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Preclosure Criticality Safety Analysis

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11. Revision No.	12. Description of Change
01	Revision 01 This is a revision of and supersedes *Preclosure Criticality Safety Analysis,* TDR-MGR-NU-000002 REV 00 to incorporate external review comments and changes from criticality validation calculations in order to confirm a number of assumptions requiring verification.
00	Initial Issue

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ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
ANS	American Nuclear Society
BWR	boiling water reactor
CAAS	Criticality Accident Alarm System
CRCF	Canister Receipt and Closure Facility
CSNF	commercial spent nuclear fuel
DOE	U.S. Department of Energy
DPCs	dual purpose canisters
EROA	extension of range of applicability
HLW	high-level waste
GROA	geologic repository operations area
IHF	Initial Handling Facility
k_{eff}	effective neutron multiplication factor
LLW	low-level waste
NRC	U.S. Nuclear Regulatory Commission
PCSA	Preclosure Safety Analysis
PWR	pressurized water reactor
ROP	range of parameters
SAR	Safety Analysis Report
SNF	spent nuclear fuel
SSC	structures, systems, and components
STC	shielded transfer cask
TAD	Transportation, Aging and Disposal
TRIGA	Training, Research, and Isotope General Atomics
USL	upper subcritical limit
WVDP	West Valley Demonstration Project
WHF	Wet Handling Facility
WP	waste package

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1. INTRODUCTION

The means to prevent and control criticality must be addressed as part of the Preclosure Safety Analysis (PCSA) required for compliance with 10 CFR Part 63 [DIRS 180319], where the preclosure period covers the time prior to permanent closure activities. This technical report presents the nuclear criticality safety evaluation that documents the achievement of this objective.

This report is the primary preclosure criticality safety reference for the License Application and it is structured as described below to allow for direct correlation with the content in the License Application.

- Section 2.1 presents the preclosure criticality safety regulatory requirements and the project criteria applied to address those requirements
- Section 2.2 describes the analysis process implemented to comply with the project criteria
- Section 2.3 presents the detailed criticality safety analysis including a summary of the waste forms and their packaging (Section 2.3.1), a discussion of criticality control parameters (Section 2.3.2), and the criticality safety evaluation for each of the seven facilities in which fissile material could be present (Initial Handling Facility (IHF), Receipt Facility (RF), Canister Receipt and Closure Facility (CRCF), Wet Handling Facility (WHF), Intrasite Operations including Aging Facility, Low-Level Waste Facility, and Subsurface Facility (Sections 2.3.3 through 2.3.9)
- Section 2.3.10 defines the Criteria to Establish Subcriticality and provides the justification of the administrative margin to ensure subcriticality
- Section 2.3.11 presents the evaluation of the need for a criticality accident alarm system (CAAS)
- Section 2.3.12 discusses offsite operations and their impact on preclosure criticality safety

1.1 PURPOSE AND SCOPE

The purpose of this technical report is to document the application of the process described in *Preclosure Criticality Analysis Process Report* (BSC 2008 [DIRS 182214]) and present the nuclear criticality safety evaluation of waste forms and repository facilities for the time period beginning with waste form receipt at the Geologic Repository Operations Area (GROA) and ending at permanent closure of the Subsurface Facility. The information presented in this report is not design information that can be used to support procurement, fabrication, or construction.

The scope of this technical report is the complete preclosure criticality safety analysis for various configurations of waste forms that could occur during the preclosure period as a result of normal receipt, loading, staging, and emplacement operations or from event sequences representing off-normal conditions. The repository is designed to receive, package, and emplace canistered commercial spent nuclear fuel (SNF), uncanistered commercial SNF (CSNF), canistered high-level waste (HLW), and canistered U. S. Department of Energy (DOE) SNF. The analysis is performed for all processes starting with the receipt of transportation casks containing canistered HLW and SNF or uncanistered SNF; including the transfer of bare CSNF assemblies into canisters, aging of canistered CSNF, loading of canisters into waste packages (WPs) for closure and emplacement in the subsurface; and concluding with waste package residence in the subsurface facilities up to the time of permanent closure of the repository.

The preclosure criticality safety analysis presented in this report is commensurate with the level of design (facilities and waste form packaging) and operational detail available at the time of issuance of this technical report.

Naval SNF criticality safety analysis, including interaction with other waste forms, is not included in the scope of this technical report.

1.2 QUALITY ASSURANCE

This technical report documents the criticality safety analysis for waste forms and repository facilities prior to permanent closure of the repository. This activity is subject to *Quality Management Directive* (BSC 2007 [DIRS 184673]), and the records designator for this report is noted as QA:QA. The development of this report is controlled by PA-PRO-0313, *Technical Reports,* and LS-PRO-0201, *Preclosure Safety Analyses Process*.

1.3 USE OF COMPUTER SOFTWARE

No computer software subject to *Quality Management Directive* (BSC 2007 [DIRS 184673]) was used in the development of this report.

However, the MCNP code (MCNP V. 4B2LV, STN: 10437-4B2LV-00 [DIRS 163407]) was used in the supporting calculations (BSC 2007 [DIRS 182099], BSC 2008 [DIRS 182100], and BSC 2007 [DIRS 182101]) discussed in Section 2.2.2.1 to calculate the effective neutron multiplication factor k_{eff} for various waste form configurations. The MCNP code is described in *MCNP-A General Monte Carlo N-Particle Transport Code* (Briesmeister 1997 [DIRS 103897]).

1.4 ASSUMPTIONS THAT REQUIRE VERIFICATION

1.4.1 Transportation, Aging, and Disposal Canister Dimensions and Materials

Assumption–Certain dimensions and materials of construction of the transportation, aging, and disposal (TAD) canister are not explicitly defined in *Transportation, Aging and Disposal Canister System Performance Specification* (DOE 2007 [DIRS 181403]) and have been assumed in order to perform the analysis herein. These assumed values are noted in Table 1 for the PWR TAD canister and Table 2 for the BWR TAD canister. Cross sectional views of the PWR and BWR TAD canisters are shown in Figure 1 and Figure 2, respectively.

The following discussion describes the TAD canisters, their internal basket configurations, and their representation in the calculations supporting this safety analysis.

Section 3.1.5(2)a of the performance specification (DOE 2007 [DIRS 181403]) includes the following requirements for TAD canister internals:

- Neutron absorber plates or tubes made from borated stainless steel…

- Minimum thickness of neutron absorber plates shall be 0.433 in.…Multiple plates may be used if corrosion assumptions (250 nm/year) are taken into account [sic] for all surfaces such that 6 mm remains after 10,000 years.
- The neutron absorber plate shall have a boron content of 1.1 wt% to 1.2 wt%...
- Neutron absorber plates or tubes shall extend along the full length of the active fuel region inclusive of any axial shifting of the assemblies within the TAD canister.
- Neutron absorber plates or tubes must cover all four longitudinal sides of each fuel assembly.

These design criteria for the borated stainless steel absorber plates allow for many variations. The calculations supporting this analysis used the following parameters:

- An arrangement was selected that includes fuel compartments with borated stainless steel panels on all four sides of each compartment, with a gap (flux trap) between adjacent compartments, similar to existing transportation cask designs.
- The thickness of the individual panels is based on a minimum required thickness of 0.6 cm after 10,000 years given a corrosion rate of 250 nm/year applied to each surface. For two panels between adjacent fuel assemblies there would be four surfaces resulting in the need for an additional 1 cm of total thickness to account for corrosion (250×10^{-9} m/year-surface ×10,000 years × 4 surfaces × 100 cm/m). This gives a total minimum thickness of two panels between adjacent fuel assemblies of 1.6 cm. Therefore, the minimum thickness of an individual panel is modeled here as 0.8 cm.
- The boron content was conservatively selected to be 1.1 wt%.
- The basket height is modeled as the interior height of the TAD canister.

Table 1. Design Parameters Considered for PWR TAD Canister Model

Design Parameter	MCNP Model		Design Criteria
TAD Canister Body			
Outer diameter of TAD canister	66.0 in.	167.64 cm	66.0 in. (min), 66.5 in. (max)
Inner diameter of TAD canister(1)	65.0 in.	165.10 cm	No specific criteria
Outer length/height of TAD canister	211.5 in.	537.21 cm	211.5 in. (min), 212.0 in. (max)
TAD canister spacer(1)	Not modeled		Required for TAD canisters less than 211.5 in. in height.
Inner length/height of TAD canister(1)	210.5 in.	534.67 cm	No specific criteria
TAD canister base thickness(1)	0.5 in.	1.27 cm	No specific criteria
TAD canister lid thickness(1)	0.5 in.	1.27 cm	No specific criteria
TAD Canister Basket Structure			
Number of fuel assembly compartments	21		21
Inner width of fuel assembly compartment(1)	9.0 in.	22.86 cm	No specific criteria
Compartment inner wall thickness(1)	0.1875 in.	0.48 cm	No specific criteria
Compartment borated stainless steel panel arrangement	4 panels around each compartment with a flux trap between		Panels must surround all four longitudinal sides of fuel assemblies
Compartment borated stainless steel panel thickness	0.3150 in.	0.8 cm	6 mm left after 10,000 yr 250 nm/yr of corrosion for every surface
Basket height	Same as assembly height		The BSS plates are required to cover the entire active fuel region plus an allowance for any axial shift in the fuel assemblies
Compartment outer wall thickness(1)	0.1875 in.	0.48 cm	No specific criteria
Outer width of fuel assembly compartment(1)	10.38 in.	26.37 cm	No specific criteria
Spacing between compartments (surface-to-surface) (1)	0.0 in. - 0.91 in.	0 - 2.32 cm	No specific criteria
Axial placement of fuel in TAD canister	Fuel modeled to sit directly on the inside bottom of TAD canister		No specific criteria

NOTES: (1) These values are assumed.
BSS = borated stainless steel; max = maximum; min = minimum; yr = year

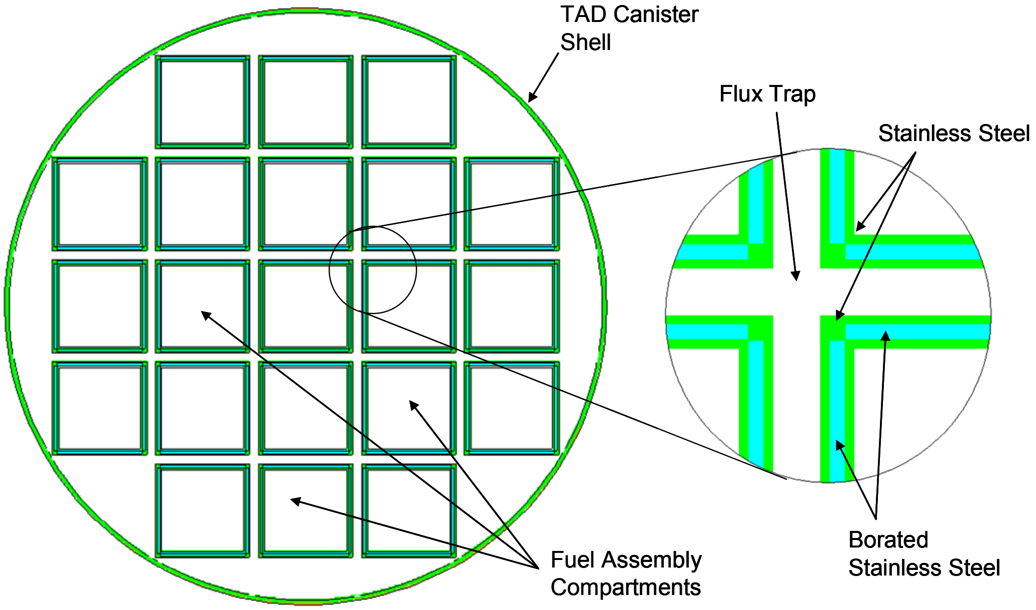
Source: Adapted from Table 1, BSC 2007 [DIRS 182099] and Table 7, BSC 2007 [DIRS 182101].

