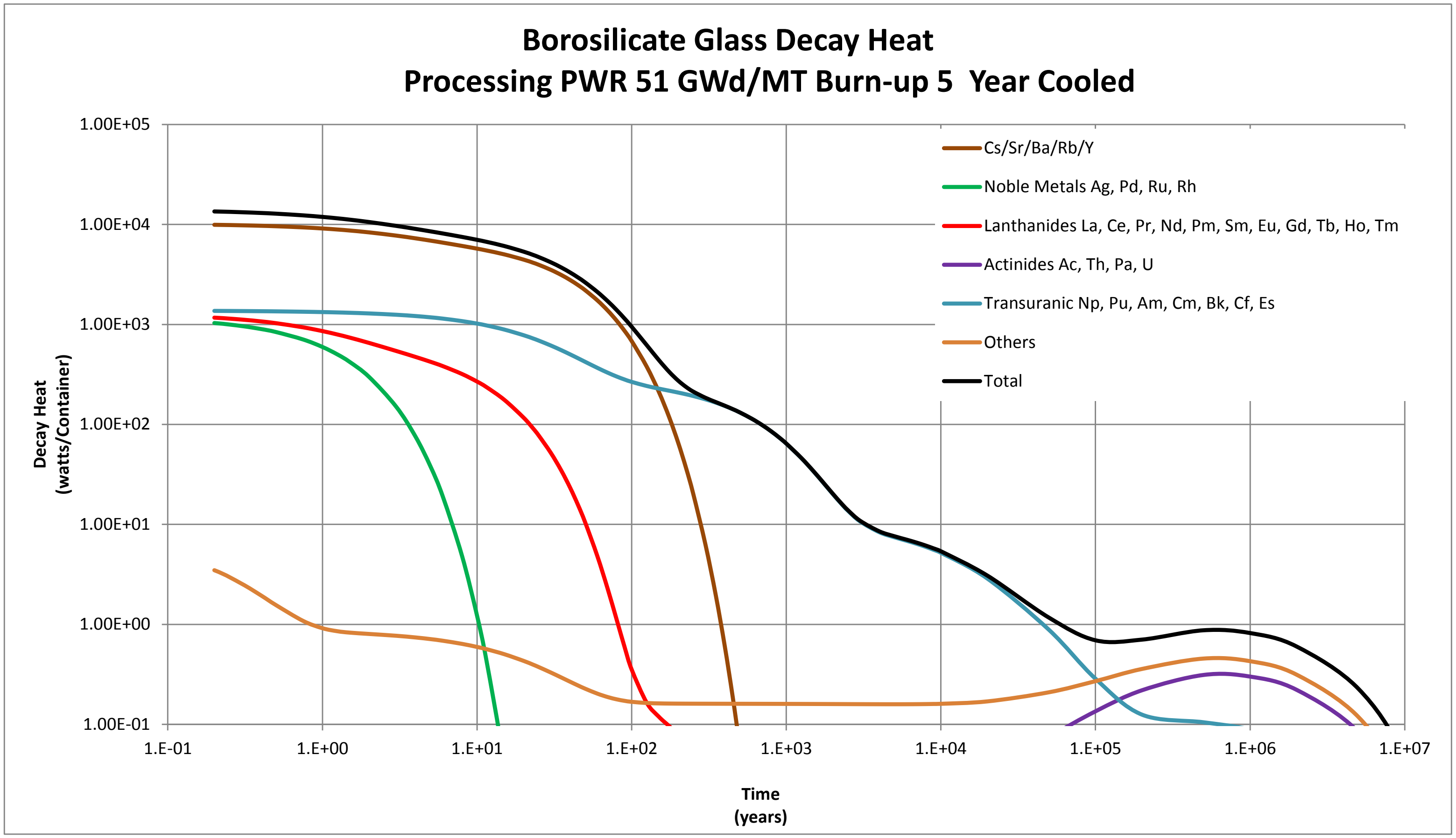

Figure E-5 Borosilicate Glass Decay Heat Generated by Co-Extraction Processing of 51 GW-d/MT 5-year Cooled PWR Fuel

Table E-9 Mixed Oxide Fuel 50 GW-d/MT Used Fuel Decay Heat

Decay Heat (Watts/MT)	Time (years)							
	Discharge	**10**	**30**	**50**	**70**	**100**	**300**	**500**
Gases H, C, Xe, Kr, I	5,737	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	13,829	991	561	352	221	110	1	0
Noble Metals Ag, Pd, Ru, Rh	23,181	12	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	46,102	110	21	4	1	0	0	0
Actinides Ac, Th, Pa, U	38,779	0	0	0	0	0	1	1
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	76,896	4,878	4,062	3,504	3,110	2,697	1,517	1,068
Others	19,517	13	2	1	0	0	0	0
Total	224,040	6,004	4,647	3,860	3,332	2,807	1,519	1,068

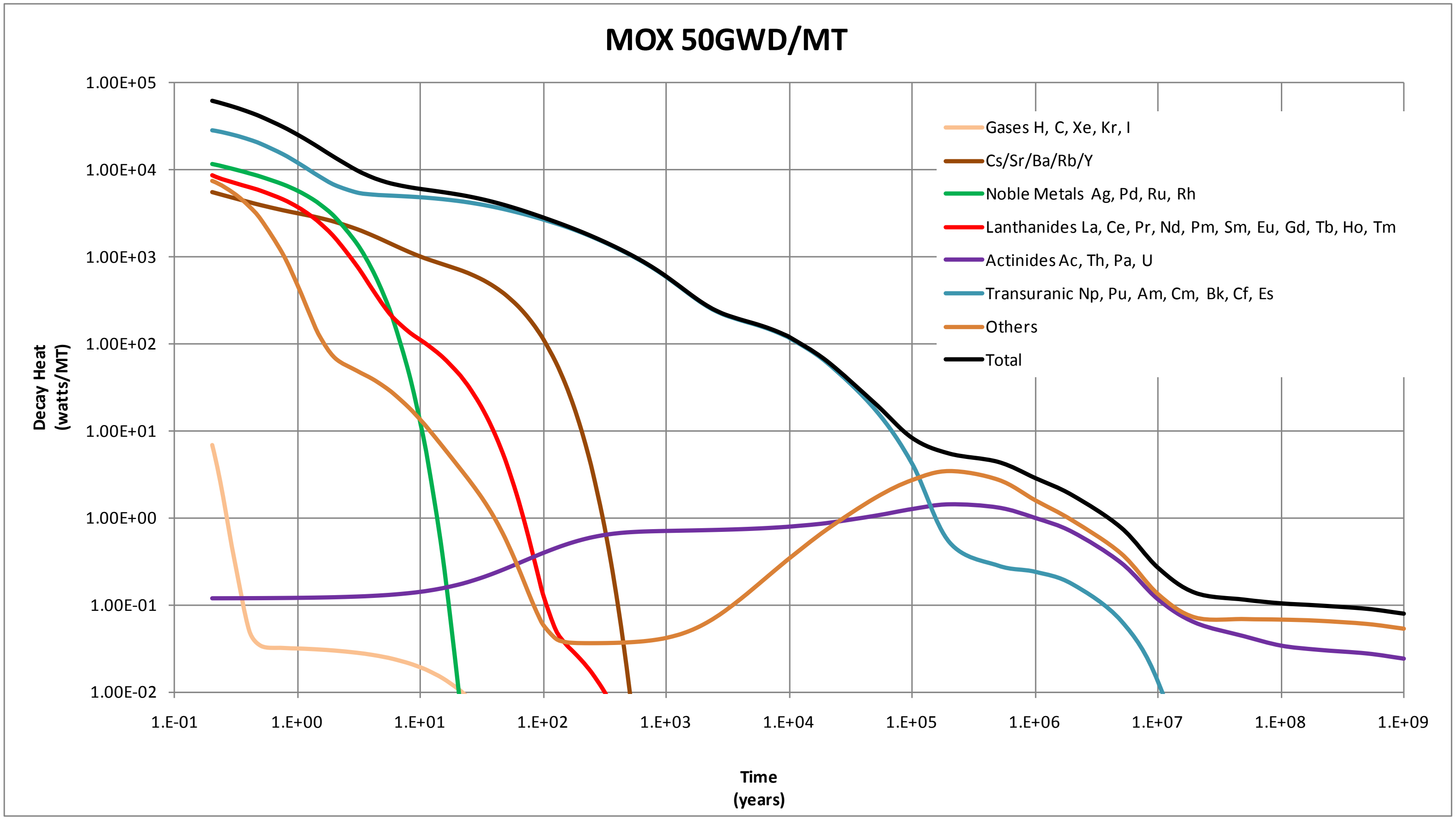

Figure E-6 Mixed Oxide Fuel 50 GW-d/MT Used Fuel Decay Heat

E.2.4 Characteristics of Modified Open Cycle Secondary Waste

Secondary waste from the operation of modified open fuel cycle facilities includes

- Operational waste such as empty containers, solidified decontamination solutions, used process filters, etc.
- Job control waste such as protective clothing, plastic suits, contamination control materials, step-off pads, etc.
- Maintenance waste such as failed equipment, high efficiency particulate air (HEPA) filters, etc.

Secondary wastes are primarily characterized as low level (Class A, B and C) waste and GTCC waste. Relatively small quantities of mixed wastes are also anticipated from modified open fuel cycle facility operations (such wastes are subject to additional statutory and regulatory requirements, such as the Resource Conservation and Recovery Act enacted by the U.S. in 1976).

Secondary Waste From Reprocessing LWR Fuel

Estimates of the volume of secondary waste resulting from a variety of recycling processes were investigated by Jones (2010). Secondary waste from reprocessing operations depends on the reprocessing technology (in this case Co-Extraction) and the facility capacity. A facility capacity of 800 metric tons of heavy metal (MTHM)/year is a reasonable size for a reprocessing facility and is chosen as the basis for this study (recently constructed reprocessing plants at La Hague in France, and Rokkasho in Japan, are built in units that are approximately this size; see Todd 2008). Table E-10 shows the annual volume of secondary waste expected from a Co-Extraction facility with a capacity of 800 MTHM/year.

Table E-10 Annual Secondary Waste Volume from an 800 MTHM/year Co-Extraction Facility

Waste Type	Annual Waste Volume	
	m^3	m^3/MTHM
Low level Class A/B/C	7,440	9.3
Greater than Class C (GTCC)	235	0.3
Mixed low level Class A/B/C	32	0.04
Mixed GTCC	48	0.06

Secondary Waste From MOX Fuel Fabrication

Estimates of the volume of secondary waste resulting from the fabrication of MOX fuel from plutonium recovered from LWR used fuel were investigated by Jones (2011). The volume of Class A/B/C secondary waste from MOX fuel fabrication depends on the facility capacity. The volume of GTCC secondary waste depends on the facility capacity and also the isotopic content of the plutonium used to fabricate the fuel, which in turn depends on the burn-up and cooling time of the used fuel from which it is derived. The isotopic content of the plutonium being processed and present in the waste streams restricts the amount of waste that can be packaged per waste package. These restrictions are driven by safety requirements imposed by transportation and facility operations. In general, higher burn-up UNF or shorter cooled UNF contains plutonium with higher activity levels, and processing of this plutonium into MOX fuel results in greater volumes of GTCC waste.

A facility capacity of 3.5 MT Pu/year is a reasonable size for a MOX fuel fabrication facility and is chosen as a basis for this study (similar to the MOX Fuel Fabrication Facility under construction at the Savannah River Site; see NRC 2010). As stated previously, used fuel with a burn-up of 60 GW-d/MT is chosen as a basis for this study. Table E-11 shows the annual volume of secondary waste expected from a MOX fuel fabrication facility processing plutonium recovered from LWR used fuel with a burn-up of 60 GW-d/MT. Data for cooling times of 5 years and 30 years are provided.

Table E-11 Annual Secondary Waste Volume from a MOX Fuel Fabrication Facility (3.5 MT Pu/year) Processing Pu Recovered from LWR UNF with Burnup of 60 GW-d/MT

Waste Type	Annual Waste Volume (m^3/year)	Equivalent Recycling Capacity (MTHM/year) [1]	Waste Volume Relative to Equivalent Recycling Capacity (m^3/MTHM) [1]
Low level Class A/B/C	372	248	1.5
Greater than Class C (GTCC)	1,680	248	6.78

Notes:
1. Equivalent recycling capacity is the amount of UNF required to be reprocessed to yield the Pu needed for the stated facility capacity (in this case 3.5 MT Pu/year)

Secondary Waste From Repository Operations

Secondary waste resulting from the disposal of used fuel from a modified open cycle at a geologic repository is the same as shown in Section E.1.2 for the once-through fuel cycle example.

E.3 Closed Fuel Cycle

A key attribute of the "fully closed" nuclear fuel cycle is that no UNF is disposed, only UNF reprocessing wastes are disposed. Fully closed power reactor systems have been previously studied with the majority of such studies using fast-spectrum reactors. These prior studies include numerous variations related to:

- The start-up core which can be produced from low enriched (<20%) uranium, weapons grade plutonium, or recovered TRU materials from existing LWR UNF
- "Equilibrium" core which can have design and operating parameters specified to result in TRU conversion ratios (CRs) of
  - Less than 1 for TRU burning modes, these cases require additional TRU materials to produce the next reactor fuel charge
  - Equal to 1.0 for breakeven reactor operation such that the TRU production and consumption are balanced over each reactor cycle or

 - Greater than 1 for systems which have a net production of TRU elements over each reactor cycle (breeders)
- Fuel type typically either oxide, metal alloy or carbon-based
- The reactor coolant, typically molten sodium, or lead mixtures, or gases, to maintain the fast neutron spectrum

Carter et al. (2012) investigated the waste generated by reprocessing oxide and metal fuel from reactors operated to produce a TRU conversion ratio (CR) of either 0.5 or 0.75. It was found that the decay heat properties of the waste were essentially the same for either fuel (Carter et al. 2012, Figure 6-2). All of the figures and tables for this case that are presented here, are based on results from that study.

To provide an example of an alternative (to aqueous) reprocessing method, this study assumes metal-based fuel with sodium-cooled fast reactor (SFR) operating parameters such that the CR is 0.75. The fuel is reprocessed by an electrochemical (EC) method.

E.3.1 Overall Mass Flows for a Closed Fuel Cycle

Advanced burner reactor (ABR) core designs have been investigated and documented (Hoffman et al. 2006; Hoffman 2007; Yang et al. unpublished). These studies document the basic design and operating parameters for a 1000 Megawatts-thermal (MW_{th}) sodium cooled reactor using U-TRU-Zr metal alloy fuel. Table E-12 summarizes key parameters for TRU CR of 0.75 for the metal fuel type. Some parameters (e.g., fuel mass per assembly) were obtained from the referenced author's working papers.

The discharged fuel isotopic concentrations associated with these studies were obtained from the System Analysis transmutation library (Piet 2010, written communication). Figure E-7 provides the decay heat of these fuels which are all similar. The parameters in Table E-12 and the UNF isotopic data were combined to generate an overall reactor, fuel recycling, and fuel fabrication material balance for the reactor configuration. The material balances are documented elsewhere (Hardin et al. 2011, Appendix D, Table D-1) and summarized in Table E-13. Since the reactors operate with a TRU CR of less than 1.0, additional TRU must be supplied to the reactor system each year. The TRU source described by the references cited above is LWR UOX fuel with a burn-up of 50 GW-d/MT cooled for 5 years. Both the TRU quantity and quantity of LWR fuel which must be reprocessed annually is provided in Table E-13.

