US RESEARCH ON DIRECT GEOLOGIC DISPOSAL OF SPENT FUEL CANISTERS

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BACKGROUND

In the U.S., every nuclear power plant (NPP) except one (Shearon Harris with 4 spent fuel pools for 1 operating NPP) has been packaging SNF into dry interim storage systems, with the majority of these systems utilizing welded dual purpose canisters (DPCs) designed for interim dry storage and transportation. For disposal at Yucca Mountain (YM), the U.S. Department of Energy (DOE) had planned for all the commercial SNF to be packaged into transportation, aging, and disposal (TAD) canisters, with the majority (~75%) of the SNF packaged into TAD canisters at the NPP and the remainder (~25%) of the SNF to be repackaged at YM's surface facilities into TAD canisters from bolted cask systems (not welded).

Although design and licensing activities had been substantially initiated by Orano TN and NAC on the TAD canisters, the DOE canceled the programs as the YM project was defunded by the U.S. Congress (not canceled). Nevertheless, these programs demonstrated the utility of a system where SNF could be packaged in spent fuel pools into canisters that would never have to be reopened (welded over bolted systems). In addition, when the YM license application (LA) was submitted to the U.S. Nuclear Regulatory Commission (NRC) for review, several groups filed contentions against various elements in the LA including the Nuclear Energy Institute (NEI), which is the U.S. nuclear energy's lobbying firm. Even though NEI supported in general the YM LA, it filed several contentions against it including its first contention "NEI - SAFETY - 01: Spent Nuclear Fuel Direct Disposal in Dual Purpose Canisters," which advocated for the direct disposal of DPCs to avoid doses associate with, and wastes produced from, the repackaging of the SNF from DPCs to TAD canisters. Based on substantial technical analysis (EPRI, 2008), industry sought to qualify DPCs that were already loaded for direct disposal in YM and to amend the YM LA accordingly.

DOE initiated a program in 2013 (Hardin and Voegele 2013) to examine the potential impact of direct disposal of DPCs into a generic repository in one of several different geologies. These studies examined the potential impacts to a repository of the direct disposal of DPCs to: (1) operational and repository post-closure safety; (2) engineering feasibility; (3) thermal management; and (4) post-closure criticality. All areas studied were concluded to be manageable through engineering analyses, studies, and potential changes to repository operations. However, (4) post-closure criticality was deemed to be the most considerable challenge due to the potential degradation of DPC aluminum-based neutron absorbers, fuel assembly spacer grids, and potentially DPC basket structures relied upon for storage and transportation in DPC licensing bases, over time in a repository environment.

As a result, the DOE with recent collaboration from the commercial nuclear industry and with the growth of the existing fleet of DPCs has turned its attention to R&D activities on the technical feasibility of: (1) modifying DPCs, either existing or future, to decrease the likelihood of criticality in a range of different disposal host media or (2) disposing of DPCs without modification and analyzing the effects from criticality events should they occur (SNL 2020). The goal of the DPC direct disposal program is to identify if one of these paths forward is workable and requires: licensing to be feasible; engineering solutions to be cost acceptable; and, in the absence of a specified repository site, it must consider all geologic host media and site conditions.

DIRECT DISPOSAL APPROACHES

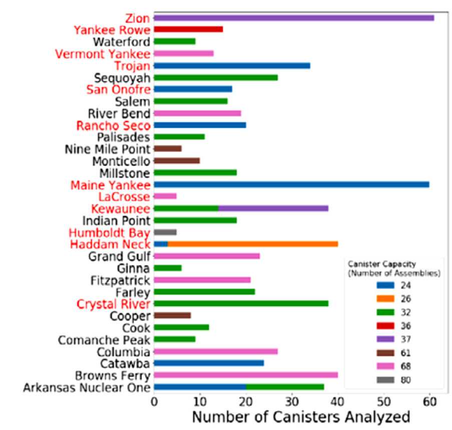
In the U.S., the feasibility of directly placing the existing welded DPCs used today at most of the independent spent fuel storage installations (ISFSIs) found at existing and shutdown reactor sites into a repository, known as “direct disposal,” is one of the following four potential methods to resolve the issue associated with a hypothesized criticality event during post-closure:

