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Review of Criticality Evaluations for Direct Disposal of DPCs and Recommendations

Spent Fuel and Waste Disposition

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Abdelhalim Alsaed
Enviro Nuclear Services, LLC

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SUMMARY

There are currently 2,462 dual-purpose canisters (DPCs) containing spent nuclear fuel (SNF) across the United States. Repackaging DPCs into specialized disposal canisters can be financially and operationally costly with undue risks. Technical feasibility of direct disposal of DPCs has been evaluated by the Department of Energy (DOE) and industry over the past 15 years. A concerted effort most recently conducted by DOE Office of Nuclear Energy (NE) Spent Fuel and Waste Science and Technology (SFWST) research and development (R&D) programs is evaluating the technical feasibility of direct disposal of DPCs in various geologies. This report focuses on reviewing the work completed by SFWST for the criticality considerations of DPC geologic disposal.

The concerted effort by SFWST over the past five years has significantly advanced the viability of direct disposal of DPCs. The effort covered a range of disposal geologies and DPC designs. However, the criticality evaluation approach has been single-faceted and did not significantly advance the overly conservative deterministic analysis bases previously developed for disposal-specialized canisters.

The strengths of the SFWST effort include as-loaded DPC criticality analysis that demonstrates a significant margin, thorough analysis of dissolved species in ground water (especially for salt geologies), a comprehensive criticality analysis process, and a valuable and capable UNF-ST&DARDS database.

The vulnerabilities of the SFWST effort include deterministic misload considerations that are either potentially unjustifiable or significantly penalizing; lack of a thorough evaluation of moderated non-flooded configurations; a deterministic analysis basis configuration with limited margin that may not be suitable as a licensing basis; modeling of "undamaged" fuel as intact in damaged fuel cans; and lack of consideration of source of burnup data including batch averages and uncertainty in assigned burnup values.

Disposal of DPCs is not only viable, but assured from a technical and assumed regulatory perspective (similar to 10 CFR 63). The analysis approach should be multi-faceted to ensure effective implementation of a licensing basis. Recommendations are provided in this report that could enhance the bases for direct disposal of DPCs by exploiting all technically attainable and regulatorily defensible options. The recommendations include the following:

- Pursuing the development of guidance for criticality-oriented loading of DPCs to demonstrate compliance with 10 CFR 72.236(m).
- Probabilistic approach for developing k_{eff} distributions that would eliminate the question of whether a DPC is critical or subcritical during disposal and places the emphasis on the probability of criticality.
- Redefining criticality features, events and processes (FEPs) to better align with the assumed regulation and to facilitate a probability-weighted consequence screening (not inclusion) of criticality FEPs from repository performance assessment.

The review objectives, including addressing several questions regarding the value of accumulating as-loaded fuel and DPC design data, suitability of DPC designs for disposal, and reasonable modifications for loading of DPCs that could facilitate eventual disposal, are also addressed in this report.

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CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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ACRONYMS

ANL	Argonne National Laboratory
BWR	boiling water reactor
DOE	US Department of Energy
DPC	dual-purpose canister
FEPs	features, events, and processes
MTU	Metric Tons of Uranium
NE	Nuclear Energy
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PWR	pressurized water reactor
SAR	Safety Analysis Report
SFWST	Spent Fuel and Waste Science and Technology
SNF	spent nuclear fuel
SNL	Sandia National Laboratory
RCRA	Resource Conservation and Recovery Act
SRNL	Savannah River National Laboratory
TAD	Transportation, Aging and Disposal
UNF-ST&DARDS	Used Nuclear Fuel – Storage, Transportation & Disposal Analysis Resource and Data Systems

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REVIEW OF CRITICALITY EVALUATIONS FOR DIRECT DISPOSAL OF DPCS AND RECOMMENDATIONS

1. INTRODUCTION

1.1 Background

There are currently (as of April 2018) 2,462 dual-purpose canisters (DPCs) containing spent nuclear fuel (SNF) across the United States (StoreFUEL 2018). DPCs are welded canisters designed to meet dry storage requirements per 10 CFR 72 and to be included as approved contents for a transportation cask licensed per 10 CFR 71. 10 CFR 72.236(m) requires that "*To the extent practicable in the design of spent fuel storage casks, consideration should be given to compatibility with removal of the stored spent fuel from a reactor site, transportation, and ultimate disposition by the Department of Energy*." Given that many of these canisters were (and continue to be) designed, licensed, and loaded without specific disposal criteria, the Safety Analysis Reports (SARs) for the licensing of these canisters for storage include simplified and superficial bases to demonstrate compliance with 10 CFR 72.236(m).

The License Application for Yucca Mountain (DOE 2008a) considered a disposal-oriented canister designed to meet storage, transportation, and disposal requirements. The performance specification for the Transportation, Aging and Disposal (TAD) canister (DOE 2008b) was informed by the specific geology and performance objectives to

- standardize design and capacity,
- optimize thermal management, and
- provide criticality control through the use of thick corrosion resistant borated stainless steel to ensure that criticality events can be of sufficiently low probability such that they can be screened out of the repository performance assessment.

Repackaging DPCs into specialized disposal canisters can be financially and operationally costly with undue risks. Technical feasibility of direct disposal of DPCs has been evaluated by the Department of Energy (DOE) and industry over the past 15 years. A concerted effort most recently conducted by DOE Office of Nuclear Energy (NE) Spent Fuel and Waste Science and Technology (SFWST) research and development (R&D) programs is evaluating the technical feasibility of direct disposal of DPCs in various geologies. The three main considerations for direct disposal of DPCs are physical attributes (weight and dimensions), thermal output, and criticality. This report focuses on reviewing the work completed by SFWST for the criticality considerations of direct disposal of DPCs.

1.2 Purpose and Objective

The purpose of this report is to document the technical review of past and ongoing SFWST activities in the area of criticality modeling and analysis in support of potential future direct disposal of DPCs. Additionally, this report provides recommendations that could advance the viability of direct disposal of DPCs. The review aims at addressing the following questions:

- What is the value of accumulating as-loaded fuel data and DPC design data for the existing fleet and future additions to the fleet of DPCs?
- What additional data could be collected to facilitate demonstration of disposal criticality control?
- What fraction of DPCs in the existing fleet is likely to be disposable with overpacks, but without other modifications? Is this likely to change significantly with future additions to the fleet?

- What DPC types currently in use are best/least suited for direct disposal?
- What reasonable modifications could be made in loading DPCs at the reactor sites to enhance the viability of direct disposal of DPCs?
- What effort is needed to follow through on the plan documented in *Criticality Analysis Process for Direct Disposal of Dual Purpose Canisters* (Scaglione et al. 2014)?

1.3 Scope

The scope of the review includes the following documents:

- *Summary of Investigations on Technical Feasibility of Direct Disposal of Dual-Purpose Canisters*, SFWD-SFWST-2017-000045, 2017.
- *Dual Purpose Canister Reactivity and Groundwater Absorption Analyses*, FCRD-UFD-2014-000520, 2017.
- *Criticality Process, Modeling, and Status for UNF-ST&DARDS*, FCRD-NFST-2015-000440, Rev. 1, 2016.
- *BWR Fuel Assembly Modeling for UNF-ST&DARDS*, SFWD-PO-2017-000161, 2016
- *Summary of Investigations on Technical Feasibility of Direct Disposal of Dual-Purpose Canisters*, FCRD-UFD-2015-000129 Rev. 0, 2015.
- *Potential Dual-Purpose Canister (DPC) Filler Materials*, FCRD-UFD-2014-000521 Rev. 0, 2014.
- *Criticality Analysis Process for Direct Disposal of Dual Purpose Canisters*, ORNL/LTR-2014/80, 2014.
- *Investigations of Dual-Purpose Canister Direct Disposal Feasibility (FY14)*, FCRD-UFD-2014-000069 Rev. 1, 2014.
- *Spent Fuel Canister Disposability Baseline Report*, FCRD-UFD-2014-000330 Rev. 0, 2013.
- *Preliminary Report on Dual-Purpose Canister Disposal Alternatives (FY13)*, FCRD-UFD-2013-000171 Rev. 1.

