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COST ESTIMATION INPUTS FOR SPENT NUCLEAR FUEL GEOLOGIC DISPOSAL CONCEPTS

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ABSTRACT

A set of 16 geologic disposal concepts is described in sufficient detail for rough-order-of-magnitude repository cost estimates, for disposal of spent nuclear reactor fuel in generic crystalline, argillaceous, and salt host geologic media. The description includes total length, diameter, and volume for all underground shafts, ramps, drifts and large-diameter borings. Basic types of ground support are specified. Total repository capacity is assumed to be approximately 140,000 MT of spent fuel, but concepts are described in terms of modular panels each containing 10,000 MT.

Waste packaging is described, and the materials and outer dimensions for disposal overpacks are given. The manner of emplacement is specified, with any additional fixturing, lining, buffer materials, and backfill needed. Thermal limits for waste package emplacement or repository closure are given, as appropriate for enclosed and open emplacement modes, respectively. The 16 disposal concepts are based on disposal concept studies performed for the Used Fuel Disposition R&D program between 2011 and 2014, and the accompanying engineering analyses.

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ACRONYMS

BWR	Boiling Water Reactor
DPC	Dual-Purpose Canister
ISF	Interim Storage Facility
KBS-3	Swedish reference geologic disposal concept for spent nuclear fuel
MT	Metric Tons (as heavy metal, in reference to SNF)
MTU	Metric Tons Uranium
PWR	Pressurized Water Reactor
SNF	Spent Nuclear Fuel
WIPP	Waste Isolation Pilot Plant
YM	Yucca Mountain

INTRODUCTION

This report provides cost estimation detail for disposal of up to 140,000 MT (as heavy metal) of commercial spent nuclear fuel (SNF). The data cover a range of disposal concepts for three major categories of host geologic media (crystalline or hard rock, salt, and argillaceous) and four waste package sizes:

- Packages containing 4-, 12- or 21-PWR (pressurized water reactor) assemblies (or equivalent fuel from boiling water reactors, BWRs), and
- Dual-purpose canisters (DPCs) assumed to contain an average 32 assemblies each.

Table I-1 shows which combinations of disposal concepts and waste package sizes are described in this report, and which are not described because they have been technically unrealistic or infeasible based on previous studies.

The 16 disposal concepts from Table I-1 are categorized as “enclosed” or “open” depending on whether bulk engineered or natural materials (e.g., buffer material or crushed-rock backfill) are placed in significant contact with the waste packages at the time of emplacement. The distinction is most important for thermal analysis, which impacts the emplacement thermal power limits. The “open” emplacement modes also raise questions as to how backfill will be installed in open emplacement drifts at the time of repository closure.

The approach for specifying details of disposal concepts closely follows that used in a previous study (Hardin et al. 2012) and it is intended that cost estimates produced using this report would be directly comparable to the previous estimates for the same or similar disposal concepts.

One of the most important disposal cost drivers is the number of waste packages to be loaded, sealed, handled, transported, emplaced in the repository, and so on. Table I-2 shows the disposal concepts (1 through 16 from Table I-1) along with the number of waste packages needed to dispose of 140,000 MT as SNF. (The total disposal inventory comes from projections described by Hardin et al. 2014, Appendix C, as well as other authors.) The number of waste packages ranges from approximately 10,000 DPC-based packages, to more than 82,000 canisters containing four PWR assemblies or nine BWR assemblies.

The types of mined openings in a repository are divided into three types: access, emplacement, and service openings (Table I-3):

- Emplacement openings are those in which waste packages are emplaced, and will be drifts (for in-drift emplacement) or boreholes (e.g., for option 1, the crystalline “enclosed” concept similar to the Swedish KBS-3V concept). Concept 2 straddles the definition by emplacing waste packages in large diameter horizontal borings, with clay-based buffer. Concepts 3 through 16 use in-drift emplacement whereby waste packages are emplaced directly on the floor, possibly on a low pallet, or into a cavity excavated to promote heat transfer. For concepts 3 through 7, backfill is installed immediately at emplacement. Each of these is discussed further in Sections 1 through 16, and all are drawn from repository R&D in the U.S. and internationally (Hardin et al. 2012; 2013a,b).

- Access drifts are immediately before emplacement openings, facilitating repository construction and operation (e.g., ventilation, waste transport, emplacement).

- Service drifts are further upstream, and are central pathways for construction, waste handling, ventilation, emergency egress, and so on.

Spacings between waste packages in the same emplacement drift, and between adjacent parallel emplacement drifts (or access drifts in the case of concept 1), are important to dissipation of waste heat (Table I-4). The spacings assigned to all 16 concepts described here are based on previously documented thermal analysis (Hardin et al. 2012; 2013a,b). Other major aspects of repository underground construction are the lengths of different types of drifts (Table I-5), the numbers of shafts and ramps needed for a repository with capacity of 140,000 MT SNF (Table I-6), and construction details for shafts and ramps (Table I-7).

Table I-1. Disposal medium vs. waste package capacity matrix.

✓ Cost estimated previously		**4-PWR/9- or 12-BWR**	**12-PWR/ 24-BWR** [1]	**21-PWR/ 44-BWR**	**DPC Direct**
		"Enclosed"			
Crystalline	Based on KBS-3V (SKB 2011)	**✓ 1**	(Note 2)	(Note 3)	(Note 3)
Argillaceous	Based on ANDRA (2005) (for SNF in horiz. boreholes)	**✓ 2**	(Note 2)	(Note 3)	(Note 3)
	Based on NAGRA (2002, 2003) (for in-drift, self-shielded pkgs, with immediate backfilling)	(Note 4)	**3**	(Note 5)	(Note 5)
Salt	U.S. reference (in-drift)	**4**	**✓ 5**	**6**	**7**
		"Open"			
Hard Rock (e.g., Crystalline)	Unsaturated, unbackfilled, open (YM concept, DOE 2008a)	(Note 6)	**8**	**✓ 9**	**10**
	Saturated, backfilled, open	(Note 6)	**11**	**12**	**13**
Argillaceous	Backfilled, open	(Note 6)	**14**	**✓ 15**	**16**

Notes:

1. The BWR equivalent to 12-PWR assemblies could be 32, and because thermal limits in this report are based on instantaneous package power, the only impact of such a change would be on Appendix A which calculates decay storage time and repository throughput.
2. T_{peak}> 100°C; canister handling problematic for borehole emplacement.
3. T_{peak}>> 100°C; canister handling problematic.
4. Can assume cost would not be significantly different from the concept based on ANDRA (2005).
5. T_{peak}>> 100°C.
6. Open-mode ventilation not needed to meet thermal goals (use enclosed concepts above).

(Green) Cost estimated previously for a similar arrangement (Hardin et al. 2012).
(Yellow) Cost estimated previously for YM TSLCC analysis (DOE 2008b)

The remainder of this report is divided into sections for each of the 16 disposal concepts identified. As indicated in Table I-1, cost estimation has been performed previously for several of these (concepts 1, 2, 5, 9 and 15). The sections below call out major differences between the previous studies and the concepts described here, but while these may be significant departures in design, the impacts on overall cost are insignificant and may be safely neglected in estimates of rough-order-of-magnitude costs. Logistical simulations of repository throughput and duration of operation are described in Appendix A.

One departure from previous studies is that repository panels are defined here to have capacity for 10,000 MT, which is particularly helpful for estimating concepts that differ only with respect to waste package size (e.g., concepts 4 through 7). Other departures include some variations in shaft and ramp dimensions (Table I-3), repository spacings (Table I-4), drift lengths (Table I-5), numbers of shafts (Table I-6), and shaft and ramp dimensions (Table I-7) compared to values used previously (Hardin et al. 2012). These changes mostly describe larger openings, spacings to accommodate higher burnup SNF, and drift length changes needed for each concept to conform to 10,000 MT per panel.

Other assumptions made in formulating disposal concepts for cost estimation are: 1) commercial SNF arrives at the repository sealed (welded) in thin-walled stainless steel canisters incorporating a shield plug on one end and suitable for loading directly into disposal overpacks; 2) SNF canisters are received at the repository only when cool enough for emplacement, so aging is not a significant cost; and 3) repository surface and underground facilities are sized to accommodate maximum disposal throughput of 3,000 MT per year (except for DPCs as discussed for concepts 7, 10, 13 and 16).

Table I-2. Summary of waste package capacity, numbers, and materials.

#	Concept	Package Capacity (PWR/BWR)	140,000 MT Repository		Disposal Overpack Material
			Total Waste Packages	Annual Waste Packages [A]	
1.	**Crystalline (enclosed)**	4/9	82,583	1,667	Cu and/or low-alloy steel
2.	**Argillaceous (enclosed)**	4/9	82,583	1,667	Low-alloy steel
3.		12/21	28,792	556	
4.	**Salt (enclosed)**	4/9	82,583	1,667	Low-alloy steel
5.		12/21	28,792	556	
6.		21/44	16,157	318	
7.		DPC	~10,000	209 [B]	
8.	**Hard rock unsaturated (open)**	12/21	28,792	556	Corrosion resistant
9.		21/44	16,157	318	
10.		DPC	~10,000	209	
11.	**Hard rock saturated (open)**	12/21	28,792	556	Corrosion resistant
12.		21/44	16,157	318	
13.		DPC	~10,000	209	
14.	**Argillaceous (open)**	12/21	28,792	556	Corrosion resistant
15.		21/44	16,157	318	
16.		DPC	~10,000	209	

Notes:

A. Figures shown for 3,000 MT per year throughput.

B. Dual-purpose canister (DPC) values are based on average capacity of 32 PWR assemblies (or BWR equivalent).

Table I-3. Diameters for mined openings for access, disposal and service drifts.

#	Concept	Diameter (m)			Comment
		Access Drifts	Disposal Drifts/ Borings	Service Drifts	
1.	**Crystalline (enclosed, 4-PWR)**	6.5	1.6	6.5	Vertical borehole emplacement
2.	**Argillaceous (enclosed, 4-PWR)**	7.2	1.8	7.2	Horizontal boring emplacement
3.	**Argillaceous (enclosed, 12-PWR)**	7.2	4.5	7.2	In-drift emplacement
4.	**Salt (enclosed, 4-PWR)**	4H x 6W	4H x 6W	5H x 7.5W	Service drifts have 50% larger area
5.	**Salt (enclosed, 12-PWR)**	4H x 6W	4H x 6W	5H x 7.5W	
6.	**Salt (enclosed, 21-PWR)**	4H x 6W	4H x 6W	5H x 7.5W	
7.	**Salt (enclosed, DPC)**	4H x 6W	4H x 6W	5H x 7.5W	
8.	**Hard rock unsaturated (open, 12-PWR)**	8.0	5.5	8.0	8-m diameters for ventilation; 5.5 m or 6.5 m for drip shield clearance
9.	**Hard rock unsaturated (open, 21-PWR)**	8.0	5.5	8.0	
10.	**Hard rock unsaturated (open, DPC)**	8.0	6.5	8.0	
11.	**Hard rock saturated (open, 12-PWR)**	8.0	4.5	8.0	Use same layout as unsaturated case, but smaller (4.5 m) diameter for DPCs since no drip shields
12.	Hard rock saturated (open, 21-PWR)	8.0	4.5	8.0	
13.	Hard rock saturated (open, DPC)	8.0	4.5	8.0	
14.	Argillaceous (open, 12-PWR)	7.2	4.5	8.0	Use same layout as hard rock backfilled case
15.	Argillaceous (open, 21-PWR)	7.2	4.5	8.0	
16.	Argillaceous (open, DPC)	7.2	4.5	8.0	

Table I-4. Waste package and drift spacings for disposal concepts.

