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Alternative Concepts for Direct Disposal of Dual-Purpose Canisters

Fuel Cycle Research & Development

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ACRONYMS

BSC	Bechtel-SAIC Co.
BWR	Boiling Water Reactor
DIREGT	Acronym (German) for Direct Disposal Concept from DBE Tec. GmbH
DOE	U.S. Department of Energy
DPC	Dual-Purpose Canister
EBS	Engineered Barrier System
EDZ	Excavation Damage Zone
EPRI	Electric Power Research Institute
FEPs	Features, Events, and Processes
FY	Fiscal Year
GW	Gigawatt
HISTORM	Trade Name for Vertical Dry Storage Systems (Holtec International)
HLW	High-Level Waste
KBS-3	Swedish Reference Disposal Concept
K_{th}	Thermal Conductivity
MT	Metric Tons
MTHM	Metric Tons of Heavy Metal
NUHOMS	Trade Name for Vault –Type Dry Storage System (Transnuclear)
PA	Performance Assessment
PWR	Pressurized Water Reactor
R&D	Research and Development
RMR	Rock Mass Rating
RQD	Rock Quality Designation
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
UFD	Used Fuel Disposition

ALTERNATIVE CONCEPTS FOR DIRECT DISPOSAL OF DUAL-PURPOSE CANISTERS

Introduction

This report is a deliverable in the project to evaluate the feasibility of direct disposal of spent nuclear fuel (SNF) in dual-purpose canisters (DPCs) and also in storage-only canisters that may be transported to a repository (Miller et al. 2012). It presents a set of alternative concepts for direct, geologic disposal of DPCs to guide follow-on project activities including engineering feasibility evaluations, preclosure safety analysis, postclosure performance assessment, postclosure criticality analysis, and identification of issues for further investigation. A description of this deliverable is provided in the current workplan (Howard et al. 2012).

The purpose is to identify a range of alternative concepts with a reasonable prospect of leading to a future finding of feasibility. It is not to generate an exhaustive list of all possible alternatives. The approach is to provide a level of detail sufficient for partial input to performance analyses such as mechanical damage to engineered barriers, postclosure criticality, and generic preclosure and postclosure safety analyses. The results draw heavily from previous concept development studies (Hardin et al. 2012) but with greater emphasis on DPC-size waste packages, thermal management, and a few important aspects of DPC disposal such as ground support and buffer performance. The concepts identified previously are included here, as are some additional variations and at least one new concept (cavern retrievable concept, Section 7).

This is a lower-level deliverable that feeds a higher level one in FY13. Accordingly, the information it contains is subject to change or refinement as the project team performs subsequent tasks.

Organization

The following numbered sections present a list of alternative concepts in outline form, and a narrative description of each. The outline numbering is consistent with previous work (Hardin et al. 2012). The information was accumulated from previous studies, technical literature, and from a working group of technical staff from the Used Fuel Disposition R&D campaign, convened 31Jan2013.

Attributes for discussion in describing the alternative concepts include:

- **Host medium characteristics** – Geomechanical, geochemical and hydrologic characteristics that are important for defining the disposal concept. For example, natural barrier performance (low groundwater flux, chemically reducing) can affect the selection of engineered barrier features such as corrosion resistant waste packaging.
- **Excavation and ground support** – Open-mode concepts may involve 100 yr or more of repository operations during which some or all of the drifts would be kept open. Rock characteristics that determine long-term opening stability may also affect groundwater movement and other aspects of the disposal environment.

- **Waste package and EBS functions and materials** – Disposal concepts may include corrosion resistant waste packaging and rely on long-term containment longevity, or they may use simpler packaging to perform only near-term functions.
- **EBS dimensions** – The size and weight of DPC-containing waste packages are important aspects of disposal feasibility, and could determine various repository dimensions and specifications.
- **Waste handling shaft or ramp access** – Movement of large, heavy waste packages in shielded transporters could be done using either shafts or ramps, in principle, and a rationale for one solution or the other would depend on site-specific factors. However, certain geologic settings are more amenable to one solution or the other, and have been associated in the past, and these relationships are discussed.
- **Postclosure criticality control features** – DPCs would not be opened prior to disposal, so the criticality control features they contain cannot be changed. Some of these features will likely degrade after closure, so criticality process screening will consider effects from other features or processes originating outside the DPCs.
- **Thermal performance and schedule for operation and closure** – Thermally driven processes can degrade natural and engineered barriers, particularly clay-based buffer/backfill materials, and host media that exhibit temperature sensitivity. Heat output is a major difference between DPC direct disposal and other concepts, and thermal analysis is a major part of this report.
- **Repository plan area** – Included because alternative disposal concepts and thermal management strategies may differ significantly with respect how much area would be needed, even if the total amount of SNF to be disposed is the same.

These key attributes are discussed in the outline-numbered sections below. As additional introduction, the following paragraphs the approach to opening stability and ground support.

Opening Size, Excavation and Ground Support

The disposal concepts presented in this report would require excavations that accommodate movement of DPC-containing waste packages into emplacement drifts, handling and final placement of the packages and other engineered barrier system (EBS) components, and repository operations and closure. Some of the disposal concepts involve tens to hundreds of years of ventilation time for heat removal, and backfilling and/or sealing operations at closure, so consideration of long-term opening stability in the various types of host media is important.

Empirical ground support estimation methods that are widely accepted in the mining industry are used to understand the types of ground support that might be needed. While such empirical methods provide little direct information on the length of time that an excavation would be stable, they do describe the stand-up time defined as the time such excavations would remain stable if left unsupported. Current underground support design technologies, such as the New Austrian Tunneling Method, have built upon the stand-up time concept. Modern underground support design typically considers that emplacement of ground support should occur as soon as possible after excavation to prevent rock movements that could result, in the long run, in greater support requirements.

The size of underground openings is key to understanding long-term stability and ground support requirements, in many rock types and applications. For this report the sizes of underground openings are estimated based on handling of large DPC-size waste packages for the various emplacement modes. The discussion is less important for the enclosed emplacement modes (Sections 1 through 3) because the emplacement openings are filled with buffer material or are backfilled at the time of emplacement.

DPC-size waste packages will be up to 2 m in diameter and approximately 5 m long, and weigh from 80 MT to much more than 100 MT depending on the type of DPC, how much shielding is included, and whether other EBS components are pre-fabricated with the package. These dimensions are somewhat larger than those used in earlier work (BSC 2008a). International programs have developed a range of concepts for waste package handling, and corresponding drift size requirements (e.g., Andra 2005).

For those emplacement modes that involve either vertical borehole emplacement, horizontal borehole emplacement, or in drift transverse emplacement, allowance is made for maneuvering waste packages into place. Typically, this means that the critical emplacement dimension is the diagonal length of the package. Allowing for a additional thickness for the waste package the critical dimension is therefore on the order of 7 to 8 m (Table 1). The other dimension of the excavation would be approximately 5 m to accommodate the width or height of the emplacement system.

Circular openings would be excavated by a tunnel boring machine, while more rectangular openings may be best excavated by drill-and-blast method using pre-splitting to minimize damage to the rock mass. If the compressive strength of the rock is low enough, excavation could be accomplished by a road header type excavator. The dimensions discussed in this section are summarized in Table 1. Note that dimensions given in Table 1 are for drifts requiring ground support, either access drifts (for emplacement in boreholes or lined borings), or emplacement drifts (for in-drift emplacement). For in-drift emplacement in crystalline rock, hard rock, or sedimentary rock a circular cross section is indicated. For access drifts in crystalline rock, the clay/shale enclosed mode, or the cavern retrievable concept, rectangular openings are indicated. In salt, all drifts and alcoves used for access or emplacement would be rectangular. For in-drift disposal in less competent sedimentary media a smaller drift diameter is selected to enhance stability. For access drifts or emplacement drifts in the cavern retrievable concept, a larger opening is selected to accommodate heavy hauling equipment used to transport storage or disposal casks in vertical orientation.

For evaluating opening stability and ground support in this report, an excavation diameter or span of 7 m is used throughout. The methods chosen to estimate the rock mass stability and support requirements are not especially sensitive to slight changes in the excavation dimensions (Appendix A). All concepts are assumed to be constructed at a depth of approximately 500 m, although shallower emplacement could be effective in some geologic settings, and could be necessary for unsaturated settings (Hardin et al. 2012).

Table 1. Dimensions of emplacement or access drifts requiring ground support, for disposal concepts presented in this report.

Concept	Critical Waste Package Dimension	Long-Term Ventilation Required	Approximate Excavation Shape
Crystalline rock, enclosed, swelling clay-based buffer			
1.1 Crystalline enclosed, vertical borehole	Diagonal		Vertical rectangle 7 m high x 5 m wide
1.2 Crystalline enclosed, horizontal borehole	Diagonal		Horizontal rectangle 5 m high x 7 m wide
1.3 Crystalline enclosed, in-drift emplacement	Diameter		Circular 5.5 m
Generic salt repository			
2.1 Horizontal in-alcove or in-drift transverse emplacement	Diagonal or Diameter		Horizontal rectangle 5 m high x 7 m wide
2.2 Borehole vertical emplacement	Diagonal		Vertical rectangle 7 m high x 5 m wide
Clay/shale, enclosed			
3. Clay/shale enclosed	Diameter		Horizontal rectangle 5 m high x 7 m wide
Sedimentary, unbackfilled open			
4.1 Sedimentary unbackfilled, low-temperature	Diameter	✓	Circular 4.5 m diameter
4.2 Sedimentary unbackfilled, high-temperature	Diameter	✓	Circular 4.5 m diameter
Sedimentary backfilled open			
5.1 Sedimentary backfilled open	Diameter	✓	Circular 4.5 m diameter
Hard-rock, open emplacement			
6.1 Hard-rock, unsaturated, unbackfilled open	Diameter	✓	Circular 5.5 m
6.2 Hard-rock, backfilled open	Diameter	✓	Circular 5.5 m
Cavern-retrievable			
7.1 Surface Storage Systems in Unsaturated-Zone Galleries	Diagonal	✓	Vertical rectangle 8 m high x 6 m wide
7.2 Purpose-Built, Shielded, Ventilated Storage/Disposal Casks	Diagonal	✓	Vertical rectangle 8 m high x 6 m wide

1. Crystalline Rock Enclosed Emplacement Concepts for HLW or SNF

This group of concepts relies on waste package integrity and a swelling-clay based buffer installed at emplacement, which can be implemented in vertical or horizontal emplacement boreholes or as in-drift emplacement (discussed separately below). Access drifts would be backfilled with low-permeability engineered material prior to closure. The engineered barriers would include the buffer and waste package, and the host rock can serve as an additional barrier if it has low enough permeability (e.g., $<10^{-16}$ m^2) and/or chemically reducing conditions. The concept could be suitable for saturated or unsaturated geologic settings (see Hardin and Sassani 2010 for analysis of clay buffer performance in unsaturated settings). With multiple engineered barriers, for example a long-lived waste package made from copper or titanium, the concepts described below could also be used in more permeable host media (EPRI 2010, Appendix B).

Constructability is good in crystalline rock and other hard, competent media in which stable openings can be readily constructed even with spans on the order of 10 m (e.g., at tunnel intersections). Crystalline rock will be fractured from the effects of the original crystallization (i.e., cooling), subsequent tectonic loading, and excavation. Borehole variations discussed below are intended to emplace and isolate waste packages beyond the excavation damage zone (EDZ) where interconnected, induced fractures could form preferential pathways for transport of released radionuclides.

Crystalline rock masses selected for disposal of SNF in DPCs would be expected to be massive (uniform, relatively unfractured) with high compressive strength. The spacing of fractures or other discontinuities would be large, and rock quality would be considered high. Infrequent joints could be present, but would likely be very tight and rough, with no infilling or weathering. Groundwater inflow would be relatively low with occasional water bearing fractures, so that even in the saturated zone excavations still could be relatively dry. Because of the small number of discontinuities in massive granite bodies, the emplacement drifts could be oriented favorably with respect to the fracture system. As a result, a Rock Mass Rating in the very good range or perhaps the high end of the good range would be expected. For such a rock mass the stand up time for an 8 m excavation would be on the order of 10 years. Accordingly, it would be possible to develop very stable excavations in massive granite with little support needed other than occasional rock bolting. If the rock mass were of somewhat lower quality (good rock category) additional support might consist of rockbolts and wire mesh for support.

Similarly, using the Q Rock Mass Classification System, the RQD would likely be excellent and the joint set number would correlate to a massive body with few if any joints. The joint roughness number could be determined by discontinuous joints or irregular undulating jointing, and the joint alteration number could reflect fresh joint walls. The expected case of dry excavations or minor water inflow would be reflected in the joint water reduction factor, and the stress reduction factor would be appropriate for a medium stress, a favorable situation. Using an excavation support ratio number of 0.8 the estimated support category using the Q Rock Mass Classification System would be in the unsupported or no support category, with at most occasional rock bolts needed.

Floors would be bare rock or poured concrete as needed to provide a running surface for rubber tired equipment. Concrete floors and access drift liners (e.g., shotcrete) would be removed at closure because they have higher permeability than low-permeability backfill or buffer materials, and could act as conduits for groundwater flow. Either shaft or ramp access would be used for waste handling; both are technically and economically feasible because the stable openings facilitate construction, maintenance and closure operations.

Waste packages would be made from materials such as pure copper or steel, that degrade slowly or not at all in the chemically reducing, moisture-limited environment within the buffer. Organic matter and reducing minerals within the buffer consume oxygen that may infiltrate with groundwater during rehydration. Corrosion may ultimately be supported by hydrolysis (with production of hydrogen) that occurs with steels, but not copper which is stable and not thermodynamically favored to reduce hydrogen in water. Thus, disposal overpacks made from steel are likely to be penetrated in approximately 100,000 yr, while copper packages could last millions of years, or less depending on buffer erosion and exposure to corrosive groundwater (SKB 2010).

The matrix permeability of crystalline rock is low, and the bulk permeability is attributable to networks of fractures. Injection of grout or other materials into boreholes surrounding repository openings can be used to control water inflow from fractures, and may be needed at some locations in a crystalline rock repository. Crystalline rock may contain minerals that are chemically reducing and tend to react with oxygen in groundwater.

The crystalline rock enclosed concepts are suitable for deployment in saturated host rock, even where groundwater flux and velocity may be relatively high compared to other host media with lower permeability. This is because the clay-based buffer and/or backfill materials have very low permeability when hydrated, and can retain their swelling and plasticity properties for geologic time scales. For example, performance of the KBS-3 concept has been intensively analyzed for the effects from future continental glaciation that increases the host rock groundwater flux and changes the composition (SKB 2010). Swelling clay installed in the compacted, dehydrated state ensures high swelling pressure throughout. The swelling clay in buffers can serve other functions including inhibiting microbial transport and preventing package movement (SKB 2006). Buffer thickness on the order of 0.35 to 0.50 m is needed to control the disposal chemical environment, resist erosion by flowing groundwater, and decrease the incidence of buffer failure by displacement dislocation along intersecting fractures. Much larger thickness could be obtained around packages in backfilled openings, but at the expense of thermal resistance that increases the peak buffer temperature and the potential for buffer alteration. Clay-based low-permeability buffers or backfill could also be effective for waste disposal in the unsaturated zone (Hardin and Sassani 2010).

EBS installation in crystalline rock enclosed concepts is amenable to prefabrication. The EBS around each waste package, plus the package itself, could be prefabricated within a thin-walled steel shell, transported underground, and emplaced as a single unit ("supercontainer"). Once the outer shell failed from corrosion, the clay buffer within would swell, sealing the opening between the wall rock and the waste package. No additional buffer material would be used around the supercontainer, also known as a prefabricated EBS module (PEM). For DPC-size packages the supercontainer could be very large and heavy. Alternatively, the buffer could be pre-constructed with an internal cavity that is lined with a steel sleeve, into which one or more waste packages could be emplaced alternating with cylindrical plugs made from buffer material.