Several other documents and reports were also reviewed in order to address the objectives and formulate the recommendations, including:

- *Yucca Mountain Repository License Application*. DOE/RW-0573, Rev. 1
- *Safety Evaluation Report Related to Disposal of High-Level radioactive Waste in a Geologic Repository at Yucca Mountain, Nevada, Volume 3: Repository Safety After Permanent Closure ,* NUREG-1949, Vol. 3
- *Screening Analysis of Criticality Features, Events, and Processes for License Application*, ANL-DS0-NU-000001, Rev. 00 ACN 01, ERD 2
- *Disposal Criticality Analysis Methodology Topical Report*, YMP/TR-004Q, Rev. 2
- *Criticality Consequence Analysis Involving Intact PWR SNF in a Degraded 21 PWR Assembly Waste Package*, BBA000000-01717-0200-00057, Rev. 00
- *Feasibility of Direct Disposal of Dual-Purpose Canisters in a High-Level Waste Repository*, 1018051
- *Feasibility of Direct Disposal of Dual-Purpose Canisters: Options for Assuring Criticality Control*, 1016629

- *The Potential of Using Commercial Dual-Purpose Canisters for Direct Disposal*, TDR-CRW-SE-000030, Rev. 00
- *US Commercial Spent Nuclear Fuel Assembly Characteristics*, NUREG/CR-7227

1.4 Report Outline

This report is structured as follows:

- Regulatory considerations and previous application are discussed in Section 2 in order to contextualize the review findings and recommendations.
- Review findings are discussed in Section 3.
- Recommendations are presented in Section 4.
- Responses to the questions listed in the review objectives are provided in Section 5.

2. REGULATORY CONSIDERATIONS AND PREVIOUS APPLICATION

The assumed regulatory structure for direct disposal of DPCs is similar to 10 CFR 63, which allows for probabilistic screening of features, events, and processes (FEPs) or for their inclusion in the repository performance assessment with an analysis period limited to 10,000 years, which may be subject to extension to later times to address peak reactivity (18,000 – 25,000 years). This assumption is adequately justified in Section 3.1.1 of Scaglione et al. (2014).

The DOE disposal criticality analysis methodology developed to demonstrate compliance with 10 CFR 63 is documented in *Disposal Criticality Analysis Methodology Topical Report* (DOE 2003). It was implemented by the DOE in the *Yucca Mountain Repository License Application* (DOE 2008a), and reviewed favorably by the Nuclear Regulatory Commission (NRC) in *Safety Evaluation Report Related to Disposal of High-Level Radioactive Waste in a Geologic Repository at Yucca Mountain, Nevada, Volume 3: Repository Safety After Permanent Closure* (NRC 2014). The methodology allowed for either probabilistic screening or inclusion of criticality FEPs in the repository performance assessment. DOE's licensing basis relied on demonstrating that the probability of criticality for a suite of sixteen criticality FEPs is less than the screening threshold for inclusion in the repository performance assessment. The sixteen criticality FEPs are as follows:

- Eight FEPs for in-package intact and degraded configurations under nominal conditions as well as seismic, rockfall, and igneous disruptive events. These FEPs are relevant to direct disposal of DPCs.
- Eight FEPs for near-field and far-field configurations under nominal conditions as well as seismic, rockfall, and igneous disruptive events. These FEPs are not relevant to direct disposal of DPCs because once the fissile material leaves the waste package in solution, whether the host canisters were disposal-specialized or DPCs would be irrelevant.

Although the conclusion for screening out criticality FEPs in the license application was probabilistic (i.e., less than 1 chance in 10,000 in 10,000 years), the basis for evaluating criticality potential was deterministic. The DOE selected a design basis configuration that would be subcritical and determined the design requirements based on 10,000 years of corrosion using a single bounding corrosion rate. This approach led to the selection of a thick (11 mm) neutron absorber made of corrosion resistant powder metallurgy borated stainless steel. The only probabilistic considerations that were included in the criticality screening analysis were neutron absorber misload and SNF assembly misload coupled with the probability of disposal overpack failure (regardless of the cause, extent, or availability of water). Note that without significant moderation, there is no potential for criticality with commercial SNF.

It is important to note that the design basis configuration selected for criticality FEPs screening is not a bounding configuration for SNF, but was considered sufficiently conservative based on deterministic judgments, which included:

- Intact fuel assemblies. Commercial SNF assemblies are designed to be under-moderated, therefore, increasing pin pitch increases reactivity. Use of intact fuel assemblies was justified on the basis that a horizontal configuration poses limited potential for buckling of the SNF rods.
- Fuel matrix composition remains unchanged through out the disposal period. Preferential leaching of material from the fuel matrix requiring the consideration of different fuel compositions for the degraded configurations was not considered because only non-soluble and non-volatile materials were considered in the criticality analysis and because failure of a significant number of fuel rods would decrease reactivity.
- Uniform compaction of fuel baskets and assemblies without preferential settling. All fuel assemblies within a TAD canister were assumed to be at the highest reactivity acceptable for loading in a TAD (i.e., all assemblies were assumed to be on the loading curve). This modeling

assumption is important for direct disposal of DPCs, where as-loaded characteristics are modeled for each assembly.

A performance specification for a specialized and relatively expensive canister was developed based on this simplified, mostly deterministic, approach for screening out criticality events from the repository performance assessment. With direct disposal of DPCs, which do not include similar inherent margins (e.g., all assemblies are not assumed to be at the loading curve limit), the analysis approach may need to be different. A different approach is proposed in Section 4.3 of this report.

3. REVIEW SUMMARY AND FINDINGS

The concerted effort by SFWST over the past five years has significantly advanced the viability of direct disposal of DPCs. The effort covered a range of disposal geologies and DPC designs. However, the criticality evaluation approach has been single-faceted and did not significantly advance the overly conservative deterministic analysis bases previously developed for disposal-specialized canisters. This section presents the strengths and vulnerabilities of the five-year SFWST effort.

3.1 Strengths

3.1.1 As-Loaded DPC Criticality Analysis to Demonstrate Margin

Reliance on the criticality margin in DPCs based on as-loaded conditions including SNF characteristics, presence of non-fuel components, and DPC basket designs is certainly a viable and defensible approach for demonstrating that DPCs could remain subcritical under a range of disposal configurations. The as-loaded analysis for 556 DPCs (as of September 2017) demonstrated that this margin could be greater than 0.05 Δk_{eff}.

The as-loaded DPC evaluations assumed disposal analysis configurations with intact assemblies and lost neutron absorbers. For DPC designs with egg-crate style baskets, the disposal analysis configurations also assumed loss of baskets. For DPC designs with tube and disks style baskets, the disposal analysis configurations assumed that the disks would maintain separation between the assemblies throughout the regulatory period.

By May 2015, 215 DPCs had been analyzed. Section 2.4.5.2 of Hardin et al. (2015) states "*Taking into account the as-loaded assembly burnup characteristics, only 34 of 215 DPCs [~16%] are critical for the loss-of-absorber scenario*." By September 2017, 556 DPCs had been analyzed. Section 2.4.5.3 of Liljenfeldt (2017a) states "*128 of 556 DPCs [~23%] are predicted to be critical for the loss-of-absorber scenario*."

The percentage of potentially critical DPCs under the analysis basis configuration using as-loaded SNF information increased from 16% to 23% with the additional, more recently loaded, DPCs. This was predicted in Section 2.4.5.2 of Hardin et al. (2015), which states "*Note that these percentages are based on the DPCs evaluated to-date, which include many from decommissioned sites, which predominantly represent first-generation DPCs. The proportions of existing DPCs that are found to be critical for these scenarios are expected to increase as more DPCs are evaluated*."