		Package Spacing (m)	Drift/Boring Spacing (m)	Comment
1.	**Crystalline (enclosed, 4-PWR)**	10	20	Access drift spacing is 20 m.
2.	**Argillaceous (enclosed, 4-PWR)**	10	30	
3.	**Argillaceous (enclosed, 12-PWR)**	10	60	
4.	**Salt (enclosed, 4-PWR)**	10	20	
5.	**Salt (enclosed, 12-PWR)**	20	25	
6.	**Salt (enclosed, 21-PWR)**	30	30	
7.	**Salt (enclosed, DPC)**	30	35	
8.	**Hard rock unsaturated (open, 12-PWR)**	5	81	12- and 21-PWR size packages are line-loaded under continuous drip shields
9.	**Hard rock unsaturated (open, 21-PWR)**	5	81	
10.	**Hard rock unsaturated (open, DPC)**	10	81	
11.	**Hard rock saturated (open, 12-PWR)**	10	81	Use same spacings as unsaturated concepts
12.	**Hard rock saturated (open, 21-PWR)**	10	81	
13.	**Hard rock saturated (open, DPC)**	20	81	
14.	**Argillaceous (open, 12-PWR)**	10	70	
15.	**Argillaceous (open, 21-PWR)**	10	70	
16.	**Argillaceous (open, DPC)**	20	70	

Table I-5. Access, disposal and service drift length and volume for disposal concepts.

#	Concept	Access Drifts [A]		Disposal Drifts/ Borings [A]		Service/ Ventilation Drifts [A]		Repository Total	
		Length (m)	Volume (m^3)	Length (m)	Volume (m^3)	Length (m)	Volume (m^3)	Length (m)	Volume (m^3)
1.	**Crystalline (enclosed, 4-PWR)**	7.8E5	2.6E7	6.2E5	1.3E6	2.3E5	7.7E6	1.6E6	3.5E7
2.	**Argillaceous (enclosed, 4-PWR)**	1.4E5	1.6E7	7.8E5	2.1E6	3.7E5	1.5E7	1.3E6	3.3E7
3.	**Argillaceous (enclosed, 12-PWR)**	3.9E5	1.6E7	2.9E5	4.6E6	3.7E5	1.5E7	1.1E6	3.6E7
4.	**Salt (enclosed, 4-PWR)**	5.6E4	1.3E6	8.5E5	2.0E7	4.2E4	1.5E6	9.5E5	2.3E7
5.	**Salt (enclosed, 12-PWR)**	5.6E4	1.3E6	6.0E5	1.4E7	4.2E4	1.5E6	7.0E5	1.7E7
6.	**Salt (enclosed, 21-PWR)**	5.6E4	1.3E6	3.4E5	8.2E6	4.2E4	1.5E6	4.4E5	1.1E7
7.	**Salt (enclosed, DPC)**	5.6E4	1.3E6	3.0E5	7.2E6	4.2E4	1.5E6	4.0E5	1.0E7
8.	**Hard rock unsaturated (open, 12-PWR)**	8.0E3	4.0E5	1.7E5	4.0E6	8.0E3	4.0E5	1.9E5	5.0E6
9.	**Hard rock unsaturated (open, 21-PWR)**	8.0E3	4.0E5	9.7E4	2.3E6	8.0E3	4.0E5	1.1E5	3.1E6
10.	**Hard rock unsaturated (open, DPC)**	8.0E3	4.0E5	1.2E5	4.0E6	8.0E3	4.0E5	1.4E5	5.0E6
11.	**Hard rock saturated (open, 12-PWR)**	8.0E3	4.0E5	1.7E5	4.0E6	8.0E3	4.0E5	1.9E5	5.0E6
12.	**Hard rock saturated (open, 21-PWR)**	8.0E3	4.0E5	9.7E4	2.3E6	8.0E3	4.0E5	1.1E5	3.1E6
13.	**Hard rock saturated (open, DPC)**	8.0E3	4.0E5	1.2E5	2.8E6	8.0E3	4.0E5	1.4E5	3.6E6
14.	**Argillaceous (open, 12-PWR)**	8.5E4	3.5E6	3.5E5	5.6E6	5.8E4	2.4E6	4.9E5	1.2E7
15.	**Argillaceous (open, 21-PWR)**	8.5E4	3.5E6	3.9E5	6.2E6	5.8E4	2.4E6	5.3E5	1.2E7
16.	**Argillaceous (open, DPC)**	8.5E4	3.5E6	3.6E5	5.7E6	5.8E4	2.4E6	5.0E5	1.2E7

Notes:

A. Access, emplacement and service drift estimates include a 10 to 20% contingency to account for unsuitable ground conditions and inefficiencies in the layout of successive panels.

Table I-6. Numbers of shafts and ramps for disposal concepts.

#	Concept	Ventilation Intake	Waste Rock	Ventilation Exhaust	Waste Transport	
					Shaft	Ramp (5 km)
1.	**Crystalline (enclosed, 4-PWR)**	1	1	2	1	0
2.	**Argillaceous (enclosed, 4-PWR)**	1	1	2	1	0
3.	**Argillaceous (enclosed, 12-PWR)**	1	1	2	1	0
4.	**Salt (enclosed, 4-PWR)**	1	1	2	1	0
5.	**Salt (enclosed, 12-PWR)**	1	1	2	1	0
6.	**Salt (enclosed, 21-PWR)**	1	1	2	1	0
7.	**Salt (enclosed, DPC)**	1	1	2	1	0
8.	**Hard rock unsaturated (open, 12-PWR)**	10 [A]	1	5 [A]	1 [B]	0
9.	**Hard rock unsaturated (open, 21-PWR)**	10 [A]	1	5 [A]	0	1
10.	**Hard rock unsaturated (open, DPC)**	10 [A]	1	5 [A]	0	1
11.	**Hard rock saturated (open, 12-PWR)**	10 [A]	1	5 [A]	1 [B]	0
12.	**Hard rock saturated (open, 21-PWR)**	10 [A]	1	5 [A]	0	1
13.	**Hard rock saturated (open, DPC)**	10 [A]	1	5 [A]	0	1
14.	**Argillaceous (open, 12-PWR)**	10 [A]	1	5 [A]	1 [B]	0
15.	**Argillaceous (open, 21-PWR)**	10 [A]	1	5 [A]	0	1
16.	**Argillaceous (open, DPC)**	10 [A]	1	5 [A]	0	1

Notes:

A. Based on the sedimentary backfilled open concept estimated previously for disposal of 140,000 MT spent fuel in 21-PWR size packages (Hardin et al. 2012).

B. Based on availability of a friction-winder shaft hoist with 85 MT or greater capacity.

Table I-7. Shaft and ramp details for disposal concepts.

Shaft/Ramp Type	Construction Type	Ground Support	Finished Diameter (m) [A]
Ventilation Intake and Men-and-Materials	Raise bore or drill-and-blast	Cast in place concrete (non-reinforced)	5.5
Ventilation Exhaust	Drill-and-blast	Cast in place concrete (non-reinforced)	8
Waste Rock Removal	Raise bore	Cast in place concrete (non-reinforced)	5.5
Waste Emplacement and Men-and-Materials	Drill-and-blast	Cast in place concrete (non-reinforced)	8
Waste Emplacement	10% ramp, mechanized excavator	Shotcrete, with rock bolts and/or steel sets and lagging as needed. Ramp floors are reinforced concrete approximately 4.5 m wide	6.5

Notes:

A. Modified from Table 4.7-2 of Hardin et al. (2012).

1. CRYSTALLINE MEDIA, ENCLOSED, 4-PWR SIZE PACKAGES, VERTICAL BOREHOLE EMPLACEMENT WITH BUFFER (KBS-3)

The following information is from a previous summary report on thermal load management and design concepts, for the Used Fuel Disposition R&D campaign (Hardin et al. 2012).

Waste Packaging: SNF is delivered to the repository sealed in 4-PWR size stainless steel canisters, with 20-cm shield lids. Waste packages consist of inserts made from cast iron or fabricated from low-alloy steel, sealed into thin-walled stainless steel canisters, which are then fitted at the repository into overpacks of copper and/or steel. The reference overpack option is a thin (2.5 cm) layer of copper electrodeposited or cold-sprayed over 4 cm of low-alloy steel, for a total wall thickness of 6.5 cm. This arrangement provides approximately twice the Cu corrosion allowance calculated for Canada's Nuclear Waste Management Organization (Keech et al. 2014). An alternative is to replace the copper with a similar thickness of stainless steel, or additional low-alloy steel. This is a departure from previous descriptions of several centimeters of copper (Hardin et al. 2012) and reflects the increasing cost of copper, and trends in repository R&D toward using less copper (SKB 2011) or only steel (NAGRA 2002; 2003). Overall package dimensions are 0.82 m outer diameter and 5.0 m length.

Emplacement: Packages are emplaced in vertical borings with 1.6 m diameter and 8 m depth, which are drilled 10 m apart along the access drifts. Emplacement borings are lined with blocks of compacted, swelling clay (13.4 m^3 per emplacement). Whereas European programs have been investigating local clay materials, Wyoming bentonite is a good choice for use in US repositories because of its availability and properties (Caparuscio et al. 2013). These access drifts and all other openings in the repository are emptied of concrete, shotcrete and utilities at closure, and backfilled with a mixture of 70% sand and 30% bentonite. The emplacement thermal power limit, by analogy to the Swedish KBS-3 concept, is 1,700 W per package.

Layout: A single repository panel containing 10,000 MT in 4-PWR size waste packages would require 56 km of access drifts. With drift spacing of 20 m (Table 1-1) the panel area is approximately 1.1 km^2. Each panel is encircled by service drifts. The overall repository has 14 such panels arranged around the five shafts, giving a total repository area of approximately 16 km^2 for 140,000 MT capacity.

Table 1-1. Summary of waste packaging and emplacement details for disposal of 4-PWR size packages in a KBS-3 type repository in crystalline rock.

Media/Concept	Mined Crystalline
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rockbolts, wire cloth & shotcrete
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Vertical emplacement boreholes in floor
WP capacity	4-PWR/9-BWR
Overpack material	Copper and/or steel
Package dimensions	0.82 m D x 5.0 m L
Overpack total wall thickness	6.5 cm
Emplacement borehole diameter/length	1.6 m/8 m
Spacings (plan view)	20 m (drifts); 10 m (borings)
Borehole liner material	NA
Buffer material	Bentonite
Access/service drift backfill material	Crushed host rock mixed with 30% granular bentonite
Line or point loading	Point
Emplacement power limit	1,700 W

2. ARGILLACEOUS MEDIA, ENCLOSED, 4-PWR SIZE PACKAGES, HORIZONTAL BOREHOLE EMPLACEMENT WITH BUFFER

The following information is similar to that presented in a previous summary report on thermal load management and design concepts, for the Used Fuel Disposition R&D campaign (Hardin et al. 2012).

Waste Packaging: SNF is delivered to the repository sealed in 4-PWR size stainless steel canisters, with 20-cm shield lids. Disposal overpacks are made from low-alloy steel, with wall thickness of 5 cm, and a single welded closure. (The fuel canister provides additional thickness and at least one additional welded closure.)