The waste unit quantities resulting from reprocessing the advanced burner reactor (ABR) fuel (Section E.3.3) are determined per MT of fuel recycled. However, the repository system analyst will likely need to know the total quantities of waste to be disposed. In order to determine the total quantities, several additional parameters need to be considered. These include the thermal efficiency and overall utility of the power plant if such studies are related to net power generation. The total quantities must also include the waste generated from reprocessing the LWR fuel as discussed in Section E.3.2.

Table E-12 Reactor Parameter Summary

	Metal Fuel Core 1000 MW_{th} CR = 0.75
Power, (MW_{th})	1000
Cycle Length (effective full power days)	232
Number of Batches (IC/MC/OC) [1]	6 / 6 / 6.5
Fuel Form	U-TRU-10%Zr
TRU Feed	Recycled ABR fuel (2-yr cooled) + LWR 50 GW-d/MT (5-yr cooled)
TRU Enrichment (IC/MC/OC) [1]	16.1 / 20.1 / 24.2
TRU Enrichment (avg.)	21.3
Number of Batches (IC/MC/OC) [1]	6 / 6 / 6.5
Conversion Ratio (TRU)	0.75
BOEC Core Loading (HM/TRU, MT)	13.4 / 2.85
Discharge Burn-up (avg./peak, GW-d/MT)	99.6 / 127
Total Assemblies	313
Drivers (IC/MC/OC) [1]	30 / 42 / 72
Control Rods (primary/secondary)	16 / 3
Reflector	90
Shield	60
Mass HM per Assembly (IC/MC/OC, kg) [1]	97.6 / 97.7 / 97.8
Mass Zr per Assembly (IC/MC/OC, kg) [1]	10.8 / 10.9 / 10.9
Mass Bond Na (kg)	2.34
Mass HT-9 Hardware (kg/assembly)	359.9

Notes:

1. IC / MC / OC refers to inner core/middle core/outer core.
2. Zr fraction is 10 wt % when the TRU fraction is less than 30 wt % (TRU/HM × 100) and increases to 40 % Zr at 100% TRU

Table E-13 Overall Reactor Material Balance Result

	Metal Fuel Core 1000 MW_{th} CR = 0.75
Initial Core Charge (HM/TRU/Zr, MT)	14.07 / 2.98 / 1.57
Annual Fuel Requirements (HM/TRU/Zr, MT)	3.55 / 0.75 / 0.25
Annual LWR to Supply TRU (MT/yr)	5.78

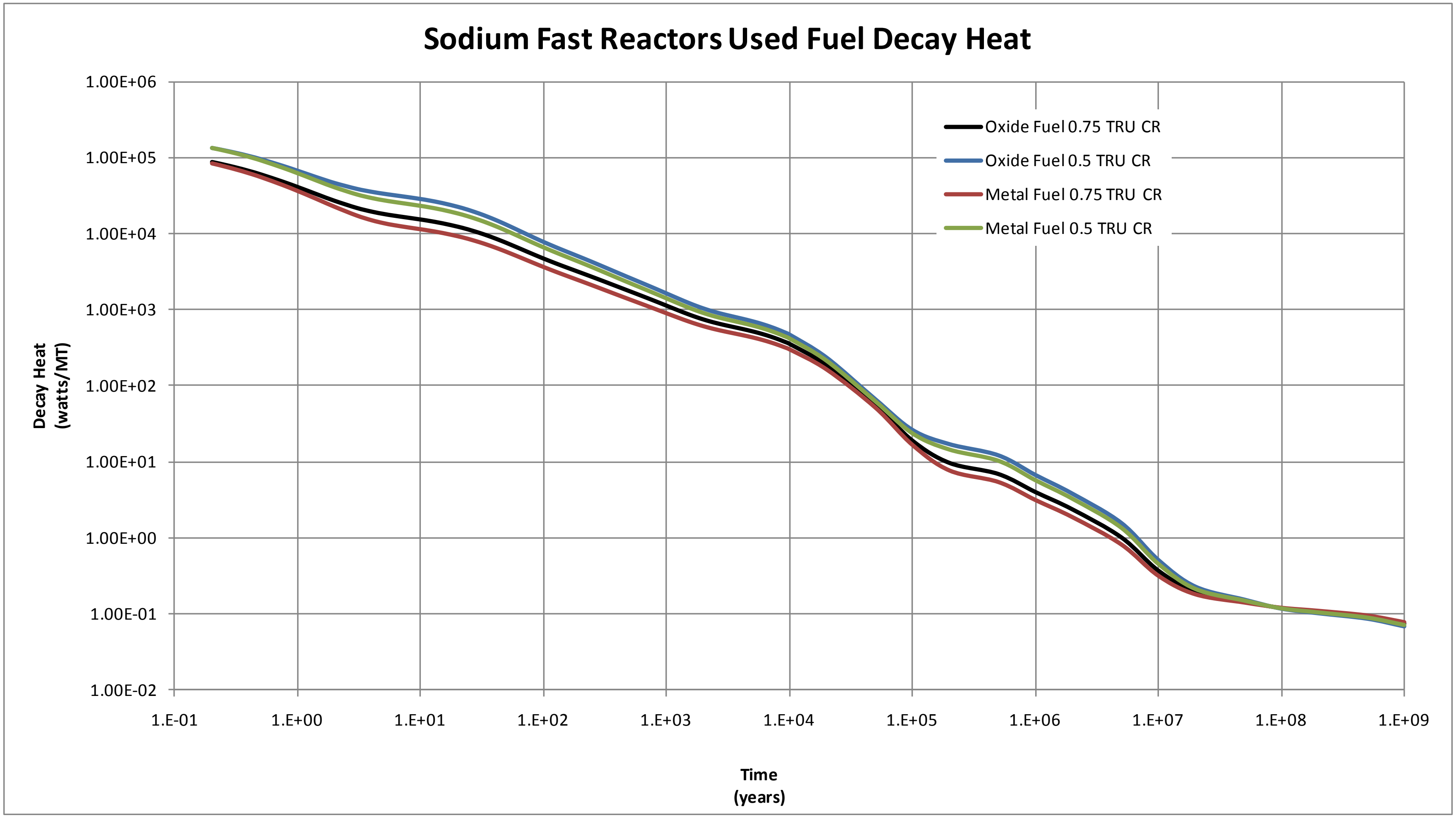

Figure E-7 Sodium Fast Reactors Used Fuel Decay Heat.

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E.3.2 Characteristics of LWR New Extraction Reprocessing Wastes

New Extraction is an advanced aqueous process which recovers all of the TRU elements for re-use. The process envisioned includes Transuranic Extraction (TRUEX) and the Trivalent Actinide Lanthanide Separation by Phosphorus-based Aqueous [K]omplexes (TALSPEAK) process for complete TRU recovery. The principal fission product wastes are combined with the UDS and separated Tc into a single borosilicate glass waste form.

The principal gaseous radionuclides I-129, Kr-85, C-14 and H-3 released during reprocessing are captured and converted to waste forms suitable for disposal.

While this process is similar in function to the NUEX industrial process proposed by Energy Solutions, the two processes assume different processing methods and steps and so the product and waste streams cannot be directly compared.

New Extraction Baseline Waste Forms

Off-Gas Waste Forms

In addition to the grouted tritium waste and I-129 waste generated by the Co-Extraction process, the New Extraction process is assumed to capture and treat C-14 and Kr-85:

- C-14 is converted to carbonate and grouted. The grout is cured in a 55 gal drum.
- Kr-85 is separated from the other off-gas components (including xenon) by cryogenic methods and the Kr-85 is stored in high pressure type A gas cylinders.

Metal Waste Forms

Compacted Hulls and Hardware – After being separated from the fuel, the assembly hardware (principally stainless steels) and zirconium and stainless steel based cladding are decontaminated, compacted and placed inside a HLW canister. Each canister is 2 ft in diameter by 10 ft tall and contains 3,600 kg of waste material.

Principal Fission Product Waste Forms

In the aqueous processes most of the fission products are incorporated into a borosilicate glass. While this waste form is the accepted standard for reprocessing waste disposal, the waste form is limited by a number of attributes which must be considered in this study.

The limits to avoid the formation of multi-phase glasses include:

- Maximum decay heat of 14,000 watts per 2-ft diameter canister to prevent the canister centerline temperature from reaching the transition temperature.
- Molybdenum trioxide is limited to 2.5% by weight to maintain solubility.
- Noble (Ag, Pd, Rh, Ru) metals are limited to 3% by weight.

The limit selected for any representative fuel allows the maximum waste loading and minimum projected waste volume, and mass. The glass is cast into a 2-ft diameter by 15-ft tall canister containing 2,900 kg of glass.

New Extraction Waste Volumes, Masses and Containers

The potential waste from reprocessing the metal ABR fuels is described in Tables E-14 through E-17.

The isotopic composition for borosilicate glass, the principal heat generating waste from the New Extraction process, was decayed using the ORIGEN 2.2 methods and isotopic parameters. Table E-18 and Figure E-8 provide the decay heat characteristics as a function of time for the New Extraction borosilicate glass. Detailed isotopic composition of the discharged New Extraction borosilicate glass after 5, 30, 100 and 500 years of cooling is provided elsewhere (Hardin et al. 2011, Appendix E, Table E-1).

Table E-14 New Extraction Reactor Fuel Reprocessing Off-Gas Waste Summary

	Captured Tritium Grouted				Captured I on Silver Mordenite Grouted			Captured C-14 as Carbonate Grouted			Captured Kr in High Pressure Cylinders			
	Containers: 10 liter poly bottle contained within a double steel box. Each bottle contains 23 kg of cured grout				Containers: 55 gallon drum. Each drum contains 460 kg of cured grout			Containers: 55 gallon drum. Each drum contains 460 kg of cured grout			Containers: Standard Type 1 A high pressure cylinders containing 43.8 liters at 50 atm pressure.			
Burn-up (GW-d/MT)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)
50	2.10	0.09	0.09	0.18	11.74	0.19	0.03	9.41	0.15	0.02	0.70	3.72	0.085	170

Table E-15 New Extraction Fuel Reprocessing Metal Waste Summary

	Compacted Metal Containers: 2 ft diameter x 10 ft tall canisters. Each Canister Contains 3,600 kg.		
Burn-up (GW-d/MT)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT
50	300.5	2.62	0.084

Table E-16 New Extraction Reactor Fuel Reprocessing Fission Product Waste Summary

	Borosilicate Glass Containers: 2 ft diameter x 15 ft tall canisters. Each Canister Contains 2,900 kg.			
Burn-up (GW-d/MT)	**Mass (kg/MT)**	**Volume (ft^3/MT)**	**Containers per MT**	**Decay Heat (W/container)**
50	309.2	5.02	0.11	14,000

Table E-17 New Extraction Fuel Reprocessing Recovered Uranium Summary

	Recovered Uranium (U_2O_3) Containers: 55 gal Drum canisters. Each Canister Contains 400 kg.		
Burn-up (GW-d/MT)	**Mass (kg/MT)**	**Volume (ft^3/MT)**	**Containers per MT**
50	1,094	20.12	2.74

Table E-18 Borosilicate Glass Decay Heat Generated by New Extraction Processing of 51 GW-d/MT 5-year Cooled PWR Fuel

Decay Heat (Watts/Container)	Time (years)							
	Initial Production	**10**	**30**	**50**	**70**	**100**	**300**	**500**
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	9,628	4,563	2,779	1,748	1,100	549	5	0
Noble Metals Ag, Pd, Ru, Rh	1,820	2	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	2,123	465	90	18	4	1	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	1	1	1	1	1	1	1	1
Others	8	1	0	0	0	0	0	0
Total	13,581	5,032	2,871	1,768	1,105	551	6	1

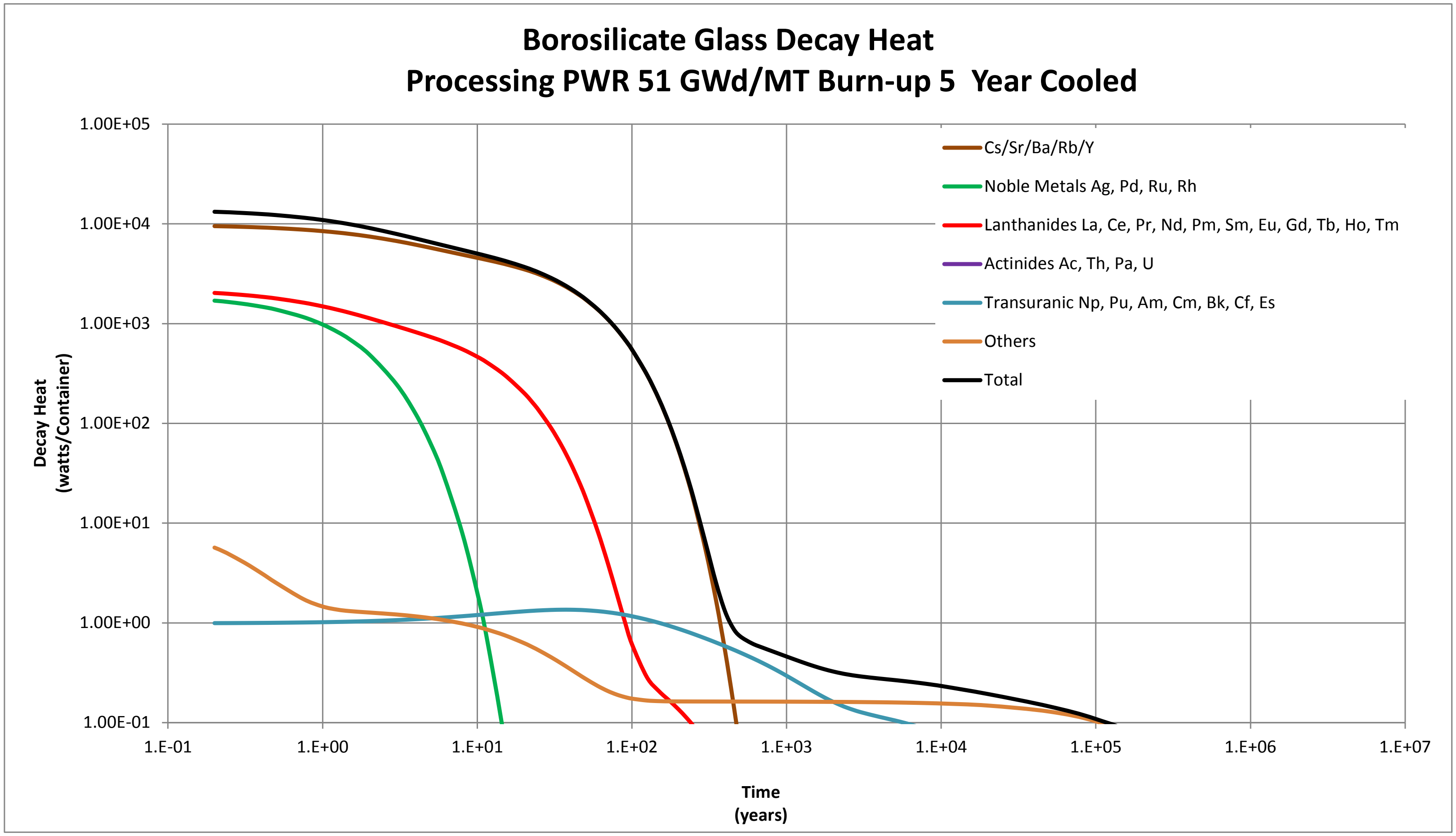

Figure E-8 Borosilicate Glass Decay Heat Generated by New Extraction Processing of 51 GW-d/MT 5-year Cooled PWR Fuel

E.3.3 Characteristics of Waste Generated by Electrochemical Reprocessing of SFR Metal Fuel

The electrochemical (EC) process is a dry process using conductive molten salt baths to recover all the TRU elements. In this process the fission products are split between three waste streams. Elements which are more noble (as measured by EC potential) than uranium, such as fuel cladding and noble metal fission products, remain as metals and are incorporated into a metal alloy waste form. Elements less noble than uranium are converted to chloride salts. The lanthanide elements are recovered from the salt by electrolysis and converted to a lanthanide glass. Excess salt is purged; the chloride is adsorbed by zeolite and bonded with glass to make the final waste form.