This work has uncovered valuable information regarding the reactivity margin in loaded DPCs that is not only of great importance to disposal of currently loaded DPCs, but also to loading of future DPCs as discussed in Section 4.1.

3.1.2 Analysis of Dissolved Species in Ground Water

The most robust disposal criticality analysis basis with essentially guaranteed success is for a salt geology. Based on the results for a bounding hypothetical configuration of optimally spaced fuel pins with limited and easily attainable burnup credit (10 GW-d/MTU burnup for 5 wt.% enriched fuel), DPCs could be demonstrated subcritical at a chlorine concentration well within expected concentrations in a salt repository (NaCl brine has a concentration of approximately 6 molal [~158,000 ppm on this scale]). This is illustrated in Figure 3-1.

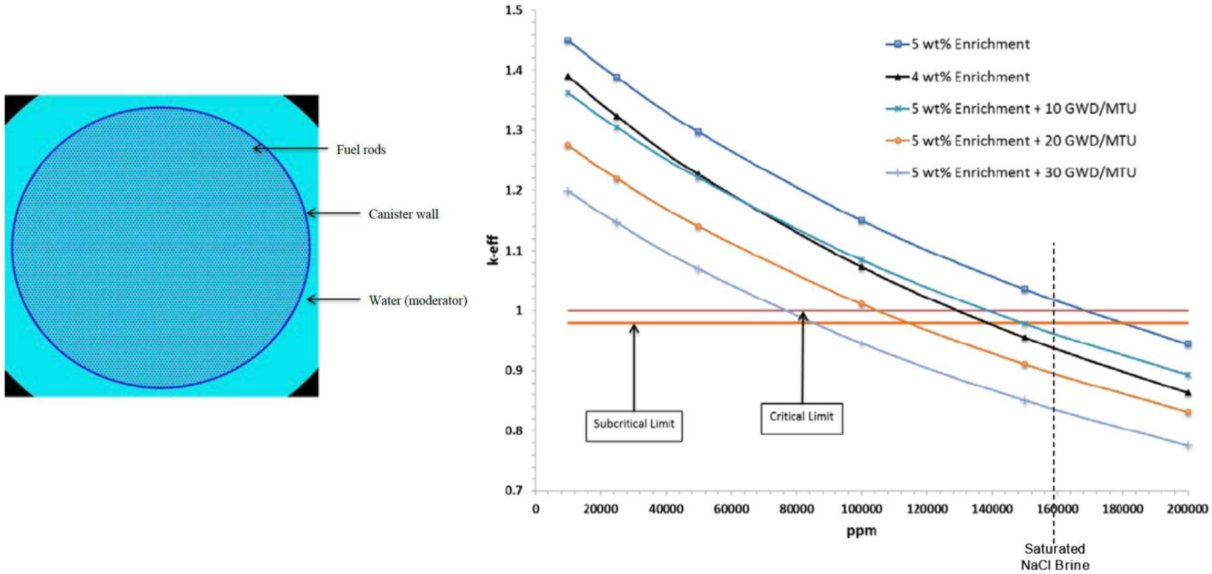

Figure 3-1. Impact of Chlorine Concentration on the Reactivity of a Theoretically Bounding SNF Configuration.

Section 4.3.1 of Hardin et al. (2014) concludes "*lithium and boron are known to be scarce in ground water, so realistically they may not provide significant reactivity reduction. Bromine and manganese may offer slight reactivity reduction…while the other elements (N, Ba, Mg, F, S, Na, K, Sr, Ca, Fe, Al, and Si) would be insignificant*." Although the impact of dissolved species may be insignificant individually as presented in Figures 4-9 and 4-10 of Hardin et al. (2014), their collective impact may not be. Their impact is not limited to neutron absorption, but also to neutron spectrum hardening as evident by the change in their reactivity worth with or without baskets. Therefore, consideration of all potential dissolved species including Cl, Li, Br, Mn, N, Ba, Mg, F, S, Na, K, Sr, Ca, Fe, Al, and Si should continue. Their inclusion in the overall probability of criticality analysis is discussed further in Section 4.2.

3.1.3 Criticality Analysis Process for Direct Disposal of DPCs

The criticality analysis process described in *Criticality Analysis Process for Direct Disposal of Dual Purpose Canisters* (Scaglione et al. 2014) includes a comprehensive approach for addressing direct disposal of DPCs including a graded analysis that allows for deterministic and probabilistic considerations for evaluating the potential for criticality and associated consequences. However, only a small number of accomplishments have been made because of the lack of advancement of the deterministic analysis basis configuration approach. Figure 3-2 (Liljenfeldt 2017b, Figure C-20) shows that although progress has been made, many areas that advance the disposal viability of DPCs have not been developed yet. The recommendations in Section 4 discuss how more aspects of the process can be implemented.

3.1.4 UNF-ST&DARDS Database

The Used Nuclear Fuel – Storage, Transportation & Disposal Analysis Resource and Data Systems (UNF-ST&DARDS) database is extremely valuable; its benefits will continue to be reaped for all future SNF management strategies including transportation, interim storage, and disposal. The benefits of the database extend across several analysis areas, including criticality, thermal, and shielding. Continuing to populate the database and to advance its capability is advisable.

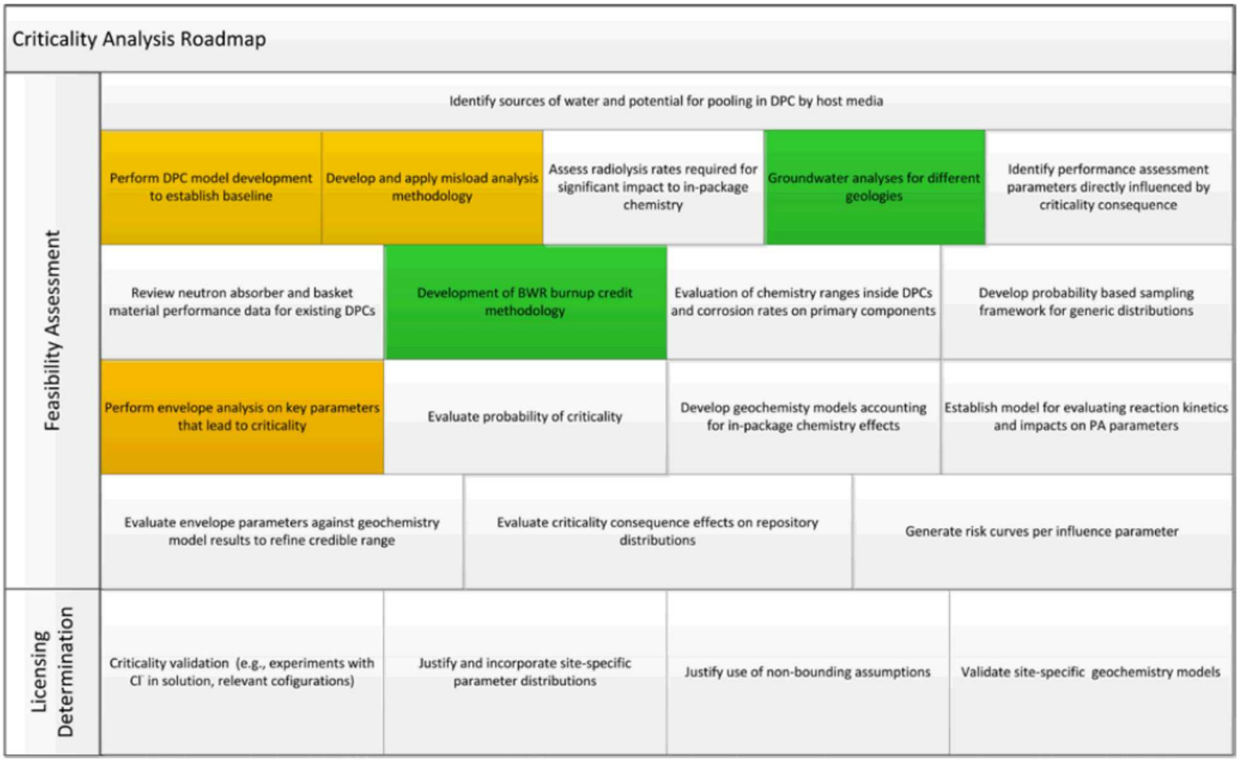

Figure 3-2. DPC Criticality Analyses Roadmap With Yellow and Green Highlights Indicating Level of Completed Effort.