Emplacement: Packages are emplaced in horizontal borings 1.82 m in diameter and approximately 100 m deep, which are drilled from access drifts and are 30 m apart. Emplacement borings are configured with a thin steel outer liner (1.8 m diameter) to stabilize the borehole, and a thin steel inner liner (0.84 m diameter) to accommodate waste packages. The space between the liners is filled with blocks of compacted bentonite. Each borehole is preconstructed in this way before waste packages are emplaced. Packages are slid into place using jacks or robot pushers, and alternated with cylindrical plugs of compacted bentonite. A shield plug is inserted at the collar of each boring. Finally, at repository (or panel) closure each access drift is filled with an engineered material consisting of 70% conditioned, crushed host rock and 30% granular bentonite. This concept is similar to a spent fuel disposal concept proposed for the French repository (ANDRA 2005).

The emplacement thermal power limit is 1,700 W, by analogy to the Swedish KBS-3 concept that uses similar package size, buffer properties, and geometry. The argillaceous host rock thermal conductivity could be significantly less than typical crystalline rock (e.g., 1.75 W/m-K compared to 2.5 W/m-K or greater). Thus, the emplacement borehole wall temperature will be a few degrees greater compared to the crystalline concept (Section 1), and the buffer and package temperatures will be greater by the same amount. The buffer peak temperature limit controls emplacement power for fuel emplacement at 100 yr age (and not the host rock temperature) so the host rock peak temperature will be less than 100°C for fuel as young as 100 yr out-of-reactor. However, the buffer peak temperature could exceed 100°C near the waste package, for higher burnup or younger fuel. The effects from buffer peak temperature greater than 100°C are currently under study. If found to be unacceptable, the fuel can be aged longer (e.g., higher burnup fuel age of at least 150 yr from discharge, at emplacement) or graphite or other admixtures can be added to the buffer blocks to increase thermal conductivity.

Layout: A repository panel containing 10,000 MT in 4-PWR size waste packages contains approximately 5,600 packages and requires nine parallel access drifts, each 1 km long. Smaller, parallel horizontal borings, 100 m deep, come off the access drifts on both sides, spaced 30 m apart. The nine parallel access drifts can be spaced approximately 230 m apart, so that the panel area is approximately 2 km^2. Each panel is encircled by service drifts. A total of 14 such panels are needed, giving a total repository plan area of 30 km^2 for capacity of 140,000 MT. Specific information is summarized in Table 2-1.

Table 2-1. Summary of waste packaging and emplacement details for enclosed, horizontal borehole emplacement of 4-PWR size packages in argillaceous media.

Media/Concept	Mined Argillaceous
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, steel sets & shotcrete
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	4-PWR (or BWR equiv.)
Overpack material	Steel
Package dimensions	0.82 m D x 5.0 m L
Overpack total wall thickness	5 cm
Drift/borehole dia.	1.82 m (drift center-center)
Spacings (plan view)	30 m (drifts), 10 m (packages; center-center)
Borehole liner material	Steel (inner 0.84 m OD, and outer 1.80 m OD, each with welded construction and nominal 8 mm wall thickness)
Buffer material	Compacted, dehydrated bentonite
Backfill material	Crushed host rock mixed with 30% bentonite
Line or point loading	Point
Emplacement power limit	1,700 W

3. ARGILLACEOUS MEDIA, 12-PWR SIZE, SELF-SHIELDED PACKAGES, IN-DRIFT EMPLACEMENT WITH CLAY BACKFILL

Waste Packaging: This alternative allows emplacement of 12-PWR size packages with sufficient decay storage, but can involve host rock peak temperature on the order of 150°C, and backfill peak temperature approaching 200°C. SNF is delivered to the repository sealed in 12-PWR size stainless steel canisters with nominal 2-cm wall thickness and 20-cm shield lids (Table 3-1). Disposal overpacks consist of 15 cm of low-alloy steel, with penetrating welds. Waste packages weigh approximately 45 MT, with nominal 1.37 m outer diameter and 5.2 m length. These dimensions are similar to the 12-PWR package for the salt concept (Table 4-1) but surrounded with an additional 10 cm of steel (a total of 25 MT of steel are needed for each overpack, compared to 8 MT for the salt package). A total of 28,792 waste packages are needed for the full projected inventory of commercial SNF. The shielding provided by 15 cm of overpack steel plus the canister, will be adequate for personnel protection if additional operator shielding is provided during emplacement and backfilling, and/or the fuel is aged sufficiently before emplacement.

Emplacement: This concept is similar to the in-drift concept for spent fuel disposal in Opalinus Clay (NAGRA 2002; 2003), but is implemented with larger, 12-PWR size waste packages. Excavated drift diameter is 4.5 m, which accommodates not only waste emplacement but ground support and equipment used for excavation, ground support construction, and backfilling. This drift diameter is similar to the argillaceous open concepts (Sections 14, 15 and 16). Waste packages are emplaced on plinth structures made from dehydrated, compacted bentonite reinforced with steel. As each package is emplaced, it is backfilled with a graded mixture of dehydrated bentonite particles having dry bulk density of 1.3 Mg/m^3 (compared with up to 1.9 Mg/m^3 for bentonite blocks). The result is low permeability ($<10^{-19}$ m^2) but swelling pressure less than what can be achieved in a buffer of compacted blocks (e.g., 1 MPa vs. 6 MPa).

Thermal conductivity is also lower for pelletized mixtures in the initial dehydrated state (~0.3 W/m-K) than for compacted block (~0.6 W/m-K). After hydration thermal conductivity for both is on the order of 1.3 W/m-K, but this does not occur for decades after the thermal peak (compare rehydration timing, Hardin et al. 2014, Section 6, with peak temperatures in Hardin et al. 2013a, Table 3-10). For this concept spent fuel is aged 100 to 200 years (depending on burnup) and peak temperature of the host rock is approximately 150°C (Hardin et al. 2012, Figure 3.1-9 and Table 3.1-1) while peak backfill temperature is on the order of 200°C. For higher burnup fuel (>45 GW-d/MT) additional measures such as backfill admixtures (e.g., 10% graphite), controlled partial backfill hydration after emplacement, or longer surface decay storage are used to further limit backfill temperature.

Service drifts in the argillaceous host rock are constructed for long lifetime (100 to 200 years), with steel and concrete liners. Emplacement drifts have much less ground support because they are quickly loaded and backfilled. A heavy, deformable liner system (e.g., 50 cm pre-cast steel fiber-reinforced segmented liner, backfilled by compliant grout) is used for service drifts, while rockbolts and 15 to 30 cm of shotcrete suffice for emplacement drifts that are open for a year or less. Use of cementitious materials dictates that clay materials perform their isolation functions after exposure to cement leachate, in the host rock environment.

Layout: Spacings are sufficient to produce a region of backfill and host rock around each package in which peak temperatures exceed 100°C, surrounded by a much larger region where peak temperature is less than 100°C. Waste packages are 20 m apart, and drift spacing is 30 m (Table 3-1). Emplacement drifts 1 km long can accommodate 50 waste packages, and a panel of 45 drifts can accommodate 10,000 MT (with 20% contingency), for a total panel area of approximately 1.4 km^2. A total of 14 such panels are needed, giving a total repository plan area of 20 km^2 for capacity of 140,000 MT. Each panel is encircled by service drifts. Specific information is summarized in Table 3-1.

Table 3-1. Summary of waste packaging and emplacement details for enclosed, in-drift emplacement of self-shielding 12-PWR size packages in argillaceous media.

Media/Concept	Mined Argillaceous
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, steel sets & shotcrete
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	12-PWR (or BWR equiv.)
Overpack material	Steel
Package dimensions	1.02 m D x 5.0 m L
Overpack total wall thickness	15 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	30 m (drifts), 20 m (packages; center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Granular and compacted bentonite
Line or point loading	Point
Emplacement power limit	1,700 W

4. SALT, 4-PWR SIZE, IN-DRIFT EMPLACEMENT

Waste Packaging: SNF is delivered to the repository sealed in 4-PWR size stainless steel canisters, with 20-cm shield lids. Disposal overpacks consist of 5 cm of carbon steel, with outer diameter of 0.82 m and length of 5 m, and loaded weight of approximately 13 MT (Table 4-1). The overpacks would have penetrating welds, and surface stress relief of heat-affected zones (burnishing or peening). These measures are taken because stress corrosion cracking has been identified as a possibility for carbon steel in brine environments. A total of 82,583 waste packages would be needed for the full projected inventory of commercial SNF of 140,000 MT.

Emplacement: Packages are unshielded, and they are placed directly on the drift (salt) floor, aligned axially. This alignment facilitates emplacement such that the transporter can straddle the waste package and simply lower it onto the floor then drive off. Also, drift width can be less and longer packages can be accommodated without widening (which is the case for alcoves). Drift width is nominally 6 m, height 4 m (Table 4-2). The width allows some flexibility in transporter design, while the height (which is minimized) allows smaller excavation equipment, reduces excavated volume and backfill handling, and facilitates stratigraphic placement in bedded salt. Ground support is minimal, with roof bolts used only where needed to stabilize openings for approximately 1 year until they are loaded and backfilled. Thus, drifts are excavated "just in time" and the excavated "mine-run"salt is used to backfill a previously mined drift as it is being loaded. Backfilling is done using a remotely controlled machine with multiple augers each approximately 8 m long, to force backfill up to the crown and provide some initial compaction (like the machine developed for Mont Terri). A storage area for crushed salt, with capacity to hold enough crushed salt to backfill one emplacement drift, would be mined underground for each panel.

Layout: Emplacement drifts are parallel (20 m apart) and nominally 1 km in length. A panel consists of 50 drifts, and therefore is approximately square in plan view. A 4-km perimeter service/access/ventilation drift is first mined, and ventilation is set up across the panel. Waste packages are spaced at approximately 10 m on centers. This is controlled mainly by the need for shielding by crushed salt backfill as each package is emplaced, with a 30° angle of repose. (At 36% porosity, with minimum cover of 2.25 m, and intact salt density of 2.1 Mg/m^3, this gives a density-thickness product greater than or equal to 0.15 m of lead.)

Finite-element calculations show that peak salt temperatures meet the target limit (200°C) with substantial margin if the average areal power loading at emplacement is limited to approx. 11 W/m^2 (analyzed for bedded Permian salt). Calculations with 20 m x 20 m spacings produce peak temperatures on the order of 150°C for 4-PWR packages and fuel age of 10 years or less (Hardin et al. 2012, App. D). For the 20 × 10 m spacings described here, package power would be limited to 2,200 W at emplacement, which would require approx. 50 years aging for high-burnup fuel (60 GWd/MT). Similar analysis is used to determine spacings for larger packages (Table 4-1). Note that high-burnup fuel could be emplaced sooner by increasing package spacing.

Other repository details are provided in the salt reference concept description (Hardin et al. 2012; although that concept uses herring-bone alcoves, it was evaluated for 4-PWR size packages in addition to 12-PWR ones, and the shafts and other infrastructure needed would be the same here). Differences would be limited to the mine-plan, the transporter design, and the shaft hoist capacity. Packages at 4-PWR size weighing 13 MT (Table 4-1) with heavy shielding would require a hoist similar to the waste shaft at WIPP, with ~40 MT capacity.

