SAND2020-3756R

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Analysis of Solutions for the Geologic Disposal of Dual-Purpose Canisters

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology
by
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with contributions from
Oak Ridge National Laboratory and
Savannah River National Laboratory

M2SF-19SN010305051, Rev. 1
March, 2020

Revision History

Analysis of Solutions for the Geologic Disposal of Dual-Purpose Canisters Deliverable: M2SF-19SN010305051 Work Package: SF-19SN01030505 – Technical and Programmatic Solutions for Direct Disposal of DPCs – SNL WBS: 1.08.01.03.05	A review draft and concurrence draft were prepared at Sandia (technical review by Sam Durbin/SNL, compliant with NTRD QAPD Rev. 5, Appendix B). The Sandia approval (Tracking # 973431) was for internal use only, and the resulting copy (Rev. 0) was submitted to PICS/NE in satisfaction of the deliverable, and to DOE for management review before publication. Subsequently, DOE comments were received and incorporated into Rev. 1, which was reviewed through Sandia R&A for unclassified, 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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ACKNOWLEDGEMENTS

This report was a group effort across multiple national laboratories with contributions from those shown in the table below.

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The authors would like to thank others who contributed their ideas to the development, particularly Tim Gunter and Bob Clark of DOE/SFWS&T, Rob Howard of ORNL, John Scaglione of Spectra Tech, Inc., and Bob MacKinnon (now retired) and Geoff Freeze of SNL. The DPC disposition R&D team extends beyond this group to include many others at SNL and ORNL. Consensus was generally reached on all questions of R&D scope and strategy (see Sections 2 and 8).

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ABSTRACT

Commercial spent nuclear fuel (SNF) is accumulating at 72 sites across the U.S., at the rate of about 2,000 metric tons of uranium (MTU) per year. There are currently more than 2,700 dual-purpose canisters (DPCs) loaded with SNF, which are designed for storage and transportation but not disposal. If current storage practices continue, about half the eventual total U.S. SNF inventory will be in about 5,500 dry storage systems by 2035, with the entire inventory stored in 10,000 or more by 2060. The quantity of SNF in DPCs is now much greater than that anticipated in the past, leading the DOE to investigate the technical feasibility of direct disposal of SNF in DPCs. Studies in 2013-2015 concluded that the main technical challenges for disposal of SNF in DPCs are thermal management, handling and emplacement of large, heavy waste packages, and postclosure criticality control (Hardin et al. 2015). Of these, postclosure criticality control is the most challenging, and the R&D needed for this aspect of DPC direct disposal is the primary focus of this report.

Direct disposal of commercial SNF in DPCs currently located across the U.S. has the potential to simplify disposal operations, minimize the number of SNF shipments, reduce collective worker dose, and significantly decrease the costs associated with geologic disposal. The greatest technical challenge is associated with postclosure criticality control, because modern DPCs depend on aluminum-based materials for neutron absorption during storage and transportation, and those materials will degrade in a few decades when exposed to ground water in a repository. This report focuses on alternative technical approaches for postclosure criticality control as targets for R&D effort, with the understanding that other questions related to safety, engineering feasibility, and thermal management can be readily resolved using available technologies.

For some geologic disposal host media, ground waters that could potentially flood a DPC-based waste package would be saline, which would help to ensure subcriticality for many, if not all existing and future DPCs. For other geologic settings, DPC modifications or repackaging would be needed to decrease the probability of a criticality event below the level of regulatory concern. Without such measures, the consequences from in-package criticality events would need to be quantified and either included or excluded from the regulatory performance assessment (PA) dose calculation. Either the consequences are shown to be insignificant and omitted from the PA, or they are included in regulatory dose assessments. For the Yucca Mountain license application (DOE 2008a) specialized site-specific transport-aging-disposal (TAD) canisters were specified, and in-package postclosure criticality was excluded on the basis of low probability. This was possible with the TAD canister because it was demonstrated that the probability of occurrence for a criticality event during the postclosure performance period would be sufficiently small.

Management of DPC direct disposal R&D can be guided by a few strategy options for DPC disposition. The options developed in this study are:

1. **Criticality Consequence Analysis** – Evaluate the consequences of potential criticality events on overall repository performance to determine if the consequences are acceptably low, given a viable method for determining consequences. This option could include the use of high-performance engineered barriers to limit the incidence and consequences from criticality events. If successful, option 1 could obviate the need for options 2, 3 and 4.
2. **Modification of Future DPCs** – Develop technical solutions for modifying future DPCs so they will remain subcritical in any repository setting: a) loading schema with the possibility to blend fuel assemblies from fuel pools based on reactivity (PWR and BWR

fuel); b) disposal control rods (PWR fuel); c) disposal control rods or rechanneling (BWR fuel); and d) replacement absorber plates (some, but not all BWR fuel baskets). DPC modification could be combined with other options, particularly options 3 and/or 4, to treat different sets of DPCs and limit the overall probability of a criticality event.

3. **Injectable Fillers** – Develop and demonstrate fillers that could be injected as liquids into existing DPCs, where they solidify, and displace or exclude ground water from breached waste packages in a repository. If successful, this approach could be used to treat all DPCs including those loaded without modifications, and those for which option 2 could prove difficult because of fuel or basket design. Use of fillers could be combined with other options, particularly option 2, to treat different sets of DPCs and limit the overall probability of a criticality event.
4. **Repackaging** – Repackage the SNF in DPCs into disposal-ready, repository-specific canisters if none of the first three options is adopted. Repackaging would be done in support of a low-probability approach to criticality process screening. It could be combined with options 2 and 3 to treat different sets of DPCs and limit the overall probability of a criticality event.

Any of these options can be reevaluated at any time during the course of the R&D program, and future decisions for R&D to continue may be based on methodological considerations (e.g., achieving advancement in technical capability) as well as projected consequences (e.g., nature of dose estimates). At this stage of the R&D program this list cannot readily be ordered with respect to future utility, funding priority, etc. Absent more detailed information for comparisons, funding prioritization should focus on the present needs for each R&D area, and on activities *within* each area. However, it is noted that option 1 is distinct because if successful it would obviate the need for the other options, and option 2 is distinct because it has greater technical maturity and might be successfully implemented sooner using generic (non-site-specific) analysis. Note that the utility of options 1 and 2, and the associated R&D efforts, is tied to how soon either option can support critical SNF management decisions leading to implementation.

The overall R&D strategy recommended here starts with a significant effort directed toward consequence screening (option 1) to determine if engineered solutions that are presently developmental (options 2 and 3) can be avoided. The greatest potential cost avoidance for final disposal, on the order of $20B, is associated with this outcome. Option 4 is relatively well understood and would be the most costly, and R&D is not planned although it could be challenging to design a canister that provides criticality control in any geologic disposal medium.

R&D is presently underway for options 1 and 3, with some preliminary work on option 2. In addition, a program to develop specifications for a standardized canister (standardized TAD or STAD) suitable for use in any geologic disposal medium has evaluated long-lived absorber plate materials (NFST 2015a,b). Also, the DOE is currently initiating a laboratory program to test advanced neutron absorbers (ANAs; Blink et al. 2019; e.g., Ni-Cr-Mo-Gd alloys). A canister development effort for DOE-owned SNF, with some similarities to DPC disposition, is also underway at Idaho National Laboratory. There may be overlap between the DPC, STAD, ANA and DOE-owned SNF canister R&D efforts that should be integrated.

Option 2 has not been investigated since the EPRI studies of DPC direct disposal in 2008-2009. The utility of modifying future DPCs would be maximized by developing the technical case (which could support critical SNF management decisions leading to implementation) in the next few

years. Based on the cost analyses in Section 7, the potential cost savings using the control rods/blades approach, compared to repackaging (comparing the two most technically mature options with a low-probability screening objective) would be approximately *$2 million per DPC*. As long as options 1 and 3 are developmental and not realized, this estimate may be viewed as the opportunity cost incurred each time a DPC is loaded without modifications to make it disposable in different geologic media.

ACRONYMS AND DEFINITIONS

AECL	Atomic Energy of Canada, Ltd.
ANA	Advance neutron absorbing material
ANL	Argonne National Laboratory
BF	Bare fuel (un-canistered)
BSS	Borated stainless steel
BWR	Boiling water reactor
CANDU	Canada deuterium uranium (fuel)
CFR	Code of Federal Regulations
DCRA	Disposal Control Rod Assembly
DOE	U.S. Department of Energy
DPC	Dual-purpose canister
FEP	Feature, event and/or process
GW-d/MTU	Gigawatt-days per metric ton of uranium
LLW	low level waste
MGy	mega-Gray (dose unit)
MTU	metric tons uranium
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PA	Performance assessment
PWR	Pressurized water reactor
RCCA	Rod Cluster Control Assembly
SFWST	Spent Fuel and Waste Science and Technology
SNF	Spent nuclear fuel
SNL	Sandia National Laboratory
SRNL	Savannah River National Laboratory
STAD	Standardized TAD
TAD	Transportation, Aging and Disposal
TC	Transportation cask
TEV	Transport-emplacement vehicle
TSLCC	Total System Life Cycle Cost
WHB	Waste Handling Building

Analysis of Solutions for the Geologic Disposal of Dual-Purpose Canisters

1. Introduction and Background

In 2008 the United States Department of Energy (DOE) submitted the Yucca Mountain Repository License Application (DOE 2008a) to the U.S. Nuclear Regulatory Commission (NRC). The license application, which was updated in 2009 (DOE 2009), included a performance assessment (PA) that analyzed the long-term performance of the repository consistent with applicable requirements given in the Code of Federal Regulations (CFR): 10 CFR Part 63 and 40 CFR Part 197. In that PA, spent nuclear fuel (SNF) was assumed to be disposed of in TAD canisters that were specified to transport fuel from storage locations, store it for aging purposes as needed, and dispose of it in a repository.

However, because the license application process was suspended in 2010, TAD canisters were never built, and utilities could not load SNF into TAD canisters. Rather, utilities have continued the practice of storing SNF in dual purpose canisters (DPCs) that are designed to meet relevant NRC requirements for storage and transport of SNF (10 CFR Part 72 and 10 CFR Part 71), but are not designed for disposal of SNF. As a result, SNF has accumulated at 72 sites across the U.S., including operating and decommissioned power plants, and continues to do so at the rate of more than 2,000 metric tons of uranium (MTU) per year (Carter and Vinson 2014). Currently (as of March, 2020) there are more than 3,000 DPCs loaded with SNF across the United States (StoreFUEL 2019), plus about 300 storage casks of other types. If current storage practices continue and no new nuclear power reactors are built, half the eventual total U.S. SNF inventory will be in about 5,000 dry storage systems by 2030, with the entire inventory stored in about 10,000 DPCs by 2060 (based on projections by Hardin et al. 2013).

The quantity of SNF now in DPCs is much greater than originally anticipated, leading the DOE to investigate the technical feasibility of direct disposal of SNF in DPCs (Howard et al. 2012; Hardin et al. 2012; Hardin and Voegele 2013; Hardin and Howard 2013; Hardin et al. 2013; Hardin et al. 2014; and Hardin et al. 2015). These studies concluded that the main technical challenges for disposal of SNF in DPCs are thermal management, handling and emplacement of large, heavy waste packages, and postclosure criticality control (Hardin et al. 2015). Of these, postclosure criticality control is the most challenging, and the R&D needed for this aspect of DPC direct disposal is the primary focus of this report.

Most dry storage systems involve loading SNF assemblies into an open DPC in a fuel pool, completing DPC sealing welds except for dewatering ports, then removing the DPC to a shielded transfer cask, then dewatering and final sealing, and then transferring the DPC to a stationary dry storage overpack. Storage overpacks provide most of the neutron and gamma shielding and protection from seismic events and projectiles. Most DPCs and their storage overpacks are oriented vertically (Figure 1-1) but some storage is horizontal (Figure 1-2). Among the common DPC designs, all use stainless steel for the canister shell, while many (but not all) use stainless for the fuel basket, shield plugs, and top and bottom containment and structural lids. Some baskets have components made from low-alloy steel (plated to prevent corrosion in the fuel pool), or aluminum-based material (e.g., Metamic™). The design capacities of these canisters have increased over time, and currently the largest ones hold 37 pressurized water reactor (PWR) assemblies or 89 boiling water reactor (BWR) assemblies (StoreFUEL 2019). There are also a limited number of dry storage systems consisting of welded canisters in storage-only configuration (without neutron

absorbing features), and there are 258 "bare fuel" casks in use that are self-shielded, with bolted closures (Figure 1-3).

Thermal limits for commonly used dry storage systems range from approximately 18 to more than 40 kW, depending on the heat rejection capacity accommodated by the design. Burnup for the fuel presently stored in DPCs ranges from a few gigawatt-days per metric ton of uranium (GW-d/MTU) to more than 60 GW-d/MTU.

The baskets inside the DPCs and bare fuel casks are designed to control nuclear reactivity in accordance with regulatory requirements for storage and transportation. Some older systems used flux traps but these take up space, and these baskets are no longer produced. To achieve greater loading density neutron absorbing materials are now built into the basket cells that hold the fuel assemblies, or the entire basket is made from a material that is both structural and neutron absorbing. Typically these materials consist of some variation of an aluminum-boron carbide cermet (Banerjee et al. 2014) although borated stainless steel was used occasionally in the past. Corrosion tests for Boral™, a borated aluminum cermet, indicated a 0.28 mil per year (7 μm per year) loss of the aluminum cladding in simulated PWR fuel pool water (EPRI 2005). Boral is essentially a sandwich with porous Al-B_4C in the middle, clad by Al layers approximately 10 mils thick. At the measured rate the clad layers would be corroded in approximately 40 years, followed by accelerated corrosion of some 80 mils of the Al-B_4C layer (from both sides) giving a chemical lifetime of a few hundred years at most. For some corrosion conditions the measured rate of Boral corrosion was slower, but still represents rapid corrosion in a geologic repository.

For most current DPC designs, reactivity calculations use "burnup credit" for PWR SNF assemblies in storage and transportation systems. This accounts for the loss of fissile radionuclides and the in-growth of radionuclides with relatively high neutron cross sections. Regulatory guidance on the use of burnup credit was issued by NRC (2012). At present, 28 actinides and fission products are approved for burnup credit analysis of PWR SNF, for storage and transportation applications. No burnup credit for BWR SNF in storage or transportation is allowed at this time, although establishing the technical bases for BWR SNF burnup credit would also be beneficial (Scaglione et al. 2014; Alsaed 2018).

There are additional radionuclides that could be included if an adequate technical basis were demonstrated to the NRC, particularly Cs-133 (Alsaed 2018). The Department of Energy (DOE) has used 29 radionuclides in reactivity analyses described in this report and supporting references.

The majority of SNF in dry storage in the U.S. is in DPCs, and nearly all future dry storage transfers will be to DPCs. The predominance of DPCs in the U.S. is due to their generally lower cost than bare fuel casks. A contributing factor is that welded stainless steel canisters do not require active processes to maintain and monitor for loss of confinement via leakage through the double O-ring seals used on casks.

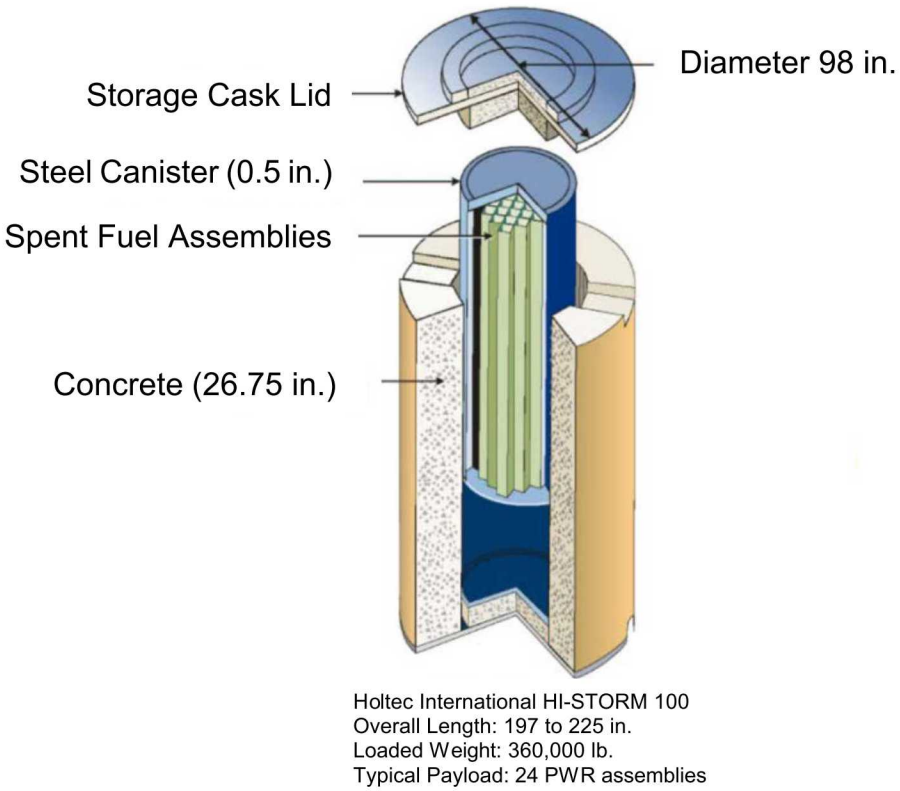

Figure 1-1. Example of a welded steel dual-purpose canister inside a concrete storage overpack or cask (modified from Easton 2011).

