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Fuel Cycle Research & Development

Multi-Pack Disposal Concepts for Spent Fuel

Fuel Cycle Research & Development

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FCRD-NFST-2016-000640 Rev. 1	Changes for consistency with Revision 1 of Hardin and Kalinina (2015). Review at SNL (SAND2016-****).

CONTEXT FOR THIS STUDY

This is a technical presentation that does not take into account the contractual limitations under the Standard Contract. Under the provisions of the Standard Contract, DOE does not consider spent fuel in canisters to be an acceptable waste form, absent a mutually agreed to contract modification.

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Acronyms

BWR	Boiling Water Reactor
CRWMS M&O	Civilian Radioactive Waste Management System Management & Operations (contractor)
EBS	Engineering Barrier System
NFST	Nuclear Fuel Storage and Transportation (planning project)
PWR	Pressurized Water Reactor
R&D	Research & Development
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
STAD	Storage, Transportation and Disposal (canister)
UFD	Used Fuel Disposition (R&D campaign)
WIPP	Waste Isolation Pilot Plant

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Multi-pack Disposal Concepts for Spent Fuel

1. Introduction and Background

At the initiation of the Used Fuel Disposition (UFD) R&D campaign, international geologic disposal programs and past work in the U.S. were surveyed to identify viable disposal concepts for crystalline, clay/shale, and salt host media (Hardin et al. 2012a). Concepts for disposal of commercial spent nuclear fuel (SNF) and high-level waste (HLW) from reprocessing are relatively advanced in countries such as Finland, France, and Sweden. The UFD work quickly showed that these international concepts are all "enclosed," whereby waste packages are emplaced in direct or close contact with natural or engineered materials. Alternative "open" modes (emplacement tunnels are kept open after emplacement for extended ventilation) have been limited to the Yucca Mountain License Application Design (CRWMS M&O 1999). Thermal analysis showed that if "enclosed" concepts are constrained by peak package/buffer temperature, that waste package capacity is limited to 4 PWR assemblies (or 9-BWR) in all media except salt (Figure 1). This information motivated separate studies: 1) extend the peak temperature tolerance of backfill materials, which is ongoing; and 2) develop small canisters (up to 4-PWR size) that can be grouped in larger multi-pack units for convenience of storage, transportation, and possibly disposal (should the disposal concept permit larger packages). A recent result from the second line of investigation is the Task Order 18 report: *Generic Design for Small Standardized Transportation, Aging and Disposal Canister Systems* (EnergySolutions 2015). This report identifies disposal concepts for the small canisters (4-PWR size) drawing heavily on previous work, and for the multi-pack (16-PWR or 36-BWR).

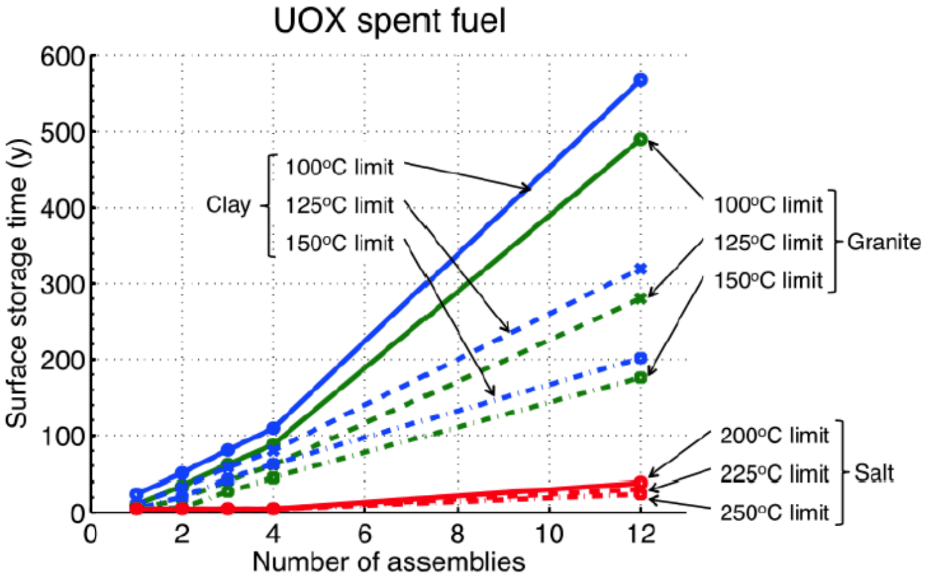

Figure 1. Required storage or aging time, vs. waste package capacity, for disposal of commercial SNF (40 GWd/MTU burnup) constrained by peak package/buffer temperature in different media as indicated (Hardin et al. 2012a, Figure 3.1-15).