Table 4-1. SNF package size, emplacement power limits, and repository spacings for salt repositories

Areal power loading limit: 11 W/m^2 Drift dimensions: 6 m W x 4 m H								
#	**Package Capacity (PWR assemblies)**	**Emplacement Power Limit (kW)**	**Time to Emplace-ment (yr)**	**Center-Center Drift Spacing (m)**	**Center-Center Package Spacing (m)**	**Package OD (m)**	**Loaded Canister Weight (kg)**	**Total Pkg. Weight (kg)**
4.	4	2.2	<10	20	10	0.82	7,000	13,000
5.	12	5.5	40	25	20	1.17	20,000	28,000
6.	21	10.0	70	30	30	1.53	33,000	45,000
7.	32 (DPC)	11.5	70 [A]	35	30	1.9	50,000	65,000
Note: [A] Using semi-cylindrical cavities in the floor to receive waste packages (Hardin et al. 2013b).								

Table 4-2. Summary of waste packaging and emplacement details for enclosed, in-drift emplacement of 4-PWR size packages in salt.

Media/Concept	Mined Salt
Repository depth	~500 m
Hydrologic setting	Nominally saturated
Ground support material	Minimal (bolts and wire cloth)
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	4-PWR (or BWR equiv.)
Overpack material	Steel
Package dimensions	0.82 m D x 5.0 m L
Overpack total wall thickness	5 cm
Emplacement drift diameter	4 m H x 6 m W
Spacings (plan view)	20 m (drifts); 10 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Crushed “mine-run” salt
Line or point loading	Point

5. SALT, 12-PWR SIZE, IN-DRIFT EMPLACEMENT

Waste Packaging: SNF is delivered to the repository sealed in 12-PWR size stainless steel canisters, with 20-cm shield lids. Packages are as described in the salt reference concept (Hardin et al. 2012; overpack outer diameter 1.17 m, wall thickness 5 cm). They weigh approximately 28 MT (Table 4-1). A total of 28,792 waste packages are needed for the full projected inventory of commercial SNF.

Emplacement: In-drift emplacement is used instead of alcoves recommended in previous studies.

Layout: Package spacing is increased to 20 m, with drift spacing of 25 m (Table 5-1) for an emplacement power limit of approx. 5,500 W (11 W/m^2). A repository panel consists of drifts spaced 25 m apart, so the panel size is approximately 1 km x 1 km for 10,000 MT of SNF. The shaft hoist capacity could be met by the 85 MT hoist designed by DBE TEC GmbH (Hardin et al. 2013a). Waste packages at 12-PWR size with heavy shielding could be accommodated by a shaft hoist with 85 MT capacity (Hardin et al. 2012, 2013a).

Table 5-1. Summary of waste packaging and emplacement details for enclosed, in-drift emplacement of 12-PWR size packages in salt.

Media/Concept	Mined Salt
Repository depth	~500 m
Hydrologic setting	Nominally saturated
Ground support material	Minimal (bolts and wire cloth)
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	12-PWR (or BWR equiv.)
Overpack material	Steel
Package dimensions	1.17 m D x 5.0 m L
Overpack total wall thickness	5 cm
Emplacement drift diameter	4 m H x 6 m W
Spacings (plan view)	25 m (drifts); 20 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Crushed “mine-run” salt
Line or point loading	Point

6. SALT, 21-PWR SIZE, IN-DRIFT EMPLACEMENT

Waste Packaging: SNF is delivered to the repository sealed in 21-PWR size stainless steel canisters, with 20-cm shield lids. Waste package outer diameter is 1.53 m (Hardin et al. 2012, Table 1.4-1), length 5 m, and weight approx. 45 MT (Table 4-1). A total of 16,157 waste packages would be needed for the full projected inventory of commercial SNF.

Emplacement: For comparison to other options described here, in-drift axial emplacement is used instead of the herring-bone alcoves recommended in previous studies.

Layout: The mine plan is similar to that described above, except that package spacing is increased to 30 m, and drift spacing to 30 m (Table 6-1). This allows packages with power output up to 10 kW (11 W/m^2). A repository panel is approximately 1 km x 1 km, accommodating ~10,000 MT of SNF, but with only 33 parallel emplacement drifts. The shaft hoist capacity could be met by the 85 MT hoist designed by DBE Tec GmbH (Hardin et al. 2013a). The shielding provided by both the waste package and a separate shield for transport underground, would total approx. 0.2 m of steel (less shielding could be used if needed to meet a shaft hoist payload capacity limit of 85 MT).

Table 6-1. Summary of waste packaging and emplacement details for enclosed, in-drift emplacement of 21-PWR size packages in salt.

Media/Concept	Mined Salt
Repository depth	~500 m
Hydrologic setting	Nominally saturated
Ground support material	Minimal (bolts and wire cloth)
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	21-PWR (or BWR equiv.)
Overpack material	Steel
Package dimensions	1.53 m D x 5.0 m L
Overpack total wall thickness	5 cm
Emplacement drift diameter	4 m H x 6 m W
Spacings (plan view)	30 m (drifts); 30 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Crushed “mine-run” salt
Line or point loading	Point

7. SALT, DPC DIRECT DISPOSAL, IN-DRIFT EMPLACEMENT

Waste Packaging: SNF is delivered to the repository sealed in stainless steel DPCs with nominal 32-PWR size, and shield lids equivalent to at least 20 cm of steel. Waste package outer diameter is 1.9 m, length 5 m, and weight approx. 65 MT (Table 4-1). Approximately 10,000 waste packages (average capacity 32-PWR assemblies or BWR equivalent) for the full projected inventory of 140,000 MT of commercial SNF.

Emplacement: For comparison to other options described here, in-drift axial emplacement is used instead of the herring-bone alcoves recommended in previous studies. For higher-burnup fuel (greater than 45 GW-d/MT) lower temperatures are achieved by milling semi-cylindrical cavities in the floor to improve heat transfer (Hardin et al. 2013b).

Layout: The layout is similar to the 21-PWR layout but with 35 m drift spacing, and 30 m package spacing (Table 7-1). At 11 W/m^2 the emplacement package power limit is 11.5 kW. Some calculations suggest that this would exceed the peak salt temperature limit of 200°C (Hardin et al. 2012, App. D). However, heat output from higher-burnup fuel is managed by milling cavities in the floor as noted above, and by allowing the crushed salt backfill temperature to exceed 200°C where it contacts the waste package (decrepitation there is not important since the salt is already crushed). High-burnup SNF (up to 60 GW-d/MT), in DPCs containing 32 PWR assemblies, is aged at least 75 years before emplacement. Previous studies (Hardin et al. 2013b; 2014) showed that this would extend DPC loading in a salt repository to a duration of approx. 80 years (maximum acceptance rate would be ~1,700 MT/yr). Waste packages large enough to contain DPCs, with heavy shielding for transport underground, would require a shaft hoist with approximately 175 MT capacity (Hardin et al. 2013a).

Table 7-1. Summary of waste packaging and emplacement details for enclosed, in-drift emplacement of DPC-based packages in salt.

Media/Concept	Mined Salt
Repository depth	~500 m
Hydrologic setting	Nominally saturated
Ground support material	Minimal (bolts and wire cloth)
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	32-PWR (or BWR equiv.)
Overpack material	Steel
Package dimensions	2.0 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	4 m H x 6 m W
Spacings (plan view)	35 m (drifts); 30 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Crushed “mine-run” salt
Line or point loading	Point

8. HARD ROCK, 12-PWR SIZE, UNSATURATED, UNBACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in 12-PWR size stainless steel canisters, with 20-cm shield lids. Disposal overpacks are corrosion resistant, consisting of an inner layer (3 cm) of 316 SS, and an outer layer (2 cm) of more corrosion resistant material (e.g., Alloy 22) for a total thickness of 5 cm (Table 8-1). Weld-affected zones in the outer layer are surface treated to inhibit stress corrosion (burnishing or peening).

Emplacement: This generic concept is similar to the Yucca Mountain concept, but with simplifications. It can be implemented in any unsaturated, hard-rock formation with reasonably low recharge flux. Drifts are ventilated for 50 to 100 years after emplacement and before closure. Fuel age at closure is therefore at least 60 years, and up to 110 years, or longer if stored longer at the surface before emplacement. Thermal power limits are defined at repository closure rather than emplacement.

Packages are set on pallets of minimal height, and robust construction from 316 SS. At closure, packages are covered by corrosion resistant drip shield structures (e.g., of titanium with nominal plate thickness 1.5 cm and total weight of 2,500 kg). The functions of the drip shields are to protect the waste packages from damage during seismic ground motion and/or rockfall events, and to prevent or limit groundwater contact.

Active ventilation prior to closure removes up to 85% of waste heat, so preclosure temperatures never approach the 200°C limit adopted for hard rock, or SNF cladding temperature limits (e.g., 350°C for long-term exposure). Packages are loaded end-to-end (line loading), and the power limit at closure is expressed as an average line load, with accepted deviation of individual packages around that average. This document uses the average line load and the hottest package at closure in the proposed Yucca Mountain (YM) repository (about 800 W/m and 7 kW, respectively; SNL 2008).

With high-burnup SNF (60 GWd/MT) at 800 W/m line loading, fuel age is approximately 75 years at closure (power output for a 12-PWR package is approx. 4 kW). For 12-PWR size packages, this result scales on fuel mass to the 7 kW maximum closure power output for 21-PWR packages (Section 9), and is therefore adopted as the maximum closure power limit. This condition lies within the limits for thermal loading in the proposed Yucca Mountain (YM) repository (SNL 2008). Where necessary, additional aging or longer repository ventilation time are options to achieve cooler conditions.

Layout: Drift spacing is similar to the Yucca Mountain concept (81 m, based on host rock thermal conductivity, moisture flux, hydrologic properties, and other factors). Emplacement drifts are approximately 600 m long (Table 8-2) so that approximately 100 packages can be emplaced per drift. A repository panel consists of 19 drifts with capacity for 10,000 MT SNF (with 20% contingency). The panel size is 0.6 x 1.6 km (or roughly the same panel area as the salt disposal concepts).

The drift diameter is 5.5 m, and ground support consists of swelling type rockbolts of 316 SS, 3 m long (5 bolts per meter of drift). The bolts support stainless wire cloth of heavy gauge, to limit rockfall during preclosure operations. (The stainless Berthold sheets in the YM design are not needed without rail conveyance.) The invert consists of compacted, crushed-rock ballast suitable for running multiple-tire transporters. Electric power for the transporters is provided by dual conductor bars or pantographs (for both power and ground). The drip shields are installed with overlapping joints, and during installation they are hoisted and conveyed above the intervening waste packages by a gantry (the drip shields are wider than the packages, so that overhead clearance above the waste packages, required for drip shield installation, is less than approx. 1.5 m.

Access to the repository is by ramp suitable for rubber-tire equipment (reinforced concrete floor; nominal grade 7.5%). Shaft requirements and other infrastructure are similar to the Shale Unbackfilled reference concept (Hardin et al. 2012, Table 4.7). Shafts are used for ventilation intake/exhaust, men/materials, and emergency egress. Forced ventilation during preclosure operations is approximately 15 m^3/sec per drift. Temperatures during ventilation range between 60 and 90°C depending on time and location. Ventilation air is routed through intake and exhaust shafts to the surface. Drift length is shortened to 600 m (plus the TBM turnout length) to facilitate ventilation (less heat to remove from each drift) and drip shield emplacement (limiting the distance for remote operations).

Table 8-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of 12-PWR size packages in unsaturated hard rock.