3.2 Vulnerabilities

3.2.1 Misloads Considerations

Consideration of misloads is an expectation for determining the potential for criticality when burnup is credited in the criticality analysis. A deterministic approach to misloads considered loading of the wrong assemblies in a DPC or loading the correct assembly but in the wrong locations within a DPC basket. As-loaded criticality analyses have been completed for a total of 556 DPCs (as of September 2017) to evaluate criticality potential for a range of disposal configurations. Of those analyzed, misload evaluations for 99 DPCs at three different sites (Sequoyah, Zion, and Browns Ferry) and for three different canister designs have been completed. For two of the three sites, all 59 DPCs would be critical for the analysis basis disposal configuration based on the bounding misload consideration. For one site, all 40 DPCs would be subcritical regardless of the misload consideration. Note that for the third site (Browns Ferry), there were no assemblies with relatively high reactivity in the pools; this situation is atypical. The expected outcome for other DPCs and sites (current and future) would likely be similar to Zion and Sequoyah.

Section C.5 of Liljenfeldt et al. (2017b) states "*In addition to the suggested misload types in ISG 8 rev. 3, an additional type (worst case configuration) was implemented to specifically address the as-loaded criticality analysis approach, where the correct inventory was assumed to be incorrectly loaded in the most reactive configuration. This worst-case configuration is considered the most likely misload scenario for disposal as the other misload scenarios involving selection of incorrect assemblies should be detected during the subsequent loadings*."

This is also reiterated in Section 2.4.5.3 of Liljenfeldt et al. (2017a), which states "*It can be argued for the disposal scenario that a fuel assembly misload would be noticed before the DPC is being emplaced. Therefore, the most realistic scenario for an undetected misload is that the correct inventory has been* *placed in the wrong configuration. This approach would significantly decrease the number of DPCs with keff over 0.98, even when considering only the most reactive misload configuration*."

It is unlikely that the above two quotes would constitute a defensible licensing basis and limit the misload analysis to only loading the correct inventory in the incorrect basket locations of a DPC for the following reasons:

- A significant contributor to misloads is error in documentation (e.g., swapping the burnup assignments for two assemblies). There is a limited path for recovery from documentation errors based on future identification. Therefore, once the documentation error occurs, error discovery would not be possible without additional measurements, which are not planned.
- The decision to emplace or repackage a specific DPC may be done prior to loading all assemblies into dry storage systems (or disposable canisters) at the originating site, therefore, reliance on belated information is not viable.

Therefore, The misload analysis should take into account loading of the wrong assembly(ies) in a DPC.

Section 2.4.5.3 of Liljenfeldt (2017a) states "*The number of DPCs that are in the risk of being critical would increase to 200 or 218 [~40% of the 556 analyzed DPCs] after accounting for the misload scenarios*," This conclusion is based on assuming that the correct DPC inventory was misloaded in the wrong DPC locations, as opposed to misloading the DPC with the incorrect assemblies from the pool. Based on misloading the DPC with the incorrect assemblies from the pool, the fraction of DPCs that could be critical would be significantly higher.

The current DPC analysis follows, and adds to, the guidance in ISG-8, Rev. 3 (NRC 2012) for consideration of misloading a single high reactivity assembly in the most reactive location or misloading multiple moderately burned assemblies in various locations in the DPC. This reflects the NRC's deterministic expectations for storage and transportation. However, a probabilistic approach should be used for a probabilistic disposal analysis. The probabilistic approach for the misload analysis is included in Section 4.2.

3.2.2 Moderated Non-Flooded Configurations

Potentially critical non-flooded configurations (e.g., by formation of schoepite) could result from the degradation of the SNF, the waste package internals, and the removal of neutron absorbers. Section 2.5 of Hardin (2013) states "*Converting commercial SNF to saturated metaschoepite was found to be less reactive than the unaltered fuel in its original configuration*." The basis for this statement is provided in SNL (2007) for the analysis of commercial SNF in TADs for igneous scenarios and Section 6.2.5 of SNL (2008) for sensitivity studies for TAD loading curves. These analyses were based on the design basis configuration, which included 6 mm of borated stainless steel between the fuel assemblies. For the DPCs analysis basis configurations (i.e., no neutron absorbers and/or no fuel baskets), the reactivity of schoepite configurations may be high enough to warrant evaluation, especially for high burnup fuel, with a relatively significant amount of plutonium. The potential for leaching out of some credited absorbers integral to the fuel would also have to be considered in this scenario. Additionally, this analysis could possibly negate some of the credit taken in the as-loaded configuration analysis if degraded fuel migration is considered. The need to address these configurations was identified previously (Scaglione et al. 2014, Assumption 3.1.4).

3.2.3 Modeling of SNF in DFCs

The fresh fuel assumption with conservative fuel reconfiguration is a robust approach for the consideration of damaged fuel in DFCs. For the analysis basis configuration, this bounding approach has minor reactivity penalties since the DFCs are usually in peripheral location. However, for configurations that may allow for fuel migration (e.g., degraded non-moderated schoepite configurations), the fresh fuel assumption for damaged fuel may become penalizing. The refinement of this modeling approach should be coordinated with addressing the moderated non-flooded configurations discussed in Section 3.2.2 above.

Section 4.2 of Hardin (2014) states "*However, some canned fuels that are not damaged, such as high burnup (>45 GW-d/MTU) assemblies in a DFC are modeled as intact with accumulated burnup.*" This approach may not be justifiable because the basis that fuel was initially intact may be challenged. For example, since it was determined that the fuel would be placed in DFCs, the guidance in ISG-11 (NRC 2007) may have not been followed to classify the fuel as intact or "undamaged" (e.g., with pinholes and hairline cracks, missing rods, but acceptable based on storage and transportation licensing analysis bases).

3.2.4 Source of Burnup Data

For a subset of the UNF inventory, only batch average information is available. Section 4.5 of Bevard (2009) states "*Record keeping requirements at individual utilities, for both the content and storage media of reactor records, have varied over time, as have the requirements for information required by NRC. For very old SNF, the reactor records may include "batch averages" for burnup information. The use of batch average values arose because the utilities were allowed to group assemblies with similar characteristics (a batch) into a single record for the purposes of reporting fuel inventories to NRC.*"

A process needs to be developed to extrapolate batch average information. This may reduce the extent of credit that can be gained for these assemblies.

There is also uncertainty in the assigned burnup values for SNF assemblies. Based on work completed for Yucca Mountain, NUREG/CR-6998 states "*the reactor records at nine PWR plants, consisting of 5,447 assemblies with assembly lifetime burnup values greater than 10 GWd/MTU, were evaluated, and their reactor records indicated an uncertainty in burnup of between 2 to 4.2% with a 95/95 confidence level.*" This uncertainty, which would reduce the available margin, was not considered in the evaluations of the as-loaded analysis basis disposal configurations.