(1) Full burnup credit for the actual canister contents and demonstration that under credible conditions, the DPC remains sub-critical;
(2) Inclusion of corrosion-resistant neutron absorber materials into the basket prior to or after the loading of SNF;
(3) Injection of fillers into the welded canisters as credit for moderator exclusion that will under credible conditions maintain the DPC sub-critical; and
(4) Ensuring the consequences of a hypothesized post-closure criticality event are acceptable to the performance of the repository.

The first approach presents the simplest means to reach a resolution, but is not always successful. The next two approaches are receiving Orano’s support in establishing the potential means for adding the filler material (e.g., cementitious and metal-based materials) to the canister to a sufficient level post-SNF loading or for the strategic addition of neutron absorbing or water displacing materials to the canister pre-SNF loading. The final approach is dependent on the modeling of the performance of a specific repository site. This paper presents the status of the efforts to support direct disposal of welded canisters and avoid SNF repackaging.

Full Burnup Credit

In order to determine the potential for criticality in a repository setting on a long-term horizon, reactivity analyses of as-loaded DPC’s (as opposed to the design-basis fuel included in the DPC safety analysis report that are intended to be bounding) providing full (actinides and fission products) burnup credit is utilized considering credible disposal configurations. These reactivity analyses with full burnup credit consider the “as-loaded” configurations with degradation of: (1) aluminum-based neutron absorbers and structures (especially in aqueous environments); (2) basket structures; and (3) fuel assembly grid-spacers. The degradation of these structures alone does not create a criticality event but, when combined with water moderation filling the DPC, a criticality event may be credible. The Used Nuclear Fuel - Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) was used to analyze the as-loaded DPCs under these conditions to establish which DPCs will remain sub-critical under all these conditions (NWTRB 2020a). To date, 708 DPCs at 32 sites have been analyzed under both design basis SNF and as-loaded SNF conditions with results summarized in Figure 1.



Description (Analysis Dates: 2020-22000)	Value
Total DPCs analyzed	708
Total DPCs below subcritical limit with loss of neutron absorber (design-basis loading)	0 (0%)
Total DPCs below subcritical limit with loss of neutron absorber (as-loaded)	556 (~79%)
Total DPCs below subcritical limit with loss of neutron absorber and carbon steel structures (as-loaded)	483 (~68%)

Figure 1. Sites for which DPCs have been Analyzed For Post-Closure Criticality in As-Loaded Condition (sites listed in red are shutdown) NWTRB 2020a.

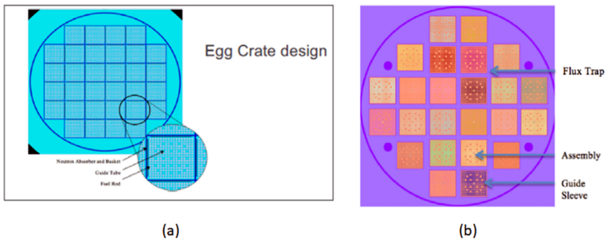


Figure 2. Differences between (a) Egg Crate and (b) Flux Trap Canister Types. NWTRB 2020a.

The findings from these assessments can be summarized as follows: (A) for BWR SNF, only DPCs loaded with damaged SNF are identified to pose a post-closure criticality risk and (B) for PWR SNF, DPCs designed with egg-crate-type baskets (e.g., Holtec MPCs) pose a clear hazard compared to baskets designed with flux-traps (e.g., NAC MPCs). Based on these results, at least some canisters will need to have additional features (e.g., corrosion-resistant absorbers or fillers) added to them to ensure sub-criticality over post-closure periods (Figure 2).