The principal gaseous radionuclides I-129, Kr-85, C-14 and H-3 released during reprocessing are captured and converted to a waste form suitable for disposal, although most of the I-129 in this process is not released to the gaseous phase but is converted to a molten salt and purged with the excess salt.

Material balance parameters and assumptions from (Carter, available on request) were used.

Electrochemical Process Baseline Waste Forms

Off-Gas Waste Forms

The off-gas waste forms are the same as those of the New Extraction LWR reprocessing method.

Principal Fission Product Waste Forms

Glass Bonded Zeolite – The EC process purges excess salt and fission products which have been adsorbed onto zeolite. Additional zeolite is added to sequester the excess salt chloride and then bonded with borosilicate glass. The glass bonded zeolite is cast into a 2 ft diameter by 15 ft tall canister containing 2,900 kg of glass. The waste form is 25% glass binder.

Lanthanide Glass – The EC process also separates the lanthanides which are converted to a lanthanide based glass. The glass is cast into a 6” diameter by 60 in tall canister containing 500 kg of glass. The waste loading is 50% lanthanides.

Metal Alloy – In the EC process those elements which are more noble (as measured by EC potential) than uranium, such as the hulls, hardware and noble metal fission products, remain as metals. The metal waste is decontaminated by volatilizing any adhered salts and then cast into a HLW canister. Each canister is 2 ft in diameter by 10 ft tall and contains 3,600 kg of waste material.

Electrochemical Waste Volumes, Masses and Containers

The potential waste inventory from reprocessing the metal ABR fuels is provided in Tables E-19 through E-21.

E.3.4 Characteristics of the Heat Generating Wastes from SFR Processes

The isotopic compositions, for the principal heat generating wastes from the electrochemical (E-Chem) process, the glass bonded zeolite, lanthanide glass, and metal alloy waste forms, were decayed using the ORIGEN 2.2 methods and isotopic parameters.

Table E-22 and Figure E-9 provide the decay heat as a function of time for the glass bonded zeolite (Carter et al. 2012, Appendix M). Detailed isotopic composition of the glass bonded zeolite after 5, 30, 100 and 500 years of cooling is provided elsewhere (Hardin et al. 2011, Appendix F, Table F-1).

Table E-23 and Figure E-10 provide the detailed isotopic composition for the lanthanide glass (Carter et al. 2012, Appendix M). Detailed isotopic composition of the lanthanide glass after 5, 30, 100 and 500 years of cooling is provided elsewhere (Hardin et al. 2011, Appendix F, Table F-2).

Table E-24 and Figure E-11 provide the decay heat of the metal alloy waste form (Hardin et al. 2011, Section 2.3.4). Detailed isotopic composition of the metal alloy after 5, 30, 100 and 500 years of cooling is provided elsewhere (Hardin et al. 2011, Appendix F, Table F-3).

Table E-19 Advanced Burner Reactor Fuel Reprocessing Off-Gas Waste Summary

Metal Based Fuel		Captured Tritium Grouted				Captured I on Silver Mordenite Grouted			Captured C-14 as Carbonate Grouted			Captured Kr in High Pressure Cylinders			
		Containers: 10 liter poly bottle contained within a double steel box. Each bottle contains 23 kg of cured grout				Containers: 55 gallon drum. Each drum contains 460 kg of cured grout			Containers: 55 gallon drum. Each drum contains 460 kg of cured grout			Containers: Standard Type 1 A high pressure cylinders containing 43.8 liters at 50 atm pressure.			
Burn-up (GW-d/MT)	Conver-sion Ratio	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)
99.6	0.75	2.10	0.09	0.09	0.65	0.00	0.00	0.000	19.62	0.31	0.043	0.93	4.89	0.112	201

Table E-20 Advanced Burner Reactor Fuel Reprocessing Metal Waste Summary

Metal Based Fuel		Electrochemical Metal Alloy Containers: 2 ft diameter x 10 ft tall canisters. Each Canister Contains 3,600 kg.			
Burn-up (GW-d/MT)	Conversion Ratio	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)
99.6	0.75	4,403	38.41	1.22	3,905

Table E-21 Advanced Burner Reactor Fuel Reprocessing Fission Product Waste Summary

Metal Based Fuel		Electrochemical							
		Glass Bonded Zeolite Containers: 2 ft diameter x 15 ft tall canisters. Each Canister Contains 2,900 kg.				Lanthanide Glass Containers: 6in diameter x 60in tall canisters. Each Canister Contains 500 kg.			
Burn-up (GW-d/MT)	Conversion Ratio	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)	Mass (kg/MT)	Volume (ft^3/MT)	Containers per MT	Decay Heat (W/container)
99.6	0.75	2,641	42.77	0.91	225	58.39	0.11	0.12	21,165

Table E-22 Electrochemical Glass Bonded Zeolite Decay Heat Generated by Processing SFR Metal Fuel with a TRU CR of 0.75

Decay Heat (Watts/Container)	Time (years)							
	Initial Production	10	30	50	70	100	300	500
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	2,255	1,785	1,106	693	435	216	2	0
Noble Metals Ag, Pd, Ru, Rh	-	-	-	-	-	-	-	-
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	-	-	-	-	-	-	-	-
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	0	0	0	0	0	0	0	0
Others	-	-	-	-	-	-	-	-
Total	2,255	1,785	1,106	693	435	216	2	0

Table E-23 Electrochemical Metal Alloy Decay Heat Generated by Processing SFR Metal Fuel with a TRU CR of 0.75

Decay Heat (Watts/Container)	Time (years)							
	Initial Production	10	30	50	70	100	300	500
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	0	0	0	0	0	0	0	0
Noble Metals Ag, Pd, Ru, Rh	3,777	4	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	113	9	1	1	1	1	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	1	0	0	0	0	0	0	0
Others	15	1	0	0	0	0	0	0
Total	3,905	14	2	1	1	1	0	0

Table E-24 Electrochemical Lanthanide Glass Decay Heat Generated by Processing SFR Metal Fuel with a TRU CR of 0.75

Decay Heat (Watts/Container)	Time (years)							
	Initial Production	10	30	50	70	100	300	500
Gases H, C, Xe, Kr,	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	1,030	815	505	317	199	99	1	0
Noble Metals Ag, Pd, Ru, Rh	-	-	-	-	-	-	-	-
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	20,135	297	52	10	2	0	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	0	0	0	0	0	0	0	0
Others	-	-	-	-	-	-	-	-
Total	21,165	1,112	556	327	201	99	1	0

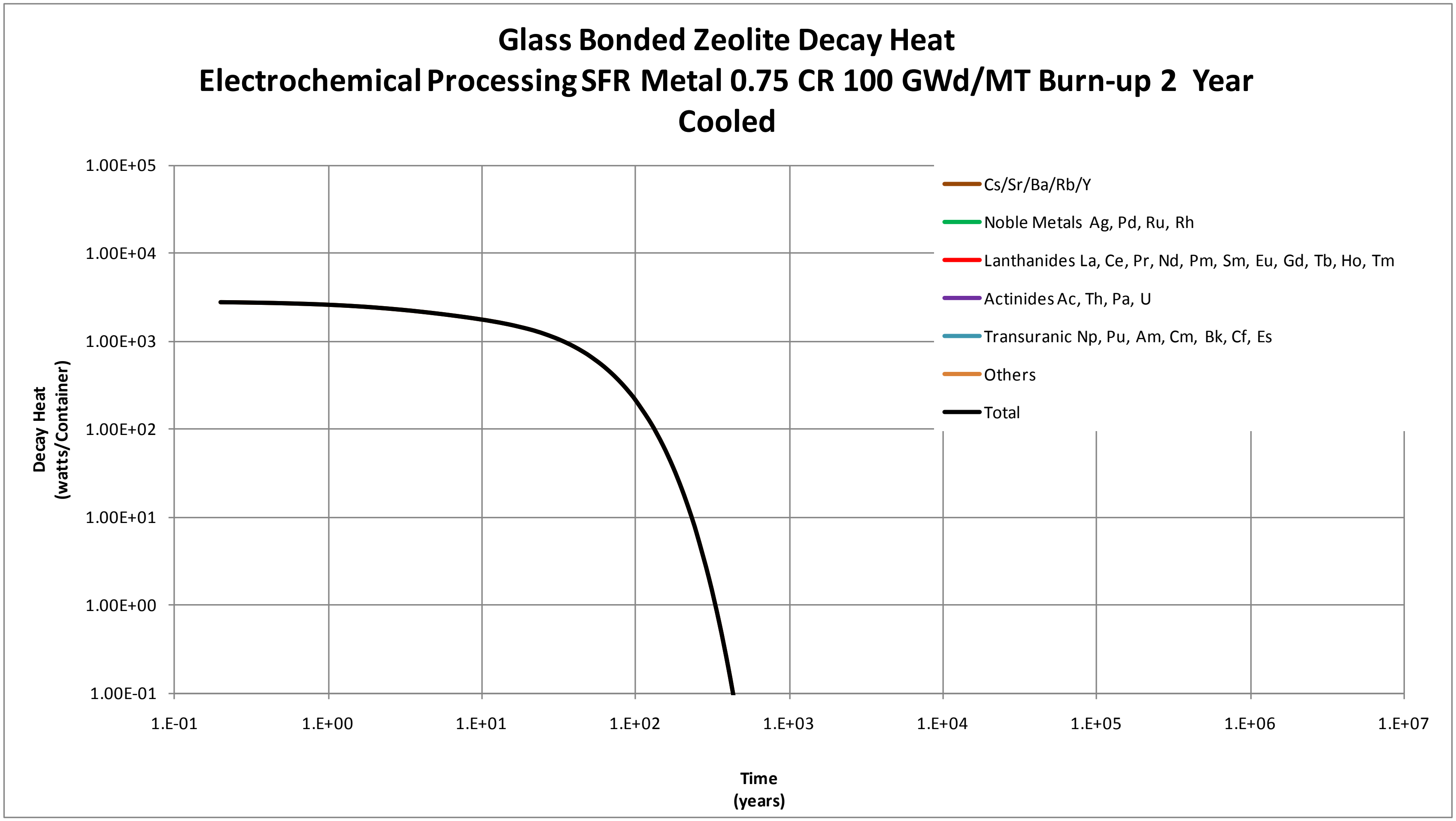

Figure E-9 Electrochemical Glass Bonded Zeolite Decay Heat Generated by Processing Sodium Fast Reactor Metal Fuel with a TRU CR of 0.75

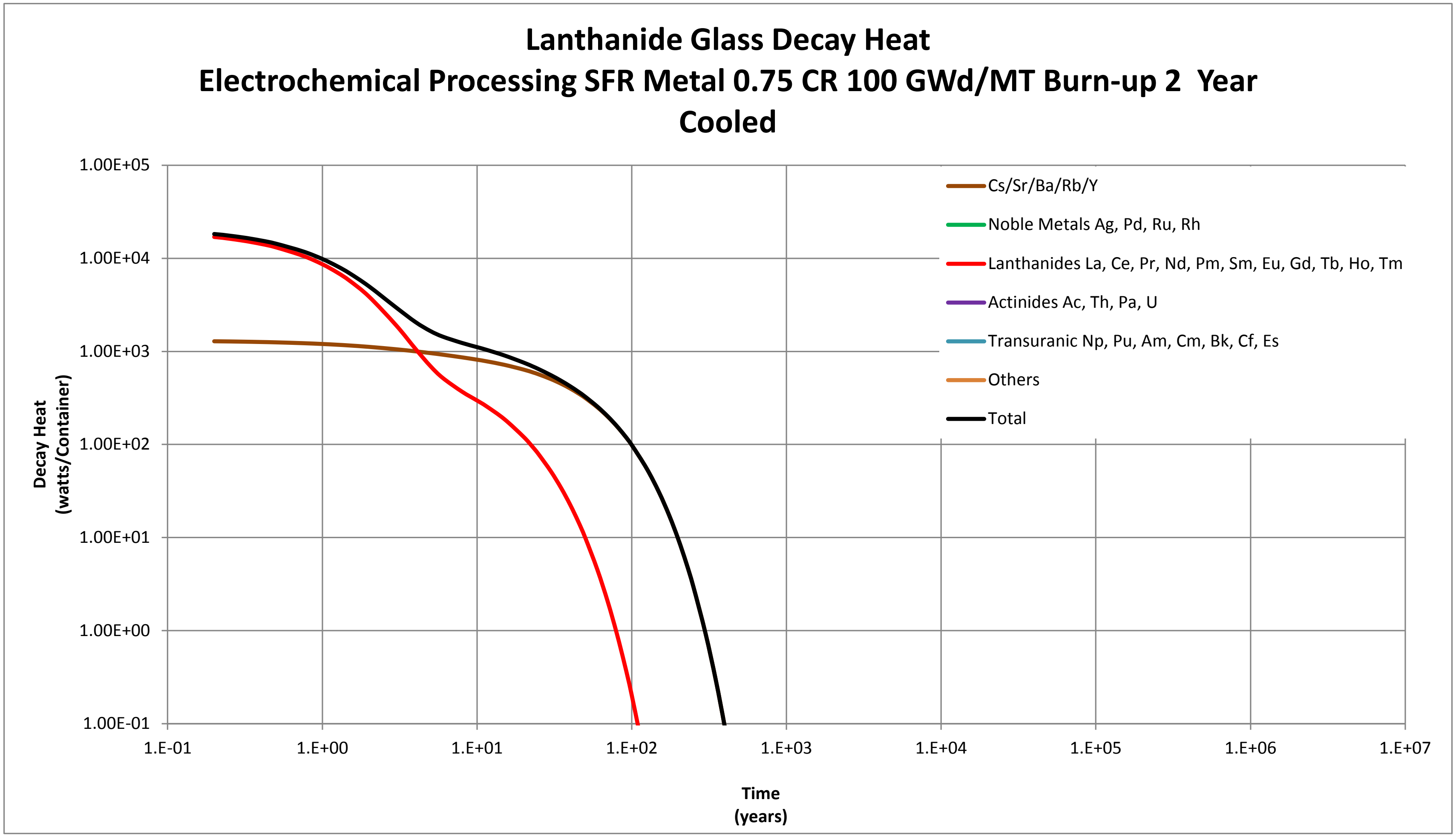

Figure E-10 Electrochemical Lanthanide Glass Decay Heat Generated by Processing Sodium Fast Reactor Metal Fuel with a TRU CR of 0.75