3.2.5 Presence of Lead in Some DPC Designs

Although this is not a criticality issue, it may be worth noting because it could have a significant impact on the disposability of specific DPC designs. Some DPC designs (e.g., some NUHOMS DSCs) use lead in the bottom and top shield plugs. Section 4.1 of BSC (2003) states "*Because lead serves as a functional component of the DPC, it would not be classified as a RCRA waste and therefore is not expected to affect the disposability of FC and FF canisters.*" This is also reiterated in Hardin el. Al (2013), which states "*Lead, chromium or other materials used in fabrication of DPCs is part of waste packaging that will not be subject to regulation under the Resource Conservation and Recovery Act (RCRA).*" This conclusion needs further investigation on what constitutes "part of waste packaging". For example, chromium being a constituent of stainless steel may be acceptable, however, a 4-inch thick 60-inch diameter lead disk used for operational shielding may not be considered "part of waste packaging". This is further supported by the TAD performance specification (DOE 2008b), which states "*The TAD canister, including the steel matrix, gaskets, seals, adhesives and solder, shall not be constructed with materials that would be regulated as hazardous wastes under the Resource Conservation and Recovery Act (RCRA) and prohibited from land disposal under RCRA if declared to be waste.*"

4. RECOMMENDATIONS

Disposal of DPCs is not only viable, but assured from a technical and assumed regulatory perspective. The analysis approach should be multi-faceted to ensure effective implementation of a licensing basis. The following is a list of recommendations that enhance the potential for success by exploiting all technically attainable and regulatorily defensible options.

- Regulatory engagement for the development of guidance to address compliance with 10 CFR 72.236(m) as discussed in Section 3.1.
- Probabilistic approach to k_{eff} as discussed in Section 4.2.
- Probability-weighted consequence screening based on redefining criticality FEPs as discussed Section 4.3.
- Credit for the stable Cs-133. Because the current analysis basis configurations assumed intact fuel pins, there is no path for release of Cs-133 from the fuel. Cs-133 is the highest yield fission product (6.8%) with a cross section of 28.9 b, and is a more valuable burnup credit isotope than most of the currently credited isotopes. Credit for Cs-133 is already accepted for storage and transportation.
- Development of a burnup verification tool. Per ISG-8 Rev. 3 (NRC 2012), burnup confirmation would eliminate the potential for misload consideration for deterministic storage and transportation applications, which is one of the most significant vulnerabilities in the current analysis approach. With a probabilistic approach, a burnup confirmation tool would significantly reduce the probability of a misload.
- Continue the evaluation of the viability of the use of a filler material that would be cost effective and meet the storage, transportation, and disposal structural, thermal, criticality, and retrievability requirements. This option is the subject of a follow-on deliverable and will be discussed in detail.
- Continue to pursue boiling water reactor (BWR) SNF burnup credit.
- Continue to gather the necessary data for DPCs to support as-loaded modeling.
- Development of overpacks or overpack treatment that would reduce the probability of early failure (e.g., use of additive manufacturing), where early failure would be more rigorously defined taking into account appropriate classes of defects and performance-based functions (e.g., maintaining moderator exclusion from the DPC with partial failures).
- Simulate the degradation of DPCs to determine the composition of the water within the DPC, relocation of neutron absorbers and extent of failure.

4.1 Pursuing the Development of Guidance for Compliance with 10 CFR 72.236(m)

Most of the analyzed DPCs could have been loaded with the same SNF inventory in a configuration optimized for disposal criticality such that they would be subcritical for the analysis basis configurations. This is illustrated in Figure 4-1, which shows the reactivity band for the same DPC inventory based loading arrangement of the SNF assemblies in the fuel baskets.

Engagement with the industry and the NRC to pursue the development of guidance (possibly in the form of an ISG) to demonstrate compliance with 10 CFR 72.236(m) is prudent. There are precedents for work completed by the DOE (and industry) that was used by the NRC and formed the basis for an ISG. DOE's effort in the late 90s and early 2000s facilitated the revision of ISG-8, Rev. 3 (NRC 2012) to allow for full burnup credit. More recently, the industry's engagement facilitated the redefinition of retrievability at the canister level (as opposed to the fuel assembly level) in ISG-2, Rev. 2 (NRC 2016b).

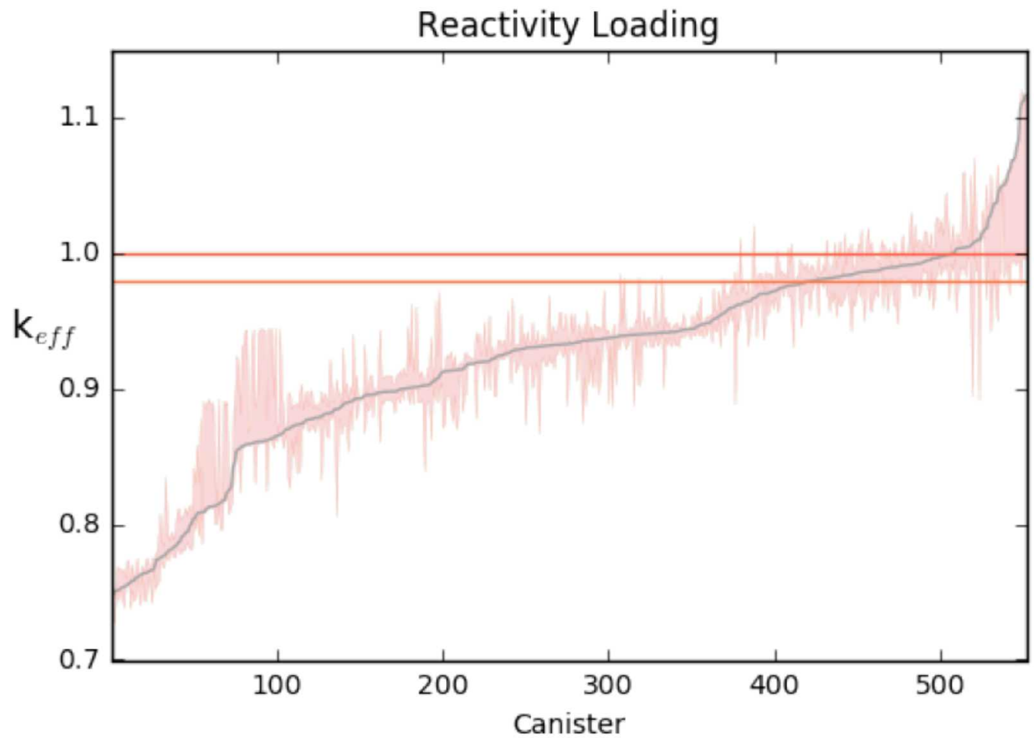

Figure 4-1. k_{eff} Range Based on Zoned Loading of DPCs.

DOE can start the engagement by the development of a family of loading curves that would minimize the reactivity of a DPC for a given loading of SNF assemblies. The loading curves could be even further refined based on site-specific and DPC design information. This approach may have an impact on the thermal management and shielding for loading DPCs. However, based on the general practice of loading low burnup SNF assemblies in the periphery locations of baskets (lower radiation source term) and high burnup SNF in the middle zone of baskets (to facilitate heat transfer), it is anticipated that the zone-based disposal criticality loading curves would be congruent with current practices. Loading maps that optimize criticality, shielding, and thermal considerations can be developed.

4.2 Probabilistic Approach to k_{eff}

k_{eff} for a system is not a single value, but rather a distribution. This is true even for the most basic of systems since neutron interactions that govern the physics of criticality are probabilistic. For DPCs, which are complex systems with a range of compositional and geometrical parameters that evolve over time, consideration of k_{eff} as a distribution not a single value is logical. The following two statements are facts:

- The SNF in all DPCs is of sufficient reactivity such that it could be critical in optimized configurations.
- All DPCs are subcritical with a significant margin without moderation.

