# CRITICALITY ANALYSIS PROCESS FOR DIRECT DISPOSAL OF DUAL PURPOSE CANISTERS*

John M. Scaglione[1], Abdelhalim A. Alsaed[2], Robert L. Howard[1], Ernest L. Hardin[3]
[1]*Oak Ridge National Laboratory, P.O. Box 2008, MS-6170, Oak Ridge, TN 37831, USA*
*ScaglioneJM@ornl.gov*
[2]*Enviro Nuclear Services LLC, 10983 Turlington Ln, Las Vegas, NV 89135, USA*
[3]*Sandia National Laboratories, P.O. Box 5800, MS 0736, Albuquerque, NM 87185, USA*

*Dual purpose canisters (DPCs) are used for both storage and transportation of spent fuel. One of the most significant challenges associated with direct disposal of loaded DPCs is addressing criticality considerations as DPCs degrade due to corrosion or disruptive events over the postclosure period of performance (thousands of years) in a geologic repository. If future repository conditions include the potential for water ingress into the DPCs, and if the neutron absorber material efficacy in a subset of the DPCs cannot be assured under geologic disposal conditions and time frames (i.e., high corrosion rate), the probability of criticality for the repository will likely exceed the screening threshold (if similar to that in 10 CFR 63) for consideration in total system performance. Therefore, the criticality evaluation for the feasibility of direct disposal of DPCs is expected to be a risk evaluation that is predicated on the consequences of potential criticality events on repository performance. This paper discusses a DPC criticality analysis framework that can be used to evaluate potential postclosure criticality impacts on repository performance and to support the investigation of the feasibility of direct disposal of DPCs for a range of relevant repository options.*

## I. INTRODUCTION

Current U.S. spent nuclear fuel (SNF) management practices rely heavily on dry storage. Nuclear-electric utility companies are meeting interim storage needs on a case-by-case basis by using large-capacity dry storage casks. The design and implementation of dry storage systems focus mainly on meeting storage and transportation requirements in part because disposal requirements are not available. There are now approximately 2,000 storage-only and dual-purpose canisters (DPCs) for storage and transportation in service in the U.S., and deployment of new DPCs continues at a rate of approximately 200 per year.[1] Disposing of these DPCs instead of repackaging the SNF for disposal could be more cost-effective, minimize the need to repackage assembles into smaller canisters, and result in less cumulative worker dose during interim storage and handling before eventual disposal in a deep geologic repository.

Disposal of SNF in a geologic repository requires multiple natural and engineered barriers. The multiple barrier approach ensures that the overall repository system is robust and not wholly dependent on any single barrier to ensure repository safety. Features, events, and processes (FEPs), as well as sequences of FEPs that might affect the repository, are examined when evaluating repository performance. In a previous geologic disposal licensing analysis,[2] criticality was considered an event with the potential to affect repository performance. During the repository evaluation process, FEPs that can affect repository performance were screened for inclusion or exclusion based on a low-probability criterion, a low-consequence criterion, or by regulation. A general methodology for addressing postclosure criticality was implemented, and it was demonstrated that criticality could be excluded from repository performance considerations on the basis of low probability of occurrence. The robust performance specifications and associated loading requirements for the transportation, aging, and disposal (TAD) canisters were key aspects of the design that supported the low probability determination. For example, the TAD canister internals were identified as items important to waste isolation solely due to their capability to reduce the probability of criticality. Because TADs had not been fully designed, licensed, or deployed, they provided a level of flexibility for reducing criticality potential that currently deployed DPCs do not possess (i.e., the TAD canister design and basket materials were selected based on specific geologic disposal conditions to meet repository requirements).

Reliance on the low-probability criterion in potential future evaluations of direct disposal of currently loaded DPCs presents a number of challenges. Most importantly, existing DPCs were not designed, licensed, or loaded with consideration of geologic disposal conditions and requirements. Therefore, the DPCs may not have the same

*Notice: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy. 

