Preliminary Evaluation of Dual-Purpose Canister Disposal Alternatives – 14506

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ABSTRACT

Disposition of commercial spent nuclear fuel (SNF) stored in thousands of dry casks at reactor sites will become a major part of back-end fuel management over the next decade. The U.S. Department of Energy (DOE) is conducting a multi-year evaluation of the technical feasibility of direct disposal of SNF in existing dual-purpose canisters (DPCs). A range of alternative concepts exists, including the salt concept, and emplacement in “hard rock” (e.g., crystalline, igneous, and highly-metamorphosed) or argillaceous sedimentary rock, with or without backfill. The salt and the hard rock concepts could accept 32-PWR size or larger packages, with high-burnup SNF ($\geq$45 gigaWatt-days/metric ton; GW-d/MT), and fewer than 100 years decay storage. Sedimentary media have lower temperature tolerance (e.g., 100°C) but low-burnup SNF could be accommodated. High-burnup SNF would require longer decay storage, larger repository area, and/or greater temperature tolerance. For control of postclosure criticality, groundwater exclusion would be important. Analyses using as-loaded assembly data and updated burnup credit show that many, although not all existing DPCs could be sub-critical even if degraded. Intrusion of chloride brine could be inconsequential because natural Cl-35 is a neutron absorber. Engineering feasibility of waste package handling and transport underground is another area of investigation, and a recent review concluded that these challenges could be met. In summary, preliminary analyses indicate that demonstration of preclosure and postclosure safety, and repository implementation, could be technically feasible for certain disposal concepts, and that cost savings might be realized compared to re-packaging DPCs.

INTRODUCTION

The U.S. nuclear power industry is accumulating spent nuclear fuel (SNF) in dry storage at the rate of approximately 2,000 metric tons per year (MT/yr). Dry storage sites are associated with both operating and decommissioned power plants. There currently are more than 1,700 casks in use containing more than 17,000 MT (metric tons) of SNF as heavy metal.[1] Projections show that by the year 2025 there will be more than 3,000 such casks in use (Figure 1) and that by approximately 2035 more than half of the SNF in the U.S. will be in dry storage.[2]

For most dry storage systems SNF is loaded and sealed into welded, stainless steel canisters which are then transferred to stationary dry storage casks. Canisters that can also be loaded into licensed transportation casks are referred to as dual-purpose canisters (DPCs). These typically hold as many as 32 pressurized water reactor (PWR) assemblies (or equivalent boiling water reactor [BWR] fuel) and recent designs hold even more.

The possibility for direct disposal of these DPCs without cutting them open and re-packaging the SNF is attractive because it would potentially save money, reduce the complexity of fuel management operations, and result in less cumulative worker dose (from fewer handling and packaging operations). The following sections describe promising direct disposal concepts, then discuss preliminary technical analyses (principally thermal response and nuclear criticality), and then estimate the timing and cost for disposal of all commercial SNF in the U.S. in DPCs.

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

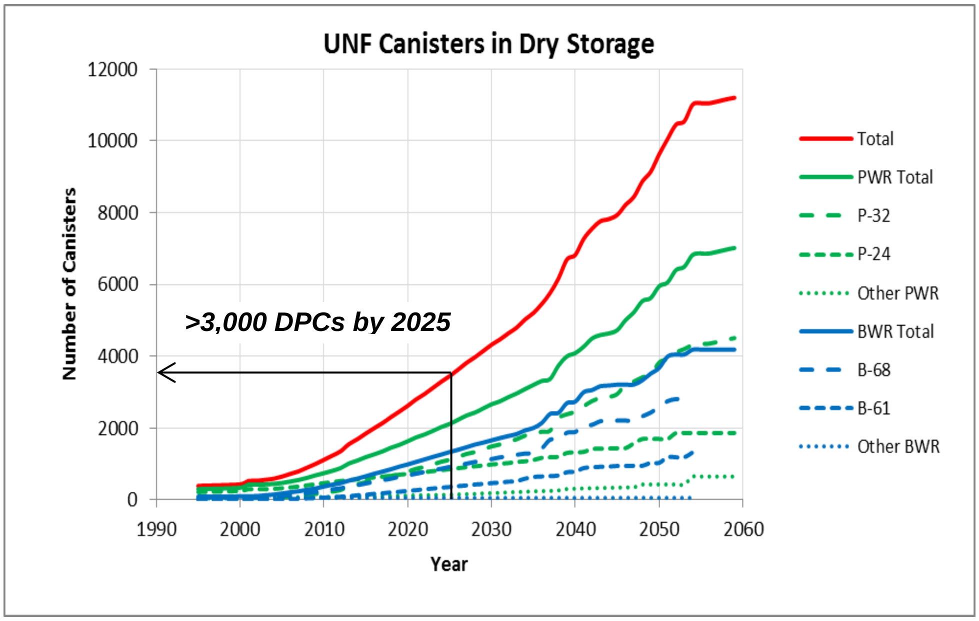


Fig. 1. Dry Storage Canister Projection for the U.S., Using the TSL-CALVIN Simulator and Assuming Existing Power Reactors are Operated with Life-Extension Licenses.

BACKGROUND

The concept of using a common canister design for SNF storage, transport and disposal originated in the 1990s as dry-storage systems were being deployed by the U.S. utility industry. The potential advantages were recognized, giving rise to multi-purpose canister (MPC) concepts developed for the U.S. DOE.[3] After preliminary studies, DOE made a decision not to pursue MPC concepts. A 2003 study specifically addressed disposal of existing DPCs and determined that post-emplacement criticality was the most important technical issue, and that fuel burnup data from reactor operations could be used to demonstrate sub-criticality for at least part of the inventory.[4]

Direct disposal of existing DPCs (up to 32-PWR size) was also examined by the Electric Power Research Institute.[5,6] These studies considered thermal and criticality issues and found no technical impediments to direct disposal for the repository concept being studied by DOE at the time. More recently, a German team has proposed direct disposal of the CASTOR-V storage/transportation cask containing approximately 10 MT of SNF, in a salt repository.[7]

OBJECTIVES

The objectives for direct disposal of SNF in DPCs would be the same as for any geologic repository: safety of workers and the public, and long-term isolation of the radioactive materials from the biosphere, achieved with reasonable cost and schedule. Achieving these will involve: 1) meeting temperature limits for the fuel and the repository, 2) mitigating the potential for criticality after waste emplacement, 3) demonstrating engineering feasibility of underground construction and operations, and 4) achieving acceptance by regulators and the public. This study has focused on technical feasibility of the first three results, assuming that such a repository would be closed by the time the SNF age reaches 150 years out-of-reactor. It is further assumed that the DPCs can be safely transported to the repository as soon as 50 years after reactor discharge, or at up to 100 years after discharge as appropriate. Some of the other technical constraints and assumptions that could help to ensure that these objectives are met are summarized in Table I.

TABLE I. Constraints and Assumptions Used in DPC Disposal Concept Development.

Canister capacity	24- and 32-PWR sizes are typical (or BWR equivalent). Newer designs such as the Magnastor (NAC International) system may hold 37 or more PWR assemblies.
Fuel burnup	≤ 60 GW-day/MT.
Transportability	SNF in DPCs can be safely transported to the repository starting at 50 years after reactor discharge, and for as long as 100 years after discharge.
Age of fuel at repository (or panel) closure	Less than 150 year (combined duration of decay storage and ventilated cooling in a repository)
Postclosure nuclear criticality parameter (effective neutron multiplication factor)	k_{eff} < 0.95 (or other limit established for waste repository licensing)
Underground handling and emplacement operations	Shielded for all operations until emplacement, and self-shielded waste packages are also an option.
Regulatory basis for waste isolation performance	Assume future regulations will be adapted from 40CFR191 and 10CFR60, incorporating probabilistic approaches from 40CFR197 and 10CFR63.
Host rock peak temperature targets: Salt	200°C
“Hard Rock” (e.g., crystalline, etc.)	200°C
Argillaceous (e.g., claystone, shale, etc.)	100°C
Cladding temperature limit after emplacement	350°C
Clay-based material peak temperature target	100°C

The peak temperature target, or limit, for salt would control decomposition of hydrous minerals that are found with halite in salt formations. It would also prevent decrepitation that can occur in bedded salt at above 250°C. For crystalline rock such as granite, or other “hard” rock types such as welded tuff, or metamorphic rock, the 200°C target would limit weakening from differential thermal expansion.[8] Whereas these mechanisms would occur only locally and would not compromise the waste isolation integrity of a host formation, they could add complexity to the safety case. Moreover, the 200°C target for salt or hard rock is already high enough to facilitate direct disposal of DPCs.

Peak temperature targets for argillaceous host media and engineered clay-based materials (Table I) are based on current understanding from international programs. Alteration of clay-based materials generally involves dissolution, aqueous transport, and precipitation (e.g., silica). Temperature limits are imposed because alteration could degrade swelling pressure and other properties. For example, the Swedish program has adopted a peak buffer temperature of less than 100°C.[9] The French authority Andra has proposed a 90°C limit for the argillaceous host medium surrounding waste packages in the proposed repository in argillite.[10]

Peak temperature targets in Table I are specified for the waste package surface or surrounding material. Past thermal analyses have shown that if the package surface meets these limits, then the temperature of fuel within the package will meet the 350°C limit intended to limit Zircaloy cladding creep rupture.[11]

DISPOSAL CONCEPTS AND THERMAL MANAGEMENT

Prospective geologic disposal concepts are readily divided into “enclosed” and “open” modes of waste package emplacement.[12] The enclosed modes involve emplacing packages directly into contact with engineered materials, or host rock, all of which have thermal limits. The open modes maintain air space around each package, through which heat dissipation is mostly radiative, and which can be ventilated to remove heat prior to repository closure. After closure these spaces may remain open and continue to contribute to heat dissipation. Open emplacement concepts combine the functions of surface decay storage (i.e., in fuel pools or dry storage) with geologic disposal, in the same underground facility. An open-mode repository could be constructed and operated much sooner than enclosed concepts that require surface decay storage of 100 years or longer.[12] Thus, much of the cost for disposal of SNF in the U.S. could be incurred before all currently operating nuclear power plants are shut down (i.e., while the Nuclear Waste Fund continues to accumulate).

Most international high-level waste (HLW) and SNF disposal programs are focused on enclosed modes in various host rock types, with inherent limits on heat generation and waste package capacity. Only the open emplacement modes and the salt concept are suited for relatively large DPC-based waste packages with heat output on the order of 10 kW at emplacement.[13] A disposal solution using larger packages is attractive for the U.S., which faces the disposal of 140,000 MT SNF (as heavy metal).[12]

Disposal overpacks would be used with any concept. Overpacks would be the interface between different types of DPCs and other elements of the system such as transporters, emplacement equipment, other engineered barriers, and the host rock. DPCs are typically made from relatively thin stainless steel plate, and overpacks could provide added strength for handling and repository closure operations such as backfilling. The materials used and the methods for fabrication and treatment would be selected to perform in the disposal environment. For example, low-alloy steel could be selected for salt [14] and a 5-cm thick steel overpack would add 15 MT to the weight of a loaded DPC (up to about 50 MT).

Salt Concept

A salt concept (Figure 2) is proposed for DPC direct disposal based on underground testing experience at the Waste Isolation Pilot Plant (WIPP) and at the Asse and Morsleben salt sites in Germany.[13,15] Excavation and construction would be similar to the WIPP. Both bedded salt and salt domes could be suitable, differing mainly in lateral extent, moisture content, and the geologic setting. Less moisture in domal salt means less brine migration, however, both types of formations offer very low brine mobility and no radionuclide releases under normal, undisturbed conditions.[16] DPC disposal overpacks could consist of low-alloy steel or other low-cost structural material. The scarcity of moisture would limit the extent of corrosion damage (water is consumed by corrosion reactions) so the overpack could remain intact for thousands of years. Access openings would be backfilled with crushed salt prior to closure (Figure 2). Because the emplacement drifts would be backfilled immediately, subsequent repository monitoring or closure operations could be performed directly and without additional shielding.

Waste packages would be transported from the surface and handled underground in the horizontal orientation to limit the height of excavations. Transport of DPC packages would require a ramp from the surface, or a shaft hoist such as that tested at Gorleben and scaled up to sufficient capacity (175 MT payload). This is twice the 85 MT capacity tested at Gorleben in the 1990's, which was demonstrated then to be technically feasible. The 175 MT hoist has been proposed in connection with the German DIREGT concept for direct disposal.[7] Importantly, site-specific factors such as the existence of an aquifer in the geologic section above the repository, may constrain possibilities for shaft or ramp construction. Note that not all potential host formations are associated with aquifers, and that structures such as salt domes may offer both shaft access from above, and ramp access through adjacent rock strata.

Salt has thermal properties that facilitate disposal of larger, hotter waste packages. Thermal conductivity is higher than many other rock types, and salt can tolerate a peak temperature of 200°C. Finite-element thermal-mechanical analysis of the disposal of large packages (32-PWR size) in a salt repository was reported previously.[12] Temperature histories (Figure 3) show that the salt peak temperature target can be met with DPC decay storage of 50 to 70 years.

While salt does creep, it does so under stress conditions imparted by overburden pressure, but is not expected to creep significantly from the much smaller weight of waste packages. Even thermally activated salt deformation in response to waste package weight is minor, as suggested by coupled thermal-mechanical simulations[17] using constitutive laws for salt that were developed from laboratory data and validated against field-scale observations.[15]

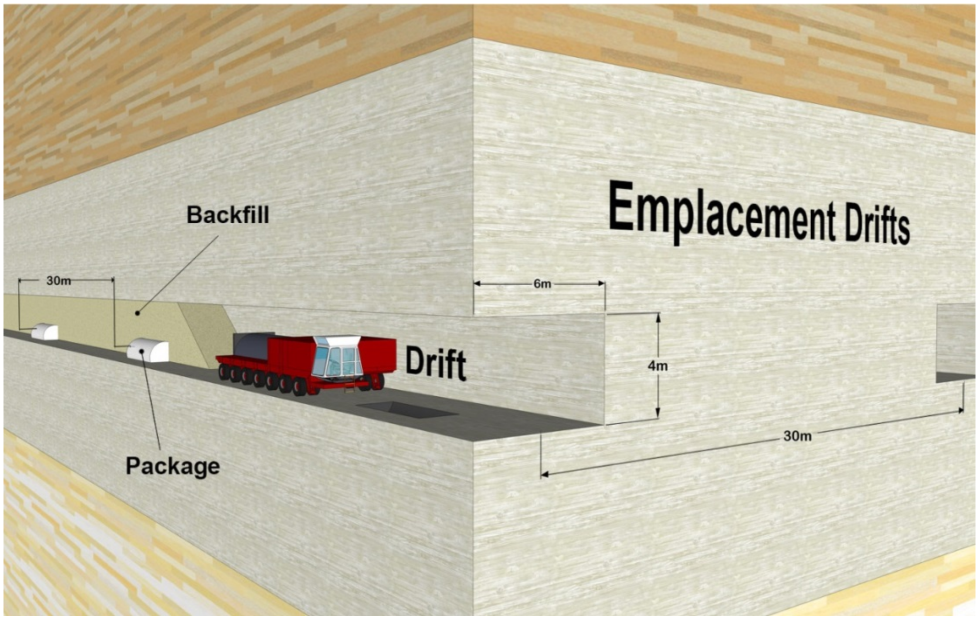


Fig. 2. Repository Concept for DPC Waste Packages in Bedded Salt.

Hard Rock Unsaturated, Unbackfilled Repository Concept

In this open-mode concept, waste packages would be emplaced axially in open drifts, and ventilated for up to 100 years to remove heat (Figure 4). The concept would use a corrosion resistant package and other, redundant engineered barriers as needed for defense-in-depth (e.g., drip shields or multiple corrosion resistant packaging materials). This concept is similar to previous work [18] and to a previous proposal for direct disposal of DPCs.[5]

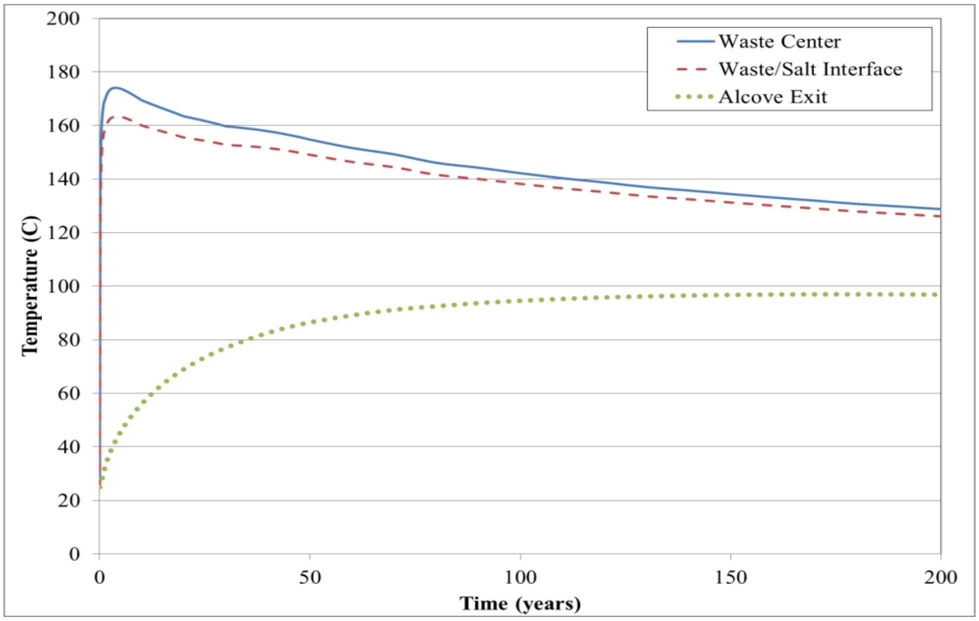


Fig. 3. Temperature Histories for a 32-PWR Size Package Containing PWR Fuel with 60 GW-day/MT Burnup, Stored 70 years Before Emplacement in a Salt Repository (zero time at emplacement; from Ref. 13).

Hard rock (e.g., competent crystalline rock, generally igneous or metamorphic) offers long-term opening stability, and typically has greater thermal conductivity and higher temperature tolerance (e.g., to 200°C) than sedimentary rock types. Virtually all hard rock types have some fracturing, so mitigating rock permeability is potentially important. If the host rock is unsaturated, the presence of sufficient permeability will make it free-draining. With drainage there is little possibility of focused groundwater flow along repository openings, so plugging and sealing may not be needed to ensure waste isolation. In saturated settings a low-permeability backfill would be installed at the time of repository closure. Thermal calculations show that a 200°C host rock peak temperature target could be readily met for SNF with high burnup, with fewer than 150 years of combined decay storage plus ventilation.

Other Disposal Concepts

The other concepts amenable to DPC direct disposal would use backfill, installed at closure, in sedimentary or hard rock host media.[19] Some of the open concepts that have been identified could remain unbackfilled after repository closure, for improved heat dissipation until eventual collapse of the emplacement openings. However, drift collapse would increase the radial extent of the disturbed rock zone (DRZ) in the rock around the openings. While this could be accommodated in unsaturated hydrologic settings as discussed above, in saturated settings the collapse rubble and the DRZ could later act as pathways for groundwater flow and transport of radionuclides released from breached packages. Thus, additional engineered barriers such as backfill would be needed to mechanically stabilize the host rock and/or control groundwater flow. Also, isolation of adjacent waste packages from one another using low permeability backfill could be advantageous in the analysis of future inadvertent human intrusion.[13]

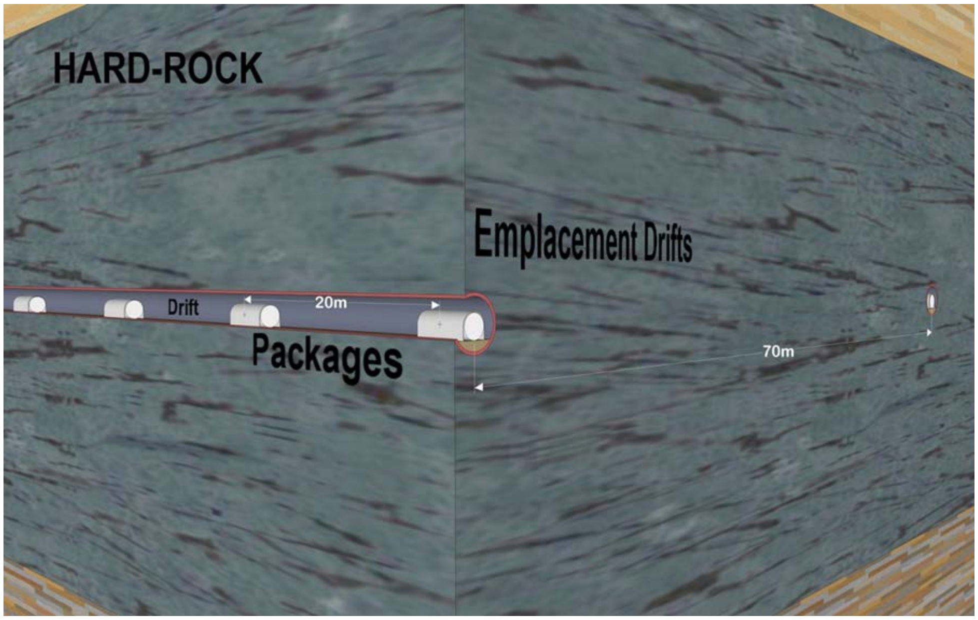


Fig. 4. Repository Concept for DPC Waste Packages in Hard Rock (crystalline), with Extended Repository Ventilation and Without Backfill.

Granular backfill materials generally have relatively low thermal conductivity (e.g., 0.6 to 1.2 W/m-K for clay-based materials) which subjects those materials and the waste package to higher peak temperatures.[12] This would generally not be a problem for waste packages, which can withstand surface temperatures approaching 300°C without significant damage to the SNF. Nor is backfill likely to significantly affect temperature in the host rock. However, elevated temperature in the backfill could impact the properties of the backfill itself, and in particular, clays that produce swelling behavior and low permeability. Scoping calculations show that backfill material capable of withstanding at least 150°C peak temperature could make the use of backfill a viable option in DPC direct disposal, but the function of such a backfill might not include swelling on rehydration.[19] This possibility is the objective of ongoing materials research in the Used Fuel Disposition (UFD) R&D campaign.

Argillaceous (containing clay) sedimentary host media typically have lower thermal conductivity than salt or crystalline media, which presents an additional challenge for repository thermal management. For open modes, peak host rock temperature occurs a short distance away from waste packages, which allows some flexibility to select repository dimensions that limit temperatures. The dimensional variables are emplacement drift diameter, spacing between packages, and spacing between drifts. These variables also determine excavation volume and repository layout size. Repository layouts have been described that limit host rock peak temperature in sedimentary media, while limiting excavation volume and repository size.[13] For direct disposal of DPC-based packages containing moderate- to high-burnup SNF, repository layout size (and the extent of tunneling) would be approximately doubled in argillaceous media compared to salt or hard rock. Scoping studies have also shown that allowing near-field, argillaceous host rock to locally reach peak temperatures greater than 100°C could significantly reduce the repository layout size.[13] Peak temperature limits and other thermal criteria for various argillaceous host media are another area of ongoing research in the UFD program.

SAFETY OF DPC DIRECT DISPOSAL

Generic safety analysis would evaluate the potential differences between direct disposal of DPCs and disposal of the same SNF in packaging (including canisters) designed specifically for disposal, in the same geologic setting. Re-packaging could produce smaller packages for use with enclosed disposal concepts, or it might produce packaging similar to DPCs in size. Generic safety analysis for DPC direct disposal is currently under development. Discussions to-date have focused on qualitative differences, pointing out ways that the performance of DPC direct disposal could differ from other concepts involving re-packaging:

- **Emplacement Mode and EBS Design** – Comparisons should include impacts from greater permeability in the near field, for example in backfill around DPC-based packages, or a in a more extensive DRZ. If transport of radionuclides through the far-field to the biosphere is slow such differences may be insignificant.
- **Thermal Effects** – DPCs are not necessarily much larger than purpose-built disposal canisters would be, and peak temperatures for larger packages could be controlled with decay storage and ventilation (although elevated temperatures could persist longer). The consequences could be minimal if host rock and backfill transport characteristics are relatively insensitive to thermal exposure (e.g., for a repository in salt).
- **Quantity of SNF** – Once a waste package breach occurs more SNF would be exposed to the disposal environment with DPCs, than with smaller containers. This difference could potentially result in a reduction in waste isolation performance depending on whether advection is an important mechanism controlling radionuclide transport.
- **Inner Canister Design** – Canisters purpose-built for disposal could have features not found in existing DPCs, such as: inserts (in lieu of baskets); thicker shells, plates and/or spacers to extend postclosure structural lifetime; more corrosion-resistant materials; thicker neutron absorbing elements with lifetime greater than 10,000 years; and fillers that would exclude moderating groundwater after package breach.

Important factors that help to ensure postclosure safety of DPC direct disposal include: 1) diffusion-controlled transport, 2) transport properties that are insensitive to temperature exposure, 3) significant far-field contributions to performance, and 4) mechanisms that limit potential postclosure criticality. These are system attributes that could benefit any repository.

POSTCLOSURE CRITICALITY SCOPING ANALYSIS

Canisters licensed for transportation are typically analyzed for criticality when fully flooded with fresh water, with geometry and neutron absorbers intact (§10CFR71.55). Analysis of postclosure criticality must also consider the potential for degradation of neutron absorbing features, and the possibility for collapse of the basket holding the fuel assemblies. These mechanisms may be important for 10,000 years (e.g., §10CFR63.114) or longer, which is likely sufficient for chemical breakdown of aluminum-based absorber materials.

For the transport/aging/disposal canister design [18] degradation was accommodated by fabricating absorber plates from borated type 304 stainless steel, and other components from nuclear-grade type 316 stainless steel, with sufficient thicknesses for corrosion allowance. Corrosion damage over 10,000+ years of exposure to groundwater was bounded based on extrapolation of laboratory test data, with margins on load-bearing and neutron absorption properties.

The challenge for existing DPCs is to account fully for factors mitigating the potential for criticality, including: as-loaded reactivity margin, burnup credit (28 nuclides including actinides and fission products), flooding with brine (for certain geologic settings), and moderator displacement or exclusion. Note that if water is excluded from the repository or from entering waste packages there is no potential for criticality, so any DPC direct disposal strategy could include aspects that inhibit flooding such as scarcity of water, or corrosion resistant overpacks.

Existing DPCs have been loaded using conservative assumptions. For example, some DPCs have been loaded in accordance with specifications based on analysis with unirradiated fresh fuel. Detailed information about the reactor in-service history of each SNF assembly, along with cask-specific loading arrangements, can be used to exploit this type of reactivity margin. Scoping calculations of criticality for two representative DPC systems [20] demonstrate this approach: the Transportable Storage Canister (TSC-24 from NAC International), and the Multi-Purpose Canister (MPC-32 from Holtec International). These two systems are reasonably representative of the overall population of DPCs (totaling 405 canisters as of June, 2013). Loading data and assembly in-service history information were provided by several operating companies.

The SCALE [21] CSAS6 analysis sequence was used to perform criticality calculations with the KENO-VI Monte Carlo code, with the continuous energy ENDF/B-VII cross-section library to determine the effective neutron multiplication factor (k_{eff}). Depletion calculations were performed using the TRITON two-dimensional depletion sequence to generate used fuel isotopic composition.[20] Scoping calculations were performed for three representative configurations:

- As-loaded canisters in original condition.
- Complete loss of neutron absorber panels (replaced by groundwater) with assembly positions unchanged.
- Complete basket degradation resulting in zero assembly spacing and loss of absorber.

These configurations are stylized but they do show the potential benefit from more detailed analyses of postclosure criticality. Computational bias and uncertainty are estimated to be approximately +0.02 (Δk_{eff}), and are not included in the figures or discussion presented here.

The NAC TSC-24 canister calculations show that when burnup credit is taken in conjunction with canister-specific loading, calculated k_{eff} ranges from 0.61 to 0.81, for the 60 casks analyzed, flooded with pure water. Most of these canisters (48 of the 60) were evaluated with no absorber credit (Figure 5) and all are conditionally sub-critical (k_{eff} <1.0) provided burnup credit and canister-specific loading are incorporated. For the degraded-basket case 31 specific canisters were evaluated, resulting in significant increase of k_{eff} that was greater than the decrease available from burnup credit and canister-specific loading. The degraded-basket calculations were repeated, flooding with sodium chloride brine (Cl-35 has a thermal neutron capture cross-section of ~44 barns). Compared with fresh water, k_{eff} decreased moderately with 1 molal NaCl (Δk_{eff} ~ -0.08). Note that the concentration of NaCl in seawater is about 0.5 molal, but brines present in some crystalline rocks are more concentrated, and saturated brine in salt formations has chloride concentration of 6 molal. The effect of such concentrations on k_{eff} would be at least 25% (Δk_{eff} ~ -0.25).

Further investigation into the geochemical behavior of canister materials and their interaction with groundwater could determine whether the degraded-basket case is needed, or needed for all DPCs. The TSC-24 system includes perpendicular, 0.5-inch thick stainless steel spacer discs, and aluminum heat transfer discs, that maintain assembly-to-assembly spacing, and would need to degrade faster than the fuel assemblies for the degraded-basket configuration to develop.

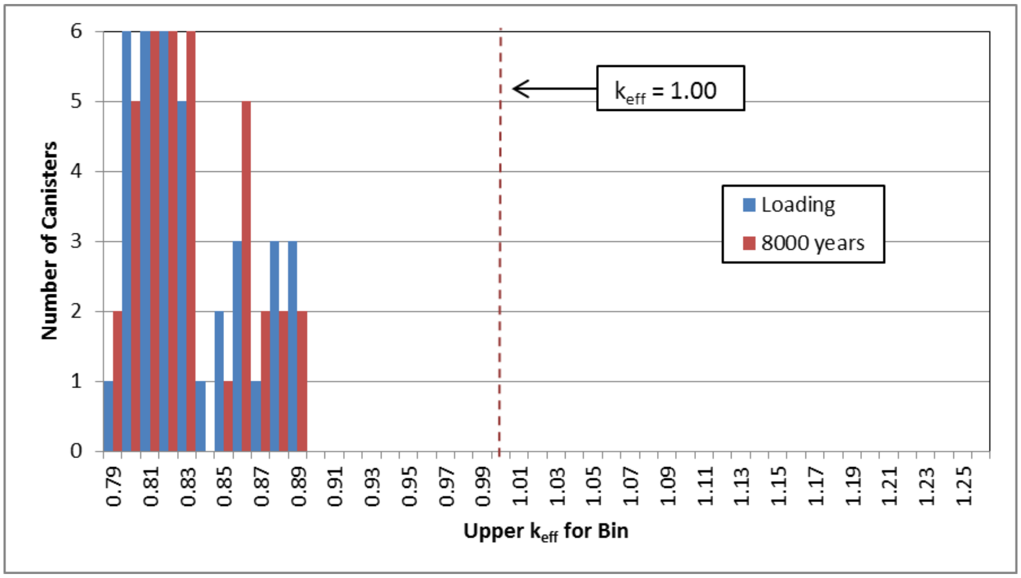


Fig. 5. Distribution of k_{eff} Values Calculated for TSC-24 Canisters (as loaded), for the Absorber-Loss Case.

Calculations for the MPC-32 system show that when burnup credit is taken in conjunction with canister-specific loading, calculated k_{eff} values range from 0.80 to 0.88 for the 26 casks analyzed, flooded with pure water. For the absorber-loss case nine of the 26 canisters analyzed were sub-critical over disposal time frames (an 8,000-year period was evaluated). Discharged burnable poison rod assemblies (BPRAs) are actually present in these 26 canisters but were not represented in the calculations. They could be credited for moderator displacement, which typically decreases k_{eff} by a few percent. With burnup credit, canister-specific loading, and moderator displacement credit for discharged BPRAs, all 26 canisters evaluated would be sub-critical for the absorber-loss case. For the degraded-basket case k_{eff} increased significantly for all 26 canisters, and as before, the effect was much greater than the decrease available with burnup credit and canister-specific loading. For the degraded-basket case, flooding with 1 molal NaCl decreased k_{eff} by approximately -0.07 (Δk_{eff}) and 2 molal NaCl produced another decrease, similar in magnitude.

TIMING AND RELATIVE COST OF DPC DISPOSAL

The TSL-CALVIN transportation-storage-logistics simulator [22] was used to evaluate when DPCs loaded at power plants could be cool enough to meet repository emplacement thermal power limits. The simulator explicitly links DPC shipments to the repository from reactor sites or from a centralized storage facility (CSF), to the emplacement thermal power limit. All dry storage canisters and casks (including those with welded and bolted closures) are assumed to be transportable either to a CSF or a repository (subject to thermal power limits). Forecasts were made for a range of thermal limits.[23] Results for the 10 kW limit (Figure 6) are appropriate to represent DPC direct disposal with either the salt concept or the hard rock unsaturated, unbackfilled concept.[13] The simulation is based on a set of assumptions including:

- SNF will be generated at all currently operating power plants, with 20-year life extensions. As power plants are decommissioned all SNF will be put into dry storage.
- A CSF would serve as the principal surface decay storage facility for DPCs (in addition to at-reactor storage). Shipment of DPCs from reactor sites to a CSF would begin in 2025 [24] at a rate of either 3,000 or 4,500 MT SNF (as heavy metal) per year.

- A repository would open and begin to package and emplace DPCs underground in 2048.[24]
- Once the repository is operating, DPCs cool enough for disposal would be shipped directly from reactor sites, or from the ISF if none are available at the reactor sites.
- Shipments to the ISF would continue after 2048 [24] as needed to transfer fuel from decommissioned plants (subject to ISF receipt rate limits).

The simulator tracks the amount of SNF that becomes available each year for disposal, the amount emplaced in a repository, and the status of SNF in storage at reactor sites and an ISF. Results show that emplacement could be substantially complete by calendar 2130 for the 10 kW thermal limit (with a few outlying, high-burnup canisters). For the salt repository concept closure could soon follow, while for the hard rock (crystalline) unsaturated, unbackfilled concept a few decades of repository ventilation would be needed before closure. An optimal disposal acceptance rate of approximately 1,700 MT/yr was calculated for the 10 kW case, to complete disposal by 2130.[23] In other words, repository throughput capacity of only 1,700 MT/yr could complete DPC emplacement in the same time as a 3,000 MT/yr facility.

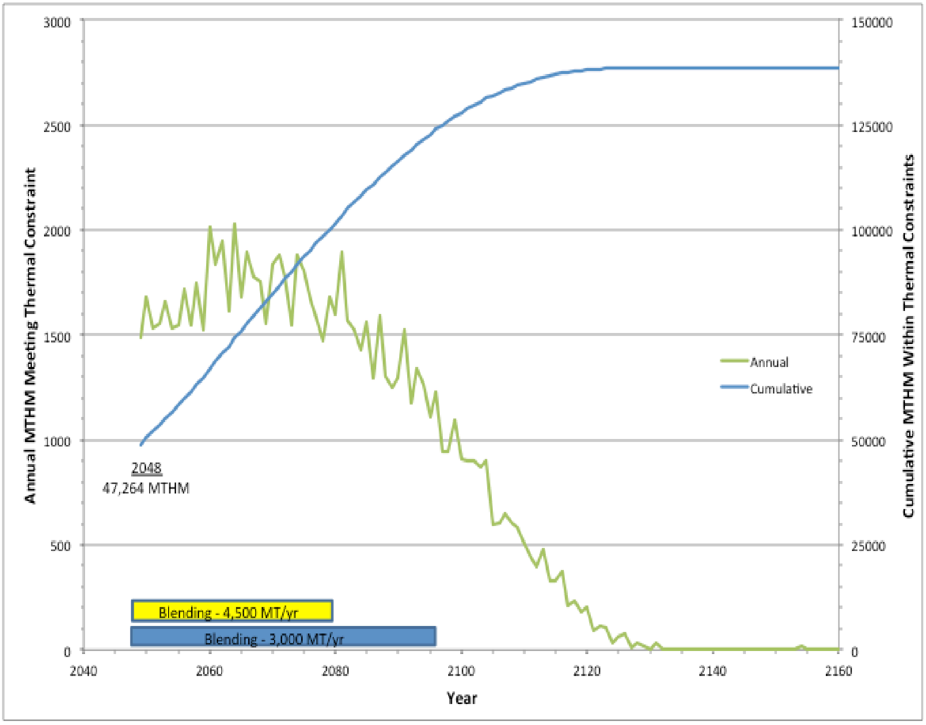
The incremental cost for storing DPCs at an ISF until cool enough for disposal was estimated and compared with the cost of re-packaging into smaller containers for disposal. The incremental ISF cost for the 10 kW disposal schedule was estimated to be $5.4 billion ($5.4B).[23] For comparison, the life-cycle cost of a 3,000 MT/yr re-packaging facility was estimated to range from $6.5B to $14.5B, depending on the size of the disposal canister, with smaller canisters resulting in higher cost. This re-packaging cost estimate is only for canistering fuel at an ISF and then transporting it to a repository, and does not include disposal.

Re-packaging could use smaller canisters containing less SNF, to reduce the cooling time, expediting disposal (see color bars on Figure 7 for 3,000 and 4,500 MT/year throughput). When a repository is sited the emplacement thermal power constraints will be better known. At that time the potential for long decay storage times could be mitigated, and throughput increased, by loading bare fuel at the power plants into smaller, purpose-built canisters that could be disposed of sooner. Package size and other requirements could be adjusted to accommodate disposal conditions, in a manner similar to the layout proposed by Andra.[10]

Re-packaging into smaller waste packages would increase disposal cost because more overpacks would be needed, with more handling operations and larger facilities. For example, Kalinina and Hardin [25] compared disposal of 140,000 MT SNF (as heavy metal) in a salt repository with 4-PWR and 12-PWR size waste packages (or BWR equivalent) requiring 86,049 and 28,648 packages, respectively. The analysis assumed that waste is received at the repository already in canisters appropriate for disposal. The additional 57,401 packages added more than $30B to the disposal cost. Thus, taking disposal costs into account, re-packaging of SNF in DPCs could add on the order of $10B and possibly several times that to the total disposal cost for commercial SNF in the U.S., compared with DPC direct disposal.

ENGINEERING FEASIBILITY

Handling and packaging of large DPCs in surface facilities at the repository or at upstream installations are well within the state of current practice. Also, handling and packaging would be very similar for any DPC direct disposal concept. Thus, there are no significant feasibility questions associated with repository operations until the waste is transported underground. Options for surface-to-underground transport of DPC-based waste packages include vertical shafts, shallow ramps with tire-mounted vehicles, and steeper ramps with rail-mounted vehicles.[26] Note that a complete transporter that includes the waste package, shielding, wheel mechanisms, and motive power could weigh 250 MT or more, but a minimum configuration without motive power could weigh 175 MT.



Note: Duration of operations to re-package into smaller containers for disposal, starting in 2048, is shown in each plot for throughput of 3,000 and 4,500 MT/yr. Quantity of SNF on hand in 2048 that meets the 10 kW thermal limit is also shown. MTHM refers to metric tons as heavy metal.

Fig. 6. TSL-CALVIN Forecasts for DPCs Cooling to a 10 kW Thermal Limit in 2048 and Each Following Year, Expressed as Quantity of SNF.

A shaft friction hoist with 175 MT capacity could be built following principles tested at Gorleben, Germany for 85 MT capacity.[27] Alternatively, such loads could be transported in ramps at up to 10% grade with a rubber-tire, self-powered transporter of the type tested by the Swedish program. Steeper ramps (up to 45°) could be engineered using a funicular system as considered for the French repository.[26] Shallow ramps (grade of 2.5% or less) can be served by conventional rail equipment.[18] The choice could be influenced by site-specific geology and local experience. All are technically feasible although the shaft hoist and funicular would be the largest of their kind. Note that any mined repository would be accessed by shafts for construction and operational functions except possibly for waste transport.

Handling underground presents a different set of engineering challenges. The disposal concepts described here use in-drift emplacement, whereby waste packages would be placed onto the floor in open drifts. Rubber-tire transporters could deliver waste packages from the surface all the way to emplacement drifts, providing shielding for all operations except final emplacement which could be done by remotely. Other transport options might require an underground transfer station, and additional, specialized equipment. Engineering development and testing for underground handling and emplacement would be needed, and licensing to verify safety, but technical feasibility is a relatively minor issue.

CONCLUSIONS

Preliminary results presented here indicate that DPC direct disposal could be technically feasible, at least for certain disposal concepts. Also that cost savings might be realized compared to re-packaging DPCs, although further analysis is needed. In summary:

- **Disposal Concepts** – DPC direct disposal could be implemented in a range of geologic settings, meeting thermal limits, and with a reasonable expectation of needed stability of mined openings. Disposal options range from the salt concept, to disposal in hard rock types or argillaceous sedimentary rock. All options would use in-drift emplacement to simplify handling of large heavy packages. Possible uses of low-permeability backfill are identified and could be viable depending on the geologic setting, and the thermal tolerance of backfill materials. The need to backfill at closure would be accommodated in the repository design.
- **Thermal Management** – The salt concept and the hard rock unsaturated, unbackfilled concept could readily meet peak temperature targets because both types of media can tolerate 200°C and have relatively high thermal conductivity. A salt repository would be backfilled immediately after emplacement, while openings in hard rock would be backfilled after a few decades of ventilation. Argillaceous, sedimentary media would have lower temperature limits to limit clay alteration, and relatively low thermal conductivity. Accordingly, longer surface decay storage and repository ventilation, or larger repository layouts, would be needed.
- **Safety** – Important factors that would help to ensure postclosure safety for DPC direct disposal include engineered and natural system attributes that would benefit any geologic repository. When prospective repository sites are identified, site-specific data will support more resolution of differences in postclosure safety associated with DPC direct disposal.
- **Engineering Feasibility** – Waste handling and transportation for DPC direct disposal would be essentially the same as current practice, with no associated engineering feasibility questions until the DPC-based waste packages are transported underground. Several options exist for surface-to-underground waste package transport in shafts or ramps, including hoists, funiculars, and tire-mounted or rail-mounted ramp transporters.
- **Criticality** –Preliminary analysis indicates that many, although not all existing DPCs would be sub-critical for at least 10,000 years even if chemically and mechanically degraded in the disposal environment. Extra reactivity margin is available for this analysis, for many existing DPCs, by using as-loaded assembly information and updated burnup credit. With further analysis, existing DPCs could be categorized according to the potential for criticality in different disposal environments.
- **Cost** –DPC direct disposal could take longer to implement compared with a re-packaging approach that proceeds at a higher rate of throughput (e.g., 3,000 MT/yr). This is because of the decay storage needed to cool DPC-based packages for disposal. The fastest timeframe for disposal of approximately 140,000 MT (i.e., the salt concept) could be comparable in terms of total duration of repository operations, to the schedule proposed previously for 70,000 MT.[18] This is mainly because the salt repository would not need to be ventilated.

As technical feasibility, safety and cost are evaluated, it is important to communicate analysis findings, collaborate with industry, discuss safety with regulatory bodies, and promote reviews by external stakeholders.

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