Because the SNF in most DPCs is of sufficient reactivity to form a critical configuration, the analysis that aims at demonstrating that DPCs would remain subcritical during disposal must conclude that

- the most reasonably credible disposal configuration is subcritical in the presence of water moderation (the deterministic design basis approach), or
- the probability of a critical configuration is sufficiently low such that it would be less than the screening threshold.

k_{eff} of a DPC in a disposal configuration can be accurately represented as illustrated in Figure 4-2. Most of the k_{eff} values in the distribution are lower than the current analysis basis configuration, but some are higher. The lower bound k_{eff} is associated with as-loaded dry configurations, which is typically around 0.5. The upper bound k_{eff} is associated with optimally moderated SNF pins (e.g., expanded pin pitch or preferential failure of fuel rods to better optimize H/X, leaching of neutron absorbers integral to the fuel), which could be as high as 1.5 for some DPCs.

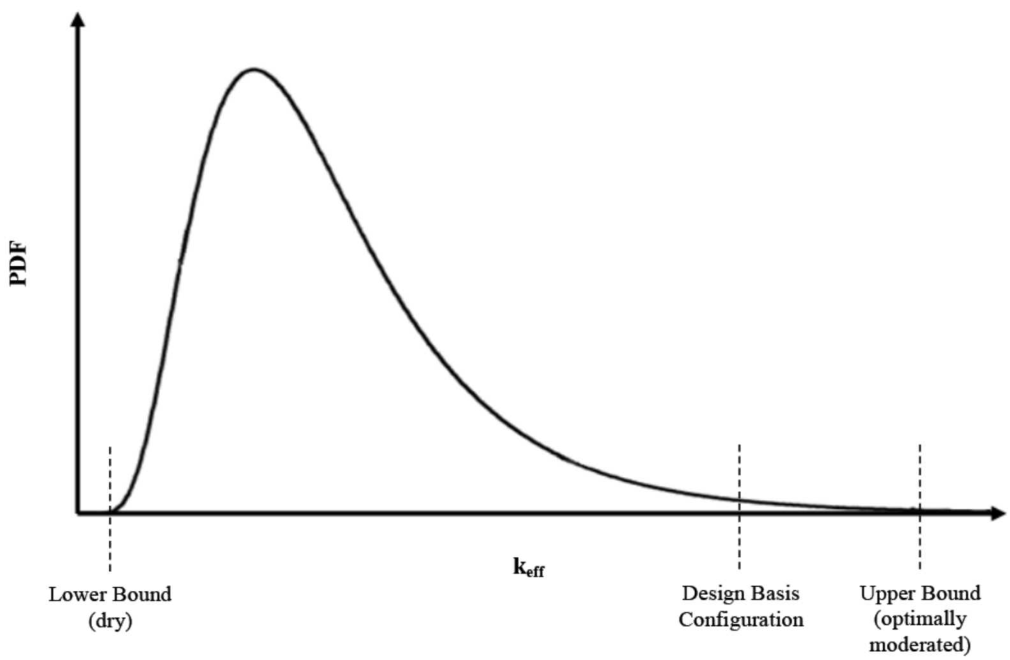

Figure 4-2. Illustration of k_{eff} distribution.

The probabilistic approach to determining k_{eff} is to generate a distribution of k_{eff} values for each DPC based on the potential parameters that could impact k_{eff}. The distribution would be sampled to determine the probability of criticality. The key parameters important developing k_{eff} distributions for DPC disposal are as follows:

- Probabilistic approach to SNF characteristics including fuel design and composition at emplacement as well as physiochemical changes during disposal. The currently used (and NRC approved) burnup credit methodology described in ISG-08, Rev. 3 (NRC 2012) is deterministic and bounding to ensure that the fuel isotopic composition (including axial profiles) is of sufficient conservatism to bound the pressurized water reactor (PWR) SNF population. There is no approved burnup credit methodology for BWR SNF. The SNF composition varies as a function of depletion characteristics (e.g., moderator density, specific power, presence of burnable poison/control rods/blades during reactor depletion). Therefore, significant variability in isotopic compositions across fuel assemblies is expected. An excessively conservative or bounding approach for the previous deterministically derived TAD design basis configuration was viable because the conservatism in the burnup credit methodology was accommodated in the performance specification of the disposal-specialized TAD canister. Because DPCs do not have the margins afforded by the TAD canister performance specification, a probabilistic SNF characteristics approach is warranted. This approach is even more viable for BWR SNF, where there is far more variability in BWR SNF assembly designs and depletion parameters with more significant impact on SNF assembly reactivity. There is enough data currently available to develop a distribution of isotopic compositions based on a range of depletion histories and a distribution of axial profiles. For example, Section 4.2.1 of Hardin et al. (2014) states "*This work used a set of bounding profiles based on analysis of 3,169 axial profiles taken from plant operating data covering 106 cycles of operation….Bounding axial burnup profiles…are implemented through UNF-ST&DARDS and used in the criticality analysis.*" The same set of 3,169 axial profiles could be used to develop the probabilistic distributions for PWR SNF. Axial profiles for BWR SNF are more complex than PWR SNF due to the use of axial enrichment zones and the wider variability in relevant BWR reactor operational parameters (e.g., moderator axial density profiles). Axial burnup distributions for 624 BWR SNF assemblies are analyzed in NUREG/CR-7224 (Marshall et al. 2016), which may be used to start the development of probabilistic distributions for BWR SNF.

- Probabilistic approach to neutron absorbers (both present in the canisters or introduced during disposal). The TAD canister design basis configuration and DPC analysis basis configuration are based on uniform corrosion, and once corroded, the corrosion constituents are not credited in the moderating solution. A probabilistic approach for corrosion products location, concentration in solution, and retention in a degrading canister could provide valuable reactivity credit and could be made viable with a probabilistic approach.
- Probabilistic approach to geometry and composition of the SNF, fuel baskets, and neutron absorbers. The analysis design basis configuration assumed intact fuel, no poisons, and fixed credit for basket separation (none for egg-crate design and full for tube and disks designs). A probabilistic approach allows for the entire range from present to completely compromised to be reflected in the k_{eff} distribution.
- Probabilistic approach to moderation characteristics including composition, temperature, and density. Current analysis assumes that once a waste package fails, water would fill the entire waste package. With a probabilistic approach water composition, extent (including location of failure), sufficiency of flow rate to fill waste package, evaporation rate, flow diversion paths could be taken into consideration.
- Probabilistic approach to misloads. The current analysis is based on the deterministic guidance provided in ISG-8, Rev. 3 (NRC 2012) and supplemented with additional misload considerations. Criticality potential due a misload does not preclude a specific DPC from being emplaced. The probability of a misload and the potential reactivity change due to a misload would be captured in the k_{eff} distribution. The answer to the misload question is not whether it results in a DPC to be critical or not, bur rather how it alters the k_{eff} distribution.

With a probabilistic approach for SNF geometry, basket geometry, neutron poison degradation, water composition, and moderation extent, justifying a specific assumption regarding intact fuel or basket condition, would not be necessary. What must be justified are the parameter distributions. Where data may be sparse, Bayesian statistical methods can be used The use of Bayesian methods is well established and has significant precedents in regulatory applications including DOE's License Application for Yucca Mountain (DOE 2008a).

The DPC k_{eff} distribution can combine all pertinent parameters (for fuel characteristics, geometries, and moderation) or it can be layered. Given that specific repository parameters are not currently available, the k_{eff} distributions can be developed in phases as follows:

- Phase I: Fuel characteristics distributions, for which the information is currently available.

- Phase II: Consideration of misloads, for which the information is currently available for some of the sites.
- Phase III: Geometry and moderator distributions, for which the architecture can be developed, but the specific parameters will be established once a repository setting has been chosen.

This approach eliminates the questions of whether a DPC is critical or subcritical during disposal, since there is no single k_{eff} value for a DPC, and places the emphasis on "what is the probability of criticality in the repository?"