Table 2. Design Parameters Considered for BWR TAD Canister Model

Design Parameter	MCNP Model		Design Criteria
TAD Canister Body			
Outer diameter of TAD canister	66.0 in.	167.64 cm	66.0 in. (min), 66.5 in. (max)
Inner diameter of TAD canister(1)	65.0 in.	165.10 cm	No specific criteria
Outer length/height of TAD canister	211.5 in.	537.21 cm	211.5 in. (min), 212.0 in. (max)
TAD canister spacer(1)	Not modeled		Required for TAD canisters less than 211.5 in. in height.
Inner length/height of TAD canister(1)	210.5 in.	534.67 cm	No specific criteria
TAD canister base thickness(1)	0.5 in.	1.27 cm	No specific criteria
TAD canister lid thickness(1)	0.5 in.	1.27 cm	No specific criteria
TAD Canister Basket Structure			
Number of fuel assembly compartments	44		44
Inner width of fuel assembly compartment(1)	6.0 in.	15.24 cm	No specific criteria
Compartment inner wall thickness(1)	0.125 in.	0.32 cm	No specific criteria
Compartment borated stainless steel panel arrangement	4 panels around each compartment with a flux trap between		Panels must surround all four longitudinal sides of fuel assemblies
Compartment borated stainless steel panel thickness	0.3150 in.	0.8 cm	6 mm left after 10,000 yr 250 nm/yr of corrosion for every surface
Basket height	Same as assembly height		The BSS plates are required to cover the entire active fuel region plus an allowance for any axial shift in the fuel assemblies
Compartment outer wall thickness(1)	0.125 in.	0.32 cm	No specific criteria
Outer width of fuel assembly compartment(1)	7.13 in.	18.11 cm	No specific criteria
Spacing between compartments (surface-to-surface) (1)	0.0 in. - 0.58 in.	0 – 1.48 cm	No specific criteria
Axial placement of fuel/basket in TAD canister	Fuel/basket modeled to sit directly on the inside bottom of TAD canister		No specific criteria

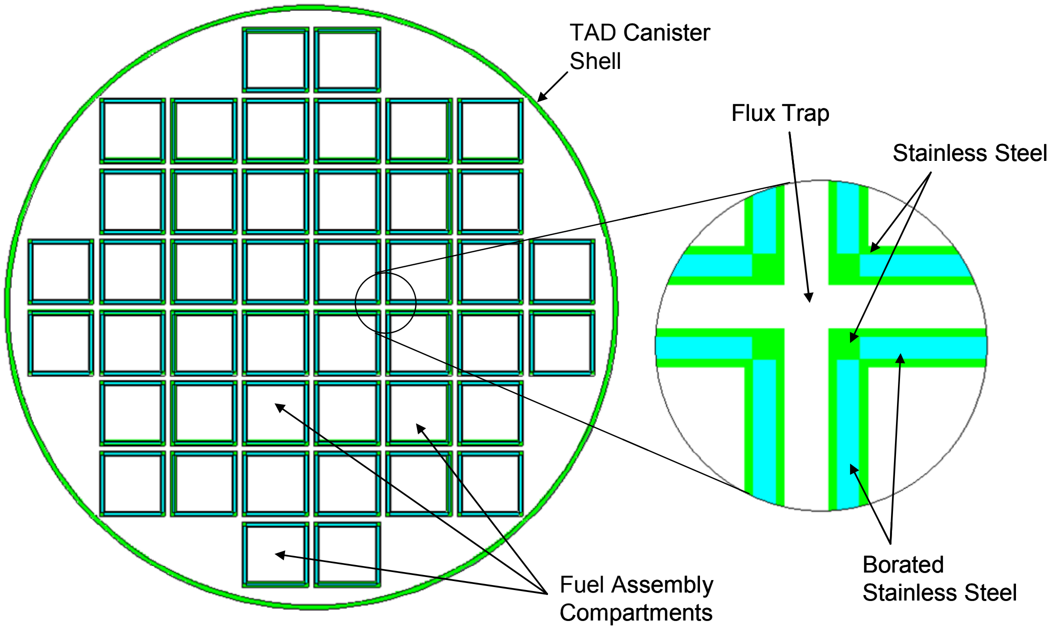
NOTES: (1) These values are assumed.
yr = year; BSS = borated stainless steel; max = maximum; min = minimum

Source: Adapted from Table 2, BSC 2007 [DIRS 182099] and Table 8, BSC 2007 [DIRS 182101].



Source: Figure 2, BSC 2007 [DIRS 182099].

Figure 1. Horizontal Cross Section of Basic PWR TAD Canister Model



Source: Figure 6, BSC 2007 [DIRS 182099].

Figure 2. Horizontal Cross Section of Basic BWR TAD Canister Model

Rationale–Knowledge of the dimensions and internal arrangement was necessary to perform the supporting calculations. The assumed dimensions and internal arrangement modeled are compliant with the requirements of *Transportation, Aging and Disposal System Performance*

Specification (DOE 2007 [DIRS 181403]), and are similar to those used in the design of existing transportation casks.

Use in the Report – The assumed dimensions and internal arrangement were used in the TAD canister and basket MCNP [DIRS 163407] models in the supporting calculations (BSC 2007 [DIRS 182099] and BSC 2007 [DIRS 182101]). Therefore, this assumption is fundamental to the results discussed in Section 2.3.

Confirmation Status–The dimensions and internal arrangement of the TAD canisters and baskets must be verified to be bounding or k_{eff} calculations and safety analyses must be performed using dimensions and arrangements from DOE-accepted TAD canister designs.

1.4.2 Moderation Event Sequences for Dry Operations

Assumption–It is assumed that no Category 1 or Category 2 event sequence will result in introduction of moderator inside breached or open a) transportation casks containing uncanistered SNF or b) canisters containing SNF for all dry operations in the IHF, RF, CRCF, WHF (outside of the pool only), intrasite operations including the Aging Facility, and the Subsurface Facility.

Rationale–Moderation is the primary criticality control parameter for all dry canister operations in the GROA. Therefore, moderation is required to be controlled such that no Category 1 or Category 2 event sequence will result in moderator introduction inside breached or open transportation casks or canisters in order to comply with the preclosure criticality safety requirement as stated in Section 2.1.3.

Use in the Report–This assumption is used in Sections 2.2.2.2 and 2.3.

Confirmation Status–This assumption requires confirmation by analysis. The analysis will demonstrate that no Category 1 or Category 2 event sequence will result in moderator introduction inside breached or open transportation casks, canisters, or waste packages for all dry operations in the IHF, RF, CRCF, WHF (outside of the pool only), intrasite operations including the Aging Facility, and the Subsurface Facility.

1.4.3 Interaction between DOE SNF Canisters

Assumption–It is assumed that no Category 1 or Category 2 event sequence will result in placing more than four DOE SNF canisters in close proximity outside of their designated staging racks or a codisposal waste package.

Rationale–Interaction is a required criticality control parameter for operation with dry DOE standardized SNF canisters in the GROA. Therefore, interaction must be controlled such that no Category 1 or Category 2 event sequence will result in placing more than four DOE standardized SNF canisters in close proximity outside of their designated staging racks or a codisposal waste package in order to comply with the preclosure criticality safety requirement as stated in Section 2.1.3.

Use in the Report–This assumption is used in Sections 2.2.2.2 and 2.3.5.3.2.

Confirmation Status–This assumption requires confirmation by analysis. The analysis will demonstrate that no Category 1 or Category 2 event sequence will result in placing more than four DOE standardized SNF canisters outside of their designated staging racks or a codisposal waste package.

1.4.4 Boron Dilution Event Sequences for Wet Operation in the WHF

Assumption–It is assumed that no Category 1 or Category 2 event sequence will result in boron dilution that will lower the soluble boron (enriched to 90 atom % ^{10}B) concentration in the WHF pool or transportation cask/DPC fill water to a value that is insufficient to maintain subcriticality.

Rationale–Soluble boron (enriched to 90 atom % ^{10}B) is the primary criticality control parameter for all wet operations in the WHF. Therefore, soluble boron must be controlled such that no Category 1 or Category 2 event sequences will result in boron dilution that will lower the soluble boron (enriched to 90 atom % ^{10}B) concentration to a value that is insufficient to maintain subcriticality. This is required in order to comply with the preclosure criticality safety requirement as stated in Section 2.1.3.

Use in the Report–This assumption is used in Sections 2.2.2.2 and 2.3.6.4.2.

Confirmation Status–This assumption requires confirmation by analysis. The analysis will demonstrate that no Category 1 or Category 2 event sequence will result in boron dilution that will lower the soluble boron (enriched to 90 atom % ^{10}B) concentration to a value that is insufficient to maintain subcriticality for all wet operations in the WHF.

1.4.5 DOE Standardized SNF Canister Breach

Assumption–It is assumed that no Category 1 or Category 2 event sequence will result in a breach of a DOE standardized SNF canister.

Rationale–The presence of the filler material (gadolinium-bearing aluminum or iron shot) ensures subcriticality in DOE standardized SNF canisters containing FFTF and Enrico Fermi SNF such that no additional geometry or fixed neutron absorber control is required for operations with these canisters. Therefore, breaching of a standardized DOE SNF canister must be controlled such that no Category 1 or Category 2 event sequences will result in a canister breach allowing loss of gadolinium-bearing aluminum or iron shot from DOE standardized SNF canisters containing FFTF or Enrico Fermi SNF in order to comply with the preclosure criticality safety requirement as stated in Section 2.1.3.

Use in the Report–This assumption is used in Sections 2.2.2.2, 2.3.2.3.3.5, and 2.3.2.3.3.6.

Confirmation Status–This assumption requires confirmation by analysis. The analysis will demonstrate that no Category 1 or Category 2 event sequence will result in a breach of a DOE standardized SNF canister.

1.4.6 ITS SSCs

Assumption–It is assumed that the ITS SSCs relied upon to maintain subcriticality include:

- DOE canister staging racks in the CRCF designed such that no Category 1 or Category 2 event sequence results in staging rack collapse that causes the spacing between the surfaces of adjacent DOE SNF canisters in a staging rack to be less than 30 cm

- Staging racks in the WHF pool designed such that no Category 1 or Category 2 event sequence results in staging rack collapse sufficient to cause loss of confinement of the fuel assemblies within the staging rack fuel compartments.

Rationale–These SSCs are relied upon to maintain subcriticality.

Use in the Report–This assumption is used in Sections 2.3.2.2.4 and 2.3.6.4.2.

Confirmation Status– This assumption requires confirmation by analysis. The analysis (event sequence development, quantification, and categorization) will demonstrate that these SSCs are credited a) to prevent an event sequence from being designated as important to criticality, or b) to prevent an event sequence that is important to criticality from being categorized as Category 1 or Category 2.

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2. PRECLOSURE CRITICALITY SAFETY

2.1 PRECLOSURE CRITICALITY SAFETY REQUIREMENTS AND CRITERIA

2.1.1 Regulatory Preclosure Criticality Safety Requirement

The only preclosure criticality safety technical requirement in 10 CFR Part 63 *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada* [DIRS 180319] is to perform:

> "…An analysis of the performance of the structures, systems, and components (SSCs) to identify those that are important to safety. This analysis identifies and describes the controls that are relied on to limit or prevent potential event sequences or mitigate their consequences. This analysis also identifies measures taken to ensure the availability of safety systems. The analysis required in this paragraph must include, but not necessarily be limited to, consideration of-- … (6) Means to prevent and control criticality…" (*10 CFR Part 63*, Subpart E, Section 112(e) [DIRS 180319]).

In addition to the identification of SSCs derived from this required regulatory analysis, preclosure criticality safety is implemented in the design of the facilities by specification of a) the project preclosure safety design criterion in Section 2.1.2, and b) the project preclosure criticality safety requirement given in Section 2.1.3.

2.1.2 Preclosure Criticality Safety Design Criterion

The preclosure criticality safety design criterion is given in *Project Design Criteria Document* (BSC 2007 [DIRS 179641], Section 4.10.2.1.1) as follows:

> "SSCs shall be designed such that adequate controls and procedures can be effectively implemented to**:** prevent criticality and institute controls that are relied on to limit or prevent potential event sequences or mitigate their consequences during processing, handling, transfer, or transport of the waste form or waste package in the preclosure period…"

2.1.3 Project Preclosure Criticality Safety Requirement

The project preclosure criticality safety requirement for all canistered and uncanistered SNF is (BSC 2008 [DIRS 185056], Section 1.4):

> …the SNF and canister designs, in conjunction with the facility systems, structures, and components, shall provide the basis for ensuring subcriticality at the time of delivery to the geologic repository and during all subsequent handling operations, including all event sequences that are important to criticality and have at least one chance in 10,000 of occurring before permanent closure.