Media/Concept	Hard Rock, Unsaturated, Unbackfilled
Repository depth	~500 m
Hydrologic setting	Unsaturated
Ground support material	Rock bolts, wire cloth and shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	12-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.17 m D x 5.0 m L
Overpack total wall thickness	5 cm
Emplacement drift diameter	5.5 m
Spacings (plan view)	81 m (drifts); 5 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	NA
Line or point loading	Line

Table 8-2. Repository emplacement drift and waste package package dimensions and emplacement power limits for hard-rock unsaturated, unbackfilled (open-mode) repositories.

Line loading power limit at closure: 0.8 kW/m

#	Package Size (PWR assemblies)	Emplacement Power Limit (kW)	Closure Power Limit (kW)	Time to Closure (yr) [D]	Drift Dia. (m)	Center-Center Drift Spacing (m)	Center-Center Pkg. Spacing, Nominal (m)	Pkg. OD (m)	Loaded Canister Weight (kg)	Total Pkg. Weight (kg)
8.	12 [A]	10	4	75	5.5	81	5	1.17	20,000	28,000
9.	21 [B]	18	7	75	5.5	81	5	1.57	33,000	50,000
10.	32 (DPC) [C]	18	7	100	6.5	81	10	1.94	50,000	70,000

Notes:

A. Emplacement and closure power limits are scaled to 21-PWR concept. Higher limits may be possible with extended aging or ventilation.

B. Similar to YM thermal analyses which showed that rock wall (200°C) and cladding temperature (350°C) limits would be met (SNL 2008).

C. Based on the 21-PWR concept. The DPC case with a 5.5-m diameter drift and 150-year fuel age at closure was analyzed by Hardin et al. (2013, Section 4.6.1).

D. Approximate years since reactor discharge, based on high-burnup (60 GW-d/MT).

9. HARD ROCK, 21-PWR SIZE, UNSATURATED, UNBACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in 21-PWR size stainless steel canisters, with 20-cm shield lids. The disposal overpack inner SS layer thickness is increased (for structural strength) to 5 cm (see Table 9-1 for other dimensions) giving a total overpack thickness of 7 cm.

Emplacement: The in-drift, ventilated emplacement concept, ground support, and invert are the same as described in Section 8. Drip shields are larger and heavier, with total weight of 3,000 kg each.

Layout: The same repository dimensions pertain as discussed above (Table 9-1; 5.5-m diameter emplacement drifts, 81-m drift spacing, 600-m long drifts, line-loading). A panel consists of 11 drifts with capacity for 10,000 MT SNF (with 20% contingency). The panel size is roughly 0.8 x 0.6 km, which is about half that of the salt concepts and the 12-PWR concept described above. The reason for the difference is that for this analysis drift spacing is being held at 81 m for all package sizes, consistent with the YM concept. Smaller drift spacings might be used based on analysis of thermal-hydrologic processes, but the impact on cost estimation is likely to be small because it would affect only the access drift interval between emplacement drifts, and the overall repository layout area. Thus, for cost estimation the same 81-m drift spacing is assumed as a simplification. Other aspects such as infrastructure, ventilation shafts, ramp transport, etc. are similar to the Shale Unbackfilled concept referenced above.

For high-burnup (60 GWd/MT) SNF with 130 year fuel age, package power at closure is approximately 4 kW and the corresponding line-load is 800 W/m. High-burnup packages up to 7 kW (the maximum for the proposed YM repository) can be interspersed with low-burnup packages to achieve earlier closure while maintaining an average 800 W/m line load. These values lie within the limits for thermal loading in the YM analysis (SNL 2008). Note that line loading allows the installed drip shields to be continuous.

Table 9-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of 21-PWR size packages in unsaturated hard rock.

Media/Concept	Hard Rock, Unsaturated, Unbackfilled
Repository depth	~500 m
Hydrologic setting	Unsaturated
Ground support material	Rock bolts, wire cloth and shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	21-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.57 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	5.5 m
Spacings (plan view)	81 m (drifts); 5 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	NA
Line or point loading	Line

10. HARD ROCK, DPC DIRECT DISPOSAL, UNSATURATED, UNBACKFILLED OPEN CONCEPT

Waste Packaging: This extension of the YM concept was formerly evaluated by BSC (2003) and analyzed by Kessler et al. (2008). SNF is delivered to the repository sealed in stainless steel DPCs with nominal 32-PWR size, and shield lids equivalent to at least 20 cm of steel. DPC-based waste packages have similar size and weight to the heaviest (Naval fuel) packages proposed for the YM repository.

For DPC direct disposal the engineered barriers would be designed for high reliability to limit the probability of nuclear criticality. Neutron absorbing components used in DPCs generally have limited lifetime (e.g., 100 years) once exposed to moisture after breach of the disposal overpack from manufacturing defects, corrosion, or disruptive events. The corrosion resistant overpack and other corrosion resistant engineered barriers (e.g., drip shields) are relied on to function with independent reliability to limit the possibility of flooding (negligible probability of failure at the same package). Unsaturated hydrologic conditions make flooding unlikely even in the event of waste package breach. The geologic setting is selected to limit the hazard from disruptive events such as faulting and seismicity which could degrade the engineered barriers. If performance assessment shows that criticality could not be excluded based on low probability, criticality consequence analysis can be used to support exclusion, or if appropriate, to include criticality in the dose assessment.

Emplacement: The in-drift, ventilated emplacement concept, ground support, and invert are the same as described in Sections 8 and 9. Drip shields have total weight of 3,300 kg each.

Layout: This concept is similar to the 21-PWR variant described in Section 9, but with 10-m (center-center) package spacing and larger (6.5 m) drift diameter (Table 10-1). With the greater spacing, the maximum package power (7 kW) and line-load (800 W/m) at closure are within the limits for thermal loading in the YM analysis (for 32-PWR, 60 GWd/MT, 100 year age). Larger, high-burnup canisters (e.g., 37-PWR) could potentially be interspersed with smaller, low-burnup canisters to maintain an average 0.8 kW/m line-loading at closure, as long as applicable cladding temperature limits are met.

A repository panel consists of 14 emplacement drifts with capacity for 10,000 MT SNF (with 20% contingency). The panel size is 0.6 x 1.2 km. With the additional spacing between packages, drip shields (which must be larger to accommodate packages with diameters up to 1.94 m) change from continuous to discrete components with end caps. For installation the drip shields are lifted completely above intervening waste packages, which is the reason for the larger drift diameter.

Table 10-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of DPC-based packages in unsaturated hard rock.

Media/Concept	Hard Rock, Unsaturated, Unbackfilled
Repository depth	~500 m
Hydrologic setting	Unsaturated
Ground support material	Rock bolts, wire cloth and shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	32-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.94 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	6.5 m
Spacings (plan view)	81 m (drifts); 10 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	NA
Line or point loading	Point

11. HARD ROCK, 12-PWR SIZE, SATURATED, BACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in 12-PWR size stainless steel canisters, with 20-cm shield lids. Corrosion resistant disposal overpacks are used to provide a second isolation barrier (in addition to low-permeability backfill) in saturated, fractured host rock. The 2-cm thick corrosion resistant package outer-barrier (e.g., Alloy 22 or titanium) increases the expected duration of containment integrity to hundreds of thousands of years in contact with conditioned, clay-based backfill. Package dimensions are the same as the unsaturated concepts (compare Tables 8-2 and 11-2).

Emplacement: In-drift emplacement is used, similar to the hard rock unsaturated, unbackfilled concepts. Waste packages are emplaced on low pallets, except that the pallets are lined with thick (0.35-m) blocks of dehydrated, compacted swelling clay. At closure, drifts are remotely filled with pelletized, clay-based backfill, so that packages are surrounded by clay-based material that has very low permeability after rehydration.

Layout: Ground support is basically the same as for the unsaturated, unbackfilled open concept (Section 8) because drifts will stand open for comparable duration (anticipating no long-term rock deformation processes for hundreds of years, after the openings have been stable for decades). This concept has smaller drift spacing but larger package spacings, compared to the unsaturated unbackfilled concept (compare Tables 8-2 and 11-2). The increased package spacing allows backfill placement between packages where the peak temperature is substantially less than at the package surface. The decreased drift spacing is possible because of lower package power limits at closure (which are controlled by backfill temperature limits). The drift spacing for 12- and 21-PWR sizes could likely be further decreased and still meet thermal goals.

Drift diameter of 4.5-m is used to limit backfill thermal resistance (Table 11-1). With 70-m drift spacing and 1-km long drifts, a panel with capacity for 10,000 MT SNF consists of approximately 44 drifts (with 20% contingency). The panel size is roughly 3.1 x 1.0 km.

Hardin et al. (2013b, Figure 4-11) showed that rock wall peak temperatures can be limited to approximately 100°C or cooler (32-PWR, high-burnup SNF, with fuel age 150 years at closure). These calculations were done for a 4.5 m drift diameter, and even lower wall temperatures are obtained for 5.5 m. Temperatures are much cooler for 12-PWR packages.

The peak temperature limit for hard rock is assumed to be 200°C. Therefore, host rock wall temperature does not constrain thermal loading for these concepts. Backfill temperature is more critical, as discussed below.

The challenge for these concepts (Table 11-2) is to mitigate peak temperature of backfill at or near the package surface, which will be in the range 150 to 200°C or hotter, for these large waste packages (i.e., compared to Cases 1 and 2). Limiting backfill temperature can be accomplished by some combination of: 1) smaller emplacement drift diameter (4.5 m) which decreases backfill thermal resistance but restricts in-drift clearances; 2) backfill admixtures such as graphite (Hardin et al. 2012, Section 3.2.2.6); and 3) backfill composition that allows higher peak temperatures (to 200°C) without significant loss of swelling, low-permeability, or radionuclide transport attenuation properties. Hotter packages can generally not be interspersed with cooler packages because peak backfill temperature occurs early and is quite localized.

If drift or panel closure takes place when fuel age is 150 years or less, then power output of a 12-PWR package will range from approximately 720 W to 2 kW depending on burnup. These values are consistent with peak backfill temperatures below 150°C (backfill thermal conductivity 0.6 W/m-K).

Table 11-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of 12-PWR size packages in saturated, backfilled (open) hard rock.

Media/Concept	Hard Rock, Saturated, Backfilled at Closure
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, wire cloth and shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	12-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.17 m D x 5.0 m L
Overpack total wall thickness	5 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	70 m (drifts); 10 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Granular and compacted bentonite, with admixtures and/or controlled hydration to increase thermal conductivity after emplacement
Line or point loading	Point

Table 11-2. Repository emplacement drift and waste package package dimensions and emplacement power limits for hard-rock saturated, backfilled (open–mode) repositories.

#	Package Size (PWR assemblies)	Emplace-ment Power Limit (kW)	Closure Power [D] Limit (kW)	Time to Closure (yr) [E]	Drift Diameter (m)	Center-Center Drift Spacing (m)	Center-Center Package Spacing (m)	Package OD (m)	Loaded Canister Weight (kg)	Total Pkg. Weight (kg)
11.	12 [A]	10	2	150	4.5	70	20	1.17	20,000	28,000
12.	21 [B]	18	3	200	4.5	70	20	1.57	33,000	50,000
13.	32 (DPC) [C]	18	3	300	4.5	70	25	1.94	50,000	70,000

Notes:

A. Emplacement power limit scaled to 21-PWR concept.

B. Similar to YM thermal analyses which showed that rock wall (200°C) and cladding temperature (350°C) limits would be met (SNL 2008).