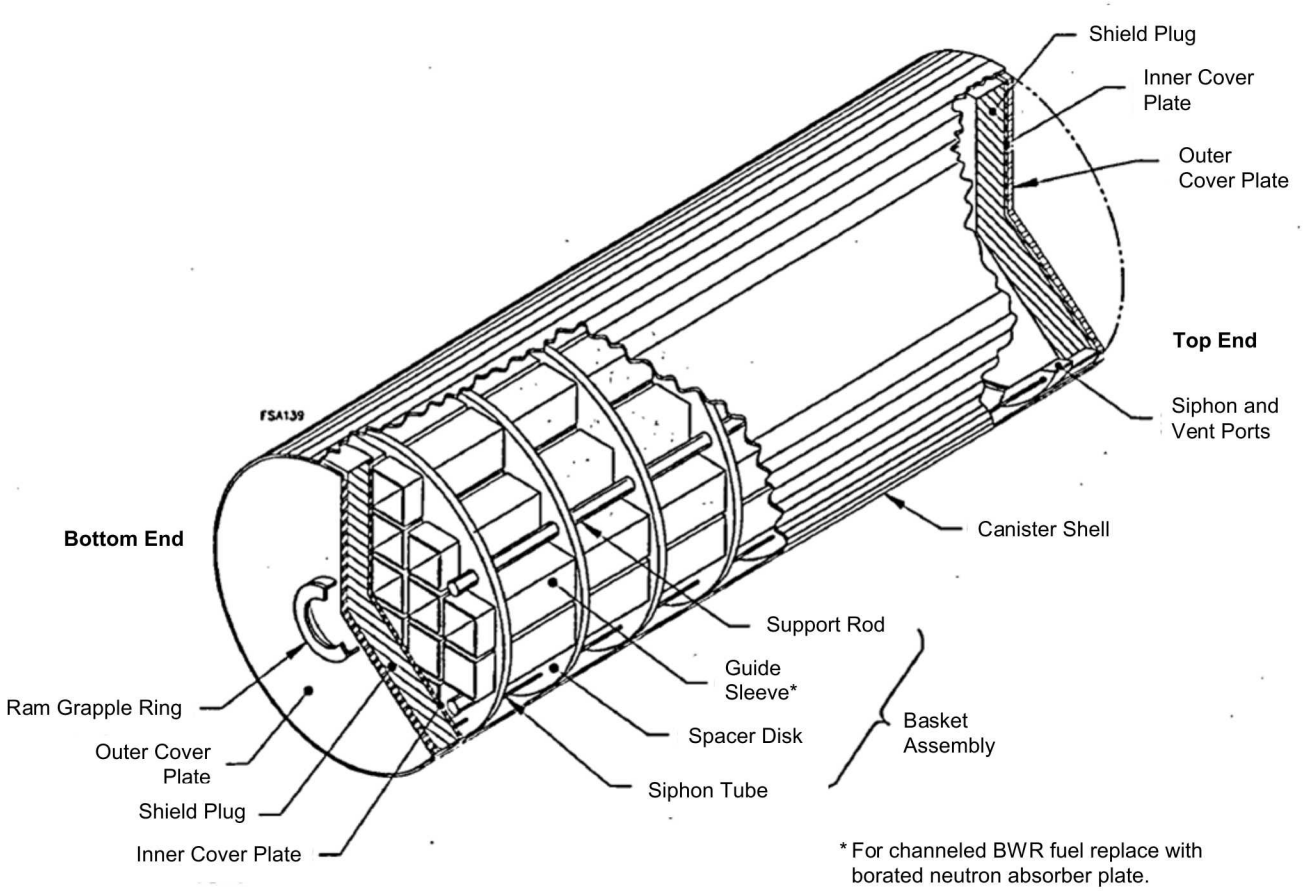

Figure 1-2. Representative design of DPC welded stainless steel canister (NUHOMS 24PHB).

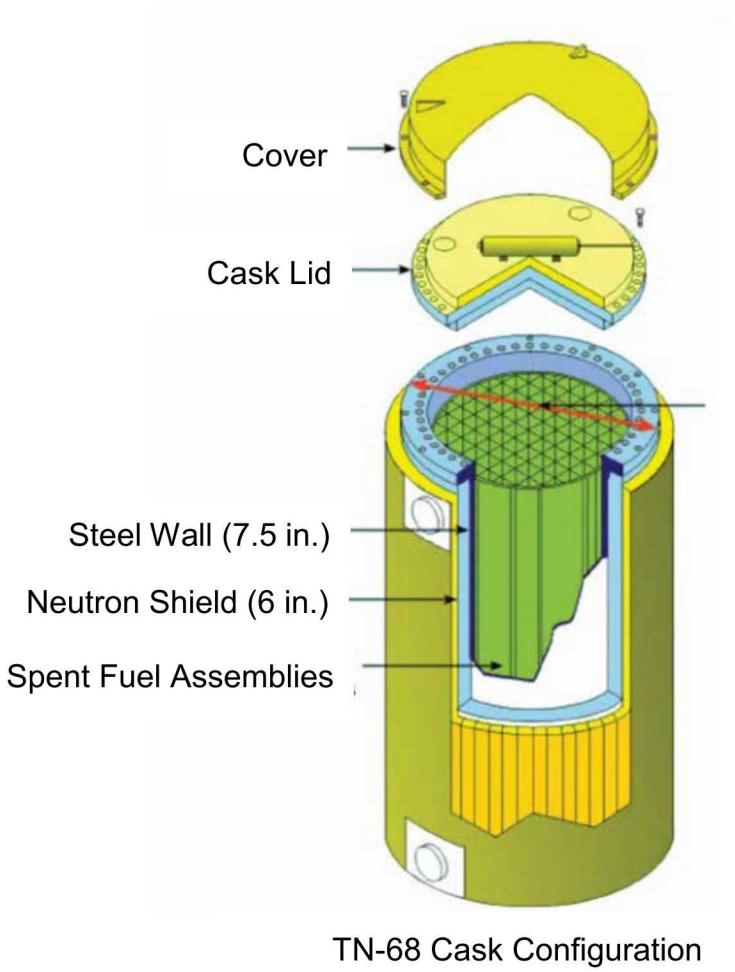

Figure 1-3. Example of bare fuel in a bolted lid cask (TN-68 cask; from Williams 2013).

The performance specification for the TAD canister (DOE 2008b) was informed by a specific geology and performance objectives to ensure that criticality events would have sufficiently low probability that they could be excluded from repository PA. It would have capacity for 21 PWR SNF assemblies or 44 BWR assemblies, which is significantly fewer than the most recent DPC designs. Using canisters smaller than the TAD for disposal would be significantly more costly (Hardin et al. 2013).

Repackaging SNF from DPCs to disposal canisters of any size, would be significantly more costly than DPC direct disposal as discussed in Section 7. Repackaging would be costly and incur additional radiological, operational safety, and management risks. There are several reasons to consider direct disposal of commercial SNF in DPCs, including: 1) lower collective worker dose associated with management of SNF to permanent disposal; 2) less complexity of SNF management activities including transportation steps, and numbers of facilities to license, construct, and operate; and 3) lower cost as summarized in Section 7 (from Alsaed 2019).

For the TAD canister the probability of occurrence for in-package criticality was less than the regulatory screening criterion for inclusion in the PA (SNL 2008). This was because the design

specification for the TAD canister (DOE 2008b) included long-lived neutron-absorbing material (borated stainless steel, powder metallurgy grade) that would prevent criticality for at least 10,000 years in an unsaturated setting. As discussed above, aluminum-based neutron-absorbing materials that meet the requirements for loading of DPCs in pools, and for SNF storage and transport, are expected to degrade by corrosion after only a few hundred years exposure to ground water in a repository. Basket structural elements would also degrade so that the internal structure supporting the fuel could collapse. If the current fleet of DPCs and the SNF they contain is disposed of directly without repackaging, generally it would not be possible to exclude in-package criticality from the postclosure PA on the basis of low probability.

A previous study considered the feasibility of disposal of SNF in DPCs at an unsaturated, unbackfilled repository (BSC 2003), and found the major concerns to be: 1) postclosure criticality; 2) physical dimensions; and 3) vertical handling modifications for canisters designed for horizontal storage. In addition, burnup credit was found to be important in performing postclosure criticality analyses. Analysis of postclosure criticality for the same repository concept, considering DPC direct disposal, was performed by EPRI (2007, 2008). These findings from previous studies were consistent with the R&D approaches described in this report.

More recently, the technical feasibility of DPC direct disposal was studied by the DOE (Howard et al. 2012; Hardin et al. 2012; Hardin and Voegele 2013; Hardin and Howard 2013; Hardin et al. 2013, 2014). Disposal concepts were considered for a range of geologic host media: crystalline (saturated), clay/shale media (nominally saturated), domal or bedded salt, and unsaturated settings. Four broad concerns with respect to the technical feasibility of DPC direct disposal were identified: safety, engineering feasibility, thermal management, and postclosure criticality control (Howard et al. 2012). A set of assumptions was developed (Hardin and Howard 2013).

Feasibility studies found no barriers to DPC direct disposal in these media, although disposal could be implemented sooner or at lower cost, in some media compared to others. For example, heat transfer is generally superior in salt and unbackfilled concepts, so that DPC-based waste packages could be emplaced 100 to 200 years sooner than for other concepts requiring preservation of clay-based buffer materials (thermal results were summarized by Hardin et al. 2015). Engineering challenges include developing equipment for underground transport and emplacement of large, heavy waste packages. Importantly, for reasons discussed throughout this report, these previous studies found that postclosure criticality control would be a technical challenge for DPC direct disposal, for all disposal concepts in which ground water is available to fill breached waste packages and is not saline.

1.1 Purpose

The purpose of this report is to develop an updated, clear strategy for using R&D to support future decision-making on disposition of commercial SNF in DPCs. The overall goal is to maximize the number of DPCs that can be disposed of directly, to avoid repackaging into purpose-designed disposal canisters (that would likely be similar to the TAD canister concept). The updated strategy is developed in Section 2, with components developed further in Sections 3 through 7.

1.2 Comparison of DPC Direct Disposal to Repackaging

DPC direct disposal options are compared to a case for which 100% of the SNF in DPCs is transferred into purpose-designed disposal canisters. Such canisters could be site-specific (like the TAD canister) or they could be standardized TAD canisters (STAD canisters) intended for possible

disposal in various geologic media. The capacities of these TAD or STAD disposal canisters are assumed for this analysis to be 21 PWR assemblies or 44 BWR assemblies (21-PWR/44-BWR). The repackaging case has been studied extensively and is summarized in Section 6.

The following discussion compares risks and benefits for DPC direct disposal vs. repackaging.

Reduced Overall Health Consequences

Although population dose from SNF transport is very low, reducing the number of SNF shipments would mean less population dose. If repackaging is done at the repository, there would be no additional shipments compared to shipping DPCs directly to the repository for disposal. However, if repackaging was done elsewhere (and all fuel was loaded into DPCs at power plants) then the full repackaging case would result in roughly twice as many shipments.

Members of the public would not be subject to significant non-radiological consequences from canister loading and transport.

Worker dose could be significantly reduced by direct disposal of SNF in DPCs. A scoping study (Weck 2013) suggested that collective worker dose from loading DPCs is approximately 250 person-mrem per canister. Analysis based on operating experience shows that greater collective dose (several times this figure) is possible from loading high-burnup, younger fuel (EPRI 2012). Cutting open and unloading of DPCs, and loading of purpose-designed disposal canisters, could readily exceed the collective dose results reported for loading DPCs. Worker dose could be greater still from modifying DPCs that were already loaded and sealed, especially if DPC lids are removed and rewelded for emplacement of fillers (Section 4) or to install additional criticality control features (Section 5).

Non-radiological worker health consequences would be related to the number of canister and waste package transfers, and the scope of the repository facility. Risks to workers could be greater with smaller but more numerous waste packages (still large and heavy) in a repository with larger layout and greater excavated volume. Smaller disposal canisters and waste packages at the surface would also involve more handling and drying steps, with greater integrated probability of internal and external initiating events (e.g., rigging failure, seismic ground motion).

Waste isolation in a permanent geologic repository could be very similar for DPC-based waste packages compared with purpose-designed disposal canisters, depending on the probability and consequences of postclosure criticality events. Evaluating the risk from postclosure criticality in a repository is an important part of the current R&D program for DPC disposition. Any future decision to implement direct disposal will take into account the probability, and possibly the consequences, for future postclosure criticality events, using comparison with the extant regulatory standards to evaluate whether radiological safety for future members of the public can be assured.

Reduced Cost

It is expected that the cost of direct disposal of commercial SNF in DPCs would be significantly less than for repackaging (Section 7).

Other Risks and Benefits

Operations for overall management of commercial SNF in the U.S. would be simplified with direct disposal in DPCs, compared with repackaging. Disposal in a repository might begin years sooner due to simpler operations and facilities (e.g., no repackaging facilities as described in Section 6). Also, some DPCs have been shown to have sufficiently low k_{eff} for direct disposal even in degraded

condition, because of the basket design and the as-loaded fuel characteristics, and are therefore amenable to direct disposal.

However, due to the relatively large capacity of DPCs, and the tendency for SNF with higher burnup to be placed in more recent and therefore larger DPCs, it will take longer for the DPCs to cool for emplacement in a repository. For example, if a 10 kW thermal power limit is imposed for emplacement, existing and nearly all projected future DPCs could be cool enough by calendar 2130 (Hardin et al. 2013). Other disposal solutions could possibly load a repository in less time, starting with repackaging into smaller purpose-designed canisters that individually produce less heat.

Direct disposal of commercial SNF in DPCs would introduce technical, financial, and regulatory issues that must be resolved during canister and repository licensing. Strategies for addressing criticality, use of fillers, and other DPC alteration alternatives are found in Sections 3, 4 and 5 of this report. Repackaging into purpose-designed disposal canisters (e.g., STAD canisters) is described in Section 6. Cost estimates for various approaches to DPC direct disposal are presented in Section 7.

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2. R&D Strategy

At present, U.S. R&D to support potential DPC direct disposal is ongoing in several technical areas. The R&D strategy includes investigating the consequences of postclosure criticality in a DPC in terms of repository waste isolation performance, and also is investigating engineered measures for decreasing the probability of postclosure criticality in a DPC, for both existing DPCs containing SNF and those yet to be loaded. These strategies are summarized below and discussed in more detail in Sections 3 through 5.

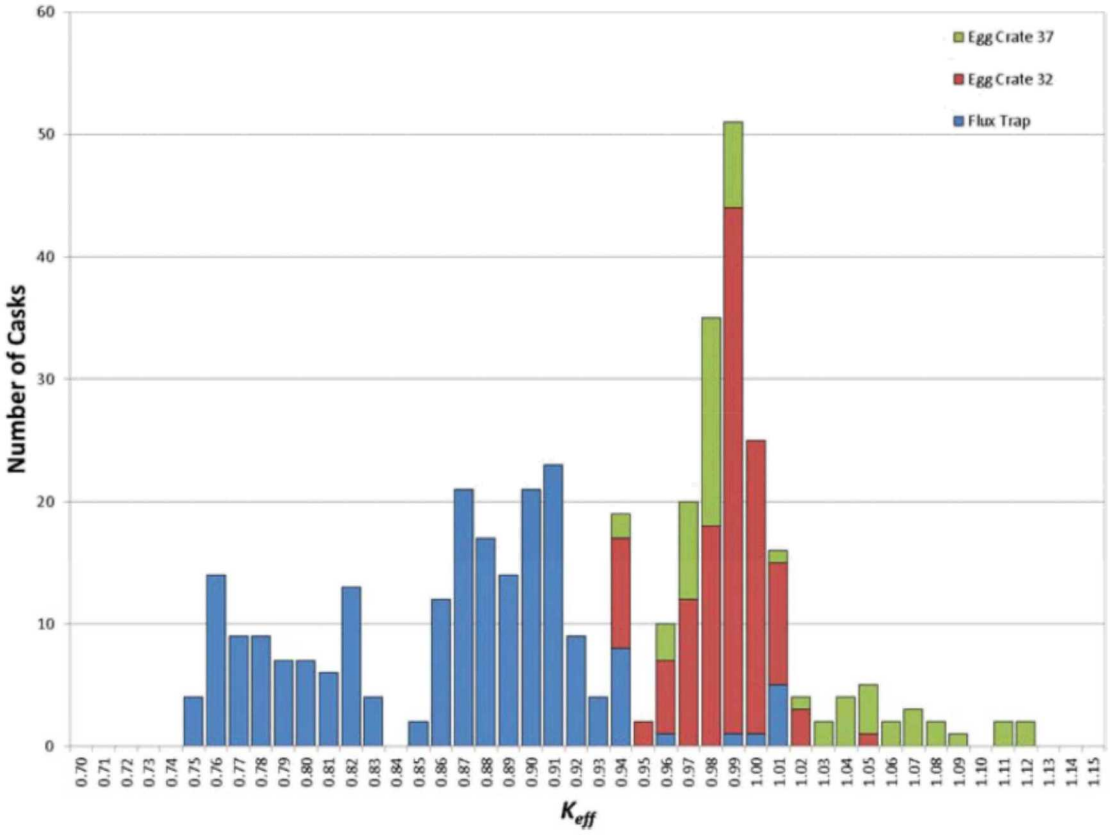
2.1 Criticality Consequence Analyses

The technical basis for calculating the consequences of postclosure criticality in DPCs is not well developed. Developing the capability to evaluate whether the consequences of postclosure criticality in a DPC are significant, could provide a basis for disposing of SNF in DPCs without treatments that involve additional costs and increased worker dose.

The consequences from some number of in-package, postclosure criticality events would be primarily a function of the repository: whether the host rock is unsaturated or saturated, the depth of the repository, whether the repository drifts are open or backfilled, how close waste packages are to each other, the chemistry and geology of the host rock, and so on. For disposal in media with saline ground water, there may be enough neutron-absorbing Cl-35 introduce into breached waste packages, that the probability of criticality for any DPC would be insignificant (Hardin et al. 2015).

For other host rock types and repository settings it is not possible to state with confidence that the probability of all DPCs remaining subcritical would be low without additional treatment. The reasons are uncertainty with respect to what characteristics can be ascribed to other host rock types in generic analysis, and the fact that DPC designs have developed since the 1990's, so that canisters loaded today and in the future have less reactivity margin (caused by larger capacity and more compact basket design, with more advanced burnup credit analysis). Figure 2-1 (from Clarity et al. 2017) summarizes analysis of reactivity for several hundred as-loaded DPCs, for a stylized degradation case representing loss of all neutron absorbing materials (complete removal and replacement by water). There is a trend toward higher reactivity for more recent DPC designs that have larger capacity, and for which burnup-credit analysis is used. These results show that some DPCs, particularly ones loaded more than 10 years ago, may be subcritical in a repository even if flooded with ground water and degraded by corrosion. Conversely, the results suggest that DPCs loaded in the future will not have as much reactivity margin, and are more likely to achieve criticality under such conditions.

As discussed in Section 3, an assessment of criticality consequences would likely consider the entire repository system including radionuclides released (source term), transport within the engineered repository (near field), attenuation by natural barriers (far-field), and exposure pathways (biosphere). Planned assessments are generic rather than site-specific, so aspects such as the far field and the biosphere will be addressed in less detail. The strategy for investigating criticality consequence screening will likely involve simplifying assumptions, but linkage between the details of criticality events, the engineered barriers, and the near-field environment will be captured. Discussion of these linkages is provided in Section 3.



Note: These results are from 3-D simulations of actual DPCs with PWR fuel characteristics as-loaded, assuming axial burnup profiles, burnup credit for 29 nuclides, and including basket materials and construction details, but with neutron absorbing materials replaced by water. For these calculations the DPCs are submerged, and flooded internally with pure water.

