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THE UNITED STATES PERSPECTIVE ON POST-CLOSURE CRITICALITY ASSESSMENTS IN THE FINAL DISPOSAL OF HIGH-LEVEL WASTE[1]

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ABSTRACT

In the United States, commercial spent nuclear fuel (CSNF) is being stored in dual-purpose canisters (DPCs). DPCs are designed for CSNF storage and transportation (dual purpose) but are not designed for disposal in a geological repository. DPCs typically use aluminum-based neutron absorber materials for criticality control during storage and transportation. These materials are not expected to provide criticality control functionality during a repository performance period (i.e., up to 1 million years). Therefore, DPCs can potentially achieve criticality configurations during a repository performance period when conditions are favorable (e.g., partially or fully flooded with water with loss of basket neutron absorbers' criticality control functionality). The United States is investigating the feasibility of direct disposal of loaded DPCs in a repository due to the significant number of DPCs already loaded. The direct disposal of DPCs would reduce the need for repackaging of CSNF into disposal-specific packages, decreasing worker dose and avoiding the significant cost associated with repackaging. This paper describes the current U.S. approaches to determining the feasibility of disposing CSNF in DPCs, including the approaches to (a) demonstrating and lowering DPC post-closure criticality probability and (b) demonstrating an insignificant consequence of criticality events on repository performance.

KEYWORDS

As-loaded analysis, disposal, dual-purpose canisters, criticality consequence

1. INTRODUCTION

In the United States, criticality assessments for the disposal of commercial spent nuclear fuel (CSNF) and high-level radioactive waste in a deep geological repository are performed to screen criticality events for inclusion or exclusion in a repository performance assessment (PA). A significant challenge for criticality assessments concerns the very long timescales (i.e., orders of magnitude longer than in any other area of the fuel cycle) over which the assessment is to be performed. Because criticality assessment, in particular in the post-closure phase of the final disposal facility, is a unique challenge for

[1] This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961).
To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this paper in no manner supersedes, overrides, or amends the Standard Contract.
This paper reflects technical work which could support future decision-making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this paper regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel (SNF) repository.
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geological disposal, there is limited opportunity to share experience within an individual waste management organization (WMO). Sharing of experience and knowledge between WMOs is beneficial to understanding where the approaches are similar and where they are not, and the reasons for this. To achieve this benefit, a project on post-closure criticality safety has been established through the Implementing Geological Disposal – Technology Platform (IGD-TP) to facilitate the sharing of this knowledge. This project currently has 11 participating nations; the United States is considering joining as an associate member.

In the United States, CSNF is being stored in dual-purpose canisters (DPCs) at nuclear utilities nationwide. These DPCs were designed and manufactured to store and transport CSNF but were not designed for disposal of CSNF. However, disposing of CSNF in DPCs could save billions of dollars in costs and reduce the collective radiation dose to workers compared to the alternative option of re-packaging the CSNF into disposal-specific canisters, and could simplify some aspects of the spent fuel management system and reduce the number of CSNF shipments. Therefore, the United States is investigating the feasibility of disposing CSNF in DPCs in a deep geologic repository. Potential criticality of the CSNF in the DPCs in a repository timeframe has been identified as one of the major challenges for DPC disposal [1]. Post-closure criticality control is challenging because the neutron absorber materials used in the existing DPC designs are aluminum based and are expected to readily degrade with long-term exposure to groundwater. The criticality aspect of the investigation can be divided according to whether post-closure criticality is (a) very unlikely and can be excluded from the PA or (b) more likely and its consequences must be considered for exclusion or inclusion in PA. This paper presents the current status of the DPC direct disposal investigation in the United States, including the regulatory framework, as-loaded criticality analysis for determining the likelihood of criticality in a repository, and the potential effect of criticality on repository performance.

2. EXPLORING APPROACHES TO EXCLUDE CRITICALITY FROM A REPOSITORY PERFORMANCE ASSESSMENT BASED ON LOW LIKELIHOOD

The U.S. Department of Energy is investigating several options for (1) demonstrating low likelihood of DPC criticality and (2) reducing the probability of occurrences of post-closure criticality events in a repository. Detailed as-loaded criticality analyses are being performed crediting the actual loaded CSNF content of the DPCs to determine whether subcriticality can be demonstrated during a repository performance period. To date, the detailed criticality analysis has shown that subcriticality may be demonstrated, at least for a fraction of currently loaded DPCs. If as-loaded criticality analysis is not sufficient to demonstrate subcriticality, groundwater contents (e.g., salt) and non-fuel components (e.g., rod cluster control assembly [RCCA]) credits are being considered to show subcriticality during a repository performance period.