C. The case with 5.5-m drift diameter and 150-yr age at closure was analyzed by Hardin et al. (2013, Section 4.6.1).

D. Closure power of 3 kW produces peak backfill temperature of approximately 200°C, while 2 kW produces 150°C (backfill thermal conductivity 0.6 W/m-K).

E. Approximate years since reactor discharge, based on high-burnup (60 GW-d/MT).

12. HARD ROCK, 21-PWR SIZE, SATURATED, BACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in 21-PWR size stainless steel canisters, with 20-cm shield lids. The disposal overpack inner SS layer thickness is increased (for structural strength) to 5 cm giving a total overpack thickness of 7 cm including a 2-cm corrosion resistant outer layer (see Table 12-1 for other dimensions).

Emplacement: The in-drift ventilated emplacement concept, ground support, invert, clay-lined pallets, and remotely installed backfill are the same as described in Section 11, and summarized in Tables I-1 through I-7. The emplacement drifts allow small clearances for emplacement and backfilling, so specialized equipment is developed and deployed.

Layout: The same repository dimensions also pertain (4.5-m diameter emplacement drifts, 70-m drift spacing, 1-km long drifts, point-loading). A panel consists of approximately 26 drifts with capacity for 10,000 MT SNF (with 20% contingency). Panel size is roughly 1.8 x 1.0 km. Ground support is basically the same as for the comparable unsaturated, unbackfilled open concept (Section 9).

For high-burnup (60 GWd/MT) SNF with 200 year age, package power at closure is limited to approximately 3 kW and the peak backfill temperature is approximately 200°C (Table 11-2). Additional measures can be taken to accommodate younger or higher burnup fuel as discussed in Section 11.

Table 12-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of 21-PWR size packages in saturated, backfilled (open) hard rock.

Media/Concept	Hard Rock, Saturated, Backfilled at Closure
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, wire cloth and shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	21-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.57 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	70 m (drifts); 10 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Granular and compacted bentonite, with admixtures and/or controlled hydration to increase thermal conductivity after emplacement
Line or point loading	Point

13. HARD ROCK, DPC DIRECT DISPOSAL, SATURATED, BACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in stainless steel DPCs with nominal 32-PWR size, and shield lids equivalent to at least 20 cm of steel. Waste packaging is similar to that described in Section 12, with total overpack thickness of 7 cm including a corrosion resistant outer layer (see Table 13-1 for other dimensions).

Emplacement: The in-drift ventilated emplacement concept, ground support, invert, clay-lined pallets, and remotely installed backfill are the same as described in Sections 11 and 12, and summarized in Tables I-1 through I-7. Package spacing is increased to 20 m to ensure regions of backfill between packages with peak temperature substantially lower than 200°C. The emplacement drifts allow small clearances for emplacement and backfilling, so specialized equipment is developed and deployed.

Layout: The other repository dimensions also pertain (4.5-m diameter emplacement drifts, 70-m drift spacing, 1-km long drifts, point-loading). A panel consists of approximately 21 drifts with capacity for 10,000 MT SNF (with 20% contingency). Panel size is roughly 1.5 x 1.0 km. Ground support is basically the same as for the comparable unsaturated, unbackfilled open concept (Section 10).

For high-burnup (60 GWd/MT) SNF with 300 year fuel age, package power at closure is limited to approximately 3 kW and the peak backfill temperature is approximately 200°C. Additional measures can be taken to accommodate younger or higher burnup fuel as discussed in Section 11.

Table 13-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of DPC-based packages in saturated, backfilled (open) hard rock.

Media/Concept	Hard Rock, Saturated, Backfilled at Closure
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, wire cloth and shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	32-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.94 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	70 m (drifts); 20 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Backfill material	Granular and compacted bentonite, with admixtures and/or controlled hydration to increase thermal conductivity after emplacement
Line or point loading	Point

14. ARGILLACEOUS, 12-PWR SIZE, SATURATED, BACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in 12-PWR size stainless steel canisters, with 20-cm shield lids. Corrosion resistant disposal overpacks are used to provide a second isolation barrier (in addition to low-permeability backfill) in saturated, argillaceous host rock. The corrosion resistant outer-barrier (e.g., Alloy 22 or titanium) increases the expected duration of containment integrity to hundreds of thousands of years in contact with conditioned, clay-based backfill. Package dimensions are the same as the hard rock concepts (compare Tables 11-2 and 14-2). Packaging consists of the sealed canister, a structural overpack layer consisting of 3 cm of stainless steel, and a 2-cm thick corrosion resistant layer (see Table 14-1 for other dimensions).

Emplacement: Waste packages are emplaced on low pallets, which are lined with thick (0.35-m) blocks of dehydrated, compacted swelling clay. At closure, drifts are remotely filled with pelletized, clay-based backfill, so that packages are surrounded by clay-based material that has very low permeability after rehydration.

Layout: Layout dimensions are shown in Tables 14-1 and 14-2. With 1-km long emplacement drifts, a panel with capacity for 10,000 MT SNF consists of approximately 44 drifts (with 20% contingency). Panel size is roughly 3.1 x 1.0 km.

Ground support consists of a thick (e.g., 0.5 to 0.75-m) pre-cast segmented high-strength concrete liner installed behind a tunnel boring machine. A compliant liner approach is taken (assuming the host medium responds plastically), by backfilling behind the liner with an injected mixture of grout and compliant aggregate such as beads of plastic foam.

Thermal performance is dominated by the backfill, and thermal limits are controlled by the backfill peak temperature (backfill peak temperature from 150 to 200°C or hotter). Closure power limits are therefore assumed to be the same as for the hard rock saturated backfilled open concepts. This assumption is consistent with previous analyses (Hardin et al. 2013a,b), but some increase of minimum time to closure is needed if the argillaceous host rock thermal conductivity is much less than that assumed for hard rock (2.5 W/m-K). Additional measures can be taken to accommodate younger or higher burnup fuel as discussed in Section 11.

Table 14-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of 12-PWR size packages in saturated, backfilled (open) argillaceous rock.

Media/Concept	Argillaceous Rock, Saturated, Backfilled at Closure
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, wire cloth and shotcrete, with steel sets and additional shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	12-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.17 m D x 5.0 m L
Overpack total wall thickness	5 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	70 m (drifts); 10 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Drift backfill material	Granular and compacted bentonite, with admixtures and/or controlled hydration to increase thermal conductivity after emplacement
Line or point loading	Point

Table 14-2. Repository emplacement drift and waste package package dimensions and emplacement power limits for argillaceous, saturated, backfilled (open–mode) repositories.

#	Pkg. Size (PWR assemblies)	Emplace-ment Power Limit (kW)	Closure Power [B] Limit (kW)	Time to Closure (yr) [C]	Drift Dia. (m)	Center-Center Drift Spacing (m)	Center-Center Pkg. Spacing (m)	Pkg. OD (m)	Loaded Canister Weight (kg)	Total Pkg. Weight (kg)
14.	12 [A]	10	2	150	4.5	70	20	1.17	20,000	28,000
15.	21	18	3	200	4.5	70	20	1.57	33,000	50,000
16.	32 (DPC)	18	3	300	4.5	70	25	1.94	50,000	70,000

Notes:

A. Emplacement power limit scaled to 21-PWR concept.
B. Closure power of 3 kW produces peak backfill temperature of approximately 200°C, while 2 kW produces 150°C (backfill thermal conductivity 0.6 W/m-K).
C. Approximate years since reactor discharge, based on high-burnup (60 GW-d/MT).

15. ARGILLACEOUS MEDIA, 21-PWR SIZE, SATURATED, BACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in 21-PWR size stainless steel canisters, with 20-cm shield lids. The disposal overpack inner SS layer thickness is increased (for structural strength) to 5 cm giving a total overpack thickness of 7 cm including a 2-cm corrosion resistant outer layer (see Table 15-1 for other dimensions).

Emplacement: The in-drift ventilated emplacement concept, ground support, invert, clay-lined pallets, and remotely installed backfill are the same as described in Section 14, and summarized in Tables I-1 through I-7. Backfill peak temperature approaches 200°C, but additional measures can be taken to accommodate higher burnup fuel as discussed in Section 11.

Layout: The same repository dimensions also pertain (Table 15-1; 4.5-m diameter emplacement drifts, 70-m drift spacing, 1-km long drifts, point-loading). A panel consists of approximately 26 drifts with capacity for 10,000 MT SNF (with 20% contingency). Panel size is roughly 1.8 x 1.0 km. Ground support consists of a heavy pre-cast segmented high-strength concrete liner with compliant backfill material injected behind the liner.

Table 15-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of 21-PWR size packages in saturated, backfilled (open) argillaceous rock.

Media/Concept	Argillaceous Rock, Saturated, Backfilled at Closure
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, wire cloth and shotcrete, with steel sets and additional shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	21-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.57 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	70 m (drifts); 10 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Drift backfill material	Granular and compacted bentonite, with admixtures and/or controlled hydration to increase thermal conductivity after emplacement
Line or point loading	Point

16. ARGILLACEOUS MEDIA, DPC DIRECT DISPOSAL, SATURATED, BACKFILLED OPEN CONCEPT

Waste Packaging: SNF is delivered to the repository sealed in DPCs of nominal 32-PWR size, with shield plugs equivalent to at least 20-cm of steel. The disposal overpack inner SS layer thickness is increased (for structural strength) to 5 cm giving a total overpack thickness of 7 cm including a 2-cm corrosion resistant outer layer (see Table 15-1 for other dimensions).

Emplacement: The in-drift ventilated emplacement concept, ground support, invert, clay-lined pallets, and remotely installed backfill are the same as described in Sections 14 and 15, and summarized in Tables I-1 through I-7. Backfill peak temperature approaches 200°C, but additional measures can be taken to accommodate higher burnup fuel as discussed in Section 11.

Layout: Repository dimensions are similar to those for 21-PWR size packages (Table 16-1; 4.5-m diameter emplacement drifts, 70-m drift spacing, 1-km long drifts, point-loading). With 25-m package spacing, a panel consists of approximately 21 drifts with capacity for 10,000 MT SNF (with 20% contingency). Panel size is roughly 1.5 x 1.0 km. Ground support consists of a heavy pre-cast segmented high-strength concrete liner with compliant backfill material injected behind the liner.

Table 16-1. Summary of waste packaging and emplacement details for open, in-drift emplacement of DPC-based packages in saturated, backfilled (open) argillaceous rock.

Media/Concept	Argillaceous Rock, Saturated, Backfilled at Closure
Repository depth	~500 m
Hydrologic setting	Saturated
Ground support material	Rock bolts, wire cloth and shotcrete, with steel sets and additional shotcrete as needed
Seals and plugs	Shaft & tunnel plugs and seals
SNF Emplacement Mode	Horizontal in-drift emplacement
WP configuration	32-PWR (or BWR equiv.)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	1.94 m D x 5.0 m L
Overpack total wall thickness	7 cm
Emplacement drift diameter	4.5 m
Spacings (plan view)	70 m (drifts); 20 m (packages, center-center)
Borehole liner material	NA
Buffer material	NA
Drift backfill material	Granular and compacted bentonite, with admixtures and/or controlled hydration to increase thermal conductivity after emplacement
Line or point loading	Point

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APPENDIX A. REPOSITORY THROUGHPUT AND DURATION OF OPERATIONS, CONSTRAINED BY COOLING TIME

This appendix presents logistical simulations used to estimate the achievable repository throughput rate and the duration of operation, for the different disposal concepts.