Figure 2-1. Example of calculated k_{eff} values for some existing DPCs, plotted by canister capacity and type of construction (Clarity et al. 2017, Figure 33).

2.2 Options for Additional Treatment of DPCs

As described above, a *consequence-based* regulatory strategy could obviate the need for treatment of existing DPCs or modifications to DPCs loaded in the future. By contrast, a *low-probability* exclusion of postclosure criticality from PA would mean remedial treatment of many loaded DPCs, possibly combined with modifications to the design and loading of DPCs loaded in the future.

The principal option for remedial treatment of loaded DPCs that is being investigated by the current R&D program is the use of a filler material. Fillers would be injected into canisters as liquid that subsequently solidifies, and later displaces some or all of the ground water that could flood a breached waste package. Without moderation by water the SNF in a DPC cannot achieve criticality. The options for modifications to the design and loading of DPCs loaded in the future include: 1) insertion of disposal control rods (PWR fuel); 2) control rods (replacing "water rods") or blades (BWR fuel); and 3) zone loading of fuel assemblies in each DPC to limit reactivity in the event of waste package breach, flooding, and internal degradation.

2.2.1 Fillers

Injectable fillers, if successfully demonstrated, could be implemented with existing loaded DPCs and with DPCs to be loaded in the future (Section 4). The current R&D program includes work on the development of filler materials and methods of injection.

Solid particulate fillers have been evaluated by several international programs (summarized by SNL 2017) and were demonstrated in the U.S. and Canada using physical models. Solid particulate fillers could enhance waste isolation by producing sorptive corrosion products and by impeding advective transport within breached waste packages. Favorable poising (redox buffering) of the in-package chemical environment is also possible with fillers such as iron or depleted uranium. Despite these potential advantages, solid particulate fillers were not selected for further development in the U.S., in the 1990s, because of the additional cost and weight and because waste isolation performance was shown to be satisfactory without fillers.

Filler options were summarized prior to the current R&D program by Jubin et al. (2014). For the current program solid fillers are not being investigated for several reasons: 1) previous work has already shown that effective filling is readily achieved if the fuel is exposed in open, dry canisters; 2) cutting open existing DPCs to implement solid particulate fillers would be comparable to repackaging in terms of cost, and could be more complex with greater risk to workers; and 3) for future DPCs (as fuel is loaded) the control rod/blade concept is a more plausible solution for implementation in utility fuel pools.

The use of fillers that could be injected through a small diameter port in the top of the DPC has the least technical maturity of any treatment option discussed in this report, but it is the only remedial measure under study that could be applied to all DPCs, both existing and future (after they are loaded). The desired attributes of a filler material and some candidate materials are discussed in Section 4.

2.2.2 Modifications to Future DPCs

The number of loaded DPCs in the U.S. (fewer than 3,000) is slightly more than one third of all DPCs projected to eventually be loaded in the U.S. (current fleet, 60-year life extensions, some early closures, two new reactor builds). With as many as 7,000 DPCs yet to be loaded, there is ample opportunity to materially change the outlook for direct disposal of commercial SNF in DPCs. Accordingly, DPC modification is a priority for the R&D program although implementation would require cooperation with utility companies that are loading DPCs for dry storage (outside the scope of technical R&D). Measures such as optimized DPC zone-loading, addition of neutron absorbing hardware, substitution of long-lived absorber plates, or other redesign of DPC baskets, would support exclusion of postclosure criticality on low probability.

Several options for future DPC modifications exist (Section 5):

- Modify the SNF loading pattern in the DPCs to lower k_{eff}. For example, more reactive SNF assemblies could be placed on the basket periphery, and less reactive assemblies centrally. Analysis would be done for every DPC loaded, similar to the thermal and external gamma dose calculations that are currently done, but adding reactivity to the optimality problem. This approach is expected to improve the number of DPCs that could be disposable without modification, but not to be universal so that a large number of loaded DPCs would need to be modified some other way, or repackaged, to support low-probability exclusion.

- Insert disposal criticality control rods (PWR fuel), or control rods to replace "water rods" (BWR fuel), or disposal criticality control blades (BWR fuel) that are designed for long-term neutron absorption performance in the disposal environment (Section 5). Fuel channels may also be replaced with neutron-absorbing material, for certain BWR fuel assemblies. Also, chevron-shaped insert plates have been used to supplement reactivity control in fuel pools, and could be adapted to disposal using existing basket designs, and corrosion-resistant neutron-absorbing materials. Disposal control features (rods, blades, channels, inserts) would be designed to degrade slowly and concurrently with the fuel assemblies, to maintain a configuration that is intimate with the fuel, in any host rock or disposal environment. Disposal control features could be required in only a few assemblies for each DPC (see Section 5).
- Design future DPCs with neutron absorbing plates or other absorbing basket features that are made from materials that are more corrosion resistant than in existing DPCs (Section 5). This approach requires an assessment of material corrosion performance in different environments, a need that has been recognized and addressed for standardized canisters (i.e., STAD canisters; see NFST 2015a,b) but not yet resolved for a range of disposal host media. Models for corrosion performance of neutron absorbers are generally empirical, based on laboratory data for representative conditions. Testing of candidate neutron absorber materials in a range of environments has not yet been completed.

Logistically, the first two options appear to be most feasible since no modifications to DPC design would be needed (at least for PWR fuel, and possibly for BWR fuel). Modifications to the loading pattern could be effective for both PWR and BWR fuel canisters, and would involve only minor changes to loading operations in utility fuel pools. Zone loading is already being done as DPCs are loaded, to address thermal and external gamma criteria.

At present, a feasibility study of disposal control rods and/or blades is in planning, and further work can follow if warranted. As discussed in Section 8 these first two options (zone loading and disposal control rods/blades) are logistically favored especially for PWR fuel, which is more than 60% of commercial SNF in the U.S.

Finally, DOE and industry could develop new DPCs with more corrosion-resistant neutron absorbers. One approach is direct replacement in absorber-plate basket designs. Corrosion testing of advanced neutron absorbing material (Ni-Cr-Mo-Gd) and borated stainless steel, for a range of disposal environments, is currently being planned at Idaho National Laboratory. A related action that could help in the design of disposable, multi-purpose canisters, would be to develop a technical standard for disposability. Once the technical requirements were established, the DPC vendor industry could more readily produce design solutions if called upon to do so.

A flow chart of options for achieving direct disposal of DPCs, combined with repackaging, is presented in Figure 2-2. An important aspect of this strategy is that, for a non-salt repository, if postclosure criticality in DPCs is demonstrated to be insignificant in terms of repository performance then it would apply to all DPCs, and it would not be necessary to exercise the other options to lower the probability of occurrence for postclosure criticality. An example is useful for explanation: if DPCs can be grouped according to whether a criticality event is less or more likely than the probability screening threshold (10^{-8} per year), then the low-probability group contributes very little to consequences, and consequence screening applies to all. Conversely, if the aggregated probability is less than 10^{-8} per year for most, but not all DPCs, then a low-probability screening

approach would require remediation or repackaging of the remaining DPCs for which a criticality event is more likely. In summary, the consequence screening approach would apply to all DPCs, while the low-probability approach could be achieved with any combination of reactivity margin, fillers, and DPC modifications (i.e., one or several).

The strategy flowchart (Figure 2-2) shows that first an analysis would be performed to determine whether the entire fleet of DPCs (up to about 10,000) would pose an acceptable risk from criticality events, if disposed of directly. A site-specific assessment would be preferable for such a finding, if a repository site is known. A site-specific assessment could include the option to use a disposal overpack that is highly corrosion resistant and reliable, with the expectation of long containment lifetime (Section 3.4). If the consequences (which could include the predicted incidence of criticality events) are acceptable, and there is no other deterrent to a consequence screening approach (such as preferred regulatory strategy), then no further work on DPC modification or repackaging would be needed.

If a criticality consequence screening approach is not selected (which is currently the case) then additional analyses would be performed to determine:

- The portion of DPC inventory (represented by X) that would remain subcritical in the disposal environment ($k_{eff} < 1$ with sufficient margin) even when degraded, because of characteristics of the fuel and/or DPC design. For a repository in salt, this portion could be close to the full inventory of existing and future loaded DPCs.
- The number of *existing* DPCs for which postclosure criticality can be prevented (at less than the regulatory probability screening threshold) using fillers or another method of remediation without cutting open and resealing DPCs (represented by Y).
- The complementary number of *existing* DPCs for which remediation is impractical or would be ineffective, and which require repackaging (calculated as N-X-Y).
- The number of DPCs that will be loaded in the *future* with modifications to prevent postclosure criticality such as loading, disposal control rods/blades, corrosion resistant absorber plates, or other design changes (represented by Z).
- The complementary number of DPCs that will be loaded in the future for which modification is impractical or would be ineffective, and which require repackaging (quantity N-X-Y-Z).

Note that as more DPCs are loaded the prospect for modification of future DPCs is diminished so it could be more difficult to avoid repackaging altogether. Also, for any disposal concept some small extent of repackaging could be needed to accommodate outliers in fuel characteristics and DPC design (e.g., damaged fuel or very low burnup fuel).

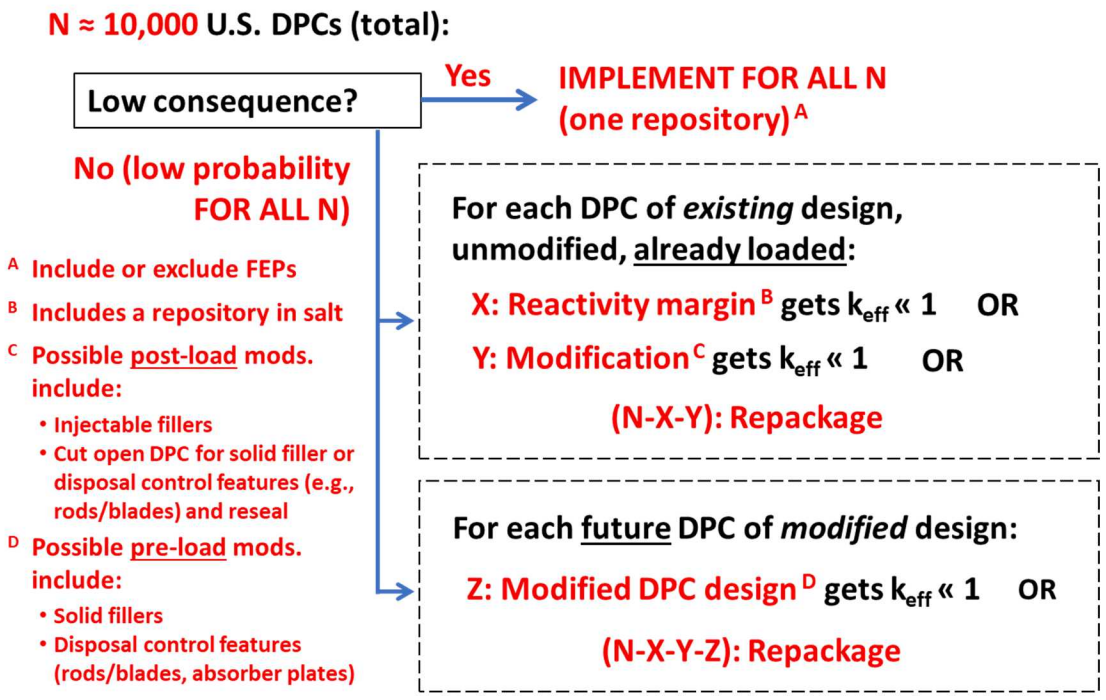


Figure 2-2. DPC direct disposal strategy flowchart.

2.3 References for Section 2

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3. Consequences from In-Package Criticality

Any repository licensed to dispose of SNF must meet requirements regarding long-term performance. A postclosure PA is used to demonstrate that the performance of the repository meets these various requirements. The PA must consider all features, events, and processes (FEPs) that could affect repository performance. All FEPs are to be included in the PA unless the probability of occurrence of the FEP is below a specified limit or the consequences of its occurrence, however probable, can be demonstrated not to be significant (EPA 2008). For the Yucca Mountain PA, in-package criticality in TAD canisters during the postclosure period was excluded from the PA on the basis of low probability. Based on recent investigations of DPC direct disposal feasibility, it is not clear that in-package criticality in DPCs could be excluded from PA for other host media, on the basis of low probability (Hardin et al. 2015).

For other media, except possibly those with saline ground water, modifications to most DPCs could be needed to decrease the probability of criticality events below the level of concern (see Sections 4 and 5). Without such modifications, the consequences from in-package criticality events would need to be considered for PA. Historically, the DOE developed a framework for evaluating the postclosure consequences of in-package criticality (DOE 2003). Either the consequences of criticality events are shown to be insignificant by omission from the PA, or the consequences are included in regulatory dose assessments.

It is important to note that criticality cannot occur unless and until the waste package, which is assumed to consist of a DPC enclosed in a disposal overpack, has failed and a sufficient amount of water has entered. Neutron absorbers in the DPC basket would be expected to prevent criticality, until they are degraded by corrosion. Criticality is then possible if the configuration inside the waste package has an effective neutron multiplication factor (k_{eff}) greater than or equal to 1. For generic studies performed to evaluate whether criticality could be excluded from a PA solely on the basis of low consequence, the probability that these conditions have occurred is not calculated. Instead they are assumed to be present as a starting point for modeling. For studies performed for a repository in a particular host medium at a specific site, the probability that these conditions have occurred would be calculated as part of the PA. Use of a corrosion resistant, long-lived, high-reliability disposal overpack could be evaluated in this situation, using site-specific information. This is discussed further in Section 3.4.

The following sections discuss the FEPs screening process (Section 3.1), criticality FEPs considered (Section 3.2), the approach to demonstrating the consequences of criticality (Section 3.3), and criticality consequence inclusion or exclusion from PA (Section 3.4).

3.1 FEPs Screening Process

As noted above, regulations from the NRC and the Environmental Protection Agency (EPA) specify that events and processes that are estimated to have less than one chance in 10^8 per year of occurring for the first 10,000 years after disposal, are not to be included in the postclosure PA.[1] In

[1] It should be noted that, in the regulations for Yucca Mountain, the EPA also specified that the DOE must assess the effects of seismic and igneous scenarios, of climate change, and of general corrosion on engineered barriers (40 CFR 197.36). If studies of criticality consequence during the postclosure period indicate that consequences are not significant in the first 10,000 years after closure but are more significant beyond 10,000 years after closure of the repository (similar to general corrosion of engineered barriers), the EPA might choose to require the DOE to assess the effects of criticality during the entire postclosure period of 1,000,000 years.

addition, the effects of events and processes or sequences of events and processes with a higher chance of occurring need not be included in the PA if their effect on repository performance (however probable) can be demonstrated not to be significant (EPA 2008). FEPs that cannot be excluded from the PA based on probability of occurrence or based on low consequence must, in general, be included in the PA.

The TAD canisters were specified such that the probability of occurrence of an in-package criticality could be demonstrated to be less than 10^{-8} per year (DOE 2008, Section 2.2.1.4.1). As discussed above, given the designs and fuel loading for DPCs currently in use it is unlikely that postclosure criticality could be excluded from a future PA (other host media) on the basis of low probability, without modifying DPCs either before or after they are loaded. This means that unless the DPCs are modified, that: 1) in-package criticality must be excluded from PA on the basis of low consequence (i.e., the probability-weighted effect on repository performance is not significant) (EPA 2008); or 2) the consequences of criticality events must be included in the PA. This section describes the approach for consequence analysis that can result in either of these two outcomes.

Calculations used to demonstrate that a particular FEP can be excluded from a postclosure PA on the basis of low consequence often employ conservative assumptions and bounding estimates. If the consequences of a particular event or process are insignificant to repository performance under worst-case or bounding conditions, then the particular event or process does not need to be considered in PA calculations. The use of assumptions in PA for criticality consequence screening is especially important with respect to fuel cladding. A starting assumption for screening analysis is that cladding remains substantially intact so that the fuel is in a critical configuration, but the cladding has small holes that allow radionuclides to be released (Price et al. 2019). Assuming that the cladding is more fully degraded would potentially allow for greater release of radionuclides, but would be inconsistent with the occurrence of criticality events if a critical configuration was not maintained. On the other hand, if the cladding were completely intact, the criticality event might have no effect on repository performance because radionuclides would not be released from the fuel rods. The key to refining this assumption is to represent the initial condition of the fuel, and the impact of criticality events on the fuel, as realistically as possible. This is one goal of the planned R&D program.

The FEPs screening process outlined in 10 CFR 63.342 specifies that FEPs must be evaluated over a time period of 10,000 years after repository closure. If a FEP can be shown to have a probability of occurrence less than 10^{-8} per year for the first 10,000 years after repository closure, or if the occurrence of the FEP can be shown to have an insignificant consequence on repository performance, then the FEP in question does not need to be included in the PA. The approach to demonstrating that a FEP has an insignificant effect on repository performance depends on the FEP in question. However, a typical approach consists of assuming that the event or process occurs (e.g., erosion, thermal expansion of an engineered barrier, microbial activity) and examining how that event or process might affect the performance of a deep geologic repository. (For example: Are erosion rates high enough to be of concern for a deep repository? Would thermal expansion of an engineered barrier affect its barrier capability? How much microbial activity could occur in a radiological environment and would it affect repository performance?) If the event or process would not affect repository performance (e.g., even maximum erosion rates would not affect repository performance, thermal expansion of engineered barriers is accounted for in repository design or would not affect barrier capability, or the little microbial activity that might occur in a radiological environment would not affect repository performance), it could be concluded that the

event or process would not have a significant effect on repository performance. The approach to demonstrating the effect that criticality has on repository performance is discussed below in Sections 3.3 and 3.4.

Current regulations stipulate that FEP screening on the basis of probability or consequence be based on the occurrence of the event in the initial 10,000-year period after disposal (e.g., 10 CFR 63.342). Therefore, initial studies of criticality consequence will focus on that time period. However, for the purposes of developing a fuller understanding of the consequences of criticality in a DPC, follow-on studies may examine those consequences at an initiation time that is beyond 10,000 years after disposal. That will support application of the predictive models beyond 10,000 years, to the period of geologic stability, consistent with 10 CFR 63.342(c).