Three main ideas to reduce the criticality probability in a repository are currently under consideration: (1) loading optimization (for future DPCs) that reduces neutron multiplication factor or k_{eff}, (2) addition of advanced neutron absorber materials (for future DPCs) to the assemblies or basket cells, and (3) addition of filler materials (for already-filled and future DPCs) to provide criticality control via moderator displacement.

2.1. As-loaded Criticality Analysis

DPCs used for storage and transportation of CSNF are typically designed and evaluated using bounding (enveloping) fuel characteristics such as fuel type, fuel dimensions, initial enrichment, discharge burnup, and cooling time. This is a design basis, bounding licensing approach for CSNF storage and transportation systems, as licensing and supporting safety analysis reviews are performed prior to the actual fuel loading. The bounding fuel characteristics for a system are developed by fully utilizing the safety limits required or recommended by the regulators, such as k_{eff} approaching 0.95 to maximize the system utilizations. In reality, there are wide variations in SNF assembly burnups, initial enrichments, and cooling times. Therefore, DPCs are typically loaded with assemblies that satisfy the bounding fuel characteristics defined in the certificate of compliance, with some unquantified and uncredited margin. This uncredited margin can be used to partially offset any k_{eff} increase due to postulated DPC degradation scenarios in a repository to demonstrate that a fraction of DPCs will maintain subcriticality during a repository performance period. The Used Nuclear Fuel-Storage, Transportation, and Disposal Analysis Resource and Data System (UNF-ST&DARDS) [2] is used to perform as-loaded criticality analysis to identify loaded DPCs that would maintain subcriticality in a repository.

An important assumption for criticality analysis is that water enters a breached waste package (DPC inside a disposal overpack) during the repository performance period. Note that if water could be excluded from the repository or from entering a package, the potential for criticality would be negligible. While different geologic settings and material degradation mechanisms might yield a large number of potential scenarios for analysis, two simplified and conservative scenarios are being used for as-loaded analysis:

- **No absorber.** Total loss of basket neutron absorber components from unspecified degradation and material transport processes, with replacement by groundwater. This hypothetical configuration could result if the fuel assemblies and the basket components were more corrosion resistant than the neutron absorber.
- **Degraded basket.** Loss of the internal basket structure (including the neutron absorber). This hypothetical configuration is potentially relevant for DPC baskets with carbon steel structural components or configurations where the assembly-to-assembly pitch is reduced.

As-loaded criticality analysis has been completed for 1154 loaded DPCs from 51 sites [1]. This analysis was performed using the conservative reactor operational parameters [3]. Figure 1 presents the analyzed sites, along with the number of canisters and the types of canisters analyzed at each site. Figure 2 shows the k_{eff} distribution of the analyzed pressurized water reactor (PWR) and boiling water reactor (BWR) DPCs using box plots for no absorber and degraded basket scenarios. As shown in Figure 2, as-loaded criticality analysis can be used to demonstrate subcriticality for many loaded DPCs in a repository.