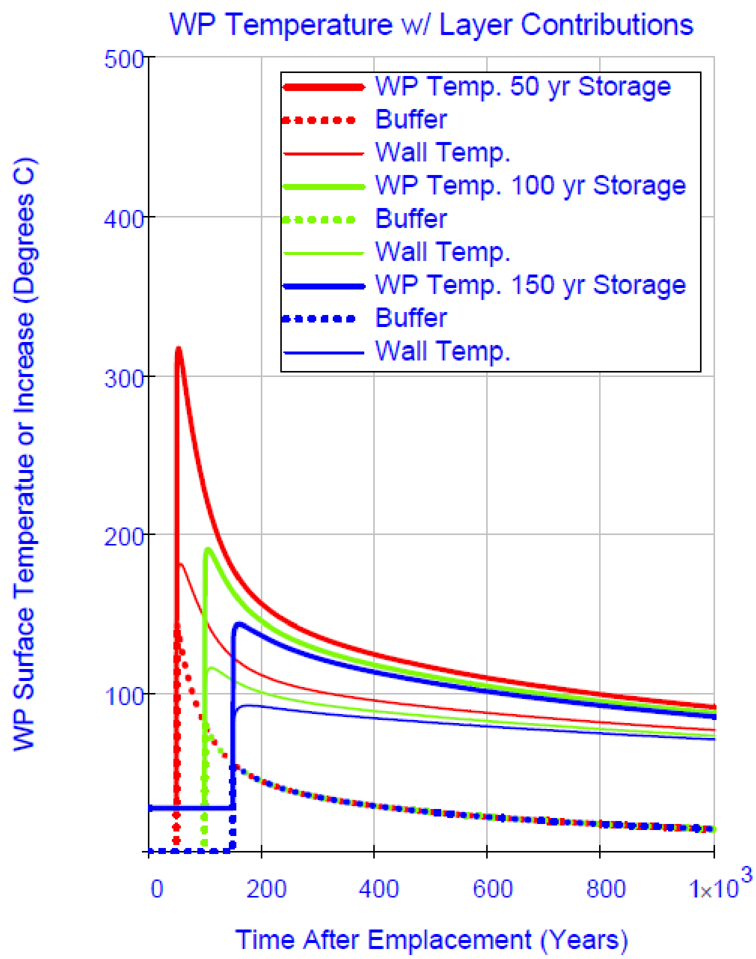
Postclosure criticality is not a concern for the KBS-3 concept with smaller packages (e.g., 4-PWR up to 12-BWR sizes proposed for the Swedish repository (SKB 2010) because the configuration is subcritical even when flooded with fresh water. This is not generally true for larger canisters such as DPCs, which have criticality control features such as control rods, absorber plates, and flux traps, but which are not designed for longevity in flooded disposal environments. An important control for postclosure criticality is moderator (water) exclusion, first by the low-permeability buffer or backfill, and then by plugging of voids within the waste package by expansive degradation of the internal structure (i.e., the basket or insert holding the fuel assemblies). DPCs are fabricated from stainless steels that may degrade too slowly (relative to the rate of buffer failures and water penetration) to prevent criticality, and DPCs contain no inserts designed to fill voids with corrosion products, so the principal barrier to water flooding is the low-permeability buffer or backfill, and the disposal overpack if it is made from corrosion resistant material. Depending on site-specific groundwater conditions, the salinity may be high enough in crystalline rock (similar to seawater or greater) for natural chloride to serve as an effective neutron absorber.

Even with these advantages the crystalline enclosed concepts are poorly suited for use with DPCs chiefly because of the high temperatures that would occur in clay-based buffer or backfill materials soon after emplacement. Large packages (e.g., 32-PWR size) would require at least 150 yr and possibly longer decay storage to achieve 200°C peak buffer temperature, so the disposal timeframe would likely exceed 150 yr total time out-of-reactor (Miller et al. 2012). For peak buffer temperature of 100°C many hundreds of years decay storage would be needed.

To test thermal performance for an enclosed mode for large packages in hard rock, enclosed in a clay-based buffer, an “optimistic” thermal analysis was performed (Figure 1). Packages containing DPCs (32-PWR) with moderate SNF burnup (40 GW-d/MT), were emplaced using expanded spacings (90 m drift spacing and 20 m package spacing), small drift diameter (3 m), typical host-rock thermal properties (K_{th} = 2.5 W/m-K), and an optimistic K_{th} of 0.9 W/m-K for partly hydrated buffer material.

Cases were analyzed with emplacement at 50, 100 and 150 yr out-of-reactor (Figure 1). The lowest peak buffer temperature calculated (at the waste package surface) is 143°C after 150 yr of storage, which exceeds the target temperature limits used in the Swedish and French programs (Hardin et al. 2012). The corresponding peak drift wall temperature is 92°C. For 20 GW-d/MTHM burnup the peak temperatures at the package surface and the drift wall are 61°C and 53°C, respectively. For 60 GW-d/MTHM burnup they are 189°C and 116°C (file: *Open UOXyy-32 (90 m) Hard Rock WP20m Enclosed* where *yy* is burnup of 20, 40 or 60). Hence, while host rock temperature limits (up to 200°C) could likely be met, the maximum temperature within a dehydrated or partly hydrated clay-based buffer would be much greater than 100°C except for disposal of a minor portion of projected SNF inventory that has low burnup.

The case analyzed in Figure 1 uses K_{th} of 2.5 W/m-K for the host rock, and granite formations may have greater conductivity (see for example, Hardin et al. 2012, Table D-1). However, thermal resistance of the buffer or backfill around the packages dominates the peak buffer temperature regardless of the host rock conductivity.



Note: Source file: *Open UOX40-32 (90 m) Hard Rock WP20m Enclosed.xmcd*

Figure 1. "Optimistic" thermal calculation for typical UOX fuel (40 GW-d/MT) in 32-PWR size packages, for an enclosed (clay buffer) emplacement mode in crystalline rock.

1.1 Crystalline Enclosed, Vertical Borehole (KBS-3V) with Swelling Clay-Based Buffer

The KBS-3 vertical concept applied to DPCs would involve larger emplacement boreholes than currently considered in the Swedish program (e.g., 3 m diameter compared with 1.7 m). The EBS could be prefabricated, but supercontainers incorporating DPCs would be large (on the order of 3 m in diameter and 6 m long) and weigh well in excess of 100 MT extrapolating from earlier work (Hardin and Sassani, 2010). However, the EBS without the waste package could be prefabricated (mainly the buffer and shield plug) and this approach is being considered for the KBS-3 repositories in Scandinavia. Suitability of the KBS-3V concept for DPC disposal does not depend critically on prefabrication, but on heat dissipation as discussed below.

Thermal analysis was performed for this concept using drift spacings of 30 m and 70 m, and waste package spacings of 10 m and 20 m. The smaller spacings (30 and 10 m) were chosen for the crystalline reference case (Hardin et al. 2012) for which 4-PWR size SNF packages were selected. Larger packages with these smaller spacings would require well in excess of 100 yr decay storage (Hardin et al. 2012). With the larger spacings (70 m drift spacing and 20 m package spacing) the required decay storage and peak temperatures are bounded by the "optimistic" case presented above (Figure 1). The same conclusion applies here to DPC disposal, that while host rock temperature limits (up to 200°C) could likely be met, the maximum temperature within a dehydrated or partly hydrated clay-based buffer or backfill would be much greater than 100°C except in the vicinity of waste packages containing SNF with low burnup.

A more extreme concept for borehole emplacement in hard rock would involve stacking of waste packages in a deep boring tens to hundreds of meters in extent, excavated from an underground access drift (EPRI 2010, Appendix B). This concept would not be suited for DPC disposal because of the size and weight of containers (or supercontainers) handled this way in an underground environment.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
1.1 Crystalline, enclosed, vertical borehole	Granite, etc. (sat. or unsat.)	Clay-based buffer, steel or corrosion-resistant package	Hundreds of years decay storage before emplacement to limit buffer temperature to 100°C	~100	Moderator exclusion

1.2 Crystalline Enclosed, Horizontal Borehole (KBS-3H) with Swelling Clay-Based Buffer

The horizontal borehole variation of the KBS-3 concept is being pursued by the Finnish and Swedish programs as a possible alternative, to reduce cost and complexity (Hardin et al. 2012). The EBS configuration would be similar to the KBS-3V, with similar waste packages, but projected along a large diameter horizontal boring extending 100 m or more through the host rock. For application to DPCs the borehole diameter would be approximately 3 m which is effectively the same as the in-drift emplacement variation described below. Fracture mapping and rock characterization to identify flowing features may be complicated by remote access, but grouting might be used extensively to address potential inflow. Prefabrication of EBS components, to include waste packages, is an important aspect of this borehole concept. However, DPC-size packages or prefabricated assemblies would be much larger and heavier than those being considered by the Finnish and Swedish programs, obviating the advantages of borehole emplacement.

Thermal considerations would be essentially the same as for KBS-3V with similar spacing between packages (i.e., 10 to 20 m). Lower-bound temperatures are provided by the "optimistic" case in Figure 1. Thus, for DPCs this concept would require well in excess of 100 yr decay storage, and the peak buffer or backfill temperature would be much greater than 100°C except in the vicinity of waste packages containing SNF with low burnup.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
1.2 Crystalline, enclosed, horizontal borehole	Granite, etc. (sat. or unsat.)	Clay-based buffer, steel or corrosion-resistant package	Hundreds of years decay storage before emplacement to limit buffer temperature to 100°C	~100	Moderator exclusion

1.3 Crystalline Enclosed, In-Drift Emplacement with Swelling Clay-Based Buffer

This concept would emplace large, steel waste packages on pedestals built from blocks of compacted, dehydrated clay-based buffer material, then backfill around them with swelling-clay based engineered backfill that achieves low permeability when hydrated (Nagra 2002). The drivers for in-drift emplacement vs. borehole emplacement are less complex construction and emplacement operations, and less excavated volume per waste package. This concept would limit the impact of an EDZ by using a tunnel boring machine to excavate emplacement drifts with circular cross-section and relatively small diameter. Waste packages would be centered in the drifts, and completely surrounded by a clay-based buffer. The concept is associated here with crystalline rock, but could also be implemented in sedimentary media (EPRI 2010, Appendix B).

The concept could be amendable to prefabrication with DPC size packages, particularly in wet host formations, except that the supercontainer weight could exceed 100 MT. Waste packages or prefabricated modules could be self-shielding or unshielded. Self-shielding would add significantly to cost and weight, while unshielded packages or modules would limit backfill to material that can be handled remotely. This concept is an enclosed emplacement mode, but the possibility for extended ventilation before backfilling is addressed in Section 6.2 on hard rock backfilled open-mode emplacement. In either case unless self-shielding disposal overpacks are used with DPCs, the backfill must be installed remotely after package emplacement, in a radiological environment at elevated temperature, making quality assurance more difficult. This could be expensive in wet, fractured rock where the backfill function is important to waste isolation. The possibility of remote backfill installation presents an opportunity to investigate how to ensure a minimum emplaced density for granular backfill containing swelling clay (e.g., using graded particles, pneumatic vs. mechanical emplacement, moisture content, etc.).

Thermal performance is similar to the other crystalline enclosed modes discussed above (lower bound temperatures estimated by the "optimistic" case in Figure 1) but only if drift diameter is small, on the order of 3 to 4 m. Larger drifts would increase the buffer thickness (the greatest thermal resistance) and thereby increase peak buffer temperature near the waste package surface.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
1.3 Crystalline, enclosed, in-drift emplace-ment	Granite, etc. (sat. or unsat.)	Clay-based buffer, steel or corrosion-resistant package	Hundreds of years decay storage before emplacement to limit buffer temperature to 100°C	~100	Moderator exclusion

2. Generic Salt Repository Concepts for HLW or SNF

In each variation of this concept packages would be enclosed by intact salt or crushed salt backfill at the time of emplacement. The generic salt repository was originally proposed for heat-generating HLW glass (Carter et al. 2011) and extended to SNF (Hardin et al. 2012). The repository would be excavated using boom-type road headers, floors would be bare rock as proven feasible at salt mines and the Waste Isolation Pilot Project (WIPP) for rubber tired equipment, and ground support would consist only of rockbolts in traffic areas.

For a salt repository the excavation and ground support methods would likely be very similar to those used for the WIPP. Excavations at the WIPP generally require only rock bolts for support, and may be as large as 8 m by 100 m, and 4 m high. Experience has shown that it is possible to maintain these large openings until waste has been emplaced, and the rooms are backfilled and closed.

For this study both bedded and domal salt are considered equally suitable for DPC disposal. Both have been proposed previously for SNF disposal (e.g., the U.S. Salt Repository Project, and the German facility at Gorleben). The water content of domal salt is typically 0.5% (w/w) or less, compared to 1 to 3% for bedded salt (Roedder and Chou 1982). This difference affects the prevalence and migration of brine in response to mechanical loading and heating, however, both bedded and domal salt formations offer very low mobility of brine, and no water-borne radionuclide releases under nominal conditions. Accumulation of brine at waste packages might be important in criticality analysis, but approximately 75% of natural chlorine is ^{35}Cl, a thermal neutron absorber.

Waste package overpacks would consist of low-alloy steel (or nodular cast iron, etc.) to maintain integrity through handling and for a few decades after emplacement (e.g., to facilitate possible retrieval for 50 yr). Repository layouts would be designed for simplicity and to spread out heat-generating packages onto a grid. No ventilation would be possible after emplacement and backfilling, other than to maintain the filled panels at lower ventilation pressure than other areas where repository construction and operations are underway. Access and other service openings would be backfilled with crushed salt prior to closure. Because the generic salt repository emplacement mode alternatives are enclosed modes, there would be little or no radiological risk to workers performing repository closure operations, once the emplacement alcoves, drifts or boreholes are backfilled.

Waste packages would be handled underground in the horizontal orientation, to limit the necessary height of excavations (important in bedded salt, which is likely to have a limited disposal interval thickness). To limit package handling operations underground, they would also be transported from the surface in a horizontal orientation. Thus, a shaft hoist would be needed similar to that used at Gorleben, scaled up to sufficient payload capacity (e.g., 175 MT). Feasibility of such hoists is an area of ongoing engineering analysis.

Shaft hoists are currently available with payload capacity up to approximately 85 MT (such a capability is being designed for the repository at Mol, Belgium and a full-scale test was performed at Gorleben, Germany). For DPC disposal the payload capacity would be 150 to 175 MT, depending on how much additional shielding is used around the loaded canister and disposal overpack. This capacity is probably feasible and has been proposed by the German program for the DIREGT direct disposal concept (Graf et al. 2012).

Vertical shafts would generally be used to access a salt repository, although this depends on site-dependent geomechanics and hydrology. Shafts are favored because the geometry minimizes the excavation area exposed to any water bearing strata in the overlying geologic section. This facilitates construction and eventual sealing of shaft openings when the repository is closed. In addition, strata in sedimentary basins where bedded or domal salt is found may be poorly indurated, complicating ground support during construction and final plugging and sealing.