2.2 PRECLOSURE CRITICALITY SAFETY ANALYSIS PROCESS

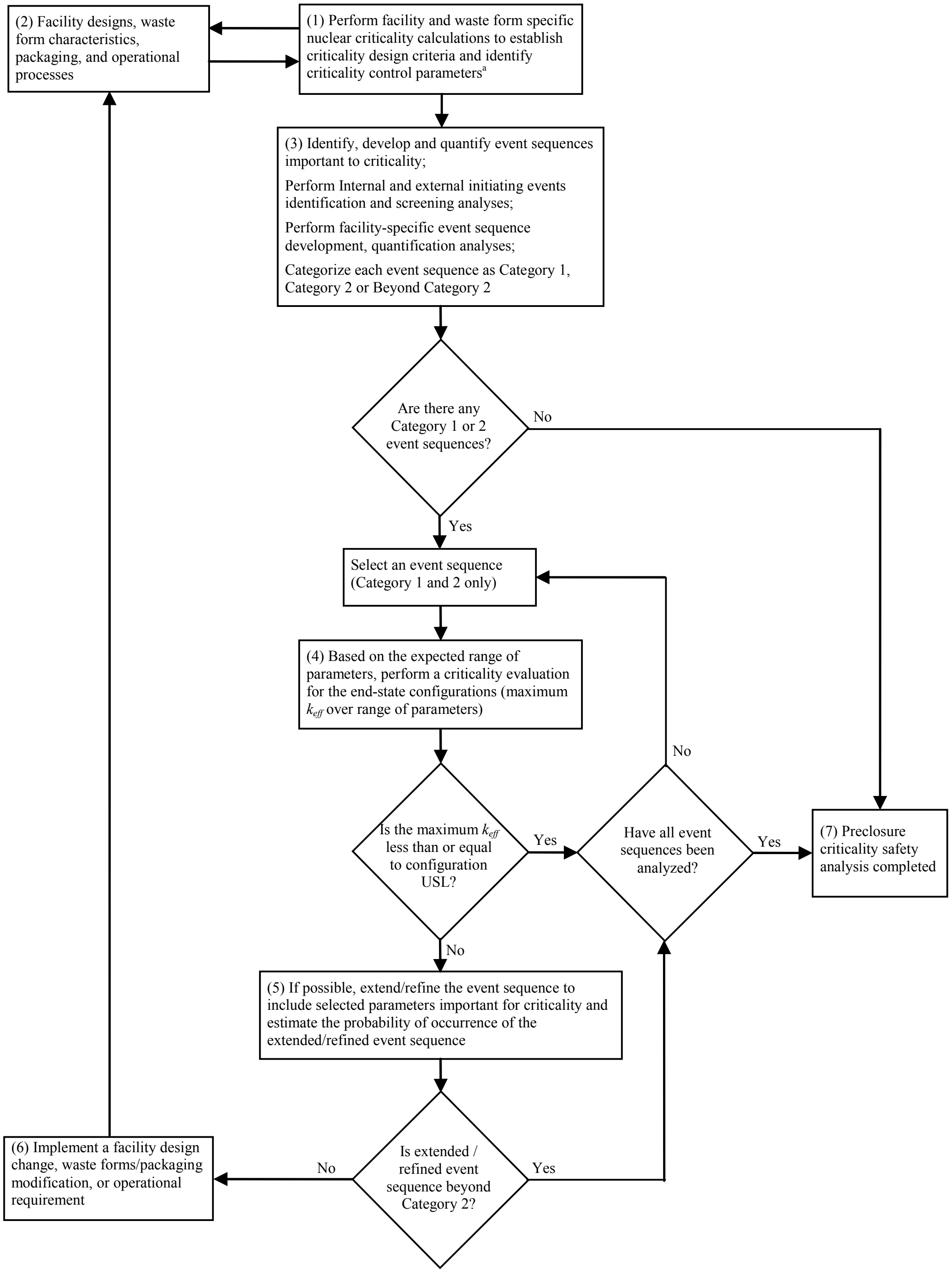
2.2.1 Process Flow

The details of the preclosure criticality safety analysis process are provided in *Preclosure Criticality Safety Analysis Process Report* (BSC 2008 [DIRS 185056]). Figure 3 provides an overview of the preclosure criticality safety analysis process. The starting point for the preclosure criticality safety analysis process is to define criticality design and operational criteria based on review and analysis of waste forms, canister designs, facility designs and characteristics, and the operational sequences within the GROA operations. In order to determine the criticality potential for each specific waste form and associated facility and handling operation, criticality sensitivity calculations are performed for each system. These calculations are described in Section 2.2.2.1.

Based on internal and external hazards identification, screening analyses, and on event sequence development and quantification analyses, the event sequences that impact the criticality control parameters that have been established as needing to be controlled (as described in Section 2.2.2.1) are identified, developed, quantified, and categorized. This analysis is described in Section 2.2.2.2. If an event sequence identified as important to criticality cannot be screened out as beyond Category 2 (less than one chance in 10,000 of occurrence during the preclosure period), criticality evaluations are performed for those end-state configurations over the range of parameters that characterize the event sequence. A configuration is considered acceptably subcritical if the maximum calculated effective neutron multiplication factor k_{eff} plus calculational uncertainties is less than or equal to the configuration-specific USL (see Section 2.3.10 for additional detail).

For end-state configurations where the maximum k_{eff} value exceeds the USL and the probability of occurrence of the end-state configuration exceeds the Category 2 criterion, the event sequence is further extended or refined to credit additional design features or procedural safety controls such that the event sequence probability is reduced to less than the Category 2 criterion. The probability of the extended or refined event sequence may include the additional probability of occurrence of parameters important to criticality, such as degree of moderation, extent of fuel rearrangement, and fuel basket geometric reconfiguration. The end-state configuration is acceptable provided that the probability of occurrence of the extended or refined event sequence does not exceed the Category 2 screening criterion. If the probability of an extended or refined event sequence exceeds the Category 2 screening criterion, design or operational requirements will be imposed to reduce the probability of the event sequence to below the Category 2 screening criterion.

The analysis process is continued until all operations and waste forms have been evaluated, criticality control parameters have been established, and event sequences important to criticality have been identified and evaluated as acceptable. The surface and subsurface facility designs are acceptable with respect to criticality when: (a) each event sequence important to criticality has been shown to have a probability less than the Category 2 screening criterion or (b) the maximum k_{eff} of normal operations and end-state configurations of all Category 1 and Category 2 event sequences important to criticality is less than or equal to the configuration-specific upper subcritical limit.



[a] May include evaluation against single- and multiparameter limits

Source: Figure 3-1, BSC 2008 [DIRS 185056]

Figure 3. Overview of the Preclosure Criticality Analysis Process

2.2.2 Preclosure Criticality Safety Calculations and Analyses

This section discusses the supporting calculations and analyses performed as part of the preclosure criticality analysis process that form the basis for the preclosure criticality safety analysis documented in this report.

2.2.2.1 Facility and Waste form Nuclear Criticality Calculations

There are three nuclear criticality calculations that support this analysis:

- *Nuclear Criticality Calculations for Canister-Based Facilities – Commercial SNF* (BSC 2007 [DIRS 182099])

- *Nuclear Criticality Calculations for Canister-Based Facilities – DOE SNF* (BSC 2008 [DIRS 182100])

- *Nuclear Criticality Calculations for the Wet Handling Facility* (BSC 2007 [DIRS 182101]).

These calculations evaluate the reactivity impacts of variations in each of the parameters important to criticality during the preclosure period. Given that the repository will handle existing waste forms without the ability to alter their form or (for canistered waste forms) their packaging, there are six parameters important to criticality that are evaluated as part of this process step:

1) **Waste form characteristics** – Waste form characteristics including physical form (e.g., size and shape) chemical form (e.g., oxide), mass, density, fissile material type (e.g., ^{235}U) and enrichment. The k_{eff} sensitivity calculations use either bounding or representative fuel characteristics. If waste form characteristics are not bounded in the calculations and the system being evaluated is subject to potential misloads based on the availability of more reactive SNF that can be mistakenly handled, then this parameter is identified as needing to be controlled.

2) **Moderation** – Potential moderators that could be present in the Geologic Repository Operations Area (GROA) including type (e.g., water), composition (e.g., borated water), density, volume, and location with respect to the SNF. The k_{eff} sensitivity calculations determine maximum or optimum moderation conditions (e.g., type, mass, volume, density) that maintain subcriticality as a function of other relevant parameters.

3) **Neutron absorber** – Potential fixed neutron absorbers (e.g., borated stainless steel) and soluble neutron absorbers (e.g., borated water) varying from as designed to complete omission. The k_{eff} sensitivity calculations determine minimum neutron absorber characteristics (e.g., type, loading, concentration) that maintain subcriticality as a function of other relevant parameters.

4) **Geometry** – Potential geometric rearrangement of the SNF (e.g., varying pin or plate pitch) and fuel baskets (e.g., varying flux trap gap)**.** The k_{eff} sensitivity calculations determine the most limiting geometric conditions that maintain subcriticality as a function of other relevant parameters.

5) **Interaction** – Potential neutronic coupling conditions in the GROA between units of similar or different waste forms**.** The k_{eff} sensitivity calculations determine the most limiting interaction conditions that maintain subcriticality as a function of other relevant parameters.

6) **Reflection** – Potential reflection conditions in the GROA including material type (e.g., concrete), density, and thickness. The k_{eff} sensitivity calculations examine all potential reflection conditions as a function of other relevant parameters.

These criticality calculations determined the sensitivity of k_{eff} to variations in any parameter(s) as a function of other relevant parameters in order to provide guidance to hazards identification and to event sequence development, quantification, and categorization on whether each parameter:

- Does not need to be controlled because it is bounded (i.e., its analyzed value is greater than or equal to the design limit) or its effect is bounded,
- Needs to be controlled if another parameter is not controlled (conditional control), or
- Needs to be controlled because it is the primary criticality control parameter.

2.2.2.2 Event Sequence Quantification and Categorization Analyses

There are six reliability and event sequence categorization analyses; one for each of the facilities that support this analysis through the verification of Assumptions 1.4.2 through 1.4.5. Categorization of event sequences is based on evaluated frequencies of occurrence and is documented in these reliability and event sequence categorization analyses for each facility. Categorization of event sequences is achieved by comparing the mean value of each event sequence probability distribution to the Category 1 and Category 2 criteria. Event sequences that have an expected number of occurrences of at least one in the preclosure period are designated as Category 1. Event sequences with a mean probability greater than or equal to one chance in 10,000 but having an expected number of occurrences less than one in the preclosure period are designated as Category 2.

The event sequences to be considered as part of the criticality safety analysis must be determined through review of the repository design and operations and identified as part of the Preclosure Safety Analysis (PCSA). The performance of the SSCs and implementation of operational requirements are evaluated to verify that all sequences important to criticality have been identified. These evaluations identify and describe the controls and procedures (ITS SSCs and procedural safety controls) that are relied upon to ensure that event sequences important to criticality do not lead to a criticality accident. The analyses also identify the measures in place to ensure the availability of safety systems.

2.2.2.3 Safety Bases Document

The safety bases and requirements for preclosure criticality safety are documented in preclosure nuclear safety design bases and procedural safety controls documents. As required in 10 CFR 63.112(e)(6) [DIRS 180319], this document describes the controls that are relied on to control or prevent potential event sequences important to criticality. This document also identifies measures taken to ensure the availability of safety systems. The availability of safety systems, designation of important to safety (ITS) SSCs, as well as procedural safety controls are the result of the reliability and event sequence categorization analyses described in Section 2.2.2.2.

2.3 PRECLOSURE CRITICALITY SAFETY EVALUATION

This section discusses the preclosure criticality safety evaluation for the surface and subsurface facilities. The surface facilities in which fissile material could be present include five types of waste-handling buildings: the IHF, the RF, a CRCF, three of which are planned, the WHF, and the Low-Level Waste Facility. In addition to operations performed within waste-handling buildings, intrasite operations, including aging, are part of surface operations. Following completion of necessary surface operations to place waste form canisters within waste packages, those waste packages are moved to and emplaced within the Subsurface Facility. Because waste forms, their containers (transportation casks, canisters, and waste packages), and staging racks are present in more than one facility, a discussion of those components is given in Section 2.3.1.

Other facilities such as the Central Control and Command Facility and Emergency Operations Center, the Heavy-Equipment-Maintenance Facility, and the Warehouse and Non-Nuclear Receipt Facility, have no operations with fissile material and are not included in this criticality safety evaluation.

The preclosure criticality safety evaluation includes normal operations and Category 1 and Category 2 event sequences that are identified as part of the PCSA, using the process described in Section 2.2.

The criticality safety evaluation presented in this section reflects the current facility designs, expected fuel operations, a conceptual TAD canister design, a representative DPC design, and a representative group of DOE SNF types. Future evaluations will be performed, as necessary, to demonstrate that actual designs and fuel characteristics, as accepted for receipt, comply with the criticality safety requirement in Section 2.1.3. If the transportation cask, canister, and waste package designs, fuel characteristics, or fuel operations are not bounded by the evaluation presented in this section, an update to the criticality safety analysis will be conducted.

2.3.1 Waste Forms, Containers and Staging Racks

2.3.1.1 Waste Forms

2.3.1.1.1 Commercial SNF Waste Form Characteristics

For CSNF operations with individual assemblies, TAD canisters, and DPCs, the analysis considered the following bounding waste form characteristics:

- 5 wt% enriched ^{235}U fresh fuel (i.e., maximum CSNF enrichment and no credit for burnup)
- UO_2 density of 10.751 g/cm^3, i.e., 98% of full theoretical density
- Use of full assembly length as active fuel length
- No burnable poison

- No credit for the presence of ^{234}U or ^{236}U absorbers
- Fuel pellet stack modeled as a simple cylinder with no density correction for dished ends
- Gap between fuel and clad filled with unborated water
- Simplified fuel assembly model neglecting spacer grids and end fittings.