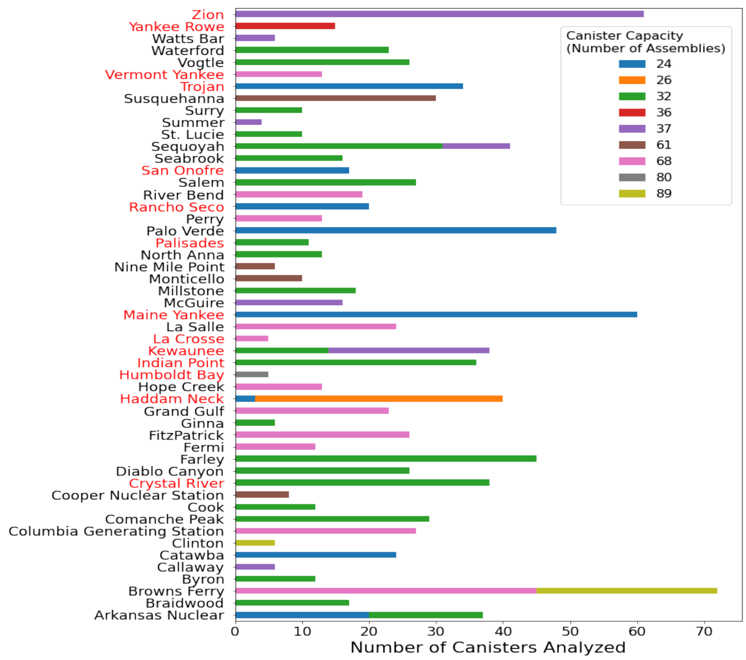

Figure 1. Number and types of loaded DPCs analyzed at each site (shutdown sites highlighted red on y-axis labels).

DPCs not meeting a representative subcriticality limit can also be further analyzed by crediting various groundwater contents, especially if any chloride salt is available in the repository environment, and with non-fuel components such as RCCAs [1, 4]. A misload analysis approach has been developed to support as-loaded DPC criticality analysis [5]. Current investigation also includes developing validation approaches for as-loaded criticality analysis [6].

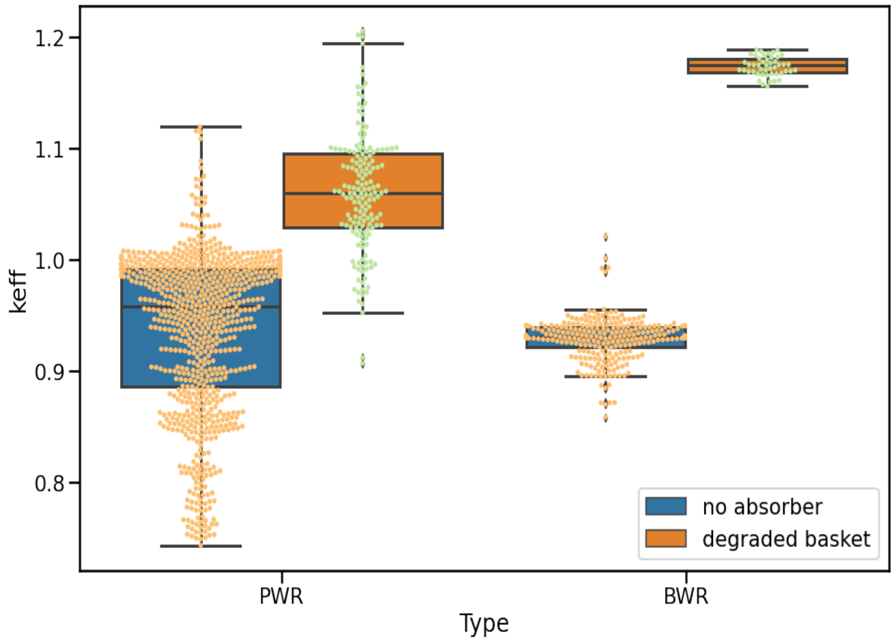

Figure 2. Neutron multiplication factor (k_{eff}) calculated for as-loaded canisters (total of 1154). The blue and the orange boxes represent the k_{eff} distributions for no absorber and degraded basket scenarios, respectively. A box is drawn to indicate first and third quartiles of k_{eff} distribution for each scenario and reactor type. The line inside a box represents the median k_{eff} value. The smallest and largest data values label the endpoints of the axis.