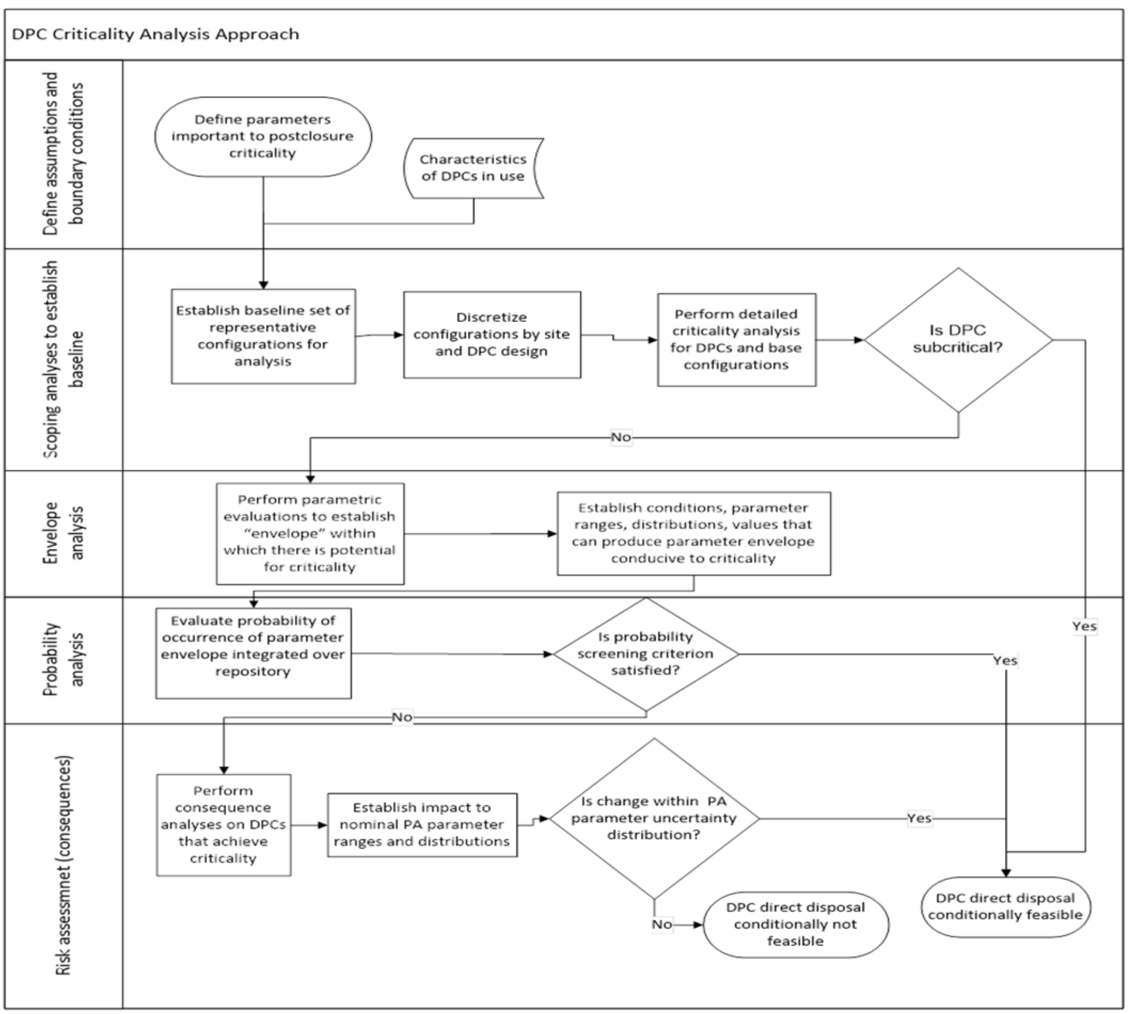
performance capabilities to enable the low probability determination for postclosure criticality. Of particular relevance to criticality, currently loaded DPC basket structures and neutron absorber materials were not designed to maintain their efficacy under geologic disposal conditions and time frames. This does not mean that DPCs cannot meet disposal objectives, but rather that some options are more limited, and additional reliance on other barrier functions or aspects may be necessary to demonstrate acceptable repository system performance.