Sixteen disposal concepts are identified in Sections 1 through 16 of this report. For each one, a specific disposal medium and emplacement mode is identified, and the associated emplacement power limit and waste package size. Ten different disposal concepts are simulated (representing all 16 as discussed below), and only seven cases are needed to do so. Mapping between the cases and disposal concepts is shown in Table A-1.

Table A-1. Description of the disposal cases

Case #	Emplacement Power Limit (kW)	Package Size (# assemblies)	Disposal Concept ID	Disposal Medium	Emplacement Type
I	1.7	4-PWR/ 9-BWR	1	Crystalline, enclosed	Vertical borehole with buffer (KBS-3)
			2	Argillaceous, enclosed	Horizontal borehole with buffer
II	2.2	4-PWR/ 9-BWR	4	Salt, enclosed	In-drift emplacement
III	1.7	12-PWR/ 24-BWR	3	Argillaceous, enclosed	Self-shielded packages, in-drift emplacement with clay backfill
IV	5.5	12-PWR/ 24-BWR	5	Salt, enclosed	In-drift emplacement
V	10.0	21-PWR/ 44-BWR	6	Salt, enclosed	In-drift emplacement
VI	11.5	DPCs	7	Salt, enclosed	In-drift emplacement
VII	10.0	12-PWR/ 24-BWR	8	Hard rock	Unsaturated unbackfilled open
			11		Saturated backfilled open concept
			14	Argillaceous	Saturated backfilled open

The logistical simulation code TSL-CALVIN (Nutt 2012) was used to simulate the SNF management system including waste emplacement. The total inventory considered in the analysis is approximately139,000 MTU. This inventory is based on 20-year license extension for all existing, operating reactors and no new builds.

The logistical simulation models was set up to assume the following conditions:

- SNF is loaded into DPCs of the size now in use at operating reactor sites to keep pool inventory at or below maximum capacity.
- SNF from pools is loaded into DPCs of the size now in use starting 5 years after reactor shutdown.
- An interim storage facility (ISF) for commercial SNF becomes operational in 2021 and accepts waste from the reactor sites at the rate of 3,000 MTU per year.
- DPCs that meet the associated transportation power limits are transported from reactor sites to the ISF until all the reactor sites are unloaded.

- DPCs are stored at the ISF until the repository begins accepting waste in 2048 at the rate of 3,000 MTU per year.
- DPCs are transported to the repository where they are repackaged into waste packages of a specified size, except for the DPC direct disposal case. No repackaging is done in the DPC direct disposal case (Case VI).
- The waste packages (or DPCs) are emplaced in the repository as soon as their thermal output is at or below the specified emplacement power limit.
- Waste packages are loaded using a blending algorithm in which cooler assemblies are mixed with hotter assemblies to achieve desired thermal output.

As discussed above, the focus of this analysis was on the achievable throughput and the duration of repository operation. Throughput rates for each year (blue curves), and cumulative fractions of total inventory disposed of (red curves), are shown as functions of time in Figures A-1 to A-7. The results are summarized in Table A-2.

In general, all the cases except Case III (emplacement power limit 1.7 kW and 12-PWR/24-BWR size packages) are very similar with regard to throughput rates and duration of operation. Throughput close to 3,000 MTU/year can be maintained from repository opening in 2048, until at least 2092. A total of 99% of U.S. SNF inventory can be emplaced during 45 to 54 years of the repository operations. The remaining 1% of the inventory (1,390 MTU) requires some additional emplacement time or a different (smaller) waste package.

The emplacement rate in Case III varies from 500 to 1,800 MTU/year during the first 170 years of operations and drops significantly after that. Emplacing 99% of the inventory requires 197 years. Two additional cases were considered for Case III: 1) 50% of the total inventory emplaced in 12-PWR/24-BWR size packages and 50% emplaced in smaller 4-PWR/9-BWR size packages; and 2) 26% of the total inventory emplaced in 12-PWR/24-BWR size packages and 74% emplaced in 4-PWR/9-BWR size packages. The time required to emplace 99% of the total inventory is reduced by 51 years in the first case and by 79 years in the second case. Even in the second case, a long repository operational time (118 years) is required.

Note that in all cases the total inventory is transported to the repository by 2102.

For the six concepts which were not simulated, conclusions can be based on the seven cases simulated. Disposal concepts 9, 12, and 15 (18 kW emplacement power limit and 21-PWR/44-BWR size packages) should produce results similar to Case V (10 kW emplacement power limit and 21-PWR/44-BWR size packages). Disposal concepts 10, 13, and 16 (18 kW emplacement power limit and DPCs) should produce the results similar to Case VI (11.5 kW emplacement power limit and DPCs).

A summary of repository throughput (enveloping maximum value, up to 3,000 MTU/year) and duration of operations for the 16 disposal concepts is presented in Table A-3.

Table A-2. Simulation summary

Case #	Emplacement Power Limit (kW)	Package Size (# assemblies)	Last Year of High Throughput (>2,000 MTU)	Year of 99% Inventory Emplacement	Duration of Operations (years)
I	1.7	4-PWR/ 9-BWR	2092	2102	54
	2.2	4-PWR/ 9-BWR	2093	2093	45
II	1.7	12-PWR/ 24-BWR	2049	2245	197
III		50% in 12-PWR/ 24-BWR	2095	2194	146
IV		26% in 12-PWR/ 24-BWR	2072	2166	118
V	5.5	12-PWR/ 24-BWR	2093	2093	45
VI	10.0	21-PWR/ 44-BWR	2093	2093	45
VII	11.5	DPCs	2093	2102	54
	10.0	12-PWR/ 24-BWR	2093	2093	45

The results for the seven cases are provided below.

Case I: Emplacement Power Limit 1.7 kW and Waste Package Size 4-PWR/9-BWR

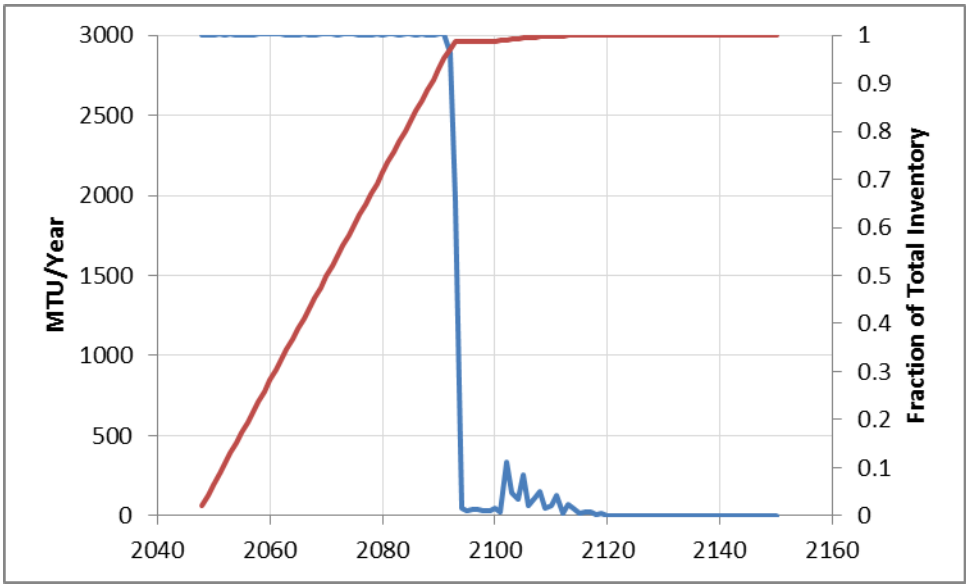


Figure A-1. Throughput rates based on 1.7 kW emplacement power limit and 4-PWR/9-BWR size waste packages

Case II: Emplacement Power Limit 2.2 kW and Waste Package Size 4-PWR/9-BWR

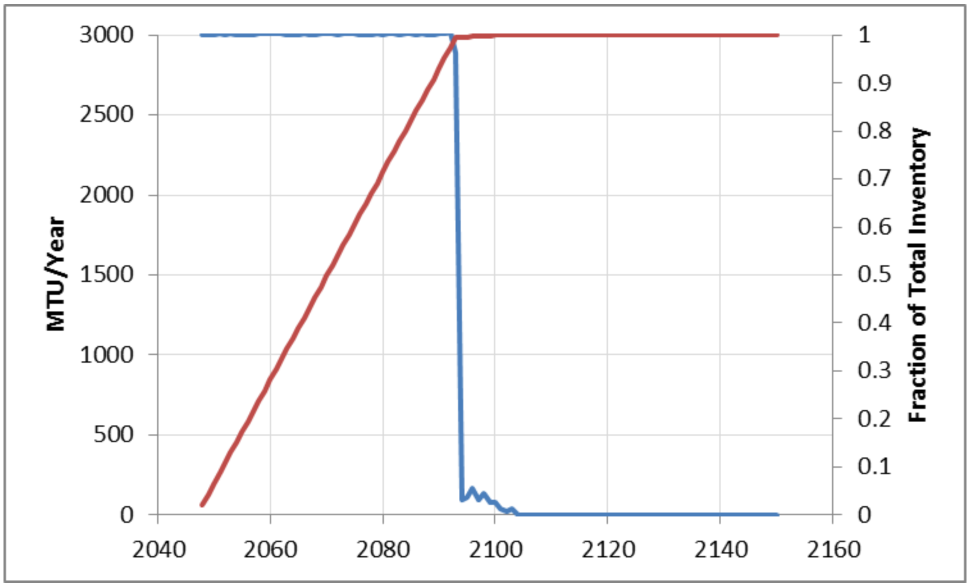
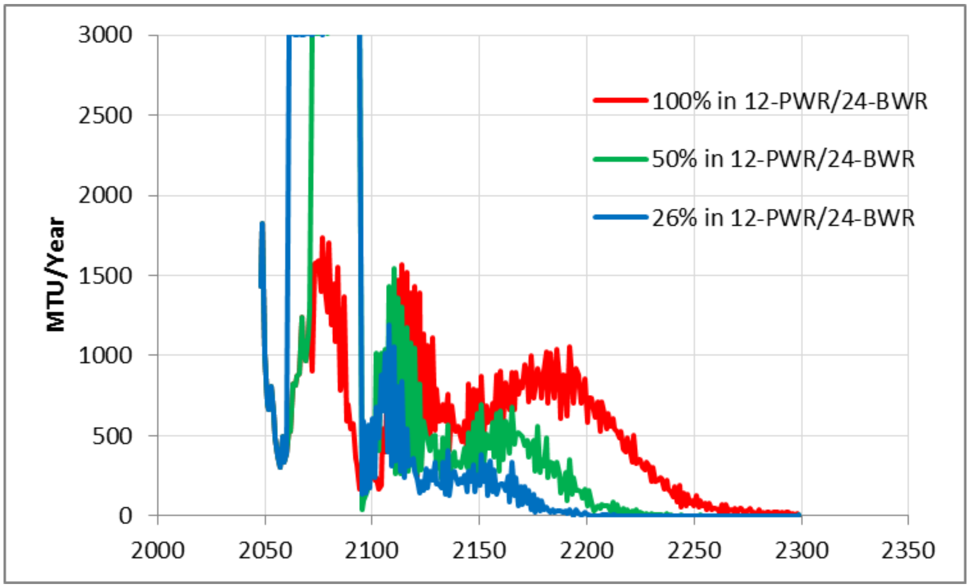


Figure A-2. Throughput rates based on 2.2 kW emplacement power limit and 4-PWR/9-BWR size waste packages

Case III: Emplacement Power Limit 1.7 kW and 12-PWR/24-BWR Size Waste Packages (up to the limit shown, with the balance in 4-PWR/9-BWR size packages)

a) Annual emplacement;



b) Cumulative emplacement.