2.2. Loading Optimization

Based on the as-loaded calculations, it is apparent that the location of fuel assemblies within a DPC can result in very different canister k_{eff} values. Furthermore, canister loading optimization performed by utility personnel primarily considers decay heat and dose when selecting assemblies for loading in DPCs and positioning them within the DPCs. It is possible that highly reactive configurations may be avoided by distributing the highly reactive assemblies amongst more DPCs (resulting in fewer highly reactive assemblies per DPC) and placing the highly reactive assemblies in locations that have high neutron leakage. To demonstrate the reductions in reactivity that may be achievable by loading DPCs with the intention of reducing reactivity, an analysis was conducted where the fuel was ranked and divided into bins based on assembly reactivity. The most-reactive and least-reactive assemblies from each bin were then sequentially assigned to DPCs until all the assemblies had been loaded. Criticality calculations were run for the original DPCs and for the sets of DPCs generated with reloaded configurations. Based on the results (Figure 3), it is possible to dramatically reduce the reactivity of a DPC by loading with reactivity minimization as an objective. A comprehensive loading optimization for DPCs [7] that utilizes artificial neural networks is currently under development, taking into account criticality, radiation dose, and decay heat. Utilities may use this scheme for future DPC loadings to reduce the probability of DPC criticality in a repository.

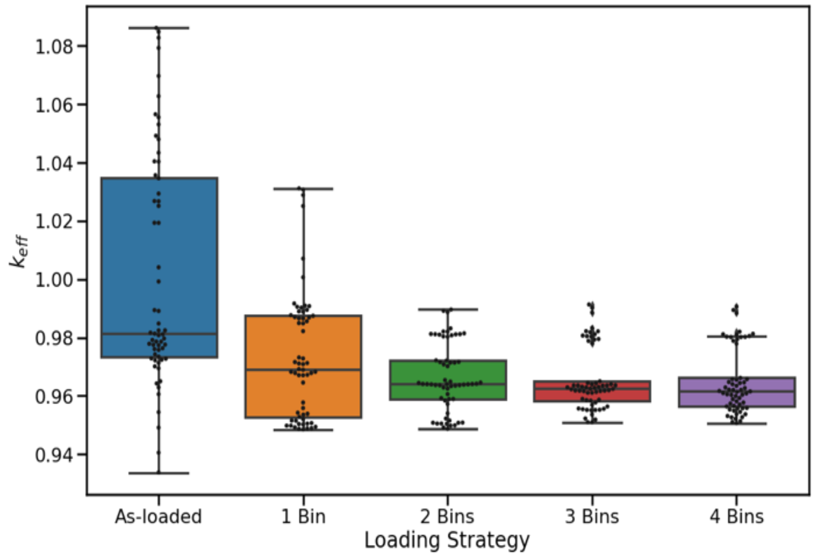

Figure 3. Results of the single site reloading analysis considering only criticality as a loading parameter.

2.3. Pre-conditioning Already-Loaded DPCs with Filler Materials

The probability of criticality of DPCs in a repository can be reduced by adding materials (i.e., fillers) to the loaded DPCs to provide criticality control via moderator exclusion or displacement [8]. The United States is investigating adding filler material in loaded DPCs. One of the objectives is to determine if filler material can be added without removing the DPC's welded lid and using the original vent or drain ports, or through new ports created by drilling through the canister shell. The focus is therefore on fillers that can be emplaced as liquids and that subsequently solidify. The two major classes of materials identified for investigation are (1) molten metals that are introduced at higher temperatures and (2) resins or cement slurries that solidify at much lower temperatures [8]. The filler demonstration plan also includes dry particle fillers such as glass beads for future study.

A set of desirable properties of filler materials has been identified, in addition to the requirements that the material is capable of moderator exclusion or displacement and that it solidify after being emplaced in the DPC as a liquid. These include (1) provide neutron absorption if needed; (2) minimize neutron moderation; (3) be compacted by no more than 10%; (4) promote heat transfer from the fuel during handling and after disposal; (5) be thermally, chemically, and radiolytically stable; (6) be chemically compatible with the materials inside the DPC; (7) have limited gas generation; (8) be homogeneous and consistent between batches; (9) have good rheological properties; (10) have good wetting behavior; (11) allow for fuel recovery should the filling operation fail; (12) be available at a reasonable cost; (13) have low density to avoid adding excess weight; (14) have good radiation shielding properties; (15) be easy to emplace; and (16) be able to be emplaced without damaging the fuel or canister [8]. These attributes may be prioritized or adjusted for specific fillers.