Inclusion of Absorbers

One means of preventing a post-closure criticality event involving a DPC in a repository is to add an absorber into the DPC either within the basket structure or within the SNF itself. Three concepts have been considered to date (see Figure 3), including adding: (1) disposal control rodlet assemblies (DCRA), which are similar to a standard guide tube–based absorber, such as a control rod or burnable absorber, to select fuel assemblies in a DPC; (2) chevron neutron absorbers (made of Gd-based advanced neutron absorber, ANA) that could be mounted to the basket or to select assembly top nozzles within a DPC; and (3) ANA BWR replacement fuel channels to replace select existing BWR channels within a DPC. Different DCRA and chevron insert loading patterns have been assessed for select DPCs to examine their ability to ensure post-closure safety against a criticality event with various levels of success. For

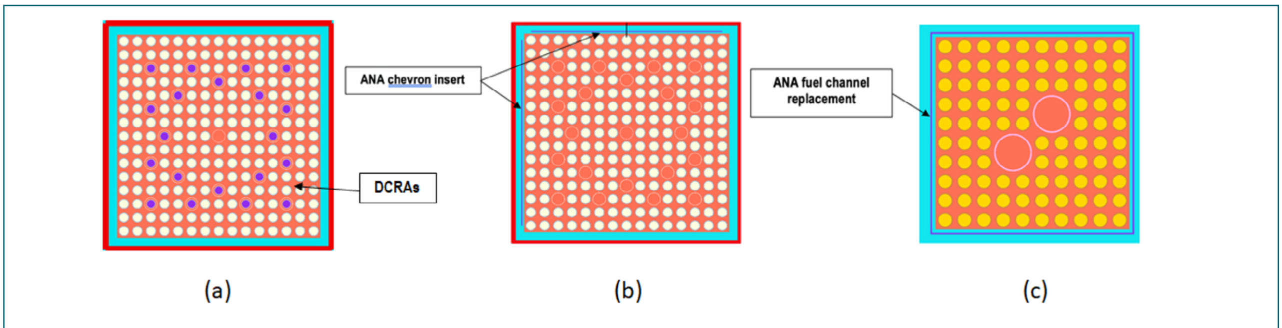


Figure 3. Inclusion of Absorbers in Fuel Assemblies within a DPC to Ensure Post-Closure Sub-Criticality: (a) addition of DCRAs, (b) addition of Chevron plates, or (c) replacement of BWR channel with ANA. NWTRB 2020a.

example for the TSC-37, at least 21 DCRAs were needed to ensure sub-criticality and no level of analyzed chevron inserts (up to 37 was analyzed) ensured sub-criticality. For the MPC-89, 40 ANA BWR channels were needed to ensure sub-criticality.

The findings from this assessment identified some positive results associated with the potential loading of DPCs with DCRAs and ANA BWR channels prior to the loading of the SNF or prior to the welding closed of the DPC. However for the existing loaded DPCs, these activities would require the opening of the welded canisters for the placement of these absorbers into the DPCs, not a favorable outcome. Hence, the main finding associated with this activity of adding absorbers to DPCs is that the loading should be performed prior to the DPC being welded closed and does not really provide a success path to treating DPCs posing a criticality hazard during the post-closure period.

While examining the impact of adding absorbers (prior to welding a DPC closed) to ensure the post-closure safety of a DPC, zone-loading of SNF was established as an alternative approach to ensuring the sub-criticality of a DPC. The zone-loading is performed in a manner that ensures post-closure sub-criticality through the breaking up of high reactivity fuel assemblies within a DPC. Again this zone-loading activity along with the absorber loading activity must be performed prior to the welding closed of a DPC and hence, does not provide a solution for already loaded DPCs, but should be considered prior to and/or while loading canisters.