4.3 Probability-Weighted Consequence Screening Based on Redefining Criticality FEPs

As discussed in Section 2, the current grouping of sixteen criticality FEPs was based primarily on location (in-package and external) and state of SNF (intact and degraded) as affected by four conditions (normal, seismic, igneous, and rockfall). Although this grouping is acceptable, a more suitable representation of criticality FEPs could be developed based on the expectations of 10 CF 63. The FEPs evaluation to support the repository performance assessment is described in 10 CFR 63.102(j) as follows:

> "*The performance assessment is a systematic analysis that identifies the features, events, and processes (i.e., specific conditions or attributes of the geologic setting, degradation, deterioration, or alteration processes of engineered barriers, and interactions between the natural and engineered barriers) that might affect performance of the geologic repository; examines their effects on performance; and estimates the radiological exposures to the reasonably maximally exposed individual*."

To develop criticality FEPs, the question that must be answered based on the quoted regulatory requirement is: is criticality a geologic attribute, a degradation process, or an alteration process? Criticality is not an attribute of the geologic setting, therefore, its correlation to geologic conditions (e.g., seismic and igneous) is not meaningful. Criticality is not a degradation or a deterioration process, therefore, its correlation to a degradation state (intact or degraded) is also not meaningful. Criticality is an alteration process; it could alter fuel composition, package chemistry, thermal conditions, etc. Therefore, criticality FEPs should be defined based on their type and alteration potential, not location and cause. In order to facilitate a criticality FEPs analysis approach based on potential impact as an alteration process, criticality FEPs could be defined as follows:

1. Momentary self-limiting criticality pulse.
2. Oscillating criticality with a defined period of oscillation as a function of water ingress rate or poison depletion.
3. Sustained non-pressurized steady-state criticality.
4. Sustained pressurized steady-state criticality.

The probability for each type of these criticality FEPs could be calculated and compared to the screening threshold (not their cumulative sum). A criticality risk curve could be developed for each of the four criticality FEPs. Only those that are consequential to repository performance with a probability higher than the screening threshold would be included in the repository performance assessment. It is expected that defensible bases and distributions could be developed for a sufficient number of parameters to demonstrate that FEPs 3 and 4 (sustained criticality events) would be of insignificant probability and FEPs and 1 and 2 (momentary or oscillating criticality events) would be of insignificant consequence, thereby, providing confidence that all criticality FEPs would be screened out from consideration in repository performance. This is illustrated in Figure 4-3 below.

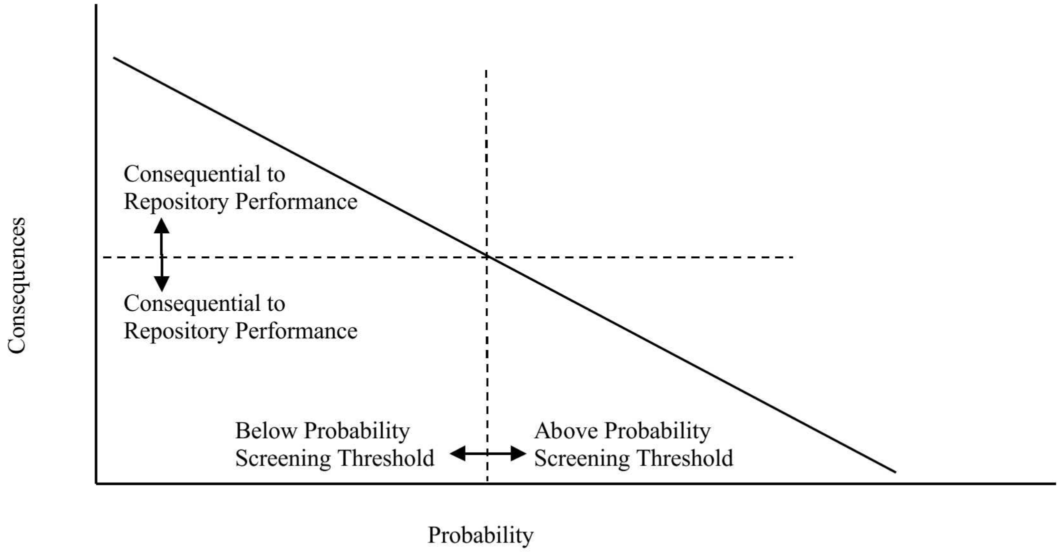

Figure 4-3. Probability-Weighted Consequence Screening of Criticality FEPs.

The basis for concluding that criticality FEPs are inconsequential to repository performance can be based on answering the following questions:

- What is the threshold of mechanical energy that would impact repository performance?
- What is the threshold of radionuclide concentration increase of those isotopes already considered in the performance assessment that would impact the dose estimate at the limiting time of release?
- What is the threshold of radionuclide concentration increase of those isotopes that are not already considered in the performance assessment (e.g., short-lived fission products)?
- What is the threshold of temperature increase that would impact repository performance. This need not be a significantly a high value given that a type 1 or type 2 criticality event may not increase system temperature by more than a few degrees, if at all.
- What is the radiolysis threshold (mainly from neutrons) that would impact waste package chemistry?

The thresholds referenced in these bullets could be deterministic values or probabilistically developed distributions (or perturbations to distributions) to match the parameters of the performance assessment. Once the above parameters have been established, the threshold of a consequential criticality as opposed to an inconsequential criticality can be determined with only two parameters, power and duration.

In order to evaluate the feasibility of this approach, simplified consequence modeling should be performed to determine the parameter thresholds to initiate a criticality, maintain it, oscillate around it, and shut it down.

5. ADDRESING REVIEW OBJECTIVES

The questions provided in Section 1.2 are addressed in this section

What is the value of accumulating as-loaded fuel data and DPC design data for the existing fleet and future additions to the fleet of DPCs?

Accumulating as-loaded fuel and DPC design data is valuable for establishing the criticality margin associated with loaded DPCs. The collected information supports two objectives:

- Calculating the criticality margin in the DPCs for the current analysis basis configurations and future repository-specific configurations. The information can eventually be used for a reasonably conservative deterministic configuration (similar to the TAD canister approach) or a probabilistic analysis as discussed in Section 4.2.
- Justifying a disposal analysis configuration based on potential degradation of the fuel basket materials.

Significant amount of data has been collected to determine a path forward. Additional data and DPC-specific analyses will be unlikely to shed new light or provide unique findings. Unless there are advancements in DPC designs that rely on different materials or methods of construction (e.g., additive manufacturing of baskets or neutron poisons), the following conclusions can be drawn regarding the remaining fleet of DPCs based on the collected and analyzed data thus far:

- For a small subset of older DPCs loaded with lower reactivity SNF, subcriticality can be demonstrated for conservative disposal configurations without consideration of neutron absorbers or baskets and with bounding misloads (e.g., the 40 DPCs at Browns Ferry). This number is not expected to increase with the analysis of more DPCs.
- For a fraction of DPC designs that use tube and disks baskets, it can be concluded that they could remain subcritical based on the basket structure remaining intact during disposal (this does represent a vulnerability due to the limited margin available and potential localized effects). The fraction of DPCs in this category may still grow because these design are still being used, but the percentage will drop because they represent a smaller fraction of manufactured canisters. The current trend is to use the same material for structural, thermal, and neutron absorbers, such as thick aluminum based baskets (e.g., METAMIC), thereby negating potential basket credit for disposal configurations.
- Limited consideration of misloads (correct SNF inventory, wrong basket locations) renders 218 of the analyzed 556 DPCs (40%) unacceptable for disposal. Analysis of additional DPCs will likely increase the unacceptable fraction based on the deterministic analysis basis configuration.
- Consideration of misloads per ISG-8, Rev. 3 (one bounding or some higher reactivity assemblies incorrectly loaded in a DPC), which will likely be required because of the limited remaining margin, 59 of the analyzed 99 DPCs (60%) are unacceptable for disposal. Analysis of additional DPCs will likely increase the unacceptable fraction based on the deterministic analysis basis configuration.