3.2 Criticality FEPs Considered

DPC baskets are constructed from various materials including stainless steels, carbon steel, and aluminum. In particular, neutron absorber plates are typically made from Boral™, a composite of aluminum and boron carbide. Some modern basket designs use an aluminum-B_4C composite for structural basket plates that also act as absorber plates and thermal shunts. Aluminum is expected to degrade much faster than SNF fuel on exposure to ground water. Hence, there will be significant neutron absorber degradation before the fuel degrades, increasing reactivity and giving rise to the possibility of criticality (Hardin et al. 2015).

DPC internal structures (aluminum, carbon steel, stainless steel) were not designed for the time periods considered in postclosure PA (e.g., 10,000 years, and the period of geologic stability which could extend to 1,000,000 years) while fuel pins were designed to withstand the extreme environment inside a nuclear reactor. Nearly all fuel is clad with zirconium alloy material, which has exceptional corrosion resistance. Hence, it is reasonable to assume that the waste form will degrade more slowly than the DPC basket structure, especially for DPC baskets made mostly from stainless steel. For DPC baskets made mostly from aluminum-based material (e.g., Metamic™) the basket structure and absorber plates are the same, so the two functions will degrade simultaneously.

All anticipated conditions of absorber and basket degradation are represented by two stylized basket configurations that will be considered as criticality consequence analysis moves forward: 1) total loss of Boral™ absorber plates (replaced by water) with the internal basket structure still intact; and 2) total loss of the internal basket structure including the absorber plates (moving the fuel assemblies into close contact). These correspond to configurations IP-3d and IP-3b, respectively, in Figure 3-2a of *Disposal Criticality Analysis Methodology Topical Report* (DOE 2003). Other degraded fuel/basket configurations may also be considered in the future as investigation of degradation mechanisms proceeds.

In addition, consistent with DOE's established methodology (DOE 2003), both steady-state and transient criticality will be considered in modeling the consequences of criticality on repository performance. According to the topical report (DOE 2003) steady-state criticality events would produce energy at a relatively low but almost constant power over a longer period of time, while transient criticality events have the potential to generate much greater power as a spike over a much shorter period of time, resulting from a rapid reactivity insertion (or increase). Accordingly, the principal consequences of steady-state criticality would be incremental increases in the radionuclide inventory, and the heat generated by the on-going criticality event. Secondary consequences would include increased radiolysis, changes to the chemistry of the water inside the

waste package, increased corrosion rates, changes to radionuclide solubilities, and changes to the barrier capability of backfill caused by higher temperatures from the power generated during the criticality event(s) (if backfill is part of the repository design). These consequences are also potentially applicable to a transient criticality event. An additional consequence of a transient criticality event is damage to the engineered barrier system, that could increase the rate at which radionuclides are available for transport to the accessible environment.

3.3 Evaluating the Consequences of Criticality

The NRC, in its requirements for disposal of high-level radioactive wastes in a geologic repository at Yucca Mountain (10 CFR 63.2), defines a *performance assessment* as analysis that:

(1) Identifies the features, events, processes (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the disposal system and their probabilities of occurring;

(2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the disposal system; and

(3) Estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence.

Although the definition was written for the proposed Yucca Mountain repository, the same analysis process is applied for studies of generic repository performance and would likely be applicable to a future proposed repository as well (Hardin and Howard 2013, Section 3.2).

In the initial phase of investigating the consequences of in-package criticality during the postclosure period, the approach will be to model the effects of both steady-state criticality and a high-power transient criticality event in a single waste package disposed of in a hypothetical repository. Two PAs will be conducted for this hypothetical site, one for each type of criticality event, and comparing results that include criticality events to the results of a closely similar PA without criticality events. This will quantify the difference between PA results with and without criticality for the cases examined.

In general, because critical conditions can occur only in a waste package that has already been breached and has water in it, the consequences of steady-state criticality represent *incremental* radionuclide releases. The breached waste package contains water and is presumably already releasing radionuclides to the near-field environment. A steady-state criticality event subsequently occurring in the waste package alters that release rate, most likely by increasing it. Therefore, it is anticipated that the *percentage* increase in modeled PA results, such as dose to a member of the public, will be about the same regardless of how many waste packages have failed. Later phases of this investigation will examine this proposition by analyzing the failure of multiple waste packages. However, if a criticality event (steady state or transient) in a breached waste package causes the failure of fuel rods inside that waste package that otherwise would not have breached, or causes the failure of an adjacent waste package that otherwise would not have failed at that time, then the consequences of criticality might be significant (i.e., beyond incremental), and this will also be analyzed.

For initial criticality consequence modeling, both the steady-state criticality and the transient criticality event will be assumed to occur 9,000 years after repository closure. Consistent with

previous studies (CNWRA 2005; Rechard et al. 2003; McClure 1999), the steady-state criticality will be assumed to last 10,000 years. That is, critical conditions will be modeled to exist in the waste package from 9,000 years after repository closure until 19,000 years after repository closure. The transient criticality event will be modeled as occurring 9,000 years after repository closure and will be a one-time event.

In addition, for the initial steady-state criticality consequence modeling, several bounding and simplifying assumptions may be made. One assumption, mentioned above, is that the fuel rod cladding is intact enough for the fuel pellets to maintain their configuration in the fuel rods, but at least some of it has small enough holes to allow dissolved radionuclides to be transported out of the fuel rods. Another assumption is that the power generated during steady-state criticality events is constant. By their nature, steady-state events with feedback processes will be associated with slight oscillations around $k_{eff} = 1$. For initial analysis of consequences, the average power of the quasi-steady process is considered to be more important than the amplitude of oscillatory fluctuations in k_{eff}. This assumption is planned to be examined in a later phase of the study.

In addition, it is anticipated that consequences from criticality events can be shown to depend on conditions in the repository, external to the waste package. Important examples include whether the repository is in an unsaturated or saturated setting, and the effectiveness of the natural system as a barrier to radionuclide transport.

3.4 Criticality Consequence Inclusion or Exclusion from PA

As discussed above, if it cannot be demonstrated that the probability of occurrence of in-package postclosure criticality for a repository is less than 10^{-8} per year, and if DPCs of existing designs are to be used for disposal without modification, then in-package criticality must either be included in the PA, or excluded on the basis of low consequence. The "inclusion" and "exclusion" options are discussed further below, and the two approaches are summarized in Table 3-1.

Exercising the exclusion option would mean performing one or more analyses designed to examine the effect of criticality on the performance of the proposed repository. Similar to what is discussed in Section 3.3, these site-specific analyses would assume that criticality occurs and examine the various consequences of criticality on various aspects of repository behavior, and then compare repository behavior with and without the criticality event. If the differences are insignificant, then an argument for excluding criticality on the basis of low consequence could be pursued. The aspects of repository behavior that might be examined include the radionuclide inventory, thermal history, engineered barrier system degradation rates, chemistry inside the waste package, and radionuclide solubilities. For example, if analysis of the criticality event shows that because of the event:

- The inventory of existing radionuclides increases by less than a few percent;
- None of the radionuclides created by the criticality event are significant to repository performance;
- The degradation rates and performance of the engineered barriers are not significantly different in the higher temperature environment than they are without the criticality event; and
- Radionuclides solubilities are not significantly different;

Then a technical basis exists for demonstrating that the effects of criticality on the performance of the disposal system are insignificant, and an argument can be made to exclude in-package criticality on the basis of low consequence.

Exercising the inclusion option means that the PA conducted for the license application for the proposed disposal system would include criticality. That PA would include both the probability of occurrence and the consequences of in-package criticality. Some or all of the SNF waste packages that breach as a result of modeled waste package degradation processes, and that subsequently fill with water, would be modeled as experiencing a criticality event. Whether a particular criticality event was steady-state or transient could be a function of the failure mechanism, for example whether a critical configuration was produced quickly as a result of seismic ground motion. If the results of the PA demonstrated compliance with the various postclosure PA requirements, then there would be a technical basis for disposing of SNF in DPCs of existing designs, without modifications to prevent postclosure criticality.

Note that engineered barriers could be designed to mitigate the consequences of postclosure criticality, as part of an inclusion or exclusion approach. One option is to develop and use a disposal overpack that is highly corrosion resistant and reliable, with the expectation of long containment lifetime. This concept could be effective if the rates of general and localized corrosion for overpack materials are well known and the projected time to containment failure is much greater than 10,000 years. It could also involve an enhancement of the "early failure" abstraction that has been used in PA (DOE 2008, Section 2.3.6.6). Recent work on overpack reliability (Groth et al. 2015) suggested that greater reliability (less likely early failure) could be attained using more modern and rigorous quality control. Importantly, this "super-overpack" approach is hypothetical and would depend on site-specific information to quantify corrosion and other damage mechanisms (e.g., disruptive events). It is generally plausible that with reliance on engineered barriers, criticality could be limited to very few DPC-based waste packages. The uncertainties associated with this approach make it unsuitable for excluding criticality on low probability, but it could be central to reducing the risk (probability and overall consequences) from criticality events. Another possibility is a backfill material that could retain low permeability and transport attenuation properties with higher temperatures resulting from a long-term steady-state criticality event. Further analysis of engineered barriers in low-consequence criticality analysis is deferred pending availability of site-specific information, and better understanding of alternatives such as modification of existing and future DPCs.

Table 3-1. Summary Comparison of Criticality Consequence Approaches.

Exclusion from PA	Inclusion in PA
Perform one or more bounding analyses that: • Assume waste package has breached. • Assume sufficient water has entered the waste package to create a critical configuration. • Examine and model consequences of criticality on various aspects of repository behavior: – Radionuclide inventory – Barrier degradation rates – In-package chemistry – Radionuclide solubilities – Barrier performance under elevated temperatures – Release rate from the waste package • Model repository behavior in the absence of criticality ○ Radionuclide inventory ○ Barrier degradation rates ○ In-package chemistry ○ Radionuclide solubilities ○ Barrier performance under expected temperatures ○ Release rate from the waste package • Compare model output (e.g., dose to a member of the public) with criticality to that *without* criticality.	As a part of the PA calculations: • Develop a model (or models) of the probability of occurrence of criticality in a breached waste package and of the duration and power produced by the critical event. The model should include the effects of criticality on – Radionuclide inventory – Barrier degradation rates – In-package chemistry – Radionuclide solubilities – Barrier performance under elevated temperatures – Release rate from the waste package • In the PA model, when a waste package is modeled to have been breached, apply the model developed as appropriate • Calculate the model output (e.g., dose to a member of the public), weighted by the probability of occurrence of waste package breach and the probability of occurrence of criticality upon waste package breach

Exercising either the exclusion option or the inclusion option requires developing a fundamental understanding of the consequences of criticality in a DPC during the repository postclosure period. Although the physics of criticality and feedback mechanisms associated with criticality in a controlled reactor are well understood, they are not so well understood in the uncontrolled and uncertain environment of a DPC in a geologic repository thousands of years in the future. The DOE has initiated a multiyear study that examines the potential consequences with respect to long-term repository performance, of criticality events that might occur in a repository during the postclosure period (Price et al. 2019). As a part of that study, both the direct and indirect effects of criticality in a disposed-of waste package have been identified as shown in Figure 3-1.

While Figure 3-1 captures the primary direct and indirect effects of in-package criticality, it does not capture possible feedback mechanisms and two-way coupling between processes. For example, a criticality excursion could cause the temperature to increase, but increasing the temperature could cause the criticality event to cease, at least temporarily, from heating or evaporation of the moderating water in the waste package. These other linkages are shown in Figure 3-2. Therefore, as a part of the same study, reactivity feedback mechanisms that are expected to operate in a breached waste package that has filled with water have been identified, along with their types, causes, timing, and impact (see Table 2 of Price et al. 2019). Understanding these feedback mechanisms and which of them are significant to repository performance will contribute to a fundamental understanding of the consequences of criticality in a DPC during the repository

postclosure period. It will be particularly important to understand which mechanisms lead to permanent cessation of the criticality event in the waste package.

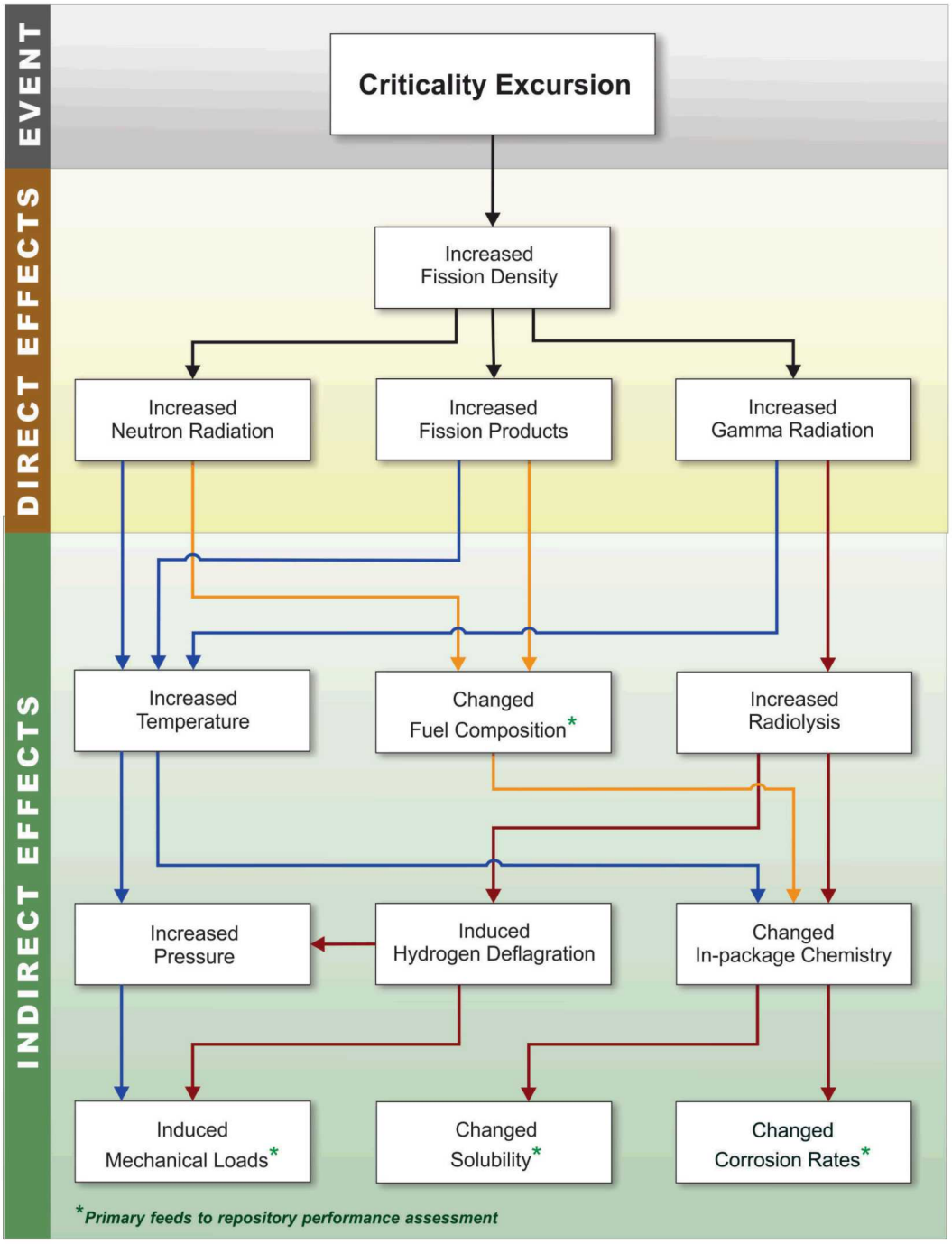

Figure 3-1. Direct and indirect effects from a criticality excursion (Price et al. 2019).

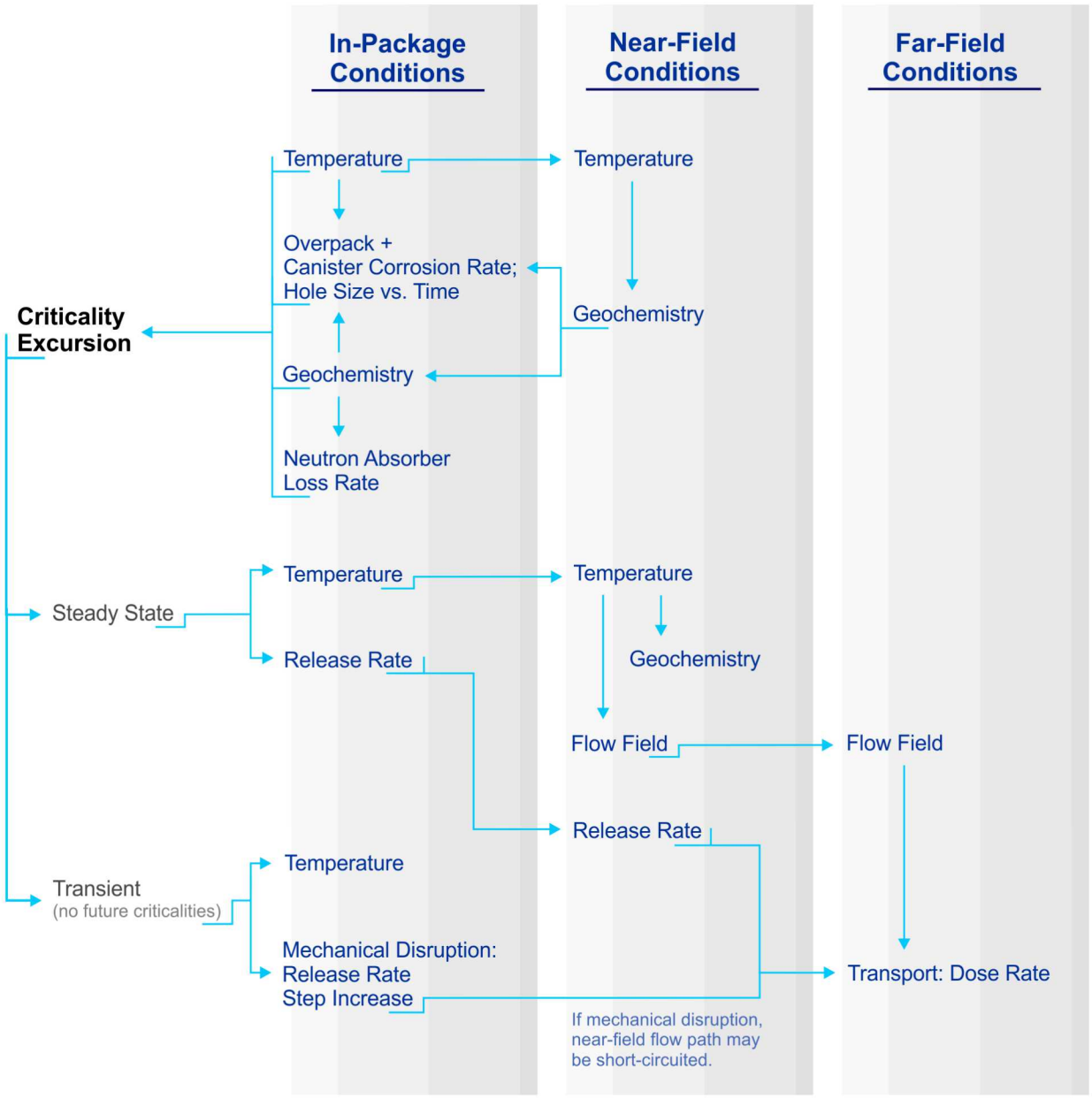

Figure 3-2. Schematic of the features, events and processes that link criticality events, in-package conditions and near-field conditions.