To date, studies of possible metal fillers have focused on developing a multiphysics simulator for down-selecting filler materials. A casting/solidification simulation model was developed and laboratory experiments were performed using tin and Sn-Bi alloys for validating the casting simulation model [9]. Tin was successfully cast on a mock-up model with a geometry that was sized accurately for the full-scale canister drain pipe and that represented nine fuel pins and one spacer grid section of a fuel bundle, as well as one of the passages between assembly shrouds (i.e., mouse holes). Sn-Bi casting experiments used more realistic DPC prototypes than tin by including longer rods (fuel pin mockup) and a substantial support structure [10]. Molten metal experiments demonstrated compatibility with the mockup DPC materials with no large voids detected. In addition, a computational fluid dynamics model was developed to simulate the filling process, and experimental data using various surrogate fillers were used to validate the simulation model [9].

Studies of possible cement fillers focused on aluminum phosphate cements, wollastonite phosphate cements, and calcium aluminate phosphate cements [11]. Efforts to date have focused on optimizing the compositions of these cements and subsequent processing to achieve dense and well-consolidated monolithic samples. To date, aluminum phosphate cements and calcium aluminate phosphate cements show the most promise for further advanced testing and scale-up; wollastonite phosphate cements remain a challenge because of their short working times [11].

Also investigated were modification of the DPC basket by placing advanced neutron absorber inserts, placing PWR CSNF with disposal control rods, and replacement of BWR fuel channel with advanced neutron absorbers to reduce probability of criticality in a repository [12].

3. DETERMINING POST-CLOSURE CRITICALITY CONSEQUENCES TO INCLUDE OR EXCLUDE CRITICALITY FROM A REPOSITORY PERFORMANCE ASSESSMENT

The U.S. Department of Energy is also studying the consequences of post-closure criticality on repository performance. Any repository licensed to dispose of CSNF must meet requirements regarding long-term performance. A post-closure 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 their probability of occurrence is below a specified limit or the consequences of their occurrence, however probable, can be demonstrated not to be significant [13]. Based on low probability, the Yucca Mountain PA excluded post-closure in-package criticality in the transportation, aging, and disposal of canisters that were to contain the CSNF. Based on recent investigations of the feasibility of DPC direct disposal, it is not clear that in-package criticality in DPCs could be excluded from the PA for non-saline host media based on low probability [1]. Therefore, if consideration is to be given to the disposal of the CSNF in DPCs without being repackaged or without the addition of fillers or other modifications discussed above, it may be necessary to model the consequences of post-closure criticality on repository performance [14].

It is important to note that post-closure 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 k_{eff} greater than or equal to 1.

To investigate the potential consequences of in-package criticality during the post-closure period, the first task was to model the effects of both a low-power steady-state criticality event and a high-power transient criticality event in a single waste package disposed of in two different hypothetical repositories (a saturated environment and an unsaturated environment), later expanding beyond a single waste package. Two PAs will be conducted for each hypothetical site, one for each type of criticality event, comparing results that include criticality events to the results of a PA of the same system but without the occurrence of criticality events. This will quantify the difference between PA results with and without criticality for the cases examined.

A study was conducted to identify FEPs that could affect the occurrence or extent of criticality (e.g., peak power, steady-state power, duration) and/or be affected by the occurrence of criticality [15] so that consideration might be given to including them in models of post-closure criticality. For a steady-state criticality event, the heat generated by the post-closure criticality event was identified as being important to both the occurrence and the extent of criticality and with respect to the effects of heat on corrosion rates, mineral alteration and thermal pressurization, radionuclide adsorption and solubility, and the chemistry of water inside the waste package. General corrosion of grid spacers at the elevated temperatures anticipated in a post-closure criticality event was identified as being important to terminating the criticality event. In addition, the change in radionuclide inventory must be considered [16]. For a transient criticality event, factors that might cause a rapid reactivity insertion were identified as important, as was mechanical damage to fuel, engineered barriers, and natural barriers that might result from such an event.

Developing the tools needed to model the relevant FEPs in a PA incorporating the occurrence of post-closure criticality required modifying PFLOTRAN [17], which is an open source, state-of-the-art, massively parallel subsurface flow and reactive transport code used to simulate subsurface earth system processes. Modifications included adding the ability to (1) specify a steady-state heat from a criticality event for a specified period, (2) change the radionuclide inventory at a specified time, (3) alter mineral types as a function of time at temperature, and (4) incorporate a model of anisotropic temperature-dependent thermal conductivity.

