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The Canister Quandary: Review of Spent Nuclear Fuel Packaging Concepts for Storage, Transportation and Disposal in the U.S.

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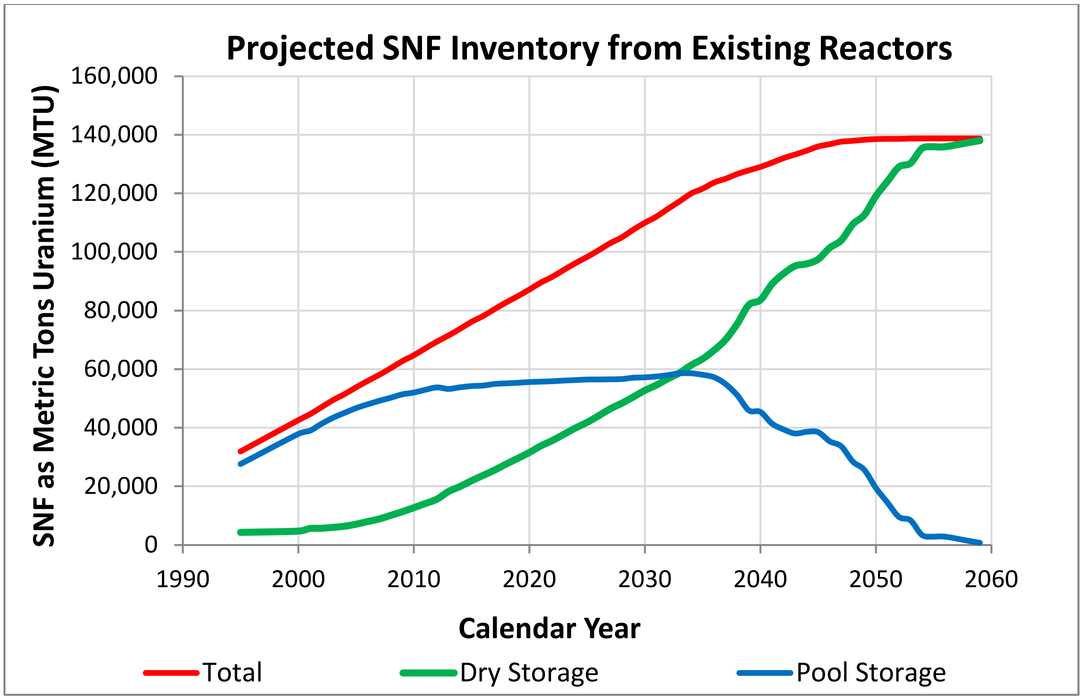
1. Introduction: The Canister Quandary

Commercial spent nuclear fuel (SNF) is accumulating in the U.S. at the rate of approximately 2,000 metric tons (MT) per year, from pressurized-water reactors (PWRs) and boiling-water reactors (BWRs). A similar amount of SNF is being transferred each year from nuclear power plant (NPP) fuel pools to dry storage. Most of the welded, sealed stainless steel canisters used for dry storage can also be used for future transport to a centralized storage facility or a geologic repository, hence these are called dual-purpose canisters (DPCs). By the year 2035 approximately half of all SNF in the U.S. is projected to be stored in DPCs (Figure 1). If nothing changes by about 2060, essentially all the SNF from existing reactors will be in DPCs (nearly 140,000 MT). Unless these DPCs can be disposed of directly, they will all need to be cut open and the SNF repackaged in new containers, at great expense. The root problem is that the DPCs in use, and those presently contemplated for future use, have not been designed or licensed for SNF disposal. This chapter identifies a range of canister design options that could be disposable, and recognizes certain solutions that are being pursued by other countries.

The disposability of SNF depends on effective safety strategies that ensure waste will be isolated in the repository, with sufficient heat dissipation, and control of nuclear criticality. Such strategies depend on repository site characteristics which may vary significantly for different host geologic media. The U.S. does not presently have any specific site in active consideration for a repository, so for a canister to be effectively disposable today it needs to be part of a disposal concept that can be demonstrated to function in multiple media. The framework presented here for understanding SNF canister disposability takes into account alternative safety strategies and different geologic media. It shows what canister design options are available, and it includes possible strategies for direct disposal of existing DPCs, an option that is under study. Functions of the canister and basket (Figure 2), and of the disposal overpack that contains the canister, are identified for a range of Design Alternatives. Example concepts for the canister and basket are proposed for these alternatives.

The potential advantages of storage canisters that are suitable for disposal, or of direct disposal of existing DPCs, include simpler SNF management, lower cost, less secondary waste (e.g., used DPC hulls), and less worker exposure to radiation during canister operations. The quandary is that canister disposability is closely linked with repository siting and selection of a disposal concept, and while siting is probably decades away, SNF continues to accumulate in DPCs of existing design. A universal canister design might help to alleviate this uneconomic situation, but the technical feasibility and design have not been determined, such as the SNF capacity and the materials used for structural and neutron absorbing elements. The quandary is somewhat unique to the U.S. because of the relatively large quantity of commercial SNF projected to accumulate, and the high reliance on dry storage in sealed, welded canisters.

This is a technical document 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.



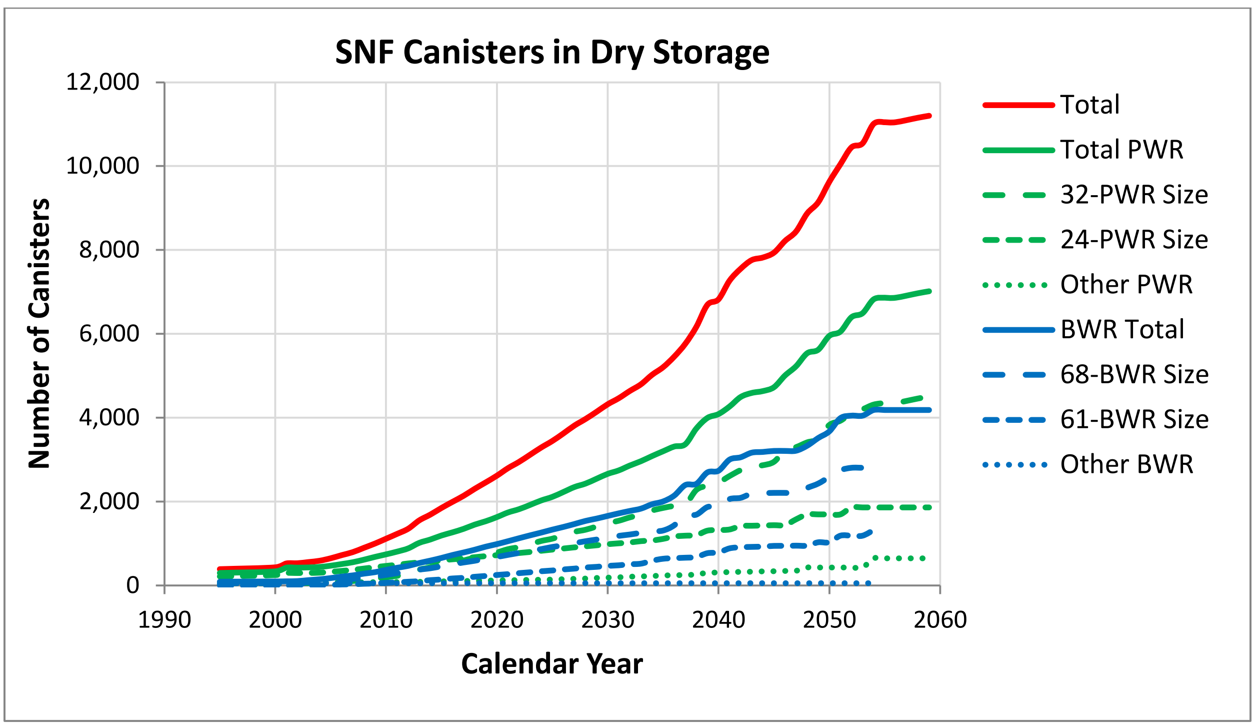


Figure 1. Projected inventory of SNF (upper), and projected number of dry-storage canisters (lower) (from Hardin et al. 2013b).

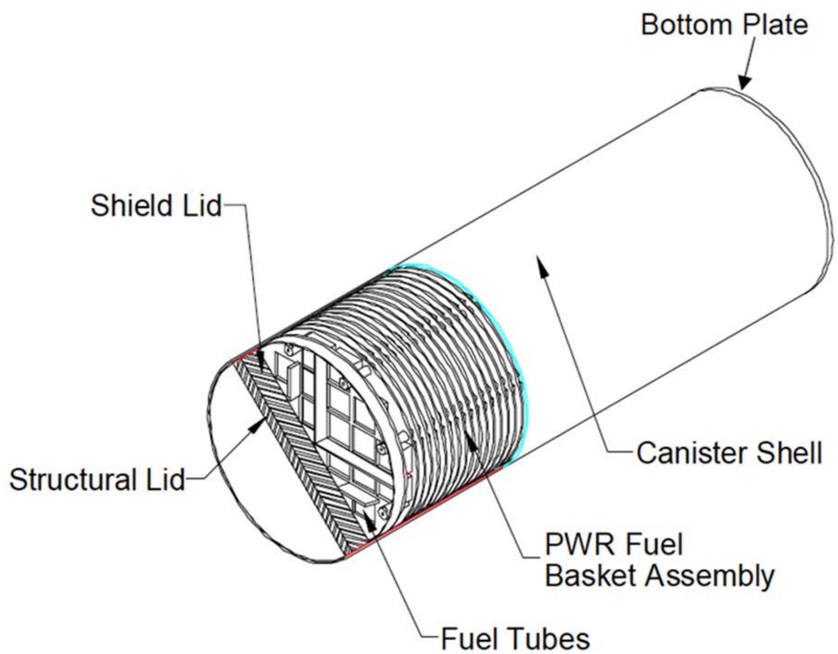


Figure 2. Typical dry storage canister (NAC International TSC-24 shown) for 24 PWR fuel assemblies.

2. Background

DPC design has changed since they came into commercial use about 20 years ago: they are larger and use various means to control criticality (see Greene et al. 2013 for a summary of DPC characteristics). Design changes have occurred in parallel with advances in the methods used to analyze thermal and criticality responses during storage and transportation. Disposal has not been a factor in DPC design due partly to the terms of the current contracts between utility companies and the government. The U.S. Department of Energy (DOE) has responsibility for final disposition of the SNF, and the utilities are to deliver it to the DOE as uncanistered ("bare") fuel.

A canister design that could be used by the utilities for storage, and is suitable for disposal also, has been proposed on two previous occasions: the multi-purpose canister (MPC) initiative of the 1990's (DOE 1994), and the 2008 transport-aging-disposal (TAD) canister concept developed for the proposed repository in volcanic tuff (DOE 2008). Both concepts were proposed for a specific site (Yucca Mountain) and both were abandoned. At present, SNF continues to accumulate in DPCs which are not purpose-designed or licensed for disposal.

So how do we start to design canisters that are suitable for SNF disposal? The answer is to look at the physical and chemical conditions of disposal, considering different geologic media. Disposal environments and applicable repository concepts have been investigated for several years in the U.S. Department of Energy's Used Fuel Disposition (UFD) R&D program (Hardin et al. 2011; 2012a; 2013a) as well as internationally. The following sections provide background discussion of disposal concepts, waste isolation strategy, approach to retrievability, thermal management, and nuclear criticality analysis.