Filler Materials

As an alternative to pre-loading absorbers into DPCs, fillers to be added to the existing DPCs (after having already been loaded) is being examined as means for ensuring post-closure sub-criticality by ensuring exclusion of moderator around the SNF. The selection of the optimum filler must consider: ease of injectability, effectiveness for moderator displacement, material compatibility, minimal intrinsic neutron moderation, minimal gas generation, long-term chemical stability, radionuclide sequestration, and reasonable cost. Past attempts to adding filler materials included glass beads (see Figure 4) and steel shot with limited success (e.g., beads and shot could pour out of the DPC upon breach). Considering the above properties, two different sets of fillers have currently been identified by DOE for further examination: (1) low melting point metals (e.g., tin) and (2) phosphate-based cements (e.g., AlPO4).

Figure 4. Waste Package Multi-Assembly Glass Particulates Fill Test. ORNL 1997.

Studies are currently being performed to examine the injectability of these fillers into the existing DPCs using computational models STARCCM+ and ProCAST and recently a TN 24PT4 canister was procured to perform filler testing on an actual DPC. Some preliminary results have indicated the need to: (1) drill holes into the top of the DPCs to add cement filler because using the existing vent and drain ports on the DPCs is ineffective for ensuring the cements adequately fill the DPC and (2) heat the DPC with external heaters to ensure metal fillers do not solidify against the walls of the DPC as the metals are added through the vent or drain port before adequately filling the DPC.

At this time, the results from the filler approach are inconclusive and appear may require modifications to the DPCs and/or heating systems for the DPCs that will require additional modeling to ensure the thermal limits of the DPC and the SNF are maintained.

Consequence Assessment

The final approach for demonstrating the viability of direct disposal of DPCs is examining the potential acceptability of the consequences of a post-closure criticality event in a repository. A criticality event must be prevented during pre-closure repository activities when operators may be present, because if a criticality event were to occur there is no reasonable means for the operator to perform self-preservation actions to minimize his dose consequences. However, for post-closure activities when personnel are not going to be present in any capacity in a repository, there is the potential for a criticality event to not challenge the performance requirements of the repository. This philosophy is illustrated in the U.S. regulations for a repository (e.g., 10CFR63.11(e)(6) identifies under pre-closure activities the need to identify structures, systems, and components (SSCs) "to prevent and control criticality," whereas for post-closure activities

10CFR63.114 does not mention anything about preventing a criticality event).

Thus, an analysis of the consequences of a criticality event post-closure is being performed. To assess these consequences, examination of past-criticality events were first assessed, including the Oklo natural reactors in Africa and ~60 criticality events that have occurred in process facilities and at reactors. A complicated coupling scheme between processes has been identified as shown in Figure 5, with the termination of the criticality event being one of the most important parts of the assessment. Initial assessments identified the collapse of the fuel pins as the most likely means to stop the criticality event (due to spacer grid failure). Once the fuel pins collapse, there is insufficient space for moderator to enter into the fuel matrix and moderate the neutrons sufficiently to sustain the criticality event.

Initial results indicate the public consequence limits for post-closure likely will not be challenged, however there are still multiple parameters (e.g., pulsed event) being further investigated to ensure the consequences are bounding.

RESULTS

Opening of DPCs and the subsequent repackaging of the SNF in these DPCs in preparation for disposal of the SNF has been assessed to cost several billions of dollars, result in increased operator doses (contrary to ALARA goals), and produce additional radiological wastes requiring disposal. To avoid these costs, doses, and wastes, the ongoing direct disposal of DPCs several alternative approaches to be studied, including: (1) performing criticality analyses using full burnup credit and as-loaded SNF conditions to demonstrate the DPC remains sub-critical under credible conditions; (2) including/adding corrosion-resistant neutron absorber materials into the basket of the DPC; (3) injecting fillers into the DPCs to provide moderator exclusion during post-closure and hence, prevent a criticality event; and (4) demonstrating the performance requirements of a repository are met in case of a criticality event during post-closure.