This paper outlines an approach evaluating the potential for and consequences of criticality in DPCs under geologic disposal conditions and time frames. Evaluation(s) are intended to support a larger effort to understand and assess the feasibility of direct disposal of DPCs containing commercial SNF in a geologic repository. The goal of this approach is to provide a framework to address postclosure criticality risk to facilitate direct disposal of existing DPCs for a range of relevant repository options.

## II. ANALYSIS PROCESS

The criticality analysis process for direct disposal of DPCs is presented in Fig. 1. The process for performing disposal criticality analyses takes into consideration the following:

(1) Evaluation of the probability of event sequences that could end in critical configurations. This evaluation would consider geology- and DPC-specific parameters for development of probabilistic degradation scenarios, and it would account for the reactivity margin based on DPC-specific information (as opposed to DPC design-basis certificates of compliance for transportation). This evaluation allows for tailoring the analysis approach for different DPC types and geologic settings.




PA = performance assessment

Fig. 1. Illustration of criticality analysis process for direct disposal of DPCs.

(2) Evaluation of the consequences of potential criticality events and associated impacts on relevant geologic repository parameters important to repository performance. The probabilities and consequences of potential criticality events would be used as input into the overall repository performance assessment (PA) and evaluated along with other potential risks. This is accomplished through the development of probability-weighted consequences of interest to parameters important to repository performance, such as thermal effects and changes in radionuclide inventory through fission and activation.

## II.A PROBABILITY ANALYSIS

The first step in the analysis process is to **define assumptions and boundary conditions** relevant to postclosure criticality evaluations. This would include reviewing existing population of DPCs and binning them based on common characteristics relevant to criticality analysis, including SNF type, design, neutron absorber materials, and basket structure. Current assumptions include the following:

(1) The disposal regulatory structure will be similar to 10 CFR 63 that allows for screening of FEPs or consideration in total system performance with an analysis period limited to 10,000 years. The basis for this assumption is that the generic health standard for mined geologic disposal (40 CFR 191) from the U.S. Environmental Protection Agency (EPA) is still in force and could in principle be applied to future repositories. The 10 CFR 60 rule is still applicable to any geologic repository other than at Yucca Mountain, and it was not revised when fundamental changes were made to PA requirements in the promulgation of 10 CFR Part 63. In particular, the Nuclear Regulatory Commission (NRC) has evolved from disposal subsystem requirements (e.g., engineered barrier system [EBS] containment) to rely on mean annual dose computed from total system PA (TSPA). Consequently, when promulgating 10 CFR 63, NRC documentation specified the "generic Part 60 requirements will need updating." [3,4] Furthermore, NRC has held that regulations for future repositories would likely be similar to 10 CFR 63 in presentations to the Blue Ribbon Commission on America's Nuclear Future (BRC) and the Nuclear Waste Technical Review Board (NWTRB).

(2) All DPCs will be placed in an overpack prior to disposal. The basis for this assumption is that the overpack provides two primary functions—(1) standardization for repository operations, including placement, conveyance, and shielding; and (2) a principal waste containment barrier that also serves to reduce the probability of water ingress into the DPC.