2. Can-in-Carrier Packaging Concept

A new canister concept, the Storage, Transportation and Disposal (STAD) canister, has been developed in response to the recognized thermal limitations of "enclosed" emplacement modes for disposal, and the need for power plant and storage operators to handle spent fuel in canisters larger than 4-PWR size. The can-in-carrier concept was developed as a compromise by the Nuclear Fuel Storage and Transportation (NFST) Planning Project (EnergySolutions 2015). In this concept, the 4-PWR (or 9-BWR) canisters are loaded, dewatered, and sealed separately, but then combined in a carrier (essentially a basket) that holds four canisters (Figure 2).

The 4-PWR canisters are essentially right circular cylinders, although the lifting ring extends slightly above the top lid. The loaded carrier (Figure 2) also fits within the contour of a right circular cylinder. Cylinder dimensions for each are given in Table 1. Carrier dimensions in this table are inner cavity dimensions for a transportation overpack, and are interpreted here as the inner cavity dimensions for a disposal overpack as well. Loaded weights for canisters, and for carriers loaded with four canisters, are given for the PWR and BWR versions in Table 2.

Canisters would be fabricated from 316SS, with a design containment lifetime of 150 years (EnergySolutions 2015). Accordingly, the canisters would not be credited for containment in the repository postclosure timeframe. Rather, containment would be provided by the disposal overpack. Selection from among reference disposal concepts are discussed below in Section 3.

Table 1. Overall dimensions of STAD canisters and carrier

	Dimensions (m)	
	STAD Canister	**Carrier**
Length	4.98 [A]	4.93 [B]
Diameter	0.737	1.98 [B]
Internal Cavity Length	4.57	
Maximum Fuel Assembly Length – PWR/BWR [C]	4.530/4.477	
Active Fuel Length – PWR/BWR [C]	3.66/3.81	
[A] Overall with lifting ring [B] Overpack cavity [C] Except South Texas		

Table 2. Maximum weight of STAD canisters (dry) (EnergySolutions 2015, Table 4.1)

	Weight (kg)	
	4-PWR	**9-BWR**
Max.Fuel Assembly Weight [A]	784.1	320.9
Canister Body Subassembly	786.4	786.4
Basket Assembly	1,204	1,691
Shield Plug	700	700
Top Plate Assembly	209	209
Spent Fuel	3,136	2,888
Canister Totals	6,036	6,275
Carrier Assembly	10,818	10,818
Total Loaded Carrier Max. [B]	34,964	35,916
[A] Except South Texas [B] Not incl. 546 kg lifting yoke		