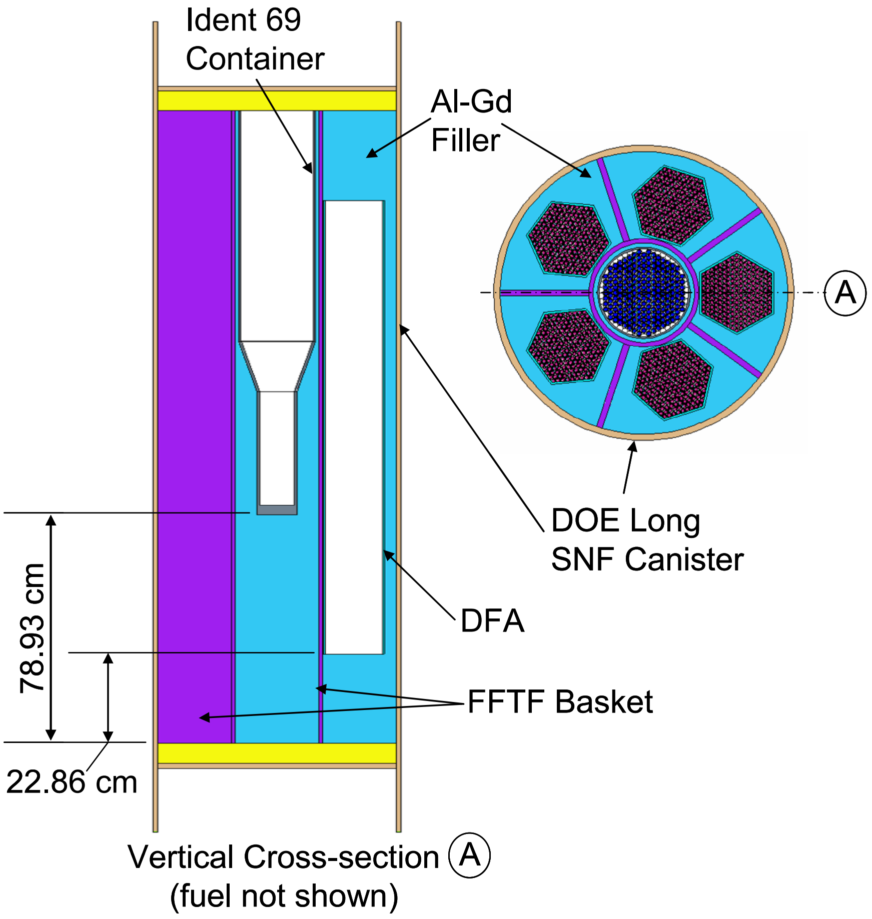
These bounding parameters are used in two models of PWR CSNF assemblies: a simplified Westinghouse 17×17 Optimized Fuel Assembly (OFA) and a simplified Babcock & Wilcox (B&W) 15×15 assembly (BSC 2007 [DIRS 182101], Section 6.1.1 and BSC 2007 [DIRS 182099], Section 6.2.1.2.1). These assembly types were shown to be the most reactive assembly designs based on a survey of eight PWR CSNF assemblies in various potential preclosure configurations (BSC 2005 DIRS [175046], Section 6). Even though the assembly survey is not comprehensive, the selected assembly types in conjunction with the waste form characteristics listed above are considered bounding to the projected PWR SNF to be handled in the repository. Prior to receipt and acceptance of PWR SNF shipments, this conclusion will be verified by comparative or computational analysis.

The bounding CSNF parameters are also used in two models of BWR CSNF assemblies: a simplified General Electric (GE) 7×7 BWR assembly and a simplified Advanced Nuclear Fuel (ANF) 9×9 BWR assembly (BSC 2007 [DIRS 182101], Section 6.1.2 and BSC 2007 [DIRS 182099], Section 6.2.1.2.2). The selected assembly types were shown to be the most reactive assembly designs based on a survey of five BWR CSNF assemblies in various potential preclosure configurations (BSC 2005 DIRS [175046], Section 6). Even though the assembly survey is not comprehensive, the selected assembly types in conjunction with the waste form characteristics listed above are considered bounding to the projected BWR SNF to be handled in the repository. Prior to receipt and acceptance of BWR SNF shipments, this conclusion will be verified by comparative or computational analysis.

2.3.1.1.2 DOE SNF Waste Form Characteristics

Due to the variety of DOE Environmental Management-owned SNF, the National Spent Nuclear Fuel Program has designated nine representative fuel groups for criticality analyses based on fuel matrix and primary fissile isotope (DOE 2000 [DIRS 118968], Section 6). For each fuel group, a fuel type that represents the characteristics of the fuels in that group has been selected for detailed analysis. The nine fuel groups and the representative fuel types for criticality analysis are described below.

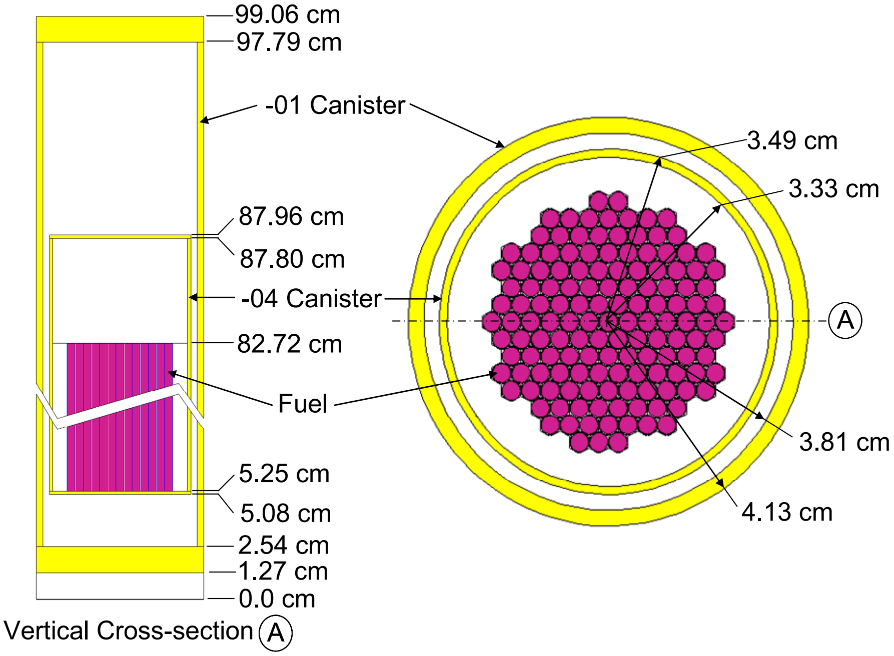
- **Mixed Oxide (MOX) -** FFTF fuel is the representative type for the mixed oxide (MOX) fuel group. There are four basic types of fuel pins and one experimental variant. Each pin contains MOX fuel ($UO_{1.96}$ and $PuO_{1.96}$) surrounded by stainless steel clad. The FFTF standard driver fuel assembly (DFA) model contains 217 Type 4.1 fuel pins (which have the highest fissile material content) within a stainless steel Type 316 hexagonal duct. Some assemblies have been disassembled, and up to 217 fuel pins have been placed in a 5 in. stainless steel pipe known as an Ident-69 container (BSC 2008 [DIRS 182100], Section 6.1.3.3.1). A long DOE SNF standardized canister contains a spoked-wheel basket constructed of nickel-gadolinium alloy holding five driver fuel assemblies (DFAs) surrounding a single Ident-69 container. Only five of the six basket compartments will be used for any fully loaded canister. The space not occupied by the fuel assemblies, the Ident-69 container, and the basket is filled with aluminum shot containing $GdPO_4$ that is used as a neutron absorber. Cross sectional views of a long DOE standardized SNF canister containing FFTF SNF are shown in Figure 4 (BSC 2008 [DIRS 182100, Section 6.1.3.3.2).



Source: Figure 6-22, BSC 2008 [DIRS 182100]

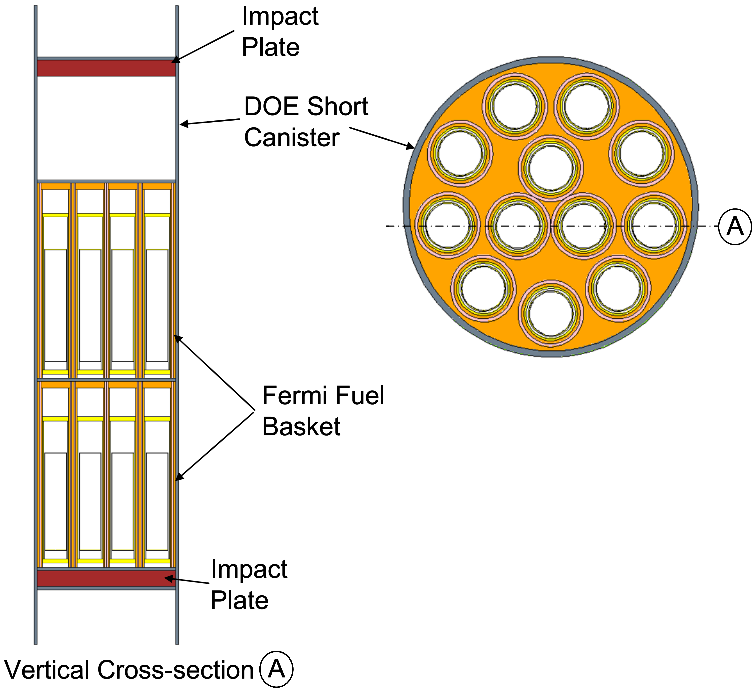
Figure 4. Cross Sections of FFTF Basket in a Long DOE Standardized SNF Canister

- **U-Mo and U-Zr Alloys -** Enrico Fermi fast reactor fuel is the representative type for the U-Mo and U-Zr Alloys fuel group. The Enrico Fermi fuel pin matrix is made of uranium-molybdenum alloy (approximately 10 wt% molybdenum alloyed with uranium of 25.69 wt% ^{235}U enrichment). The fuel is metallurgically bonded to a zirconium tube that serves as cladding, resulting in no gap between cladding and fuel. Zirconium end pieces are fitted to the fuel rods, and 140 fuel rods plus 4 stainless steel connecting rods were installed in each fuel assembly (BSC 2008 [DIRS 182100], Section 6.1.3.2.1). A short DOE SNF standardized canister contains two basket assemblies, with each basket assembly consisting of 12 nickel-gadolinium alloy tubes. Each tube contains an -01 aluminum canister, which itself contains an -04 aluminum canister holding 140 loose fuel pins from a single assembly. The space between the tubes is filled with Fe/$GdPO_4$ shot. Cross sections of the -01 and -04 canisters are shown in Figure 5. Cross sectional views of a short DOE standardized SNF canister containing Enrico Fermi SNF are shown in Figure 6.



Source: Figure 6-10, BSC 2008 [DIRS 182100]

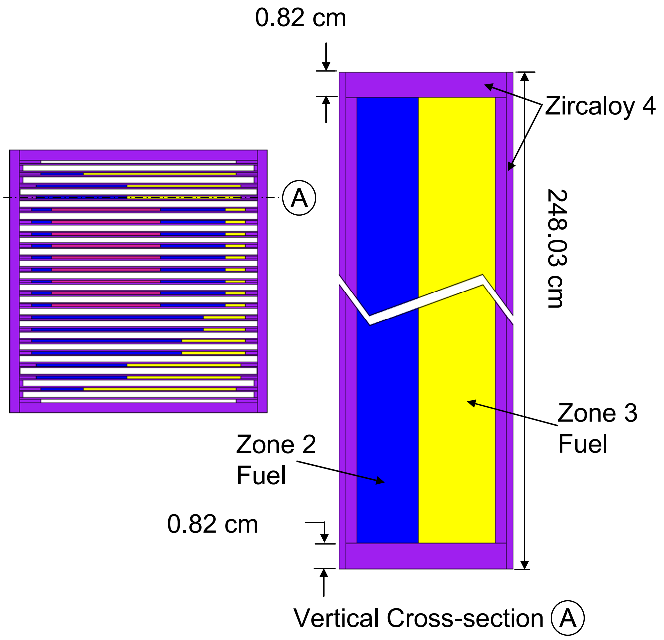
Figure 5. Cross Sections of Enrico Fermi Fuel in -01 and -04 Canisters



Source: Figure 6-12, BSC 2008 [DIRS 182100]

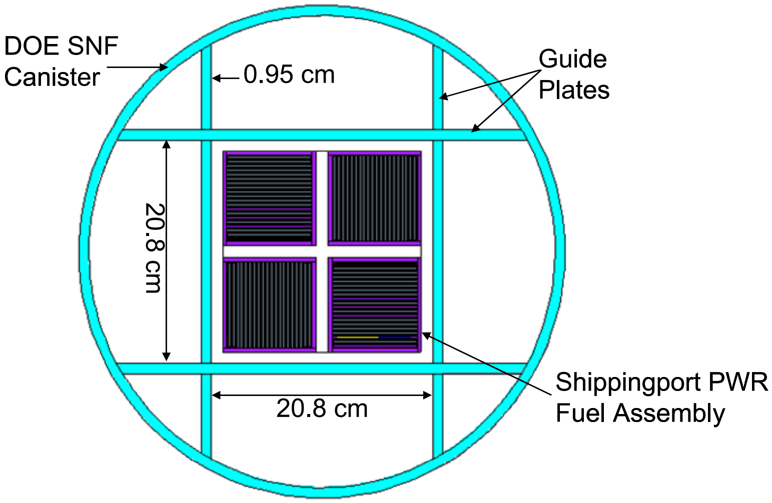
Figure 6. Cross Sections of Enrico Fermi Fuel Baskets in a Short DOE Standardized SNF Canister

- **Highly Enriched Uranium (HEU) Oxide** - Shippingport PWR fuel is the representative fuel type for the HEU Oxide fuel group. The Core 2 Seed 2 fuel cluster is used because it has a higher ^{235}U loading per cluster than other types of fuel clusters. It is composed of four fuel subclusters arranged in a square array with spacing between them that accommodated a cruciform-shaped control rod during operation. Each subcluster contains 19 fuel and two neutron absorber plates. A fuel plate is formed by sandwiching UO_2-ZrO_2-CaO alloy wafers between two Zircaloy-4 cover plates and four side strips. The initial ^{235}U enrichment is 93.2 wt% (BSC 2008 [DIRS 182100], Section 6.1.3.6). A long DOE SNF standardized canister contains a single square basket of stainless steel guide plates holding a single PWR fuel cluster. Cross sections of a Shippingport PWR Sub Assembly are shown in Figure 7. A cross sectional view of a long DOE standardized SNF canister containing Shippingport PWR SNF is shown in Figure 8.