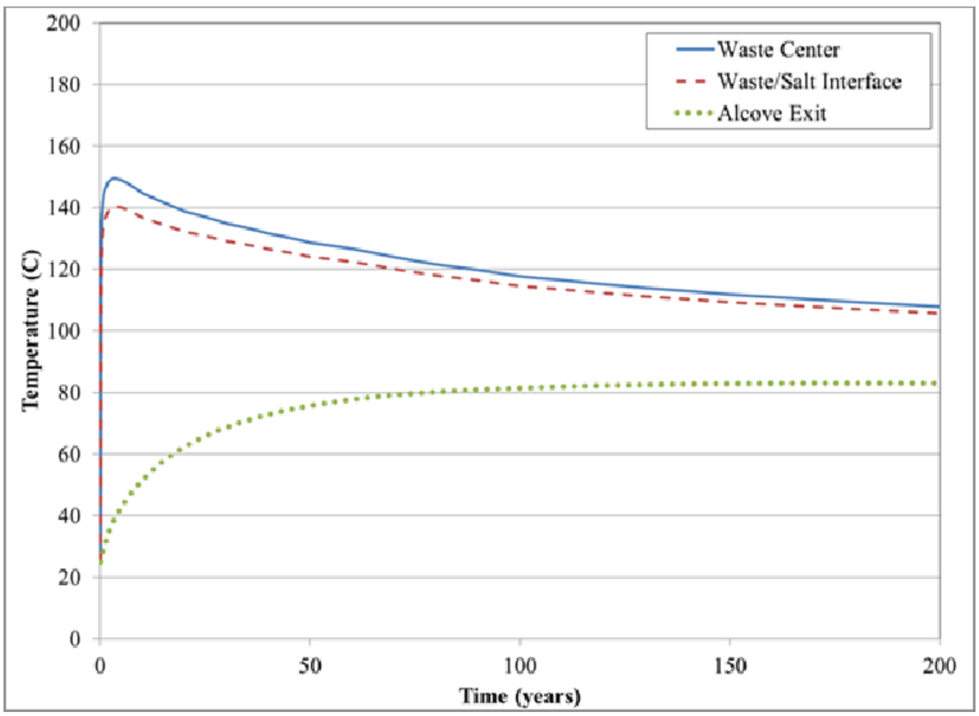
The choice of a vertical shaft for waste handling is conservative but not required. Importantly, shaft access would be used for construction, operation, and ventilation of any salt repository. Discussion of ramps is brought on by uncertainty as to the feasibility of vertically lowering large heavy waste packages (e.g., a fully loaded DPC with shielding and undercarriage, 175 MT) versus conveying them down ramps on wheeled transporters. Ramps are common within salt or potash mines to access different levels, so the stability of ramp openings within evaporite sequences during repository operations is not a major concern. For domal salt settings a waste handling ramp could be constructed well outside the dome structure, with horizontal access to the host formation, possibly at different levels. Thus, depending on site-specific conditions the most important seals associated with a ramp could be in horizontal openings, in strata with low permeability and minimal groundwater inflow. By moving the ramp away from the repository and using site-specific geomechanical and geohydrologic characteristics to optimize its design, the postclosure risk associated with groundwater inflow along the ramp could be mitigated.

A similar approach to ramp design, construction and sealing could be taken for a repository in bedded salt. Access to the stratigraphic interval for disposal could be provided by a ramp located at sufficient horizontal distance from the repository emplacement areas, possibly in ground that is unsuitable for waste disposal because of previous drilling or mining activities. Heavy rubber-tired transporters could be used in ramps with up to approximately 10% grade (Fairhurst 2012). Postclosure risk would be mitigated by sealing a long horizontal drift within the disposal interval, as well as backfilling, plugging, and sealing the ramp opening itself. Another option is to build a steep funicular railway (e.g., linear, with up to 15° or 27% slope) with sufficient hoist capacity and safety features to accommodate DPC packages, thereby shortening the ramp length by a factor of 2 or more (Fairhurst 2012). Thus, whereas vertical shafts are favored, ramps may be used if heavy shaft hoist equipment proves to be infeasible.

Site-specific factors are likely to constrain or eliminate possibilities for shaft or ramp construction, for example, the existence of a high-transmissivity aquifer in the geologic section above the host salt formation could favor vertical shafts for all mined accesses to the repository.

Salt has unique thermal properties that facilitate disposal of larger, hotter waste packages. Thermal conductivity is high (5.2 W/m-K for WIPP salt at ambient temperature; 3.2 W/m-K at 200°C), and salt can tolerate peak temperatures of 200°C or greater. While salt does creep, the shear stresses imparted by emplaced waste packages are small compared to the effects from excavation, so even large packages will probably not move significantly.

Finite-element thermal analysis of the disposal of large packages (32-PWR) in a generic salt repository was reported previously (Hardin et al. 2012; Jove-Colon et al. 2012). The results shown in Table 2 were obtained using an updated model for crushed salt (applicable to all salt emplacement modes discussed below with similar spacings). The model does not include the effect of moisture in the backfill, which accelerates reconsolidation and lowers temperatures in the first few decades after emplacement (Jove-Colon et al. 2012). A typical temperature history is also presented (Figure 2). Thermal analysis reported for the alcove emplacement variation of the concept applies approximately to in-drift and borehole emplacement variations. Heat transfer is probably worse for in-drift emplacement and better for borehole emplacement, but based on sensitivity analysis the differences in peak temperatures are on the order of ±10 C°, which is also the approximate magnitude of lower temperatures computed incorporating the effects of moisture on backfill reconsolidation.



Note: Alcove configuration and WIPP salt properties described by Hardin et al. (2012, Appendix C). Waste-salt interface temperature is the maximum at the package surface, contacting crushed salt backfill.

Figure 2. Temperature histories for disposal of 21-PWR packages with moderate SNF burnup (40 GW-d/MT), aged 50 yr, in a salt repository with waste packages on a 20-m grid.

Table 2. Summary of FEM simulations of the generic salt repository.

Package Type	Burnup (GW-d/MT)	MTIHM	Age OoR (yr)	Initial Heat Output (kW) [A]	Ventilation	Approx. Peak Salt Temperature (°C)
WASTE PACKAGE SIZE						
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 (50 yr)						
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

NOTES:
[A] SNF heat generation functions from Carter et al. (2012).

2.1 Horizontal In-Alcove or In-Drift Transverse Emplacement Concepts in Salt

Emplacement in alcoves constructed off linear access drifts was originally proposed for HLW (Carter et al. 2011) to spread the heat-generating HLW packages on a grid. The access drifts would remain accessible after package emplacement, until eventually backfilled. Transverse orientation of packages (e.g., horizontal, and perpendicular to the axis of each alcove or emplacement drift) facilitates handling in smaller openings because packages do not need to be fully turned. Shielded clam-shell type handling equipment would provide shielding until emplacement, protecting the equipment operator, but backfilling would be done by remote control. Packages would be emplaced directly on the floor. Shallow, cylindrical cavities could be milled in the floor to accept the packages and improve heat transfer to intact salt. With alcove emplacement once the alcoves are backfilled with crushed salt, the access drifts would remain open and accessible for maintenance or monitoring.

The in-drift variation (Robinson et al. 2012) has simpler, linear emplacement drift geometry that could be readily adapted to large SNF packages. This variation converts the access drifts for alcoves to emplacement, so there would be no access to the emplacement panel after emplacement (e.g., for monitoring).

The generic salt repository concept is scalable and well suited for disposal of DPC-sized packages, mainly because of superior heat dissipation properties of salt (Figure 2, Table 2). SNF with moderate burnup (40 GW-d/MT) can be disposed in 32-PWR sized packages after a little more than 50 yr of decay storage, while meeting a 200°C limit for peak salt temperature. Disposal of higher burnup fuel (60 GW-d/MT) is feasible after approximately 70 yr decay storage.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
2.1 Salt (enclosed) alcove or in-drift emplacement	Domal or bedded salt	Crushed salt backfill, steel overpack	SNF emplacement after 50 to 75 yr decay storage depending on burnup	~60	Brine scarce in salt; chloride brine acts as neutron poison

2.2 Borehole Emplacement in Salt

Borehole emplacement openings would be drilled or bored, which is readily accomplished in salt although the boreholes can distort after construction, complicating emplacement. Borehole emplacement tends to optimize heat transfer compared to concepts that use crushed salt backfill, especially in the first few years after emplacement when peak temperatures occur (and crushed salt has not yet fully reconsolidated).

Horizontal borehole emplacement could more readily accommodate bedded stratigraphy and thinner disposal intervals, helping to ensure that all emplacement and access openings are constructed in an interval selected for low permeability and consolidation behavior. For horizontal emplacement a shielded handling machine would be used similar to that used for the NUHOMS dry storage system or that proposed for the DIREGT concept (Graf et al. 2012). Skids, casing, and/or dedicated trolleys can be used to help slide each package into its borehole. A rigid, prefabricated borehole plug would be installed after emplacement for immediate shielding, and to stabilize the collar opening as the salt creeps. Such a plug would occupy less volume (requiring a shorter borehole) than full backfilling. After emplacement of all packages, the access drifts would be completely backfilled.

The slant borehole variation would involve construction of downward dipping emplacement boreholes, to facilitate emplacement by using gravity to provide some or all of the force needed to overcome sliding friction as packages are emplaced. Also, the downward orientation would tend to retain crushed salt backfill so that rigid shielding plugs would not be needed.

A more extreme concept for borehole emplacement in salt would involve stacking of waste packages in a deep boring tens to hundreds of meters in extent, excavated from an underground access drift (EPRI 2010, Appendix B). This is a reference concept for disposal of consolidated SNF assemblies in small canisters in salt domes (Bollingerfehr and Filbert 2010). It would not be well suited for DPC disposal because of the size and weight of the containers, the difficulty of retrieval, and the challenge of implementing borehole plugs to support large, heavy packages so that crushing loads do not develop.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
2.2 Salt (enclosed) borehole emplacement	Domal salt, possibly bedded salt	Shield plug or crushed salt backfill, steel overpack	SNF emplacement after 50 to 75 yr decay storage depending on burnup	~60	Brine scarce in salt; chloride brine acts as neutron poison

3. Clay/Shale Enclosed, Borehole Emplacement Concept

This concept is based loosely on the French concept for SNF (type C) waste in a clay or shale repository (Andra 2005; Hardin et al. 2012). In the original concept for 4-PWR size packages, horizontal emplacement borings 40 m long and spaced 30 m apart, would be excavated from parallel access drifts spaced approximately 100 m apart. The length of these emplacement borings would be based on the efficiency of boring and emplacement methods, and on waste isolation performance considerations. For DPC disposal applications these spacings and the dimensions of the emplacement borings would be increased, with emplacement borings approximately 70 m apart, and up to 3 m in diameter (consistent with the buffer thickness needed for waste isolation). The horizontal length of each emplacement boring would be nominally 50 m to accommodate three packages on 20-m center-center spacing. The horizontal orientation is best for stratified sediments, but construction challenges could limit boring length and the number of packages (EPRI 2010, Appendix B).

Emplacement borings would be lined with steel tubing or segmented plate (e.g., 2-cm wall thickness) to ensure opening stability throughout repository operations. A thicker liner would be used in longer borings, so there is a tradeoff with constructability (i.e., with boring stability, or variability in gauge). An inner liner would be installed to accept packages, and the annulus filled with compacted, dehydrated, swelling-clay buffer material. Both the inner and outer liners would be subject to thermal expansion before they finally corrode (EPRI 2010, Appendix B) that could require accommodation in the design (e.g., crumple sections and control of buffer swelling pressure). Packages with low-alloy steel overpacks would be slid into place within the inner liner, alternating with plugs of buffer material, and finishing with a sealing/shielding plug at the collar.

Access drifts would be large enough to transport packages in horizontal orientation (e.g., 8 m wide and 5 m high) with turnouts excavated around each emplacement boring collar to permit turning of packages in a shielded transporter. A jacking apparatus would be used to push packages out of the shield and into the inner liner of the emplacement boring. Jacking would be done against a reinforced plate fixed to the opposite side of the access drift from the collar. Emplacement borings would be constructed every 35 m from opposite sides of each access drift.

As described above the buffer would be pre-constructed to facilitate emplacement of unshielded packages. Steel liner corrosion would proceed slowly due to the anoxic environment, the contact with clay, and limited availability of water in the disposal environment. Swelling of the buffer, once hydrated, would seal off the packages and the corroded inner liner. Performance would depend on the buffer, and the host medium as a natural barrier. The concept could be suited for a range of mudstone, claystone or shale facies with low permeability (e.g., less than 10^{-16} m^2). With multiple barriers, for example adding a corrosion resistant waste package, it could be suited for more indurated and potentially fractured shales with greater permeability.

Repository construction in thick, clay-rich sediments would be facilitated by fast excavation and lack of water inflow. Immediate ground support would be needed, and an additional function of the lining system would be to prevent the host rock from drying out due to ventilation. Access drift floors would be poured concrete to limit damage from heavy, rubber-tired equipment. Both shaft and ramp access would likely be feasible in thick, low-permeability sediments because sealing would be straightforward (the French program is considering ramp access for access to thick argillite layers at 500 m depth).

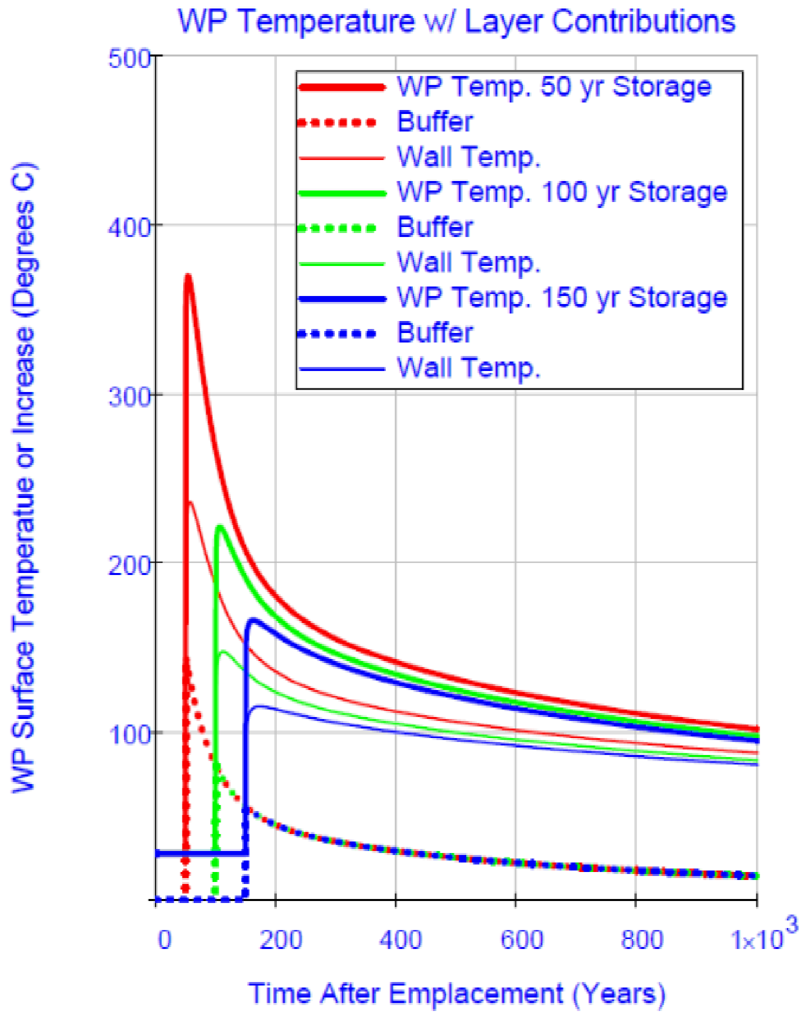
Use for DPCs would require long (200 yr or longer) decay storage to achieve peak buffer temp. below 200°C, which would exceed the assumed disposal timeframe (up to 50 yr decay storage and 100 yr repository operations; see Miller et al. 2012). Note that the steel liner (e.g., 2 cm thick) used around the buffer would protect the dehydrated, clay-based buffer material from alteration by steam or from moisture invasion leading to multiphase thermally driven coupled thermal-hydrologic-chemical processes, for as long as it remains intact. Thus, this concept offers an approach for preserving swelling clay buffer function even if the buffer temperature is above 100°C for hundreds of years. For lower peak temperatures (e.g., 100°C) many hundreds of years decay storage would be needed.