Models that are used to analyze the consequences of criticality in a DPC will likely not have experimental data available for validation. Two known sources of data that might be helpful are studies of the Oklo natural reactor and data from nuclear accidents (McLaughlin et al. 2000). At Oklo, self-sustaining fission chain reactions occurred approximately 2 billion years ago in very rich uranium ore pockets and were sustained for at least several hundred thousand years (Cowan and Norris 1978). Oklo has been studied by several investigators and insights into its behavior may be helpful in understanding criticality behavior in a repository (particularly steady-state criticality). In addition, data collected from various nuclear accidents that have occurred around the world, most if not all of which were transient, prompt-critical events, may also be helpful.

3.5 References for Section 3

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4. Fillers

As discussed in Section 3, direct disposal of DPCs without modification, in some possible geologic disposal settings, could produce one or more criticality events. If the consequences from such events are deemed unacceptable (see Sections 2 and 3) then three options exist:

1. Repackage the DPCs into site-specific disposal canisters, or into STAD canisters suitable for a range of disposal environments, with the objective to decrease the probability of a criticality event below the threshold of regulatory concern (discussed in Section 6).
2. Engineered changes to loaded, sealed DPCs that would render them sub-critical for disposal conditions, with the objective to decrease the probability of a criticality event.
3. Packaging of DPCs into high-performance overpacks that can maintain containment reliably for tens of thousands of years, limiting the incidence and overall consequences of criticality events (discussed in Section 3).

This section presents the current best case for the second option, injectable fillers, which would fill DPCs with a material that maintains subcriticality after waste package breach and flooding with ground water. The third option would depend on site specific characteristics and is not currently being investigated by the R&D program.

4.1 Background

To decrease the probability of a postclosure criticality event in a DPC, injectable fillers are proposed. We assume that fillers would be developed to support a low-probability screening approach to postclosure criticality, and not a low-consequence screening approach. Although it is plausible that fillers could decrease the incidence and overall consequences of criticality events, the effort needed to develop and implement injectable fillers is more readily justified in support of a low-probability screening approach.

Filler materials and operations would have the following attributes:

- Can fill the DPC canister throughout its void space to exclude or displace moderating ground water.
- Provide a vehicle for including a neutron poison, as a chemical constituent or fine solid dispersed in the filler, to provide additional reactivity margin.
- Can be injected using existing small-diameter ports for draining and venting the DPC. This would require removal of the outer lid and the port covers. (Supplemental ports could be fabricated by drilling into the DPC shell or lid, although this would not be preferred.)
- Does not degrade significantly over the timeframe of concern for criticality, either within the canister prior to breach, or after breach when flooded with ground water.
- Does not cause excessive corrosion of DPC internals including the cladding and fuel.
- Does not cause excessive stress on internal components due to differential thermal expansion.
- Can be removed if desired, for safety, economic, or other reasons (retrieval, recovery, or reversal). Depending on the imposed requirements, filler removal capability could be specified in terms of removing fuel assemblies individually without compromising criticality control.

- Does not generate enough gas pressure to cause canister overpressure, or generate sufficient hydrogen and oxygen to exceed a flammability limit, while the waste package is intact in the repository (prior to breach).
- Engineering design and operational issues such as filler handling and setting time can be managed.
- Licensing issues are manageable, for example, a need to demonstrate substantially complete filling of fuel/basket void spaces.
- Reasonable cost for filler materials and implementation.

As discussed below, incorporation of fillers into SNF waste packages has been discussed for several decades, but for different reasons than motivate current investigations in the U.S. Originally, fillers were considered with the objective to enhance the waste isolation performance of a repository. Later, Atomic Energy of Canada, Ltd. (AECL) investigated fillers to provide mechanical support internally, for thin-wall waste packages loaded externally by ground water pressure.

Maheras et al. (2012) conducted a study directed to whether fillers could be used to stabilize SNF in DPCs, to prevent or control fuel damage during transport. They reviewed filler material studies from:

- The U.S. Department of Energy (DOE) (Fish et al. 1982; Forsberg 1997, 2000; Forsberg et al. 1995; Pope et al. 1996; Wynhoff et al. 1982)
- Allied-General Nuclear Services (Anderson 1981)
- The Canadian Nuclear Fuel Waste Management Program (Johnson et al. 1994; Shelson 1983; Teper 1987a,b)
- The Belgian waste management program (Bennett and Gens 2008)
- Spain (Puig et al. 2008a,b)
- Sweden (Oversby and Werme 1995; Puig et al. 2008a,b)
- The U.S. DOE Yucca Mountain Project (Arthur 2000; Cogar 1996a,b; Mobasheran 1999; Montierth 2000; Moscalu et al. 2000; Radulescu 2001; Wallin 1996).

The main purpose of presenting this information here is to show that international investigators have concluded that fillers could be effective for waste isolation. Filler materials considered previously include oxides/silicates, injected metal alloys, organic binders, sand, air/gases, glass, graphite, boron carbide, cements, glass beads, bauxite, depleted uranium compounds, metallic shot, zeolites, phosphate minerals, and clays. Past work has emphasized dry particulate fillers, for example Oversby and Werme (1995) considered glass beads, lead shot, copper spheres, sand, olivine, hematite, magnetite, crushed rock, bentonite clay, other clays, and concrete.

4.2 Filler Materials

The only *experimental* investigations of filler placement in SNF assemblies have been with dry particulate materials. AECL investigated emplacement of glass beads and other particulate materials in canisters containing CANDU fuel bundles. The DOE investigated filling PWR fuel assemblies with different grades of steel shot. No experimental work has been attempted to

investigate injection of fillers in liquid form through small openings in DPCs that are already loaded and sealed by welding (Maheras et al. 2012).

4.2.1 Molten Materials

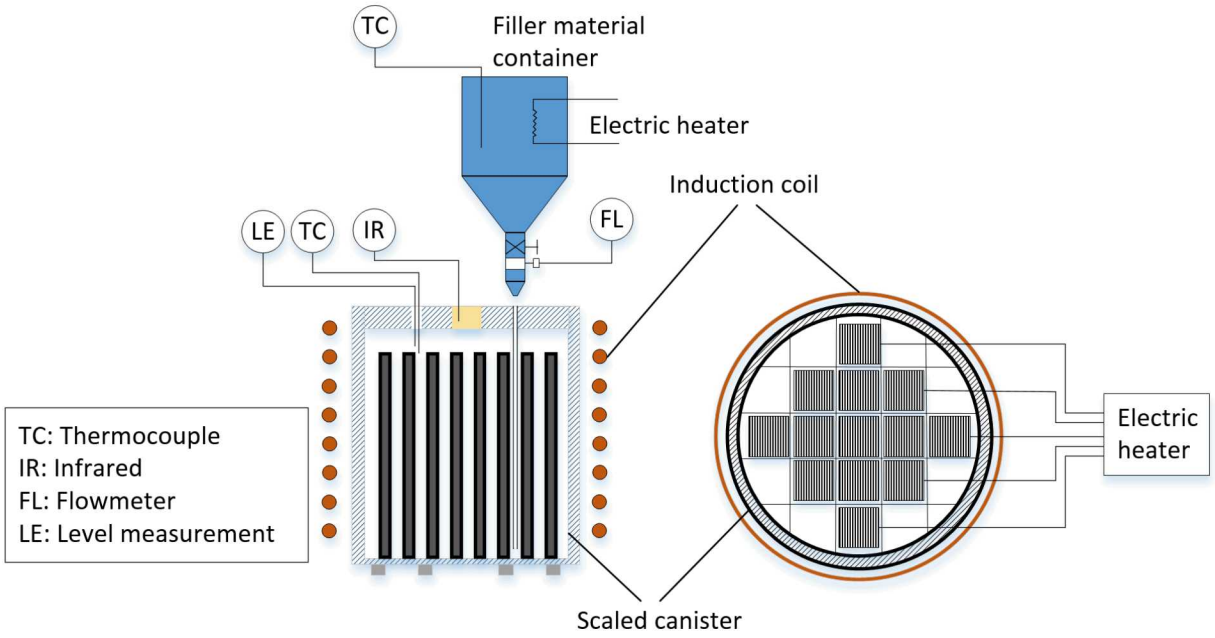
Solid materials such as metals, alloys, and glasses could achieve postclosure criticality control by excluding ground water, while providing little moderation. The eutectic of tin-silver-copper is an example with melting temperature less than 260°C, that should not cause thermal damage to DPC internals including the cladding and fuel. The eutectic of tin-zinc melts at less than 200°C (although the zinc could corrode zirconium-based cladding). Glasses are also available with melting temperatures low enough not to cause thermal damage to cladding. A vanadate glass composition, for example, is reported to melt below 300°C (SNL 2017).

Degradation rates for such solids in the disposal environment could be determined from experiments and/or the solubility limits of alteration products, and limits on ground water flow and penetration of fillers or alteration products through small breaches in the waste package. Little is known about how molten materials would work as injectable DPC fillers other than the melting temperatures of various metals and alloys, and the potential for chemical incompatibilities such as the possible interaction between molten zinc and Zircaloy cladding. Flow properties such as temperature dependence of viscosity, and wettability of stainless steel and Zircaloy surfaces, need to be evaluated in bench-scale testing (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 4-1. As shown, the molten material would be gravity fed although pumping is also feasible. The canister would be heated uniformly, and induction heating technology borrowed from metal-cooled reactors has been suggested as a means to do so.

4.2.2 Cement Slurries

Details on the suitability of resins, foams, geopolymers, common cements, and chemically bonded cements as injectable fillers were provided by previous studies (SNL 2017). With cumulative radiation dose as high as 50 MGy in the postclosure time frame, organic and silane resins can be eliminated. Foams (whether organic or inorganic) could expand into the interstices of fuel assemblies, but could leave excessive porosity (i.e., 60% or more), so that criticality control in a flooded waste package could depend solely on added neutron absorbing material. Common cements and geopolymers are activated by alkaline pH that could affect fuel cladding over time, and these cement types would form relatively weak bonds with canister and fuel surfaces. Accordingly, chemically bonded cements are emphasized in the range of water-based slurry cement types currently being investigated by DOE R&D program. The following discussion describes phosphate based, chemically bonded cements, and speculates that they will be proven suitable as DPC fillers. The development work is still in progress, and other cementitious materials could ultimately be shown to be suitable as well.



Note: For this demonstration test concept, electric heaters would be used inside the mockup canister to represent waste-generated heat. Filler would introduced from the container above, through the DPC drain tube leading to the bottom of the canister as shown. Not to scale.

Figure 4-1. Concept for testing of molten filler injection into a simulated DPC (SNL 2017).

4.2.3 Chemically Bonded Phosphate Cements

Chemically bonded ceramics rely on ionic or covalent bonds for cohesion, instead of relying on hydrogen bonding and van der Waals bonds that are active in Portland cement (Wagh 2004). So-called ceramic cements are ceramic because of chemical bonding, but they are cements because they are mixed and set at low temperature. Phosphate ceramics are inorganic, nontoxic, have neutral pH when fully reacted, and are insoluble at circum-neutral pH. They are made from low-cost naturally occurring materials, and they are self-bonding, i.e., a second layer will bond to the previous one. Encapsulation of radioactive waste in the U.S. and other countries is an important application of chemically bonded phosphate cement (Wagh 2004).

Phosphate cements typically involve reaction of a soluble source of metal cations (e.g., MgO or ZnO) and an acidic phosphate salt. Calcium-phosphate cements rely on Ca-compounds such as phosphates, aluminates, or carbonates (not oxide) to limit the reaction rate. There is a body of literature on phosphate cements that have been studied for medical and dental applications, and for engineering applications also (some phosphate cement products are commercially available).

Aluminum phosphate cements are produced from slurries of alumina and phosphoric acid or other acidic phosphate compounds, that set after being heated to 150°C or greater. The slurry components form crystalline binder species such as berlinite ($AlPO_4$) that attach to particles of insoluble alumina. The amount of precipitated binder can be small compared to the insoluble particles (Wagh 2004). Whereas water is required to create a slurry and transport the reacting species, it may not be chemically incorporated into the final solids so it is likely to be expelled, creating porosity that requires dewatering. Composition and setting conditions will be investigated

as a means to control the final porosity and water content, and dewatering protocols will be evaluated as part of testing to determine if radiolytic gas generation can be limited.

4.3 Performance Criteria for Injectable Fillers

Previous evaluations of fillers have identified attributes or criteria that would be met for an ideal injectable filler (SNL 2017; Maheras et al. 2012). The reader is referred to those studies for details. The following discussion summarizes current understanding of how those criteria could be met for molten and cementitious fillers.

Injectability – Molten materials are injectable if the DPC and its contents can be held at sufficiently high temperature. Cement slurries are injectable if mixed with enough water (which degrades other properties such as porosity and residual moisture).

Void Filling – Molten materials will fill voids most effectively if they wet the surfaces of the basket and fuel (including spacer grids, channels and nozzles as well as fuel rods). Wettability of common basket and canister materials such as stainless steel to molten materials must be determined experimentally. All cement types under consideration rely on water as the slurry vehicle and will wet fuel/basket materials.

Long-Term Chemical Stability – For metallic fillers the likely mechanism of degradation is oxidative corrosion, and the removal of filler material will be determined by the solubility of secondary phases and the removal of filler constituents by ground water. For cementitious fillers an important analog is hydroxyapatite, an important component of bone. Bone is stable for thousands of years in nature if kept dry, or if leaching by ground water cannot occur because of low permeability, or if ground water has near-neutral pH and is reducing as in organic bogs. Other phosphate compounds such as berlinite also exist in nature but tend to be dissolved or modified by leaching over geologic time scales. These are conditions comparable to the evolution of environments inside a waste package. Small breaches in disposal overpacks (e.g., with corrosion resistant packaging) would limit access by ground water flow, and limit the ingress of oxidants and the escape of hydrogen. The long-term stability of fillers will result from their intrinsic properties, and the rates of interactions with other engineered components and the repository environment.

Retrievability/Recoverability – Metallic or glass fillers can be removed, in principle, by melting. Metal-phosphate bonds can be dissolved with a dilute acid. Each of these approaches may leave residues, and the importance to removal of assemblies from fuel baskets must be determined experimentally.

Material Compatibility – Metallic fillers will likely act as protective anodes in galvanic interaction with fuel assemblies and basket structural materials (except aluminum and possibly carbon steel). Metals such as tin, zinc, or vanadium (a constituent of low-temperature glasses) would be tested for compatibility during filling and after cooling.

Phosphate cement formulations should not attack stainless steel or Zircaloy if the pH is circum-neutral, and fluoride and zinc are scarce. Bonding to metallic surfaces and to previously poured cement, and controlled expansion/shrinkage, have been established for representative commercial cement products (SNL 2017).

Moderator Displacement – Moderating ground water would be *excluded* by solid metals, alloys, or glasses, and would be *displaced* by corrosion products (which are typically hydrous). Cement fillers would *displace* ground water, and the water content could remain less than that needed for

critical moderation as long as the filler mass remains in the canister (and is not dissolved or otherwise removed by ground water transport).

Gas Generation – Production of gas by corrosion or radiolysis could be problematic in closed DPCs prior to waste package breach. Residual water would be radiolyzed to form H_2, O_2, and related gases with the potential to overpressure the thin-walled DPC shell, and subsequently to pressurize the disposal overpack. Residual moisture could also react with basket materials (stainless steel, carbon steel, aluminum) to produce H_2 gas. To limit gas generation in a slurry-filled canister it is important to effectively dewater the filler before weld-sealing. The capability to dewater such a DPC by heating and venting steam is a key uncertainty, as is the radiolytic efficiency for residual moisture. The allowable residue of moisture would be determined by the resistance of the waste package to internal pressure, gamma dose, radiolytic efficiency, the possible use of getters or recombination catalysts, and other factors. Multiple interacting processes require appropriate-scale testing to establish specifications on residual moisture. Residual moisture prior to waste package breach would not be a problem for molten material fillers that contain no water.

Melting/Solidification Temperature – Molten materials would require a canister/fuel temperature above the melting point to ensure injectability. Thermal-setting cements such as aluminum-phosphate would be injected with canister/fuel temperature less than approximately 150°C, then heated for thermal setting.

Toxicity – Toxicity could be problematic for some metals (Pb, Cd) but not for others (Sn). Toxicity is low for all cement types being considered.

Radionuclide Sequestration – Actinides (mainly U, Pu) are readily immobilized by phosphate in ground water environments.

Material Cost – Material cost could be low for cement formulations, but greater for metals or specialty glasses.

4.4 Engineering Feasibility

Temperature control during filler injection and dewatering (for cements) could require a dedicated thermal well for the entire canister, situated within a hot cell because the canister is open at the ports. For metallic fillers, canister temperature control would be provided by heating to a minimum surface temperature, while the internal fuel temperature would be greater due to self-heating. A typical DPC would generate approximately 10 kW or less from radioactive decay during filling operations, corresponding to thermal power limits for emplacement in a repository. Additional thermal power could be needed to heat DPCs during filling operations. Induction heating has been proposed for metallic fillers to increase efficiency and limit peak temperatures (SNL 2017). A means of measuring temperature over the entire external surface of the canister during all filling operations could be required.

For cementitious fillers a similar arrangement would be needed except that the initial internal temperature would be limited to prevent premature setting. It could be cooled first, externally and possibly internally by circulating a cool dry 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 DPC would then be heated to more than 200°C over a few days for curing and dewatering, using externally applied heat and internal self-heating by radioactive decay, accounting for the enthalpy of the cement

setting reaction. For dewatering a maximum surface temperature could be reached (e.g., 300°C) whereupon the DPC surface would be cooled to maintain constant temperature conditions for further dewatering. Once a satisfactory indication of residual moisture (or lack thereof) was obtained, the canister ports would be resealed by welding. The cement mixing and pumping equipment would be needed for only a few hours, but the thermal well could be needed for many days.