Source: Figure 6-42, BSC 2008 [DIRS 182100]

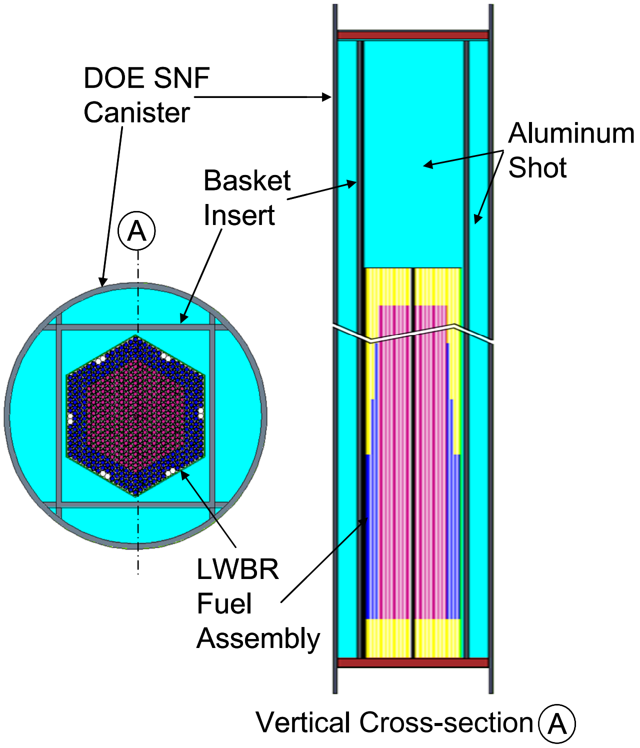
Figure 7. Cross Sections of Shippingport PWR Sub Assembly



Source: Figure 6-43, BSC 2008 [DIRS 182100]

Figure 8. Cross Section of Shippingport PWR Fuel Assembly and Guide Plates in a Long DOE Standardized SNF Canister

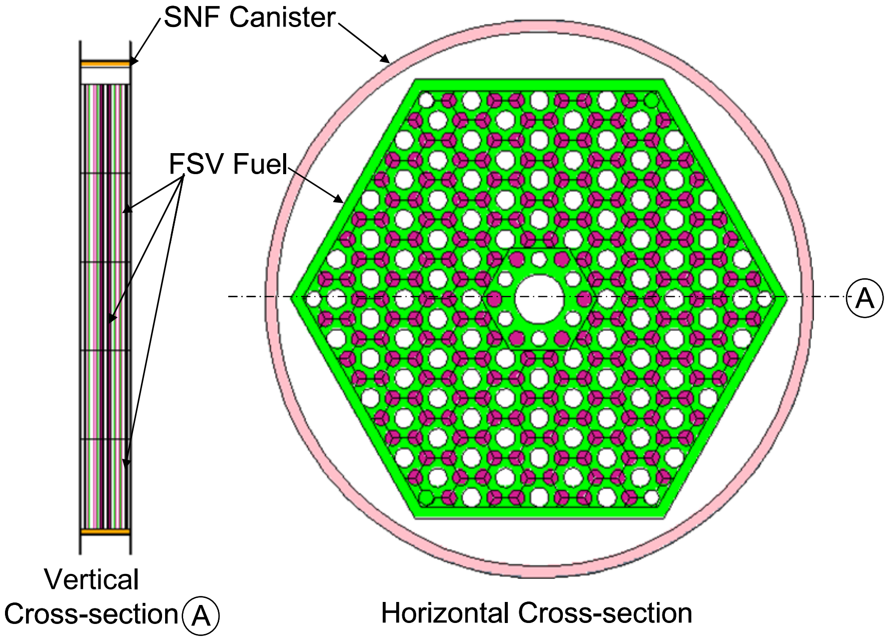
- **^{233}U/Th Oxide** - Shippingport LWBR fuel is the representative fuel type for the ^{233}U/Th Oxide fuel group. A seed assembly contains eight types of seed rods in four fuel regions, with a total of 619 cylindrical fuel rods in a triangular pitch array, supported by a hexagonal Zircaloy-4 outer shell. The fuel rods contain either thoria (ThO_2) or a mixture of thoria and UO_2. The uranium is 98.23 wt% ^{233}U. Two different enrichments (ratio of the mass of fissile isotopes to the total heavy metal mass) of the UO_2-ThO_2 matrix were used, a lower enrichment of 4.337 wt% and a higher enrichment of 5.202 wt% (BSC 2008 [DIRS 182100], Section 6.1.3.5.1). A long DOE SNF standardized canister contains a rectangular stainless steel basket holding a single LWBR seed assembly. The space not occupied by the fuel assembly and basket is filled with aluminum shot containing $GdPO_4$ that is used as a neutron absorber. Cross sectional views of a long DOE standardized SNF canister containing Shippingport LWBR SNF are shown in Figure 9.



Source: Figure 6-33, BSC 2008 [DIRS 182100]

Figure 9. Cross Sections of Shippingport LWBR Fuel Assembly in a Long DOE Standardized SNF Canister

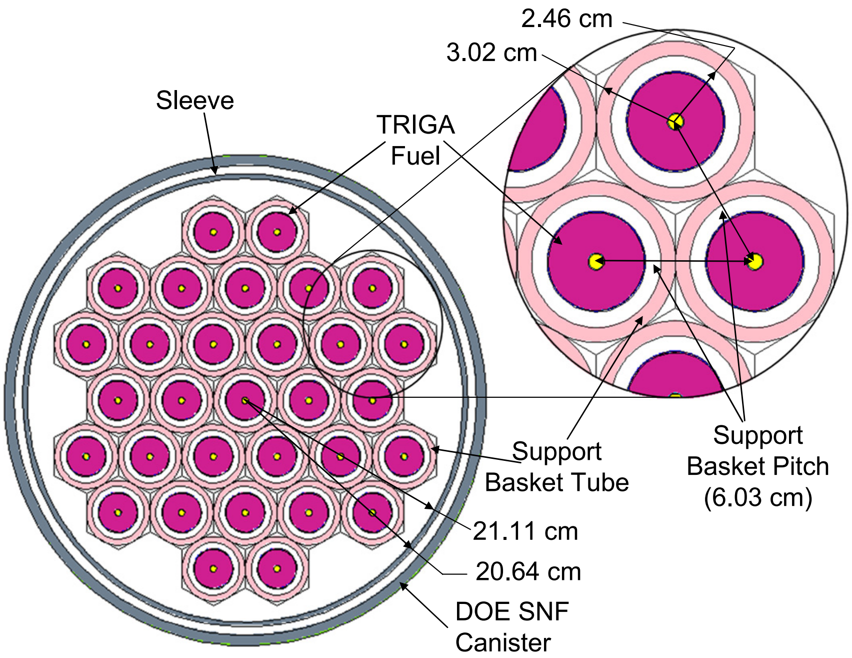
- **U/Th Carbide -** Fort St. Vrain fuel is the representative fuel type for the U/Th Carbide fuel group. It consists of a mixture of small spheres of the order of 0.0450 to 0.0750 cm diameter of uranium (enriched to 93.5 wt% ^{235}U) and thorium carbide. The individual spheres are coated with multiple, thin layers of pyrolytic carbon and silicon carbide, which serve as tiny pressure vessels to contain fission products and the Th/U carbide matrix. In the fuel elements, the coated spheres are bound in a carbonized matrix to form fuel compacts that are loaded into drilled holes in a large hexagonal graphite prism that comprises one fuel element. Fuel holes containing the fuel compacts and coolant channels are distributed in a triangular array within the fuel element (BSC 2008 [DIRS 182100], Section 6.1.3.4). A long DOE SNF standardized canister contains five hexagonal graphite fuel elements with no separate basket. Cross sectional views of a long DOE standardized SNF canister containing Fort St. Vrain SNF are shown in Figure 10.



Source: Figure 6-25, BSC 2008 [DIRS 182100]

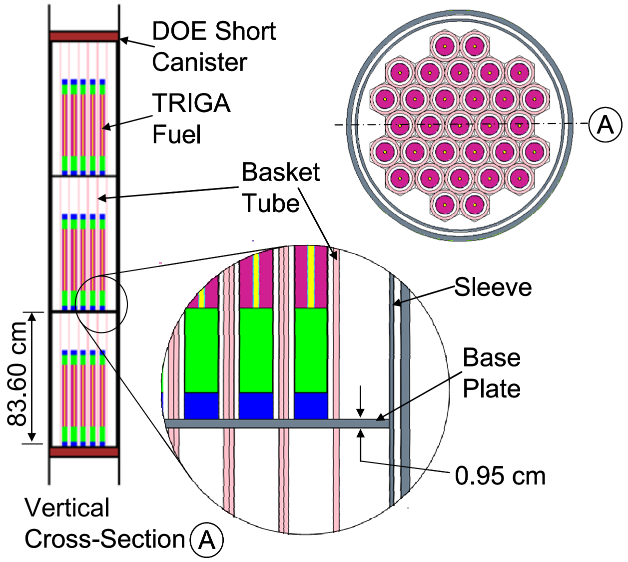
Figure 10. Cross Sections of Fort St. Vrain Fuel in a Long DOE Standardized SNF Canister

- **Uranium-Zirconium Hydride (UZrH) -** TRIGA fuel is the representative fuel type for the UZrH fuel group. The HEU Fuel Life Improvement Program (FLIP) variant is used in the analysis. A stainless steel fuel element contains 70 wt% enriched ^{235}U in a self-moderating zirconium-hydride matrix ($UZrH_{1.6}$). A short DOE SNF standardized canister contains three baskets, each holding 31 fuel elements, with basket tubes made of nickel-gadolinium alloy (BSC 2008 [DIRS 182100], Section 6.1.3.7). A horizontal cross section of the TRIGA fuel basket model is shown in Figure 11. Cross sectional views of a short DOE standardized SNF canister containing TRIGA SNF are shown in Figure 12.



Source: Figure 6-47, BSC 2008 [DIRS 182100]

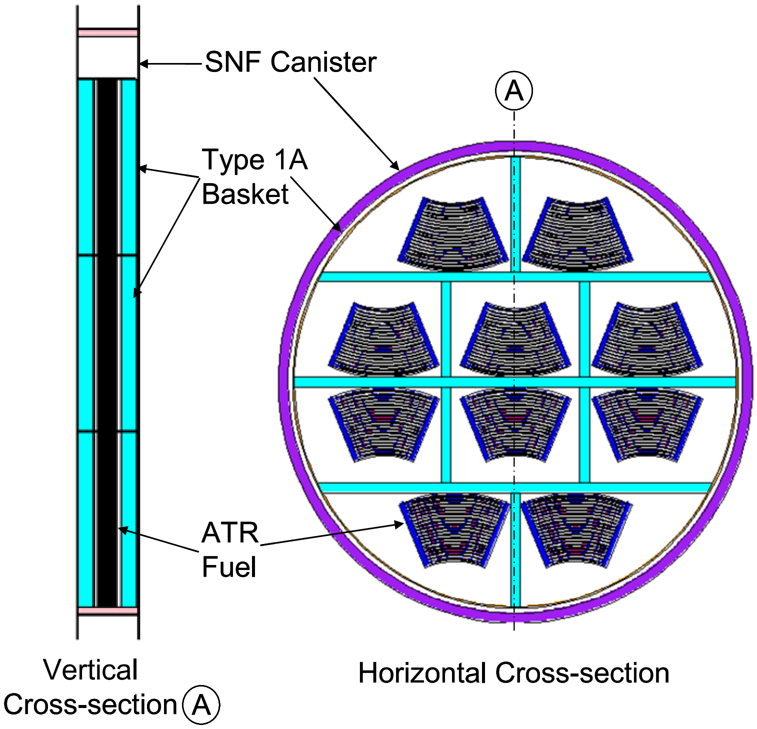
Figure 11. Horizontal Cross Section of TRIGA Fuel Basket Model



Source: Figure 6-48, BSC 2008 [DIRS 182100]

Figure 12. Cross Sections of TRIGA Fuel Baskets in a Short DOE Standardized SNF Canister