(3) SNF characteristics are based on full burnup credit that includes actinides and fission products consistent with the approach developed for the previous repository effort that included credit for 29 principal isotopes as follows:

| | | | | |
|---|---|---|---|---|
| $^{95}Mo$ | $^{145}Nd$ | $^{151}Eu$ | $^{236}U$ | $^{241}Pu$ |
| $^{99}Tc$ | $^{147}Sm$ | $^{153}Eu$ | $^{238}U$ | $^{242}Pu$ |
| $^{101}Ru$ | $^{149}Sm$ | $^{155}Gd$ | $^{237}Np$ | $^{241}Am$ |
| $^{103}Rh$ | $^{150}Sm$ | $^{233}U$ | $^{238}Pu$ | $^{242m}Am$ |
| $^{109}Ag$ | $^{151}Sm$ | $^{234}U$ | $^{239}Pu$ | $^{243}Am$ |
| $^{143}Nd$ | $^{152}Sm$ | $^{235}U$ | $^{240}Pu$ | |

Note that the burnup credit methodology for pressurized water reactor (PWR) SNF is widely accepted (e.g., Interim Staff Guidance [ISG] 8 Rev. 3, NUREG/CR-7108 and -7109).[5,6,7] However, the boiling water reactor (BWR) SNF burnup credit approach needs further refinement in analysis and the acquisition of additional data.

When burnup credit is relied upon in the criticality analysis, the potential for SNF assembly misload must be considered. Consideration of SNF assembly misload is consistent with the guidance in ISG-8 Rev 3 for storage and transportation of SNF when burnup levels had not been verified via measurement prior to loading. Additionally, consideration of misloads was required for the previous repository licensing analyses. Therefore, potential SNF assembly misloads will be considered in the criticality analysis process for direct disposal of DPCs, which could be included in the parametric envelope or probability analyses discussed below.

The next step involves performance of **scoping analyses to establish a baseline** with representative loaded DPCs for understanding key parameters and sensitivities. Configurations representative of different degraded states are analyzed. These configurations will identify DPC design attributes that may impede/promote the formation of certain degraded configurations and identify a subset of DPCs that (1) do not have potential for criticality, and (2) do not need to be considered further; albeit, this is expected to be a small fraction. Baseline configurations consist of three primary configurations for initial scoping analyses that would be expected to bound the majority of credible configurations considered under geologic disposal conditions:

(1) nominal, as-designed configuration with as-loaded contents,

(2) intact basket with complete loss of absorber plates, and

(3) intact basket for DPCs with stainless steel baskets, degraded basket/encapsulated fuel cells for DPCs with baskets made of other materials (complete loss of basket structure).

Discussions on some of the initial scoping analyses and results are provided in separate papers.[8, 9]

The DPCs will remain subcritical unless certain combinations of events and physical changes to the system occur. To determine the potential for criticality in a DPC or a group of DPCs, a parameter **envelope analysis** must be conducted to evaluate the criticality control parameters relevant to direct disposal of DPCs to understand the impacts of key parameters and sensitivities on system reactivity (both positive and negative). In general, the key parameters important for any criticality analysis are:

(1) SNF characteristics including fuel design and composition at emplacement and physiochemical changes due to degradation;
(2) neutron absorbers (both present in the canisters or introduced during disposal);
(3) geometry of the SNF, fuel baskets, and neutron absorbers over time;
(4) moderation; and
(5) reflection.

Other criticality control parameters traditionally considered in criticality safety (e.g., mass, density, enrichment, concentration, interaction) are subsumed into the five parameter groups summarized above. The product from these parametric evaluations will be the establishment of parameter envelopes within which there is potential for criticality.

Based on generic disposal geology information and material degradation processes, the event sequences that could end in one or more of the configurations within the parameter envelope with potential for criticality would be constructed. These event sequences, including the associated initiating and pivotal events, would be considered in the **probability analysis** integrated over the repository.

The determination of the probability of a sequence of events—for which the end states violate the envelope of parameters important to criticality—is strongly dependent upon two primary attributes:

1. the specific DPC design, and
2. the characteristics of the host geology.

Although the architecture of the probability evaluation can be initially developed, the probabilistic distributions accounting for the parameters discussed above cannot be fully developed until a specific repository geology is selected and fully characterized. However, even without a selected and fully characterized repository geology, an uncertainty quantification (UQ) analysis can be performed to evaluate the overall importance of certain parameters. This allows initial screening evaluations to be performed to assess DPC disposal feasibility.