2.1 Summary of Alternative Disposal Concepts

A range of disposal concepts needs to be defined in order to delineate how SNF canister Design Alternatives could work. A geologic disposal concept is defined to include a waste form, geologic setting, and engineering concept of operations. For this discussion the waste form is commercial SNF assemblies. The generic (non-site specific) geologic settings being considered by the UFD R&D program include:

- Crystalline, including igneous intrusive or extrusive, and metamorphic rock types
- Argillaceous (clay-rich) sedimentary rock
- Salt (bedded or domal)

The engineering concept of operations includes the waste packaging, emplacement mode (e.g., in-drift, borehole, vertical, horizontal, etc.), and other engineered barriers (e.g., buffer, backfill, plugs, seals, etc.). This chapter describes canister Design Alternatives that could ensure safety of mined geologic disposal in conjunction with other engineered barriers (disposal overpacks, backfill, etc.) and the host rock. Only mined geologic disposal concepts are considered (as opposed to other concepts such as disposal in deep boreholes).

This discussion considers canister Design Alternatives that could possibly replace existing DPC designs in the future, including smaller canisters. For example, canisters containing four fuel assemblies from pressurized-water reactors (4-PWR) are considered in addition to the current 24-PWR, 32-PWR and 37-PWR DPCs. The discussion also includes alternatives that would reopen existing or future loaded canisters for modification, and then reseal them for disposal.

2.1.1 Enclosed Emplacement Mode Concepts

An important distinction in disposal concepts is whether waste packages are emplaced in direct contact with a surrounding medium such as buffer, backfill, or host rock. This is contrasted with open modes in which packages are emplaced with surrounding, connected air spaces that can be ventilated to remove heat. The following enclosed modes are based on international experience and previous repository concept studies in the U.S. (Mariner et al. 2012; Hansen and Leigh 2011; Hansen et al. 2010).

Crystalline Rock, Enclosed (Clay Buffer) Concept – A repository constructed at several hundred meters depth in crystalline rock (igneous or metamorphic). Corrosion resistant waste packages would be installed in large-diameter borings, surrounded by buffer material consisting of swelling clay that has been dehydrated and compacted into blocks. The buffer would be installed at emplacement (e.g., Swedish KBS-3 concept; SKB 2011, Section 5.5). Possible corrosion resistant materials for the waste package outer layer include copper and titanium (SKB 2011, Section 5.4; Shoesmith et al. 1995). Waste packages would be relatively small with limited heat output to maintain buffer temperature less than 100°C (e.g., 4-PWR size with less than 1,700 W heat output at emplacement; SKB 2011, Sections 5.2 and 5.3). For the Swedish KBS-3 concept the fuel basket is proposed to take the form of a cast iron insert that separates the fuel assemblies (but contributes substantial weight). Access and service tunnels (also called drifts) would be backfilled with low-permeability, clay-based backfill at closure (Hardin et al. 2012a, Section 1.4.5.1; Hardin et al. 2013a, Section 4.1).

Salt Concept – A repository constructed at approximately 500 to 1,000 meters depth in bedded or domal salt. Disposal overpacks would consist of thick carbon or low-alloy steel, and waste packages would be emplaced on the floor in drifts or alcoves, and immediately backfilled with crushed salt (e.g., from excavating the next emplacement drift). This concept is similar to an option developed in Germany (Graf et al. 2012) and to a concept developed for heat-generating high-level waste glass (Carter et al. 2011). Waste packages of any size (including 32-PWR size or larger) could be used with heat output limited to approximately 10 kW at emplacement (Hardin et al. 2013a, Section 4.2). The fuel basket would be designed to meet preclosure structural and criticality control requirements. Any liquid water present in the repository would be chloride brine. All repository openings would be backfilled at closure (Hardin et al. 2012a, Section 1.4.5.2; Hardin et al. 2013a, Section 4.2).

Clay/Shale Enclosed Concept – A repository constructed at several hundred meters depth in clay-rich, low-permeability sedimentary rock. Waste packages would be emplaced in steel-lined horizontal borings, surrounded by clay-based buffer material. Waste packages for SNF could be made from carbon steel or other corrosion allowance material. This concept is similar to that developed in France for SNF waste (Andra 2005, Section 4.5.2). Waste packages would be small with limited heat output (e.g., 4-PWR size with heat output on the order of 1 kW at emplacement; Hardin et al. 2012a, Section 3.1.2). The fuel basket (including neutron absorber components, if any) would be designed to meet preclosure structural and criticality control requirements. Access drifts would be backfilled with low permeability clay-based backfill at closure (Hardin et al. 2012a, Section 1.4.5.3; Hardin et al. 2013a, Section 4.3).

2.1.2 Open Emplacement Mode Concepts

Open modes can be used to achieve thermal goals with larger packages containing more than four PWR assemblies, or equivalent SNF from boiling water reactors, in host media other than salt (for which waste packages could be backfilled immediately). Waste packages would be placed horizontally on the emplacement drift floor, either parallel or transverse to the axis of the drift. Emplacement drifts would remain open for cooling, remote inspection, and maintenance for as long as 50 years. Drift opening stability could be important for underground design, especially in soft sedimentary rock. Long-term stability of drift openings is one reason for limiting the operational period to 50 years (Hardin et al. 2012a, Section 1.5) but longer operations with little or no maintenance might be achieved.

Hard Rock Unsaturated, Unbackfilled, In-Drift Concept – A repository constructed and operated in competent, hard rock (e.g., igneous or metamorphic) using in-drift emplacement and forced ventilation for up to 50 years. Disposal overpacks would be made from materials that resist corrosion in chemically oxidizing conditions (e.g., BSC 2007a; DOE 2006). The hydrologic setting would be unsaturated, so backfill would not be needed but other engineered barriers might be installed such as long-lived shields to divert downward water percolation (DOE 2008; Hardin et al. 2012a, Section 1.5.3; Hardin et al. 2013a, Section 4.6.1).

Hard Rock Saturated, Backfilled, In-Drift Concept – A repository constructed and operated in competent, hard rock in a saturated hydrologic setting. This concept would use in-drift emplacement with forced ventilation for up to 50 years. Disposal overpacks would be designed to perform in the disposal environment (i.e., oxidizing or reducing conditions, or both). A low permeability buffer or backfill would be installed prior to closure, to condition the chemical and physical environment at the waste package surface, and to limit groundwater flow along repository openings. Backfill would be installed remotely, or directly if waste packages are self-shielding. Unlike argillaceous media discussed above, hard rock typically has numerous, permeable fractures. Thus, a principal function of backfill would be to impede groundwater flow, so low-permeability materials would be required (Hardin et al. 2013a, Sections 4.6.2 and 6.3.2). Postclosure performance would be similar to the crystalline enclosed concept discussed above. This backfilled concept could also be implemented in unsaturated formations (Hardin and Sassani 2010).

Argillaceous Rock, Backfilled, In-Drift Concept – A repository constructed and operated in soft, clay-rich sedimentary rock, with in-drift emplacement, and forced ventilation for up to 50 years after emplacement. Emplacement, access, and service drifts would be backfilled at closure, with a low-permeability engineered material (Hardin et al. 2012a, Section 1.5.2; Hardin et al. 2013a, Section 4.5). Backfill would be installed either remotely, or directly if waste packages are self-shielding. Options for backfill materials are discussed by Hardin and Voegele (2013, Appendix B). Backfill functions would include low permeability, and mechanical support after roof collapse so as to limit the extent of damage in the host formation. Disposal overpacks could include an outer layer of corrosion resistant material, however, less resistant packaging could be used if a complementary containment function were demonstrated for the backfill (Hardin et al. 2013a, Sections 4.5 and 6.3.3). Postclosure performance would be similar to a reference concept for Opalinus clay that uses in-drift emplacement and clay-based backfill (NAGRA 2002; 2003; 2009).

2.2 Waste Isolation Performance

A geologic repository is a system, with waste isolation functions typically described as: 1) limiting water that contacts waste forms; 2) limiting rates of radionuclide release; and 3) attenuating radionuclide concentrations along potential transport pathways. The first of these (water contact) would be assigned to the disposal overpack, while the second (rates of release) would be assigned to both the overpack and the waste form. The third function (attenuated transport) would be assigned to engineered and natural barriers outside the canister. The canister and fuel basket would not necessarily contribute to any of these functions. This is consistent with precedent (DOE 2008; 2006) wherein no long-term containment credit was taken for the SNF canister. It is also consistent with expected limitations on the corrosion lifetime of existing DPCs in disposal environments. Note that in addition to containment performance, the overpack would also provide the mechanical support needed for waste transport underground and final emplacement.

Depending on the disposal concept, the overpack could consist of a single layer or multiple layers of different materials. There are significant differences in the behavior of candidate overpack materials, especially with respect to corrosion processes, and numerous analyses have been developed to describe corrosion behaviors (BSC 2008, for example, Sections 1.1.07.00.0A, 2.1.03.10.0A and 2.1.09.03.0B). Corrosion allowance materials (e.g., cast iron, carbon steel, or low-alloy steel) and corrosion resistant materials (copper, titanium, Ni-Cr-Mo alloys) are mentioned frequently in Section 4 below. However, the primary focus of this chapter is not the overpack, but the design and performance of existing and future canisters. Assigning containment and structural functions solely to the overpack simplifies the treatment of canisters, and while overpack concepts are discussed, details are not elaborated.

Compliance with U.S. Nuclear Regulatory Commission (NRC) postclosure performance requirements (e.g., 10CFR63 Subpart L) can be assumed for all the alternative design concepts considered here (with appropriate performance of overpacks and other engineered and natural barriers). Compliance would actually need to be demonstrated through performance assessment analysis and supporting process models (for example, see DOE 2008). Waste isolation is best achieved through redundant natural and engineered barriers including the host rock, disposal overpack, and the rate-limited dissolution of SNF. Note that for some of the alternative canister/basket concepts discussed in Section 4, overpack containment integrity is used to exclude groundwater, or reduce the probability for groundwater flooding, for control of postclosure criticality.

2.3 Waste Package Retrievability

Retrievability requirements are covered in the NRC regulations on geologic disposal (see 10CFR60.111(b) and 10CFR63.111(e)), and are generally posed to ensure removal of emplaced waste from a repository should there be a safety concern of sufficient magnitude to warrant such action. For open emplacement modes, retrieval prior to backfilling would involve picking up packages and transporting them to the surface by the same means used to emplace them. Handling and containment functions would be assigned to the disposal overpack (the same functions assigned for emplacement). In salt or any medium in which backfill is emplaced soon after emplacement, or in the event of rockfall or roof collapse, retrieval would involve excavation. In such cases any additional containment functions would also be assigned to the disposal overpack. Accordingly, SNF canisters need have no retrievability function.

2.4 Thermal Management

For thermal analysis discussed here, decay storage was limited to 100 years, and repository or panel operation after waste emplacement (such as ventilation, prior to panel closure) was limited to 50 years. The overall objective to limit storage and repository operations to 150 years is comparable to previous plans (DOE 2008) which would have closed a repository when the oldest SNF would have been approximately 150 years out-of-reactor. The 100-year decay storage limit is also similar to the 60-year and 160-year timeframes considered in the NRC's draft "waste confidence" environmental impact statement (NRC 2013). These limits imply the capability for safe storage and transport of SNF to the repository for 100 years or longer after reactor discharge. They also imply that underground openings can remain stable with little or no maintenance for 50 years.