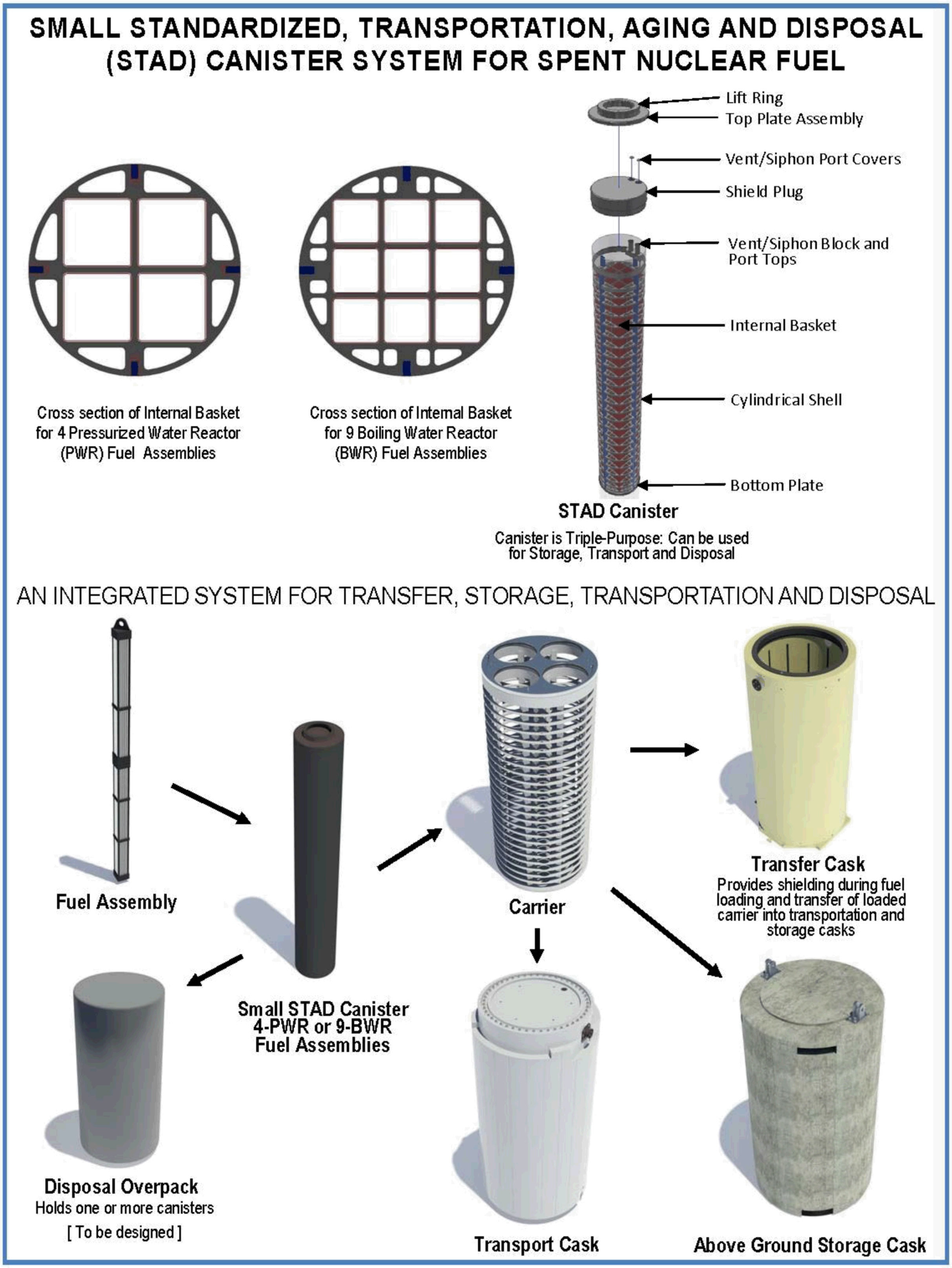

Figure 2. Can-in-canister concept for commercial spent fuel (figure from EnergySolutions 2015, Appendix H)

3. Disposal Concept Options

For consistency with previous work supporting NFST system-level analyses, disposal concepts are based on the 2015 set of reference concepts (Hardin and Kalinina 2015). These include "enclosed" emplacement modes appropriate for use with 4-PWR size waste packages, and also "open" modes that are needed for waste packages 12-PWR size or larger, in crystalline and argillaceous media. Emplacement thermal power limits for the 4-PWR size packages would be exactly those published previously (Hardin and Kalinina 2015).

The can-in-canister packaging arrangement would contain 16 PWR assemblies (or 36 BWR assemblies) with heat output about halfway between the 12-PWR and 21-PWR size options in the reference set. The diameter of the can-in-canister waste package would be approximately 2.13 m (overpack with 1.981 m diameter cavity and 7 cm wall, with 1 cm diametral clearance), which is comparable to the proposed packaging of dual-purpose canisters containing 32-PWR assemblies (Hardin and Kalinina 2015). Heat flux at the package surface would be comparable to 12-PWR size packages (actually less) because of the larger package diameter. Emplacement and closure power limits would be similar to 21-PWR packages, but the fuel age implications would be closer to 12-PWR size packages. For this report, thermal power limits are taken from 21-PWR concepts and aging requirements are taken from assembly thermal power decay curves, using thermal power limts (Hardin et al. 2013a).

3.1 Small (4-PWR Size) Canister Disposal

This section recommends disposal concepts with "enclosed" emplacement modes that are taken directly from a previous report (Hardin and Kalinina 2015) which in turn draws on earlier work (Hardin et al. 2012a).

3.1.1 Disposal of STAD 4-PWR Size Canisters in Crystalline Rock

The following description corresponds directly to Concept #1 from Hardin and Kalinina (2015) with small changes to the package diameter and buffer thickness. The variant is referred to as #1A in this report.

Waste Packaging: SNF is delivered to the repository sealed in 4-PWR size STAD canisters. These are then fitted at the repository into overpacks of copper and 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 thicker steel, or a layer of another corrosion resistant material, reflecting trends in repository R&D toward using less copper (SKB 2011) or only steel (NAGRA 2002; 2003). The overpack outer diameter would be 0.877 m, while the inner diameter would be 0.747 m to accommodate STAD canisters.

Emplacement: Packages are unshielded, and are emplaced in vertical (or possibly horizontal) borings with 1.6 m diameter (leaving a 36 cm thick buffer) and 8 m depth. The borings are drilled 6 to 10 m apart along the access drifts depending on waste heat output and host rock thermal diffusivity. Emplacement borings are lined with blocks of compacted, swelling clay (approximately 13 m^3 per emplacement). Wyoming bentonite is a good choice for buffer 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 up to 65 km of access drifts (less if the package-package spacing is less than 10 m). Each panel is encircled by two service drifts totaling approximately 11 km. With access drift spacing of 20 m (Table 3) and the encircling service drifts, the panel area is approximately 1.8 km^2. Each panel is encircled by service drifts totaling approximately 11 km. The overall repository has 14 such panels arranged around five shafts, giving a total repository area of approximately 25 km^2 for 140,000 MT capacity.