### II.B. CRITICALITY CONSEQUENCES

The consequences of a criticality event in the repository are highly dependent upon the type of event and configuration. Potential criticality consequences in a geologic setting have been previously evaluated.[10,11,12,13,14,15] However, the focus of each of these evaluations was broader than DPCs with assumptions intended to maximize the consequences. The criticality consequence scoping methodology discussed in this section is informed by previous analyses, but it aims to provide a realistic range of consequences considering more feedback parameters that could impact system kinetics than was previously possible because of the more focused analysis objectives and improved computational capability.

The primary attributes of a criticality event in a DPC are characterized by the following:

- **Thermal**. Because the SNF enrichment in DPCs is limited to 5 wt %, only a thermal criticality and associated consequences are of relevance to direct disposal of DPCs; there is no potential for a fast criticality.
- **Under- or optimally moderated**. Because the only path for a criticality event in a DPC is through the introduction of water, before a critical over-moderated condition could occur, a criticality would have occurred at under-moderated or optimally moderated conditions. Once a critical configuration is formed, it will start to immediately reduce system moderation by increasing water temperature. This in turn increases evaporation and reduces water density. Although hypothetically conjecturable for a very brief period of time (e.g., system collapse into an over-moderated configuration), under-moderated or optimally moderated conditions would be the more likely configuration to lead to a criticality event in a DPC.
- **Quasi-steady-state.** Because DPCs must be breached to allow for water ingress, and thus there is no potential for over-pressurization, and because DPCs do not have significant excess reactivity to be inserted rapidly due to the presence of baskets, fixed neutron absorbers, and neutron poisons in the depleted SNF, a quasi-steady-state criticality is the primary type with potential for occurrence. A rapid transient criticality event associated with a rapid reactivity insertion rate, along with a rapid increase in neutron density and power generation rate in a non-pressurized thermal under- or optimally moderated DPC, is not plausible. Additionally, the rapid transient event, if it were to occur, would be short-lived due to changes in geometry (caused by the kinetic energy of the event),

reduced water density (due to heating), and Doppler broadening. With geometry changes, the potential for forming another critical configuration in the same DPC would become remote. Reactivity insertion analyses based on actual DPC designs, SNF loading, and corrosion characteristics must be performed to support the discussion regarding the limited potential for a significant rapid transient criticality event in a disposed DPC.

An under- or optimally moderated thermal quasi-steady-state criticality in a DPC would oscillate between critical and subcritical as a direct function of the following:

1. water flow rate,
2. water density (if repository is pressurized),
3. fuel temperature,
4. generation rate of neutron poisons through fission and neutron absorption,
5. depletion of fissile material,
6. decay of fissile material, and
7. decay of neutron absorbers into fissile material.

Items 6 and 7 only need to be considered if the criticality analyses are not based on peak SNF reactivity during the disposal time period.

Ultimately the consequence of the actual criticality event is measured with respect to impact on repository performance, which is dependent upon a variety of features, events, and processes. The primary parameters of repository performance with relevance to criticality event(s) and that can be impacted by these events in DPCs are:

1. radionuclide inventory,
2. water flow rates and distribution, which are correlated to thermal power of disposed waste, and
3. chemistry inside DPCs, which is correlated to temperature and radiolysis

An under- or optimally moderated thermal quasi-steady-state criticality event in a DPC could impact these three primary repository performance parameters with the following consequences:

1. **Radionuclide inventory changes**. The radionuclide inventory in a DPC can increase during a criticality event due to fission and neutron activation, which would introduce short-lived fission products that otherwise would not be considered for geologic disposal. Additionally, some of the newly generated elements could have an impact on waste package chemistry.
2. **Thermal effects.** Increase in thermal output in a DPC could impact water flow through the repository and waste containers. Additionally, increased temperatures during a criticality could influence DPC chemistry affecting corrosion rates, formation of chemical species, mineral solubility, etc.
3. **Radiolysis.** A criticality event could increase radiolysis, which could influence DPC chemistry affecting corrosion rates, formation of chemical species, mineral solubility, etc.