The terms repository closure and panel closure are used interchangeably in this discussion. The concept of panel closure is needed because commercial SNF will be generated in the U.S. over about 90 years (from 1965 to 2055, considering presently operating reactors and no new builds; Carter et al. 2012). A geologic repository could therefore operate for much longer than 50 years if a similar disposition path is used for all the SNF. However, disposal areas within a repository, designated as panels, could be operated and closed periodically.

Final disposal of SNF will not necessarily take until calendar 2205 (final plant shutdown in 2055 plus 150 years) because in the coming decades there will be a point in time when the repository site and disposal concept are known, and from that point forward canisters and other packaging can be designed for earlier disposal. Therefore, capability for earlier disposal could be an important factor in choosing the design for future, disposable SNF canisters.

Thermal analyses discussed in this chapter are based on limiting waste package thermal power at repository closure, to control the peak postclosure temperature in the host rock or at the waste package surface. Peak temperature limits can control threshold responses such as groundwater boiling, other phase changes in the host rock or backfill, and decrepitation of the host rock. Peak temperature at the waste package surface correlates closely with instantaneous thermal power, and package diameter is a second-order effect (Hardin et al. 2012b, Section 5). Other types of thermal constraints, such as time-temperature integrated measures, may also apply (e.g., see BSC 2008a, Section 6.5). Integrated long-term power is generally greater for larger packages than smaller ones, even if aging is used to limit peak power at closure, because of greater inventory of heat-generating nuclides with intermediate half-lives (e.g., ^{241}Am is not significantly reduced by decades of decay storage).

It is possible to perform useful thermal analyses using only thermal conduction physics, plus radiative heat transfer if there are any opening spaces around the waste packages after repository closure. Convective heat transfer can occur in porous media such as backfill or rock debris, or in fractures, but is limited especially in unsaturated settings (Stauffer et al. 1997). Also, host media and backfill materials are typically selected for low permeability in addition to other attributes.

Thermal conductivity of the host geologic medium is a key parameter, and can be characterized as low, medium, or high (less than 2, 2 to 3, and greater than 3 W/m-K, respectively). Average thermal conductivity for argillaceous media is typically low, while crystalline rock is medium and salt is high (Hardin et al. 2012b). Materials used for buffer and backfill are assumed to be dry at emplacement and throughout the maximum thermal period (i.e., up to a few hundred years). This is appropriate because maximum temperatures in clay-based engineered materials could exceed boiling, in which case they would resist hydration. Rehydration timing is uncertain and could take hundreds of years with low permeability in the host rock and low permeability in partially rehydrated engineered barriers.

Temperature tolerances of the host rock and engineered barrier materials also have an important impact on thermal management. For salt and hard rock settings, a host rock peak temperature of 200°C is reasonable based on many years of investigations (Hardin et al. 2012a; 2013a). For argillaceous media a host rock peak temperature target of 100°C is similar to limits imposed by international programs (SKB 2011, Section 5.2.1; Andra 2005, Section 1.2.3.4). For backfill materials, higher limits are needed (of the order of 150°C or greater) for disposal of larger waste packages (greater than 4-PWR size) in the 150-year timeframe discussed above. Thermal limits for argillaceous host media and clay-based backfill materials are the focus of active investigation in the UFD R&D program.

An exception to the use of simple thermal models arises when material properties change significantly during the thermal period. For example, for salt repository calculations below a numerical finite-element method is used primarily to represent backfill consolidation which increases thermal conductivity by an order of magnitude (Hardin et al. 2012a, Appendix C).

Repository maximum temperature behavior is determined by fuel burnup, fuel age at closure, waste package capacity, repository geometry including spacings, and properties of the host rock and engineered materials. Fuel burnup refers to the amount of energy produced from fission in power plants, which in turn determines the heat output of SNF for disposal. Analyses have shown that repositories in salt, hard rock and argillaceous media could meet peak temperature targets, with a range of fuel burnup, and repository panel closure when the SNF age is 70 to 150 years (Hardin et al. 2012a; 2013a). The following paragraphs summarize thermal analysis results for different disposal concepts:

Enclosed emplacement modes (crystalline and clay/shale media) – Thermal results for crystalline and clay/shale enclosed concepts are similar because of the similarity of the clay-based buffer and clay/shale host media. Where used, the clay-based buffer constitutes the dominant thermal resistance. SNF with high burnup (up to 60 GW-d/MT) could be emplaced in 4-PWR waste packages after approximately 100 years of surface decay storage, without exceeding the 100°C peak temperature target for clay-based materials in this concept. This result is similar to SNF management practices being implemented by the Swedish program. Waste packages containing a single high-burnup SNF assembly could be emplaced after approximately 10 years of surface decay storage.

Salt enclosed concept – High thermal conductivity of intact rock salt, and tolerance for elevated temperatures (200°C), allow waste packages to be emplaced relatively early and the repository to be backfilled immediately. Thermal management for DPC direct disposal in salt is illustrated with a reasonably bounding calculation, for a simple disposal concept, 32-PWR size packages containing SNF with 60 GW-d/MT burnup, emplaced and backfilled at 70 years after reactor discharge (Figure 3). The calculation shows that a 200°C salt peak temperature limit can be met using a simple disposal concept (Figure 4). Such calculations are performed using temperature-dependent rock properties, and full thermal-mechanical coupling to represent thermally activated creep of the intact salt and crushed salt backfill (Hardin et al. 2013a).

Open emplacement modes – Open, ventilated emplacement is generally required for non-salt media (hard rock and argillaceous) unless waste package capacity is approximately 4-PWR size or smaller, or unless surface decay storage can extend for hundreds of years (Hardin et al. 2012a). This statement results from thermal analysis of enclosed emplacement modes such as those being investigated in European disposal R&D programs, and temperature limits for clay-based buffer and backfill materials (e.g., 100°C). Note that open modes permit extended repository ventilation, but the emplacement drifts may still be backfilled at or before repository closure as discussed below.

Thermal histories for open emplacement modes with large waste packages (21-PWR size) were evaluated by Hardin et al. (2012a, Section 3.2). Direct disposal of typical existing DPCs (32-PWR size) using open modes was also evaluated (Hardin et al. 2013a, Section 5). The results from these calculations are summarized as follows:

- The peak temperature target (200°C) for crystalline rock (thermal conductivity 2.5 W/m-K) at the emplacement drift wall can be readily met for all package sizes, up to 60 GW-d/MT burnup, within the 150-year assumed disposal timeframe.
- For argillaceous media (1.75 W/m-K) the host rock peak temperature target (100°C) cannot be met for moderate to high burnup, without: 1) increasing drift and package spacings; and/or 2) increasing the timeframe (e.g., 200 years). Alternatively, a region of host rock around each waste package of approximately 1-meter thickness, could be heated to a higher temperature.
- Installation of backfill at or before closure dramatically increases peak temperature at the waste package surface, such that backfill peak temperature tolerance of 150 to 200°C is needed for waste packages larger than 4-PWR size, within the 150-year timeframe.

The timing of open-mode disposal of SNF in large (32-PWR size) waste packages is summarized in Figure 5. For smaller waste packages (e.g., 21-PWR size), smaller repository spacings and earlier disposal are possible (Hardin et al. 2012a, Section 3.2) but if backfill is installed the peak temperature will exceed 100°C except for smaller waste packages (4-PWR size or smaller).

Another thermal management tool that is available, especially with loading of large canisters, is thermal de-rating of the canisters by loading fewer SNF assemblies (e.g., as few as 24 assemblies in a canister designed for 32). For example, de-rating might be used with disposal of a relatively small portion of high-burnup SNF in large canisters, in argillaceous media, to meet the host rock peak temperature target. Alternatively, it might arise for backfilled concepts in order to keep the peak waste package surface temperature below a limit associated with protecting the SNF cladding from temperatures greater than 350°C (NRC 2003). Both of these de-rating situations might occur only for the youngest SNF and/or SNF with the highest burnup, so it might be inappropriate to let them dictate major features of the repository design such as the schedule for closure. Instead, the repository could be designed for low and moderate burnup, and a de-rating strategy could be used for high-burnup SNF whereby fewer assemblies are loaded into individual canisters.