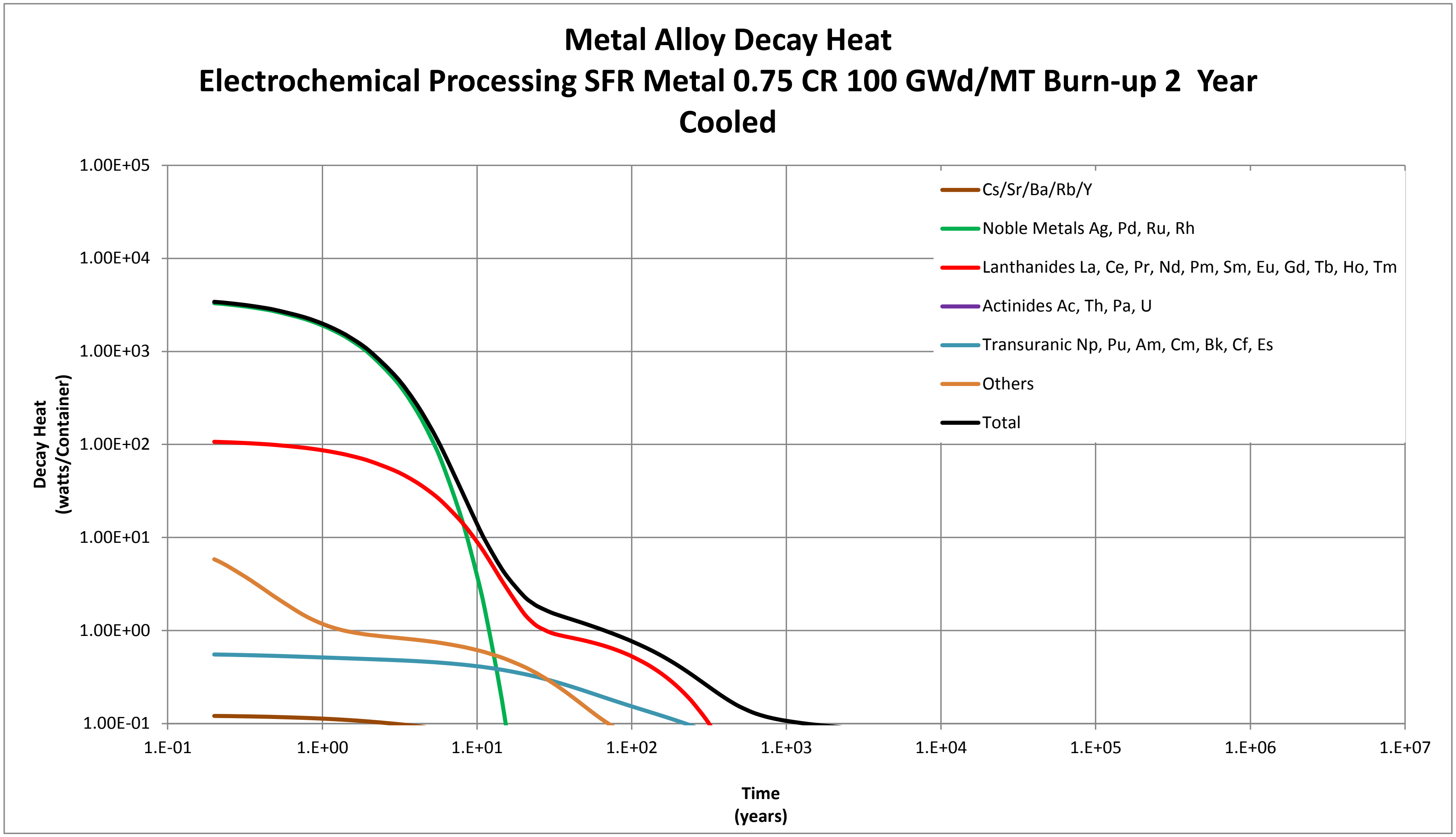

Figure E-11 Electrochemical Metal Alloy Decay Heat Generated by Processing Sodium Fast Reactor Metal Fuel with a TRU CR of 0.75

E.3.5 Characteristics of Closed Cycle Secondary Waste

Secondary wastes from the operation of closed fuel cycle facilities include:

- Operational waste such as empty containers, solidified decontamination solutions, used process filters, etc.
- Job control waste such as protective clothing, plastic suits, contamination control materials, step-off pads, etc.
- Maintenance waste such as failed equipment, HEPA filters, etc.

Secondary wastes are primarily characterized as low level (Class A, B and C) waste and GTCC waste. Relatively small quantities of mixed wastes are also anticipated from closed fuel cycle facility operations (such wastes are subject to additional statutory and regulatory requirements, such as the Resource Conservation and Recovery Act enacted by the U.S. in 1976).

Secondary Waste From Reprocessing LWR Fuel

Estimates of the volume of secondary waste resulting from a variety of recycling processes were investigated by Jones (2010). Secondary wastes from reprocessing operations depend on the reprocessing technology (in this case New Extraction) and the facility capacity. A facility capacity of 800 MTHM/year is a reasonable size for a reprocessing facility and is chosen as the basis for this analysis. Table E-25 shows the annual volume of secondary waste expected from a Co-Extraction facility with a capacity of 800 MTHM/year.

Table E-25 Annual Secondary Waste Volume from an 800 MTHM/year New Extraction Facility

Waste Type	Annual Waste Volume	
	(m^3)	(m^3/MTHM)
Low level Class A/B/C	8,821	11.0
Greater than Class C (GTCC)	477	0.6
Mixed low level Class A/B/C	32	0.04
Mixed GTCC	48	0.06

Secondary Waste From Advanced Burner Reactor Fuel Fabrication

Secondary waste from the fabrication of ABR fuel using transuranic radionuclides from UNF has not been estimated. It is anticipated that the waste volume would be on the order of that estimated for MOX fuel fabrication using plutonium recovered from UNF. Waste volume from ABR fuel would be expected to be slightly higher though, given the expected higher activity level of the feedstock which would contain additional radionuclides. At this time, the waste volume estimates for MOX fuel fabrication given in this appendix should be used for ABR fuel fabrication.

Secondary Waste From Repository Operations

Secondary waste volumes specifically for the disposal of HLW forms (e.g., vitrified waste forms) have not been estimated. It is expected that the HLW forms will require some repackaging at the repository similar to that required for UNF in the once-through cycle (see

Section E.1). Accordingly, it is recommended that the waste volume estimates provided in Section E.1 be used for secondary wastes associated with the disposal of HLW resulting from a closed fuel cycle.

Secondary Waste From Electrochemical Reprocessing of ABR Fuel

Secondary waste volume estimates for the electrochemical re-processing of ABR fuels were obtained from Jones (2010) and are shown in Table E-26.

Table E-26 Summary of Annual Waste Volume Estimates For Electrochemical Recycling Of Sodium Fast Reactor Used Fuel

Data Reference	Estimate Basis	Waste Volume	LLW Class A, B & C	GTCC Waste (CH & RH)	Mixed LLW	Mixed GTCC
EAS Electro-chemical	**300 MTHM/yr**	**m^3/yr**	2,716	919	29	43.6
		m^3/MTHM	9.1	3.1	0.1	0.15

Appendix F – Analysis of Shielding for Open-Mode Closure Operations

As noted in Section 1.5, the open mode repository concepts described in this report could require backfill to be placed in the emplacement drifts or plugs and seals to be emplaced prior to repository closure. These activities could require workers to enter repository service drifts (Figure 4.4-1) or access drifts (Figure 4.5-1) crossing emplacement drifts. Additionally, routine maintenance or performance confirmation activities could require worker entry into these drifts. This appendix presents a preliminary investigation of the feasibility and effectiveness of different radiation shielding concepts that could facilitate worker access to service or access drifts, for the open emplacement mode concepts. The maximum dose to workers in the access drift was estimated using MCNP5 with variance reduction parameters generated by the ORNL code ADVANTG.

F.1 MCNP5 Model

The dosimetry model includes a long section of the access drift with one emplacement drift, i.e., Figures 1 and 2. Six SNF waste packages with 32 PWR fuel assemblies each are placed in each side of the emplacement drift, i.e., Fig 3. The 32 PWR fuel assembly waste package is used to bound the 21 PWR fuel assembly waste packages used in the open mode concepts in Section 4 and for the purpose of showing the feasibility of the concept. The doses from a line of 21 PWR waste packages would be lower that the results presented here. The drift invert is 200 cm below the springline of the drifts, and the drifts are lined with 10 cm of shotcrete.

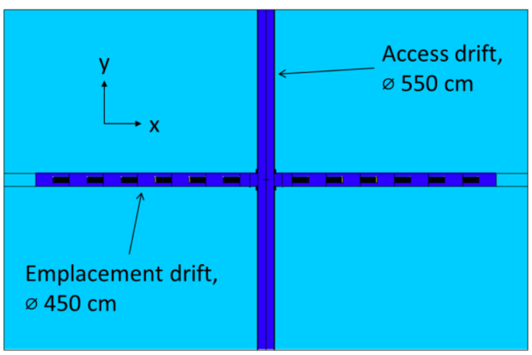

Figure F-1 Horizontal Slice Through the MCNP Model of the Open Mode Concept Showing Access and Emplacement Drifts

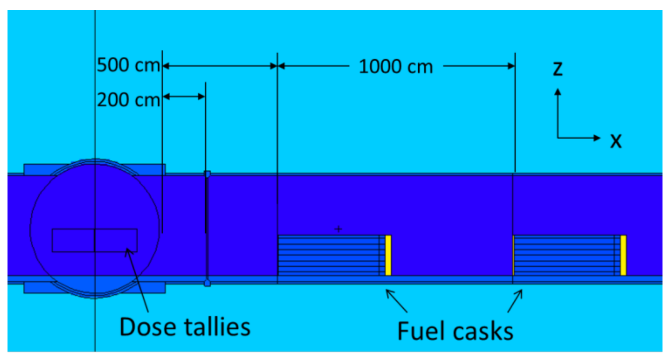

Figure F-2 Vertical Slice Through the MCNP Model of the Open Mode Concept (dose is tallied between 100 and 200 cm above the drift invert in several segments along the access drift)

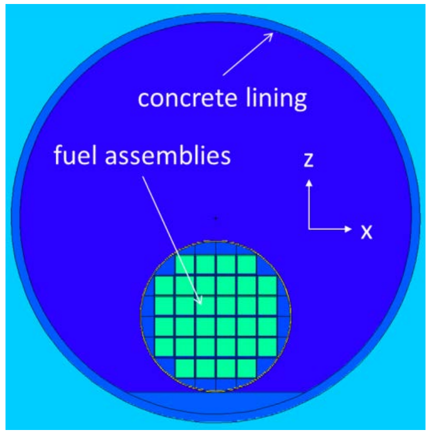

Figure F-3 Waste Package Represented on the Invert 200 cm below Springline of Emplacement Drift (drift diameter is 4.50 m)

As described in Section 2, the SNF waste packages do not include over-pack shielding. However, some of the cases described below assume that a depleted uranium shield plug is included on the end of the last waste package facing the access drift. The waste package is represented as a 304 stainless steel (SS-304) canister with 32 PWR used fuel bundles at 60 GWd/MTU burnup after 40 years of cool-down.

The drifts are filled with dry air at 0.0012479 g/cm^3. The shotcrete composition is approximated by the Oak Ridge concrete composition in the SCALE 6.0 documentation (2.2994 g/cm^3) since the materials have similar ratios of low- and mid-Z components [Petrie 2009]. The drifts are surrounded by dry clay at 1.746 g/cm^3.

F.2 Shielding Configurations

Several shielding configurations were modeled to estimate the dose rates in the access drift. An ideal configuration would maximize airflow into the emplacement drift while minimizing dose rates in the access drift.

F.2.1 Enclosure Shields

Several shielding configurations with concrete partly or completely filling the ~200 cm space between the access drift and the plug seat were modeled, i.e., Figures F-4 through F-6. Enclosure configuration A uses no shielding; concrete fills configuration B to a height z=125 cm above the drift springline; and configuration C has the space between the access drift and plug seat entirely filled with concrete. Configuration C does not allow airflow for cooling and is considered as a limiting case for the minimum achievable dose.

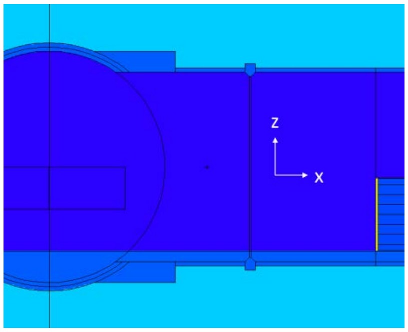

Figure F-4 Enclosure Configuration A (no shielding)

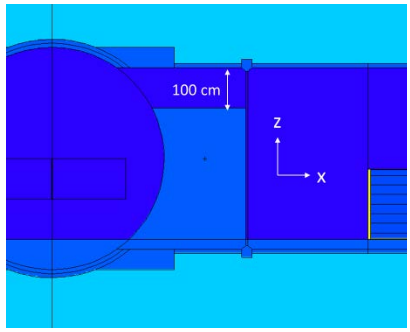

Figure F-5 Enclosure Configuration B (concrete fill 125 cm above the springline)

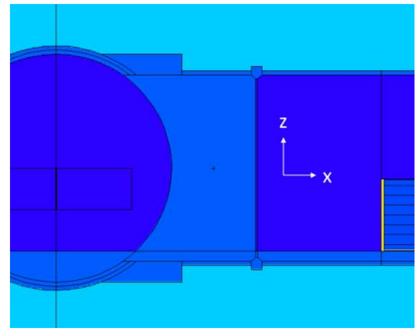

Figure F-6 Enclosure Configuration C (total enclosure)

F.2.2 Labyrinthine Shields

Labyrinthine concrete shielding configurations attempt to leave a curved path for airflow while reducing the streaming pathways for radiation, i.e., Figures F-7 through F-9. Labyrinthine configuration A is shown as 2-D array of dog-leg pipes that shift 30 cm mid-way through the shield. Configurations B and C allow airflow through a curved or dog-leg gap (respectively) running from the invert of the emplacement drift to the ceiling. The curve radii in model B are specifically designed to ensure that radiation must pass through concrete shielding at least twice.

A significant portion of the dose in configurations B and C comes from radiation that is scattered multiple times in the airflow channel. To demonstrate the effectiveness of high-Z material in reducing albedo in the airflow channel, configurations with 1 cm-thick lead lining along the curved channel surfaces of model B and the surfaces of configuration C near the access drift are included in the results.

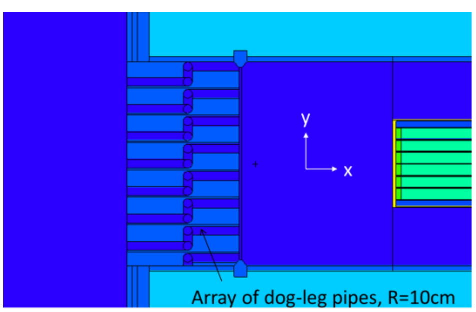

Figure F-7 Labyrinth Configuration A (cylindrical dog-leg ducts)

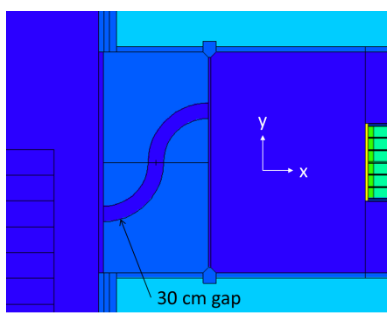

Figure F-8 Labyrinth Configuration B (curved gap)

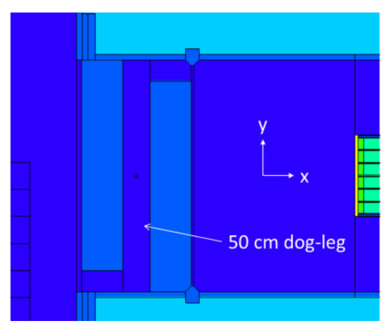

Figure F-9 Labyrinth Configuration C (dog-leg gap)

F.2.3 Photon-Attenuator Shields

A ventilated dry cask storage overpack photon radiation scattering attenuator is described in US Patent 6519307 [Singh 2003] which allows for air flow and reduced dose. Several variations of this concept were evaluated for use as a means to reduce dose rates in the access drift while allowing airflow. . Photon-attenuator configurations A through R use a 38.1 cm depleted uranium (DU) disk to shield direct photons, and SS-316 grids of varying channel length, airflow channel width, and SS thickness to reduce the dose from scattered photons (see Figures F-10 and F-11).