The consequences of a criticality event(s) are a function of several factors, but they are strongly tied to water flow rates into and out of the DPC. Because the DPC conditions such as thermal output and the magnitude and duration of the criticality event are coupled with repository geology behavior, there is an iterative feedback between water flow rate in a DPC and thermal output. This could be further complicated for pressurized repository geologies. To determine the extent of coupling between in-DPC criticality events and repository geology, a scoping parametric evaluation must first be conducted to determine the oscillatory period of criticality in a DPC as a function of flow rate and water density (which is a function of temperature and pressure) for both pressurized and unpressurized repository geologies.

Any repository total system performance would be based on a set of parameters that are a combination of deterministic considerations and probabilistic distributions. Many of these key parameters are a function of time (e.g., waste heat output and radionuclide inventory). Repository geology characteristics are also a function of time and are perturbed by events that are correlated to time (e.g., seismicity). Because many key repository performance characteristics are time-based, the perturbations of these parameters due to a potential criticality event in a DPC must also be time based. A criticality event is not possible unless water pools inside a DPC; therefore, the correlation between time and the criticality-induced perturbation can be simplified by considering these perturbations at any time during the repository performance period past the point at which pooling inside a DPC is possible. For example, this can occur at any point in time at which liquid water can exist inside a DPC.

These probability-weighted criticality consequence perturbations must be developed in a similar fashion as the perturbed parameter important to repository performance (e.g., radiological inventory, water flow rate, water chemistry), as illustrated in Fig. 2. If the perturbed geologic repository parameter is a conservative value or a simple range (i.e., uniform distribution), the criticality-induced perturbation would be considered only if the perturbation is not bounded by the value or distribution considered for the geologic repository.

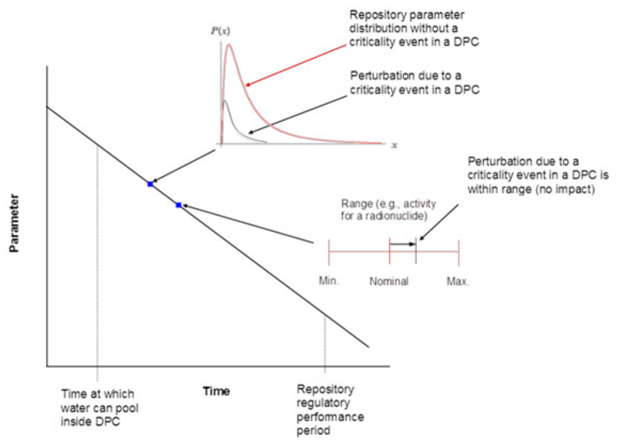



Fig. 2. Illustration of consideration of criticality consequences on PA parameters.

## III. SUMMARY

This paper discusses an analysis framework for the evaluation of postclosure criticality risks to facilitate the investigation of the feasibility of direct disposal of DPCs for a range of relevant repository options. The framework for the probability of criticality analysis process considers geologic and DPC-specific parameters for development of probabilistic degradation scenarios, and it accounts for the reactivity margin based on DPC-specific information (as opposed to DPC design-basis certificates of compliance for transportation). This evaluation allows for tailoring the analysis approach for different DPC types and geologic settings. The framework for the criticality consequences analysis process focuses on evaluating impacts to relevant geologic repository parameters important to overall repository performance. The probabilities and consequences of potential criticality events would need to be used as input into the overall repository PA and evaluated along with other potential risks.

Although considerable data, technical work, selection of a geologic repository, and a regulatory framework are required to support a licensing determination, the process described for addressing criticality with respect to directly disposed DPCs can be implemented by the discussed framework for evaluating likelihood of criticality occurrence and potential impacts on key repository performance parameters.