Table 3. Summary of waste packaging and emplacement details for disposal of 4-PWR size STAD-canister based packages in a KBS-3 type repository in crystalline rock (Concept #1A)

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	0.877 m D x 5.13 m L
Overpack total wall thickness	6.5 cm
Emplacement borehole diameter/length	1.6 m/8 m
Spacings (plan view)	20 m (drifts); 6 to 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
Total weight of waste package (PWR)	42.3 MT

3.1.2 Disposal of STAD 4-PWR Size Canisters in Argillaceous Rock

The following description corresponds directly to Concept #2 from Hardin and Kalinina (2015) with small changes to package dimensions, emplacement borehole diameters, and buffer thickness. The variant is referred to as #2A in this report.

Waste Packaging: SNF is delivered to the repository sealed in 4-PWR size STAD canisters. Disposal overpacks are made from low-alloy steel, with wall thickness of 5 cm, and a single welded closure (the STAD canister provides two additional welded closures).

Emplacement: Packages are unshielded, and are emplaced in horizontal borings 1.6 m in diameter and approximately 100 m deep, drilled 30 m apart from access drifts. Emplacement borings are configured with a thin steel outer liner (1.57 m outer diameter) to stabilize the borehole, and a thin steel inner liner (0.89 m outer diameter) to accommodate waste packages. The space between the liners is filled with donut-shaped blocks of compacted bentonite. Each borehole is preconstructed in this way before waste packages are emplaced. Packages are alternated with cylindrical plugs of compacted bentonite, slid into place using jacks or robot pushers. A total of approximately 16 m^3 of buffer material would be used for each package. A shield plug is inserted at the collar of each boring. Finally, at 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 less than for typical crystalline rock (e.g., 1.75 W/m-K compared to 2.5 W/m-K), so the peak EBS temperature could be a few degrees greater.

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 1.23 km long (with approximately 10% contingency). Smaller, parallel horizontal borings, 100 m deep, come off the access drifts on both sides, spaced 30 m apart. Each of these borings contains nine waste packages, spaced 10 m apart on centers, plus a 10-m plug at the collar. The nine parallel access drifts can be spaced approximately 230 m apart. Each panel is encircled by two service drifts totaling approximately 14 km. Including the encircling service drifts, the panel area is approximately 2.96 km^2. A total of 14 such panels are needed, giving a total repository plan area of approximately 41 km^2 for capacity of 140,000 MT.

Table 4. Summary of waste packaging and emplacement details for "enclosed" emplacement of 4-PWR size STAD-canister based packages in argillaceous media (Concept #2A).

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	0.847 m D x 5.10 m L
Overpack total wall thickness	5 cm
Drift/borehole dia.	1.6 m
Spacings (plan view)	30 m (borings), 10 m (packages; center-center)
Borehole liner material	Steel (inner 0.89 m OD, and outer 1.57 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
Total weight of waste package (PWR)	40.8 MT

3.1.3 Disposal of STAD 4-PWR Size Canisters in Salt

The following description corresponds directly to Concept #4 from Hardin and Kalinina (2015) with small changes to package dimensions. The variant is referred to as #4A in this report.

Waste Packaging: SNF is delivered to the repository sealed in 4-PWR size STAD canisters. Disposal overpacks consist of 5 cm of carbon steel, with outer diameter of 0.847 m and length of 5.10 m, and loaded weight of approximately 40.8 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 not the case for alcoves). Drift width is nominally 6 m, height 4 m (Table 5). 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 an emplacement 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 the HE test at the Mont Terri Underground Research Laboratory). 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 approximately 1.2 km in length. A panel consists of 50 emplacement drifts. Two perimeter service/ventilation drifts totaling 10.4 km are first mined, and ventilation is set up across the panel. Access drift length equal to half of this (5.2 km) is also assumed for each 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 minimum cover of 2.25 m, 36% porosity, 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). Panel area is approximately 1.5 km^2, and 14 such panels are needed for 140,000 MT of SNF (21 km^2).

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. 2012a, 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 5). 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. 2012a; 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 40.8 MT (Table 5) with heavy shielding would require a hoist similar to that proposed by DBE TEC (Hardin et al. 2013a) with ~85 MT capacity.

Table 5. Summary of waste packaging and emplacement details for "enclosed" in-drift emplacement of 4-PWR size STAD-canister based packages in salt (Concept #4A).

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	0.847 m D x 5.10 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)
No buffer or borehole liner	NA
Backfill material	Crushed "mine-run" salt
Line or point loading	Point
Emplacement power limit	1,700 W
Approx. total weight of waste package	40.8 MT

3.2 Multi-Canister Carrier (16-PWR) Disposal

This section presents disposal concepts with "open" emplacement for crystalline, clay/shale, and unsaturated hard rock settings, and "enclosed" emplacement for salt (Hardin and Kalinina 2015).