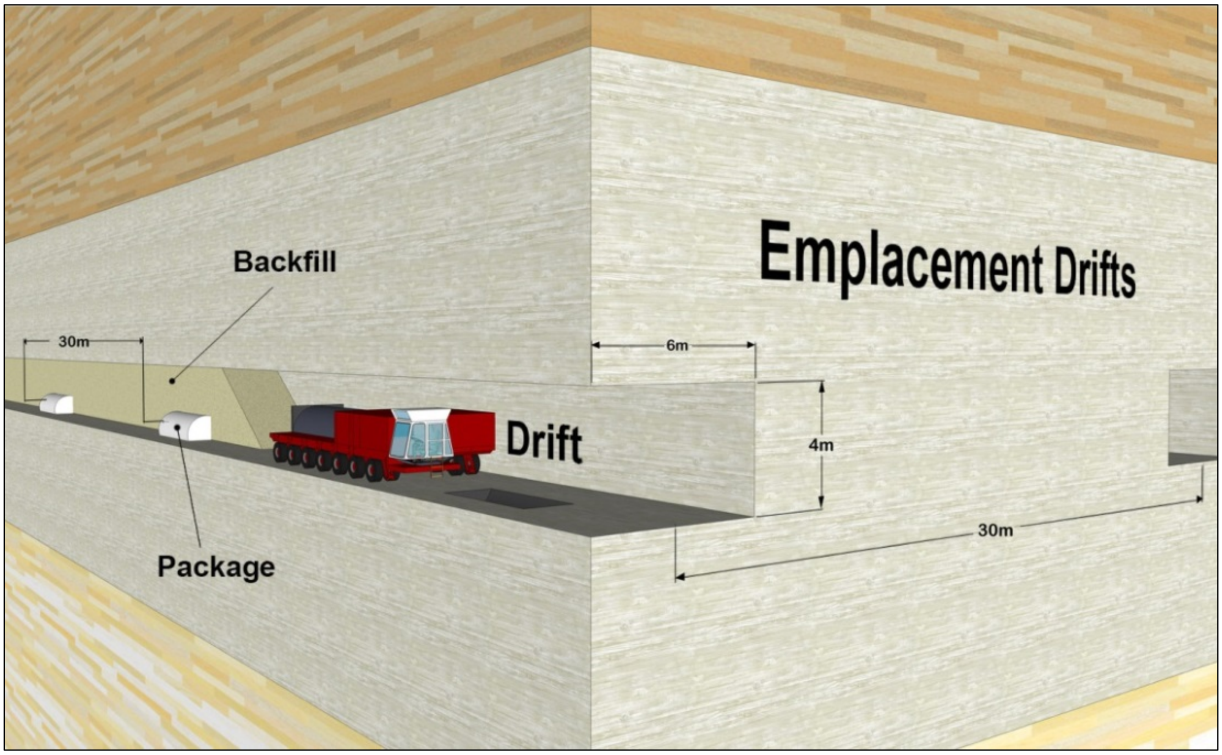
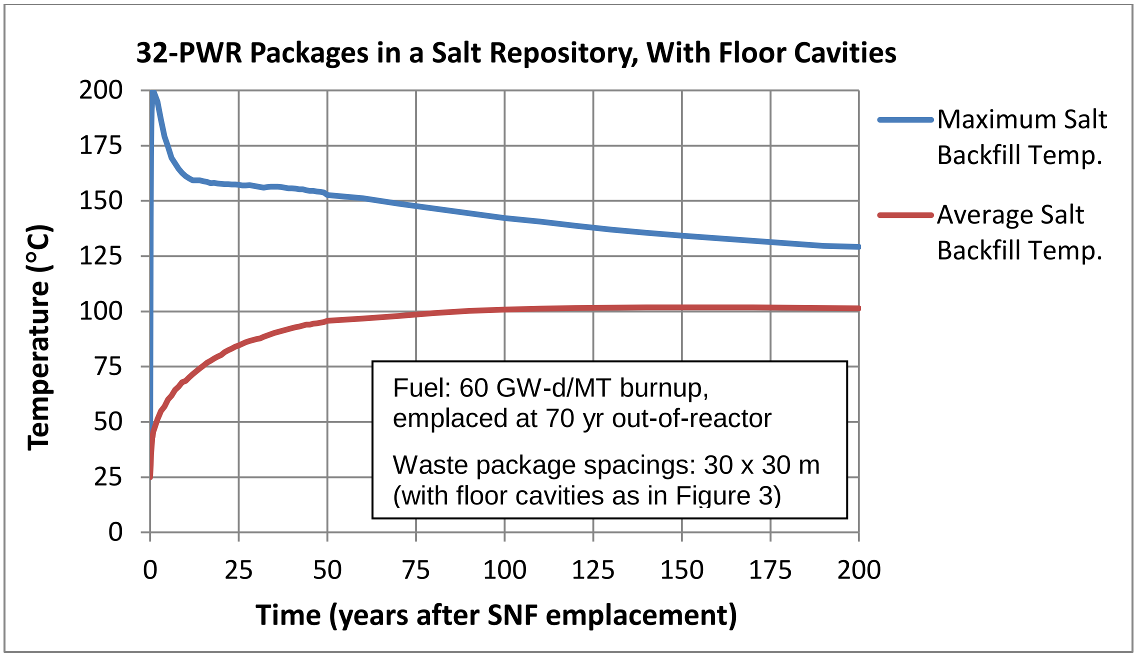
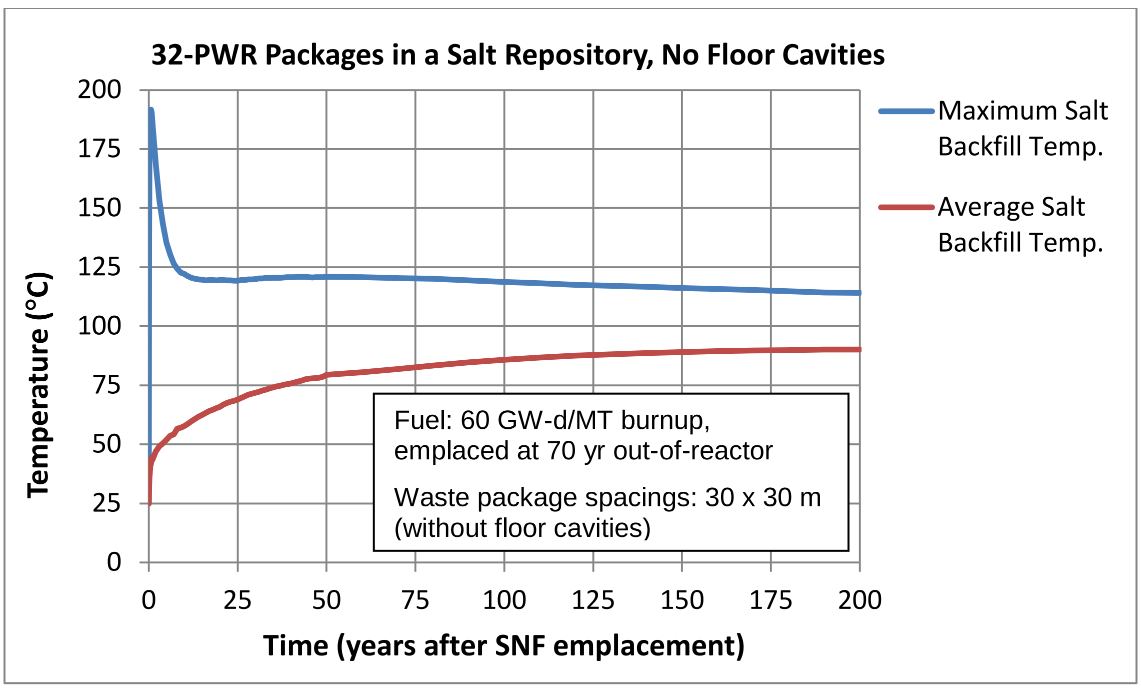


Figure 3. Schematic concept for disposal of large waste packages (e.g., containing DPCs or other large SNF canisters) in a salt repository.





Source: Hardin et al. (2013a, Figure 5-5). Note: Floor cavities are semi-cylindrical cavities cut to the diameter of waste packages, into which packages would be emplaced to facilitate heat transfer to the host salt.

Figure 4. Temperature histories for high burnup SNF in 32-PWR size packages, for the salt concept, showing ways to lower temperature with in-drift emplacement: floor cavities (upper) and 100-year decay storage (lower).

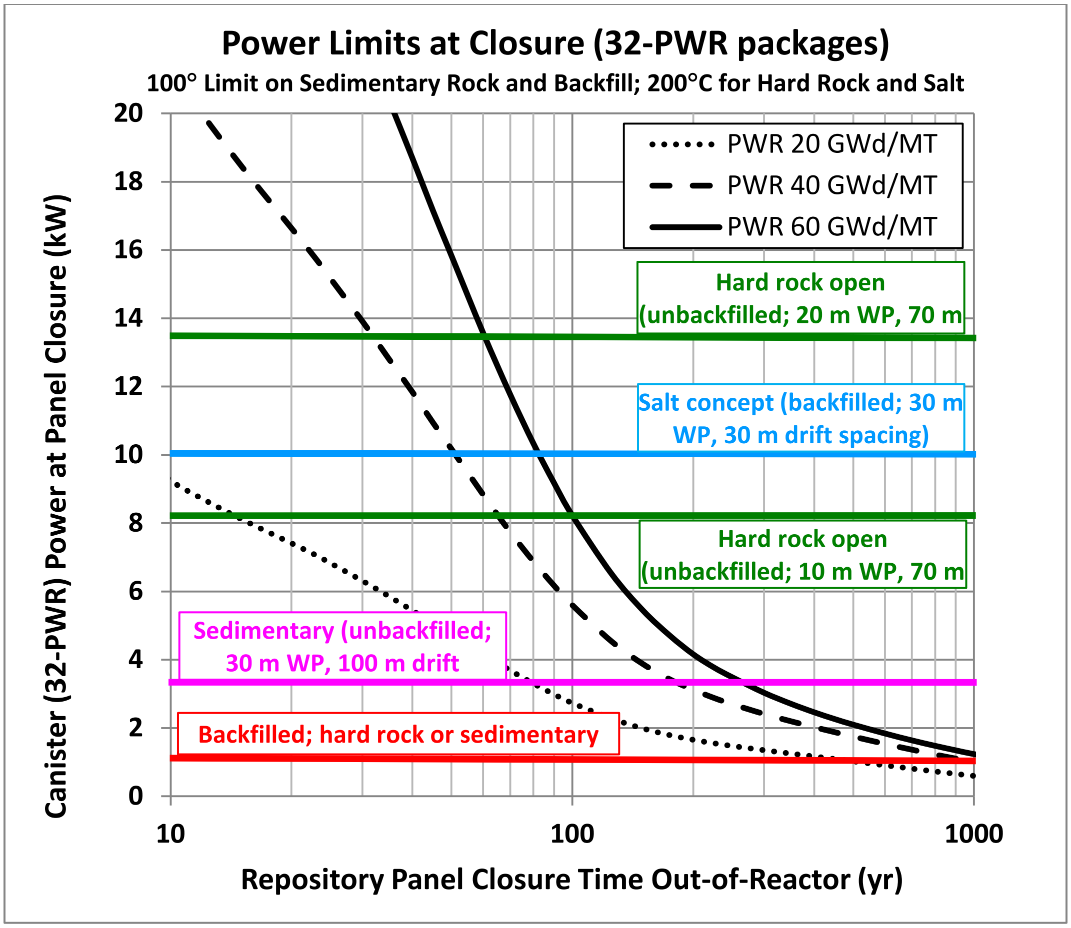


Figure 5. Summary of disposal timing for SNF with different fuel burnup (20, 40, and 60 GW-d/MT), in 32-PWR size packages, for various disposal concepts (salt, hard rock, and sedimentary, unbackfilled and backfilled). Curves represent thermal decay for 32 PWR assemblies, and intersections with horizontal lines show minimum cooling time before repository closure (after Hardin et al. 2013c).

2.5 Postclosure Criticality Control

SNF canisters that could be considered for geologic disposal will be subcritical in the disposal environment unless they are: 1) flooded with groundwater; and 2) the canister internals (e.g., basket and neutron absorbers) are degraded by corrosion. For transportation licensing (10CFR71.55) canisters are typically analyzed in a flooded condition, within a transportation overpack. For most of the canisters licensed for transport, neutron absorber features such as Boral® sheets are installed at manufacture and prevent criticality under such temporary accident conditions. For disposal criticality a similar flooded analysis may also be used, but with basket and neutron absorber components degraded from long-term exposure to groundwater. Analysis to-date suggests that some existing canisters may have conservative design, and/or may be loaded with less reactive SNF, so that degradation of the internals could occur without causing criticality (Hardin et al. 2013a; Sections 8 and 10). Direct disposal of such canisters is discussed in Section 4.3 for Design Alternative III.D. The following discussion focuses on the significant fraction of DPCs for which flooding and degradation of internals would likely lead to criticality.

Neutron absorbing features used in existing SNF canisters have been summarized (Hardin et al. 2013a, Section 3.1.4) and the materials used in existing canisters have been tabulated (Greene et al. 2013). Features include absorber plates interposed between adjacent assemblies, flux traps, control rods, depleted burnable poisons in different configurations, etc. Absorbing materials used in different canister designs typically include the aluminum-boron-carbide cermet Boral®, nonmetal matrix composites, Metamic®, Bortec®, Tetrabor®, and Carborundum B_4C (Rigby 2010).

Analysis of postclosure criticality in accordance with 10CFR Part 63 must consider whether the total probability is greater than 10^{-4} for 10,000 years after disposal (i.e., 10^{-4} per repository realization, see 10CFR63.102(j)). If the probability is greater than 10^{-4} then a consequence assessment may be performed, and the result combined probabilistically (i.e., as risk) with the dose consequences from other repository release pathways (DOE 2003, Section 3.7). This report emphasizes strategies for limiting the total probability of postclosure criticality to less than 10^{-4}. Even if a consequence approach were selected, one or more of the alternatives discussed in Section 4 would still be used to limit the probability of a criticality event.

The timeframe for criticality analysis is assumed to be 10,000 years based on prior regulation (10CFR63.114). Dose assessment is extended beyond 10,000 years, through the "period of geologic stability." However, for screening criticality FEPs under the assumed regulatory framework (see Section 3 below) only a 10,000-year regulatory period needs to be analyzed.