The heating and cooling steps involved with any type of filler would require a DPC to occupy the treatment facility for days. A filled DPC could have heat capacity on the order of 3 MJ/°C so the heating/cooling rate would be limited to approximately 100°C/day. Dewatering could take more time, potentially doubling the scale of the facility. A modular facility with capacity for 1,000 MTU per year (approximately 70 DPCs per year) would require at least three parallel processing lines, and possibly more. Several facilities as described here would be needed to process all projected DPCs in the U.S. inventory in a 30- to 50-year operating period.

An important question associated with fillers is how to determine that filling is complete, and in the case of cement, how to determine the residual moisture content. Careful gravimetric measurements and dewatering measurements would be needed. Tomographic imaging methods could also be used.

Another concern is the added weight of fillers, which could vary from 10 MT for cement fillers, to more than 50 MT for metallic fillers with specific gravity of 9 (e.g., tin alloys). Maheras et al. (2012) described this concern for canister handling, and for transport accident analysis. Filling would likely be done at the site of a final repository to minimize additional transport risks. Regulatory analysis would be needed, and possible redesign of handling features (e.g., skirts or trunnions) to handle heavier DPCs.

4.5 R&D Program

The R&D program currently underway and supported by the DOE is evaluating filler materials, both molten and cement slurry types. Numerical simulation is also underway for single-phase liquid filling of fuel and basket geometries, with the expectation that models will be modified to be non-isothermal and to include temperature-dependent fluid properties (density, viscosity), and enthalpies associated with solidification. The models could also be used to evaluate thermal contraction behavior that could produce cracking. The same modeling capability can be used for molten materials and cementitious fillers.

A program of bench-scale testing supported by numerical simulations is described in the fillers workplan (SNL 2017). For efficiency a single filler type and composition will be selected to begin such testing. The methodology for initial selection, and the selection itself, are planned to be developed in the next 2 to 3 years. The approach to implementation for a selected filler material, may be part of an independent peer review in the same time frame. Note that an independent technical assessment of the fillers R&D program was conducted by Alsaed (2018).

4.6 Estimated Cost of Fillers

The cost of filler materials and operations is assumed to be $200k per DPC, except for materials such as tin that have higher raw material cost (Table 4-1). This cost estimate is based on the use of a relatively inexpensive filler material such as some type of cement in an aqueous slurry. Table 4-1 lists current market or otherwise assumed bulk prices for various raw materials that

might be used in fillers (SNL 2017). Additional candidate filler materials and properties were tabulated by SNL (2017).

Table 4-1. Cost of Various Candidate Filler Raw Materials (modified from Alsaed 2019).

Material	Density (g/cm^3)	Cost (Feb. 2019; $/kg)	Cost ($) per DPC [A]
Cement (assumed bulk price for phosphate-type cement)	2.5	2.20	$33,000
Tin	7.32	21.52	$946,969
Zinc	7.14	2.68	$115,224
Aluminum	2.7	1.85	$30,000
[A] Approximately 6 m^3 void volume in a typical DPC.			

The cost for operations to inject fillers, and dewatering if needed, was included in the $200k estimate (Section 7). This estimate can be justified by comparison to operational costs for loading a DPC but with no fuel transfers, welding, canister movements, or dewatering (total operational cost for loading a DPC was estimated to be $450k; Alsaed 2019). The actual cost could be much greater if a more costly material is selected (e.g., a tin-rich molten alloy) and if the material requires an extensive facility for handling. The possibility that treatment options could cost more than estimated was addressed in the comparative analysis of Alsaed (2019). We note that filler process design would involve value engineering, so that the cost of filler implementation, if selected, would be an appropriate fraction of the cost of the repackaging alternative.

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5. DPC Modifications

Another option for addressing postclosure criticality in DPCs would be to change the loading or design of future DPCs to decrease the probability of a criticality event in a repository below levels of concern. Modification of existing loaded DPCs by adding fillers is discussed in Section 4. This section focuses on potential modification to the design and loading of future DPCs.

The goal of modifications to DPC basket designs 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 ground water). Therefore, materials and geometries are needed that have corrosion lifetimes comparable to or better than Zircaloy cladding, spacer grids, and other components of the fuel assemblies and basket. Corrosion processes in a future breached waste package will 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 they already are) so that their performance would meet this longevity design goal.

5.1 Disposal Control Rods/Blades

Insertion of control rods into PWR assemblies would use existing assembly guide tubes (not occupied by spent reactor control rods). Control rods could also be inserted into the "water rod" voids in BWR fuel assemblies, although many BWR assemblies may not have contiguous voids that are readily accessible from above. Control blades for BWR fuel would be inserted between assemblies (or groups of four assemblies) which could require basket redesign.

The concept for postclosure criticality control features ("surrogate control rods") was originally analyzed by EPRI (2008, 2009). The effectiveness of control rods inserted in PWR assemblies, or control blades inserted between BWR assemblies, is proven based on their use in reactor operations. Typical rod cluster control assemblies (RCCAs) for PWRs contain Zircaloy-clad rods with a strong neutron absorber such as boron-carbide (B_4C) or silver-indium-cadmium. Disposal control rod assemblies (DCRAs) similar in design to RCCAs (without the components necessary for reactor operations) would have similar corrosion and mechanical properties to Zircaloy-clad fuel rods. Disposal control rods could be of similar construction, with a Zircaloy tube filled with B_4C. Alternatively, control rods could be made without cladding, such as extruded borated stainless steel (BSS) (ASTM A887-89 Grade A, UNS S30464) or Ni-Cr-Mo-Gd alloy tubes (ASTM-B 932-04, UNS N06464). Control blades for BWRs are typically stainless steel clad hafnium plates or stacked B_4C rods. The effectiveness of all disposal criticality control solutions, for PWR and BWR fuel, will be verified by analysis.

There are no anticipated regulatory or technical barriers anticipated for the insertion of DCRAs into PWR assemblies, because irradiated RCCAs are routinely placed into assemblies for storage and transportation. Inserting BWR disposal control rods into "water rod" voids may also have a strong technical basis. However, there could be operational challenges caused by bowing of guide tubes or design features that block access.

DCRAs (for this discussion taken to include BWR control assemblies) would likely be needed for only a subset of the assembly positions in a DPC (see for example, EPRI 2008). Based on the efficacy of RCCAs in reactor operations, the anticipated DCRA loading criteria would include:

- No DCRAs are needed for high-leakage peripheral basket locations.

- No DCRAs are needed for assemblies near an assembly with a DCRA (side or corner proximity).

For a typical 37-PWR DPC basket, DCRAs for seven assemblies could be sufficient to ensure subcriticality as illustrated in Figure 5-1. The actual number and arrangement of required DCRAs would be determined from detailed reactivity calculations. The calculations would also consider the availability of fuel assemblies with empty and accessible guide tubes, or "water rods," and would include the enrichment and burnup characteristics for the SNF.

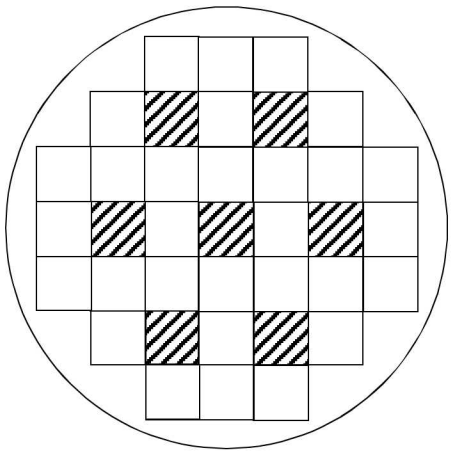


Figure 5-1. Illustration of notional DCRA placement in a 37-PWR DPC.

There is no precedent for installing control blades in current DPC designs for BWR SNF. Existing reactor control blade designs would have to be modified to ensure longevity. Placement of control blades between BWR assemblies (or groups of four assemblies) could involve significant changes to BWR DPC basket designs. Control blades would likely require changes in DPC basket design because BWR reactor control blades are inserted from below the reactor core during operation. In summary, the disposal control blade solution for BWR fuel is significantly less mature than the disposal control rod solution for PWR fuel (with the "water rod" replacement solution somewhere between).

Implementation of DCRAs in PWR DPCs could be readily implemented in the near-term, from the technical and regulatory perspectives. Use of control rods or blades for BWR DPCs would require more development and could be more challenging than the alternative DPC design modification discussed in Section 5.2.

5.2 Corrosion Resistant Neutron Absorber Plates/Channels/Inserts

There are two alterative materials with promising corrosion characteristics that could be used for corrosion resistant neutron absorbing criticality control features 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 a well-known material that is widely available in various grades, whereas Ni-Cr-Mo-Gd materials were developed more recently at Idaho National Laboratory. To ensure sufficient

corrosion allowance for postclosure criticality control, a relatively thick BSS plate (11 mm) could be required (BSC 2008b). This thickness specification is specific to the TAD canister but can serve as a rough estimate for other disposal environments. Alternatively, corrosion resistant advanced neutron absorbing (ANA) material (Ni-Cr-Mo-Gd) with general corrosion rate less than for BSS, could be used in smaller thicknesses on the order of 3 to 5 mm depending on the corrosion rate in the disposal environment.

Neutron absorbers in current DPC designs are predominantly either thin (~0.1 in) sheets of aluminum-based materials encased in stainless steel sheathing, or thicker (~0.5 in) boron-aluminum composite material that also serves as the structural basket and the thermal shunt (e.g., Metamic™). Whereas the alternative neutron absorbing materials discussed above have greater density than aluminum and are relatively poor thermal conductors, the addition of thicker, heavier plates (either substituting or in addition to the aluminum-based materials) could involve significant changes in DPC basket design.

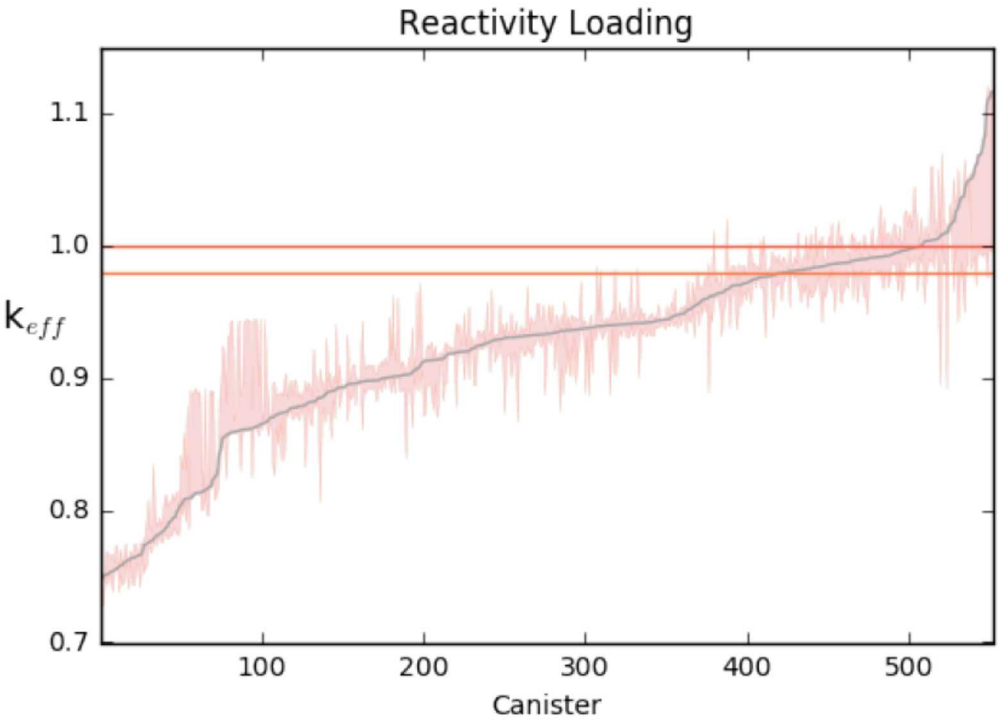
Another approach to incorporating corrosion resistant ANA material is the use of chevron inserts in the baskets cells. Inserts have been used to supplement reactivity control in spent fuel pool racks, and consist of folded plates that fit against two sides of each fuel cell in a rack. The same approach could be used in existing DPC baskets if there is sufficient clearance (e.g., at least 3 mm available clearance to be taken up by inserts in both x- and y-directions).

BWR fuel assemblies each have a shroud or channel around the outside, typically made from Zircaloy material, the purpose of which is to protect the fuel during handling and to guide the flow of coolant water in the reactor. These channels extend the full length of the assembly on all sides are and typically 2 to 3 mm thick. They have been replaced on a few assemblies which had warped channels, but were to be reused in a subsequent refueling cycle. The design of BWR fuel channels facilitates replacement from the top, with removal of one or two fasteners. Rechanneling with ANA material is an option for postclosure criticality control.

All of the modifications discussed above (absorber plates, inserts, rechanneling) would probably not be needed for every assembly in a DPC. As with DCRAs, the actual number and arrangement of required modifications would be determined from detailed reactivity calculations. The calculations would include the enrichment and burnup characteristics for the SNF.

5.3 Disposal-Oriented Zoned Loading

The concept of zone loading to decrease reactivity was extensively analyzed for 32-PWR size canisters by EPRI (2008). Recent criticality calculations for as-loaded DPCs demonstrated that many existing DPCs could have been loaded with the same SNF inventory in a configuration optimized such that they would be subcritical without any credit for fixed neutron absorbers. Application to as-loaded DPCs is illustrated in Figure 5-2, which shows the reactivity bands for individual as-loaded DPCs based on multiple hypothetical rearrangements of the SNF assemblies in each one (Liljenfeldt et al. 2017, Figure 42). These are burnup credit calculations (29 nuclides) for the loss-of-neutron-absorber (replacement by water) degradation case. Note that the DPCs represented toward the left side of Figure 5-2 are early canisters from the 1990's and early 2000's, and that those on the right represent more current, high-capacity DPC designs.



Note: The horizontal line at k_{eff} = 0.98 represents a hypothetical subcriticality criterion.

Figure 5-2. k_{eff} range based on various rearrangements of the SNF assemblies in as-loaded DPC fuel baskets, calculated for the loss-of-neutron-absorber degradation case.

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 map is shown in Figure 5-3 for the MAGNASTOR™ DPC (NAC 2010).

Zone	Designator	Maximum Heat Output at Loading (W/Assembly)	Number of Assemblies
Inner	A	922	9
Middle	B	1,200	12
Outer	C	800	16

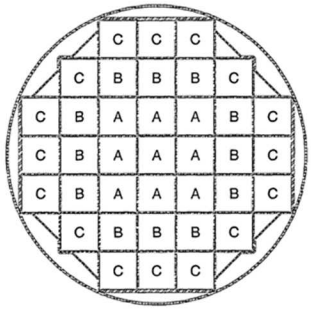


Figure 5-3. Thermal loading map for the MAGNASTOR™ TSC.

Table 5-1 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). Also, the

reactivity of fuel assemblies discharged more recently than the fuel represented in Figure 5-2 may be too great even with optimized loading, to ensure subcriticality for the DPC total-loss-of-absorber or total-basket-degradation cases. Nevertheless, optimal loading could be analyzed canister-by-canister, or using a loading curve approach, with the prospect of achieving postclosure subcriticality (and avoiding costs associated with DPC modification) for a fraction of DPCs loaded in the future.

Table 5-1. Potential Loading Guidelines for the 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.

5.4 References for Section 5

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6. Repackaging Concepts

As discussed above, disposable TAD canisters were never produced or provided to the utilities. This has led to widespread use of large capacity dry storage casks. Repackaging of fuel from these larger canisters into smaller ones for disposal may be required to avoid prolonged surface decay storage, to meet physical constraints on disposal systems, or because additional criticality controls are determined to be necessary and repackaging is the selected method.

This section differs in scope from Sections 3, 4 and 5 of this report because the state of knowledge about repackaging (i.e., technical maturity) is relatively advanced. Current understanding is based on a foundation of previous design work (summarized by DOE 2008). Accordingly, this section can cite previous studies, and present process descriptions, layout drawings, and independently derived cost estimates. These cost estimates are included in the comparative analysis in Section 7.

SRNL, ORNL, ANL and industry consultants have teamed three times since 2010 to develop repackaging facility concepts.

2012 Study (wet handling) – The first study (Nutt et al. 2012) was conducted with the objective to provide timely system analysis with cost and throughput data for analyzing the back end of the commercial fuel cycle. The concept was based on current practices at power plant spent fuel pools. It is described in more detail below as a wet handling option for future DPC repackaging.

2016 Study (wet and dry handling, including canister-in-canister) – This study (NFST 2016a,b) examined small, medium, and large canister sizes, and addressed the objective to reduce the surface handling facility footprint and therefore capital and operating costs compared to the 2012 study. This study examined both pool and dry SNF assembly transfer processes. Aspects of the study are described in more detail below to represent a dry handling option for future DPC repackaging.

2019 Study – A third study was begun in 2019 to further investigate dry handling. The study is ongoing, and it includes reevaluation of conclusions reached during the design process for the Yucca Mountain license application concerning handling of irradiated SNF assemblies in air. It will address handling of intact and failed SNF fuel, and how to reduce or eliminate operational failures that could cause increased exposure time to air. The results of the 2019 study are not available for discussion in this report.

Cost estimates for wet and dry repackaging are presented in Section 7.

6.1 Common Study Bases

The 2012 and 2016 studies to be summarized here include common assumptions:

1. Modular facility SNF throughput rate 1,500 MTU per year (two or more facilities would be used for greater throughput).
2. Annual SNF receipt rates consist of 1,000 MTU PWR fuel (0.436 MTU/assembly) and 500 MTU of BWR fuel (0.179 MTU/assembly).
3. Fuel shipments will arrive by rail.
4. Fuel will be received either in welded DPCs or as bare fuel (BF) assemblies in bolted, reusable transportation casks (TCs).

5. The capacity of a TC (containing either a DPC or BF) is nominally 32 PWR or 68 BWR assemblies.
6. Fuel arriving at the facility in damaged fuel cans can be handled with no impact to packaging operations. (Fuel that is damaged in transport to the facility may require remediation.)

The 2012 and 2016 studies presented concepts involving loading of various sizes of disposal canisters. For this report only the 21-PWR/44-BWR size is addressed since the purpose is comparative evaluation of the scope and cost for different options for direct disposal of SNF in DPCs. This is a reasonable simplification because the 21-PWR/44-BWR disposal canisters are the least costly among the three sizes to procure and load, while repackaging is the most costly of all options considered for DPC disposition. Throughput assumptions and canister counts are summarized in Table 6-1.