There would be no long-term requirements on access drift stability, because this is an enclosed mode. Access drifts, service drifts, etc. would be constructed using shotcrete, steel supports, rockbolts, and other measures as needed to provide service during repository operations. The emplacement mode is shielded so there would be no little or no radiological risk to workers performing repository closure operations.

The clay/shale enclosed geologic disposal concept would likely be implemented in mudstone or claystone media that behave more like cohesive soil than massive rock. The excavation method could use road header type equipment, or tunnel boring machines with full shielding. Ground support would consist of either cast concrete segments or liner plate, fully supporting the circumference of the excavation. If properly designed there would be little uncertainty associated with maintaining excavation stability for the length of time needed to emplace waste packages, buffer, and/or backfill.

To test thermal performance for an enclosed mode for large packages in clay/shale media, an "optimistic" thermal analysis was performed for 32-PWR packages (40 GW-d/MT), using expanded spacings (90 m drift spacing and 20 m package spacing), typical clay/shale thermal properties, and an optimistic K_{th} of 0.9 W/m-K for dehydrated clay-based buffer material, with emplacement at 50, 100 and 150 yr out-of-reactor. The lowest peak buffer (waste package surface temperature reached is 166°C (Figure 3) which is significantly greater than current maximum temperature targets for clay-based buffer material (approximately 100°C). The corresponding peak drift wall temperature is 115°C. This calculation shows that buffer temperature could be maintained below 150 to 200°C, with DPC decay storage of 100 to 150 yr, for all SNF except that with the highest burnup.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
3. Clay/shale, enclosed	Mudstone, claystone, shale	Clay-based buffer, low-alloy steel package	Hundreds of years decay storage before emplacement to limit buffer temperature to 100°C	~60	Moderator exclusion by low-permeability host rock; formation waters may be saline



Note: Source file: *Open UOX40-32 (90 m) Clay WP20m Enclosed.xmcd*

Figure 3. “Optimistic” thermal calculation for average UOX fuel (40 GW-d/MT) in 32-PWR size packages, for an enclosed (clay buffer) emplacement mode in clay/shale media.

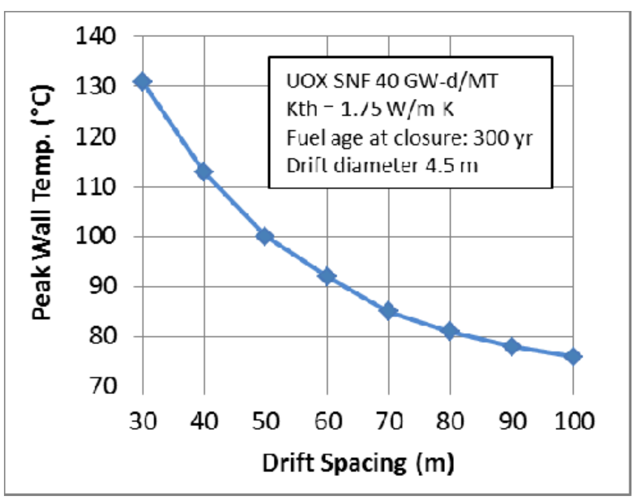
4. Sedimentary Unbackfilled, Open, In-Drift Emplacement Concepts for SNF

This concept is based on the shale unbackfilled open-mode reference case (Hardin et al. 2012) with drift and package spacings expanded slightly to 70 m and 20 m, respectively. Waste package spacing is more effective than drift diameter at lowering peak EBS temperatures outside the waste package, and slightly more effective than drift spacing. Note that drift spacing has a greater effect on temperatures in later time (e.g., after 300 yr) when the entire repository heats up and the contribution from adjacent drifts dominates contributions from the package itself, or adjacent packages in the same drift.

The sedimentary unbackfilled case involves segmented emplacement drifts that are ventilated for up to 100 yr or longer (but consistent with the timing assumptions from Miller et al. 2012), then sealed in segments containing small numbers of packages. Thus, packages are not sealed off from others within the same segment, but segments are sealed off from other segments in the repository. The idea is that isolating every package with low-permeability backfill is not necessary in a massive, low-permeability formation that does not have through-going faults or other features that conduct groundwater flow. However, the uncertain possibility of such faults or other features intersecting emplacement drifts makes it prudent to isolate segments of the repository so that only a few waste packages could be affected. By isolating each segment from the remainder of the repository, the potential radionuclide migration from each segment effectively resembles that from a single, large waste package.

The unbackfilled approach does not require backfilling emplacement drifts at closure, and therefore does not need to meet backfill temperature limits. Backfill installed in non-emplacement areas would be situated far from waste packages where temperatures are much lower. The approach also leaves the emplacement drifts open after closure for heat transfer to occur. The drifts would be expected collapse eventually, but mostly after the time period when peak temperatures occur.

A drift spacing of 70 m is selected because it incorporates much of the peak temperature reduction possible using drift spacing (Figure 4). The characteristic time for a given temperature rise in diffusive systems is proportional to the square of the distance from a heat source, but decreasing SNF heat output in a repository overwhelms the effect from distance, after decay of short-lived fission products in the first hundred years out-of-reactor.



Note: Source files: *Open UOX40-21 (xx m) Clay.xmcd, where xx is drift spacing in meters.*

Figure 4. Effect of drift spacing on peak drift wall temperature, for typical SNF in 21-PWR size packages, in a sedimentary repository, unbackfilled, that closes at 300 yr out-of-reactor.

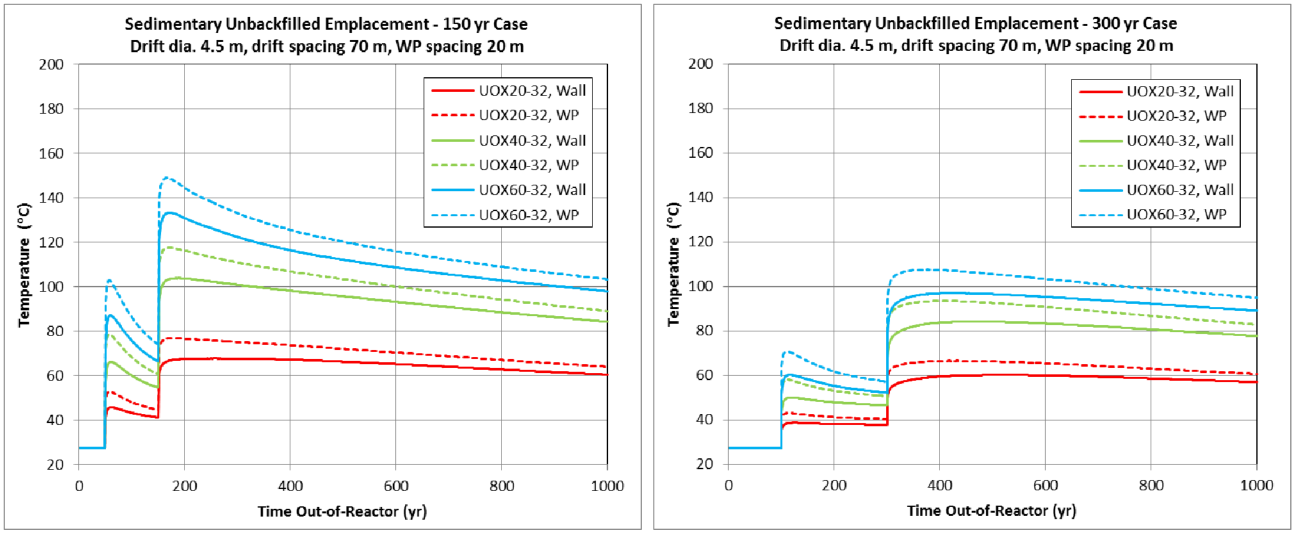
Using empirical rock mass classification systems without site-specific information, it is difficult to differentiate between sedimentary rock and hard rock. Perhaps the best way to look at this is in comparison to the Rock Mass Rating and Q Rock Mass Classifications presented earlier for crystalline rock (Section 1). Sedimentary rock could be well indurated; but if not, excavation and support methods would be similar to those described above for the clay/shale enclosed concept (Section 3). Neither sedimentary rock or hard rock would be as massive and strong as crystalline rock, and excavation could be feasible using tunnel boring machines. Compressive strength could be half or less that of granite; with more frequent discontinuities and lower RQD. Joints are likely to have greater length and persistence than in the case of massive crystalline rock; however it is likely that any rock mass being considered would have tight unweathered joints with rough mating surfaces. As with crystalline rock, it is likely that a rock mass with limited groundwater inflow would be sought, and that the underground facility would be oriented favorably with respect to discontinuities. Thus, the Rock Mass Rating could be in the good category or perhaps the very good category. The corresponding stand-up time could be from 10 yr to perhaps as short as 1 yr.

Using the Q Rock Mass Classification System, RQD could be classified as good, perhaps excellent. One or more joint sets would likely be present. It is likely that a rock mass with rough irregular undulating joint walls would be sought, which means the joint roughness and joint alteration characteristics would be favorable. The joint water reduction factor likely would reflect dry excavations or limited water inflow, while the stress reduction factor would reflect a well chosen rock mass with medium stress and favorable stress orientation. Using an excavation support ratio number of 0.8, the estimated support category using the Q Rock Mass Classification System would require rock bolting and perhaps shotcrete.

Waste packages would have overpacks made from low-alloy steel to facilitate handling, emplacement, resistance to rupture by rockfall, and containment for an initial period of a few hundred years. Packages would be emplaced on simple pedestals to control radiative heat transfer and provide additional height in the event of rockfall.

Underground openings and ground support would be designed to allow only minor rockfall for 50 to 100 years to facilitate inspection and retrieval as well as ventilation. After closure, accumulating rockfall would increase temperatures within the debris piles, but drift wall temperature limits could still be met because expanding the drift wall contour effectively increases drift diameter and spreads the outward heat flux. Note that package temperatures are projected to be much lower than limits that could be imposed to preserve fuel cladding integrity (350°C) or prevent package material thermal sensitization (e.g., Fox and McCright 1983; Farmer et al. 1988). Thus, blanketing by limited rockfall debris would not produce excessive package temperatures (see BSC 2008b for similar analysis). Postclosure heat dissipation with substantial rockfall would be limited by debris bulking that would eventually fill the opening. This discussion leads to a need to define rockfall extent in terms of heat removal by ventilation, and peak postclosure temperatures.

Thermal calculations for this concept (Figure 5) show that closure at approximately 200 yr out-of-reactor (storage plus ventilation time) limits the peak drift wall temperature to 100°C for SNF with 40 GW-d/MT burnup. Segments with lower burnup SNF (20 GW-d/MT) could be closed before 150 yr, while those with higher burnup SNF (60 GW-d/MT) could take up to 300 yr. Thermal management options are discussed in the next sections.



Note: Source files: *Open UOXxx-32 (70 m) Clay WP20m.xmcd, where xx is burnup of 20, 40 or 60.*

Figure 5. Temperature histories (drift wall and waste package surface) for various SNF burnup levels in 32-PWR sized packages, in a sedimentary unbackfilled repository with spacings shown, for: (left) 50 yr decay storage and 100 yr ventilation, and (right) 100 yr decay storage and 200 yr ventilation.

4.1 Sedimentary Unbackfilled, Open, In-Drift, Low-Temperature Concept

As shown on the left-hand part of Figure 5, only low burnup SNF (less than 40 GW-d/MT) could be emplaced in sedimentary host rock in DPCs (32-PWR size or equivalent, drift spacing 70 m, package spacing 20 m) while maintaining drift wall temperature at 100°C or less, without exceeding the assumed 150-yr disposal timeframe (Miller et al. 2012). A suitable low-temperature concept could use further expanded package spacing, and possibly drift spacing and diameter, for higher burnup SNF. For example, 60 GW-d/MTHM SNF and expanded layout and drift diameter (100 m drift spacing, 30 m package spacing, and 6.5 m drift diameter), and closure at 150 yr out-of-reactor, the peak wall temperature is 96°C reached 19 yr after closure (*** file name).

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
4.1 Sedimentary, in-drift emplacement, unbackfilled, low temperature	Sedimentary rock (e.g., mudstone, claystone or soft shale)	Carbon steel overpack	Repository closure at 150 yr; additional decay storage or concept modification for higher burnup SNF to limit peak drift wall temperature to 100°C	~100	Moderator exclusion by low-permeability host rock; formation waters may be saline

4.2 Sedimentary Unbackfilled, Open, In-Drift, High-Temperature Concept

This concept could accept the full range of SNF burnup in DPCs (32-PWR size) if heating of the near-field host rock to temperatures greater than 100°C is allowable. This possibility was investigated in the "design test case" developed previously as a reference (Hardin et al. 2012) which would heat the drift wall to 130°C and push the 100°C isotherm into the host rock 3 m beyond the drift wall. The 100°C isotherm would envelope the waste packages in a segment, but adjacent host rock where plugs and seals were installed would see much lower temperatures. The potential pathways for transport of released radionuclides could transect virtually the same distance through the host rock formation as for the low-temperature concept (Section 4.1) in an appropriate geologic setting.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
4.2 Sedimentary, in-drift emplacement, unbackfilled, high temperature	Sedimentary rock (e.g., mudstone, claystone or soft shale)	Carbon steel overpack	Repository closure at 150 yr with peak drift wall temperature greater than 100°C for higher burnup (>40 GW-d/MT).	~100	Moderator exclusion by low-permeability host rock; formation waters may be saline

5. Sedimentary Backfilled, Open, In-Drift Emplacement Concept for SNF

For saturated host rock, repository openings need to be plugged and/or sealed to prevent groundwater moving preferentially throughout the repository. Low-permeability backfill of all repository openings is one approach. Since these are open emplacement modes, the plugging, sealing and/or backfilling must be undertaken in a radiological environment, at elevated temperature. Backfill could also mitigate effects from roof collapse, seismic shaking, and other processes. The advantages of backfill, and the related thermal management issues, are also discussed in Section 6 for hard rock.

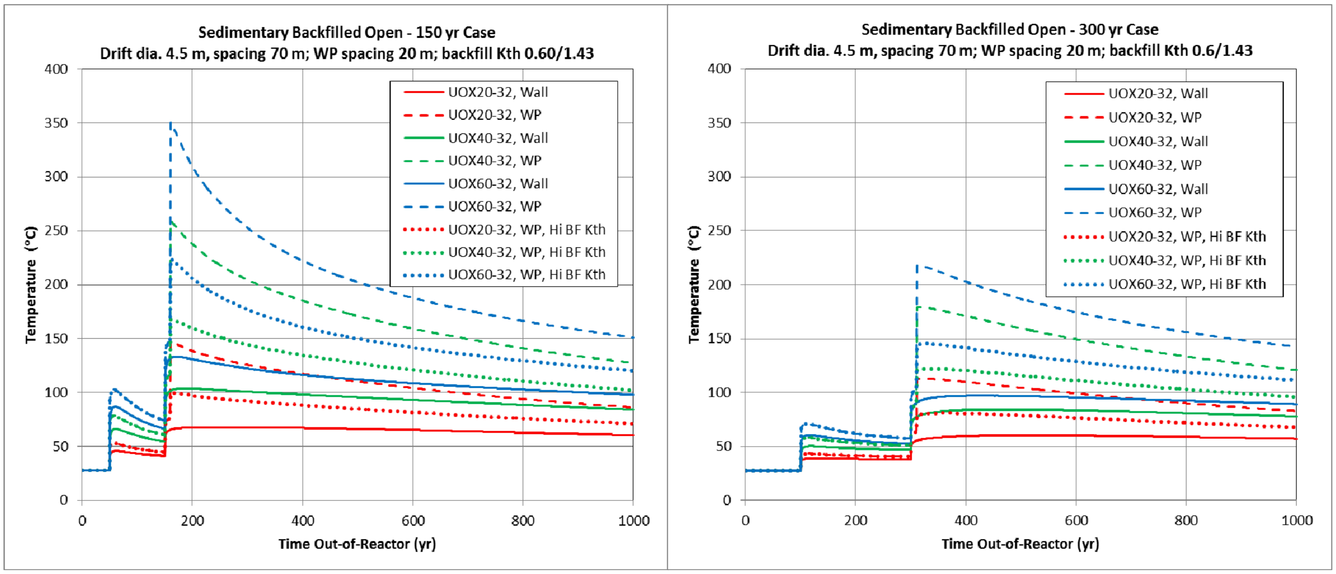
In a low-permeability host formation the function of backfill may depend less on swelling properties than for higher permeability host rock settings (see Sections 1.3 and 6.2). Thus, a non-swelling low-permeability could be selected, or a water-sensitive swelling material could be emplaced in a wet state. Some possible options for non-clay and/or non-swelling materials are discussed in Appendix B.