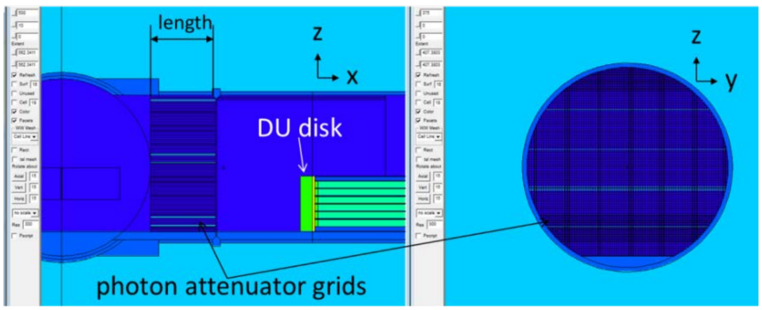

Figure F-10 Vertical Slices of the Access Drift Showing the Photon Attenuator Grids (configuration E: length is 200 cm)

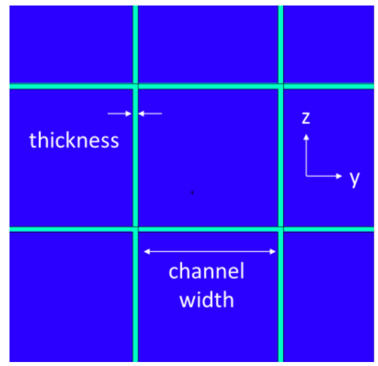

Figure F-11 Detail of Photon Attenuator Configuration E (thickness and channel width are 0.2 cm and 5.08 cm, respectively)

One additional variation (configuration S) has photon-attenuators only along the shotcrete walls of the emplacement drift. The attenuators extend up to 15.24 cm from the walls, and the channels run parallel to the y-axis to prevent streaming toward the access drift.

F.3 Results

The shielding configurations described in the previous section were simulated with MCNP5 for 10 to 100 CPU-hours. The results for the enclosure configurations, labyrinth configurations, and photon-attenuator configuration S are listed in Table F-1. Results for photon attenuator models with 100 and 200 cm channel lengths are listed in Tables F-2 and F-3, respectively. Results for photon attenuator configurations A through R are generally less precise than the other results due to challenges associated with modeling the intricate photon attenuator array in ADVANTG.

Table F-1 Dose Rate Estimates from Select Shielding Configurations (units of mrem/hour)

Configuration	Neutron dose	(n,γ) dose	Photon dose	Total dose
Enclosure A (no shield)	2.17E+02	7.86E+00	7.35E+04	7.37E+04
Enclosure B (partial shield)	7.41E+00	6.25E-01	1.48E+03	1.49E+03
Enclosure C (total enclosure)	1.11E-06	6.68E-05	2.00E-07	6.81E-05
Labyrinth A	6.35E-02	4.41E-02	9.33E-01	1.04E+00
Labyrinth B	1.98E-01	4.11E-02	6.36E+00	6.60E+00
Labyrinth B (lead-lined)	2.04E-01	2.63E-02	9.70E-02	3.28E-01
Labyrinth C	3.58E-02	2.83E-02	4.48E-01	5.12E-01
Labyrinth C (lead-lined)	3.66E-02	1.18E-02	1.28E-01	1.76E-01
Photon attenuators S (lining-only)	1.65E+02	7.11E+00	4.83E+04	4.85E+04

Table F-2 Total Dose Rate Estimates (mrem/hour) as a Function of Grid Thickness and Airflow-Channel Width (configurations J through R: attenuator grids are 100 cm long)

	Channel Width (cm)		
Thickness (cm)	**2.54**	**5.08**	**10.16**
0.1	1.4E+03	6.5E+03	1.8E+04
0.2	8.1E+02	2.1E+03	8.5E+03
0.4	4.9E+01	1.9E+03	3.9E+03

Table F-3 Total Dose Rate Estimates (mrem/hour) as a Function of Grid Thickness and Airflow-Channel Width (configurations A through I: attenuator grids are 200 cm long)

Thickness (cm)	Channel Width (cm)		
	2.54	**5.08**	**10.16**
0.1	7.8E+01	1.0E+03	6.2E+03
0.2	3.6E+01	4.4E+02	1.7E+03
0.4	6.2E+00	3.0E+02	7.3E+02

Summary

Occupational dose limits for radiation protection as described in 10 CFR 20.1201 are the more limiting of a total effective dose equivalent of 5 rem (0.05 Sv), or the sum of the deep dose equivalent and committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 50 rem (0.5 Sv). The lens dose equivalent may not exceed 15 rem (0.15 Sv), and the shallow dose equivalent to skin may not exceed 50 rem (0.5 Sv). The results presented in this appendix show sufficient margins may be realizable for several different shielding configurations while allowing adequate air flow. Future refinements would require more detailed evaluations in conjunction with controls for ensuring doses are as low as is reasonably achievable (ALARA).

Options that could be considered for reducing the dose rates at the access main include preferential loading of the drift as the majority of the dose is projected from the package closest to the access main. Hotter (i.e., higher source term or shorter decay time) packages could be loaded at the back with cooler packages loaded near the front.

Appendix G – Unit Cost for Mining

FERMILAB tunnel cost estimate models, developed in 2001, were utilized in this study to develop parametric quantities and costs for parts of the generic disposal concept cost estimates. The cost models were used in conjunction with industry standard rock classification guidelines for determining quality of rock, and modified to account for the dimensions and equipment needed for the generic repository. Using DOE Escalation data, the 2001 FERMILAB Tunnels Cost Estimate Models were escalated to bring the cost current as of 2012. The basis for escalation is as follows: 2001 Cost are Indexed at 0.731 and the 2012 cost are Indexed at 1.019. This equates to an escalation factor of 1.288 (28.8%) applied to 2001 costs. From there a current unit cost was developed in meters, later to be converted to linear feet for use in the cost estimates.

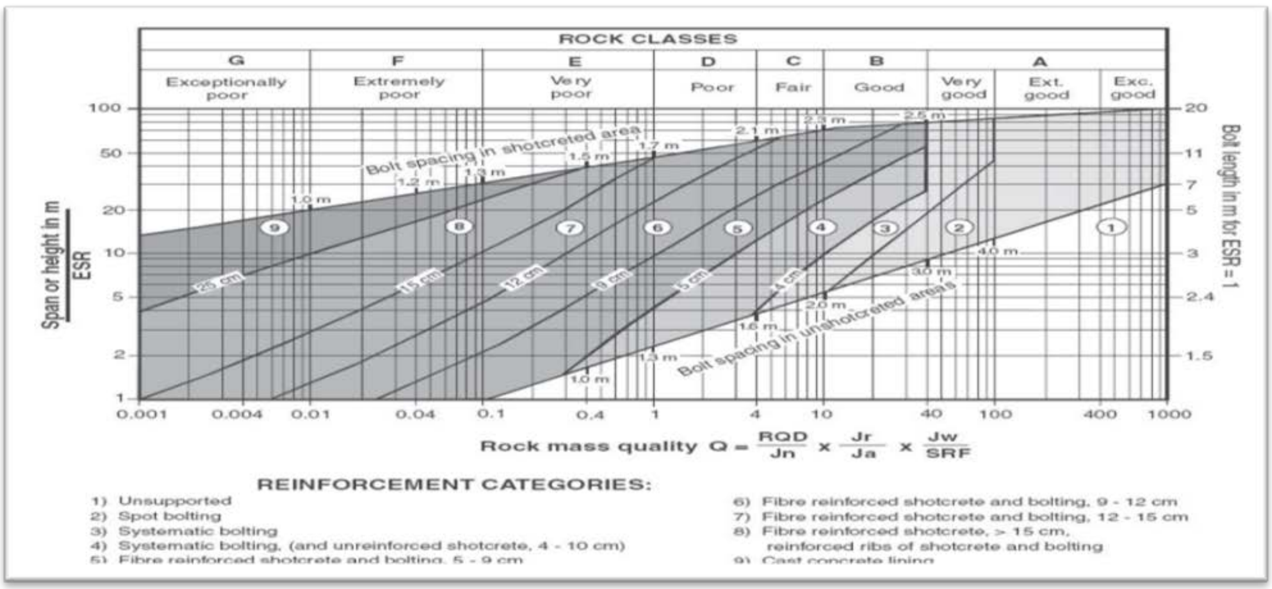

Figure G-1 Rock classification Guidelines

Other reference data include: Project Nueva Andina Phase I (Fluor proprietary information), Internet vendor data, estimates for the Olkiluoto facility, the WIPP Project, Andra 2005b (Granite), and various others. For this generic study mining estimates rely on Figure G-1 for determining rock classification and the reinforcement.

Crystalline Rock is classified as "B Good Rock" and applies Mining Methods and Reinforcement Category (3-4). Clay/Shale Rock is classified as "C Fair Rock" and applies Mining Methods and Reinforcement Category (4).

Note that evaluation of cost factors is provided here and in Section 5, to show how design features and thermal management strategies affect relative costs. Application of these cost results beyond this purpose should be avoided.

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Table G-1 Unit Cost Details for Shale Unbackfilled Open Disposal Concept

Generic Repository Tunnel								
4800 m - 3.66 m dia - Rock Type "C" Shale/Clay Supported - Open								
Length of Tunnel	**4800**	**meters**						
Diameter of Tunnel	**3.66**	**meters**						
Qty of Neat Excavation	**69706**	**Cu. meters**						
Secondary Lining Volume	**11641**	**Cu. meters**						
Theoretical Grout Volume	**7564**	**Cu. meters**						
Advance Rate and Shift Details								
Shift details - 2 X 10 hours - 5 Days per week								
Avg. advance per Shift	10.6	meters						
Avg. Advance per Week	106	meters						
Duration of Tunneling	45	weeks						
Number of Shifts	453	each		`			**Escalation Factor**	
							1.288	
					Rate	**Total**	**Total**	
Labor Crew		FTE	Hours		**2001**	**2001**	**2012**	
General Foreman		2	9057		$ 66.95	$ 606,340	$ 780,965	
Working Foreman		2	9057		$ 61.80	$ 559,698	$ 720,891	
Tunnel Miner		4	18113		$ 48.66	$ 881,389	$ 1,135,229	
Tunnel Laborer		6	27170		$ 39.45	$ 1,071,849	$ 1,380,542	
Locomotive Driver		3	13585		$ 46.29	$ 628,845	$ 809,953	
Shaft Bottom Support		2	9057		$ 39.45	$ 357,283	$ 460,181	
Mining Equipment Operators		3	13585		$ 56.61	$ 769,042	$ 990,525	
Tunnel Fitter		2	9057		$ 44.89	$ 406,551	$ 523,638	
Tunnel Electrician		2	9057		$ 55.28	$ 500,649	$ 644,836	
Shaft Top Support		2	9057		$ 39.45	$ 357,283	$ 460,181	
Crane Operator		2	9057		$ 46.29	$ 419,230	$ 539,968	
Surface laborer		2	9057		$ 39.45	$ 357,283	$ 460,181	
Equipment Laborer		4	18113		$ 46.94	$ 850,234	$ 1,095,101	
		36	163,019			**$ 7,765,675**	**$ 10,002,190**	
Tunneling Operations		Resource Qty	Unit Qty	Unit	Unit Cost	Total 2001	**Total 2012**	
Boom Cutter Machine		1	45	Wks	$ 45,000	$ 2,025,000	$ 2,608,200	
Mob Set up		1	1.00	Wks	$ 200,000	$ 200,000	$ 257,600	
Mucking Machine		1	45	Wks	$ 30,000	$ 1,350,000	$ 1,738,800	
Locomotives		3	45	Ea	$ 4,200	$ 567,000	$ 730,296	
Muck Cars and Grout Cars		18	45	Ea	$ 1,450	$ 1,174,500	$ 1,512,756	
Flat Cars		6	45	Ea	$ 260	$ 70,200	$ 90,418	
Man Ride Cars		1	45	Ea	$ 260	$ 11,700	$ 15,070	
Track		1	109710	m/wks	$ 2.00	$ 219,420	$ 282,613	
Air Pipe		1	109710	m/wks	$ 3.00	$ 329,130	$ 423,919	
Water Pipe		1	109710	m/wks	$ 3.00	$ 329,130	$ 423,919	
Pump main		1	109710	m/wks	$ 2.00	$ 219,420	$ 282,613	
Cabling		1	109710	m/wks	$ 4.00	$ 438,840	$ 565,226	
Lighting		1	109710	m/wks	$ 4.50	$ 493,695	$ 635,879	
Vent Ducting		1	109710	m/wks	$ 3.00	$ 329,130	$ 423,919	
Booster Fans		3	45	Wks	$ 575	$ 77,625	$ 99,981	
Grout Mixers		1	45	Wks	$ 4,000	$ 180,000	$ 231,840	
Grout Pumps		1	45	Wks	$ 2,800	$ 126,000	$ 162,288	
Grout Hoses and Pipes		1	45	Wks	$ 200	$ 9,000	$ 11,592	
Transformers and Switchgear		1	45	Wks	$ 650	$ 29,250	$ 37,674	
Small Tools		1	45	Wks	$ 500	$ 22,500	$ 28,980	
Other Plant		1	45	Wks	$ 1,500	$ 67,500	$ 86,940	
Hoists		1	45	Wks	$ 450	$ 20,250	$ 26,082	
Man Hoists		1	45	Wks	$ 1,700	$ 76,500	$ 98,532	
Cranes		1	45	Wks	$ 4,000	$ 180,000	$ 231,840	
Compressors		1	45	Wks	$ 800	$ 36,000	$ 46,368	
Pipework and Controls		1	45	Wks	$ 550	$ 24,750	$ 31,878	
Generators		1	45	Wks	$ 1,400	$ 63,000	$ 81,144	
Transformers and Switchgear		1	45	Wks	$ 1,700	$ 76,500	$ 98,532	
Surface Fans		2	45	Wks	$ 561	$ 50,490	$ 65,031	
Rack and Pinion		1	1	Wks	$ 109,710.00	$ 109,710	$ 141,306	
Vertical Conveyor		1	45	Wks	$ 5,000	$ 225,000	$ 289,800	
Loaders		2	45	Wks	$ 5,046	$ 454,140	$ 584,932	
Off-road Dump Trucks		4	45	Wks	$ 5,046	$ 908,280	$ 1,169,865	
Other Suface Plant		1	45	Wks	$ 2,200	$ 99,000	$ 127,512	
						$ 10,592,660	**$ 13,643,346**	
Consumables						$ -		
Electrical Power		1500	3800	kWh	$ 0.10	$ 570,000	$ 734,160	
Fuel		1	100000	liter	$ 0.60	$ 60,000	$ 77,280	
Lube Materials		1	45	Wks	$ 90	$ 4,050	$ 5,216	
Machine Spares, Cutters		1	4800	meter	$ 60	$ 288,000	$ 370,944	
Filters		1	45	Wks	$ 400	$ 18,000	$ 23,184	
Hydraulic Oil		1	45	Wks	$ 2,500	$ 112,500	$ 144,900	
Other Consumables		1	45	Wks	$ 200	$ 9,000	$ 11,592	
						$ 1,061,550	**$ 1,367,276**	
Materials						$ -		
Rockbolts		1.5	4800	meter	$ 60	$ 432,000	$ 556,416	
Strapping		1	4800	meter	$ 90	$ 432,000	$ 556,416	
Temporary Materials		1	45	Wks	$ 1,000	$ 45,000	$ 57,960	
Shotcrete		3	6840	m3	$ 150	$ 3,078,000	$ 3,964,464	
Lagging		1	4800	meter	$ 50	$ 240,000	$ 309,120	
Grout		1	7564	m3	$ 145	$ 1,096,780	$ 1,412,653	
Concrete Plugs		1	84	ea	$ 10,000	$ 840,000	$ 840,000	
Void Filler		1	150	m3	$ 150	$ 22,500	$ 28,980	
Packers		1	200	ea	$ 20	$ 4,000	$ 5,152	
Invert Forms		1	9600	meter	$ 20	$ 192,000	$ 247,296	
Lining Forms		1	4800	meter	$ 50	$ 240,000	$ 309,120	
Concrete		1	9600	m3	$ 180	$ 1,728,000	$ 2,225,664	
Membrane		3	4800	m2	$ 45	$ 648,000	$ 834,624	
						$ 8,998,280	**$ 11,347,865**	
Subcontracts								
Heavy Transport Railing		0	9600	meter	$ 300	$ -	$ -	
Ventilation Doors		1	92	ea	$ 20,000	$ 1,840,000	$ 1,840,000	
Muck Disposal		1.8	69706	m3	$ 10	$ 1,254,708	$ 1,616,064	
Foam		0.3	4800	m3	$ 100	$ 144,000	$ 185,472	
						$ 3,238,708	**$ 3,641,536**	
					Total Estimated Cost	**$ 31,656,873**	**$ 40,002,213**	
					Per linear Meter	**$ 6,595.18**	**$ 8,333.79**	
					Per Cubic Meter	**$ 573.87**	**$ 438.07**	**Per Cubic Yard**
							$ 883,382.2	**Per Week**