Table 6-1. Canister Throughput Assumptions.

Fuel Type	MTU/year	Assemblies/year	Average Number of DPCs or BF Casks/year	21-PWR/44-BWR Disposal Canisters Loaded/year
PWR	1000	2,294	72	110
BWR	500	2,794	41	64
Total	1500	5,088	113	173

6.2 Wet Handling Concept (2012 and 2016)

This repackaging approach was based on typical commercial SNF handling in spent fuel pools at nuclear power plants (Nutt et al. 2012; NFST 2016a). Fuel exposure to air at utility facilities is generally limited to canister (or bare fuel cask) evacuation and drying prior to dry storage in an inert atmosphere. Handling commercial SNF in air for extended duration (more than 24 hr), such as might be common at a repository facility using dry handling, does not have a clear licensing precedent with the NRC.

The 2012 wet handling facility concept is illustrated in Figure 6-1. The main handling units within the facility include a receipt bay, a waste handling building (WHB), and a discharge bay. Air locks are included between the receipt bay and the WHB, and between the WHB and the discharge bay. The facility depicted in Figure 6-1 would simply repackage SNF into disposal canisters, and not also seal the canisters into disposal overpacks to produce waste packages ready for emplacement.

The configurations of the receipt bay and discharge bay could be considerably different if the repackaging facility is co-located with a consolidated interim storage facility, or a geologic repository, or both. For example, if the repackaging facility is co-located with a repository, then the discharge bay could be replaced with a transfer corridor to a facility for placing waste package overpacks on the canisters (see Hardin et al. 2012). Conversely, if the repackaging facility is co-located with an interim storage facility and designed for out-processing of SNF from storage, the receipt bay would be modified to receive DPCs from the storage inventory, and the discharge bay would prepare disposal canisters for transport to a repository.

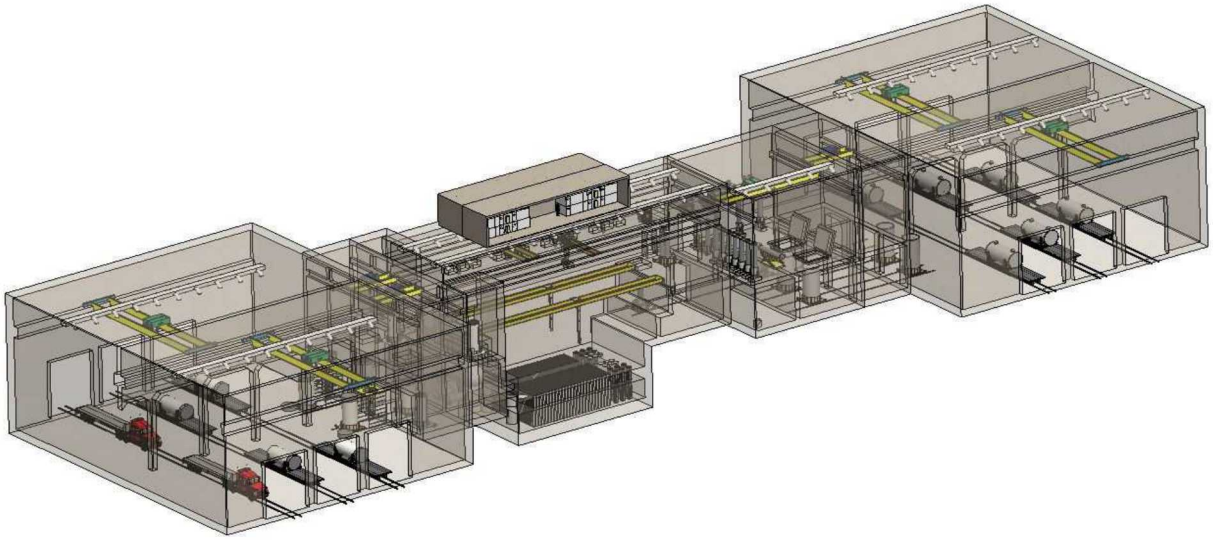

Figure 6-1. Isometric view of the modular repackaging facility concept, including (left to right) receipt bay, airlock, waste handling building, airlock, and discharge bay.

The receipt bay would receive and inspect transport casks delivered by rail, prepare the casks for unloading, and unload casks onto handling trolleys internal to the repackaging facility. The receipt bay is envisioned as a structural steel high-bay structure, nominally 23 m high. For throughput of 1,500 MTU/year, at least two lines would be needed, with two 250-ton gantry cranes. A third line is shown in Figure 6-1 for additional flexibility. The transport cask would be up-righted to a vertical orientation and placed on a trolley to enter the WHB air lock.

The WHB would be a multi-level reinforced concrete structure made of noncombustible materials with interior and exterior shear walls, concrete floor, concrete roof slab diaphragms, concrete mat foundations, and a fuel pool. The nominal footprint of the WHB including air locks would be about 86 m by 28 m. The maximum height of the building would be 30 m above grade, with the majority of the building under a roof approximately 24 m above grade. The concrete base mat for the basement structure (fuel pool and surrounding rooms) would be 17 m below the top of the at-grade concrete mat. The spent fuel pool would be sized to hold 750 MTU (6 months of inventory for a 1,500 MTU/year module) in separate basins for BWR and PWR assemblies. This capacity would provide flexibility for fuel blending and to decouple critical-path operations between receipt and discharge.

DPC cutting would be conducted dry, within a hot cell area of the WHB. Unloading of SNF from DPCs would be completed in the pool.

An empty canister (e.g., STAD canister, or site-specific disposal canister) would be prepared on the discharge bay side of the facility, placed in a transfer shield, and moved through the airlock and into the WHB on a transfer trolley. For this discussion the destination canister is referred to as a STAD canister, although site-specific canisters could be used instead. The STAD canister would be filled with (borated) water and lowered into the fuel pool, with the shield. A SNF transfer

machine would then load the canister from the fuel rack one assembly at a time. The shielded STAD canister lid would be seated, and the canister removed from the pool in its shield, placed on a trolley, and moved to a welding station. After welding the lid, the canister would be moved to a drying station, and dried using a vacuum or forced helium drying system.

If the loaded STAD canister is to be sealed into an overpack and emplaced in a repository, then it would be transported to a waste package loading/welding cell where a disposal overpack (consisting of one or two nesting cylinders) and its lid(s) would be staged. The overpack shell (unshielded) will have been placed into the transfer shield to be used for transport underground. The sealed STAD canister would then be lowered into the overpack, and the waste package lid(s) welded. Treatment of the outer closure weld (e.g., peening or burnishing) would be performed as required. Fixturing to restrain the sealed waste package in the transfer shield would be applied, and the waste package in its shield would be shifted to a horizontal position and coupled by lifting or bolting to the transport-emplacement vehicle (TEV) for transport underground.

6.3 Dry Handling Concept (2016)

To improve throughput and potentially reduce cost, a design concept using a dry transfer cell was developed to simplify STAD canister loading and closure operations (NFST 2016b). For this discussion the destination canister is referred to as a STAD canister, although site-specific canisters could be used instead.

Fuel transfers would be completed in remotely operated fuel transfer cells (Figure 6-2) with the incoming DPC (or bare fuel cask) and receiving (STAD) canister docked below the cell floor to allow access by the fuel handling cranes. Storage racks would be provided for limited staging of fuel assemblies, to allow complete unloading of DPCs and some blending. Wet storage would be provided on a limited basis to ensure that fuel cladding temperatures remain below established limits.

An unloading pool would also be provided for remediation of damaged fuel. If analysis of gas samples from received DPCs or BF casks confirms the presence of failed fuel, the fuel would be transferred to the unloading pools for packaging in damaged fuel cans (as necessary) prior to loading into STAD canisters. The unloading pool would also include rack storage for staging, and an adjacent area for cask and canister decontamination.

The process building footprint would be approximately 209 m by 72 m, substantially larger than the wet facility described above. The additional space would mainly be for separate railroad bays for receipt and shipment and dedicated areas for STAD canister closure.

Movement of casks containing DPCs and STAD canisters would be accomplished using rail trolleys on the first level, equipped with scissor-lift mechanisms to raise casks to docking ports at the second level.

Fuel transfer cells would be 25 m by 11 m, and 18 m high, with 1.3-m thick concrete walls and serviced by two 2-ton fuel transfer machines (Figure 6-2). The incoming cask would be positioned and raised to mate with a docking flange in the floor of the hot cell. Individual fuel assemblies would be raised into a sheath (for contamination control) and transferred to a receiving STAD canister docked at the opposite end of the cell. Storage racks would be provided for 200 assemblies to provide lag storage and for blending. One fuel transfer cell would have dry storage racks, while another would have a pool for immersed storage racks to accommodate fuel that is too hot to meet specified cladding temperature limits.

The STAD canister closure area would be accessible to the second level via three docking ports. Loaded canisters would be positioned and raised into position for operator access to complete closure operations. After welding of the canister lid, drying, inerting, inspection, and closure weld mitigation (for fuel going to dry storage), the canisters would be lowered and moved to a transfer area for loading into a waste package, or into a transfer cask (for storage), or into a transportation cask. Waste packages being prepared for emplacement in a repository would be welded at this station, with closure weld mitigation. The sealed waste package would be placed into a shielded TEV for transport underground. Alternatively, for multi-purpose (STAD) canisters being prepared for storage/transport, the transfer/transportation cask lids would be affixed at this station. Finally, the loaded system would be transferred through an airlock to a discharge bay.

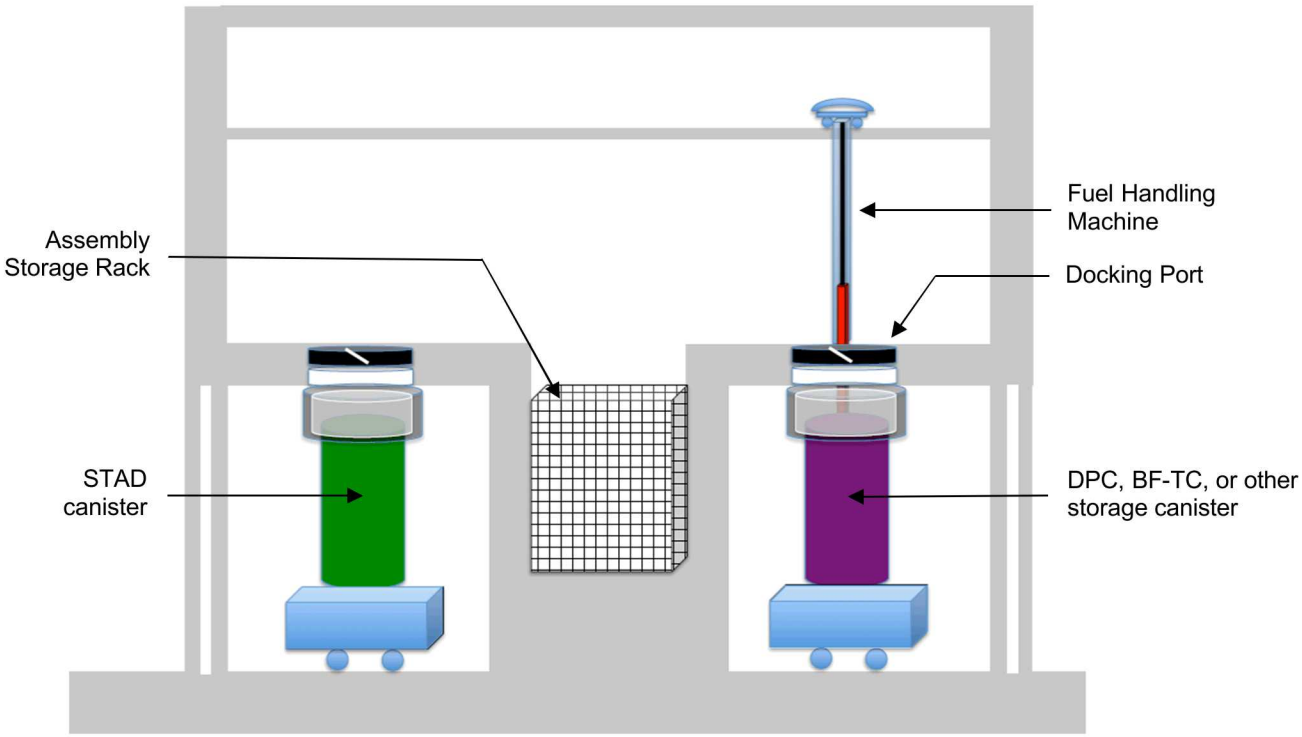

Figure 6-2. Dry fuel transfer cell conceptual arrangement.

6.4 References for Section 6

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7. Cost Analyses

7.1 Comparative Cost Analysis

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

- Cost of specialized disposal-ready canisters
- Cost of repackaging the SNF from DPCs
- Cost for disposal of DPC hulls and baskets as low-level waste (LLW)
- Cost for DPC treatment/modification to facilitate direct disposal
- Cost of disposal overpacks (but with no additional cost for high-performance super-overpacks discussed in Section 3)

The analysis is taken from Alsaed and Hardin (2019) which in turn draws from Alsaed (2019).

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

- **Case 1 (Dispose of all DPCs with No Treatment or Modification):** Direct disposal of DPCs without treatment of existing DPCs or design/loading modifications to future DPCs. This case would likely be associated with consequence-based consideration of postclosure criticality (possibly including high-performance engineered barriers), or disposal in a repository in salt.
- **Case 2 (Fillers for Existing DPCs + Modified Loading for Future DPCs):** Direct disposal of DPCs, treating existing DPCs with fillers, and using reactivity-based zone loading for DPCs loaded in the future.
- **Case 3 (Fillers for Existing DPCs + BSS for Future DPCs):** Direct disposal of DPCs, treating existing DPCs with fillers, and using design modifications for future DPCs that incorporate borated stainless steel plates.
- **Case 4 (Fillers for Existing DPCs + DCRAs/ Modified Blades for Future DPCs):** Direct disposal of DPCs, treating existing DPCs with fillers, and using design modifications for future DPCs that incorporate DCRAs for PWR fuel, and modified rods or control blades for BWR fuel.

7.2 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 relatively small number of existing bare fuel casks (258 according to StoreFUEL 2019).
- 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 zone-loading schema described in Section 5.3 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 TAD canister, 21-PWR/44-BWR size (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 for DPCs. This facility would accommodate packaging of fuel from bare fuel casks, and other uncanistered SNF arriving at the repository in rail or truck casks (e.g., from decommissioning of fuel pools without use of dry storage).
- The repackaging facility is assumed to provide the infrastructure for 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 2008a, 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 less 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 (Alsaed 2019, Section 5.1).
- 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 (Alsaed 2019, Section 3.1). To simplify the cost analysis assumptions, the cost of modified control blades for a BWR DPC is also assumed to be $350k.
- The costs for borated stainless steel plates for future DPCs with an average capacity of 34 PWR assemblies or 78 BWR assemblies (average capacities over the existing fleet; see Alsaed 2019, Section 3.2) are $174,000 and $354,000, respectively.

7.3 Comparative Cost Analysis Parameters

The cost analysis parameters and their sources/bases are summarized in Table 7-1 (adapted from Alsaed 2019, Table 3). 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 7-1 (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 7-1. Comparative Cost Analysis Parameters.

Parameter ($ values are rounded)	Value	Basis/Source
SNF Total Inventory (MTU)	109,300	DOE (2008a, Table A-2)
Total number of TAD canisters	12,983	
Total number of existing DPCs (as of January 2019)	2,700	Alsaed (2019, Appendix B) and StoreFuel (2019)
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.
Total number of future DPCs	5460	Calculated based on the TSLCC inventory (DOE 2008a) assuming future DPC capacities, and using data on existing DPCs from StoreFUEL (2019).
Total projected number of DPCs	8160	
Cost per TAD canister	$937k	Cost of TAD canister including materials and fabrication (DOE 2008a, Table 3-7).
Total cost of TAD canisters	**$12.2B**	Calculated based on the number of TAD canisters and the cost per canister.
Cost of loading or unloading operations per canister (TAD or DPC).	$450k	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	**$3.26B**	Calculated based on the number of DPCs to be repackaged at a repository beyond the currently assumed 920 DPCs in the TSLCC (DOE 2008a, Table A-2).
LLW volume for a DPC (m^3)	12.0	This is estimated based on the size of a typical DPC (Diameter 70 in., length 190 in.) per ATI-TR-13047 (Greene et al. 2013).
LLW disposal cost ($/$m^3$)	$14.0k	Shropshire et al. (2009) Table J-7 for disposal and Section G3-8 for characterization, packaging and treatment.
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	Alsaed (2019, Section 5.1).
Treatment cost for all existing DPCs	**$540M**	Calculated based on the fillers cost per DPC and total number of DPCs.
DCRAs or modified control blades cost per DPC	$350k	Alsaed (2019, Section 3.1).
BSS Cost for PWR DPC	$174k	Alsaed (2019, Section 3.2).
BSS Cost for BWR DPC	$354k	Alsaed (2019, Section 3.2).
Cost of DPC modification	**Varies per Case**	
Cost per disposal overpack	$961k	Calculated based on the cost of CSNF overpacks (DOE 2008a, Table 2-4) with 78.2% cost share and inflation escalation) and the total number of TAD canisters.
Disposal overpacks cost reduction	**$4.64B**	This cost delta takes into account the reduced number of disposal overpacks needed for DPCs compared to TAD canisters.

7.4 Comparative Cost Analysis Results

The cost analysis results for the four scenarios are summarized in Table 7-2 and illustrated in Figure 7-1. Negative values in the table represent savings compared to the full repackaging option, which can be summed to represent the total savings for each case.

Table 7-2. Comparative Cost Analysis Results ($ billions).

Cost Element	Case 1 Dispose all DPCs with No Treatment or Modification	Case 2 Fillers for Existing DPCs + Modified Loading for Future DPCs	Case 3 Fillers for Existing DPCs + BSS for Future DPCs	Case 4 Fillers for Existing DPCs + DCRAs/ Modified Blades for Future DPCs
TAD Canisters	-$12.2	-$12.2	-$12.2	-$12.2
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	-$21.4	-$20.9	-$19.6	-$19.0
Note: The cost of modified loading is assumed to be minimal (Section 7.1).				