Excavation method and ground support requirements would be the same as those discussed for the sedimentary unbackfilled open concept (Section 4), except that selection of backfill could address the presence of more rock fracturing and/or groundwater flow. Thus, more robust ground support could be needed to keep emplacement drifts open for 100 yr, such as shotcrete, with steel supports as needed.

Peak backfill temperature would exceed 100°C for all burnups, for hundreds of years. For higher burnups (greater than 20 GW-d/MT) peak backfill temperature would be 200°C or greater (Figure 6). Like the corresponding hard rock concept (Section 6.2) increased drift spacing and waste package spacing would decrease the drift wall temperatures but would have less influence on peak backfill temperatures. The viability of this concept would depend on a backfill thermal strategy that could include: 1) reducing drift diameter and/or the effective backfill thickness; 2) increasing the minimum thermal conductivity for backfill material, for example using wet emplacement at closure; and/or 3) establishing a higher limit (e.g., up to 200°C or higher) for backfill material, for example, by proving the performance of smectite clay-based materials or selecting a different material not subject to the same limitations. These alternatives represent opportunities for R&D to evaluate buffer or backfill responses to elevated temperature, and new low-permeability, temperature resistant backfill/buffer materials.

Another variation of this concept could emplace supercontainers containing waste packages surrounded by a buffer material, held together by a thin-walled steel shell. The supercontainers would remain substantially intact during repository ventilation, and the spaces around and between them would be backfilled at closure. After subsequent failure of the shell, the buffer would serve as an additional barrier to groundwater movement and radionuclide mobility. The supercontainers could be designed for self-shielding, greatly simplifying repository closure operations.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
5. Sedimentary, in-drift emplacement, backfilled	Sedimentary rock (e.g., mudstone, claystone or soft shale)	Carbon steel overpack	Repository backfilling and closure at 150 yr, with high-temperature backfill/buffer material (limit ~200°C); concept modification for higher burnup SNF to limit peak drift wall temperature to 100°C	≥ 100	Water exclusion by low-permeability rock; formation waters may be saline



Note: Source files: *Open UOXxx-32 (70 m) Clay Backfilled WP20m.xmcd, where xx is burnup of 20, 40 or 60.*

Figure 6. Temperature histories (drift wall and waste package surface) for various SNF burnup levels in 32-PWR sized packages, in a sedimentary backfilled repository with spacings shown, for: (left) 50 yr decay storage and 100 yr ventilation, and (right) 100 yr decay storage and 200 yr ventilation.

6. Hard-Rock Open, In-Drift Emplacement Concepts for SNF

Open emplacement modes allow extended ventilation of the repository for heat removal after waste emplacement, prior to permanent closure. These concepts combine the functions of surface decay storage (i.e., in fuel pools or dry cask storage) with geologic disposal, in the same facility. Earlier emplacement of SNF waste (rather than after lengthy surface decay storage of up to 100 yr) allows much of the cost for repository construction and operation to be incurred sooner, before currently operating nuclear power plants are shut down. In addition, earlier repository implementation reduces any future risks associated with SNF degradation caused by extended surface storage (up to 100 yr, which is beyond currently licensed terms for storage facilities).

Hard rock can provide reliable opening stability and maintenance (e.g., for 100 yr) for ventilation (depending on site-specific factors such as the probability of disruption by seismic ground motion). In addition, hard rock (e.g., tuff, or carbonate rock) typically has greater thermal conductivity, and higher temperature limits (e.g., 200°C) than sedimentary media (e.g., rock types containing significant clays or other hydrous minerals).

As discussed in Section 4, using empirical rock mass classification systems without site-specific information, it is difficult to differentiate between sedimentary rock and hard rock. Given the strength, fracturing and groundwater characteristics of a well chosen hard rock setting, the Rock Mass Rating could be in the good category or perhaps the very good category, and the corresponding stand-up time could be up to 10 yr. The RQD could be classified as good or excellent. Joint characteristics, stress conditions, and groundwater flow conditions in a hard rock setting would comparable to (or possibly better than) those for sedimentary clastic rock settings. Using an excavation support ratio number of 0.8, the estimated support category using the Q Rock Mass Classification System would require rock bolting and perhaps shotcrete.

Indurated hard rock types are subject to brittle behavior in response to geologic processes, and the relative lack of creep or plasticity ensures that fractures persist over geologic time periods. With a network of fractures, bulk permeability may orders of magnitude greater than the intact rock (i.e., small-scale) permeability. Virtually all hard rock units have some fracturing, and therefore have bulk permeability (or permeable features) that are addressed in disposal concept development and repository design.

If the host rock is unsaturated, sufficient bulk permeability will make it free-draining (DOE 2008). With drainage possible throughout the host rock, there is little or no possibility of focused groundwater flow along repository openings, so plugging and sealing of emplacement and access drifts is not needed. For saturated host rock, such flow is possible and repository openings need to be plugged and/or sealed. Moreover, in saturated, permeable host rock an impermeable backfill/buffer barrier is desirable to isolation of waste packages from the flow. Since these are open emplacement modes, the plugging, sealing and backfilling must be undertaken in a radiological environment, at elevated temperature.

As noted previously, shaft or ramp access could be used in conjunction with disposal in hard rock, since rock opening stability facilitates construction of liners, plugs and seals to control groundwater inflow.

For enclosed emplacement modes in which backfill/buffer is emplaced concurrently with waste packages, see the crystalline concepts described above.

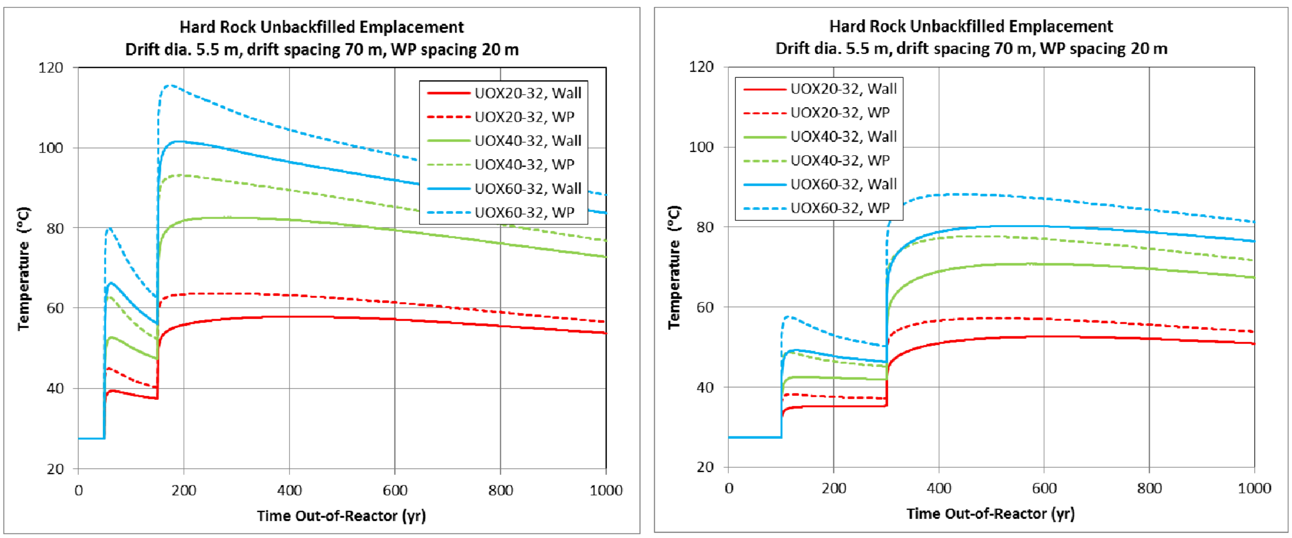
6.1 Hard-Rock Unbackfilled, Open, Unsaturated, In-Drift Concept

This concept would use a corrosion resistant package and other, redundant barriers as needed to enhance performance and limit regulatory risk (e.g., delay in licensing). Other barriers could include water diversion features (e.g., drip shields) or multiple corrosion resistant materials (e.g., Ti and Hastelloy).

This concept is similar to previous work (DOE 2008) and to a previous proposal for direct disposal of DPCs (Kessler et al. 2008). The DPC proposal considered only nominal thermal performance, i.e., whether nominal host rock temperatures would exceed 200°C (or waste package outer barrier temperature would exceed 300°C). It did not consider the higher temperatures that could be caused by seismically induced rockfall or collapse soon after closure (Hardin et al. 2008). That thermal analysis could be further refined to address these other aspects, and could likely be adapted and shown to be viable for direct disposal of DPCs.

The concept is well suited for disposal of DPC-sized packages. Hard rock offers long opening stand-up times and resistance to temperatures up to approximately 200°C. Thermal calculations (Figure 7) show that a 200°C wall temperature limit could be met for SNF with high burnup, with less than 150 yr decay storage plus ventilation (except possibly for minor fuel types such as irradiated Pu-MOX which could require longer storage/ventilation). The left-hand side of Figure 7 corresponds to the maximum storage and ventilation durations assumed for this study (Miller et al. 2012), while the right-hand side extends closure to 300 yr out-of-reactor. This calculation is based on host rock thermal conductivity of 2.5 W/m-K, which is greater than welded tuff at Yucca Mountain but less than some granites. The results shown in Figure 7 envelope low-thermal operating mode calculations published previously (DOE 2002). They also suggest that the hard rock repository layout could be optimized with smaller drift and waste package spacings, and shorter durations for decay storage and ventilation.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
6.1 Hard rock, unsaturated, unbackfilled	Granite, tuff or other competent rock type	Corrosion resistant overpack; other barriers as needed (e.g., drip shields)	Repository closure after less than 150 yr (decay storage plus ventilation)	< 100	Package flooding probability for unsat. environments.



Note: Source files: *Open UOXxx-32 (70 m) Hard Rock WP20m.xmcd, where xx is burnup of 20, 40 or 60.*

Figure 7. Temperature histories (drift wall and waste package surface) for various SNF burnup levels in 32-PWR sized packages, in a hard rock open (unbackfilled) repository with spacings shown, for: (left) 50 yr decay storage and 100 yr ventilation, and (right) 100 yr decay storage and 200 yr ventilation.

6.2 Hard-Rock Backfilled, Open, In-Drift Concept

This concept would add a low permeability backfill installed prior to closure, and could be implemented in saturated host formations. Adding backfill addresses the need to control groundwater flow throughout the repository, as discussed above. Postclosure performance would be similar to the crystalline enclosed concept with in-drift emplacement discussed above (Section 1.3). Possible strategies for backfilling using remotely operated equipment in a radiological environment at elevated temperature, include drift turnouts, plugs or labyrinths for worker shielding (Hardin et al. 2012), and emplacement of dehydrated granular backfill material using conveyors, pneumatic delivery, or auger feeds.

The concept could also be implemented in unsaturated formations, where clay-based backfill/buffer materials could perform better than in saturated formations (Hardin and Sassani 2010). For unsaturated conditions a low-permeability backfill can serve as an additional barrier to radionuclide migration. Backfill could also mitigate effects from roof collapse, seismic shaking, and other processes. Backfill could produce reducing conditions at the waste package and waste form, which could be reflected in the EBS design (e.g., less corrosion resistant but less costly waste package materials). On the other hand, use of a corrosion resistant disposal overpack along with low-permeability backfill would provide multiple engineered barriers in addition to the waste form.

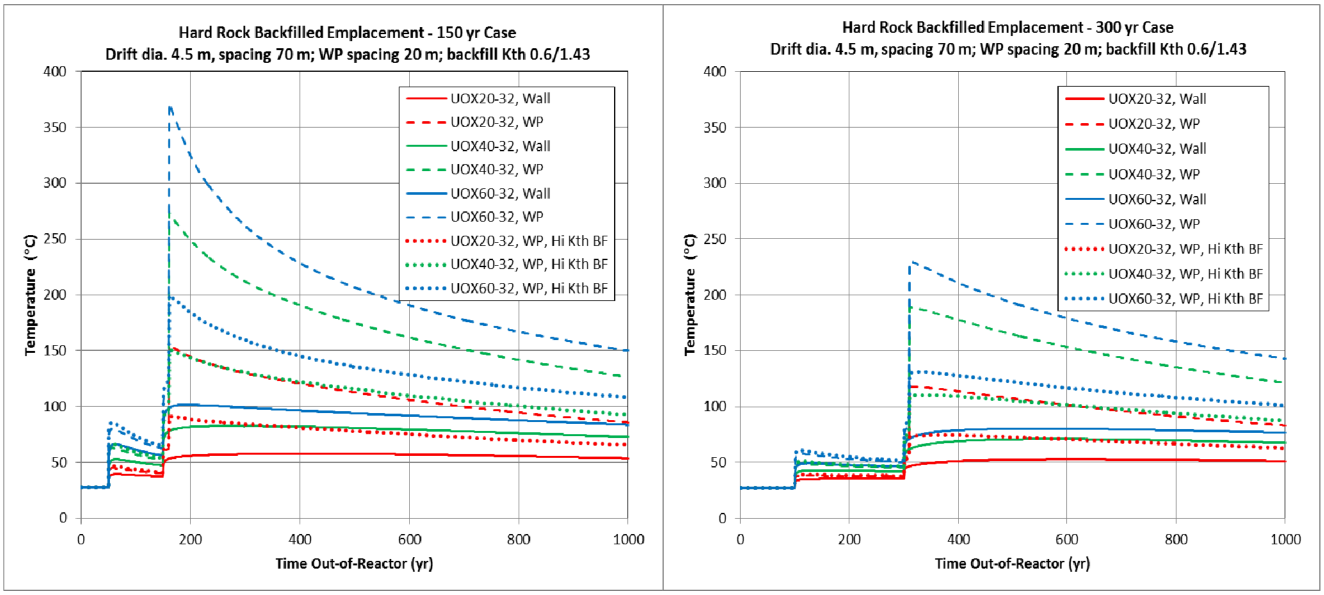
Similar to the concept variation discussed in Section 5, waste packages could be emplaced in supercontainers in which they are surrounded by buffer material, held together by a thin-walled steel shell. The supercontainers would remain substantially intact during repository ventilation, and the spaces around and between them would be backfilled at closure. After subsequent failure of the shell from corrosion, the buffer would serve as an additional barrier to groundwater movement and radionuclide mobility.