As stated above, flooding and degradation of fuel canisters are necessary for criticality. If the geologic setting or disposal overpack excludes groundwater for at least 10,000 years, then the SNF will remain subcritical for that time. Some host geologic media may exclude groundwater over the long term, such as the salt concept. In host media where groundwater is abundant, or may become so in the future, overpack containment performance by itself may be insufficient for excluding SNF criticality on the basis of low probability (less than 10^{-4} per repository realization). That is because studies of manufacturing defects show that the probability of an early package failure (generalized to result in waste package breach) is of the order of 10^{-5} per package (BSC 2007b, Table 7-1) whereas a value less than 10^{-8} per package (i.e., per disposal overpack) would be needed to exclude criticality for 10,000 waste packages for which flooding results directly from breach. The possibility of such a high-reliability containment is addressed by Design Alternative III.A. External events such as seismicity and faulting might also contribute to overpack breach, increasing the total probability of criticality.

Once canisters are flooded, criticality control depends on the configuration of the degraded internals. Degraded configurations for an open, hard rock, unsaturated disposal concept have been analyzed extensively (BSC 2008c; 2008d). In more recent numerical simulations (Clarity and Scaglione 2013) two degraded configuration cases were considered: 1) a loss-of-absorber case in which neutron absorber plates are replaced by groundwater; and 2) a basket degradation case in which both the absorber plates and the basket are removed and the assemblies are positioned together tightly. Postclosure criticality analyses are reported for existing DPCs from two storage sites, using burnup credit (i.e., neutron interaction with transmuted isotopes) for 28 nuclides, actual assembly burnup data, and actual canister loading data. The results showed that some, but not all, of these DPCs could be subcritical after flooding with groundwater, even with highly degraded internals. These are stylized configurations designed to be reasonably conservative, and additional realism might decrease reactivity. For example, reactivity might be decreased by including in the model: metal corrosion products (displacing water as a neutron moderator), irradiated control rods (displacing water), and fuel degradation (lowering the hydrogen content of interstices between fuel rods). Analysis of degraded configurations for DPC disposal is an area of ongoing investigation (Hardin et al. 2013a, Sections 8 and 10).

Canister misloading is a configuration anomaly that could contribute to nuclear reactivity in the event of waste package breach and flooding. The probability of misloading a SNF assembly into a waste package is of the order of 10^{-5} per assembly, and the joint probability of a misload leading to the potential for criticality is of the order of 10^{-7} (BSC 2008d, Section 4.1.5). These probabilities might be decreased using additional direct measurements for verification of loaded canisters before sealing (i.e., in fuel pools). Criticality analysis numerical methods and supporting data are beyond the scope of this chapter, but current reviews and technical reports are available (Wagner et al. 2011).

3. Assumptions

Assumptions have been identified for evaluating the possibility for direct disposal of SNF in existing DPCs (Hardin et al. 2013a; Hardin and Howard 2013), and by analogy, for evaluating other canister alternatives. Highlights include:

- Disposal timeframe is limited to 150 years after discharge (maximum of 100 years decay storage, and 50 years of repository operations such as forced ventilation).
- Regulatory context for disposal licensing will be similar to 10CFR63 and 40CFR197, including a 10,000-year performance period for screening criticality FEPs.
- Reactor operating records can be accessed to provide more realistic inputs to criticality models.
- Criticality consequence analysis may be incorporated into FEP screening arguments and repository performance assessment.

With some exceptions, these assumptions could be applicable to evaluations needed to design and license new canister designs intended for direct disposal.

4. SNF Canister/Basket Design Alternatives

This section offers a set of alternatives for overpack, canister, and basket characteristics to achieve waste isolation, thermal management goals, and postclosure criticality control. This constitutes a range of approaches for addressing the requirement from 10CFR72:

> *(m) To the extent practicable in the design of spent fuel storage casks, consideration should be given to compatibility with removal of the stored spent fuel from a reactor site, transportation, and ultimate disposition by the Department of Energy. §10CFR72.236(m)*

The Design Alternatives and examples are summarized in Table 1. Some observations common to all the alternatives are discussed here for brevity:

As noted previously, waste containment and structural functions are assigned to the disposal overpack. Unless disposal overpack containment is specifically discussed for the alternatives, overpacks could be constructed either from corrosion allowance materials (e.g., carbon steel) with containment lifetime of the order of 10^4 years, or from corrosion resistant materials (e.g., Ni-Cr-Mo alloys) with containment lifetime of 10^5 to 10^6 years. The selection would depend on the safety strategy for a particular Design Alternative.

The term “multi-purpose canister” (MPC) is defined to mean a canister that could be licensed for storage, transportation, and disposal. The term “bolted closure” refers to mechanical closures with seals, that can be opened and resealed without cutting the canister or lid. Thus, “bolted” closures could involve threaded lids, swaging, etc. and would not necessarily mean the use of bolts. The term “resealing” is reserved for bolted closures, and “rewelding” for welded canisters that have been cut open for modification of internals, but will be reused. All canister alternatives discussed here would be MPCs, but some would have bolted closures, some welded closures, and some would have combinations. All would include redundant closures (here called inner and outer lids) as required by 10CFR72.236(e).

Table 1. Summary of Design Alternatives for SNF canister disposability.

Group	Design Alternative	Example	Description
Group I Small canisters (up to 4 PWR assemblies or BWR equiv.) with no neutron absorbers	**I.A Small capacity waste package**	I.A.1 Example: Small capacity waste package, welded closure	Canisters closures could be welded without sacrificing flexibility for disposal in a full range of geologic settings, because criticality control may not depend on whether flooding occurs, or on groundwater composition (Section 4.1). This type of canister could also be used in the corresponding can-within-can alternative (Example II.C.1).
		I.A.2 Example: Small capacity waste package, bolted closure	Bolted canisters could preserve flexibility to modify the internals (e.g., add fillers; Section 4.5), or unload the SNF and reuse the canister. This type of canister could also be used in the corresponding can-within-can alternative (Example II.C.2).
	I.B Small capacity waste package combined with heavy insert	I.B.1 Example: Small capacity waste package combined with heavy insert, welded closure	Canisters closures could be welded without sacrificing flexibility for disposal in a full range of geologic settings, because criticality control would not depend on whether flooding occurred, or on groundwater composition.
Group II Larger canisters with bolted closures or bolted/welded combinations	**II.A Bolted closures (both inner and outer canister lids)**	II.A.1 Example: Larger canisters, bolted inner and outer closures	Bolted canisters could enhance flexibility to reopen and add reactivity control improvements or unload the SNF and reuse the canister. Postclosure performance of reactivity control improvements (e.g., “surrogate” control rods, Section 4.2) might depend on congruent degradation with SNF rods. Canister design could facilitate later installation of a third, welded lid as needed for transportation or disposal.
	II.B Bolted closure combined with welded closure	II.B.1 Example: Larger canisters, bolted inner and welded outer closures	The outer lid could be cut off and removed (e.g., dry) for access to the inner bolted lid without exposing fuel. The inner lid and shield plug could be readily removed for modification of absorber and structural components prior to disposal, then replaced and resealed. Canister design could add the capability to re-weld another outer lid, even if the original outer lid is cut off by cutting through the canister wall.
		II.B.2 Example: Larger canisters, welded inner and bolted outer closures	Removing the outer bolted lid would be relatively straightforward and could be done dry, but cutting out the inner lid would involve essentially the same choices as for existing (welded) DPC designs discussed in Group III.
	II.C Can-within-can arrangements using bolted or welded closures	II.C.1 Example: Larger can-within-can systems with welded inner/welded or bolted outer canisters	Inner canisters would have welded closures (similar to Example I.A.1), and could be cool and nonreactive enough to never require reopening for disposal. The outer canister lid could be welded or bolted. However, the inner canisters could be credited for storage and transportation licensing as containment envelopes, reducing performance requirements on a bolted outer canister closure could be practical.

Table 1, continued. Summary of Design Alternatives for SNF canister disposability.

Group	Design Alternative	Example	Description
	II.C Can-within-can arrangements using bolted or welded closures (continued)	II.C.2 Example: Larger can-within-can systems with bolted inner/welded or bolted outer canisters	Inner canisters would have bolted closures (similar to Example I.A.2). These could also be cool and non-reactive enough to never require reopening for disposal, and bolted closures may have operational advantages during loading and dewatering. The outer canister lid could be welded or bolted, but a welded lid could simplify monitoring of canister integrity during storage.
Group III Existing DPC designs (welded closures) used for disposal without reopening	**III.A High reliability (10^{-8}/yr) overpack performance**	III.A.1 Example: Existing DPC designs with high-reliability overpacks	High-reliability disposal overpack performance prevents breach and DPC flooding and degradation, in a saturated or unsaturated environment, for at least 10,000 years.
	III.B Disposal in unsaturated conditions with multiple engineered and natural groundwater exclusion/diversion barriers	III.B.1 Example: Existing DPC designs loaded with relatively non-reactive SNF	Canisters remain subcritical even after flooding with groundwater of dilute composition, and degradation of basket structure and neutron absorbers. Demonstrated using analysis of degraded configurations, with as-loaded assembly arrangements and fuel burnup characteristics.
		III.B.2 Example: Existing DPC designs protected by multiple barriers	Multiple natural and redundant engineered barriers prevent DPC flooding (e.g., in an unsaturated disposal environment) for at least 10,000 years.
	III.C Flooding possible only with chloride brine	III.C.1 Example: Existing DPC designs in a salt repository	Disposal of DPCs in a salt repository, with thick-walled steel overpacks, prevents flooding and mitigates the consequences of any condition that might cause flooding (i.e., with chloride brine).
	III.D Disposal of existing DPCs containing relatively non-reactive SNF, so that packages are subcritical after flooding and degradation of canister internals	III.D.1 Example: Existing DPC designs loaded with relatively non-reactive SNF	Canisters remain subcritical even after flooding with groundwater of dilute composition, and degradation of basket structure and neutron absorbers. Demonstrated using analysis of degraded configurations, with as-loaded assembly arrangements and fuel burnup characteristics.
Group IV Existing DPC designs (welded closure) used for disposal with modifications	**IV.A Reactivity control improvements**	IV.A.1 Example: Reactivity control improvements in DPCs at initial loading	Future disposal of existing DPC designs, with reactivity control improvements installed at initial loading, for postclosure criticality control.
		IV.A.2 Example: Reactivity control improvements in reopened/rewelded DPCs	Future disposal of existing DPC designs, with reactivity control improvements installed after reopening. Canisters would be cut open, modified, and rewelded.
	IV.B Fillers for reactivity control	IV.B.1 Example: Fillers installed in DPCs at initial loading	Future disposal of existing DPC designs, with filler installed at initial loading, for postclosure criticality control.
		IV.B.2 Example: Fillers installed in reopened/rewelded DPCs	Future disposal of existing DPC designs, with filler installed after reopening (e.g., via dewatering ports). If canisters are cut open for filler installation (i.e., lids removed), they would be reused, by rewelding lids or by welding on a new head that fits on the canister end.

Table 1, continued. Summary of Design Alternatives for SNF canister disposability.

Group V Multi-purpose canisters with long-lived baskets and neutron absorbers	**V.A Larger canisters, with basket and absorber materials selected for longevity in oxidizing environments**	V.A.1 Example: Larger canisters and baskets designed for ≥10,000-year life exposed to oxidizing disposal environments	Larger canisters with stainless steel based canister shell and basket materials, designed to maintain initial SNF basket configuration and neutron absorption for >10,000 years exposure to groundwater or humidity environments, in oxidizing conditions.
	V.B Larger canisters, with basket and absorber materials selected for longevity in a range of chemically reducing and oxidizing environments	V.B.1 Example: Larger canisters and baskets designed for ≥10,000-year life exposed to reducing or oxidizing disposal environments	Larger canisters with corrosion resistant canister shell and basket materials, designed to maintain initial SNF basket configuration and neutron absorption for >10,000 years exposure to groundwater or humidity environments, in reducing or oxidizing conditions.