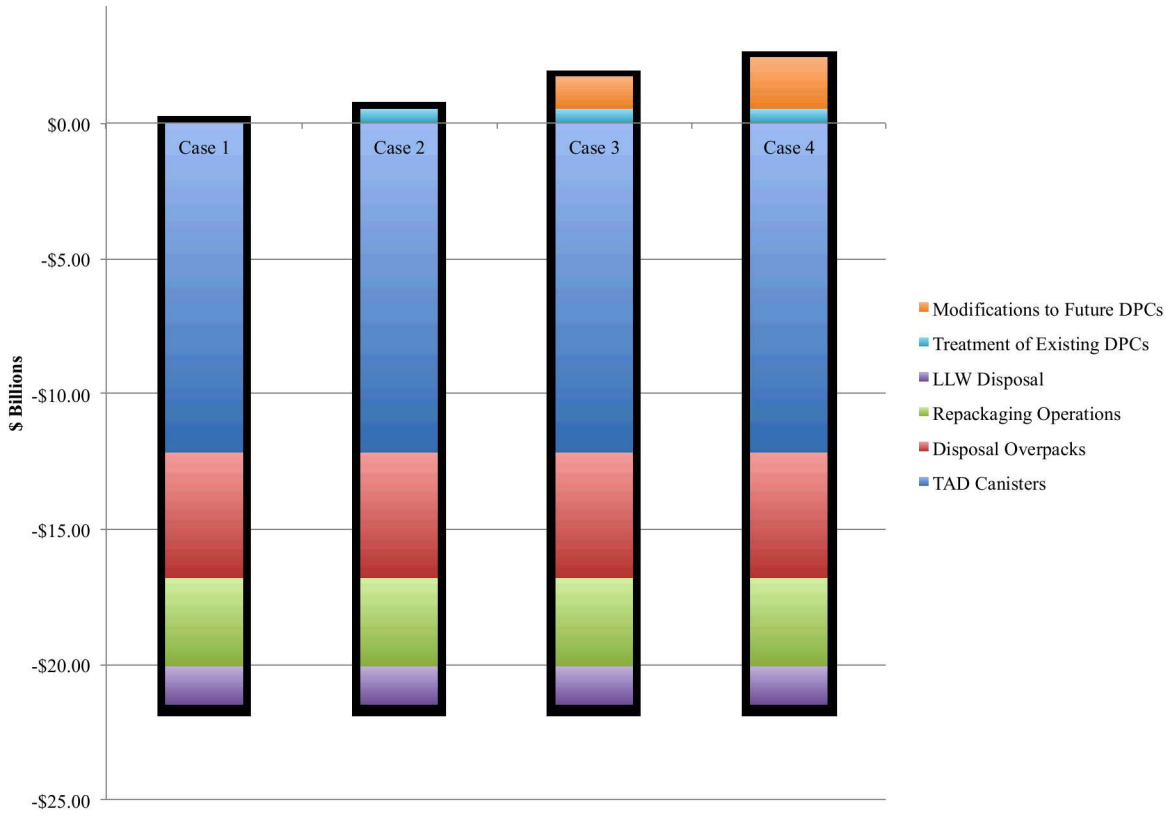

Figure 7-1. Comparative cost analysis chart.

The cost avoidance associated with direct disposal of DPCs is approximately $20 billion (escalated to 2019) for disposing of 109,300 MTU (quantity 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 canister procurement 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 LLW accounts for $1.4 billion.

The primary contributors to additional costs associated with direct disposal of DPCs are:

- 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.

The costs associated with potential treatment options for 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.

7.5 Repackaging Facility Cost Estimates

Pre-conceptual designs and cost estimates were developed for repackaging SNF into disposal canisters of a variety of sizes using wet (NFST 2016a) or dry (NFST 2016b) transfer capabilities at a rate of 1,500 MTU/year. The following discussion presents cost estimates based on repackaging the SNF into disposal canisters with a capacity of 21 PWR or 44 BWR assemblies.

Wet Repackaging Facility Concept and Cost Estimate

The wet repackaging option is described in Section 6.2. The capital cost for a wet repackaging facility was estimated at approximately $1.4 to $1.6 billion (NFST 2016a, Table S-3). The annual operating cost was estimated at approximately $79.8 million for staffing, consumables, and utilities (NFST 2016a, Table 7-4).

The total cost for wet repackaging 109,300 MTU taking into account capital cost and operations costs for approximately 70 years would be approximately $7.2 billion.

Dry Repackaging Facility Concept and Cost Estimate

The capital cost for a dry repackaging facility was estimated at approximately $2.06 to $2.3 billion (NFST 2016b, Table S-1), which is about 48% higher than that for the wet repackaging facility. The major contributor to the higher cost is the additional architectural and civil scope for the larger dry facility, and the inclusion of a remediation pool for handling damaged fuel.

The annual operating cost for the dry repackaging facility operations was estimated at approximately $97.1 million for staffing consumables and utilities (NFST 2016b, Table 6-5).

The total cost for dry repackaging 109,300 MTU taking into account capital cost and operations costs for approximately 70 years would be approximately $9.1 billion.

7.6 Cost Analysis Summary and Conclusions

This analysis considered total U.S. SNF inventory of 109,300 MTU loaded into 8,160 DPCs. The total SNF inventory is consistent with the previous TSLCC study (DOE 2008a) which was 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.

Repackaging cost estimates for wet handling ($7.2 billion) and dry handling ($9.1 billion) are greater than the costs assumed in the comparative cost analysis (Table 7-1, $3.26 billion). Part of the difference is attributed to the larger facility and greater throughput assumed for the repackaging facility estimate, which were not considered in the comparative cost analysis. With these significantly greater repackaging costs, the cost avoidance by direct disposal of DPCs and not repackaging, increases by $4 to $6 billion.

Each of the DPC treatment options would be associated with additional scientific, engineering, and licensing effort. Modification of future DPCs by including disposal control features (e.g., 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 solution. Notwithstanding these challenges there is the potential for large cost savings by direct disposal of existing and future DPCs. Repackaging before a repository site is selected would require development of a standardized canister (e.g., STAD canister) suitable for licensed deployment in multiple geologic settings.

As stated in Section 7.1, the estimated cost avoidance is based on the costs of disposal canisters, repackaging, LLW waste disposal, and DPC treatment/modification. The following is a list of parameters and variables that were not considered in the comparative cost analysis that could impact the estimated avoided cost of direct disposal of DPCs:

- **Disposal Timing** – Because DPCs generate more decay heat than smaller canisters, additional thermal aging may be needed prior to disposal. The cost of longer aging and delayed repository emplacement could reduce the avoided cost estimate.
- **Transportation** – Because DPCs generally have greater capacity than the assumed 21-PWR/44-BWR size disposal canisters, fewer shipments would be required for the same SNF inventory. Depending on where the standardized canisters are loaded (e.g., utility sites, centralized storage facility, repository facility) transportation considerations could increase the avoided cost estimate.
- **Alternate Geology** – The estimated avoided cost could be impacted if direct disposal of DPCs significantly impacts the emplacement drift design, emplacement method, overpack design, and other major engineering components relative to disposal-oriented canisters.
- **DPC Cost Considerations** – The current comparative cost analysis assumes that the cost of DPCs is a sunk cost, however, if DPC costs were factored into the analysis the results could change.
- **Licensing Considerations** – Licensing for direct disposal of commercial SNF in DPCs could require more effort than licensing for repackaging in purpose-designed disposal canisters. Such effort could take the form of additional R&D and regulatory analysis, which could add years to the preparation of an application. The costs of these activities could reduce the estimated avoided cost.

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8. Summary and Recommendations

Direct disposal of commercial SNF in DPCs currently located across the U.S. has the potential to simplify disposal operations, minimize the number of SNF shipments, reduce collective worker dose, and significantly decrease the costs associated with geologic disposal. Technical feasibility of direct disposal has been evaluated with respect to safety, engineering feasibility, thermal management, and postclosure criticality control (Hardin et al. 2015; EPRI 2008a, 2008b; BSC 2003). The greatest technical challenge is associated with criticality control, because modern DPCs depend on aluminum-based materials for neutron absorption, and those materials will degrade in a few decades when exposed to ground water in a repository after waste package breach. This report focuses on investigating alternative approaches for postclosure criticality control, with the understanding that other questions related to safety (operational and waste isolation), engineering feasibility, and thermal management can be readily resolved as demonstrated by previous studies, using available technologies.

As background, the Yucca Mountain license application specified 21-PWR/44-BWR size TAD canisters with site-specific postclosure criticality control measures (absorber plates with specified BSS material and thickness). Most SNF to be shipped to Yucca Mountain was to be loaded into TAD canisters at the nuclear utility sites. A relatively small number of DPCs was assumed to be delivered to the repository, which would be repackaged (along with uncanistered "bare fuel" deliveries) into TAD canisters in a wet-handling facility. Since this plan was formulated, thousands more DPCs have been loaded and are being stored at the nuclear utility sites. The present technical challenge is whether and how to dispose of these DPCs directly without repackaging into TAD canisters or into any other purpose-designed disposal canister.

8.1 R&D Strategy Summary

Management of DPC direct disposal R&D is guided by a few strategy options for DPC disposition:

1. **Criticality Consequence Analysis** – Evaluate the consequences of potential criticality events on overall repository performance to determine if the consequences are acceptably low, using a viable method for determining consequences (Section 3). Engineering and calculation support is important for successful implementation. This option could include the use of high-performance disposal overpacks and/or other engineered barriers to limit the incidence and overall consequences from criticality events. If successful, option 1 could obviate the need for options 2, 3 and 4.
2. **Modification of Future DPCs** – Develop technical solutions for modifying future DPCs so they will remain subcritical in any repository setting: a) loading schema with the possibility to blend fuel assemblies from fuel pools based on reactivity (PWR and BWR fuel); b) disposal control rods (PWR fuel); c) disposal control rods (replacing "water rods") or disposal control blades (BWR fuel); and d) replacement absorber plates (could be important for some, but not all BWR fuel baskets). Engineering and calculation support is important for successful design and implementation. DPC modification could be combined with other options, particularly options 3 and/or 4, to treat different sets of DPCs and limit the overall probability of a criticality event.
3. **Injectable Fillers** – Develop and demonstrate fillers that could be injected as liquids into existing DPCs, where they solidify, and displace or exclude ground water from breached waste packages in a repository (Section 4). Injectable fillers, if successful, could mitigate

postclosure criticality for all DPCs including those for which option 2 could prove relatively difficult (e.g., BWR fuel in egg-crate style baskets made from Metamic™). Use of fillers could be combined with other options, particularly option 2, to treat different sets of DPCs and limit the overall probability of a criticality event.

4. **SNF Repackaging** – Repackage the SNF in DPCs into disposal-ready canisters (STAD canisters or site-specific disposal canister) if none of the other three options above is adopted, and a repository in salt is unavailable. Repackaging would be done in support of a low-probability approach to criticality process screening. It could be combined with options 2 and 3 above to treat different sets of DPCs and limit the overall probability of a criticality event.

Any of these options can be reevaluated at any time during the course of the R&D program, and future decisions for R&D to continue may be based on methodological considerations (e.g., state of advancement in technical capability) as well as projected consequences (e.g., dose estimates). At this stage of the R&D program this list cannot readily be ordered with respect to future utility, funding priority, etc. Absent more detailed information for comparisons, funding prioritization should focus on the present needs for each R&D area, and on activities *within* each area. However, it is noted that option 1 is distinct because if successful it would obviate the need for other options, and option 2 is distinct because it has greater technical maturity and might be successfully implemented sooner using generic (non-site-specific) analysis. Note that the utility of options 1 and 2 is tied to how soon they can support critical management decisions leading to implementation.

The overall R&D strategy recommended here starts with a significant effort directed toward consequence screening (option 1) to determine if engineered solutions that are presently developmental (options 2 and 3) can be avoided. The greatest potential cost avoidance for final disposal, on the order of $20B, is associated with this outcome. Option 2 will be investigated to determine technical feasibility, and studies for option 3 will continue to investigate filler materials and selections for further testing.

R&D is presently underway for options 1 and 3, with preliminary work on option 2. In addition, a program to develop specifications for a standardized (e.g., STAD) canister has evaluated long-lived absorber plate materials (NFST 2015a,b). Currently, the DOE is planning a program to test advanced neutron absorbers (Blink et al. 2019; e.g., Ni-Cr-Mo-Gd alloys, and also borated stainless steels). A canister development effort for DOE-owned SNF, with some similarities to DPC disposition, is underway at Idaho National Laboratory. There may be overlap between the DPC, STAD, and DOE-owned SNF canister R&D efforts that should be integrated.

Option 2 has received only preliminary consideration in the R&D program, since the EPRI studies of 2008-2009. The utility of modifying future DPCs would be enhanced by developing the technical case as soon as reasonably possible (which could support a subsequent process for implementation). Based on the cost analyses in Section 7, the potential cost savings using the control rods/blades approach, compared to repackaging (comparing the two most technically mature options with a low-probability screening objective) would be approximately $2 million *per DPC*. As long as options 1 and 3 are developmental and not realized, this estimate may be viewed as the opportunity cost incurred each time a DPC is loaded without modifications to make it disposable in different geologic media.

8.2 R&D Program Goals

The DPC disposition R&D program is designed to support decisions related to whether and how to proceed with direct disposal of commercial SNF in DPCs. The program is planned to eventually provide information on engineering feasibility, regulatory strategy, implications for radiological and non-radiological safety of workers and members of the public, and implementation cost.

This section presents success criteria for the disposition options described in Sections 3 through 5. These criteria can be used to evaluate progress, to prepare for independent expert review, and generally to support decisions whether and how to proceed.

Criticality Consequence Screening Goals

- Describe the nature of criticality events (e.g., steady-state, transient, prompt transient) with sufficient detail to bound energy release and other aspects.
- Describe process-level interactions between the fuel, the waste package, the near field environment and the repository far field. This description should include changes in the source term and radionuclide transport, that result from criticality events.
- Results from PAs that include DPCs (whether they achieve criticality or not) should meet the regulatory performance objectives with ample margin (especially generic, non-site-specific assessments) to justify further investigation.
- Criticality analyses should not depend on the details of the contents of individual DPCs, such as fuel assembly enrichment, burnup, and loading schema, if possible. In this way, predictive simulations for a repository would not need to be performed for every as-loaded waste package.

Goals for Modifying Future DPCs

- Installation of control rods/blades into PWR or BWR fuel assemblies, or installation of ANA material inserts, or rechanneling of BWR assemblies, should be safe and uncomplicated commensurate with current DPC loading practices.
- Arrangement of control rods/blades, chevron inserts, or fuel channels with the fuel must maintain subcriticality as the fuel and basket degrade, for 10,000 years or until criticality is no longer a concern.
- Control rods/blades should be made from readily available materials, at reasonable cost. They should be chemically compatible with borated water in fuel pools, and with fuel and baskets.
- Absorber plates, inserts, or fuel channels made from alternative neutron-absorbing materials should be chemically compatible with fuel and baskets, and thin enough not to require canister redesign.

Injectable Filler Goals

- The filling process should be safe, commensurate with existing DPC loading, drying, and welding operations. Filler materials should be easily handled, not hazardous, and should be reasonably priced and available in sufficient quantity.

- Fillers should be demonstrated capable of completely filling the void space in DPCs, with inspection methods available for verification.
- Fillers should not produce gas prior to waste package breach, by radiolysis or interaction with fuel/basket materials, in sufficient quantities to exceed the DPC pressure rating.
- Neutron moderation and capture properties for fillers should be sufficient to maintain subcriticality for a wide range of SNF enrichment and burnup.
- Filler longevity in the disposal environment should be consistent with at least 10,000 years of criticality control.
- Fillers should be removable in a manner that does not expose or dissolve the fuel matrix, allows removal of assemblies one at a time, and does not exacerbate the criticality hazard.

R&D program scope and funding decisions based on the foregoing criteria, can impact the DPC disposition strategy depicted in Figure 2-2. This includes the proposition that consequence screening should be applied to all waste packages in a repository, or none. R&D progress in the DPC modification and filler areas principally supports low-probability screening.

8.3 Questions Not Addressed in This Report

The following issues were not addressed in this report because they were out of scope, or they are already detailed elsewhere:

- **DPC direct disposal in salt**. Earlier work on DPC disposal in salt (Hardin et al. 2015; SNL 2019) concluded that ground water in a salt repository, if present due to disruption (e.g., human intrusion) would be saturated chloride brine, and that criticality would not occur as long as the SNF had moderate burnup (and typical enrichment). This is identified as an option in Figure 2-2 along the low-probability branch. There are unresolved questions associated with the feasibility of disposing of commercial SNF in large waste packages in a salt repository (SNL 2019).
- **Thermal limits on disposal in potential host media**. Whereas DPC modifications are discussed that could be used for a range of host media, DPC direct disposal may be impractical for disposal concepts that depend on clay-based buffer materials in the near field, because of extended thermal aging needed to preserve buffer properties (e.g., 200 to 300 years; Hardin et al. 2015). Disposal timeframes have been studied for a full range of potential host media and disposal concepts, with the recommendation that the unsaturated hard rock and salt repository options are most favorable on thermal management considerations. A possible solution for disposal of large-capacity waste packages in clay/shale media with aging limited to 150 years, that does not depend on preserving near-field material integrity, has also been proposed. Disposal of DPC-based waste packages using the saturated, crystalline concept being developed in Sweden and Finland, could require thermal aging of DPCs for 300 years prior to emplacement.
- **Engineering feasibility**. An initial analysis of engineering feasibility found no barriers to DPC direct disposal (Hardin et al. 2015). However, extensive engineering analysis, design, and testing would be done for a repository in any host medium.
- **Uncertainty in regulatory requirements**. Current repository regulations include 10 CFR 60 and the Yucca Mountain specific 10 CFR 63 from the NRC, and the corresponding EPA rules.

Licensing DPC direct disposal under the Part 60 framework would be significantly different than with a future variation of Part 63. Differences could arise for aspects such as whether a dose-based standard is applied, definition of the postclosure regulatory period, and definition of a human intrusion scenario, to name a few. Each of these could affect how postclosure criticality is treated in FEP screening.

- **Use of enhanced engineered barriers.** Although alluded to in Sections 3.4 and 8.1 (e.g., the super-overpack concept) this option has not received much attention. Use of a long-lived overpack could add significantly to the cost of DPC direct disposal, but could be more cost effective than repackaging. The challenge with this option is that containment longevity depends on repository site characteristics, including the corrosion environment and disruptive events. From a recent review of overpack reliability prospects (Groth et al. 2015) there is optimism, but no certainty that "early failure" (and thus postclosure criticality, in some environments) could be excluded on low probability. Hence, the concept of enhanced engineered barriers for postclosure criticality control is assigned to the low-consequence branch of Figure 2-2.

8.4 References for Section 8

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