Thermal calculations show that limiting the peak postclosure temperature of backfill near the waste package surface would drive the timing of surface decay storage, emplacement, repository ventilation, and backfilling at closure (Figure 8). The left-hand side of Figure 8 corresponds to the maximum storage and ventilation durations assumed for this study (Miller et al. 2012), while the right-hand side extends closure to 300 yr out-of-reactor. Even closure at 300 yr produces peak backfill temperatures of 120°C or much higher depending on SNF burnup. These calculations were made using a drift diameter of 5.5 m (same as used for the unbackfilled cases) and a backfill thermal conductivity of 0.6 W/m-K representing dehydrated, compacted clay. Comparison with Figure 2 shows what lower temperatures might be achieved "optimistically" by decreasing drift diameter to 3 m (with 90 m drift spacing and backfill K_{th} of 0.9 W/m-K).

For backfilled concepts, larger drift diameter increases buffer thickness and therefore package temperature, whereas for unbackfilled concepts, larger drift diameter decreases package temperature. Increased drift spacing and waste spacing would decrease the drift wall temperatures but would not significantly lower peak backfill/buffer temperatures.

The viability of this concept would depend on a backfill temperature strategy that could include: 1) reducing drift diameter and/or the effective backfill/buffer thickness; 2) increasing the minimum thermal conductivity for backfill material, for example using wet emplacement at closure; and/or 3) establishing a higher limit (e.g., up to 200°C or higher) for backfill material, for example, by proving the performance of smectite clay-based materials or selecting a different material not subject to the same limitations. These alternatives represent opportunities for R&D to evaluate buffer or backfill responses to elevated temperature, and new low-permeability, temperature resistant backfill/buffer materials.

Variations on this concept include a thick-walled disposal overpack made from corrosion allowance material such as low-alloy steel, with reliance on the low-permeability backfill/buffer to inhibit groundwater flow and provide a reducing chemical environment to limit radionuclide mobility. In addition, waste packages could be self-shielding which could greatly simplify repository closure operations.



Note: Source files: *Open UOXxx-32 (70 m) Hard Rock Backfilled WP20m.xmcd, where xx is burnup of 20, 40 or 60.*

Figure 8. Temperature histories (drift wall and waste package surface) for various SNF burnup levels in 32-PWR sized packages, in a hard rock open (backfilled) repository with spacings shown, for: (left) 50 yr decay storage and 100 yr ventilation, and (right) 100 yr decay storage and 200 yr ventilation.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
6.2 Hard rock, saturated or unsaturated, backfilled	Granite, tuff or other competent rock type	Corrosion resistant overpack; low-permeability backfill/buffer)	Repository backfilling and closure at 150 yr, with high-temperature backfill/buffer material (limit 200°C or higher)	≥ 100	Water exclusion by low-permeability backfill/buffer

7. Cavern-Retrievable Storage and Disposal Concept for SNF

The disposal concepts described here emphasize retrievability of the DPCs from the underground facility, throughout the repository operations period (up to 150 yr according to the timing assumptions adopted for this study; Miller et al. 2012). At closure casks containing DPCs would be encapsulated in low-permeability backfill/buffer material. Casks would be fully encapsulated, including low-permeability material supporting them from below. The concepts could be implemented in saturated or unsaturated host media, although unsaturated settings could offer less potential for groundwater penetration of the engineered barriers (particularly through the load-bearing buffer material supporting the casks from below). Also, backfill/buffer materials could perform well in unsaturated settings where groundwater flux and velocity are less than in many saturated settings, for example, saturated hydrology impacted by continental glaciation

(Hardin and Sassani 2010). They would require large galleries and minimum 100-yr opening stability, although storage casks or their contents could be readily moved for gallery maintenance. One motivation for cavern-retrievable storage is the option to extend storage well beyond 100 yr, and another is a small repository footprint (with extended ventilation) that could be useful in limited settings (EPRI 2010, Appendix B).

The cavern retrievable concepts could likely be developed in rock masses encompassed by the range of support estimates given for the crystalline rock, sedimentary rock, and hard rock cases. Because the excavations would likely have smooth, curved roof spans their stability would be similar to that of circular openings. The excavation dimensions considered for the cavern retrievable concepts are of the same order of magnitude as those considered for the in-drift emplacement concepts described previously. Without detailed site-specific information more refined estimates of ground support requirements are not possible. We note, however, that the ground support estimates for all of these disposal concepts are relatively minimal.

The problem faced when designing for a potential ventilation period of 100 yr or longer, is accommodating ground support maintenance. Because of the lengthy ventilation times, and limited access to emplacement drifts for ground support maintenance, previous design work selected stainless steel liner plate and stainless steel rock bolts that were point-anchored (DOE 2008). If the geochemistry of the system is compatible, fully grouted rock bolts could provide one alternative for limiting maintenance and extending opening stability.

The cavern-retrievable emplacement concepts for DPC storage and disposal have a distinct advantage in being shielded, ventilated systems in an underground environment. This would allow access for preventive maintenance and would significantly enhance confidence in long-term opening stability.

Storage casks cool by natural convection which would be interrupted by installation of backfill at closure. Thermal performance would be bounded by the hard rock backfilled concept (Section 6.2) but not quite as hot because the large size of surface storage casks would spread the heat flux out and reduce thermal gradients in the surrounding backfill. Also, for the subterranean concept (Section 7.2) optimal buffer properties would be ensured during pre-construction, and the backfill emplaced at closure would contact only the top plug.

The most direct access for waste handling would be via shallow ramp (a few percent maximum grade, accessible to heavy-haul equipment) into the side of an escarpment in mountainous terrain. The facility could be built above or below the regional water table, which could impact the steps taken to seal the openings at closure.

The host medium would be selected for constructability and maintenance of long galleries (totaling tens of km) with spans of at least 6 m, and height at least 8 m (for vertical emplacement), to accommodate transport and emplacement equipment. To optimize constructability and geohydrologic performance the host medium would be compositionally uniform and relatively unfractured (e.g., relatively young granite, or thick volcanic tuffs, with bulk permeability of 10^{-15} m^2 or less).

7.1 Surface Storage Systems Emplaced Underground in Unsaturated-Zone Galleries

This concept is close to that proposed by the original authors (Figure 9, after McKinley et al. 2008). It would use existing dry cask storage systems, which would be relocated in large galleries or caverns underground. Ramp access would be needed to move the heavy shielded casks underground.

Initial construction would provide the means to limit groundwater contact with the casks after closure, e.g., by emplacing storage casks on engineered pads of low-permeability material with sufficient shear strength for long-term stability. Hydraulic containment liners for landfill disposal applications are typically constructed in such a manner using mixtures of sand and clay (Kenney et al.1992). Such construction would be especially effective in the unsaturated zone where pore pressures and groundwater flow velocities are minimal (e.g., see Hardin and Sassani 2010; discussion of potential erosion in unsaturated flow).

Shielded surface storage casks for DPCs cool by natural convection into the surrounding air. Emplacement galleries would be ventilated using a combination of forced and natural convection to remove this heat. \ conditions would be dry during ventilation, especially for host rock of sufficiently low permeability, or in the unsaturated zone. Operations to close the facility would consist of removing services such as electrical conductors, and backfilling with granular material. Convective cooling would continue, circulating heated air into the dry granular backfill until backfill hydration occurred (at which point thermal conductivity would increase). Closure operations could proceed when heat output had decayed sufficiently to maintain backfill temperature (in dehydrated and hydrated regions) below 100°C.

This concept would use the storage casks already deployed wherever DPCs exist, which would be transported to the repository separately from waste. It could also be used for self-shielded containers such as CASTOR casks. Use of existing hardware could limit disposal cost. The concept is similar in principle to in-drift disposal in crystalline rock (Section 1.3) with reliance on the low-permeability backfill/buffer and natural barrier performance. This concept has not been thoroughly evaluated in the technical literature and presents opportunities for R&D, for example: 1) to understand the performance of licensed storage casks in the underground environment, both preclosure and postclosure; 2) to evaluate whether the concept would function significantly better in the unsaturated zone; 3) to define the geometry, materials, and waste isolation performance of the backfill and other engineered barriers installed around the storage casks; and 4) to simulate temperature histories for the casks and the EBS.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
7.1 Surface storage systems in caverns, backfilled at closure	Uniform, competent material (e.g., nonwelded tuff, deep alluvium, granite)	Storage cask, low-k backfill	Repository backfilling and closure at 150 yr, with high-temperature backfill/buffer material (limit 200°C). Postclosure natural convection could mitigate temperature rise.	~50 or greater	Water exclusion by low-permeability backfill

7.2 Transfer DPCs into Purpose-Built, Self-Ventilating, Large-Vertical-Borehole Casks

This concept would use specially built vaults in an underground facility to store, and eventually dispose of SNF in DPCs. Emplacement could be horizontal or vertical; in either case vaults would be constructed using low-permeability material, while also providing for cooling by natural convection. Vaults would be similar to surface storage concepts such as the NUHOMS systems (horizontal) or the subterranean Hi-Storm 100 system (vertical), optimized for waste isolation after closure. Vault design would incorporate the waste isolation performance of an enclosed mode (Sections 1 through 3) with heat dissipation capability of an open mode at least during repository operation. This concept is similar to that originally proposed (Section 7.1) but with vaults optimized for postclosure waste isolation. It also presents opportunities for R&D, for example, developing a configuration for the subterranean storage system that accepts a range of existing DPC types, and optimizing heat transfer.

Concept	Host Media	EBS	Thermal/Schedule Aspects (32-PWR)	Area (m^2/MTHM)	Criticality Control Aspects
7.2 Underground vaults for storage and disposal, backfilled at closure	Uniform, competent material (e.g., nonwelded tuff, deep alluvium, granite)	Purpose-built vault system, low-k buffer and backfill	Repository backfilling and closure at 150 yr, with high-temperature buffer material (limit 200°C). Postclosure natural convection could mitigate temperature rise.	~50 or greater	Water exclusion by low-permeability buffer

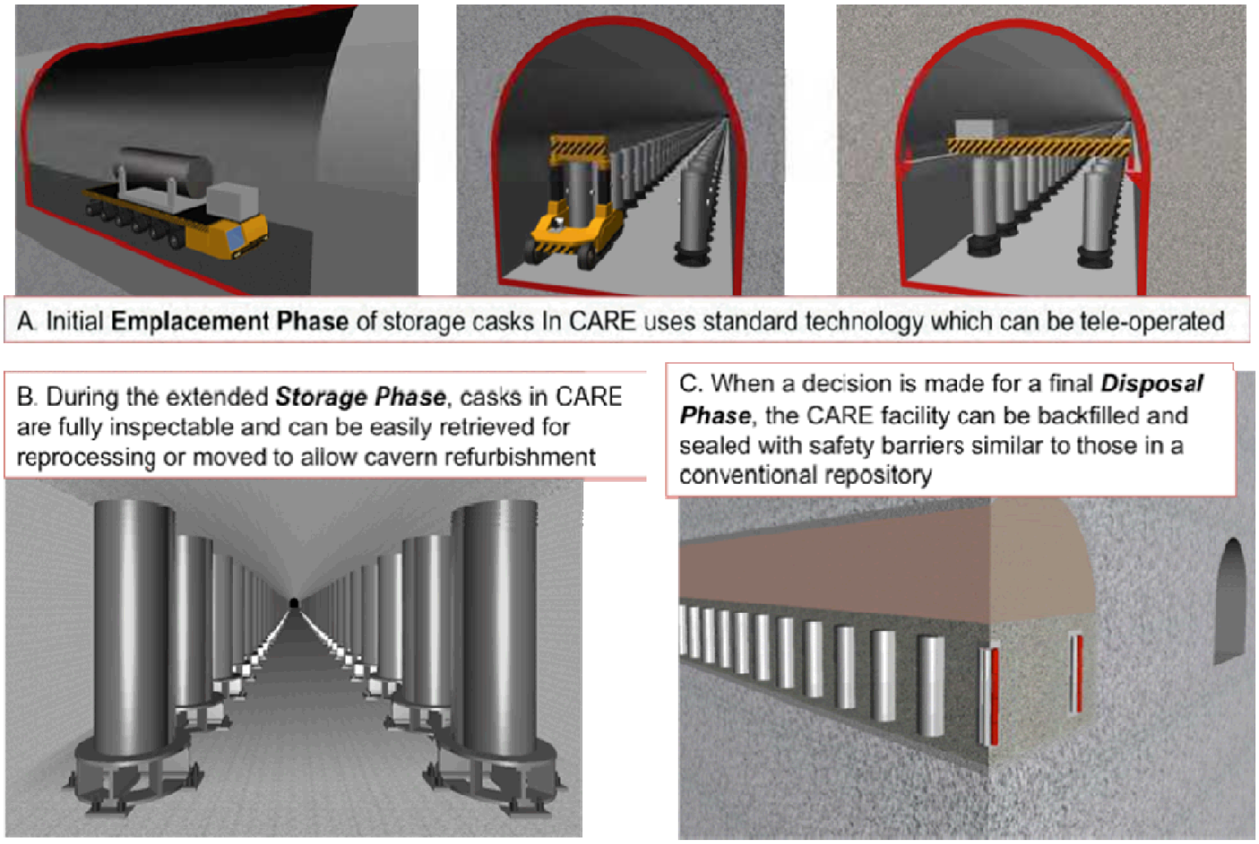


Figure 9. Cavern-retrievable storage/disposal conceptual diagrams (after McKinley et al. 2008 and EPRI 2010).

Summary

A number of alternatives have been identified for direct disposal of DPCs (up to 32-PWR size, or BWR equivalent). Meeting maximum temperature targets ("limits") for EBS materials and the near-field host rock, is a significant factor in determining feasibility. The alternatives offer features external to the waste package that could help limit in-package postclosure criticality. Other factors such as opening stability and ground support, waste package transport and emplacement, and shaft vs. ramp access, may be less important but depend on site-specific characteristics.

The generic salt repository and the unbackfilled hard rock concepts could accept SNF in 32-PWR size packages, with SNF burnup to 60 GW-d/MT, and approximately 50 to 100 yr decay storage depending on burnup. These repository concepts could likely close within the 150-yr timeframe adopted for this study (Miller et al. 2012), while meeting target values for peak host rock temperature (200°C in both types of media).

In sedimentary media with lower thermal conductivity and a lower target value for peak rock temperature (100°C) only lower burnup SNF could be accommodated. For higher burnup SNF (e.g., ≥ 40 GW-d/MT) a modified concept would be needed that uses some combination of longer decay storage plus ventilation, and/or peak buffer/backfill temperature limits greater than 100°C. For the same reason, the enclosed emplacement modes (crystalline or sedimentary media) cannot meet the peak buffer temperature target without decay storage much longer the assumed timeframe.

The cavern retrievable storage and disposal concept was first proposed several years ago and remains an important alternative that combines the heat removal performance of an open mode prior to closure, with an enclosed mode after closure. The storage casks would be shielded, facilitating closure operations. This concept could involve repository and storage/disposal cask designs that accommodate a wide range of different DPC types. Use of existing surface storage casks could be cost effective, but would involve close integration among SNF management efforts on a national level.

Various R&D opportunities are identified in this report, associated with alternative DPC disposal concepts. This information anticipates later steps in the DPC disposal feasibility evaluation (Howard et al. 2012) where key issues will be identified and workplans proposed. The major opportunities identified so far include:

- Determine buffer and backfill responses to elevated temperature (e.g., hydrothermal activity at temperatures of 100°C or higher).
- Establishing a higher limit (e.g., up to 200°C or higher) for backfill material, for example, by proving the performance of smectite clay-based materials under controlled conditions (e.g., dry, and/or protected by a supercontainer shell).
- Increasing the thermal conductivity for backfill material, for example using wet emplacement at closure.
- Identify and characterize new low-permeability, thermally resistant backfill/buffer materials.
- Evaluate in-drift disposal concepts that minimize drift diameter and/or backfill/buffer thickness to optimize heat transfer.
- Simulate temperature histories for cavern retrievable concepts, representing the storage casks and the EBS.
- Develop a configuration for the subterranean storage system that accepts a range of existing DPC types, and optimizes heat transfer during preclosure and postclosure.