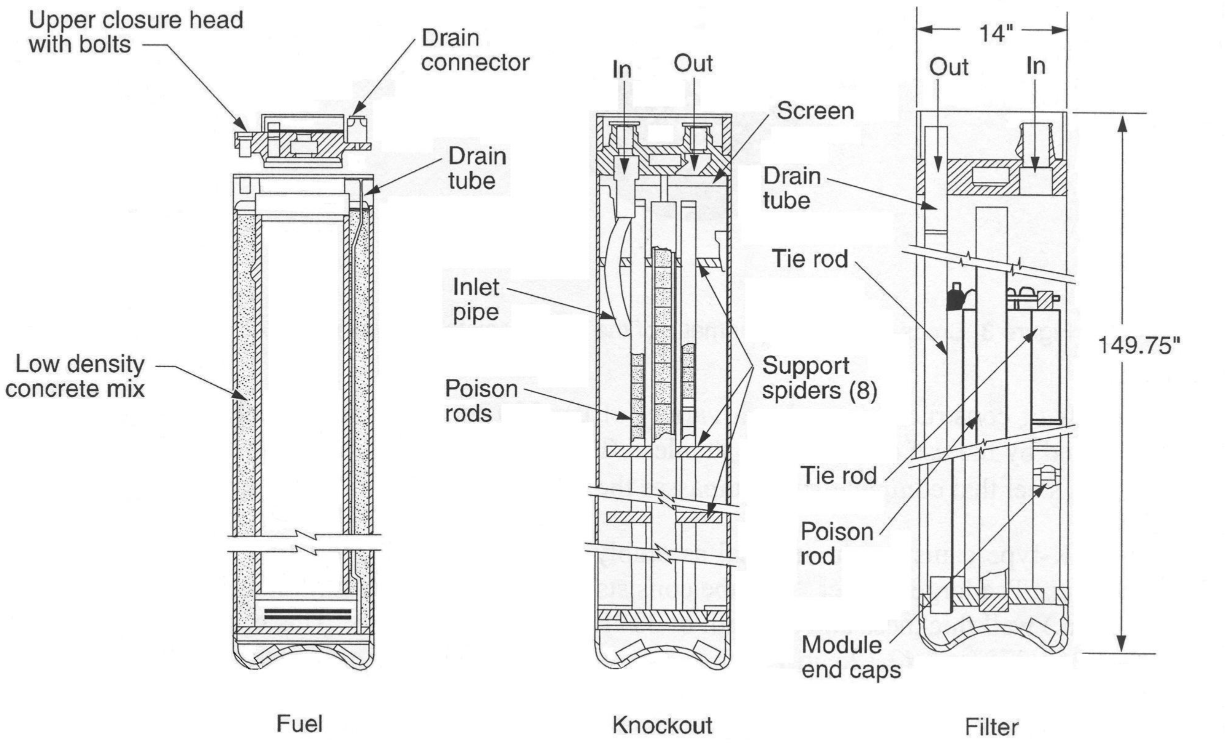
- **HEU-Al** - ATR fuel is the representative fuel type for the Al Clad fuel group. The ATR fuel element consists of 19 curved aluminum clad uranium aluminide (UAl_x) plates containing highly enriched (93±1 wt% ^{235}U) uranium. The highest nominal fuel loading for a fresh fuel element is 1075 g of ^{235}U (BSC 2008 [DIRS 182100], Section 6.1.3.1.1). A long DOE SNF standardized canister contains three baskets, each holding 10 fuel elements, with basket plates made of nickel-gadolinium alloy. Cross sectional views of a short DOE standardized SNF canister containing ATR SNF are shown in Figure 13.



Source: Figure 6-7, BSC 2008 [DIRS 182100]

Figure 13. Cross Sections of ATR Fuel in a Long DOE Standardized SNF Canister

- **Low Enriched Uranium (LEU) Oxide -** TMI-2 debris is the representative fuel type for the LEU Oxide fuel group. The typical fuel assembly constituting the debris is a Babcock & Wilcox 15×15 with maximum enrichment of 2.96 wt% ^{235}U and a maximum beginning-of-life ^{235}U content of 13.72 kg. A long DOE SNF standardized canister contains one of three TMI-2 canister types: a defueling canister holding debris large enough to grapple, a knockout canister holding vacuumed debris, or a filter canister holding debris caught in filters. Cross sections of the three canister types are shown in Figure 14. The uranium loading for a single TMI-2 canister ranges from zero to 441.9 ±99.9 kg (DOE 2003 [DIRS 164970], Section 3.2).



Source: Figure 2, DOE 2003 [DIRS 164970]

Figure 14. Cross Sections of TMI-2 Canister Types

- **U Metal -** N-Reactor fuel is the representative fuel type for the U Metal fuel group. There are two design variants of fuel elements (Mark IV and Mark IA), each of which is made of two concentric tubes of uranium metal co-extruded with zircalloy cladding. Initial enrichments range from 0.947 to 1.25 wt% ^{235}U (DOE 2000 [DIRS 150095], Section 3.1.1). A multicanister overpack (MCO) holds five stainless steel baskets. There are basket designs for intact Mark IV and Mark IA fuel and for scrap fuel elements (DOE 2000 [DIRS 150095], Section 4.1). Prior to receipt and acceptance of MCOs, preclosure safety analyses of the MCOs will be completed to demonstrate compliance with the preclosure criticality safety requirement in Section 2.1.3.

2.3.1.1.3 HLW Waste Form Characteristics

The only waste form characteristic important to criticality for HLW is the concentration of fissile isotopes. The estimated quantities of fissile isotopes in HLW canisters are shown in Table 3, as well as the total fissile isotope concentration. The minimum subcritical limit for fissile solute (aqueous solution of fissile isotopes) from Table 1 of ANSI/ANS-8.1-1998 [DIRS 123801], is 7.3 g/L for ^{239}Pu(NO$_3$)$_4$. Because concentration limits for aqueous solutions are lower than those for other physical/chemical forms, the fact that the concentrations of fissile isotopes in Table 3 are approximately one order of magnitude less than 7.3 g/L demonstrates that the HLW glass has a significant margin of subcriticality. The limits in Table 1 of ANSI/ANS-8.1-1998 [DIRS 123801] assume a uniform homogeneous mixture. Because the glass canisters are poured as a melt, they will be relatively homogeneous. Even if the glass is not completely homogeneous, the significant margin of subcriticality will compensate for any inhomogeneities in the glass. Therefore, individual HLW canisters and codisposal waste packages will be subcritical. No further analysis is required to demonstrate the subcriticality of individual HLW glass canisters and codisposal waste packages containing only HLW glass canisters.

Table 3. Fissile Isotopes in HLW Glass Canisters

Fissile Isotope	**Hanford Canister**	**Idaho National Laboratory Canister**	**Savannah River Site Canister**	**West Valley Demonstration Project Canister**
^{233}U Mass (g)[a]	0.217	6.29×10^{-4}	5.80	9.37
^{235}U Mass (g)[a]	257	304	307	172
^{239}Pu Mass (g)[a]	343	32.4	280	141
^{241}Pu Mass(g)[a]	1.18	.208	8.16	3.01
Total Fissile Isotope Mass (g)	601	337	601	325
Nominal Glass Volume (L)	1080[b]	625[c]	670[d]	665[e]
Fissile Isotope Concentration (g/L)	0.557	0.539	0.897	0.489

[a] Source: ORIGEN-S output files hsc.out (Hanford), inlc.out (Idaho National Laboratory), srsc.out (Savannah River), and wvc.out (West Valley) in folder ORIGEN of Attachment E, BSC 2008 [DIRS 184923]
[b] Source: Table RL-3, Picha 1997 [DIRS 104406]
[c] Source: Footnote c, Table ID-2, Picha 1997 [DIRS 104406]
[d] Source: Minimum canister volume from Table 2, Ray 2007 [DIRS 181690]
[e] Source: Minimum canister volume from Appendix A
NOTE: The justification for use of glass volumes from Picha 1997 [DIRS 104406] is that these volumes are provided by the DOE and were taken directly from the waste generator, which represents the most authoritative source of information. Therefore, these volumes are considered suitable for their intended use in this report, i.e., to calculate the fissile isotope concentration.

2.3.1.2 Transportation Casks, Canisters and Waste Packages

Transportation casks, dual-purpose canisters (DPCs), DOE SNF canisters, HLW canisters, naval SNF canisters, and most TAD canisters are loaded prior to shipment to the repository. Some TAD canisters are loaded at the repository in the WHF. All canisters except DPCs are disposal canisters. Disposal canister loading is performed in a manner to meet the 10 CFR Part 63 [DIRS 180319] requirements for preclosure and postclosure. In addition, transportation casks and canisters loaded elsewhere for shipment to the repository will meet 10 CFR Part 71 [DIRS 181967] transportation requirements. Loading criteria for fuel in DOE SNF canisters and transportation casks will be developed by the DOE prior to shipment to the repository. Repository nuclear criticality safety evaluations for transportation casks begin when the cask enters the Geologic Repository Operations Area (GROA).

2.3.1.2.1 Transportation Casks

CSNF assemblies that are not loaded into TAD canisters at utility sites can be handled and shipped to the repository in transportation casks certified by the NRC under 10 CFR Part 71 [DIRS 181967]. Criticality safety design for transportation casks containing CSNF is similar to to that for the representative DPCs discussed in Section 2.3.1.2.2 and the TAD canisters discussed in Section 2.3.1.2.3. In this evaluation, the results for analyses of TAD canisters and DPCs with close-fitting full-thickness reflectors are expected to be representative or bounding for transportation casks containing CSNF.

DOE SNF canisters will also be shipped to the repository in transportation casks certified by the NRC under 10 CFR Part 71 [DIRS 181967]. Prior to receipt and acceptance of transportation casks containing DOE SNF canisters, criticality safety analyses will be performed for specific DOE SNF transportation cask designs to demonstrate compliance with the preclosure safety requirement in Section 2.1.3.

2.3.1.2.2 Dual-Purpose Canisters

A DPC is the inner canister of a CSNF storage and transport cask system. DPCs are available in both vertical and horizontal configurations. They provide a structural support system into which various arrangements of CSNF assemblies are placed. These arrangements are supported and controlled by a fuel basket made up of fuel compartments, fixed neutron poisons (e.g., Boral plates), and flux traps (primarily for PWR DPCs). For the purpose of this analysis, the DPC and fuel baskets evaluated are based on the HOLTEC HI-STAR 100 Multi-Purpose Canister (MPC) and the associated MPC-24 (PWR) and MPC-68 (BWR) fuel baskets as described in *Storage, Transport, and Repository Cask Systems, (Hi-Star Cask System) Safety Analysis Report, 10 CFR 71, Docket 71-9261* [DIRS 172633].

2.3.1.2.3 Transportation, Aging, and Disposal Canisters

The TAD canister is designed to a) transport CSNF from purchaser (e.g., reactor) sites to the repository inside a suitable transportation overpack, b) age CSNF, if necessary (e.g., for cooling), inside an aging overpack, and c) provide the structure for permanent disposal inside a waste package. There are two configurations of TAD canisters, both of which fit inside the same TAD waste package configuration. The 21-PWR TAD canister contains 21 PWR CSNF assemblies, and the 44-BWR TAD canister contains 44 BWR CSNF assemblies. Criticality control design features provided by the TAD canister design include moderator control (provided by the shell) as well as geometry control and fixed neutron absorber (both provided by the basket).

Certain dimensions, materials of construction, and design features of the TAD canister are not explicitly defined in *Transportation, Aging and Disposal Canister System Performance Specification* (DOE 2007 [DIRS 181403]) and, therefore, have been assumed in order to perform the analysis herein. The assumed values and the rationale for their use are described in Assumption 1.4.1.

2.3.1.2.4 DOE High-Level Waste Canisters

DOE HLW canisters are described in Sections 6.3, 6.4, 6.5, and 6.6 of *Source Terms for HLW Glass Canisters* (BSC 2008 [DIRS 184923]). Criticality control design features are not necessary for HLW canisters because criticality is not possible due to the low concentration of fissile isotopes in a HLW glass canister (Section 2.3.1.1.3).

2.3.1.2.5 DOE Standardized Spent Nuclear Fuel Canisters

The characteristics of the DOE standardized canister shell are described in Section 3.2 of *Design Specification*, Volume 1 of *Preliminary Design Specification for Department of Energy Standardized Spent Nuclear Fuel Canisters*, DOE/SNF/REP-011, Rev. 3 (DOE 1999 [DIRS 140225]).

The characteristics of the DOE standardized canister internals are described in *Design Considerations for the Standardized DOE Canister Internals* (DOE 2006 [DIRS 179793]). The eight combinations of canister, basket, and representative fuel are described in Section 2.3.1.1.2 as part of DOE SNF waste form characteristics.

2.3.1.2.6 DOE Multicanister Overpacks

The characteristics of the DOE MCO shell and canister internals are described in Section 4 of *N Reactor (U-Metal) Fuel Characteristics for Disposal Criticality Analysis*, DOE/SNF/REP-056, Rev. 0 (DOE 2000 [DIRS 150095]). The MCO is a stainless steel canister designed to hold fuel from the U Metal fuel group, for which N-Reactor fuel is the representative type. The baskets and fuel are described in Section 2.3.1.1.2 as part of DOE SNF waste form characteristics. Prior to receipt and acceptance of MCOs, preclosure safety analyses of MCOs will be completed to demonstrate compliance with the preclosure criticality safety requirement in Section 2.1.3.