Collecting additional data and continuing to perform as-loaded DPC evaluations are important, but may not be urgent for the following reasons:

- The analysis basis configurations are speculative without a specific geology.
- It is unlikely that new information could be found based on analyzing additional DPCs. The ratio of critical DPCs under assumed analysis basis configurations may increase, but new unique findings are not anticipated.

What additional data could be collected to facilitate demonstration of disposal criticality control?

The following information would further facilitate the demonstration of disposal criticality control and bolster the viability of direct disposal of DPCs:

- Data and associated modeling to attain BWR SNF burnup credit. The data needs are discussed in detail in NUREG/CR-7194 (Marshall 2015).
- Improvements in the specificity of the GC-859 data. For example, GC-859 defines initial enrichment of the fuel assembly as the "*Average enrichment for a fresh fuel assembly as specified and ordered in fuel cycle planning. This average should include axial blankets and axially and radially zoned enrichments.*" BWR fuel typically uses a significantly larger number of radial enrichments, and a significant fraction of BWR fuel includes axial blankets.
- Depletion history for each assembly with information relevant to generating the isotopic composition of SNF. This would cover the parameters used in the burnup credit analysis (e.g., moderator density, specific power, presence of burnable poison/control rods/blades during reactor depletion).
- Presence of non-fuel hardware in the SNF assemblies (e.g., used control rod assemblies, used burnable poison rods).
- Pool SNF inventory at the time of DPC loading, which could be used in the misload analysis.
- Indication of whether BWR SNF assemblies are channeled.
- Fuel basket design information, including materials of construction, compositions, and dimensions of structural, thermal, and criticality control components. This should also include materials present within the DPC of limited amount that may promote localized degradation of the fuel baskets (e.g., galvanic effects).

What fraction of DPCs in the existing fleet is likely to be disposable with overpacks, but without other modifications? Is this likely to change significantly with future additions to the fleet?

Based on the assumed regulatory structure of 10 CFR 63, all DPCs in the current fleet and future DPCs are disposable. The key question is "what is the fraction of DPCs that could be disposable based on a given a licensing position?" which is highly dependent on the repository geology. Table 5-1 presents an estimate of the fraction of disposable DPCs for a range of disposal parameters and licensing bases. The estimate is based on an extrapolation of the results for the analyzed 556 DPCs taking into account the strengths, vulnerabilities, and recommendations discussed above.

Table 5-1. Projected Fraction of Disposable DPCs Based on Licensing Position.

Disposal parameter	Fraction of Disposable DPCs	Level of Confidence	Basis for Projection
Salt Repository	100%	High	Figure 3-1 demonstrates that a chlorine concentration well within the expected rage in a salt repository is sufficient to ensure subcriticality with minimal and easily attainable burnup credit. The only relatively minor uncertainty is associated with reactions within the disposal canister that may result in chlorine removal from solution.
Probability-weighted consequence screening of criticality FEPs from repository performance., This is the recommended approach discussed in Section 4.3.	100%	High	Criticality events would be screened from repository performance based on the following: (a) Probability-based screening of consequential criticality events that may impact dose (i.e., FEPs 2 and 3 from Section 4.3). The probability of these events would be demonstrated to be below the screening threshold of one chance in 10,000. (b) Consequence-based screening of inconsequential criticality events that would not impact dose (i.e., FEPs 1 and 2 from Section 4.3). The quantified probability of these events may be above the screening threshold.
Use of Fillers	100%	Medium-High	Use of fillers essentially guarantees that criticality can be screened out of repository performance assessment on the basis of low probability. Although promising, its viability remains unproven until demonstrated for a range of DPC baskets and SNF designs. A future deliverable will discuss fillers considerations in detail.
Screening based on a probabilistic approach. A distribution-based k_{eff} evaluation taking into account probabilistic material compositions, geometries, and moderation characteristics.	90%+	Medium	Developing distributions for all key compositional and geometry parameters is challenging, but can be accomplished with a planned concerted long-term effort. However, given the variability (current and future) in DPC designs, SNF loading configurations, reactivity, site-specific information (which may impact misload considerations), it is unlikely to demonstrate that all DPCs would be demonstrated acceptable for disposal.

Disposal parameter	Fraction of Disposable DPCs	Level of Confidence	Basis for Projection
Informing the loading of future DPCs to minimize reactivity for disposal configurations (the ISG approach discussed in Section 4.1) in conjunction with the burnup confirmation tool discussed in Section 4.	75%	Medium	The fraction is based on the fact that a significant number of DPCs have been loaded without this guidance. Additionally, there may be sites that do not have enough of the high/low reactivity assembly mix to meet all thermal, shielding, and disposal criticality needs. This option is also predicated on demonstrating that non-flooded moderated configurations pose insignificant criticality potential as discussed in Section 3.2.2. Additionally, the limited margin in the analysis basis configuration, as compared to the TAD design basis configuration may be more scrutinized.
Screening based on a deterministic design basis configurations with misloads per the deterministic considerations described in ISG-8, Rev. 3. Probabilistic consideration for overpack failure only (this is the current approach).	<50%	Medium	A significant number of DPCs could not be demonstrated subcritical with the consideration of misloads including loading of higher reactivity assemblies, not just loading of the correct SNF inventory in the wrong basket locations.
Use of an overpack with sufficiently low failure probability.	100%	Medium-Low	The probability of early waste package failure can only be lowered so much based on current manufacturing and closure processes that involve human actions. This situation may improve with advanced manufacturing techniques (e.g., additive manufacturing that does not involve welding). Additionally, failures associated with disruptive events (e.g., seismic) cannot be excluded).
Risk-based analysis with criticality included in repository performance.	100%	Medium-Low	There may be technical as well as regulatory and litigation complexities associated with the phenomenological and modeling considerations of a range of criticality events and associated impacts on repository performance, which could be unduly lengthy.

What DPC types currently in use are best/least suited for direct disposal?

The differences in DPC design are unlikely to play a significant role in their disposability. What really matters is their loading pattern and SNF reactivity. If credit is taken for the baskets under a deterministic design basis approach with limited margin for the SNF (i.e., credit specific loading pattern), the defensibility of maintaining separation between the assemblies would likely be highly scrutinized. Due to the potential for localized corrosion (e.g., galvanic, crevice), the corrosion rate of the disks that are currently credited for some DPC designs could be accelerated and may allow for a few assemblies to lose separation.

What reasonable modifications could be made in loading DPCs at the reactor sites to enhance the viability of direct disposal of DPCs?

- Burnup verification to eliminate the potential (or reduce the probability) for misload.
- Follow a criticality oriented loading map as discussed in Section 4.1 that would also meet desired thermal and shielding considerations.
- Insertion of control elements (or moderator exclusion rods) in the guide tubes of PWR SNF assemblies would essentially eliminate the potential for criticality for PWR DPCs and ensure their screening from repository performance on the basis of low probability. PWR SNF makes up ~40% of the projected number of SNF assemblies and ~60% of the projected number of DPCs. Note that control elements would not be required in all assemblies in a DPC to ensure criticality screening; selective checkerboard insertion would be sufficient. There may be some operational complications (e.g., bowing of guide tubes) that would have to be resolved for some assemblies. This approach is not viable for BWR SNF assemblies, which do not have guide tubes. BWR SNF makes up ~60% of the projected number of SNF assemblies and ~40% of the projected number of DPCs.

What effort is needed to follow through on the plan documented in Criticality Analysis Process for Direct Disposal of Dual Purpose Canisters (Scaglione et al. 2014)?

There are two primary activities that should be pursued from the criticality analysis process report:

- Probabilistic approach to determining k_{eff} as discussed in Section 4.2.
- Evaluation of the criticality parameters that would allow for differentiation between a consequential criticality, whose frequency must be determined to be below the screening threshold, and an inconsequential momentary chain reaction, whose probability may be higher than the screening threshold but can be screed out of repository performance due to “obvious” insignificance, as discussed in Section 4.3

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