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Appendix A – Rock Mass Classification Systems

Estimates of opening stability and rock support requirements depend on site specific parameters important to rock mass stability, which include the quality of the rock, the presence of joints, the number of joint sets, their orientation, and their spacing, the character of the joints, including roughness and any alteration, groundwater conditions, weakness zones, the compressive strength of intact rock material, time dependent properties of the rock, and the stress state.

While rock mass stability can be influenced by combinations of these parameters, the three most important are the degree of jointing, which determines block size, joint friction, and the stress state. The degree of jointing and block size are determined by the joint spacing, patterns, and orientation. At a specific location there will be a more or less well-defined joint pattern. Often several prominent joint directions exist, and most of the joints will be parallel with these directions. Joint sets comprise nearly parallel joints with a relatively consistent spacing. In fracture or shear zones, however, the joint spacing may be considerably smaller. In hard rock, the deformations that occur typically involve shear displacement along the joints; the friction along the joints is therefore important. Joint friction depends on joint roughness and the thickness and types of mineral fillings. Rough joints, or those with no filling or only a thin hard mineral filling, are favorable for stability. On the other hand, smoothness and a thick filling of weak material result in low friction and less stability. Rock mass stability generally worsens when joint spacing decreases and the number of joint sets increases.

In soft rock where deformation can occur independently of joints, the degree of jointing typically matters less than it does in hard rock. Where deformation is more or less independent of joints, the joint friction factor is less important. The stress state in the rock mass usually depends on the depth below the surface, however, for some settings purely tectonic or residual stresses can be more influential. Stability generally depends on the ratio of the stress induced by excavation to the rock strength. Moderate stresses are usually the most favorable for stability. In rock masses intersected by zones of joints with weak mineral fillings such as clay or crushed rock, the stress situation may vary considerably over relatively small areas.

Generic schemes exist that support generalized conclusions about opening stability and the types of rock support needed. These rock mass classification schemes are empirical, derived from observations about actual openings. They are not design tools because the empirical observations give no information about the factor of safety of the system. In other words, the data points could represent a system that is on the verge of failure or one that has a very high factor of safety. While the rock mass classification schemes provide indications of the types and amounts of support needed, they do not address maintenance, which could be a significant concern for openings that must function for 100 years or longer in some of the disposal concepts presented in this report.

The numerous rock mass classification schemes are derived from principles developed by Terzaghi, Lauffer, and others who proposed that the stand-up time for an unsupported span is related to the quality of the rock mass. The unsupported span, or active span, is defined as either the span of the tunnel or the distance between the face and the nearest support, if this is greater than the tunnel span. It is important to note that the stand-up time concept was developed to provide an indication of the time available to install rock mass support before collapse occurred.

The significance of the stand-up time concept is that an increase in the span of the tunnel leads to a significant reduction in the time available for the installation of support (leftward slant of the diagonal lines in Figure A-1). For example, a small pilot tunnel may be successfully constructed with minimal support, while a larger span tunnel in the same rock mass may not be stable without the immediate installation of substantial support. The shaded band in Figure A-1 represents data observed during the construction of numerous tunnels.

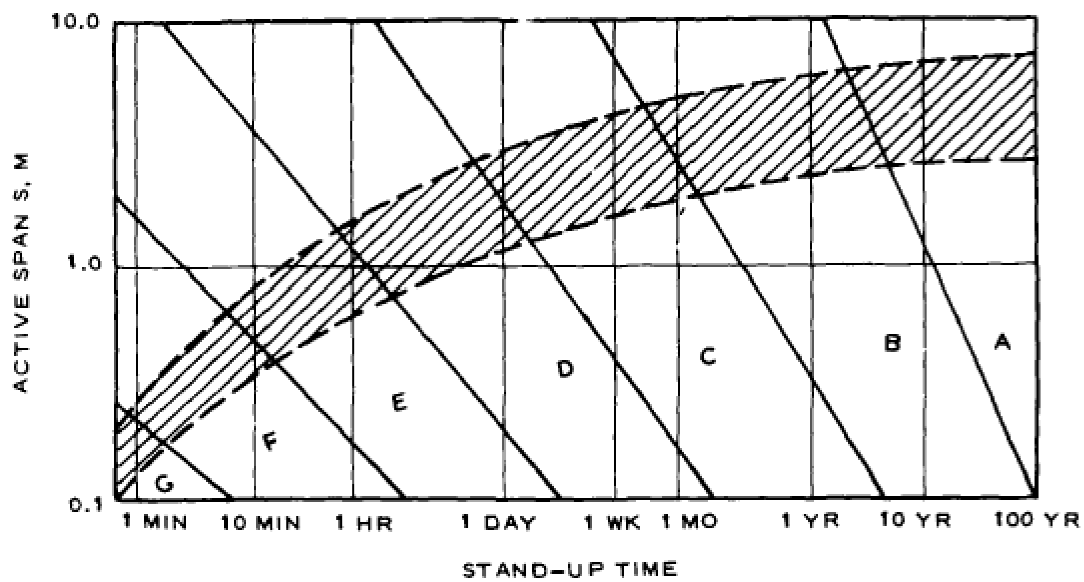

Figure A-1. Lauffer's relationship between active span and the stand-up time for different classes of rock mass ranging from A-very good rock to G- very poor rock (after Bieniawski).

Examination of Figure A-1 and its basis yields several important observations:

- Diagonal lines indicate stand up time decreases appreciably with excavation span (opening)
- Relationships are empirical; shaded area represents data from real excavations
- Stand-up times in good to very good rock can approach tens to many tens of years
- Not included in the Figure, but described in the attributes of the system:
    - Excavations that parallel strata have longer stand-up times that those that are perpendicular
    - Circular excavations are more stable than rectangular
    - Machine bored openings are more stables than blasted ones, and pre-splitting produces the most stable openings from blasting
    - Openings supported by rock bolts with shotcrete are more stable than with shotcrete alone, and shotcrete produces more stable openings than steel supports alone (timber is not considered for support of repository openings)

These concepts are incorporated in the New Austrian Tunneling Method, whereby supports are installed quickly before deformation can lead to the need for greater support, and a sequenced approach is used for larger openings to maximize the effectiveness of support measures.

Both of the rock mass classification systems discussed here include a parameter known as the rock quality designation or RQD. The RQD index was introduced about 50 years ago when rock quality information was usually available only from geologists' descriptions and the percent of core recovered. RQD is a modified core recovery percentage in which recovered core fragments, small pieces of rock, and altered rock are not counted to downgrade the quality designation; all the pieces of sound core over 100 mm long are summed and divided by the length of the core run. The RQD thus measures the percentage of good rock in a borehole (Deere and Deere 1988). It is an index of rock quality in that problematic rock that is highly weathered, soft, fractured, sheared, and/or jointed is counted against the rock mass quality.

Of the many Rock Mass Classification systems used in practice, the most likely to be used are the Rock Mass Rating and the Q Rock Mass Classification System.

A.1 Rock Mass Rating

The Geomechanics Classification or the Rock Mass Rating (RMR) System was developed by Bieniawski in 1973. This engineering classification of rock masses, especially evolved for rock engineering applications, uses the following six parameters, all of which are measurable in the field and can be obtained from borings:

- Uniaxial compressive strength of intact rock material
- RQD defined previously
- Spacing of discontinuities
- Condition of discontinuities
- Ground water conditions
- With an adjustment for orientation of discontinuities

In practice, the RMR system rating is developed by selecting the appropriate values from a table (Figure A-2) and summing the values. The summed value is then used to provide an estimate of stand-up time (Figure A-3).

INPUT PARAMETERS TO RMR_{1989}

(from Bieniawski, 1989)

	PARAMETER		Range of values // RATINGS				
1	Strength of intact rock material	Point-load strength index	> 10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range uniaxial compr. strength is preferred
		Uniaxial com- pressive strength	> 250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / < 1 MPa
		RATING	**15**	**12**	**7**	**4**	**2** / **1** / **0**
2	Drill core quality RQD		90 - 100%	75 - 90%	50 - 75%	25 - 50%	< 25%
		RATING	**20**	**17**	**13**	**8**	**5**
3	Spacing of discontinuities		> 2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm
		RATING	**20**	**15**	**10**	**8**	**5**
4	Condition of discon- tinuities	Length, persistence	< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m
		Rating	**6**	**4**	**2**	**1**	**0**
		Separation	none	< 0.1 mm	0.1 - 1 mm	1 - 5 mm	> 5 mm
		Rating	**6**	**5**	**4**	**1**	**0**
		Roughness	very rough	rough	slightly rough	smooth	slickensided
		Rating	**6**	**5**	**3**	**1**	**0**
		Infilling (gouge)	none	Hard filling		Soft filling	
			-	< 5 mm	> 5 mm	< 5 mm	> 5 mm
		Rating	**6**	**4**	**2**	**2**	**0**
		Weathering	unweathered	slightly w.	moderately w.	highly w.	decomposed
		Rating	**6**	**5**	**3**	**1**	**0**
5	Ground water	Inflow per 10 m tunnel length	none	< 10 litres/min	10 - 25 litres/min	25 - 125 litres/min	> 125 litres /min
		$p_w / \sigma 1$	0	0 - 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5
		General conditions	completely dry	damp	wet	dripping	flowing
		RATING	**15**	**10**	**7**	**4**	**0**

p_w = joint water pressure; $\sigma 1$ = major principal stress

RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS

		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
RATINGS	Tunnels	**0**	**-2**	**-5**	**-10**	**-12**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**
	Slopes	**0**	**-5**	**-25**	**-50**	**-60**

ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 20
Class No.	I	II	III	IV	V
Description	**VERY GOOD**	**GOOD**	**FAIR**	**POOR**	**VERY POOR**

MEANING OF ROCK MASS CLASSES

Class No.	I	II	III	IV	V
Average stand-up time	10 years for 15 m span	6 months for 8 m span	1 week for 5 m span	10 hours for 2.5 m span	30 minutes for 1 m span
Cohesion of the rock mass	> 400 kPa	300 - 400 kPa	200 - 300 kPa	100 - 200 kPa	< 100 kPa
Friction angle of the rock mass	< 45°	35 - 45°	25 - 35°	15 - 25°	< 15°

Figure A-2. Rock Mass Rating classification charts (Palmstrom 2009).

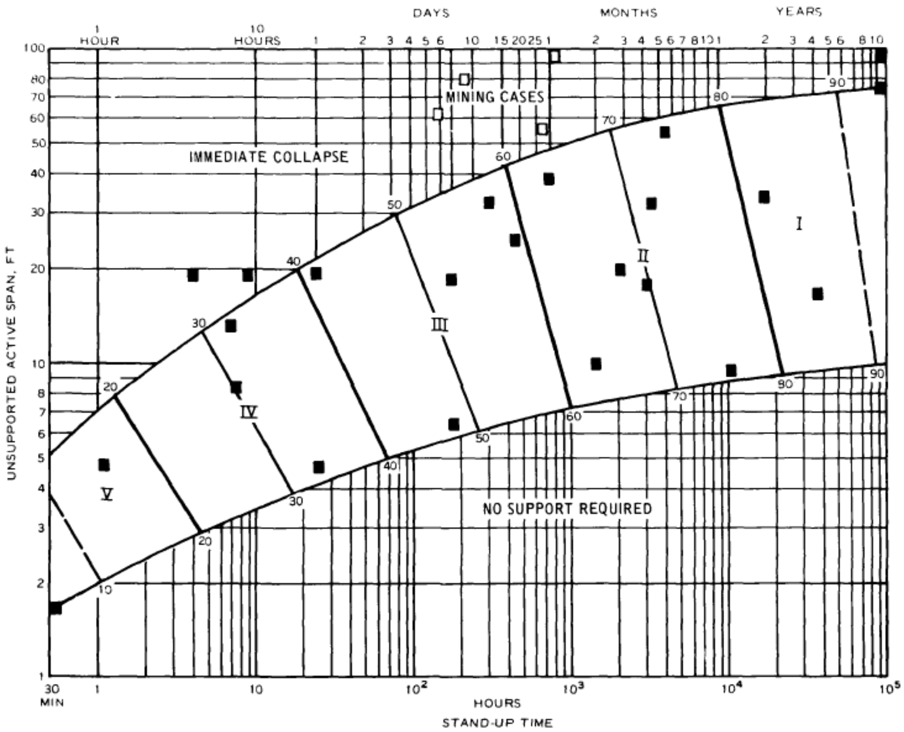

Figure 9. Geomechanics classification - output of stand-up time versus unsupported span

Figure A-3. Rock Mass Rating stand-up time.

A.2 The Q Rock Mass Classification System

Based on a large database of tunnel projects, Barton et al. (1974) of the Norwegian Geotechnical Institute (NGI) developed the Q Rock Mass Classification System for estimating rock support in tunnels. The Q-system is developed as an empirical design method for estimating rock support. The value of Q is defined by six parameters combined in the following equation:

$$Q = RQD/Jn \times Jr/Ja \times Jw/SRF$$

where RQD = Rock Quality Designation, defined previously
Jn = ratings for the number of joint sets;
Jr = ratings for the joint roughness;
Ja = ratings for the joint alteration,
Jw = ratings for the joint or ground water, and
SRF = ratings for the rock mass stress situation.

Barton et al (1974) defined an additional parameter which they called the equivalent dimension, *De*, of the excavation. This dimension is obtained by dividing the span, diameter or wall height of the excavation by a quantity called the excavation support ratio, *ESR*. Hence:

De=Excavation span, diameter or height (m) / *ESR*

The value of *ESR* is related to the intended use of the excavation and to the degree of security which is demanded of the support system installed to maintain the stability of the excavation:

A. Temporary mine openings: *ESR* = 3 to 5

B. Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large excavations: *ESR* = 1.6

C. Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels: *ESR* = 1.3

D. Power stations, major road and railway tunnels, civil defense chambers, portal intersections: *ESR* = 1.0

E. Underground nuclear power stations, railway stations, sports and public facilities, factories: *ESR* = 0.8

The classification system defines the rock support (Figure A-5) based on Q values developed from the charted inputs (Figure A-4).