Mine Plan for Clay/Shale (Open) Mode

Ventilation system capacity: 1,000 kg/s

Ventilation per drift: 5 to 20 kg/s

Drifts per panel: 12 (+/-)

Emplacement Drift length: 700 m (+/-)

Segments per drift: 8 (+/-)

Waste packages per segment: 10 (+/-)

Waste capacity per panel: 10,000 MT (+/-)

Number of panels supported (as shown): up to 8 (+/-)

Notes:

1. All drifts excavated with boom cutter. Drill-and-blast for exhaust shaft, raise-bore all other shafts.
2. See detail for pre-constructed drift intersections.
3. Construct all access and service drifts (but not necessarily all emplacement drifts) before emplacing waste.
4. Waste rock shaft, men/matls. shaft, and waste transport shaft/ramp, can support additional panels in the opposite direction (with addl. ventilation).
5. Access and service drift ground support: 2-m rockbolts, steel sets and steel lagging, and 3 cm of shotcrete; 270° coverage.
6. Access and service drift floors: reinforced concrete with heavy rail (approx. 4m wide by 0.5 m deep in the center)
7. Emplacement drift ground support: 2- and 3-m rock bolts, wire mesh, and 5 cm low permeability shotcrete.
8. Shaft support: non-reinforced cast-in-place concrete with steel internals (remove liner and seal shaft at closure)
9. Recommend ramp (not shaft) as reference mode for waste transport because shale basins are extensive and repository depth can be <500 m. Choose a simple ramp (10% grade) over funicular railway because of long operating period (100 yrs or longer).
10. Ramp support: see access and service drift ground support.
11. Ramp floor: reinforced concrete. Use diesel-powered heavy transporter (payload ~120 tons with shielding) and transfer
12. Backfill all openings at closure.
13. Use plugs/seals for ramp and inter-connecting drifts.

Table G-2 Unit Cost Details for Clay/Shale (enclosed) Disposal Concept

Generic Repository Tunnel								
4800 m - 3.66 m dia - Rock Type "C" Shale/Clay Supported - Enclosed								
Length of Tunnel	**4800**	**meters**						
Diameter of Tunnel	**3.66**	**meters**						
Qty of Neat Excavation	**69706**	**Cu. meters**						
Secondary Lining Volume	**11641**	**Cu. meters**						
Theoretical Grout Volume	**7564**	**Cu. meters**						
Advance Rate and Shift Details								
Shift details - 2 X 10 hours - 5 Days per week								
Avg. advance per Shift	10.6	meters						
Avg. Advance per Week	106	meters						
Duration of Tunneling	45	weeks						
Number of Shifts	453	each			`		**Escalation Factor**	
							1.288	
					Rate	**Total**	**Total**	
Labor Crew		FTE	Hours		**2001**	**2001**	**2012**	
General Foreman		2	9057		$ 66.95	$ 606,340	$ 780,965	
Working Foreman		2	9057		$ 61.80	$ 559,698	$ 720,891	
Tunnel Miner		4	18113		$ 48.66	$ 881,389	$ 1,135,229	
Tunnel Laborer		6	27170		$ 39.45	$ 1,071,849	$ 1,380,542	
Locomotive Driver		3	13585		$ 46.29	$ 628,845	$ 809,953	
Shaft Bottom Support		2	9057		$ 39.45	$ 357,283	$ 460,181	
Mining Equipment Operators		3	13585		$ 56.61	$ 769,042	$ 990,525	
Tunnel Fitter		2	9057		$ 44.89	$ 406,551	$ 523,638	
Tunnel Electrician		2	9057		$ 55.28	$ 500,649	$ 644,836	
Shaft Top Support		2	9057		$ 39.45	$ 357,283	$ 460,181	
Crane Operator		2	9057		$ 46.29	$ 419,230	$ 539,968	
Surface laborer		2	9057		$ 39.45	$ 357,283	$ 460,181	
Equipment Laborer		4	18113		$ 46.94	$ 850,234	$ 1,095,101	
		36	163,019			**$ 7,765,675**	**$ 10,002,190**	
Tunneling Operations		Resource Qty	Unit Qty	Unit	Unit Cost	Total 2001	**Total 2012**	
Boom Cutter Machine		1	45	Wks	$ 45,000	$ 2,025,000	$ 2,608,200	
Mob Set up		1	1.00	Wks	$ 200,000	$ 200,000	$ 257,600	
Mucking Machine		1	45	Wks	$ 30,000	$ 1,350,000	$ 1,738,800	
Locomotives		3	45	Ea	$ 4,200	$ 567,000	$ 730,296	
Muck Cars and Grout Cars		18	45	Ea	$ 1,450	$ 1,174,500	$ 1,512,756	
Flat Cars		6	45	Ea	$ 260	$ 70,200	$ 90,418	
Man Ride Cars		1	45	Ea	$ 260	$ 11,700	$ 15,070	
Track		1	109710	m/wks	$ 2.00	$ 219,420	$ 282,613	
Air Pipe		1	109710	m/wks	$ 3.00	$ 329,130	$ 423,919	
Water Pipe		1	109710	m/wks	$ 3.00	$ 329,130	$ 423,919	
Pump main		1	109710	m/wks	$ 2.00	$ 219,420	$ 282,613	
Cabling		1	109710	m/wks	$ 4.00	$ 438,840	$ 565,226	
Lighting		1	109710	m/wks	$ 4.50	$ 493,695	$ 635,879	
Vent Ducting		1	109710	m/wks	$ 3.00	$ 329,130	$ 423,919	
Booster Fans		3	45	Wks	$ 575	$ 77,625	$ 99,981	
Grout Mixers		1	45	Wks	$ 4,000	$ 180,000	$ 231,840	
Grout Pumps		1	45	Wks	$ 2,800	$ 126,000	$ 162,288	
Grout Hoses and Pipes		1	45	Wks	$ 200	$ 9,000	$ 11,592	
Transformers and Switchgear		1	45	Wks	$ 650	$ 29,250	$ 37,674	
Small Tools		1	45	Wks	$ 500	$ 22,500	$ 28,980	
Other Plant		1	45	Wks	$ 1,500	$ 67,500	$ 86,940	
Hoists		1	45	Wks	$ 450	$ 20,250	$ 26,082	
Man Hoists		1	45	Wks	$ 1,700	$ 76,500	$ 98,532	
Cranes		1	45	Wks	$ 4,000	$ 180,000	$ 231,840	
Compressors		1	45	Wks	$ 800	$ 36,000	$ 46,368	
Pipework and Controls		1	45	Wks	$ 550	$ 24,750	$ 31,878	
Generators		1	45	Wks	$ 1,400	$ 63,000	$ 81,144	
Transformers and Switchgear		1	45	Wks	$ 1,700	$ 76,500	$ 98,532	
Surface Fans		2	45	Wks	$ 561	$ 50,490	$ 65,031	
Rack and Pinion		1	1	Wks	$ 109,710.00	$ 109,710	$ 141,306	
Vertical Conveyor		1	45	Wks	$ 5,000	$ 225,000	$ 289,800	
Loaders		2	45	Wks	$ 5,046	$ 454,140	$ 584,932	
Off-road Dump Trucks		4	45	Wks	$ 5,046	$ 908,280	$ 1,169,865	
Other Suface Plant		1	45	Wks	$ 2,200	$ 99,000	$ 127,512	
						$ 10,592,660	**$ 13,643,346**	
Consumables						$ -		
Electrical Power		1500	3800	kWh	$ 0.10	$ 570,000	$ 734,160	
Fuel		1	100000	liter	$ 0.60	$ 60,000	$ 77,280	
Lube Materials		1	45	Wks	$ 90	$ 4,050	$ 5,216	
Machine Spares, Cutters		1	4800	meter	$ 60	$ 288,000	$ 370,944	
Filters		1	45	Wks	$ 400	$ 18,000	$ 23,184	
Hydraulic Oil		1	45	Wks	$ 2,500	$ 112,500	$ 144,900	
Other Consumables		1	45	Wks	$ 200	$ 9,000	$ 11,592	
						$ 1,061,550	**$ 1,367,276**	
Materials						$ -		
Rockbolts		1.5	4800	meter	$ 60	$ 432,000	$ 556,416	
Strapping		1	4800	meter	$ 90	$ 432,000	$ 556,416	
Temporary Materials		1	45	Wks	$ 1,000	$ 45,000	$ 57,960	
Shotcrete		3	6840	m3	$ 150	$ 3,078,000	$ 3,964,464	
Lagging		1	4800	meter	$ 50	$ 240,000	$ 309,120	
Grout		1	7564	m3	$ 145	$ 1,096,780	$ 1,412,653	
Concrete Plugs		1	50	ea	$ 3,200	$ 160,000	$ 206,080	
Void Filler		1	150	m3	$ 150	$ 22,500	$ 28,980	
Packers		1	200	ea	$ 20	$ 4,000	$ 5,152	
Invert Forms		1	9600	meter	$ 20	$ 192,000	$ 247,296	
Lining Forms		1	4800	meter	$ 50	$ 240,000	$ 309,120	
Concrete		1	9600	m3	$ 180	$ 1,728,000	$ 2,225,664	
Membrane		3	4800	m2	$ 45	$ 648,000	$ 834,624	
						$ 8,318,280	**$ 10,713,945**	
Subcontracts								
Heavy Transport Railing		0	9600	meter	$ 300	$ -	$ -	
Muck Disposal		1.8	69706	m3	$ 10	$ 1,254,708	$ 1,616,064	
Foam		0.3	4800	m3	$ 100	$ 144,000	$ 185,472	
						$ 1,398,708	**$ 1,801,536**	
				Total Estimated Cost		**$ 29,136,873**	**$ 37,528,293**	
				Per linear Meter		**$ 6,070.18**	**$ 7,818.39**	
				Per Cubic Meter		**$ 538.38**	**$ 410.98**	**Per Cubic Yard**
							$ 828,749.8	**Per Week**

Mine Plan for Clay/Shale (Enclosed) Mode

Ventilation system capacity: 500 kg/s

Ventilation per drift: 1 to 5 kg/s (variable)

Access drifts per panel: 4 (nom.)

Emplacement drift length: 40 m (+/-)

Waste packages per drift: up to 6 (+/-)

Package size: 4-PWR or eqiuv. (~2 MT each)

Waste capacity per panel: 2,000 MT (+/-)

Number of panels supported (as shown): up to 25 (+/-) limited by safe egress, services, and ventilation.

Notes:

1.All drifts excavated with boom cutter. Drill-and-blast for exhaust shaft, raise-bore all other shafts.

2.Emplacement drifts are 40-m blind bores, machine excavated. At completion each empl. drift requires a shield plug.

3.Complete construction of each access drift with emplacement borings (not necessarily entire panel) before emplacing waste.

4.Waste rock shaft, men/matls. shaft, and waste transport shaft/ramp, can support additional panels in the opposite direction (with addl. ventilation).

5.Access and service drift ground support: 2-m rockbolts, steel sets and steel lagging, and 3 cm of shotcrete; 270° coverage.

6.Access and service drift floors: reinforced concrete with heavy rail (approx. 4m wide by 0.5 m deep in the center)

7.Emplacement drift ground support: tubular steel liner grouted in place, with rails welded for buffer installation and package transit.

8.Shaft support: non-reinforced cast-in-place concrete with steel internals (remove liner and seal shaft at closure)

9.Recommend ramp (not shaft) as reference mode because shale basins are extensive and repository depth can be less than 500 m. Choose a simple ramp (10% grade) over funicular railway because of long operating period (100 yrs or longer).

10.Ramp support: same as access and service drift ground support.

11.Ramp floor: reinforced concrete. Use diesel-powered heavy transporter and transfer to shielded rail transporter underground.

12.Backfill all openings at closure.

13.Use plugs/seals for ramp and inter-connecting drifts.