## ACKNOWLEDGMENTS

This work is part of a collaborative effort between Oak Ridge National Laboratory and Sandia National Laboratory funded by the United States Department of Energy Office of Nuclear Energy.

## REFERENCES


1. Ux Consulting 2014. “Store Fuel.” V.15, N.190. (2014).
2. DOE (US Department of Energy). *Yucca Mountain Repository License Application for Construction Authorization*. DOE/RW-0573 (2008). Washington, D.C.: U.S. Department of Energy.
3. Rubenstone, J. 2012. "Emerging regulatory challenges in the management of spent nuclear fuel and high-level radioactive waste." *The Bridge*. National Academy of Engineering. 42(2):32-9.
4. NRC (U.S. Nuclear Regulatory Commission). 2001. *10 CFR Parts 2, 19, 20, 21, etc.: Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada; Final Rule.* Federal Register 2001;66(213):55732-816. U.S. Nuclear Regulatory Commission.
5. NRC (U.S. Nuclear Regulatory Commission), “Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks,” Interim Staff Guidance 8, Rev. 3, Division of Spent Fuel Storage and Transportation (2012).
6. G. RADULESCU, I.C. GAULD, G. ILAS, AND J. C. WAGNER, “An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Isotopic Composition Predictions,” NUREG/CR-7108 (ORNL/TM-2011/509), prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, TN(2012).
7. J. M. SCAGLIONE, D. E. MUELLER, J. C. WAGNER, AND W. J. MARSHALL, “An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Criticality ($k_{eff}$) Predictions,” NUREG/CR-7109 (ORNL/TM-2011/514), prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, TN (April 2012).
8. K. BANERJEE, J. SCAGLIONE, AND J. CLARITY, “Disposability of Loaded US Dual-Purpose Canisters from a Criticality Standpoint,” *Proc. International High-Level Radioactive Waste Management Conference*, Charleston, South Carolina April 12–16, 2015.
9. E. HARDIN, et al., “A Case For Direct Disposal of SNF in Existing DPCs – *12266, Proc. International High-Level Radioactive Waste Management Conference*, Charleston, South Carolina April 12–16, 2015.
10. J.A. MCCLURE, “Consequence Analysis of Transient Criticality Internal to a Codisposal Waste Package Containing Intact FFTF SNF Pins,” ANL-EDC-NU-000002 REV A, U.S. Department of Energy Office of Civilian Radioactive Waste Management System, Las Vegas, Nevada, CAL-DS0-NU-000001 (2002).

11. J.A. MCCLURE, “Sensitivity Study of Reactivity Consequences to Waste Package Egress Area,” CAL-EBS-NU-000001 REV 00, U.S. Department of Energy Office of Civilian Radioactive Waste Management System, Las Vegas, Nevada (1999).
12. J.A. MCCLURE, “Criticality Consequence Calculation Involving Intact PWR MOX SNF in a Degraded 21 PWR Assembly Waste Package,” CAL-EBS-NU-000008 REV 00, U.S. Department of Energy Office of Civilian Radioactive Waste Management System, Las Vegas, Nevada (1999).
13. J.A. MCCLURE AND J.R. WORSHAM III, “Criticality Consequence Analysis Involving Intact PWR SNF in a Degraded 21 PWR Assembly Waste Package,” BBA000000-01717-0200-00057 REV 00, U.S. Department of Energy Office of Civilian Radioactive Waste Management System, Las Vegas, Nevada (1997).
14. P. GOTTLIEB, J.W. DAVIS, AND J.R. MASSARI, “Probabilistic Criticality Consequence Evaluation” (SCPB: N/A), BBA000000-0 1717-0200-00021 REV00, U.S. Department of Energy Office of Civilian Radioactive Waste Management System, Las Vegas, Nevada (1996).
15. J.A. MCCLURE, “Steady-State Criticality Consequence Model Report,” CAL-DS0-NU-000001 REV 00A, U.S. Department of Energy Office of Civilian Radioactive Waste Management System, Las Vegas, Nevada (2005).