Input parameters to Q system

Rock quality designation (RQD)

Very poor	RQD = 0 - 25%
Poor	25 - 50
Fair	50 - 75
Good	75 - 90
Excellent	90 - 100
Notes:	
(i) Where RQD is reported or measured as < 10 (including 0), a nominal value of 10 is used to evaluate Q	
(ii) RQD intervals of 5, i.e. 100, 95, 90, etc. are sufficiently accurate	

Joint set number (Jn)

Massive, no or few joints	Jn = 0.5 - 1
One joint set	2
One joint set plus random	3
Two joint sets	4
Two joint sets plus random	6
Three joint sets	9
Three joint sets plus random	12
Four or more joint sets, heavily jointed, "sugar-cube", etc.	15
Crushed rock, earthlike	20
Notes: *(i) For tunnel intersections, use (3.0 x Jn); (ii) For portals, use (2.0 x Jn)*	

Desciption and ratings for the parameter Jr *(joint roughness number)*

a) Rock-wall contact, b) rock-wall contact before 10 cm shear		**c) No rock-wall contact when sheared**	
Discontinuous joints	Jr = 4	Zone containing clay minerals thick enough to prevent rock-wall contact	Jr = 1.0
Rough or irregular, undulating	3		
Smooth, undulating	2	Sandy, gravelly or crushed zone thick enough to prevent rock-wall contact	1.0
Slickensided, undulating	1.5		
Rough or irregular, planar	1.5	***Notes:***	
Smooth, planar	1.0	*i) Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m*	
Slickensided, planar	0.5	*ii) Jr = 0.5 can be used for planar, slickensided joints having lineations, provided the lineations are oreintated for minimum strength*	
Note *: i) Descriptions refer to small scale features, and intermediate scale features, in that order*			

Descriptions and ratings for the parameter Ja *(joint alteration number)*

	JOINT WALL CHARACTER		**Condition**	***Wall contact***
Contact between joint walls	CLEAN JOINTS	Healed or welded joints:	filling of quartz, epidote, etc.	Ja = 0,75
		Fresh joint walls:	no coating or filling, except from staining (rust)	1
		Slightly altered joint walls:	non-softening mineral coatings, clay-free particles, etc.	2
	COATING OR THIN FILLING	Friction materials:	sand, silt calcite, etc. (non-softening)	3
		Cohesive materials:	clay, chlorite, talc, etc. (softening)	4

	FILLING OF:	**Type**	***Partly wall contact*** *Thin filling (< 5 mm)*	***No wall contact*** *Thick filling*
Partly or no wall contact	Friction materials	sand, silt calcite, etc. (non-softening)	Ja = 4	Ja = 8
	Hard cohesive materials	compacted filling of clay, chlorite, talc, etc.	6	5 - 10
	Soft cohesive materials	medium to low overconsolidated clay, chlorite, talc, etc.	8	12
	Swelling clay materials	filling material exhibits swelling properties	8 - 12	13 - 20

Description and ratings for the parameter Jw *(joint water reduction factor)*

Dry excavations or minor inflow, i.e. < 5 l/min locally	$p_w < 1$ kg/cm^2	Jw = 1
Medium inflow or pressure, occasional outwash of joint fillings	1 - 2.5	0.66
Large inflow or high pressure in competent rock with unfilled joints	2.5 - 10	0.5
Large inflow or high pressure, considerable outwash of joint fillings	2.5 - 10	0.3
Exceptionally high inflow or water pressure at blasting, decaying with time	> 10	0.2 - 0.1
Exceptionally high inflow or water pressure continuing without noticeable decay	> 10	0.1 - 0.05
Note: *(i) The last four factors are crude estimates. Increase Jw if drainage measures are installed*		
(ii) Special problems caused by ice formation are not considered		

Description and ratings for parameter SRF *(stress reduction factor)*

A. Weakness zones intersecting excavation	Multiple weakness zones with clay or chemically disintegrated rock, very loose surrounding rock (any depth)			SRF = 10
	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation < 50 m)			5
	Single weakness zones containing clay or chemically disintegrated rock (depth of excavation > 50 m)			2.5
	Multiple shear zones in competent rock (clay-free), loose surrounding rock (any depth)			7.5
	Single shear zones in competent rock (clay-free), loose surrounding rock (depth of excavation < 50 m)			5
	Single shear zones in competent rock (clay-free), loose surrounding rock (depth of excavation > 50 m)			2.5
	Loose, open joints, heavily jointed or "sugar-cube", etc. (any depth)			5
Note: *(i)*	*Reduce these valued of SRF by 25 - 50% if the relevant shear zones only influence, but do not intersect the excavation*	σ_c / σ_1	σ_θ / σ_c	
B. Competent rock, rock stress problems	Low stress, near surface, open joints	> 200	< 0.01	2.5
	Medium stress, favourable stress condition	200 - 10	0.01 - 0.3	1
	High stress, very tight structure. Usually favourable to stability, may be except for walls	10 - 5	0.3 - 0.4	0.5 - 2
	Moderate slabbing after > 1 hour in massive rock	5 - 3	0.5 - 0.65	5 - 50
	Slabbing and rock burst after a few minutes in massive rock	3 - 2	0.65 - 1	50 - 200
	Heavy rock burst (strain burst) and immediate dynamic deformation in massive rock	< 2	> 1	200 - 400
Notes: *(ii)*	*For strongly anisotropic stress field (if measured): when $5 < \sigma_1/\sigma_3 < 10$, reduce σ_c to $0.75\,\sigma_c$. When $\sigma 1/\sigma 3 > 10$, reduce σ_c to $0.5\,\sigma_c$*			
(iii)	*Few case records available where depth of crown below surface is less than span width. Suggest SRF increase from 2.5 to 5 for low stress cases*		σ_θ / σ_c	
C. Squeezing rock	*Plastic flow of incompetent rock under the influence of high pressure*	Mild squeezing rock pressure	1 - 5	5 - 10
		Heavy squeezing rock pressure	> 5	10 - 20
D. Swelling rock	*Chemical swelling activity depending on presence of water*	Mild swelling rock pressure		5 - 10
		Heavy swelling rock pressure		10 - 15

Figure A-4. The Q Rock Mass Classification System classification charts (Palmstrom 2009).

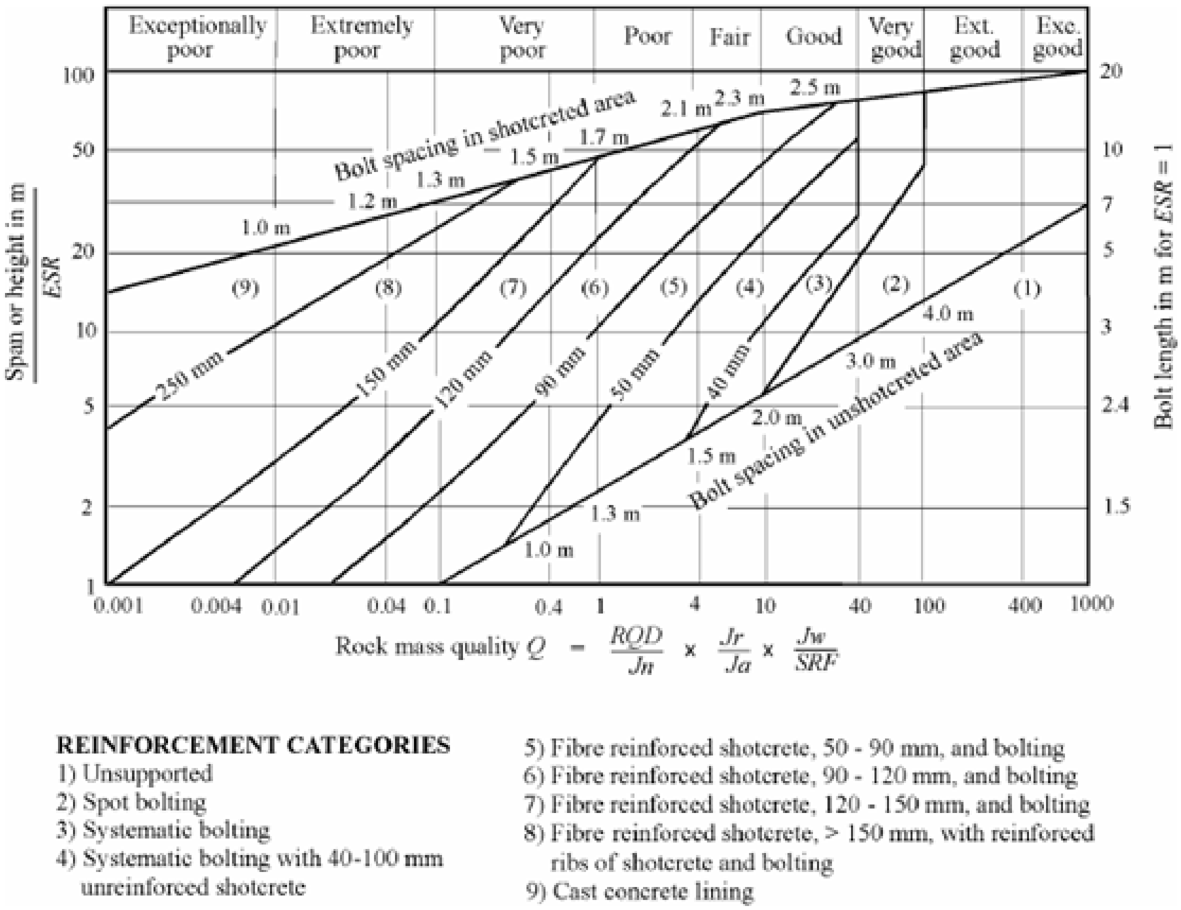

Figure A-5. Estimated support categories based on the Q index (Grimstad and Barton 1993).

Appendix B – Alternatives to Clay-Based Buffer/Backfill Materials

Thermal loading associated with larger, hotter DPC disposal packages could require long ventilation or surface decay storage durations to achieve temperature conditions (e.g., peak temperature, thermal gradients) that are compatible with the use of montmorillonite clay-based buffer or backfill materials. Montmorillonite clays are members of the smectite group which swell when hydrating. The montmorillonite clay buffer component of an engineered barrier system serves at least two purposes. Firstly, the expansive properties allow it to swell and fill voids that might occur as the EBS or the near-field host rock evolve or degrade. Swelling pressure exerted on the host rock causes closure of fractures, and extrusion of buffer material into fractures can plug ground water flow in the vicinity. The other principal function of the clay buffer is to retard the movement of radionuclides away from degrading waste packages, by imposing diffusion-dominated transport. Backfill and buffer materials proximal to waste packages must also conduct heat, which they do much more effectively when hydrated than dehydrated.

Smectite-based buffer materials do not transform and lose their beneficial properties at some threshold temperature (such as 100°C). Rather, as temperature increases they may be more prone to dissolve in the presence of moisture and re-precipitate silica and other product phases. This is partly due to thermally driven dissolution/precipitation reactions and prograde solubilities. In addition, the clay buffer will tend to hydrate inward from the outside exposed surface, while an inner region remains dehydrated. Hydrothermal activity involving hydrated and dehydrated regions may produce liquid-vapor counterflow, dissolution in the wetter region, and chemical precipitation in the drier region. The impetus for liquid flow is capillary or gravitational. As the waste package cools and hydration proceeds, the hydrothermally active region sweeps through the buffer toward the package surface, so the entire buffer could be affected. Possible impacts include loss of swelling pressure (as clays are depleted), decreased plasticity (from more rigid precipitates), and greater transmissibility to groundwater and radionuclides. The impacts may accumulate faster if the temperature in the hydrated region is above the local boiling point determined by the total pressure (a transient as the buffer hydrates). When hydration begins the boiling point is approximately 100°C, controlled by gas trapped in the buffer. As hydration proceeds the total pressure will increase, approaching hydrostatic, and the effective boiling temperature will increase as well.

One option to decrease decay storage or ventilation time by changing the buffer composition is to use an admixture such as graphite to increase its thermal conductivity (Jobmann and Buntebarth 2009). Graphite can increase the thermal conductivity of hydrated bentonite by a factor of 2 or more, even at concentrations as low as 5% w/w. This approach appears to have limited value because the maximum allowable temperatures in the buffer and host rock are the same, and the admixture may be expensive and is a direct tradeoff with additional decay storage. However, it could be used in a SNF management system where disposal is a high priority, to dispose of SNF for which decades or centuries of decay storage could be avoided, and where smectite alteration for hundreds of years at temperatures at or near 100°C is acceptable.

Another option is to redefine the buffer functions so that low permeability, but not swelling is needed to assure waste isolation performance. Other clays that do not possess the swelling attributes of smectites could be used for buffer material provided they retain low permeability after exposure to elevated temperature.

There are other natural, low-permeability, non-swelling materials that could be used. Lambe and Whitman (1969) include permeability data for a number of non-clay materials with permeability in the range of 10^{-16} m^2 to 10^{-14} m^2, including silts, silty sands, and loess. Standard mining practices deal with emplacement of such materials (i.e., stacking, slinging, auger feeds, pneumatic or slurry emplacement) and it appears likely that such methods could be adapted to emplace low permeability buffer or backfill materials.

Many underground mines contain pillars of ore left in place for structural support and for mine stability. The use of engineered backfill with predictable structural properties has allowed some of these valuable pillars to be recovered. Special processing, transport, and emplacement technologies have been developed for mine use. The simplest type of hydraulically placed backfill comprises partially classified tailings and water, often with added cement, that is transported through boreholes and steel pipes using centrifugal pumps or gravity flow, at slurry concentrations up to 75% by weight. While simplifying transport, the use of large amounts of slurry water can cause problems at the point of use. The fill must be dewatered after emplacement to consolidate, a process that tends to flush out the entrained fines and cement along with the excess water. Low water content paste backfills have been developed to reduce the problems associated with slurry, and can achieve greater strength with no excess water (Clark et al. 1995). Slurry or paste compositions could be engineered to chemically condition the disposal environment, mitigating corrosion of the waste package overpack or waste forms.

Sivakugan, et. al (2006) provide additional information about hydraulic fills and paste fills. Hydraulic fills typically comprise silty sands or sandy silts without a clay fraction (Table B-1). The clay fraction is removed through a process known as desliming, whereby the entire potential fill material is circulated through cyclones and the fine fraction removed and sent to a tailings pond. The remaining hydraulic fill fraction is recirculated in the form of slurry through pipelines to use underground. There has been a steady increase in the solid content of hydraulic fill slurry placed in mines in an attempt to reduce the quantity of excess water that must be drained. Solid contents of 75-80% are common, although even at 75% solid content, assuming a specific gravity of 3.0 for the solid grains, 50% of slurry volume is water. Therefore a substantial amount of water remains to be drained from hydraulically filled openings.

Paste fill also falls into the category of thickened tailings (Table B-1). In an application for low permeability buffer material, grinding and milling of rock excavated from the emplacement drifts could provide the source, or appropriate (and existing) materials such as fly ash could be imported from other sites. Paste fill comprises full mill tailings with a typical effective grain size of 5 µm, mixed with a small percentage of binder (about 3 to 6% w/w) and water. It is the densest form of backfill in the spectrum of thickened tailings used underground. A generic ‘‘rule of thumb’’ for the grain size distribution is a minimum of 15% of the material to be finer than 20 µm, so that the specific surface area is large enough to provide adequate surface tension to hold water to the solid particles and to provide a very thin, permanent lubricating film. Paste fill typically shows non-Newtonian-Bingham plastic flow characteristics, resulting in plug flow. As most of the early research performed on paste fills was on the transportation and deposition of the paste, the majority of the definitions of the paste are based on its rheological characteristics. Table 1 summarizes some common characteristics of the thickened tailings continuum. A significant difference to note is that the water content in paste fill is retained on placement, eliminating the need for drainage.

Research and development are needed to understand how paste fill and other thickened tailings, natural low-permeability non-swelling materials, and clay admixtures would perform when exposed to temperatures as high as 200°C in saturated and unsaturated disposal environments.

Table B-1. Material properties for thickened tailings continuum (after Sivakugan, et. al 2006).

Material Property	Slurry	Thickened tailings	Paste
Particle size	Coarse fraction only. No particles less than 20 µm. Segregation during transportation and or placement is dependent only on the coarse fraction	Some fines included (typically <15%). Fines tend to modify behavior from slurry, i.e. rheological characteristics more similar to paste. However, will segregate when brought to rest. Segregation during transportation and or placement depends only on the coarse fraction	Mostly fines; typically 15% (min) <20 µm
Pulp density (%)	60-72	70-78	78-82
Flow regimes and line velocities	Critical flow velocity: to maintain flow must have turbulent flow >2 m/sec average velocity or settling occurs. Newtonian flow	Critical flow velocity: to maintain flow must have turbulent flow >2 m/sec average velocity or partial settling occurs. Newtonian flow	No critical pipeline flow velocity, i.e. no settling in pipe. Laminar/plug flow
Yield stress	No minimum yield stress	No minimum yield stress	Minimum yield stress
Preparation	Cyclone	Cyclone end elutriation	Filter/centrifuge
Segregation in stope	Yes/high	Slight/partial	None
Drainage from Stope	Yes	Partial/limited	None/insignificant
Final density	Low	Medium/high	High
Supernatant water	High	Some	None
Post placement shrinkage	High	Insignificant	Insignificant
Permeability	Medium/low	Low	Very low