4.1 Group I – Small Canisters (up to 4 PWR assemblies or BWR equivalent) With No Neutron Absorbers

Small capacity waste packages can be used with both enclosed emplacement modes (Section 2.1.1) or open modes (Section 2.1.2), and therefore offer maximum flexibility for thermal management in disposal. The alternatives in this group different with respect to the type of basket used to position the SNF (fabricated from plate and tube, or solid cast insert). Bolted or welded closures may be used.

Design Alternative I.A – Small capacity waste package

Capacity: Up to 4 PWR assemblies (or BWR equivalent) depending on enrichment and burnup.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is consistent with the safety strategy.

Canister and Basket: Maintains positions of assemblies after flooding with groundwater (to be consistent with analyzed configurations) for at least 10,000 years after waste package initial breach (which might occur soon after repository closure). Maintains material compatibility with a range of potential overpack designs.

Discussion: If canister capacity is small enough, criticality control for intact or degraded canisters flooded with groundwater could require no internal absorbers. Examples include 1- or 2-assembly legal-weight transport casks described by Greene et al. (2013). The subcritical limit for fuel assemblies positioned in a tight array is on the order of four or fewer PWR assemblies (or BWR equivalent) by analogy to analysis of partial flooding of a horizontal, 32-PWR canister (EPRI 2008a, Section 3.4). Canisters could be de-rated by loading fewer than four PWR assemblies, if necessary to control criticality when flooded. Alternatively, subcriticality might be ensured by situating the repository in a host medium with saline groundwater (and not necessarily saturated brine as discussed for Design Alternative III.C). Criticality control without neutron absorber materials could have the advantage that the safety strategy would not rely on long lifetimes of those materials. Spent fuel loading and packaging steps could be performed in a fuel pool, or dry in a hot cell. Dewatering procedures might be modified (e.g., by operating with the canister in a heated cell; SKB 2010b, Section 6.1) if the small canisters do not get hot enough.

Example I.A.1 – Small capacity waste package, welded closure - *Canister closures could be welded without any need for further modification, for disposal in a wide range of geologic settings, if subcriticality is maintained when flooded with fresh (dilute) or mildly saline water (e.g., seawater).*

Example I.A.2 – Small capacity waste package, bolted closure – *Bolted canisters could maximize flexibility to modify the internals (e.g., to add fillers as in Design Alternative IV.B), or to unload the SNF and reuse the canister.*

Design Alternative I.B – Small capacity waste package combined with heavy insert

Capacity: Up to approximately 4 PWR assemblies (or BWR equivalent) depending on enrichment and burnup.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is consistent with the safety strategy.

Canister and Basket: Maintains positions of assemblies after flooding with groundwater (to be consistent with analyzed configurations) for at least 10,000 years after waste package initial breach (which might occur soon after repository closure). Maintains material compatibility with a range of potential overpack designs.

Discussion: A few assemblies separated from each other within a solid insert also may require no absorbers when flooded with groundwater. Examples include the 4-PWR and 12-BWR SNF waste packages proposed for disposal in Sweden (SKB 2011). In the KBS-3 concept the cast iron insert is assigned to bear externally applied loads such as would be applied by the swelling clay buffer. It also reduces reactivity by spreading the assemblies apart, displacing moderator between them. Note that whereas a massive, monolithic cast iron insert could be appropriate for SNF disposal, other approaches to insert design and fabrication could be more appropriate for other waste forms (SKB 2013).

The SNF canister capacity could be limited by weight, since the KBS-3 insert alone weighs between 13.7 and 16.4 MT, compared to the total waste package weight of 24.6 to 26.8 MT (SKB 2010a, Section 1.7). For larger capacity (e.g., more than four PWR assemblies) some efficiency in total weight might result if criticality control could be achieved without further expanding the spacing between assemblies.

In the Swedish example, center-to-center spacings between assemblies are maintained (SKB 2011, Section 5.4.3; 37-cm separations, compared to 21-cm side dimensions for PWR assemblies). Burnup credit analysis is used for flooded canisters (SKB 2011, Section 8.4.1; $k_{eff} < 0.95$ including uncertainties). A burnup-enrichment loading curve was calculated for a reference waste package design (SKB 2010a, Table 2-3). Exceedance of this loading curve by individual assemblies may be possible based on package-specific analysis (SKB 2011, Section 5.3.4). Cast iron composition is controlled to limit neutron reflection (C<4.5% and Si<6%), and to limit gamma-embrittlement (Cu<0.05%)(SKB 2011, Section 5.4.1). Spent fuel loading and packaging steps could be performed in a fuel pool, or dry as proposed for the encapsulation plant for the Swedish repository (SKB 2011, Section 5.4.2).

One advantage of this alternative could be that degradation of the heavy cast iron insert will produce voluminous corrosion products that stabilize the fuel geometry and displace groundwater (compared to canisters with open spaces between assemblies). Iron corrosion products that form in reducing chemical environments, such as magnetite (Fe_3O_4), tend to form cohesive, compact layers (Smart 2008.) Whereas the KBS-3 concept uses copper as a corrosion-resistant outer layer on the waste package, for oxidizing environments a different corrosion resistant material could be used, and it could help maintain a reducing environment within the canister. Progressive degradation of the insert could increase neutron reflection but also increase moderator displacement by partly displacing interstitial water from within assemblies.

Example I.B.1 – Small capacity waste package combined with heavy insert, welded closure – *Like Example I.A.1, canister closures could be welded without any need for further modification, for disposal in a wide range of* *geologic settings, if subcriticality is maintained when flooded with fresh (dilute) or mildly saline water (e.g., seawater).*

4.2 Group II – Larger Canisters with Bolted Closures or Bolted/Welded Combinations

This group includes alternatives with larger capacity canisters (greater than 4-PWR size, possibly 9- or 12-PWR size or larger; or BWR equivalent) based on new designs. Bolted canisters could be reopened and resealed without disposing of major canister hardware. Heat output would be related to canister capacity and SNF characteristics, and would be independent of the type of closure. For canisters up to the size of existing DPCs, heat output and its effects would fall into the range of canisters already analyzed (Section 2.4).

For typical SNF enrichment and burnup, criticality control features would be needed for transportation and possibly disposal. Bolted closures could provide flexibility to match canister fuel loading and criticality control features, to future transportation and disposal requirements. Canisters with bolted closures could be initially loaded with one absorber configuration, then reopened later for modification as needed for disposal. Criticality control features to be added upon reopening (see Group IV) could be selected to serve both for transportation and disposal, once the disposal requirements are known (e.g., canisters loaded with PWR SNF in borated fuel pools). Alternatively, certain fuel assemblies could be removed prior to final packaging for disposal. Because the objective for Group II is flexibility at relatively low cost, basket structure and criticality control features built into the canisters at manufacture would likely not include long-lived materials such as those used for later Group V, but could be added later.

Design Alternative II.A – Bolted closures (both inner and outer canister lids)

Capacity: Any capacity up to limits imposed by handling, hoisting, and transportation.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy.

Canister and Basket: Maintains positions of assemblies after flooding with groundwater (to be consistent with analyzed configurations) for at least 10,000 years after waste package initial breach (which might occur soon after repository closure). Maintains material compatibility with a range of potential overpack designs.

Discussion:

Canisters with two bolted closures would offer maximum flexibility, but mechanical seals could be more costly to maintain (periodic testing requirements are typically required for bolted, but not welded closures).

Example II.A.1 – Larger canisters, bolted inner and outer closures – *One example of double-bolted closures is the CASTOR-V and CASTOR-X casks used at the Surry NPP in southeastern Virginia (Greene et al. 2013) and similar casks at many dry storage locations internationally, have two bolted lids. These are heavy, self-shielded storage casks licensed for storage but not transport in the U.S. Thin-walled canisters (with separate storage and transportation casks) with bolted lids are not generally available.*

Design Alternative II.B – Bolted closure combined with welded closure

Capacity: Any capacity up to limits imposed by handling, hoisting, and transportation.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy.

Canister and Basket: Maintains positions of assemblies after flooding with groundwater (to be consistent with analyzed configurations) for at least 10,000 years after waste package initial breach (which might occur soon after repository closure). Maintains material compatibility with a range of potential overpack designs.

Discussion: Same internal configurations possible as for bolted lids (Design Alternative II.A) but with one welded inner or outer lid. Possible advantages of combined welded and bolted closures include simplified containment monitoring during storage, and simplified accident analysis for transportation licensing.

Example II.B.1 – Larger canisters, bolted inner and welded outer closures - *The outer lid could be cut off and removed (e.g., dry) for access to the inner bolted lid without exposing fuel. The inner lid and shield could be readily removed for modification of internal components prior to disposal, then replaced and resealed. Canister design could add the facility to re-weld another outer lid (e.g., an extra chamfer).*

Example II.B.2 – Larger canisters, welded inner and bolted outer closures – *Removing the outer bolted lid would be relatively straightforward and could be done dry, but cutting out the inner lid would involve essentially the same choices as for existing (welded) DPC designs discussed in Group III.*

Design Alternative II.C – Can-within-can arrangements using bolted or welded closures

Capacity: The inner canisters would be limited to 4-PWR capacity (or BWR equivalent), while the outer canisters could hold any number of inner canisters, up to limits imposed by handling, hoisting, and transportation.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy. Disposal overpacks would contain the outer canister, which in turn would contain two or more inner canisters.

Canister and Basket: For the inner canisters: maintains positions of assemblies (consistent with analyzed basis), after flooding with groundwater, for at least 10,000 years after waste package initial breach (e.g., breach from early failure).

For the outer canister, maintains positions of inner canisters (consistent with analyzed basis), after flooding with groundwater, for at least 10,000 years after waste package initial breach. Maintains material compatibility with inner canisters, and with a range of potential overpack designs.

Discussion: The can-within-can ("canister-within-canister" of Scaglione et al. 2012) alternatives would package SNF in small canisters (up to 4-PWR size, or BWR equivalent), and provide a larger canister to hold two or more small ones. Sealing SNF in small canisters would preserve flexibility to use small waste packages (Group I) in the repository without exposing SNF during handling. The small inner canisters could be sealed in small overpacks for disposal using both enclosed and open emplacement modes. This approach would help to meet thermal and criticality control requirements for a wide range of disposal concepts, while also providing for handling, storage, and possibly transportation and disposal in a larger container.

Following the methods used currently for DPCs, shielding would be installed on the inner canisters, integral to the lid and/or as a separate shield plug. Shielding for the outer canister would be limited to that needed to control radiation scattered from the inner canisters.

Differences between welded and bolted outer canister closures are somewhat indistinct, so these options are not identified below as separate examples. Inner canisters, regardless of type, would tend to limit contamination of the outer canister which could potentially be reused or disposed of in a landfill. Bolted closure of the outer canister, or design features to allow welding a replacement outer lid after reopening, might be preferred to allow later installation of a filler (Group IV) in the interstitial volume between the inner canisters. Such capability could require additional ports or pass-throughs as part of the original outer canister basket design.

Loading of the smaller and more numerous inner canisters could impose operational burdens on fuel handling facilities (e.g., at NPPs), especially the time required for canister sealing and dewatering.