The challenge for concepts with larger packages (greater than 4-PWR size) and clay-based backfill (Sections 3.2.1 and 3.2.2) is to mitigate peak temperature at the package surface, which will be on the order of 150°C for the concepts presented here. This is a slight departure from previous work (Hardin and Kalinina 2015) which allowed peak temperatures for hotter packages (21-PWR and DPC-based packages) to approach 200°C. This difference for the concepts with clay-based backfill (Sections 3.2.1 and 3.2.2) is reflected in the lower thermal power limit for closure (2 kW instead of 3 kW for larger packages in the previous study). Greater thermal power at closure (when backfill is installed) would cause a proportionate increase in temperature rise.

In general, 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. 2012a, Section 3.2.2.6); and 3) backfill composition that allows higher peak temperatures (to 200°C) without loss of important properties. Peak temperatures cannot be mitigated by interspersing hotter packages with cooler ones because peak backfill temperature occurs early and is quite localized.

3.2.1 Disposal of STAD 16-PWR Size Canisters in Saturated Hard Rock with Backfilling

The following description is similar to Concept #11 from Hardin and Kalinina (2015) with changes to package loading and dimensions. The variant is referred to as #11A in this report.

Waste Packaging: SNF is transported to the repository in 16-PWR carriers, each containing four STAD canisters. The disposal overpack has a corrosion resistant outer layer to provide a second isolation barrier (in addition to low-permeability backfill) in saturated, fractured host rock. The 2-cm thick 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. The overpack inner layer consists of 5 cm of Grade 316 stainless steel, for a total wall thickness of 7 cm. The same configuration is proposed for the argillaceous case (Section 3.2.2) and the hard rock unsaturated case (Section 3.2.4).

Emplacement: In-drift emplacement is used, similar to the other “open” concepts. Waste packages are emplaced on low pallets made of stainless steel, lined with thick (minimum 0.35 m) blocks of dehydrated, compacted swelling clay. All voids within the pallets are initially filled with backfill material to promote complete filling at closure. At closure, drifts are remotely filled with granular, swelling clay-based, dehydrated backfill at the maximum achievable dry density (approaching 1.4×10^3 kg/m^3) so that packages will be completely surrounded by backfill with very low permeability after rehydration. Remote filling is done with long auger conveyors suspended from the drift crown, and using parallel access drifts with boreholes drilled to the emplacement drift crown above each package.

Ground support is basically the same as for the unsaturated, unbackfilled “open” concept (Concept #8 from Hardin and Kalinina, 2015) because drifts will stand open for comparable duration (approximately 100 years). The peak temperature limit for hard rock is assumed to be 200°C, but rock wall temperatures never exceed 100°C with thermal loading constrained by backfill requirements.

Layout: This concept has smaller drift spacing but larger package spacing (compared to Hardin and Kalinina 2015, Section 8). The increased package spacing allows backfill to perform between packages where the peak temperature is substantially less than at the package surface, and meets peak backfill temperature limits (e.g., peak below 100°C). The decreased drift spacing is possible because of lower package power limits at closure (which are controlled by backfill temperature limits).

Drift diameter of 4.5-m is used to limit backfill thermal resistance (Table 6). Layout dimensions are the same as Concept #11 of Hardin and Kalinina (2015) but the overall repository footprint, drift lengths, and volume extent of excavation are reduced by approximately 25% (representing the smaller number of waste packages).

If drift or panel closure takes place when fuel age is 150 years or less, then power output of a 16-PWR size package will range from approximately 1.2 kW to 2.7 kW depending on burnup (scaled from the 12-PWR values from Hardin and Kalinina, 2015). These values are consistent with peak backfill temperatures below 150°C (with backfill thermal conductivity assumed to be 0.6 W/m-K) given that the 16-PWR size can-in-canister package circumference is 39% and 80% greater than the reference 12-PWR and 21-PWR packages, respectively.

Table 6. Summary of waste packaging and emplacement details for “open” in-drift emplacement of 16-PWR STAD canister based packages in saturated, backfilled hard rock (Concept #11A).

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	16-PWR (or 36 BWR)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	2.13 m D x 5.14 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
Emplacement power limit	18 kW
Closure power limit	2 kW (backfill conductivity 0.6 W/m-K)
Approx. fuel age at closure	150 yr
Approx. total weight of waste package	59.1 MT

3.2.2 Disposal of STAD 16-PWR Size Canisters in Saturated Argillaceous Rock with Backfilling

The following description is similar to Concept #14 from Hardin and Kalinina (2015) with changes to package loading and dimensions. The variant is referred to as #14A in this report.