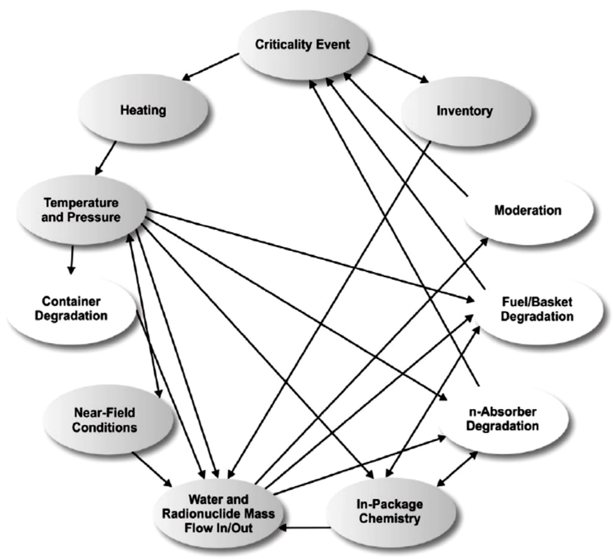


Figure 5. Coupling Scheme between Processes Associated with a Criticality Event. NWTRB 2020b.

Initial results indicate a significant fraction of the DPCs will not be able to go critical during post-closure of a repository due to the burned in actinides and fission products that provide additional neutron absorbers would require when the DPCs are modeled with as-loaded SNF. Figure 6 shows the initial results for the currently analyzed DPCs as identified in Figure 1.

The inclusion of absorbers, in the form of DCRAs and ANA BWR replacement fuel channels, into the DPCs appears to be beneficial to newly loaded DPCs. However for the existing DPCs, adding these absorbers requires them to be opened, which will be expensive and an ALARA concern. Similarly, the addition of filler materials into a DPC may require DPC modifications and/or heaters to ensure sufficient filler material is added to the DPC to provide it credit for moderator exclusion. None of these activities have been demonstrated yet for the filler materials.

Finally, consequence modeling for a criticality event has been initiated for those DPCs that may go critical during post-closure under hypothesized conditions (e.g., loss of aluminum absorbers, loss of geometry, etc.). Although results have not been released, the consequences are likely to meet regulatory limits to the public, but need to be aligned with repository performance requirements.

CONCLUSIONS

In the U.S., the repackaging of SNF from DPC systems into waste disposal packages would be an expensive endeavor. Directly disposing of SNF in DPCs into a geologic repository (within a disposal overpack) has the potential to avoid safety concerns associated with direct dose, inhalation hazards, thermal hazards, and criticality hazards of a repository. To avoid repackaging in the U.S., the DOE has has initiated an R&D program to examine the potential for direct disposal of the SNF in the existing welded DPCs into various geo-

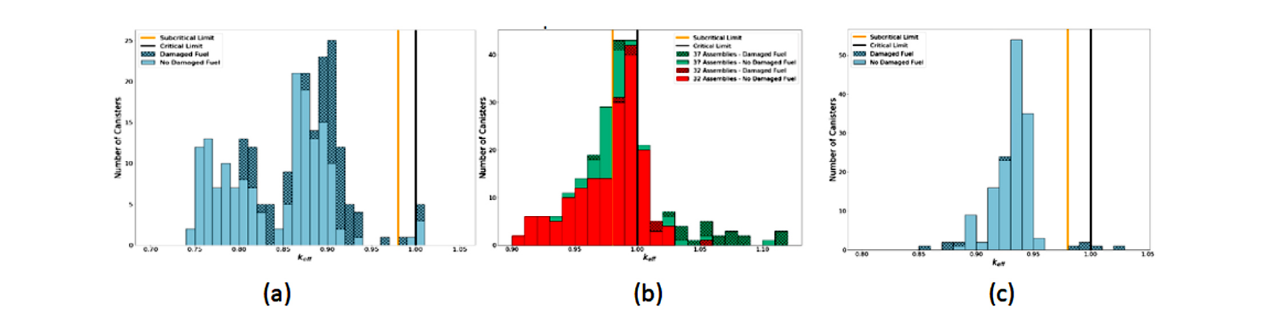


Figure 6. Preliminary Criticality Results for: (a) PWR Flux Trap DPCs; (b) PWR Egg Crate DPCs; and (c) BWR DPCs. NWTRB 2020a

logic media (clay, tuff, salt, granite, etc.). After an initial assessment, the DOE identified the primary safety concern as intrusion of water into a degraded DPC (over geologic timeframes) resulting in a subsequent criticality event in the repository.