Example II.C.1 – Larger can-within-can systems with welded inner/bolted or welded outer canisters – *Inner canisters would have welded closures (similar to Example I.A.1), and would be cool and nonreactive enough to never require reopening prior to disposal. The outer canister lid could be welded or bolted. The inner canisters could be credited for storage and transportation licensing as containment envelopes, instead of, or in addition to the outer canister.*

Example II.C.2 – Larger can-within-can systems with bolted inner/bolted or welded outer canisters – *Inner canisters would have bolted closures (similar to Example I.A.2). These would also be cool and non-reactive enough to never require reopening prior to disposal, and bolted closures could be faster to implement. The outer canister lid could be welded or bolted, but a welded lid could simplify monitoring of canister integrity during storage.*

4.3 Group III – Existing DPC Designs (welded closures) Used for Disposal Without Reopening

For this group of alternatives, neutron absorber materials such as Boral® which are used for criticality control during storage and transportation, are assumed to corrode in fewer than 10,000 years if the canister is breached. Waste isolation performance would be allocated to the disposal overpack, and thermal management would be described by the salt concept or an open emplacement mode (Section 2.4).

Group III consists of existing DPC designs without internal modifications. Heat output would be related to canister capacity and SNF characteristics. For canisters up to the size of existing DPCs, heat output and its effects would fall into the range of canisters already analyzed (Section 2.4). Postclosure criticality control would be assigned to external features (overpack, other barriers) or to non-reactive fuel characteristics. Group III is unique in assigning control to external features, because it represents possible pathways for direct disposal of existing DPCs without reopening.

Design Alternative III.A – High reliability (10-8) overpack performance

Capacity: Consistent with existing DPC designs and loading practices.

Overpack: Mechanically robust for transport and handling. Provides high-reliability containment in the disposal environment. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption for at least 10,000 years (without overpack breach, or until breach by disruptive events).

Discussion: This alternative would prevent criticality by preventing flooding of the waste canister for 10,000 years or longer, relying mainly on the disposal overpack. The probability of breach would need to be less than approximately 10^{-8} per package, from all causes including manufacturing defects. Overpack failure would be defined as degradation to an extent that allows flooding of the fuel canister and basket, and would therefore include localized corrosive attack. The overpack could be designed with thickness and materials such that corrosion slows with time. Note that reliance on unsaturated conditions with redundant engineered and natural barriers, is described by III.B below.

Overpacks would be designed, fabricated, loaded, and emplaced so that integrating over 10^4 overpacks gives a total probability less than 10^{-4} (per repository realization)of breach (and flooding with relatively rapid degradation of the neutron absorber components and possibly the basket). This alternative could require that the probability of manufacturing defects is small, i.e., less than previous estimates (DOE 2008). Also, at such low probability levels other hazards such as seismic ground motion and faulting could be important even for geologic settings that are not normally associated with these hazards.

This alternative could be challenging because of the high overpack reliability and quiescent geological conditions that could be needed to make it work. However, it might be part of a low-consequence argument whereby the total probability of criticality is greater than 10^{-4} per repository realization but still small, and the risks are shown by additional analysis to be insignificant.

Example III.A.1 – Existing DPC designs with high-reliability overpacks – *High-reliability disposal overpack performance prevents breach and DPC flooding and degradation, in a saturated or unsaturated environment, for at least 10,000 years.*

Design Alternative III.B – Disposal in unsaturated conditions with multiple engineered and natural groundwater exclusion/diversion barriers

Capacity: Consistent with existing DPC designs and loading practices.

Overpack: Mechanically robust for transport and handling. Provides high-reliability containment in the disposal environment. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption for at least 10,000 years (without overpack breach, or until breach by disruptive events). Degrade slowly under disposal conditions, in a humidity environment, after waste package breach (consistent with analyzed basis).

Discussion: This alternative precludes criticality by effectively preventing waste package flooding, relying on unsaturated natural conditions (especially low groundwater flux), and redundant engineered barriers. This alternative was previously analyzed by EPRI (2008b).

Sites exist where groundwater is too scarce to flood a waste package, such as the deep unsaturated alluvium of Yucca Flat, Nevada (zero net infiltration except during glacial pluvial periods; Hardin et al. 2012a, Appendix B). Other unsaturated sites may have greater percolation flux, but redundant natural and engineered diversion and exclusion barriers could significantly reduce the probability of canister flooding.

The disposal environment would likely be humid even if groundwater intrusion did not occur, and degradation of SNF in a humidity environment can produce secondary hydrous precipitates. The reactivity of the SNF waste form altered to a form such as metaschoepite (a low-temperature hydrated secondary uranium mineral) would need to be evaluated, although previous analyses have excluded this as a process leading to criticality (BSC 2008e, Section 6.2.5). For unsaturated conditions (not flooded) there would be substantial reactivity margin to accommodate degradation of neutron absorbers.

In this alternative, the probability of flooding a breached canister would be shown to be insignificant because of the performance of the overpack and other barriers outside the canister. For two engineered barriers, a sufficiently low probability of flooding might be achieved for 10^4 packages, if the barriers behave independently, the individual barrier failure rate is small, and the incidence of water as seepage is limited. Independent barrier performance would be demonstrated given the possibility of possible common initiating events such as seismicity or climate change. To be successfully implemented, this alternative could require some combination of high-reliability overpacks (Design Alternative III.A), low probability of seepage into breached packages, and slow degradation of canister internals and SNF, to achieve a total probability of criticality less than 10^{-4} in 10,000 years, per repository realization.

Example III.B.1 – Existing DPC designs protected by multiple barriers – *Multiple natural and redundant engineered barriers prevent DPC flooding in an unsaturated disposal environment, for at least 10,000 years.*

Design Alternative III.C – Flooding possible only with chloride brine

Capacity: Consistent with existing DPC designs and loading practices.

Overpack: Mechanically robust for transport and handling. Provides limited containment as needed in the salt disposal environment. Reacts with brine to form hydrogen gas and solid precipitates, consuming moisture that migrates toward waste packages. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains positions of assemblies (without overpack breach, or after breach for disrupted scenarios, consistent with analyzed basis).

Discussion: The possibility of waste package flooding in a salt repository is remote because moisture is scarce after repository closure. Intact and crushed salt in the near-field environment would be heated and dried out, then reconsolidated under lithostatic load. After a few hundred years when thermal conditions return to near-ambient, and rock stress conditions return to lithostatic, potential gradients for brine movement would be greatly reduced. Limited moisture that migrated toward waste packages (e.g., from potential gradients associated with gradients in brine saturation) would react with the disposal overpack. The overpack would have sufficient thickness of reactive, iron-bearing, corrosion-allowance material (i.e., steel) to react with such brine without resulting in breach.

Criticality analysis of existing, as-loaded DPCs (Scaglione and Clarity 2013) suggests that flooding with NaCl solutions could decrease the neutron multiplication factor (k_{eff}) on the order of -25%. This results because natural chlorine is 75% Cl-35, an effective neutron absorber. This calculated reduction in reactivity occurs even for absorber-loss and basket degradation cases. Package flooding in a salt repository might only be possible in a stylized scenario of human-caused intrusion from drilling of oil-and-gas wells. The drilling fluid in such wells is nearly always saline, and is often a chloride brine. Such drilling fluid, or other fluids produced in such wells, could be shown to have sufficient chloride concentration to prevent criticality. Seawater (~0.5 molal NaCl) is typical of saline groundwaters in many (non-evaporite) geologic settings, and the k_{eff} decrease for seawater would be only a few percent. Accordingly, this alternative would likely be limited to repositories within evaporite deposits, and particularly salt repositories.

Example III.C.1 – Existing DPC designs in a salt repository – *Disposal of DPCs in a salt repository, with thick-walled steel overpacks, prevents flooding and mitigates the consequences of any condition that might cause flooding (i.e., with chloride brine).*

Design Alternative III.D – Disposal of existing DPCs containing relatively non-reactive SNF, so that packages are subcritical after flooding and degradation of canister internals

Capacity: Consistent with existing DPC designs and loading practices.

Overpack: Mechanically robust for transport and handling. Provides high-reliability containment in the disposal environment. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption until waste package breach. Degrades slowly under disposal conditions after waste package breach (consistent with analyzed basis).

Discussion: Criticality is prevented because the SNF is relatively non-reactive and remains subcritical even when canisters are flooded, and neutron absorbers and basket structure are degraded. The possibility of relatively non-reactive SNF was evaluated by Clarity and Scaglione (2013) for selected, actual DPCs. They found that some, but not all existing DPCs could be subcritical if flooded with pure water, for the degradation cases analyzed (see Section 2.5).

For implementation this alternative would benefit from high-reliability overpack performance, and slow overpack degradation for delayed breach. The probability of criticality will be related to: 1) uncertain degradation rates for the overpack and canister internals; 2) the uncertain conceptual bases for degraded fuel configurations; 3) the probabilities for different types of misloads; and 4) the uncertainty inherent to criticality analysis.

Example III.D.1 – Existing DPC designs loaded with relatively non-reactive SNF – *Canisters remain subcritical even after flooding with groundwater of dilute composition, and degradation of basket structure and neutron absorbers. Demonstrated using analysis of degraded configurations, with as-loaded assembly arrangements and fuel burnup characteristics.*

4.4 Group IV – Existing DPC Designs (welded closures) Used for Disposal With Modifications

This group of alternatives considers how existing DPC designs could be modified at fuel loading, or in the future after canister reopening, to mitigate the potential for postclosure criticality. Reopening could be limited to accessing the dewatering ports, or it could include cutting off lids. The canister would be reused (re-packaging is beyond the scope of this report). The basket and neutron absorber materials used in existing DPC designs are assumed to corrode readily if a canister is flooded with groundwater. For similar approaches for canisters with bolted closures, see Group II.

Like Group II, which is also based on existing DPC designs, heat output would be related to canister capacity and SNF characteristics, and would be independent of internal modifications. For canisters up to the size of existing DPCs, heat output and its effects *outside* the waste package would fall into the range of canisters already analyzed (Section 2.4). Thermal effects *inside* the canisters could be strongly impacted by modification (e.g., fillers, see Design Alternative IV.B).

Design Alternative IV.A – Reactivity control improvements

Capacity: Consistent with existing DPC designs, but may be reduced as one possible measure to control reactivity.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption for at least 10,000 years (without overpack breach). Degrades slowly under disposal conditions (consistent with analyzed basis) after waste package breach.

Discussion: Reactivity control improvements could include fuel rearrangement, de-rating canisters by loading fewer assemblies, and installation of control rods. They were proposed by EPRI (2008b) for MPC-32 canisters, using "surrogate" control rod assemblies. Surrogate control rods would replace, or be added to, reactor control rods in some or all assemblies. Any irradiated control rods or other hardware that were removed would be managed as a separate waste stream (e.g., as "greater-than-Class-C" waste defined in regulation 10CFR Part 72).

Control rods could be designed to degrade at the same rate and in a similar manner to irradiated fuel rods, in any disposal environment, so that the geometrical association of neutron absorbing material with fissile fuel material in the waste package, would not be significantly changed. Importantly, this alternative could require a new type of criticality analysis that represents configurations during progressive degradation of fuel and control components, and of the basket structure.

This alternative would modify initial loading of existing DPC designs, either prior to initial closure welding, or after cutting open the canisters and rewelding. Flexibility to reopen canisters later and adjust to disposal requirements could be maximized by using the same reactivity improvement measures in bolted canisters (see Design Alternatives II.A and II.B). This alternative is a possible transitional strategy between the use of existing canisters without modification (Group III) and the use of new designs (Group V).