Waste Packaging: SNF is transported to the repository in 16-PWR carriers, each containing four STAD canisters. The disposal overpack has a corrosion resistant outer layer to provide a second isolation as discussed above. The 2-cm thick outer-barrier (e.g., Alloy 22 or titanium) increases the expected duration of containment integrity to hundreds of thousands of years in contact with clay-based backfill. The overpack inner layer consists of 5 cm of Grade 316 stainless steel, for a total wall thickness of 7 cm. The same configuration is proposed for the hard rock saturated case (Section 3.2.1) and the hard rock unsaturated case (Section 3.2.4).

Emplacement: In-drift emplacement is used similar to the other “open” concepts. Waste packages are emplaced on low pallets made of stainless steel, lined with blocks of dehydrated, compacted swelling clay and filled with backfill material. At closure, drifts are remotely filled with granular, swelling clay-based, dehydrated backfill.

Layout: Layout dimensions are the same as Concept #14 of Hardin and Kalinina (2015) but the overall repository footprint, drift lengths, and volume extent of excavation are reduced by approximately 25% (representing the smaller number of waste packages).

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 grout mixture, or a paste of non-swelling clay.

Thermal performance is dominated by the backfill, and thermal limits are controlled by the backfill peak temperature (150°C is assumed). Closure power limits are assumed to be the same as for the hard rock saturated backfilled "open" concept (Section 3.2.1) but some increase of fuel age at closure is needed if the argillaceous host rock thermal conductivity is much less than that assumed for hard rock (2.5 W/m-K).

Table 7. Summary of waste packaging and emplacement details for "open" in-drift emplacement of 16-PWR size packages in saturated, backfilled argillaceous rock (Concept #14A).

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	16-PWR (or 36 BWR)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	2.13 m D x 5.14 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
Emplacement power limit	18 kW
Closure power limit	2 kW (backfill conductivity 0.6 W/m-K)
Approx. fuel age at closure	150 yr
Approx. total weight of waste package	59.1 MT

3.2.3 Disposal of STAD 16-PWR Size Canisters in Salt

The following description is similar to Concept #5 from Hardin and Kalinina (2015) with changes to package loading and dimensions. The variant is referred to as #5A in this report.

Waste Packaging: SNF is transported to the repository in 16-PWR carriers, each containing four STAD canisters. The overpack geometry is the same as described for the "open" concepts above (7 cm wall thickness) but the salt overpack would be made entirely from low-alloy steel.

Emplacement: In-drift emplacement is used, with packages set directly on the floor and backfilled with crushed salt immediately. The same package spacing (20 m) and drift spacing (25 m) are used as for Concept #5, but the minimum fuel age at emplacement is increased to approximately 60 years (between Concepts #5 and #6) so that the maximum areal thermal power density is about the same (11 W/m^2). There is ample flexibility for thermal loading because of the excellent heat dissipation properties and temperature tolerance of salt.

Layout: Layout dimensions are the same as Concept #5, but the overall repository footprint, drift lengths, and volume extent of excavation are reduced by approximately 25% (representing the smaller number of waste packages).

Waste packages would weigh enough, with heavy shielding for transport underground, to require a shaft hoist with 175 MT capacity as proposed for Concept #7 (Hardin and Kalinina 2015; Hardin et al. 2013a). Alternatively, packages could be transported down a ramp by rubber-tire conveyance.

Table 8. Summary of waste packaging and emplacement details for “enclosed” in-drift emplacement of 16-PWR size packages in salt (Concept #5A).

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	16-PWR (or 36 BWR)
Overpack material	Low-alloy steel
Package dimensions	2.13 m D x 5.14 m L
Overpack total wall thickness	7 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
Emplacement power limit	5.5 kW
Approx. fuel age at emplacement	60 yr
Approx. total weight of waste package	59.1 MT

3.2.4 Disposal of STAD 16-PWR Size Canisters in Unsaturated Hard Rock

The following description is similar to Concept #8 from Hardin and Kalinina (2015) with changes to package loading and dimensions. The variant is referred to as #8A in this report.

Waste Packaging: SNF is transported to the repository in 16-PWR carriers, each containing four STAD canisters. The disposal overpack has a corrosion resistant outer layer, and a stainless steel inner layer as discussed above. The same configuration is proposed for the hard rock saturated case (Section 3.2.1) and the argillaceous case (Section 3.2.2).

Emplacement: This generic concept can be implemented in any unsaturated, hard-rock formation with reasonably low recharge flux. Drifts are ventilated for at least 50 years after emplacement and before closure. Thermal power limits are defined at repository closure rather than emplacement.

Packages are set on low pallets made from stainless steel. 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 3,000 kg). The functions of the drip shields are to protect the waste packages from damage due to rockfall or disruptive events, and to prevent or limit groundwater contact.