2.3.1.2.7 Waste Package Configurations

There is a single waste package design with six configurations (BSC 2007 [DIRS 184505], Section 1):

- TAD Waste Package holding either a 21-PWR TAD canister or a 44-BWR TAD canister
- 5-DHLW/DOE Short Waste Package nominally holding a single 18-in. diameter short (10 ft.) standardized DOE SNF canister surrounded by five 24-in. diameter short HLW canisters
- 5-DHLW/DOE Long Waste Package nominally holding a single 18-in. diameter long (15 ft.) standardized DOE SNF canister surrounded by five 24-in. diameter long HLW canisters
- 2-MCO/2-DHLW Waste Package holding two 25.51-in. diameter MCOs and two 24-in. diameter long HLW canisters
- Naval Short Waste Package holding a single short naval SNF canister
- Naval Long Waste Package holding a single long naval SNF canister.

The criticality control feature provided by all sealed waste packages is moderator control. The 5-DHLW/DOE Short, 5-DHLW/DOE Long, and 2-MCO/2-DHLW waste packages also include geometry control by providing a basket structure with specific locations for DOE SNF and HLW canisters.

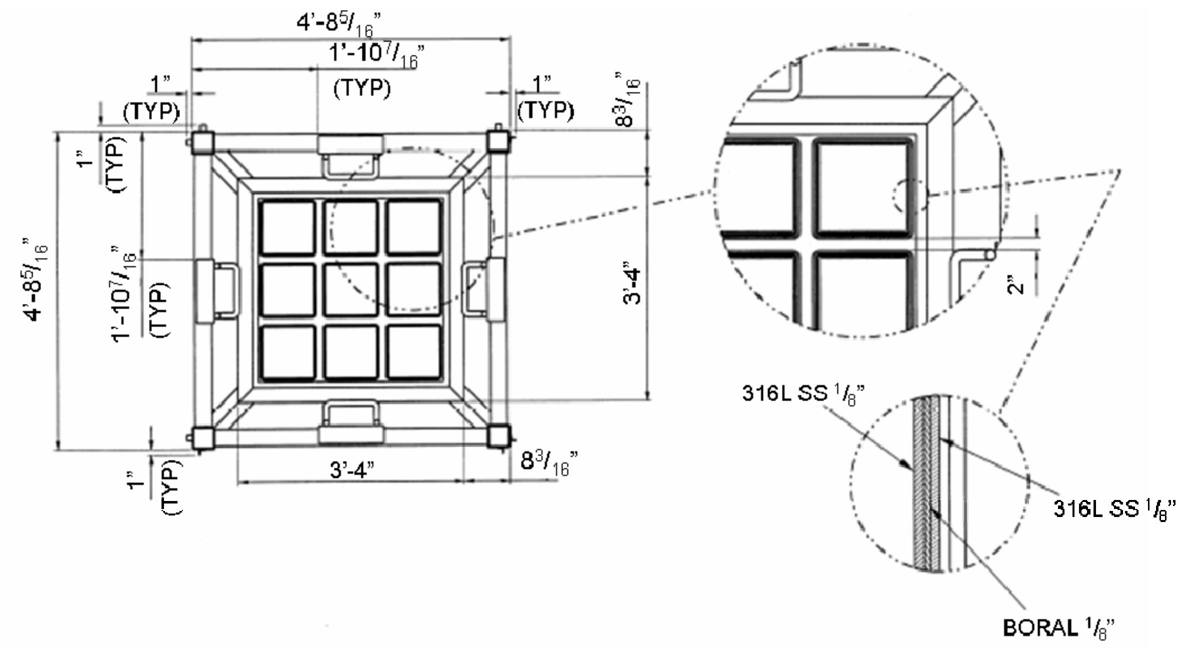
2.3.1.3 Staging Racks

Staging of CSNF assemblies in the pool is needed in order to allow for mixing of fuel assemblies (having different initial enrichments, burnups, and cooling times) in the TAD canisters to ensure that thermal and postclosure criticality requirements of the TAD canisters are met.

2.3.1.3.1 PWR SNF Staging Racks

Nine PWR CSNF staging racks are located in the WHF pool as shown in *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope Sheet 1 of 3* (BSC 2007 [DIRS 183710]). These staging racks accommodate up to 81 PWR SNF assemblies. The basic design of the PWR CSNF staging racks is provided in *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope Sheet 2 of 3* (BSC 2007 [DIRS 183711]). A simplified plan view of the PWR racks is shown in Figure 15.

The spacing between compartments is 2 in.. There is a Boral plate on each of the four sides of the fuel compartment. The Boral plates are $^{1}/_{8}$-inch thick with boron areal density of 0.0279 g/cm^2 (BSC 2007 [DIRS 182101], Section 6.2.6). The Boral plates are designed such that, at a minimum, the entire active fuel region of the fuel assemblies is covered.



NOTE: ‘ = feet; “ = inch; SS = stainless steel; TYP = typical

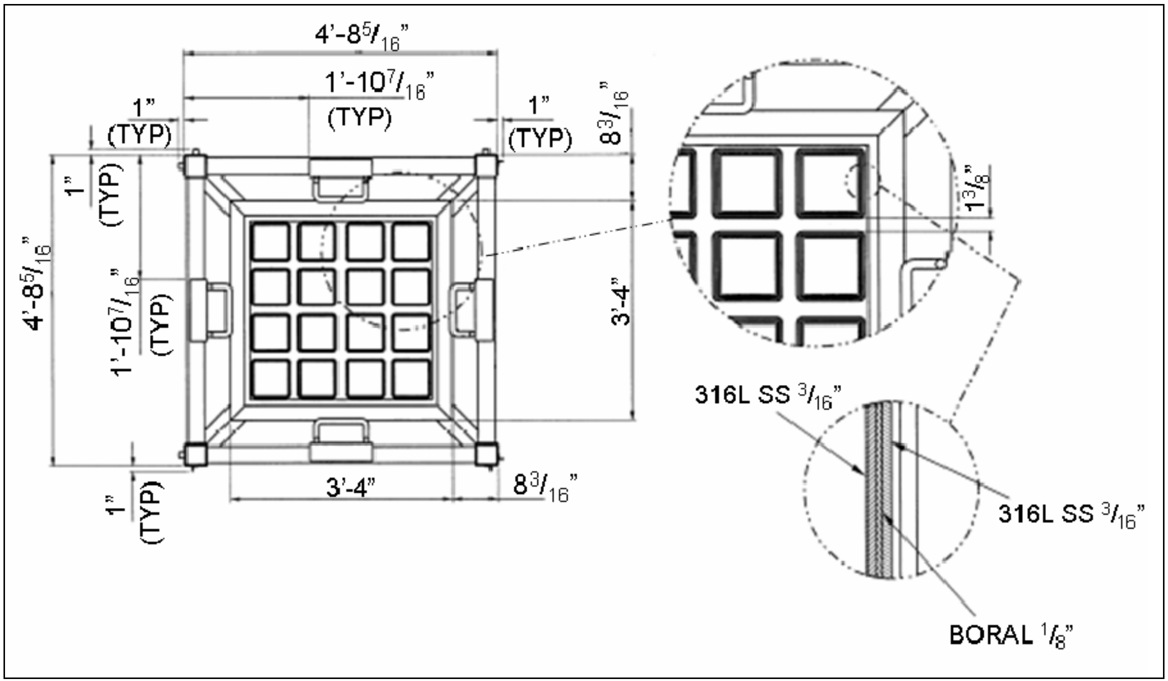
Source: Adapted from *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope Sheet 2 of 3* (BSC 2007 [DIRS 183711])

Figure 15. Plan View of PWR SNF Staging Rack for WHF Pool

2.3.1.3.2 BWR SNF Staging Racks

Eight BWR CSNF staging racks are located in the WHF pool as shown in *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope Sheet 1 of 3* (BSC 2007 [DIRS 183710]). These staging racks accommodate up to 128 BWR SNF assemblies. The basic design of the BWR CSNF staging racks is provided in *Wet Handling Facility SNF Staging Racks Mechanical Equipment Envelope Sheet 2 of 3* (BSC 2007 [DIRS 183711]). A simplified plan view of the BWR racks is shown in Figure 16.

The spacing between compartments is 1 3/8 in.. There is a Boral plate on each of the four sides of the fuel compartment. The Boral plates are $^1/_8$-inch thick with boron areal density of 0.0279 g/cm^2 (BSC 2007 [DIRS 182101], Section 6.2.6). The Boral plates are designed such that, at a minimum, the entire active fuel region of the fuel assemblies is covered.



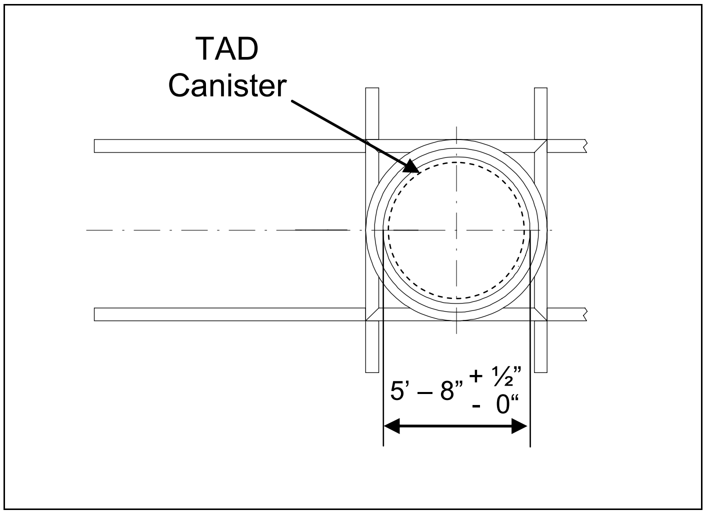
NOTE: ' = feet, " = inch; SS = stainless steel; TYP = typical

Source: Adapted from BSC 2007 [DIRS 183711]

Figure 16. Plan View of BWR SNF Staging Rack for WHF Pool

2.3.1.3.3 TAD Canister Staging Racks

A CRCF provides one TAD canister staging rack in Staging Area 1 and one in Staging Area 3. Details of the design are given in *CRCF 1 TAD Canister Staging Rack Mechanical Equipment Envelope* (BSC 2008 [DIRS 184909]). A simplified diagram of a single rack is shown in Figure 17.

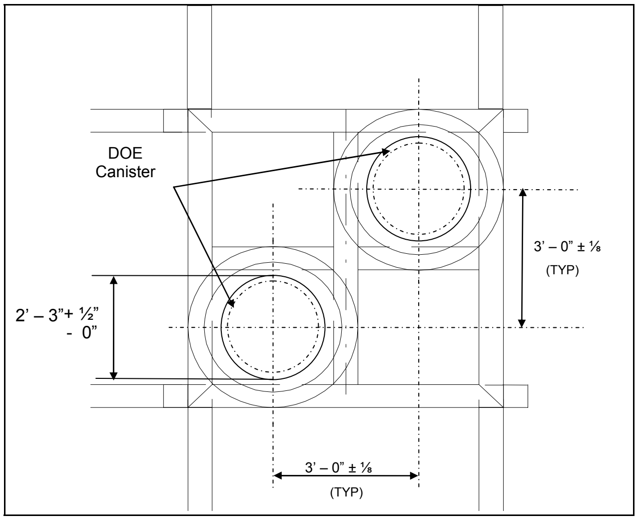


Source: Adapted from BSC 2008 [DIRS 184909].

Figure 17. Plan View of TAD Canister Staging Rack

2.3.1.3.4 DOE Canister Staging Racks

A CRCF provides staging racks with a capacity for 10 standardized DOE SNF, MCO, or HLW canisters. Details of the design are given in *CRCF 1 DOE Canister Staging Rack Mechanical Equipment Envelope* (BSC 2008 [DIRS 184908]). A simplified diagram of two adjacent racks is shown in Figure 18. Based upon the minimum center-to-center distance of 50.7 in. ($[(36\text{-}1/8)^{2}\times 2]^{1/2}$) between two adjacent staging racks and the minimum staging rack diameter of 27 in. (Figure 18), the minimum surface-to-surface separation distance between two DOE canisters in the staging racks is 23.7 in. (60.3) cm.



Source: Adapted from BSC 2008 [DIRS 184908]

Figure 18. Plan View of DOE Canister Staging Rack

2.3.2 Criticality Control Parameters

As summarized in Section 2.2.2.1, in order to identify the parameters that are important to criticality prevention during the preclosure period, a series of k_{eff} calculations were performed for each specific waste form that cover the possible conditions to which the waste form may be exposed during handling operations in the GROA. These calculations evaluated the impact on system reactivity of variations in each of the parameters that could be important to criticality during the preclosure period. These sensitivity calculations demonstrated that each parameter:

- Does not need to be controlled because it is bounded (i.e., its analyzed value is greater than or equal to the design limit) or its effect on k_{eff} is bounded,
- Needs to be controlled if another parameter is not controlled (conditional control), or
- Needs to be controlled because it is the primary criticality control parameter.

The following six parameters important to criticality were examined in the k_{eff} calculations to determine their impact on reactivity and the extent to which they need to be controlled: waste form characteristics (physical and chemical form, mass, density, fissile material composition, and enrichment), moderation, neutron absorbers (fixed and soluble), geometry, interaction, and reflection.