Example IV.A.1 – Reactivity control improvements in DPCs at initial loading – *Future disposal of existing DPC designs, with reactivity control improvements installed at initial fuel loading, for postclosure criticality control.*

Example IV.A.2 – Reactivity control improvements in reopened/rewelded DPCs – *Future disposal of existing DPC designs, with reactivity control improvements installed after cutting canisters open. Canisters would then be modified and rewelded.*

Design Alternative IV.B – Fillers for reactivity control

Capacity: Consistent with existing DPC designs and loading practices.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption until waste package breach. Facilitates filler installation with dewatering ports and pass-throughs in the basket ("mouse holes"). Degrades slowly under disposal conditions after waste package breach, interacting with filler material (consistent with analyzed basis).

Discussion: Fillers would displace groundwater from the interstitial volume of fuel assemblies, and could also include neutron absorbing components. Fillers would be designed to remain immobile (e.g., solid) for at least 10,000 years after package breach. They would be resistant to temperatures reached immediately after installation, and facilitate heat transfer to limit SNF cladding temperature to 350°C or lower (NRC

2003). They would maintain material compatibility with the basket, neutron absorber components, and fuel.

Filler material could be installed at initial loading or later upon canister reopening. Various filler delivery strategies are available, such as pumping or pouring in a chemically curing liquid mixture or foam, or emplacing particulate materials that react with groundwater. Filler installation could be done dry in a hot cell, or possibly in a pool. The development approach would focus on candidate materials and their long-term performance. Investigation of filler materials and methods of installation is currently underway in the UFD R&D program. Previous work looked at the use fillers to mechanically stabilize SNF for transportation after extended storage (Maheras et al. 2012).

Like other reactivity control improvements (Design Alternative IV.A) this is a possible transitional strategy between the use of existing canisters without modification (Group III) and the use of new designs (Group V).

Example IV.B.1 – Fillers installed in DPCs at initial loading – *Future disposal of existing DPC designs, with filler installed at initial loading, for postclosure criticality control.*

Example IV.B.2 – Fillers installed in reopened/rewelded DPCs – *Future disposal of existing DPC designs, with filler installed after reopening (e.g., via dewatering ports). If canisters are cut open for filler installation (i.e., lids removed), the canister might be reused, for example by rewelding lids or by welding on a new head that fits on the canister end.*

4.5 Group V – Multi-Purpose Canisters With Long-Lived Baskets and Neutron Absorbers

This group includes alternatives with larger capacity canisters (e.g., 12-PWR size or larger) based on new designs, which would require criticality control features for transportation and possibly disposal, designed for lifetime of at least 10,000 years. Basket structure and criticality control components would be designed to maintain initial configuration, and preserve required neutron absorptivity, for at least 10,000 years after waste package breach (thus addressing the possibility for breach soon after repository closure). This group of alternatives is similar to Group II (larger canisters with bolted closures) but with: 1) long-lived internals; 2) either bolted or welded closures; and 3) criticality control through basket design rather than sole reliance on overpack reliability or added reactivity control improvements. This group of alternatives would attempt to envelope disposal requirements, with a canister design that meets performance requirements in a range of possible disposal environments. In the following discussion the range of disposal environments is subdivided to distinguish a design solution developed previously for oxidizing conditions.

Design Alternative V.A – Larger canisters, with basket and absorber materials selected for longevity in oxidizing environments

Capacity: Any capacity up to limits imposed by handling, hoisting, and transportation.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption for at least 10,000 years (without overpack breach). Degrades slowly under disposal conditions (consistent with analyzed basis) after waste package breach. Maintains material compatibility with a range of potential overpack designs.

Discussion: This approach was adopted for postclosure criticality control, as part of a previous design for disposal of commercial SNF using the TAD canister (DOE 2008; 2006). The canister and basket structure would be fabricated from Type 316 (nuclear grade) stainless steel, and the neutron absorber plates from a stainless steel-boron alloy. Thicknesses would be prescribed based on measured corrosion rate data for appropriate environments, for corrosion allowance, to ensure subcriticality for at least 10,000 years after waste package breach. This could control criticality in case of early waste package failure from any cause.

Example V.A.1 – Larger canisters/baskets designed for ≥10,000-year life exposed to oxidizing disposal environments – *Larger canisters with stainless steel based canister shell and basket materials, designed to maintain initial SNF basket configuration and neutron absorption for >10,000 years exposure to groundwater or humidity environments, in oxidizing conditions.*

Design Alternative V.B – Larger canisters, with basket and absorber materials selected for longevity in a range of chemically reducing and oxidizing environments

Capacity: Any capacity up to limits imposed by handling, hoisting, and transportation.

Overpack: Mechanically robust for transport and handling. Provides containment for waste isolation, for a duration that is determined by the safety strategy. Maintains material compatibility to limit corrosion or mechanical processes that could promote degradation of the fuel canister or basket.

Canister and Basket: Maintains configuration and neutron absorption for at least 10,000 years (without overpack breach). Degrades slowly under disposal conditions (consistent with analyzed basis) after waste package breach. Maintains material compatibility with a range of potential overpack designs.

Discussion: This alternative could implement a similar configuration to that for oxidizing conditions (Design Alternative V.A) but with structural and neutron absorbing components fabricated from materials with corrosion resistance over a broader range of environmental conditions. Chemically reducing conditions, while limiting the mobility of most waste radionuclides in aqueous transport, can require different engineered materials to achieve corrosion resistance, than oxidizing conditions. The possibility of radiolytic oxidation complicates the chemical environment, and could add to the advantages from using materials that remain corrosion resistant over a broad range of conditions. Materials such as Alloy 22 could exhibit such corrosion resistance (Rebak and Crook 2004) and might be used for basket structures and neutron absorber components. Other materials such as copper and titanium have also been identified (Rebak 2007). Application of such materials in canister and basket designs is developmental. International programs have generally not investigated corrosion resistant neutron absorbing materials because they have pursued small canisters (Group I).

Example V.B.1 – Larger canisters/baskets designed for ≥10,000-year life exposed to reducing or oxidizing disposal environments – *Larger canisters with corrosion resistant canister shell and basket materials, designed to maintain initial SNF basket configuration and neutron absorption for >10,000 years exposure to groundwater or humidity environments, in reducing or oxidizing conditions.*

6. Summary

Many different alternatives are available for SNF canisters that would be used for storage, transportation, and disposal (MPCs). A total of 13 Design Alternatives with 19 examples are identified and organized in five groups in Table 1 and Section 4. Current DPC designs reflect only Group II, although some earlier designs with bolted closures reflect Group II.

The applicability of Design Alternatives to different disposal concepts, including enclosed and open emplacement modes (Hardin et al. 2013a) and different types of geologic host media, is shown in Table 2. The small canisters (Group I) could support disposal in any geologic setting. The bolted canisters (Group II) including the can-within-can alternative (Design Alternative II.C) appear to have excellent flexibility to support implementation of various disposal concepts in different geologic settings. The salt disposal concept and the open modes can accept larger canisters containing more SNF assemblies. Existing DPCs may be directly disposable without modification (Group III) but only from canisters (as-loaded) and for some disposal concepts and geologic settings. The range of possible disposal solutions for existing DPCs is expanded if they can be reopened and modified (Group IV). It may be possible to develop an enveloping MPC design (Group V) that is directly disposable with a range of disposal concepts and geologic settings.

Some of the Design Alternatives are incompatible with certain design concepts and geologic settings. For example, Groups II through V represent canisters that would be too large (or would contain too many SNF assemblies) for enclosed emplacement modes. Similarly, alternatives III.B and V.A are specific to unsaturated settings, and Design Alternative III.C is specific to the salt concept. Smaller canisters may be disposable in any geologic setting, but some disposal concepts may be infeasible (e.g., enclosed emplacement may be preferable, and in-drift, open emplacement may be unnecessary).

Some of the alternatives could be transitional, allowing direct disposal of existing DPCs with or without modifications (Groups IV and III, respectively), while other solutions are being prepared. Bolted closures or combinations of bolted and welded closures (Groups I and II) offer flexibility to respond to future fuel management decisions (e.g., repository siting, or a decision to reprocess SNF) that require re-packaging or modification of canister internals.

Estimated cost savings from implementing MPCs in the U.S. nuclear waste management system for SNF dry storage, and later transportation and disposal, depend on when such measures are introduced. Timely implementation in the next 10 to 20 years is projected to save on the order of $10 billion in re-packaging costs. The capability to dispose of SNF in larger packages (e.g., larger than 4-PWR size) would allow similar additional savings in disposal costs (Kalinina and Hardin 2012). Such savings could approach a third of the total cost of disposal (Hardin et al.

2012a, Section 5). The outlook for deploying MPCs depends on progress in disposal planning and repository siting, and cooperation of the nuclear power utilities, the vendor industry, and government.

Table 2. Applicability of SNF canister disposability Design Alternatives to disposal concepts.

	Disposal Concepts >>>>	Enclosed		Open		
		Crystalline	Clay/Shale	Salt	Hard Rock	Argillaceous
Group I – Small canisters (up to 4 PWR assemblies or BWR equivalent) with no neutron absorbers	I.A Small capacity waste package	√	√	a	a	a
	I.B Small capacity waste package combined with heavy insert	√	√	a	a	a
Group II – Larger canisters with bolted closures or bolted/welded combinations	II.A Bolted closures (both inner and outer canister lids)	b	b	√	√	√
	II.B Bolted closure combined with welded closure	b	b	√	√	√
	II.C Can-within-can arrangements using bolted or welded closures	√ (b)	√ (b)	√	√	√
Group III - Existing DPC designs (welded closures) used for disposal without reopening	III.A High reliability (10^{-12}/yr) overpack performance	b	b	c	√	√
	III.B Disposal in unsat. conditions with multiple natural and engineered groundwater diversion/exclusion barriers	b	b	d	√	d
	III.C Flooding possible only with chloride brine	e	e	√	e	e
	III.D Disposal of existing DPCs so that packages are subcritical after flooding with dilute ground water, and degradation of canister internals	b	b	√	√	√
Group IV - Existing DPC designs (welded closure) used for disposal with modifications	IV.A Reactivity control improvements	b	b	c	√	√
	IV.B Fillers for reactivity control	b	b	c	√	√
Group V – Multi-purpose canisters with long-lived baskets and neutron absorbers	V.A Larger canisters, with basket and absorber materials selected for longevity in oxidizing environments	b	b	c	√	f
	V.B Larger canisters, with basket and absorber materials selected for longevity in a range of chemically reducing and oxidizing environments	b	b	c	√	√

Notes:
- √ Directly applicable.
- ☐ Shaded cells represent combinations that would not be applicable.
- **(a)** Small packages (up to 4-PWR size) could be workable for these disposal concepts, but are unnecessary.
- **(b)** Larger canisters (>4-PWR size, and the outer canister for the can-within-can) would require too much decay storage (>>150 years) to meet peak temperature targets.
- **(c)** These a would add confidence in performance of a salt repository, but are likely unnecessary.
- **(d)** Host media for these disposal concepts are nominally saturated.
- **(e)** Chloride brine of sufficient concentration would likely be found only in evaporite deposits (especially a salt repository)
- **(f)** Argillaceous media typically have low permeability and organic content that render them chemically reducing.

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