Ventilation prior to closure removes up to 85% of waste heat, so preclosure temperatures never approach temperature limits for the host rock, waste package, or fuel cladding. Packages are loaded end-to-end (line loading), and the power limit at closure is expressed as an average line load, with acceptable deviation of individual packages around that average. Hardin and Kalinina (2015) used the average line load and the hottest package at closure in the proposed Yucca Mountain 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 for a 21-PWR package (Concept #9 of Hardin and Kalinina, 2015). With only 16 PWR fuel assemblies (or BWR equivalent) the fuel age could be reduced to approximately 60 years.

Layout: Layout dimensions are the same as Concept #8 of Hardin and Kalinina (2015), but the overall repository footprint, drift lengths, and volume extent of excavation are reduced by approximately 25% (representing the smaller number of waste packages). Ramp access, ground support and invert construction, ventilation, and drip shield installation would be similar to Concept #8.

Table 9. Summary of waste packaging and emplacement details for “open” in-drift emplacement of 16-PWR size packages in unsaturated hard rock (Concept #8A).

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	16-PWR (or 36 BWR)
Overpack material	Corrosion resistant (e.g., Hastelloy or titanium)
Package dimensions	2.13 m D x 5.14 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
Emplacement power limit	18 kW
Closure power limit	7 kW
Approx. fuel age at closure	60 yr
Approx. total weight of waste package	59.1 MT

4. Discussion

4.1 Thermal Analysis

Peak waste package surface temperature for the "enclosed" modes presented above (Section 3.1) were previously described by Hardin et al. (2012a). Concepts #1 and #2 from Hardin and Kalinina (2015) were analyzed using a semi-analytical solution (Hardin et al. 2012b). For Concepts #1A and #2A presented here, the waste package dimensions are slightly different but the previous thermal results apply, to well within the uncertainty of thermal properties.

For disposal of 4-PWR size waste packages in salt, previously published finite-element calculations (Hardin et al. 2012a, Appendix C) provide the best available estimates of peak package surface temperature. Previous results for "enclosed" Concepts #1A, #2A and #4A are summarized in Table 10.

Table 10. Summary of peak waste package temperature estimates for "enclosed" modes used for disposal of commercial SNF in 4-PWR size STAD-canisters

			Fuel Age at Emplacement							
			10		**50**		**100**		**200**	
Host Rock and Concept	**Burnup (GW-d/MTU)**	**PWR Assy. per WP**	**Peak Temp. (°C)**	**Peak Time (yr)**	**Peak Temp. (°C)**	**Peak Time (yr)**	**Peak Temp. (°C)**	**Peak Time (yr)**	**Peak Temp. (°C)**	**Peak Time (yr)**
#1 Crystalline	60	4	256.9	17	141.2	65	92.8	134	68.9	299
	40	4	167.0	19	101.8	67	73.3	144	60.3	351
#2 Clay/Shale	60	4	341.9	12	174.0	55	106.4	111	72.9	273
	40	4	216.2	12	122.1	55	81.7	113	63.3	323
#4 Salt	60	4	110		65					
	40	4	75		60					

Estimates for "open" concepts for disposal of 16-PWR size STAD canister based packages are shown in Table 11. Thermal analyses for disposal of 16-PWR size STAD canister based packages using the crystalline, saturated, backfilled concept (#11A) and the crystalline, unsaturated, unbackfilled concept (#8A) follow the work of Hardin et al. (2013b, Section 4.6). Thermal analysis for the argillaceous, saturated, backfilled concept (#14A) was done in the same manner as #11A.

For the backfilled cases a buffer thermal conductivity of 0.6 W/m-K representing dehydrated, compacted clay was used. For all cases a ventilation period of 50 years and a closure period of 10 years were used. Peak waste package surface temperatures for 60, 40 and 20 GW-d/MT burnup are shown in Table 11. Calculations were done for decay storage times of 10, 50, 100 and 200 years prior to emplacement; for the crystalline and argillaceous cases an additional 50 years repository ventilation and 10 years closure were applied. For the salt case no ventilation or closure time was applied because backfilling would be immediate.

Peak temperatures for the 16-PWR packages are greater than for 4-PWR size packages in the same media. However, longer surface decay storage or repository ventilation time could provide the desired temperature limits. Use of a higher thermal conductivity buffer material would also result in lower peak temperatures. Peak temperature estimates for salt were obtained from a correlation of peak waste package surface temperature and waste package power at emplacement (Hardin et al., 2012a, D-5).