To eliminate the repackaging from DPCs of SNF, four paths are being examined: (1) demonstrating the as-loaded DPC with full burnup credit is sub-critical under all credible conditions; (2) adding a sufficient number of corrosion resistant neutron absorbers to the DPC to prevent the system from critical; (3) injecting filler material into the DPC and around the SNF in the DPC to a sufficient level to act as moderator exclusion around the SNF and hence, prevent the hypothesized post-closure criticality events; and (4) demonstrating the consequences of a hypothesized post-closure criticality event are acceptable from a regulatory and repository performance position.

Based on initial results, approaches (1) and (4) may provide a success path for the direct disposal of the existing DPCs, with the preference to approach (1) over (4). In addition, approach (3) may be beneficial to existing DPCs that cannot be demonstrated for direct disposal using approach (1). Approach (2) be considered for implementation into DPCs that have yet to be loaded with SNF or welded shut after loading of SNF. Overall, the proposed approaches appear to provide a solid foundation for successfully arguing for the direct disposal of the current and future DPCs utilized by the commercial industry.

REFERENCES

– EPRI (Electric Power Research Institute) 2008, Feasibility of Direct Disposal of DPCs: Options for Assuring Criticality Control, EPRI report number 1016629.
– Hardin, E. and M. Voegele 2013. Alternative Concepts for Direct Disposal of Dual Purpose Canisters. FCRD-UFD-2013-000102, Rev.0. U.S. DOE.
– NWTRB (Nuclear Waste Technical Review Board) 2020a, Reactivity Analyses, Kaushik Banerjee, Oak Ridge National Laboratory, Summer 2020 Board Meeting, presentation.
– NWTRB 2020b, Ongoing Research and Development: Consequences of Nuclear Criticality in DPCs After Disposal, Laura Price, Sandia National Laboratories, Summer 2020 Board Meeting, presentation.
– ORNL (Oak Ridge National Laboratory) 1997, Description of the Canadian Particulate-Fill Waste Package (WP) System for Spent Nuclear Fuel (SNF) and its Applicability to Light-Water Reactor SNF WPs with Depleted Uranium Dioxide Fill, Forsberg, C.W., ORNL/TM-13502.
– SNL (Sandia National Laboratory) 2020, DPC Disposal Concepts of Operations. M3SF-20SN010305052 Rev. 1. U.S. DOE, Office of Spent Fuel and Waste Science and Technology. (SAND2020-2901 R)

ACRONYMS

ALARA – As Low As Reasonably Achievable
ANA – Advanced Neutron Absorber
BWR – Boiling Water Reactor
DCRA - Disposal Control Rodlet Assembly
DOE - U.S. Department of Energy
DPC – Dual Purpose Canister
EPRI – Electric Power Research Institute
ISFSI - Independent Spent Fuel Storage Installation
LA – License Application
MPC – Multi-Purpose Canister
NEI – Nuclear Energy Institute
NPP – Nuclear Power Plant
NRC – U.S. Nuclear Regulatory Commission
NWTRB – U.S. Nuclear Waste Technical Review Board
ORNL – Oak Ridge National Laboratory
PWR – Pressurized Waste Reactor
SNF – Spent Nuclear Fuel
SNL – Sandia National Laboratory
SSC – Structure, System, and Component
TAD – Transportation, Aging, & DIsposal
TSC – Transportable Storage Canister
UNF-ST&DARDS - Used Nuclear Fuel - Storage, Transportation & Disposal Analysis Resource and Data System
YM – Yucca Mountain ■