Table G-3 Unit Cost Details for Crystalline (enclosed) Concept, Service and Access Drifts

Generic Repository Tunnel

4800 m - 3.66 m dia - Rock Type "B" Crystalline Requiring Some Support

Length of Tunnel	**4800**	**meters**						
Diameter of Tunnel	**3.66**	**meters**						
Qty of Neat Excavation	**64180**	**Cu. meters**						
Primary Lining Volume	**6840**	**Cu. meters**						
Secondary Lining Volume	**0**	**Cu. meters**						
Advance Rate and Shift Details								
Shift details - 2 X 10 hours - 5 Days per week								
Avg. advance per Shift	12.6	meters						
Avg. advance per Day	25.2	meters						
Avg. Advance per Week	126	meters						
Duration of Tunneling	38.10	weeks						
Number of Shifts	381.0	each					**Escalation Factor**	
							1.288	
					Rate	**Total**	**Total**	
Labor Crew		FTE	Hours		**2001**	**2001**	**2012**	
General Foreman		2	7619		$ 66.95	$ 510,095	$ 657,003	
Working Foreman		2	7619		$ 61.80	$ 470,857	$ 606,464	
Tunnel Miner		4	15238		$ 48.66	$ 741,486	$ 955,034	
Tunnel Laborer		12	45714		$ 39.45	$ 1,803,429	$ 2,322,816	
Locomotive Driver		4	15238		$ 46.29	$ 705,371	$ 908,518	
Shaft Bottom Support		4	15238		$ 39.45	$ 601,143	$ 774,272	
TBM Operator		1	3810		$ 56.61	$ 215,657	$ 277,766	
Micro TBM Operator		1	3810		$ 56.61	$ 215,657	$ 277,766	
Tunnel Fitter		2	7619		$ 44.89	$ 342,019	$ 440,521	
Tunnel Electrician		2	7619		$ 55.28	$ 421,181	$ 542,481	
Shaft Top Support		2	7619		$ 39.45	$ 300,571	$ 387,136	
Crane Operator		2	7619		$ 46.29	$ 352,686	$ 454,259	
Surface laborer		4	15238		$ 39.45	$ 601,143	$ 774,272	
Equipment Laborer		4	15238		$ 46.94	$ 715,276	$ 921,276	
		46	175,238			**$ 7,998,572**	**$ 10,301,596**	
Tunneling Operations		Resource Qty	Unit Qty	Unit	Unit Cost	Total 2001	**Total 2012**	
Tunnel Boring Machine (TBM)		1	38.00	Wks	$ 80,308	$ 3,051,692	$ 3,930,579.69	
Micro Tunnel Boring Machine		1	38.00	Wks	$ 40,154	$ 1,525,846	$ 1,965,289.85	
TBM Backup		1	1	LS	$ 457,754	$ 457,754	$ 589,586.95	
Mob Set up (TBM)		1	1.00	Wks	$ 300,000	$ 300,000	$ 386,400.00	
Locomotives		3	38.00	Ea	$ 4,200	$ 478,800	$ 616,694.40	
Muck Cars and Grout Cars		18	38.00	Ea	$ 1,450	$ 991,800	$ 1,277,438.40	
Flat Cars		5	38.00	Ea	$ 260	$ 49,400	$ 63,627.20	
Man Ride Cars		2	38.00	Ea	$ 260	$ 19,760	$ 25,450.88	
Track		1	93366	m/wks	$ 2.00	$ 186,732	$ 240,510.82	
Air Pipe		1	93366	m/wks	$ 3.00	$ 280,098	$ 360,766.22	
Water Pipe		1	93366	m/wks	$ 3.00	$ 280,098	$ 360,766.22	
Pump main		1	93366	m/wks	$ 2.00	$ 186,732	$ 240,510.82	
Cabling		1	93366	m/wks	$ 4.00	$ 373,464	$ 481,021.63	
Lighting		1	93366	m/wks	$ 4.50	$ 420,147	$ 541,149.34	
Vent Ducting		1	93366	m/wks	$ 3.00	$ 280,098	$ 360,766.22	
Booster Fans		3	38.00	Wks	$ 550	$ 62,700	$ 80,757.60	
Grout Mixers		2	38.00	Wks	$ 6,000	$ 456,000	$ 587,328.00	
Grout Pumps		2	38.00	Wks	$ 2,800	$ 212,800	$ 274,086.40	
Grout Hoses and Pipes		1	38.00	Wks	$ 200	$ 7,600	$ 9,788.80	
Transformers and Switchgear		1	38.00	Wks	$ 650	$ 24,700	$ 31,813.60	
Small Tools		1	38.00	Wks	$ 500	$ 19,000	$ 24,472.00	
Other Plant		1	38.00	Wks	$ 1,500	$ 57,000	$ 73,416.00	
Hoists		1	38.00	Wks	$ 450	$ 17,100	$ 22,024.80	
Man Hoists		1	38.00	Wks	$ 1,700	$ 64,600	$ 83,204.80	
Cranes		1	38.00	Wks	$ 4,000	$ 152,000	$ 195,776.00	
Compressors		1	38.00	Wks	$ 800	$ 30,400	$ 39,155.20	
Pipework and Controls		1	38.00	Wks	$ 550	$ 20,900	$ 26,919.20	
Generators		1	38.00	Wks	$ 1,400	$ 53,200	$ 68,521.60	
Transformers and Switchgear		2	38.00	Wks	$ 1,700	$ 129,200	$ 166,409.60	
Surface Fans		1	38.00	Wks	$ 1,100	$ 41,800	$ 53,838.40	
Concrete Cars		1	38.00	Wks	$ 900	$ 34,200	$ 44,049.60	
Concrete Pumps		1	38.00	Wks	$ 2,500	$ 95,000	$ 122,360.00	
Loaders		1	38.00	Wks	$ 5,046	$ 191,748	$ 246,971.42	
Other Suface Plant		1	38.00	Wks	$ 1,500	$ 57,000	$ 73,416.00	
						$ 10,609,369	**$ 13,664,868**	
Consumables						$ -		
Electrical Power		1100	3800	kWh	$ 0.10	$ 418,000	$ 538,384.00	
Fuel		1	100000	liter	$ 0.60	$ 60,000	$ 77,280.00	
Lube Materials		1	38	Wks	$ 90	$ 3,420	$ 4,404.96	
TBM Spares, Cutters		1	4800	meter	$ 60	$ 288,000	$ 370,944.00	
Filters		1	38	Wks	$ 400	$ 15,200	$ 19,577.60	
Hydraulic Oil		1	38	Wks	$ 2,500	$ 95,000	$ 122,360.00	
Other Consumables		1	38	Wks	$ 200	$ 7,600	$ 9,788.80	
						$ 887,220	**$ 1,142,739**	
Materials						$ -		
Rockbolts		3	4800	meter	$ 60	$ 864,000	$ 1,112,832	
Strapping		90	4800	meter	$ 2	$ 864,000	$ 1,112,832	
Temporary Materials		1	38	Wks	$ 1,000	$ 38,000	$ 48,944	
Lagging		1	4800	meter	$ 50	$ 240,000	$ 309,120	
Shotcrete		3	6840	m3	$ 150	$ 3,078,000	$ 3,964,464	
Membrane		3	4800	m2	$ 45	$ 648,000	$ 834,624	
Invert Forms		1	9600	meter	$ 20	$ 192,000	$ 247,296	
Lining Forms		1	4800	meter	$ 50	$ 240,000	$ 309,120	
Concrete		1	10800	m3	$ 180	$ 1,944,000	$ 2,503,872	
						$ 8,108,000	**$ 10,443,104**	
Subcontracts						$ -		
Heavy Transport Railing		0	9600	meter	$ 300	$ -	$ -	
Surface Muck Handling		1.8	64180	m3	$ 10	$ 1,155,240	$ 1,487,949	
						$ 1,155,240	**$ 1,487,949**	
				Total Estimated Cost		**$ 28,758,402**	**$ 37,040,256**	
				Per linear Meter		**$ 5,991.33**	**$ 7,716.72**	
				Per Cubic Meter		**$ 577.13**	**$ 440.56**	**Per Cubic Yard**
							$ 972,306.7	**Per Week**
Backfilling Operations								
Purchase Bentonite Clay			32702	m3	$ 140	$ 4,578,294		
Mix 30/70 ratio bentonite and mine muck			73807	m3	$ 35	$ 2,583,245		
Remove concrete and rail			0	meter	$ 250	$ -		
Fill cannister boreholes with bentonite			10560	m3	$ 120	$ 1,267,200		
Fill remaining areas with 30/70 mix			73807	m3	$ 120	$ 8,856,840		
						$17,285,579.00		
				Per Cubic Meter		**$ 234.20**	**$ 178.78**	**Per Cubic Yard**
							$ 453,746.4	**Per Week**

Mine Plan for Crystalline (enclosed) Mode

Ventilation system capacity: 500 kg/s

Ventilation per drift: 1 to 5 kg/s (variable)

Drifts per panel: 12 (nom.)

Emplacement Drift Length: 700 m (+/-)

Waste packages per drift: 100 (+/-)

Package size: 4-PWR or eqiuv. (~2 MT each)

Waste capacity per panel: 2,400 MT (+/-)

Number of panels supported (as shown): up to 10 (+/-) limited by safe egress, services, and ventilation

Notes:

1.TBM excavation of all drifts. Drill-and-blast for exhaust shaft, raise boring for all other shafts.

2.At completion each vertical empl. hole requires shield plug.

3.Complete construction of each drift, with emplacement borings (not entire panel) before emplacing waste.

4.Waste rock shaft, men/matls. shaft, and waste transport shaft/ramp, can support additional panels in the opposite direction (with one or more addl. ventilation shafts).

5.Large-dia., vertical emplacement boreholes in floor of emplacement drifts not shown.

6.Drift ground support: 2-m rockbolts, wire mesh, and 3 cm of shotcrete; 270° coverage.

7.Access and service drift floors: reinforced concrete (approx. 4m wide by 1 m deep in the center) with heavy rail.

8.Emplacement drift floors: lightly reinforced concrete (approx. 3 m wide by 0.75 m deep in center; must be removed at closure) with heavy rail.

9.Shaft support: non-reinforced cast-in-place concrete with steel internals (remove liners and seal shafts at closure)

10.Recommend shaft (not ramp) because of small waste packages (~100 ton for canister, disposal overpack, and shielded carriage), and likely limited extent of crystalline rock.

11.Backfill all openings at closure.

12.Use plugs/seals for acess drifts.

Table G-4 Unit Cost Details for Crystalline (enclosed) Concept, Emplacement Borings

Generic Repository								
(1) 40 m - 2.64 m dia - Steel Pipe Casing								
Length of Disposal Drift	**40**	**meters**						
Diameter of Tunnel	**2.67**	**meters**						
Qty of Neat Excavation	**282.7**	**Cu. meters**						
Secondary Lining Volume		**Cu. meters**						
Theoretical Grout Volume	**110.0**	**Cu. meters**						
Advance Rate and Shift Details								
Shift details - 2 X 10 hours - 5 Days per week								
Avg. advance per Shift	4	meters						
Avg. Advance per Week	40	meters						
Duration of Tunneling	1	weeks						
Number of Shifts	10	each					**Escalation Factor**	
							1.288	
					Rate	**Total**	**Total**	
Labor Crew		FTE	Hours		**2001**	**2001**	**2012**	
General Foreman		0.5	50		$ 66.95	$ 3,348	$ 4,312	
Working Foreman		1	100		$ 61.80	$ 6,180	$ 7,960	
Tunnel Miner		2	200		$ 48.66	$ 9,732	$ 12,535	
Tunnel Laborer		4	400		$ 39.45	$ 15,780	$ 20,325	
Locomotive Driver		1	100		$ 46.29	$ 4,629	$ 5,962	
Shaft Bottom Support		1	100		$ 39.45	$ 3,945	$ 5,081	
Mining Equipment Operators		1	100		$ 56.61	$ 5,661	$ 7,291	
Tunnel Fitter/welder		4	400		$ 44.89	$ 17,956	$ 23,127	
Tunnel Electrician		1	100		$ 55.28	$ 5,528	$ 7,120	
Shaft Top Support		1	100		$ 39.45	$ 3,945	$ 5,081	
Crane Operator		1	100		$ 46.29	$ 4,629	$ 5,962	
Surface laborer		1	100		$ 39.45	$ 3,945	$ 5,081	
Equipment Laborer		2	200		$ 46.94	$ 9,388	$ 12,092	
		20.5				**$ 94,666**	**$ 121,929**	
Tunneling Operations		Resource Qty	Unit Qty	Unit	Unit Cost	Total 2001	**Total 2012**	
Boring Machine w/temp. casing		1	1.00	Wks	$ 25,000.00	$ 25,000	$ 25,000	
Welding Machine/Cutting		1	2	Ea	$ 2,500	$ 5,000	$ 5,000	
Boom Cutter Machine		1	0	Wks	$ 45,000	$ -	$ -	
Mucking Machine		1	0	Wks	$ 30,000	$ -	$ -	
Locomotives		1	1	Ea	$ 4,200	$ 4,200	$ 5,410	
Muck Cars and Grout Cars		1	1	Ea	$ 1,450	$ 1,450	$ 1,868	
Flat Cars		1	1	Ea	$ 260	$ 260	$ 335	
Man Ride Cars		1	1	Ea	$ 260	$ 260	$ 335	
Track		1	2438	m/wks	$ 2.00	$ 4,876	$ 6,280	
Air Pipe		1	2438	m/wks	$ 3.00	$ 7,314	$ 9,420	
Water Pipe		1	2438	m/wks	$ 3.00	$ 7,314	$ 9,420	
Pump main		1	2438	m/wks	$ 2.00	$ 4,876	$ 6,280	
Cabling		1	2438	m/wks	$ 4.00	$ 9,752	$ 12,561	
Lighting		1	2438	m/wks	$ 4.50	$ 10,971	$ 14,131	
Vent Ducting		1	2438	m/wks	$ 3.00	$ 7,314	$ 9,420	
Booster Fans		3	1	Wks	$ 575	$ 1,725	$ 2,222	
Grout Mixers		1	1	Wks	$ 4,000	$ 4,000	$ 5,152	
Grout Pumps		1	1	Wks	$ 2,800	$ 2,800	$ 3,606	
Grout Hoses and Pipes		1	1	Wks	$ 200	$ 200	$ 258	
Transformers and Switchgear		1	1	Wks	$ 650	$ 650	$ 837	
Small Tools		1	1	Wks	$ 500	$ 500	$ 644	
Other Plant		1	1	Wks	$ 1,500	$ 1,500	$ 1,932	
Hoists		1	1	Wks	$ 450	$ 450	$ 580	
Man Hoists		1	1	Wks	$ 1,700	$ 1,700	$ 2,190	
Cranes		1	1	Wks	$ 4,000	$ 4,000	$ 5,152	
Compressors		1	1	Wks	$ 800	$ 800	$ 1,030	
Pipework and Controls		1	1	Wks	$ 550	$ 550	$ 708	
Generators		1	1	Wks	$ 1,400	$ 1,400	$ 1,803	
Transformers and Switchgear		1	1	Wks	$ 1,700	$ 1,700	$ 2,190	
Surface Fans		2	1	Wks	$ 561	$ 1,122	$ 1,445	
Rack and Pinion		1	1	Wks	$ 2,438.00	$ 2,438	$ 3,140	
Vertical Conveyor		1	1	Wks	$ 5,000	$ 5,000	$ 6,440	
Loaders		2	1	Wks	$ 6,500	$ 13,000	$ 13,000	
Off-road Dump Trucks		4	1	Wks	$ 6,500	$ 26,000	$ 26,000	
Other Suface Plant		1	1	Wks	$ 2,200	$ 2,200	$ 2,834	
						$ 135,322	**$ 161,623**	
Consumables						$ -		
Electrical Power		1500	84.4	kWh	$ 0.10	$ 12,667	$ 16,315	
Fuel		1	2222.2	liter	$ 0.60	$ 1,333	$ 1,717	
Lube Materials		1	1	Wks	$ 90	$ 90	$ 116	
Machine Spares, Cutters		1	40	meter	$ 60	$ 2,400	$ 3,091	
Filters		1	1	Wks	$ 400	$ 400	$ 515	
Hydraulic Oil		1	1	Wks	$ 2,500	$ 2,500	$ 3,220	
Other Consumables		1	1	Wks	$ 200	$ 200	$ 258	
						$ 19,590	**$ 25,232**	
Materials								
Steel Pipe		2	40	meter	$ 8,002	$ 640,189	$ 640,189	
End Cap		2	1	ea	$ 8,002	$ 16,005	$ 16,005	
Seal Door		1	1	ea	$ 30,000	$ 30,000	$ 30,000	
Temporary Materials		1	1	Wks	$ 2,500	$ 2,500	$ 2,500	
Buffer Railing		2	40	meter	$ 150	$ 12,000	$ 12,000	
Grout		2	110.0	m3	$ 145	$ 31,887	$ 41,070.77	
Grout Plugs		2	4	ea	$ 3,200	$ 25,600	$ 32,972.80	
Void Filler		2	0	m3	$ 150	$ -		
Invert Forms		1	0	meter	$ 20	$ -		
Lining Forms		1	0	meter	$ 50	$ -		
Concrete		1	0	m3	$ 180	$ -		
Lining		1	0	meter	$ 2,000	$ -		
						$ 758,181	**$ 774,737**	
Subcontracts								
Muck Disposal		1.8	282.7	m3	$ 10	$ 5,088	$ 6,553.42	
Foam		0	0	m3	$ 100	$ -	$ -	
						$ 5,088	**$ 6,553**	
					Total Estimated Cost	**$ 1,012,846**	**$ 1,090,074**	
					Per linear Meter	**$ 25,321.16**	**$ 27,251.86**	
							$ 27,251.86	**Per Meter**
							$ 1,090,074.2	**Per Week**

Mine Plan for Clay/Shale (Enclosed) Mode

Ventilation system capacity: 500 kg/s

Ventilation per drift: 1 to 5 kg/s (variable)

Access drifts per panel: 4 (nom.)