Table 11. Summary of peak waste package temperature estimates for disposal of commercial SNF in 16-PWR size packages based on STAD-canisters

			Fuel Age at Emplacement							
			10 yr		**50 yr**		**100 yr**		**200 yr**	
Host Rock and Concept	**Burnup (GW-d/MTU)**	**PWR Assy. per WP**	**Peak Temp. (°C)**	**Peak Time (yr)**	**Peak Temp. (°C)**	**Peak Time (yr)**	**Peak Temp. (°C)**	**Peak Time (yr)**	**Peak Temp. (°C)**	**Peak Time (yr)**
#11A Crystalline Backfilled (open)	**60**	**16**	**377**	**71**	**247**	**111**	**178**	**161**	**127**	**268**
	40	**16**	**257**	**71**	**178**	**111**	**135**	**161**	**105**	**282**
	20	**16**	**55**	**71**	**46**	**111**	**42**	**161**	**39**	**426**
#14A Argillaceous Backfilled (open)	**60**	**16**	**415**	**71**	**270**	**111**	**193**	**161**	**138**	**273**
	40	**16**	**286**	**71**	**197**	**111**	**149**	**162**	**116**	**284**
	20	**16**	**148**	**71**	**110**	**111**	**89**	**165**	**76**	**308**
#8A Hard Rock Unsaturated	**60**	**16**	**220**	**69**	**149**	**113**	**114**	**451**	**100**	**806**
	40	**16**	**156**	**69**	**113**	**113**	**98**	**543**	**87**	**732**
	20	**16**	**90**	**71**	**72**	**477**	**68**	**602**	**63**	**762**
			50 yr		**60 yr**					
			Peak Temp. (°C)		**Peak Temp. (°C)**					
#5A Salt[A]	**60**	**16**			**130**					
	40	**16**	**130**							
[A] Estimated from correlation (Hardin et al. 2012a, Figure D-5)										

4.2 Criticality

For the disposal concepts presented in this report, we assume that regulatory requirements for excluding postclosure criticality from the dose assessment can be met with the basket construction described for the STAD canister design (EnergySolutions 2015). The current technical basis for reliance on borated stainless steel for neutron absorption in flooded waste packages, is part of the STAD canister performance specification rationale (ORNL 2015a,b).

4.3 Waste Isolation

The disposal concepts presented in this report are consistent with recent generic performance analysis (Vaughn et al. 2011), and with performance assessment for the proposed Yucca Mountain repository (DOE 2008). Further definition of waste isolation performance, including consideration of disruptive events like faulting and seismicity, and climate change effects, will require site-specific information.

4.4 Cost Comparisons to Previous Work

Costs were not estimated for the specific concept variants presented in this report, however, costs for the “enclosed” modes (Section 3.1) can be taken directly from earlier work (SRNL 2015), and costs for the “open” modes (Section 3.2) can be bracketed. These cost estimates (Table 12) are based on a common set of assumptions (Hardin and Kalinina 2015; SRNL 2015) including receipt of fuel in sealed canisters suitable for disposal, at the repository. The estimates include costs for procuring and implementing disposal overpacks.

The bracketing of 16-PWR size package disposal between 12-PWR and 21-PWR estimates, provides a lower bound, and a reasonable high estimate (Table 12). The differences among these estimates are strongly related to the total number of waste packages. There are fewer 21-PWR size packages than 16-PWR size packages, and they are slightly smaller (typically 1.53 m diameter vs. 2.13 m), so the low estimate for 21-PWR size packages is a lower bound on 16-PWR size package implementation.

At the upper end, the estimates for 12-PWR size packages involve more packages, but they may be significantly less costly because they are smaller (typically 1.29 m diameter vs. 2.13). Hence, the high estimate for 12-PWR size packages is not an absolute bound, but a reasonable high estimate.

Table 12. Cost estimates for disposal of STAD-canister based waste packages totaling 140,000 MTU of commercial SNF.

Concept (variant)	Described in Section	Previous Estimate (low – high)	Bracketed by “Open” Concepts (low – high)	Cost Range (low – high)
Disposal of 4-PWR Size STAD Canisters with “Enclosed” Emplacement				
1A	3.1.1	\$62.9B – \$85.4B		\$62.9B – \$85.4B
2A	3.1.2	\$83.4B – \$116.4B		\$83.4B – \$116.4B
4A	3.1.3	\$44.1B – \$60.1B		\$44.1B – \$60.1B
Disposal of STAD Canisters in 16-PWR Size Packages				
11A	3.2.1		Concept #11 (\$57.2B – \$76.3B)	\$42.4B – \$76.3B
			Concept #12 (\$42.4B – \$57.3B)	
14A	3.2.2		Concept #14 (\$60.4B – \$80.9B)	\$46.2B – \$80.9B
			Concept #15 (\$46.2B – \$62.2B)	
8A	3.2.3		Concept #8 (\$59.8B – \$80.0B)	\$43.9B – \$80.0B
			Concept #9 (\$43.9B – \$59.3B)	
5A	3.2.4		Concept #5 (\$30.0B – \$41.6B)	\$24.7B – \$41.6B
			Concept #6 (\$24.7B – \$34.3B)	

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