This section presents a deterministic screening evaluation for the type and level of control required for criticality prevention. The conclusions of this section form the bases of the event sequence development and quantification analysis for event sequences important to criticality. Event sequences that impact criticality parameters which must be controlled are then identified, developed, quantified, and categorized as described in Section 2.2.2.2.

As presented in Section 2.3.10, the USL for all CSNF operations is 0.93, whereas the USL for all DOE SNF operations is 0.89.

2.3.2.1 Criticality Control Parameters for Commercial SNF Dry Operations

2.3.2.1.1 Waste Form Characteristics for Commercial SNF Dry Operations

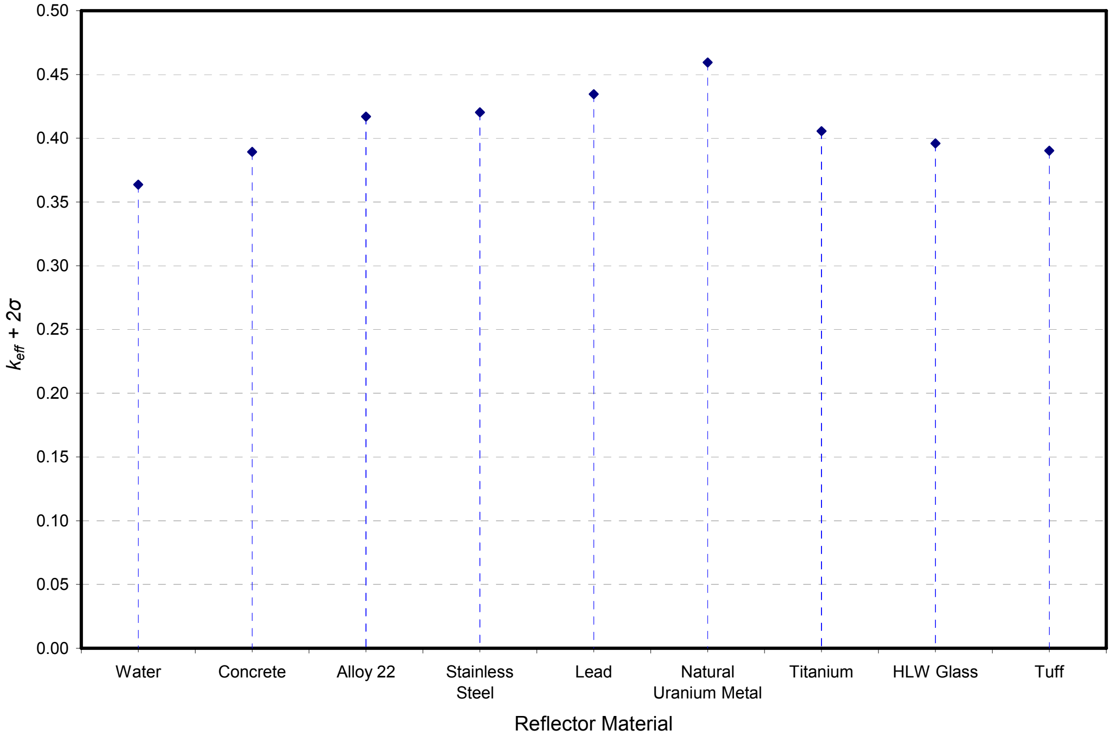
For CSNF, the k_{eff} calculations use the waste form characteristics given in Section 2.3.1.1.1. Because these waste form characteristics are considered bounding, no event sequences involving misloads of CSNF need to be identified.

2.3.2.1.2 Moderation for Commercial SNF Dry Operations

Moderation is the primary criticality control parameter during dry operations. The extent to which moderation must be controlled is dependent on the control of fixed neutron absorbers and geometry as discussed in Section 2.3.2.1.3.

Because moderator control is required to maintain subcriticality, event sequences involving introduction of moderator into breached or open transportation casks, DPCs, and TAD canisters containing CSNF must be identified, developed, quantified, and categorized.

Control of moderation is sufficient to maintain subcriticality during normal, dry CSNF operations with a maximum k_{eff}, including calculational uncertainty, less than a) 0.50 for TAD canisters as shown in Figure 19 for a PWR TAD canister with a variety of close-fitting full-thickness reflectors and in Table 24 of BSC 2007 [DIRS 182099] for a BWR TAD canister with the limiting natural uranium reflector; or b) 0.60 for dry DPCs as shown in Table 30 (PWR DPC) and Table 34 (BWR DPC) of BSC 2007 [DIRS 182101] for a variety of reflectors. For additional details on reflection, see Section 2.3.2.1.5.



Source: Adapted from Figure 25, BSC 2007 [DIRS 182099]

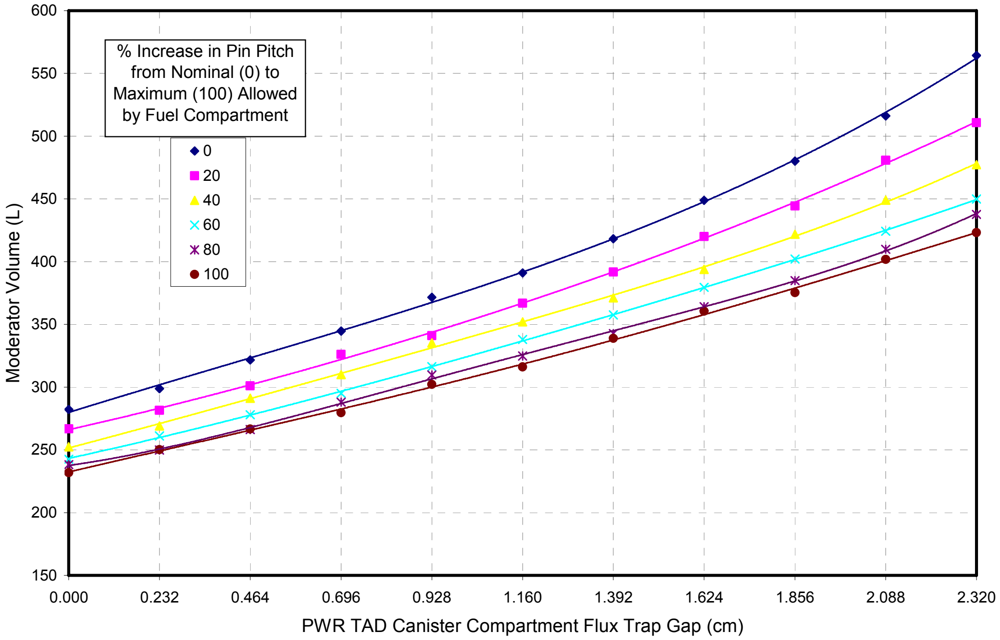
Figure 19. k_{eff} for a Single Undamaged Dry PWR TAD Canister Containing Intact, Undamaged CSNF, with Close-fitting Full-thickness Reflectors

2.3.2.1.3 Fixed Neutron Absorber and Geometry for Commercial SNF Dry Operations

Geometry control is provided in transportation casks, TAD canisters, and DPCs by the structure of the canister baskets and of the fuel assemblies themselves. Fixed neutron absorber is present in these containers as part of the basket design.

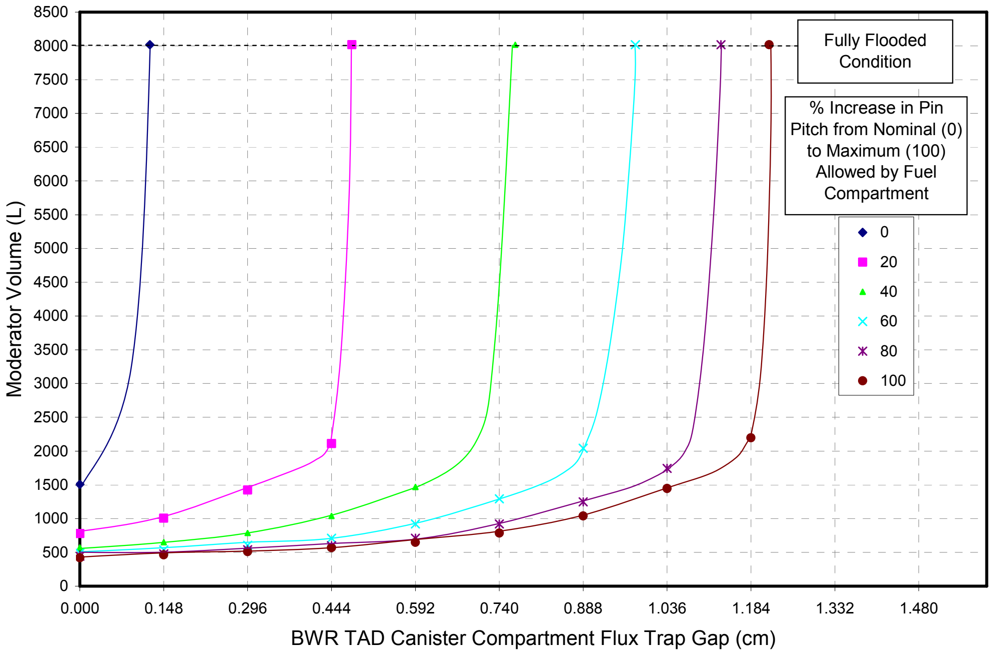
In the k_{eff} sensitivity calculations, aspects of the geometry such as pin pitch and flux trap gap size were varied between their nominal and most reactive or physically limiting state as idealized representations of potential off-normal conditions. For the nominal amount of fixed neutron absorber, Figure 20 and Figure 21 illustrate the effect of changes in pin pitch and flux trap gap size on the maximum safe quantity of moderator in a PWR and BWR TAD canister, respectively. For details of the parameter variations, see Section 6.3.2.1.1 of BSC 2007 [DIRS 182099].

It can be seen that the need for geometry control is dependent on the control of moderation. Therefore, initiating events and event sequences that impact geometry for dry CSNF operations need to be identified and quantified only if there are Category 1 or Category 2 event sequences that result in moderation inside a CSNF container.



Source: Adapted from Figure 29, BSC 2007 [DIRS 182099].

Figure 20. Maximum Safe Water Volume as a Function of Fuel Assembly Pin Pitch, and Flux Trap Gap for a Single Damaged PWR TAD Canister with a Close-fitting Full-thickness Stainless Steel Reflector

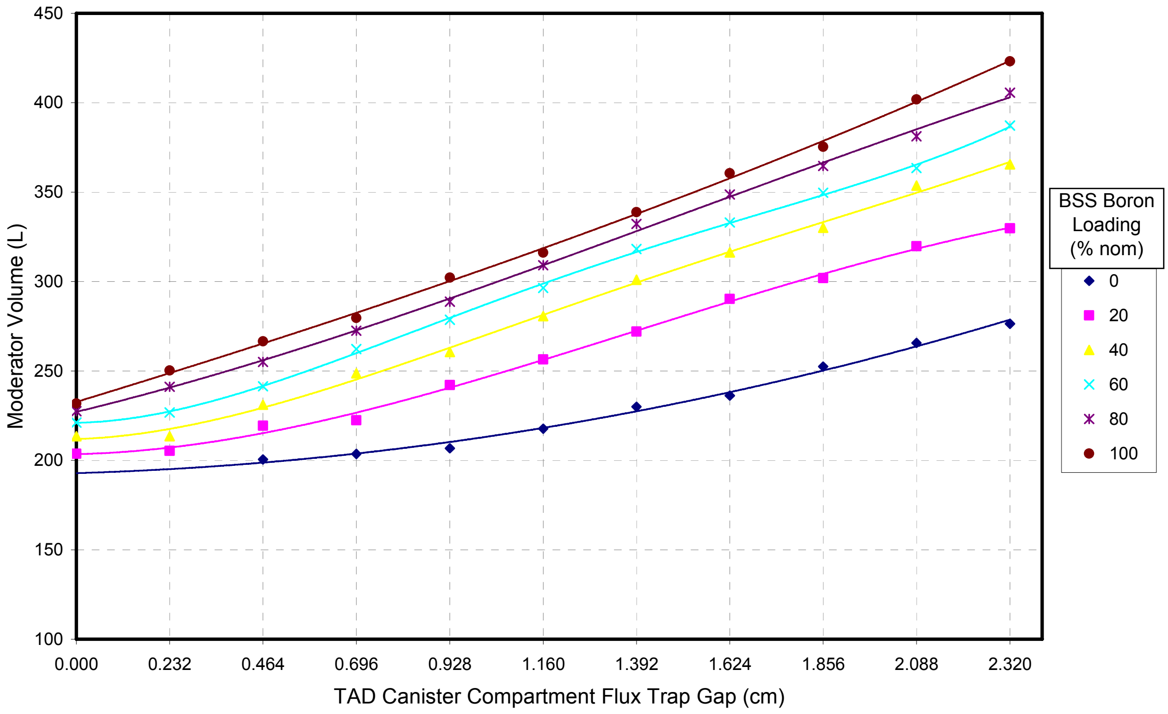


Source: Adapted from Figure 30, BSC 2007 [DIRS 182099]

Figure 21. