APPENDIX E

FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/ Revision No.: Preliminary Engineering and Cost Analysis for DPC Disposal Solutions (Milestone M4SF-19SN010305053)

Work Package Title and Number: Technical and Programmatic Solutions for Direct Disposal of DPCs – SNL (SF-19SN01030505)

Work Package WBS Number: WBS 1.08.01.03.05

Responsible Work Package Manager: Ernest Hardin
(Name/Signature)

Date Submitted

Quality Rigor Level for Deliverable/Milestone[2]	☒ QRL-1 ☐ Nuclear Data	☐ QRL-2	☐ QRL-3	☒ QRL-4 Lab- Specific

This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☒ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
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Name and Signature of Reviewers

Laura Price/SNL — Laura Pri

John Kessler/Subcontractor to SNL

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Preliminary Engineering and Cost Analysis for DPC Disposal Solutions

Spent Fuel and Waste Disposition

FINAL DRAFT

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology

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M4SF-19SN010305053
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Revision History

Preliminary Engineering and Cost Analysis for DPC Disposal Solutions Deliverable: M4SF-19SN010305053 Work Package: SF-19SN01030505 – Technical and Programmatic Solutions for Direct Disposal of DPCs – SNL WBS: 1.08.01.03.05 QRL 4	Technically reviewed, approved through Sandia R&A (SAND2019-4938 R) and submitted to PICSNE as a deliverable. Based closely on SAND2019-4070 which was approved by DOE and Sandia in April, 2019 for unlimited release.

ADDITIONAL NOTICE: This is a technical report that does not take into account the contractual limitations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). Under the provisions of the Standard Contract, the U.S. Department of Energy does not consider spent nuclear fuel in canisters to be an acceptable waste form, absent a mutually agreed-to contract amendment. To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract provisions prevail.

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LIST OF FIGURES

LIST OF TABLES

ABSTRACT

There are currently (as of January, 2019) more than 2,700 dual-purpose canisters (DPCs) loaded with spent nuclear fuel (SNF) across the United States. DPCs continue to be loaded at a rate of more than 200 per year by mid-century there are likely to be more than 8,160 DPCs in service. Options for disposing of SNF loaded in DPCs include repackaging into specialized disposal canisters, directly disposing of the loaded DPCs (with or without modification), or some combination of the two.

The main technical challenges for direct disposal of loaded DPCs are thermal management, handling and emplacement operations for the large, heavy packages, and postclosure criticality control. This report focuses on postclosure criticality control which is the most challenging. The challenge lies in determining how to modify DPCs so as to minimize the probability that a criticality event might occur in a repository, or if the DPCs are not modified, to understand the nature and consequences of postclosure criticality events. There are several approaches that could facilitate direct disposal of loaded DPCs with acceptable repository performance. This report describes these approaches and presents comparative analysis of the rough-order-of-magnitude (ROM) costs.

Repackaging SNF in DPCs into specialized disposal canisters could be financially and operationally costly with additional radiological, operational safety, and management risks. A disposition approach that would not involve repackaging or modifications to DPCs (future or already loaded) is development of a new licensing strategy that addresses the risk (probability and consequence) from criticality events. A different approach would modify existing loaded DPCs (some or all of them), and change the loading or design of future DPCs, to decrease the probability of a criticality event in a repository below levels of concern.

This report investigates the cost to modify existing loaded DPCs, and the cost to modify the loading or design of future DPCs to facilitate direct disposal. It establishes the ROM cost for repackaging SNF that has been loaded into DPCs, into specialized canisters for disposal. It also identifies technical and regulatory challenges associated with the potential design modifications and loading considerations. It is left to future analyses to compare radiological, operational safety, and management risks associated with the available approaches.

The primary modification option for existing DPCs considered in this report is injectable fillers, either cementitious material, molten metal or glass. In order to use solid fillers, the DPCs would be cut open to expose the fuel assemblies, which is considered infeasible for this study because once the DPCs were cut open the assemblies could readily be transferred to new disposal-ready canisters.

Modifications to future DPCs that could minimize the potential for postclosure criticality include the use of alternative neutron absorber materials, disposal control rods, and modified control blades. This report also elevates the viability of disposal-oriented zone-based loading criteria for DPCs that would minimize reactivity while maintaining desirable thermal and shielding performance.

The estimated cost avoidance associated with direct disposal of loaded DPCs is approximately $20 billion compared to full repackaging, for disposing of the full projected inventory of SNF amounting to 109,300 MTU. Note that this cost avoidance does not take into consideration the

sunk cost associated with loading of DPCs at utility sites. The significant contributors to cost avoidance are as follows:

- Eliminating the purchase of new disposal canisters (e.g., TAD canisters) accounts for \$12.2 billion
- Reducing the number of disposal overpacks (because TAD canisters generally hold less SNF than DPCs) accounts for \$4.6 billion
- Eliminating repackaging operations accounts for \$3.3 billion
- Eliminating the disposal of DPC hulls and baskets as Low Level Waste (LLW) accounts for \$1.4 billion

The primary contributors to the additional cost associated with direct disposal of loaded DPCs are as follows:

- Treating existing DPCs (i.e., fillers, if selected) accounts for \$0.54 billion
- Design modifications for future DPCs account for \$1.3 billion if using upgraded neutron absorber plates (e.g., borated stainless steel) or \$1.9 billion if using disposal control rods and modified control blades.

The costs associated with modifying existing loaded DPCs, and modifying the loading or design of future DPCs, would be much less than the cost for repackaging.

ACRONYMS AND DEFINITIONS

BSS	borated stainless steel
BWR	boiling water reactor
DBA	design basis accident
DCRA	disposal control rod assembly
DOE	U.S. Department of Energy
DPC	dual-purpose canister
GTCC	greater-than-class-C
LLW	low-level waste
MTU	metric tons uranium
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
RCCA	rod cluster control assembly
ROM	rough-order-of-magnitude
SFWST	Spent Fuel and Waste Science and Technology
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TAD	Transportation, Aging and Disposal
TSLCC	Total System Life Cycle Cost

1. INTRODUCTION

1.1 Background

There are currently (as of January, 2019) more than 2,700 dual-purpose canisters (DPCs) containing spent nuclear fuel (SNF) were in service across the United States (StoreFUEL 2019). DPCs are welded canisters (sealed by welding) designed to meet dry storage requirements per 10 CFR 72 and transportation requirements per 10 CFR 71, with appropriate storage and transportation overpacks. Although 10 CFR 72.236(m) requires that “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,” DPCs have been designed, licensed, and loaded without comprehensive disposal criteria, particularly not any that address postclosure criticality.

The Yucca Mountain repository License Application (DOE 2008a) described a specialized disposal canister specified to meet storage, transportation, and disposal requirements. The performance specification for the Transportation, Aging and Disposal (TAD) canister (DOE 2008b) was informed by a specific geologic setting and performance objectives, to ensure that criticality events would be sufficiently unlikely that they could be excluded from performance assessment on the basis of low probability.

Repackaging DPCs into specialized disposal canisters could be financially and operationally costly with additional radiological, operational safety, and management risks. A disposition approach that would not involve repackaging or modifications to DPCs (future or already loaded) is the development of a new licensing strategy that addresses the risk (probability and consequence) from criticality events. A different approach would modify existing loaded DPCs (some or all of them), and change the loading or design of future DPCs, to decrease the probability of a criticality event in a repository below levels of concern.

1.2 Purpose and Scope

This report investigates the cost to modify existing loaded DPCs, and the cost to modify the loading or design of future DPCs to facilitate direct disposal. It establishes the rough-order-of-magnitude (ROM) cost for repackaging SNF that has been loaded into DPCs, into specialized canisters for disposal. It also identifies technical and regulatory challenges associated with the potential design modifications and loading considerations. It is left to future analyses to compare radiological, operational safety, and management risks associated with the available approaches.

This report is structured as follows:

- Potential use of injectable fillers in loaded DPCs (Section 2)
- Potential design modifications for future DPCs (Section 3).
- Disposal oriented zoned loading criteria for SNF in future DPCs (Section 4).
- Comparative cost analysis (Section 5).

The estimated costs of fillers, design modifications, and zoned loading are compared to repackaging in disposal-ready canisters.

Results for ROM estimates are generally reliable to one or two significant figures, and are generally reported that way here. However, for editorial reasons a ROM estimate may be reported with trailing zeroes. Also, intermediate results from calculations in Appendices A and B are reported at full precision, then rounded at the conclusion of the analysis.

2. POTENTIAL USE OF INJECTABLE FILLERS IN LOADED DPCs

Two filler approaches are currently being investigated that would involve injection of either a cementitious slurry or molten materials such as low-temperature metal alloys or glasses. Cements would be selected for chemical stability and low water content, for example a binder consisting of chemically bonded $AlPO_4$ (berlinite) in a matrix of alumina (Al_2O_3) particles. As currently understood, setting of berlinite requires heating to approximately 200 °C, and the result would be chemically anhydrous. The process would require careful control of temperature throughout, which could be achieved by self-heating and by externally cooling and heating the DPC in an insulated well.

In the filling facility a DPC would be inserted into a well with cooling and heating capability. A typical DPC could generate approximately 10 kW (or less) from radioactive decay, when acceptable for emplacement in a repository. It would be cooled externally first, supplemented by circulating chilled gas. The filler slurry would be mixed and injected over a few hours using a mixing plant similar to those used for borehole cement (approximately 40 barrels of cement per DPC, comparable to a small oilfield cementing job). The well would then be heated slowly to 200 °C over a few days using externally applied heat, self-heating by radioactive decay, and the exothermic reaction of the cement. After setting of the cement but still at elevated temperature, the canister would be depressurized with vents open to remove residual water. Dewatering would continue for days or weeks until a satisfactory residual was obtained, then the canister ports would be resealed by welding. The cement mixing and pumping equipment would be needed only for a few hours, but the well could be needed for 14 days or longer. For a throughput of 1,500 MTU/yr, a filling facility might require 5 to 10 parallel lines (wells and supporting equipment).

Molten materials would be selected for chemical stability, wetting of canister and fuel surfaces, and low melting temperature. Eutectics of tin-silver-copper, or tin-zinc, are examples that have melting temperatures well below 300 °C. Glasses are also available with melting temperatures low enough not to cause cladding damage. A vanadate glass composition, for example, has a melting temperature below 300 °C (SNL 2017).

A challenge with molten materials would be safe and effective handling. A concept for a demonstration of molten material injection is depicted in Figure 1. As shown, the molten material would be gravity fed although pumping capabilities are available. The canister would be heated uniformly, and induction heating is one technology that could be borrowed from metal-cooled reactors. Injection and cooling would be slow operations, to maintain required temperatures and avoid transients. Each DPC could require a duration on the order of 5 to 10 days. The facility scale and complexity of equipment would be comparable to cement slurry.

The cost estimate for fillers in Section 5, covering filler materials and operations, is a placeholder value (and a target for economic feasibility). Greater cost could be acceptable if it is much less than the repackaging cost.

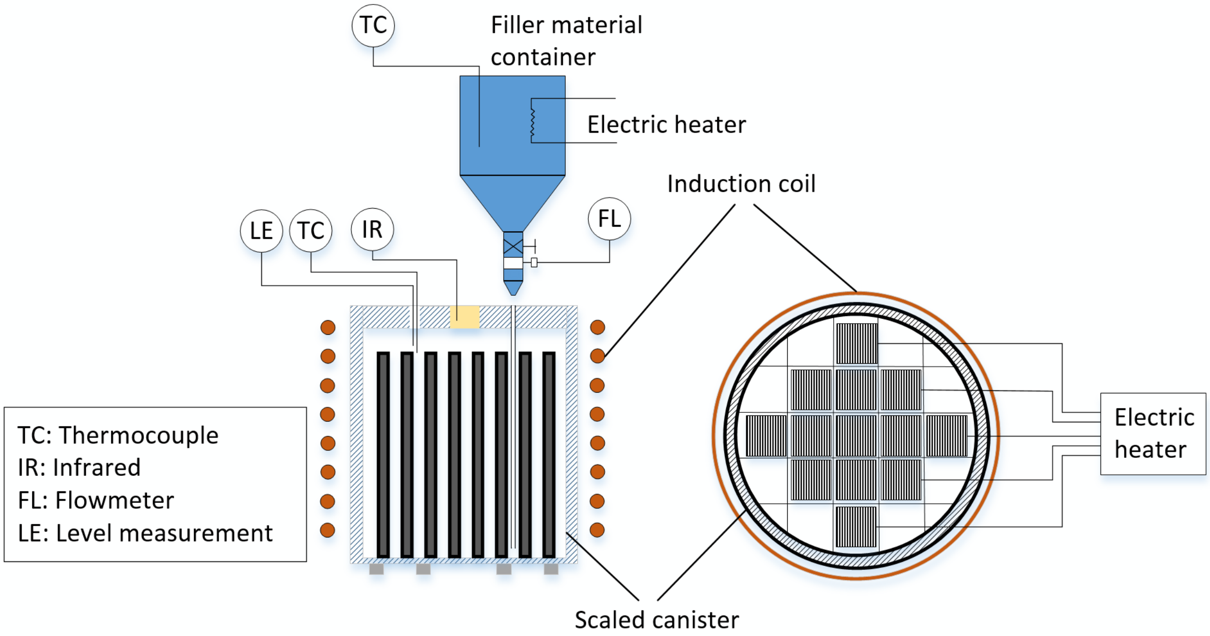

Figure 1. Concept for testing of molten filler injection into a simulated DPC (SNL 2017).

3. POTENTIAL DESIGN MODIFICATIONS FOR FUTURE DPCs

The goal of modifications to DPC basket design, to facilitate probabilistic screening of postclosure criticality, would be to ensure the presence of neutron absorbers between or within the fuel assemblies for as long as the SNF assemblies remain in a geometry capable of criticality in the disposal environment (package breached, DPC flooded with groundwater). Therefore, materials and geometries are needed that have corrosion lifetimes comparable to or better than Zircaloy cladding, and also better than spacer grids and other components of the assemblies, and the DPC basket. Corrosion processes generally depend on chemistry which in turn depends on other materials in the package, radiolysis, temperature, and the geologic setting. The materials discussed below would be sufficiently characterized (or already are) so that their performance would meet the longevity design goal.

3.1 Disposal Control Rod Assemblies

The effectiveness of control rods inserted in the guide tubes of pressurized water reactor (PWR) assemblies or control blades inserted between boiling water reactor (BWR) assemblies is proven based on their use in reactor operations. Typical rod cluster control assemblies (RCCAs) are Zircaloy-cladded rods with a strong neutron absorber such as boron-carbide (B_4C) or silver-indium-cadmium. Control blades are typically stainless steel-cladded hafnium plates or stacked B_4C rods. Disposal control rod assemblies (DCRAs) similar in design to RCCAs (without the components necessary for reactor operations such as spider assembly) would have similar corrosion properties or better (due to lack of reactor irradiation) compared to Zircaloy-cladded SNF. Alternatively, control rods could be made of non-cladded materials such as extruded borated stainless steel (BSS) (ASTM A887-89 Grade A, UNS S30464) or Ni-Cr-Mo-Gd alloy (ASTM-B 932-04, UNS N06464) tubes.

There are no anticipated regulatory or DPC design challenges associated with the insertion of DCRAs into PWR assemblies since used RCCAs are routinely placed into assemblies for pool and dry storage. However, there may be operational challenges with the insertion of DCRAs into some assemblies due to potential bowing of guide tubes during reactor operations and storage in the pool. It is anticipated that bowing would impact a small fraction of the assemblies. DCRAs are needed for only a subset of the assemblies in a DPC. Based on their efficacy at controlling reactivity for reactor operations, the following are anticipated DCRA loading considerations in a DPC:

- No DCRAs are needed for high-leakage peripheral basket locations
- No DCRAs are needed for assemblies near (side or corner) an assembly with a DCRA

For a typical 37 PWR DPC, DCRAs for seven assemblies would likely be sufficient to ensure subcriticality as illustrated in Figure 2. The actual number of required DCRAs would have to be determined with detailed criticality calculations.

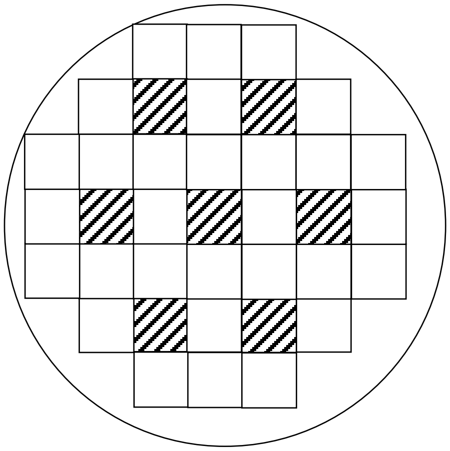

Figure 2. Illustration of DCRA placement in a 37 PWR DPC.

There is no precedent for installing control blades in current DPC designs. Additionally, control blade designs would have to be modified to ensure longevity. The placement of control blades between BWR assemblies (or groups of four assemblies) would entail significant changes to BWR DPC basket designs.

The cost of RCCAs depends closely on the type of absorber material. For example, silver-indium-cadmium RCCAs are higher in cost with fluctuating prices compared to B_4C. Additionally RCCAs are generally sold to utilities as part of a larger refueling purchase subject to bids and negotiations. Based on various informal inputs, the estimated cost of a DCRA that includes Zircaloy-clad rods containing a B_4C core, but without a spider assembly, is ~\$50k; the total cost for seven DCRAs in a DPC would then be \$350k. To simplify the cost analysis assumptions, the cost of modified control blades for a BWR DPC is also assumed to be \$350k. The cost for using extruded tubes in DCRAs could potentially be lower, however, for corrosion allowance more of such rods could be required per DPC.

3.2 Use of Alternative Materials for Neutron Absorber Plates

There are two alterative materials with promising corrosion characteristics that could be used for neutron absorber plates in DPCs:

- Powder metallurgy BSS (ASTM-A887-89 Grade A, UNS S30464)
- Ni-Cr-Mo-Gd alloy (ASTM-B 932-04, UNS N06464)

BSS is an established material, whereas the Ni-Cr-Mo-Gd alloy was more recently developed at Idaho National Laboratory. The following discussion is limited to BSS because more information is available.

To ensure favorable corrosion characteristics and sufficient corrosion allowance, a relatively thick BSS plate (11 mm) would be required (BSC 2008b). Current DPC designs either use relatively thin aluminum-based materials encased in stainless steel sheathing, or relatively thick borated aluminum that also serves as the structural basket and the thermal shunt. Whereas the alternative materials listed above are more dense than aluminum and relatively poor thermal conductors, the addition of heavier, potentially thicker, and less conductive plates (either substituting or in addition to the aluminum-based materials) would entail significant changes in DPC basket design. These modifications would require a new license from the Nuclear Regulatory Commission (NRC).

To provide perspective on cost, this report assumes that the DPC cost change is only limited to the addition of borated stainless steel plates. Any cost reduction associated with omission of the aluminum-based material and its fabrication is assumed to be offset by the additional features needed to maintain heat rejection capacity.

A recent estimate for the cost of BSS was developed for a standardized canister concept with a capacity of 4 PWR or 9 BWR SNF assemblies (EnergySolutions 2015). The estimated cost, taking into account materials and fabrication, was $18,881 per 4 PWR canister and $37,762 per BWR SNF canisters. To approximate the cost for the larger capacity DPCs, a capacity ratio is used. This approximation is reasonable because the number of required neutron absorber plates is a direct function of the number of assemblies. For example, the cost of borated stainless steel plates for a future DPC with an average capacity of 34 PWR assemblies (per Appendix B) would be $174,000 (rounded), whereas the cost of BSS plates for a modified DPC with an average capacity of 78 BWR assemblies (per Appendix B) would be $354,000 (rounded, and taking into account an assumed annual inflation rate of 2%).

4. DISPOSAL-ORIENTED ZONED LOADING FOR FUTURE DPCs

Recent criticality calculations for as-loaded DPCs demonstrated that most DPCs could have been loaded with the same SNF inventory in a configuration optimized for disposal criticality such that they would be subcritical without any credit for fixed neutron absorbers. This is illustrated in Figure 3, which shows the reactivity band for the same DPC inventory based on various loading arrangements of the SNF assemblies in the fuel baskets (Liljenfeldt et al. 2017).

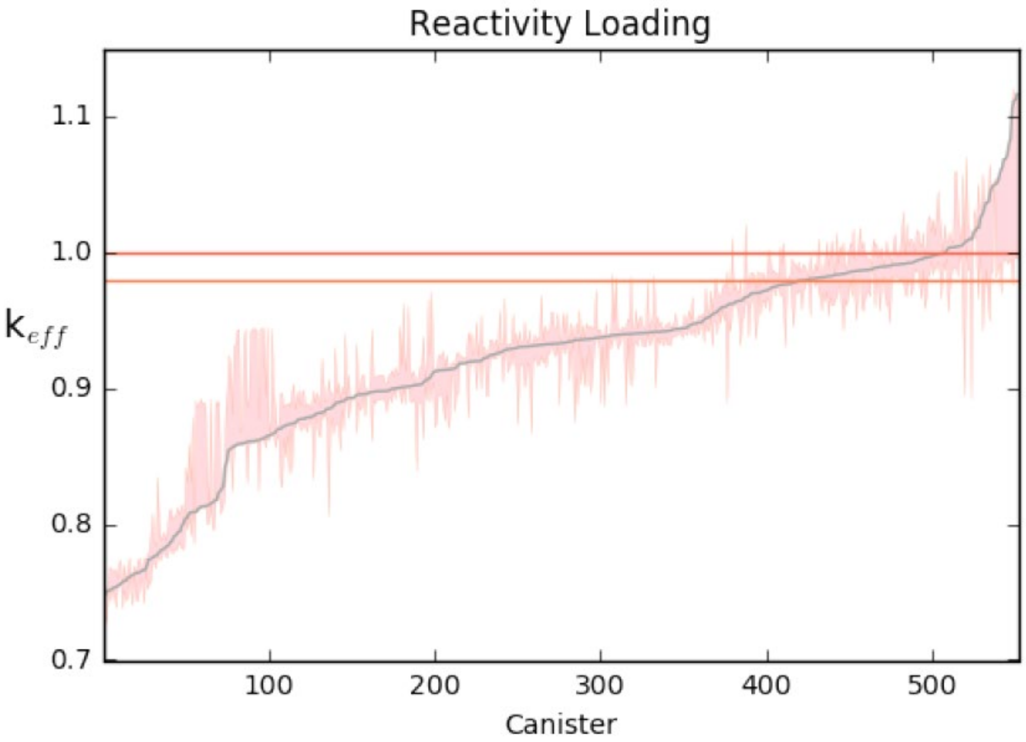

Figure 3. k_{eff} range based on various rearrangements of the SNF assemblies in as-loaded DPC fuel baskets.

In order to accommodate the design-basis thermal load and to ensure that surface dose rates are sufficiently low, DPC loading is generally governed by zone-based loading maps. An example loading maps is provided in Figure 4 for the MAGNASTOR DPC (NAC 2010).

Zone	**Designator**	**Heat Load (W/Assembly)**	**Assemblies**
Inner	A	922	9
Middle	B	1,200	12
Outer	C	800	16

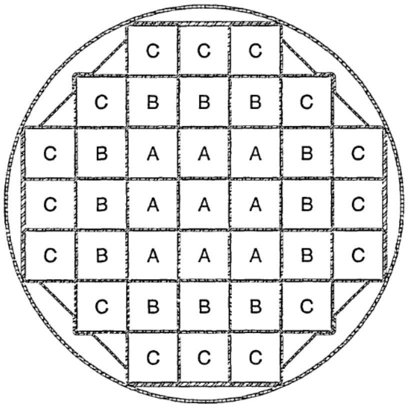
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Figure 4. Loading map for the MAGNASTOR® DPC.

Table 1. Loading requirements for MAGNASTOR® TSC.

Initial Enrichment	Burnup	Reactivity	Thermal Output	Radiation Level	Appropriate Zone	Comments
Low	Low	Low	Low	Low	A	Typically older assemblies.
	Medium	Low	Medium	Medium	A	Not many assemblies
	High	Low	High	High	B	These assemblies are rare, if any.
Medium	Low	High	Low	Low	C	Potentially damaged assemblies or last cycle before shutdown.
	Medium	Medium	Medium	Medium	C	Significant fraction of existing SNF inventory. May require longer decay time.
	High	Low	High	High	B	Not many assemblies.
High	Low	High	Low	Low	C	Few assemblies. Typically damaged assemblies or last cycle before shutdown.
	Medium	High	Medium	Medium	C	Not many assemblies. May require longer decay time.
	High	Medium	High	High	B	Significant fraction of future SNF inventory.

Table 1 illustrates that there is congruity between the criticality, thermal, and shielding loading criteria taking into account the existing and future anticipated SNF inventory collectively. Potential complexity may arise once specific pool inventories are taken into consideration and the need to load SNF into DPCs with restrictions on decay time (e.g., during decommissioning).

5. COMPARATIVE COST ANALYSIS

This section presents a comparative cost analysis between direct disposal of DPCs with or without modifications, and repackaging the SNF into disposal-specialized canisters. This cost analysis does not consider repository development and design and is limited to the following parameters only:

- Cost of disposal-specialized canisters
- Cost of repackaging the SNF from DPCs
- Cost of disposal of DPC hulls and baskets as LLW waste
- Cost of DPC treatment/modification to facilitate disposal
- Cost of disposal overpacks

The costs of some parameters are taken from the Total System Life Cycle Cost (TSLCC) for Yucca Mountain (DOE 2008c). These costs are escalated to 2019 based on an assumed fixed annual inflation rate of 2%. The comparative cost analysis is provided for the following four cases:

- **Case 1:** Direct disposal of DPCs without treatment of existing DPCs or design/loading modifications to future DPCs. This case would likely be associated with a consequence-based consideration of postclosure criticality, disposal in a salt geology, or the use of overpacks/engineered barriers that would preclude water from entering DPCs.

- **Case 2:** Direct Disposal of DPCs with treatment of existing DPCs and loading modifications to future DPCs based on disposal-oriented zone-based loading criteria as discussed in Section 4.
- **Case 3:** Direct Disposal of DPCs with treatment of existing DPCs and design modifications to future DPCs using borated stainless steel plates as discussed in Section 3.2.
- **Case 4:** Direct Disposal of DPCs with treatment of existing DPCs and design modifications to future DPCs using DCRAs for PWR DPCs and modified control blades for BWR DPCs as discussed in Section 3.1.

5.1 Comparative Cost Analysis Bases and Assumptions

The following are key bases and assumptions for the comparative cost analysis:

- This cost analysis is time-independent and does not consider length of storage or repository availability.
- The entire SNF inventory is assumed to be loaded in DPCs, except for the small number of existing bare fuel casks (258).
- The cost of loading DPCs at utility sites is assumed to be a sunk cost and is not reflected in this comparative cost analysis.
- Costs specific to alternative loading schema described in Section 4 and part of Case 2, and which would be included with the cost of loading DPCs at utility sites, are assumed to be insignificant for this cost analysis.
- Where repackaging of fuel from DPCs to disposal canisters is analyzed, the disposal canister type is assumed to be equivalent to the Yucca Mountain TAD 21-PWR/44-BWR canister (DOE 2008b).
- The disposal drift length and associated engineered features are stronger functions of thermal load than the number of packages, therefore, these costs are assumed to be non-discriminating across the cases considered. Drip shields (for the unsaturated hard rock concept) are more closely linked to the number of packages, but cost savings from fewer drip shields are assumed to be minor because some redesign of drip shields will be needed if packages are spaced apart.
- A packaging facility similar in size and throughput capacity to the Yucca Mountain Wet Handling Facility would be needed regardless of the disposal strategy of DPCs to accommodate packaging of fuel from bare fuel casks, of which there are currently 258 casks (StoreFuel 2019), and SNF arriving at the repository in bare fuel rail/truck casks.
- The repackaging facility is assumed to be used for the introduction of fillers into existing DPCs to facilitate disposal. It is assumed that the reduction in operational costs associated with repackaging 920 DPCs, which is the basis for the TSLCC cost estimate (DOE 2008c, Table A-2), would offset the added cost associated with the addition of fillers to existing DPCs (currently more than 2,700).
- Transportation cost considerations are not reflected in the comparative cost analysis, although the transportation cost for direct disposal of DPCs would be lower than the transportation costs assumed in the TSLCC, which is based on transporting a larger number of lower capacity canisters.
- Fillers are assumed to be an acceptable treatment to facilitate disposal of DPCs. The cost of fillers is assumed to be $200k per DPC. To provide perspective on this assumed cost,

Table 2 lists the current prices (as of 2/22/2019) for various raw materials that may be used in fillers (SNL 2017). Material costs per DPC are also provided in Table 2 based on an assumed DPC void volume of 6 m^3 (SNL 2017) and material densities.

Table 2. Cost of various candidate materials that could be used in fillers.

Material	Density (g/cm^3)	Cost as of 2/22/19 ($/pound)	Cost per DPC ($)
Cement	3.15	$0.03	$1,250
Tin	7.32	$9.78	$946,969
Zinc	7.14	$1.22	$115,224
Aluminum	2.7	$0.84	$30,000

5.2 Comparative Cost Analysis Parameters

The cost analysis parameters and their sources/bases are summarized in Table 3. The detailed cost analysis for the four cases is presented in Appendix A. All costs are escalated to 2019 based on an assumed 2% annual inflation rate. Some parameters (e.g., numbers of existing DPCs) are current values that are certain to change with time.

Note that the total SNF inventory figure from Table 3 (109,300 MTU) is consistent with the TSLCC and reflects an estimate of SNF production from reactors with 40-year lifetime, that do not seek or receive 20-year life extensions.

Table 3. Comparative cost analysis parameters.

Parameter ($ values are rounded)	Value	Basis/Source
SNF Total Inventory (MTU)	109,300	DOE 2008c, Table A-2
Number of PWR TADs	7,978	
Number of BWR TADs	5,005	
Total number of TADs	12,983	
Capacity of PWR TAD	21	
Capacity of BWR TAD	44	
Total number of assemblies	387,758	Calculated based on total SNF inventory, total number of TADs, and TAD capacity
Number of PWR assemblies	167,538	
Number of BWR assemblies	220,220	
Total number of existing DPCs	2,700	Calculated in Appendix B based on StoreFuel 2019. All values are as of 1/1/2019.
Total number of PWR DPCs	1,734	
Total number of BWR DPCs	966	
Total number of assemblies in DPCs	113,835	
Average capacity of loaded PWR DPC	29	
Average capacity of loaded BWR DPC	66	
Assumed average capacity of future PWR DPC	34	Assumed by averaging 37 and 32 PWR DPC capacities.
Assumed average capacity of future BWR DPC	78	Assumed by averaging 68 and 89 BWR DPC capacities.
Projected number of PWR Assemblies currently not in DPCs	117,396	Calculated based on the TSLCC inventory in BSC 2008c, assumed future DPC capacity, and existing DPCs from StoreFuel 2019.
Projected number of BWR Assemblies currently not in DPCs	156,537	
Number of future PWR DPCs	3453	
Number of future BWR DPCs	2007	
Total number of future DPCs	5460	
Total projected number of PWR DPCs	5187	
Total projected number of BWR DPCs	2973	
Total projected number of DPCs	8160	
Cost per TAD canister	$937k	Cost of TAD canister including materials and fabrication. DOE 2008c, Table 3-7.
Total cost of TAD canisters	**$12.2B**	Calculated based on number of TAD canisters and cost per TAD.
Cost of loading or unloading operations per canister (TAD or DPC).	$450k	This cost element is based on the operations associated with preparing a canister for loading into the pool, transfer of assemblies into the canister, removal from the pool, draining, drying, backfilling, welding, and transfer. This cost element is independent of canister capacity because most of the time consuming operations are not associated with assembly movements. The cost of unloading operations per canister, which include retrieval from storage, cutting lids, cooling, flooding, and unloading of assemblies, is assumed to be similar to the loading operations cost. The value used is a rounded average from the estimates in Energy Northwest v. United States, 2010, Entergy 2007, and EPRI 2012.

Repackaging cost beyond what is assumed in the TSLCC	**$3.26B**	Calculated based on the number of DPCs to be repackaged at a repository beyond the currently assumed 920 DPCs in the TSLCC (BSC 2008c, Table A-2).
LLW volume for a DPC (m^3)	12.00	This is estimated based on the size of a typical DPC (Diameter 70 in., length 190 in.) per ATI-TR-13047 2013.
LLW disposal cost ($/$m^3$)	$14.0k	LLW disposal cost is provided in Shropshire et al. 2009, Table J-7 for disposal and Section G3-8 for characterization, packaging and treatment. The estimated cost for LLW near surface disposal is $2,500/$m^3$. The estimated cost for debris characterization, packaging and treatment, which may be assumed for DPC disposal, is $9,000/$m^3$. Escalation to 2019 has been added to this cost.
Total LLW Disposal Cost	**$1.37B**	Calculated based on the total volume of repackaged DPCs and the disposal cost per m^3.
Cost of treatment of existing DPCs to facilitate disposal (per DPC)	$200k	See Section 5.
Treatment cost for all existing DPCs	**$540M**	
DCRAs or modified control blades cost per DPC	$350k	See Section 3.2.
BSS Cost for PWR DPC	$174k	
BSS Cost for BWR DPC	$354k	
Cost of DPC modification	**Varies per Case**	
Cost of disposal overpacks for all TAD canisters	$12.5B	DOE 2008c, Table 2-4, taking into account the CSNF cost share of 78.2% and inflation.
Cost per disposal overpack	$961k	Calculated based on the cost of CSNF overpacks and the total number of TADs.
Disposal overpacks cost reduction	**$4.64B**	This cost delta takes into account the reduced number of disposal overpacks needed for DPCs compared to TADs. Note that there is no reduction in drip shield cost because the drift length and associated drip shields are a function of thermal load not number of waste packages.

5.3 Comparative Cost Analysis Results

The cost analysis results for the four scenarios are summarized in Table 4 and illustrated in Figure 5.

Table 4. Comparative cost analysis results ($ billions).

Cost Element	Case 1 Dispose all DPCs with no treatment or modification	Case 2 Fillers for existing DPCs and modified loading for future DPCs	Case 3 Fillers for existing DPCs and BSS for future DPCs	Case 4 Fillers for existing DPCs and DCRAs/modified blades for future DPCs
TAD Canisters	-$12.16	-$12.16	-$12.16	-$12.16
Disposal Overpacks	-$4.64	-$4.64	-$4.64	-$4.64
Repackaging Operations	-$3.26	-$3.26	-$3.26	-$3.26
LLW Disposal	-$1.37	-$1.37	-$1.37	-$1.37
Treatment of Existing DPCs	$0.00	$0.54	$0.54	$0.54
Modifications to Future DPCs	$0.00	See note	$1.31	$1.91
Total Cost Avoidance	-$21.43	-$20.89	-$19.58	-$18.98
Note: The cost of modified loading is assumed to be minimal (Section 5.1).				

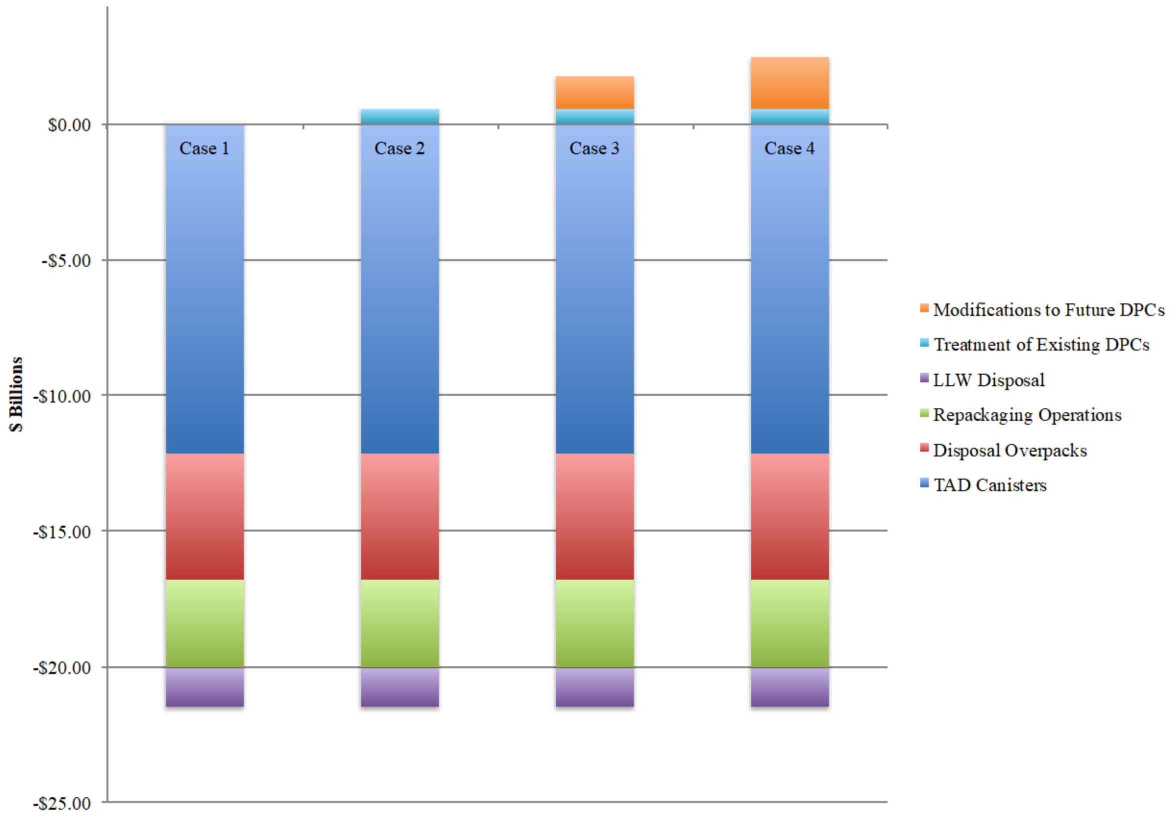

Figure 5. Comparative cost analysis chart.

The cost avoidance associated with direct disposal of DPCs is approximately $20 billion (escalated to 2019) compared to the estimated total system life cycle cost for disposing of

109,300 MTU (this quantity of fuel is consistent with the TSLCC source). If more SNF is produced and more DPCs are loaded, the cost avoidance would increase. Note that this cost avoidance does not take into consideration the sunk cost associated with loading of DPCs at utility sites. The significant contributors to cost avoidance are as follows:

- Elimination of TAD canisters accounts for $12.2 billion
- Reduction in the number of disposal overpacks accounts for $4.6 billion
- Elimination of repackaging operations accounts for $3.3 billion
- Elimination of disposal of DPC hulls and baskets as Low Level Waste (LLW) accounts for $1.4 billion

The primary contributors to the additional cost associated with direct disposal of DPCs are as follows:

- Treatment of existing DPCs (i.e., fillers) accounts for $0.54 billion
- Design modifications for future DPCs account for $1.3 billion if using BSS plates or $1.9 billion if using DCRAs and modified control blades.

6. CONCLUSIONS

The costs associated with potential treatment options of existing DPCs (represented for this analysis by injectable fillers and low-consequence screening) and design modifications to future DPCs, even if greater than estimated in this report, are far outweighed by the costs avoided by direct disposal of commercial SNF in DPCs.

This analysis considered total U.S. SNF inventory of 109,300 MTU loaded into 8,160 DPCs. This is consistent with the previous TSLCC study which is used as input. If more SNF were produced and more DPCs loaded, the potential cost avoidance from DPC direct disposal would increase beyond $20 billion.

Each of the treatment options would be associated with additional scientific, engineering, and licensing effort. Modification of future DPCs by including DCRAs at the time of fuel loading has higher technical maturity for disposal application (and a more reliable cost estimate) than the other treatment options considered, but is potentially not the lowest cost. We note also that repackaging before a repository site is selected would require development of a standardized canister suitable for licensed deployment in multiple geologic settings. Notwithstanding these challenges there is the potential for large cost savings and also reduction of worker dose, by direct disposal of existing and future DPCs.

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APPENDIX A. COST ANALYSIS

Parameter ($ values are rounded for ROM estimate)	Case 1	Case 2	Case 3	Case 4
SNF Total Inventory (MTU)	109,300	109,300	109,300	109,300
Number of PWR TADs	7,978	7,978	7,978	7,978
Number of BWR TADs	5,005	5,005	5,005	5,005
Total number of TADs	12,983	12,983	12,983	12,983
Capacity of PWR TAD	21	21	21	21
Capacity of BWR TAD	44	44	44	44
Total number of assemblies	387,758	387,758	387,758	387,758
Number of PWR assemblies	167,538	167,538	167,538	167,538
Number of BWR assemblies	220,220	220,220	220,220	220,220
Total of number of existing DPCs	2,700	2,700	2,700	2,700
Total of number of PWR DPCs	1,734	1,734	1,734	1,734
Total of number of BWR DPCs	966	966	966	966
Total number of assemblies in DPCs	113,835	113,835	113,835	113,835
Total number of PWR assemblies in DPCs	50,142	50,142	50,142	50,142
Total number of BWR assemblies in DPCs	63,683	63,683	63,683	63,683
Average capacity of loaded PWR DPC	29	29	29	29
Average capacity of loaded BWR DPC	66	66	66	66
Assumed average capacity of future PWR DPC	34	34	34	34
Assumed average capacity of future BWR DPC	78	78	78	78
Projected number of PWR assemblies currently not in DPCs	117,396	117,396	117,396	117,396
Projected number of BWR assemblies currently not in DPCs	156,537	156,537	156,537	156,537
Number of future PWR DPCs	3453	3453	3453	3453
Number of future BWR DPCs	2007	2007	2007	2007
Total number of future DPCs	5460	5460	5460	5460
Total projected number of PWR DPCs	5187	5187	5187	5187
Total projected number of BWR DPCs	2973	2973	2973	2973
Total projected number of DPCs	8160	8160	8160	8160
Average number of PWR TADs per DPC	1.54	1.54	1.54	1.54
Average number of BWR TADs per DPC	1.68	1.68	1.68	1.68
Cost per TAD canister	$937k	$937k	$937k	$937k
Total cost of TAD canisters	**$12.2B**	**$12.2B**	**$12.2B**	**$12.2B**
Cost of loading or unloading ops. per canister (TAD or DPC)	$450k	$450k	$450k	$450k
Repackaging cost beyond what is assumed in the TSLCC	**$3.26B**	**$3.26B**	**$3.26B**	**$3.26B**
LLW volume for a DPC (m^3)	12.00	12.00	12.00	12.00
LLW disposal cost ($/$m^3$)	$14k	$14k	$14k	$14k
Total LLW Disposal Cost	**$1.37B**	**$1.37B**	**$1.37B**	**$1.37B**
Cost for treatment of existing DPCs for disposal (per DPC)	$200k	$200k	$200k	$200k
Treatment cost for all existing DPCs	**$0**	**$540M**	**$540M**	**$540M**
DCRA or modified control blade cost per DPC	$350k	$350k	$350k	$350k
BSS Cost for PWR DPC (rounded)	$174k	$174k	$174k	$174k
BSS Cost for BWR DPC (rounded)	$354k	$354k	$354k	$354k
Cost of DPC modification	**$0**	**$0**	**$1.31B**	**$1.91B**
Cost of disposal overpacks for all TAD canisters	$12.5B	$12.5B	$12.5B	$12.5B
Cost per disposal overpack	$961k	$961k	$961k	$961k
Disposal overpacks cost reduction	**$4.64B**	**$4.64B**	**$4.64B**	**$4.64B**
Cost Avoidance (rounded)	**$21.4B**	**$20.9B**	**$19.6B**	**$19.0B**

APPENDIX B. AVERAGE EXISTING DPC CAPACITY

System	Type	Reactor	SNF Type	GTCC	PWR Assemblies		BWR Assemblies	
					Per can	Total	Per can	Total
VSC-24	Long	ANO	PWR		24	576		
FuelSolutions	W150/W74	Big Rock Point	BWR	1			7	441
VSC-24	STD	Palisades	PWR		18	432		
VSC-24	Short	Point Beach	PWR		16	384		
HI-STAR	MPC-68	Dresden	BWR				4	272
HI-STAR	MPC-68	Hatch	BWR				3	204
HI-STAR	MPC-80	Humboldt Bay	BWR	1			5	390
HI-STORM	MPC-24	ANO	PWR		32	768		
HI-STORM	MPC-32	ANO	PWR		28	896		
HI-STORM	MPC-32	Braidwood	PWR		24	768		
HI-STORM	MPC-68	Browns Ferry	BWR				45	3060
HI-STORM FW	MPC-89	Browns Ferry	BWR				33	2937
HI-STORM	MPC-32	Byron	PWR		31	992		
HI-STORM UMAX	MPC-37	Callaway	PWR		18	666		
HI-STORM FW	MPC-89	Clinton	BWR				11	979
HI-STORM	MPC-68	Columbia	BWR				45	3060
HI-STORM	MPC-32	Comanche Peak	PWR		36	1152		
HI-STORM	MPC-32	D.C. Cook	PWR		44	1408		
HI-STORM	MPC-32	Diablo Canyon	PWR		58	1856		
HI-STORM	MPC-68	Dresden	BWR				60	4080
HI-STORM	MPC-68M	Dresden	BWR				14	952
HI-STORM	MPC-32	Farley	PWR		51	1632		
HI-STORM	MPC-68	Fermi 2	BWR				12	816
HI-STORM	MPC-68	Fitzpatrick	BWR				21	1428
HI-STORM	MPC-68M	FitzPatrick	BWR				5	340
HI-STORM	MPC-68	Grand Gulf	BWR				28	1904
HI-STORM	MPC-68M	Grand Gulf	BWR				6	408
HI-STORM	MPC-68	Hatch	BWR				60	4080
HI-STORM	MPC-68M	Hatch	BWR				19	1292
HI-STORM	MPC-68	Hope Creek	BWR				29	1972
HI-STORM	MPC-32	Indian Point 1	PWR		5	160		
HI-STORM	MPC-32	Indian Point 2&3	PWR		37	1184		
HI-STORM	MPC-68	LaSalle	BWR				24	1632
HI-STORM	MPC-68M	LaSalle	BWR				9	612
HI-STORM FW	MPC-37	Palisades	PWR		4	148		
HI-STORM	MPC-68	Perry	BWR				20	1360
HI-STORM	MPC-68	Pilgrim	BWR				17	1156
HI-STORM	MPC-68	Quad Cities	BWR				53	3604
HI-STORM	MPC-68M	Quad Cities	BWR				2	136
HI-STORM	MPC-68	River Bend	BWR				31	2108
HI-STORM	MPC-32	Salem	PWR		27	864		
HI-STORM	MPC-32	Sequoyah	PWR		44	1408		
HI-STORM	MPC-37	Sequoyah	PWR		10	370		

System	Type	Reactor	SNF Type	GTCC	PWR Assemblies		BWR Assemblies	
					Per can	Total	Per can	Total
FW								
HI-STORM UMAX	MPC-37	SONGS 2&3	PWR		29	1073		
HI-STORM FW	MPC-37	V.C. Summer	PWR		4	148		
HI-STORM	MPC-68	Vermont Yankee	BWR				23	1564
HI-STORM	MPC-68M	Vermont Yankee	BWR				35	2316
HI-STORM	MPC-32	Vogtle	PWR		34	1088		
HI-STORM FW	MPC-37	Watts Bar	PWR		10	370		
HI-STORM	MPC-32	Waterford	PWR		23	736		
MAGNASTOR	TSC-37	Catawba	PWR		15	555		
MAGNASTOR	TSC-37	Kewaunee	PWR		24	888		
MAGNASTOR	TSC-37	McGuire	PWR		20	740		
MAGNASTOR	TSC-37	Zion	PWR	4	61	2226		
NAC-MPC	MPC-26	Conn Yankee	PWR	3	40	1019		
NAC-MPC	MPC-36	Yankee Rowe	PWR	1	15	533		
NAC-MPC	LACBWR	LaCrosse	BWR				5	333
NAC-UMS	UMS-24	Catawba	PWR	4	20	576		
NAC-UMS	UMS-24	Maine Yankee	PWR		64	1434		
NAC-UMS	UMS-24	McGuire	PWR		28	672		
NAC-UMS	UMS-24	Palo Verde	PWR		152	3648		
NAC-I28	NAC-I28	Surry	PWR		2	56		
NUHOMS	37PTH	Beaver Valley	BWR				10	370
NUHOMS	61BTH	Brunswick	BWR				36	2196
NUHOMS	24P	Calvert Cliffs	PWR		48	1152		
NUHOMS	32P	Calvert Cliffs	PWR		30	960		
NUHOMS	32PHB	Calvert Cliffs	PWR		11	352		
NUHOMS	61BT	Cooper	BWR				8	488
NUHOMS	61BTH	Cooper	BWR				22	1342
NUHOMS	32PTH1	Crystal River	PWR	5	34	1243		
NUHOMS	24P	Davis-Besse	PWR		3	72		
NUHOMS	32PTH1	Davis-Besse	PWR		4	128		
NUHOMS	61BT	Duane Arnold	BWR				20	1220
NUHOMS	32PT	Fort Calhoun	PWR		10	320		
NUHOMS	32PT	Ginna	PWR		10	320		
NUHOMS	12T	INEEL	PWR		29	177		
NUHOMS	32PT	Kewaunee	PWR	2	12	448		
NUHOMS	61BT	Limerick	BWR				19	1159
NUHOMS	61BTH	Limerick	BWR				27	1647
NUHOMS	32PT	Millstone	PWR		34	1088		
NUHOMS	61BT	Monticello	BWR				10	610
NUHOMS	61BTH	Monticello	BWR				20	1220
NUHOMS	61BT	Nine Mile Point	BWR				16	976
NUHOMS	61BTH	Nine Mile Point	BWR				19	1159
NUHOMS	32PTH	North Anna	PWR		36	1152		
NUHOMS	24PHB	Oconee	PWR		64	1536		
NUHOMS	24P	Oconee	PWR		84	2016		
NUHOMS	24PTH	Oconee	PWR		4	96		

System	Type	Reactor	SNF Type	GTCC	PWR Assemblies		BWR Assemblies	
					Per can	Total	Per can	Total
NUHOMS	61BT	Oyster Creek	BWR				8	488
NUHOMS	61BTH	Oyster Creek	BWR				26	1586
NUHOMS	24PTH	Palisades	PWR		13	312		
NUHOMS	32PT	Palisades	PWR		11	352		
NUHOMS	32PT	Point Beach	PWR		34	1088		
NUHOMS	24PT	Rancho Seco	PWR	1	21	493		
NUHOMS	24PTH	Robinson	PWR		23	552		
NUHOMS	7P	Robinson	PWR		8	56		
NUHOMS	32PTH	Seabrook	PWR		22	704		
NUHOMS	24PT1	SONGS 1	PWR	1	17	395		
NUHOMS	24PT4	SONGS 2&3	PWR		33	792		
NUHOMS	32PTH	St. Lucie	PWR		29	928		
NUHOMS	32PTH	Surry	PWR		34	1088		
NUHOMS	52B	Susquehanna	BWR				27	1404
NUHOMS	61BT	Susquehanna	BWR				48	2928
NUHOMS	61BTH	Susquehanna	BWR				24	1464
NUHOMS	32PTH	Turkey Point	PWR		28	896		
			Total	23	1734	50142	966	63693
			Average Canister Capacity		**29**		**66**	