To date, we have completed a PA for the case of steady-state criticality in a hypothetical saturated shale repository; preliminary results (Figure 4) indicate no difference in repository performance, as measured by dose to a member of the public, between the simulation with post-closure criticality and the simulation without post-closure criticality. Transport of fission products that are generated by the critical event but that do not usually need to be considered in a PA because they have decayed to insignificant quantities by the time the waste package fails, such as ^{90}Sr and ^{137}Cs, was also studied. Results indicate that, for the hypothetical saturated shale repository, transport of these fission products is slow enough that it is not necessary to include them in the PA.

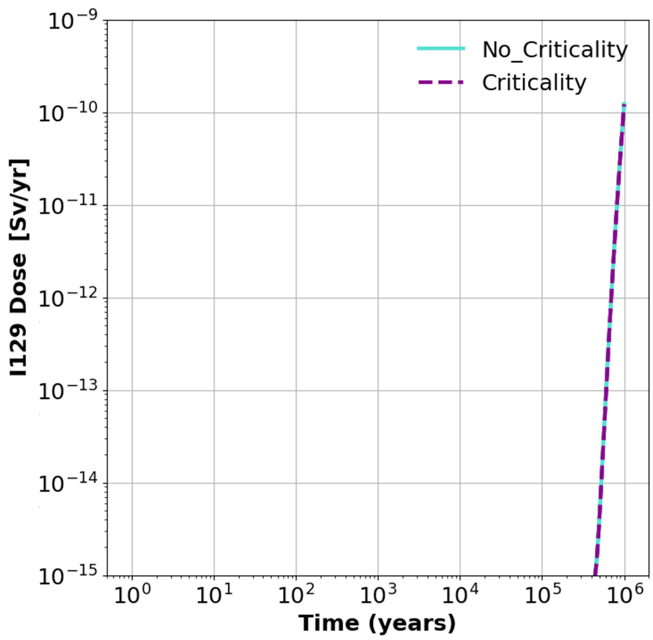

Figure 4. ^{129}I Comparison for the Base Case and the Steady-State Criticality Case [18]

The PA for steady-state criticality in a hypothetical unsaturated repository has not reached the point where we would calculate the dose to a member of the public. Indeed, it may not be necessary to calculate dose to a member of the public because results to date indicate that, in an unsaturated environment, the post-closure criticality event can sustain only very low power levels for only short periods, limiting both possible thermal effects on engineered and natural barriers and the change in radionuclide inventory. With respect to the two transient cases, we are refining our neutronic models of a transient criticality event that estimate peak power, temperatures, total energy released, and other indicators of performance with the goal of using those calculated values in a solid mechanics model to estimate effects on engineered and natural barriers.

4. CONCLUSIONS

Disposal of CSNF in DPCs in a deep geologic repository was not planned and has not been implemented domestically or internationally. Therefore, the prospect of direct disposal of DPCs presents new engineering and scientific challenges. Demonstration of subcriticality of the loaded DPCs has been identified as one of the challenges. A repository PA examines the FEPs, and sequences of FEPs, that might affect the repository. Criticality is considered as an event within the FEP nomenclature with the potential to affect repository performance. Before a PA is conducted, any FEPs that can affect repository performance are screened for inclusion or exclusion. Based on previous screening criteria, criteria available for excluding a FEP consisted of a low-probability criterion, a low-consequence criterion, and regulation. As-loaded criticality analysis showed that, in many cases, considering the as-loaded contents of DPCs is enough to offset the potential degradation of the aluminum-based neutron absorbers. However, there are a substantial number of DPCs for which subcriticality cannot be demonstrated based on crediting the as-loaded contents alone. Therefore, other options are being considered to exclude criticality from a repository PA based on the low probability of occurrence. These include (a) taking credit of non-fuel hardware, specifically RCCAs; (2) taking credit for groundwater contents, specifically any available chloride salt in the repository environment; (3) loading optimization that reduces k_{eff} of the DPCs; (4) DPC basket modification with advanced neutron absorber materials; (5) loading CSNF in DPCs with disposal control rods; and (6) preconditioning DPCs with filler materials. Additionally, methodologies and tools are being developed to assess the consequences of DPC criticality events for inclusion or exclusion in a repository PA based on significance.

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