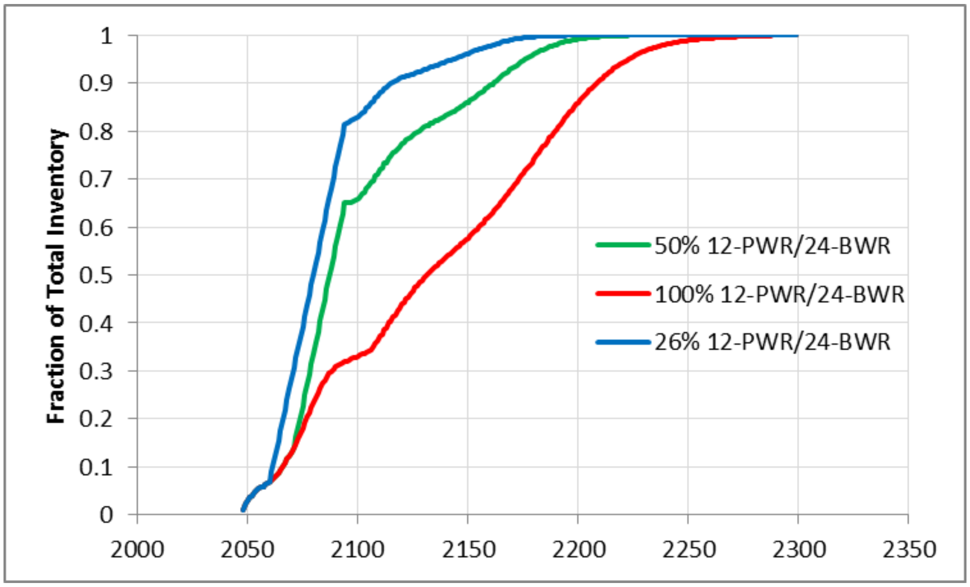


Figure A-3. Throughput rates based on 1.7 kW emplacement power limit and 12-PWR/24-BWR size waste packages

Case IV: Emplacement Power Limit 5.5 kW and Waste Package Size 12-PWR and 24-BWR

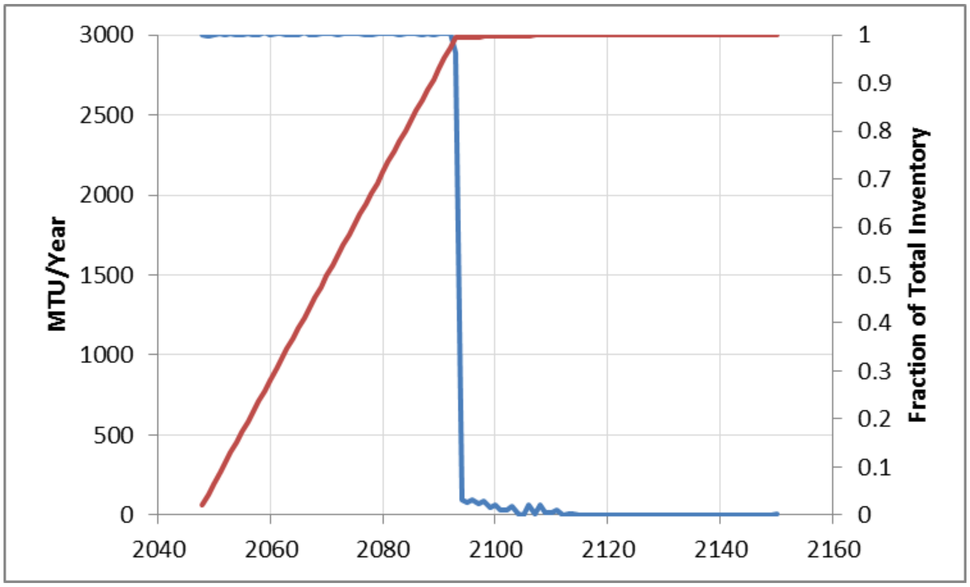


Figure A-4. Throughput rates based on 5.5 kW emplacement power limit and 12-PWR/24-BWR size waste packages

Case V: Emplacement Power Limit 10.0 kW and Waste Package Size 21-PWR and 44-BWR

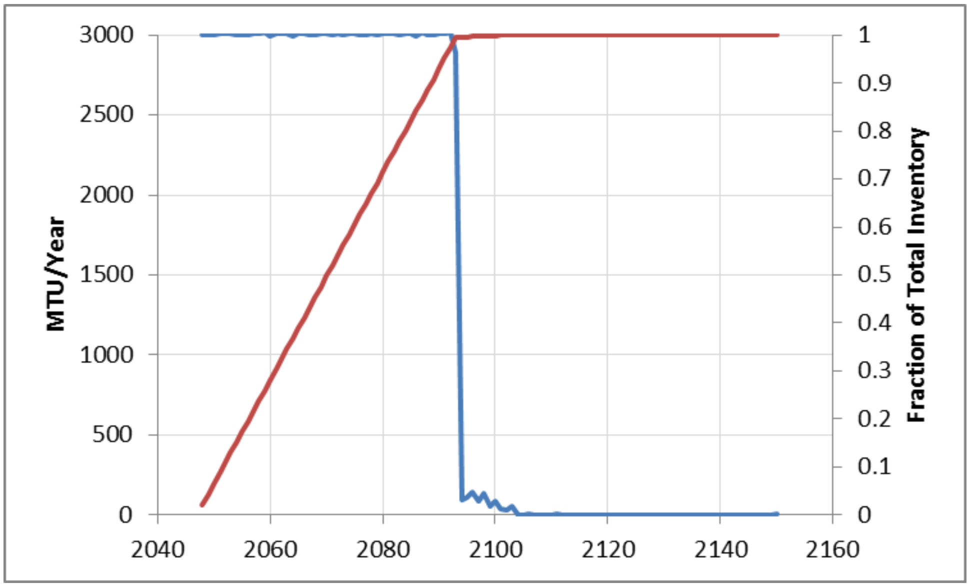


Figure A-5. Throughput rates based on 10 kW emplacement power limit and 21-PWR/44-BWR size waste packages

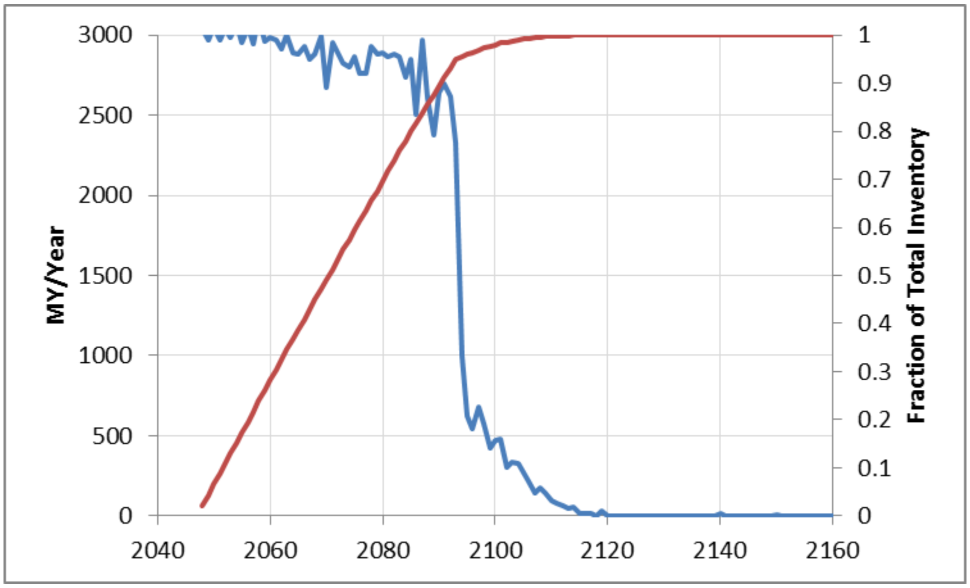


Figure A-6. Throughput rates based on 11.8 kW emplacement power limit and direct disposal of DPCs

Case VII: Emplacement Power Limit 10.0 kW and Waste Package Size 12-PWR and 24-BWR

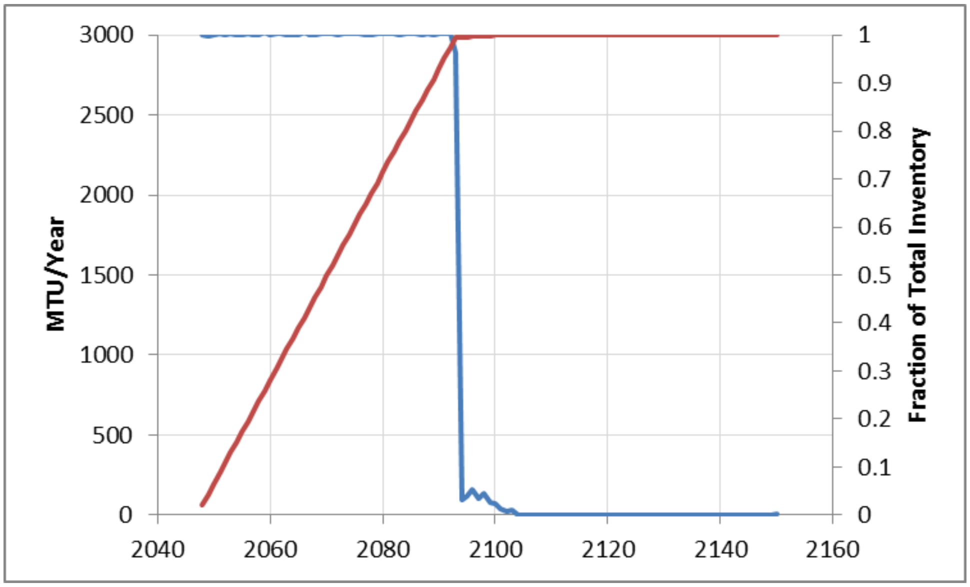


Figure A-7. Throughput rates based on 10 kW emplacement power limit and 12-PWR/24-BWR size waste packages

Table A-3. Summary of enveloping throughput and duration of operation, for 16 disposal concepts

#	Case	Concept	Package Capacity (PWR/BWR)	140,000 MT Repository	
				Enveloping Throughput (MTU/year)	**Repository Duration of Operation (yr)**
1.	**I**	**Crystalline (enclosed)**	4/9	3,000	46
2.		**Argillaceous (enclosed)**	4/9	3,000	46
3.			12/21	1,700	~200 [A]
4.		**Salt (enclosed)**	4/9	3,000	46
5.			12/21	3,000	46
6.			21/44	3,000	46
7.			DPC	3,000	54
8.		**Hard rock unsaturated (open)**	12/21	3,000	46
9.			21/44	3,000	46
10.			DPC	3,000	54
11.		**Hard rock saturated (open)**	12/21	3,000	46
12.			21/44	3,000	46
13.			DPC	3,000	54
14.		**Argillaceous (open)**	12/21	3,000	46
15.			21/44	3,000	46
16.			DPC	3,000	54

Note: [A] Shorter durations can be achieved by substituting smaller 4-PWR/9-BWR packages as indicated in Figure A-3.

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