Emplacement drift length: 40 m (+/-)

Waste packages per drift: up to 6 (+/-)

Package size: 4-PWR or eqiuv. (~2 MT each)

Waste capacity per panel: 2,000 MT (+/-)

Number of panels supported (as shown): up to 25 (+/-) limited by safe egress, services, and ventilation.

Notes:

1.All drifts excavated with boom cutter. Drill-and-blast for exhaust shaft, raise-bore all other shafts.

2.Emplacement drifts are 40-m blind bores, machine excavated. At completion each empl. drift requires a shield plug.

3.Complete construction of each access drift with emplacement borings (not necessarily entire panel) before emplacing waste.

4.Waste rock shaft, men/matls. shaft, and waste transport shaft/ramp, can support additional panels in the opposite direction (with addl. ventilation).

5.Access and service drift ground support: 2-m rockbolts, steel sets and steel lagging, and 3 cm of shotcrete; 270° coverage.

6.Access and service drift floors: reinforced concrete with heavy rail (approx. 4m wide by 0.5 m deep in the center)

7.Emplacement drift ground support: tubular steel liner grouted in place, with rails welded for buffer installation and package transit.

8.Shaft support: non-reinforced cast-in-place concrete with steel internals (remove liner and seal shaft at closure)

9.Recommend ramp (not shaft) as reference mode because shale basins are extensive and repository depth can be less than 500 m. Choose a simple ramp (10% grade) over funicular railway because of long operating period (100 yrs or longer).

10.Ramp support: same as access and service drift ground support.

11.Ramp floor: reinforced concrete. Use diesel-powered heavy transporter and transfer to shielded rail transporter underground.

12.Backfill all openings at closure.

13.Use plugs/seals for ramp and inter-connecting drifts.

Table G-5 Unit Cost Details for Clay/Shale Ramp Construction

Generic Repository							
5000 m - 5.00 m dia - Transport Ramp Clay-Shale							
Length of Tunnel	**5000**	**meters**					
Diameter of Tunnel	**5.00**	**meters**					
Qty of Neat Excavation	**98175**	**Cu. meters**					
Secondary Lining Volume	**0**	**Cu. meters**					
Theoretical Grout Volume	**0**	**Cu. meters**					
Advance Rate and Shift Details							
Shift details - 2 X 10 hours - 5 Days per week							
Avg. advance per Shift	7.2	meters					
Avg. Advance per Week	72	meters					
Duration of Tunneling	69	weeks					
Number of Shifts	694	each					
						Escalation Factor	
Labor Crew	FTE	Hours				**1.288**	
General Foreman	1	6944		**Rate**	**Total**	**Total**	
Working Foreman	1	6944		**2001**	**2001**	**2012**	
Tunnel Miner	4	27778		$ 48.66	$ 1,351,667	$ 1,740,947	
Tunnel Laborer	6	41667		$ 39.45	$ 1,643,750	$ 2,117,150	
Locomotive Driver	1	6944		$ 46.29	$ 321,458	$ 414,038	
Shaft Bottom Support	1	6944		$ 39.45	$ 273,958	$ 352,858	
Equipment Operators	7	48611		$ 56.61	$ 2,751,875	$ 3,544,415	
Tunnel Fitter	0	0		$ 44.89	$ -	$ -	
Tunnel Electrician	1	6944		$ 55.28	$ 383,889	$ 494,449	
Shaft Top Support	1	6944		$ 39.45	$ 273,958	$ 352,858	
Crane Operator	1	6944		$ 46.29	$ 321,458	$ 414,038	
Surface laborer	2	13889		$ 39.45	$ 547,917	$ 705,717	
Equipment Laborer	2	13889		$ 46.94	$ 651,944	$ 839,704	
	28	194,444			**$ 8,523,876**	**$ 10,978,187**	
Tunneling Operations	Resource Qty	Unit Qty	Unit	Unit Cost	Total 2001	**Total 2012**	
Boom Cutter Machine	1	69	Wks	$ 45,000	$ 3,105,000	$ 3,999,240	
Mucking Machine	0	69	Wks	$ 30,000	$ -	$ -	
Locomotives	1	69	Ea	$ 4,200	$ 289,800	$ 373,262	
Muck Cars and Grout Cars	3	69	Ea	$ 1,450	$ 300,150	$ 386,593	
Flat Cars	3	69	Ea	$ 260	$ 53,820	$ 69,320	
Man Ride Cars	1	69	Ea	$ 260	$ 17,940	$ 23,107	
Track	1	97222	m/wks	$ 2.00	$ 194,444	$ 250,444	
Air Pipe	1	97222	m/wks	$ 3.00	$ 291,666	$ 375,666	
Water Pipe	1	97222	m/wks	$ 3.00	$ 291,666	$ 375,666	
Pump main	1	97222	m/wks	$ 2.00	$ 194,444	$ 250,444	
Cabling	1	97222	m/wks	$ 4.00	$ 388,888	$ 500,888	
Lighting	1	97222	m/wks	$ 4.50	$ 437,499	$ 563,499	
Vent Ducting	1	97222	m/wks	$ 3.00	$ 291,666	$ 375,666	
Booster Fans	3	69	Wks	$ 575	$ 119,025	$ 153,304	
Grout Mixers	1	69	Wks	$ 4,000	$ 276,000	$ 355,488	
Grout Pumps	1	69	Wks	$ 2,800	$ 193,200	$ 248,842	
Grout Hoses and Pipes	1	69	Wks	$ 200	$ 13,800	$ 17,774	
Transformers and Switchgear	1	69	Wks	$ 650	$ 44,850	$ 57,767	
Small Tools	1	69	Wks	$ 500	$ 34,500	$ 44,436	
Other Plant	1	69	Wks	$ 1,500	$ 103,500	$ 133,308	
Hoists	1	0	Wks	$ 450	$ -	$ -	
Man Hoists	1	0	Wks	$ 1,700	$ -	$ -	
Cranes	1	69	Wks	$ 4,000	$ 276,000	$ 355,488	
Compressors	1	69	Wks	$ 800	$ 55,200	$ 71,098	
Pipework and Controls	1	69	Wks	$ 550	$ 37,950	$ 48,880	
Generators	1	69	Wks	$ 1,400	$ 96,600	$ 124,421	
Transformers and Switchgear	1	69	Wks	$ 1,700	$ 117,300	$ 151,082	
Surface Fans	2	69	Wks	$ 561	$ 77,418	$ 99,714	
Rack and Pinion	1	0	Wks	$ -	$ -	$ -	
Vertical Conveyor	1	0	Wks	$ -	$ -	$ -	
Loaders	2	69	Wks	$ 6,500	$ 897,000	$ 897,000	
Off-road Dump Trucks	4	69	Wks	$ 6,500	$ 1,794,000	$ 1,794,000	
Other Suface Plant	1	69	Wks	$ 2,200	$ 151,800	$ 195,518	
					$ 10,145,126	**$ 12,291,914**	
Consumables					$ -		
Electrical Power	1500	3800	kWh	$ 0.10	$ 570,000	$ 734,160	
Fuel	1	100000	liter	$ 0.60	$ 60,000	$ 77,280	
Lube Materials	1	69	Wks	$ 90	$ 6,210	$ 7,998	
Machine Spares, Cutters	1	5000	meter	$ 60	$ 300,000	$ 386,400	
Filters	1	69	Wks	$ 400	$ 27,600	$ 35,549	
Hydraulic Oil	1	69	Wks	$ 2,500	$ 172,500	$ 222,180	
Other Consumables	1	69	Wks	$ 200	$ 13,800	$ 17,774	
					$ 1,150,110	**$ 1,481,342**	
Materials					$ -		
Rockbolts	1.5	5000	meter	$ 60	$ 450,000	$ 579,600	
Strapping	0.5	5000	meter	$ 90	$ 225,000	$ 289,800	
Temporary Materials	1	69	Wks	$ 1,000	$ 69,000	$ 88,872	
Lagging	0	5000	meter	$ 50	$ -	$ -	
Grout	0	7564	m3	$ 145	$ -	$ -	
Ramp Edge Forms	2	5000	meter	$ 20	$ 200,000	$ 257,600	
Wall Forms	4	5000	meter	$ 50	$ 1,000,000	$ 1,288,000	
Concrete, Flat	1	10000	m3	$ 180	$ 1,800,000	$ 2,318,400	
Concrete Knee Wall	1	6000	m3	$ 180	$ 1,080,000	$ 1,391,040	
Concrete Reinf. Steel @ 200#/m3	200	16000	kg	$ 0.54	$ 1,728,000	$ 2,225,664	
Railing	2	5000	meter	$ 150	$ 1,500,000	$ 1,932,000	
Heavy Transport Railing	2	5000	meter	$ 300	$ 3,000,000	$ 3,864,000	
					$ 11,052,000	**$ 14,234,976**	
Subcontracts							
Muck Disposal	1.8	98175	m3	$ 10	$ 1,767,150	$ 2,276,089	
Placing Rebar	1	1500	mt	$ 1,300	$ 1,950,000	$ 1,950,000	
Placing Concrete	1	16000	m3	$ 360	$ 5,760,000	$ 5,760,000	
					$ 9,477,150	**$ 9,986,089**	
			Total Estimated Cost		**$ 40,348,262**	**$ 48,972,508**	
			Per linear Meter		**$ 8,069.65**	**$ 9,794.50**	
			Per Cubic Meter		**$ 498.83**	**$ 380.79**	**Excav Per Cubic Yard**
			Per Cubic Meter		**$ 949.42**	**$ 725.86**	**Conc. Per Cubic Yard**
						$ 705,204.1	**Per Week**

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Table G-6 Unit Cost Details for Drifts Backfill

Backfilling Operations with 30/70 Bentonite						
Purchase Bentonite Clay	22142	m3	$ 140	$ 3,099,894		
Mix 30/70 ratio bentonite and mine muck	73807	m3	$ 35	$ 2,583,245		
Remove concrete and rail	0	meter	$ 250	$ -		
Fill cannister boreholes with bentonite	0	m3	$ 120	$ -		
Fill remaining areas with 30/70 mix	73807	m3	$ 120	$ 8,856,840		
				$ 14,539,979		
		Per Cubic Meter		**$ 197.00**	**$ 150.38**	**Per Cubic Yard**
					$ 381,674.4	**Per Week**
Backfilling Operations Mine Muck Only						
Purchase Bentonite Clay	22142	m3	$ -	$ -		
Haul and screen and mine muck	73807	m3	$ 25	$ 1,845,175		
Remove concrete and rail	0	meter	$ 250	$ -		
Fill cannister boreholes with bentonite	0	m3	$ 120	$ -		
Backill remaining areas **not** 30/70 mix	73807	m3	$ 120	$ 8,856,840		
				$ 10,702,015		
		Per Cubic Meter		**$ 145.00**	**$ 110.69**	**Per Cubic Yard**
					$ 280,927.89	**Per Week**

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Appendix H – Peer Review Plan

Deliverable: M2FT-13SN0804031

QRL: 2

Title: Reference Repository Disposal Concepts and Thermal Load Management Analysis

Due Date: 15Nov2012

Purpose:

Peer reviews shall include identification of the following: 1) work to be reviewed; 2) scope of the peer review; 3) size and required capabilities of the peer review team (there shall be at least two members on each peer review team); and 4) expected method and reporting schedule.

Comments:

The work to be reviewed is that performed in the Design Concepts/Thermal Load Management work packages in FY11 and FY12, and documented in: Disposal Concepts/Thermal Load Management (FY11/12 Summary Report) (FCRD-UFD-2012-000219 Rev. 0). *The scope of peer review will include all information and analyses described in that report. The peer review team will consist of two members: Dr. Michael Voegele, a consultant, and Dr. William Halsey of LLNL. Qualifications of these members are discussed below.The peer review will be conducted by email and teleconference, starting with distribution of the report and review instructions, followed by an information meeting to discuss any issues raised by the reviewers, submittal of written comments, report revision, and reviewer concurrence on the original comments, and issuance of FCRD-UFD-2012-000219 Rev. 2 in final form.*

Scope of Peer Review:

The scope of Peer Review shall include the following considerations as they apply to the work being reviewed:

1. Determine the reasonableness of the assumptions and validity of inputs that were used as the basis for the research and analyses.
2. Verify the adequacy of experimental requirements and criteria (e.g., acceptance criteria from testing) including the use of any applicable national or international standards described.
3. Verify the appropriateness of the methods and implementing documents used to complete the work under review.
4. Determine if the software applications (e.g., simulation, or computer model) used to complete the work under review are appropriate and adequate.
5. Determine the accuracy of the calculations and final documentation.
6. Determine the reasonableness and validity of the conclusions.
7. Verify that the conclusions are clearly stated such that misinterpretation is minimized. Identify any different conclusions that can be drawn from the results presented.
8. Verify that any uncertainty in the results is clearly and adequately discussed.

Additional criteria may be defined by the team and shall be defined in the review criteria documentation.

Comments:

Experiments were not performed for this work, so item 2 does not apply.

Qualification Requirements for Peer Reviewers:

Peer reviews shall be conducted by individuals who have independence from the work under review. Independence means that the individual was not involved as a participant, supervisor, or advisor in the work under review and is, to the extent practical, free from other conflicts of interest.

The number of reviewer(s) is commensurate with the complexity of the work to be reviewed, its importance to program objectives, the number of technical disciplines involved, and the degree to which the subject issue is considered controversial by stakeholders and differing viewpoints are strongly held within the applicable technical and scientific community concerning issues under review. The supervisor, manager, or NTD of the performer of the work shall select peer reviewer(s) based on the complexity of the work being reviewed. Peer reviewers are individuals who meet at least one of the following criteria as judged by the responsible manager:

- Have adequate academic education in the same technical discipline in which the work is performed or in a closely related field, or have adequate work experience and technical activity in a related discipline.
- Have demonstrated evidence of proposing and solving engineering, experimental, or theoretical problems that are recognized as valid by the community of technical peers.
- Have contributed to the body of knowledge within a technical discipline such as publishing research results in the proceedings of scientific meetings or in professional journals.

The supervisor, manager, or NTD of the performer of work being peer reviewed must verify that peer reviewer(s) are qualified in accordance with the requirements herein. FCT MOs may require approval of peer reviewers, which should be called out in applicable work packages or otherwise formally requested.

Comments:

The reviewers were not involved as participants, supervisors, or advisors in the work reviewed, and to our knowledge, are free from other conflicts of interest. Selection of two reviewers is commensurate with the complexity, importance, technical disciplines, and stakeholder interest in the subject matter, so long as the reviewers have broad knowledge and experience in the back end of the nuclear fuel cycle in the U.S., as these reviewers do.

Both peer reviewers have doctoral credentials in relevant disciplines: Dr. Voegele has a Ph.D. in Geological Engineering form the University of Minnesota, and Dr. Halsey has a Ph.D. in Nuclear Engineering from the University of Michigan. Both have extensive experience in proposing and solving relevant engineering problems in nuclear waste disposal and fuel cycle technology. Evidence of their previous recognition in these areas is provided by extensive publication and presentation records. Accordingly, all three of the criteria listed above apply to both reviewers.

Documenting Peer Reviews:

The Peer Review shall be documented (hard copy or electronically) using the FCT Document Cover Sheet (Appendix E).

11/13/2012

Ernest Hardin, Technical Lead

11/13/12

Kevin McMahon, Responsible Manager

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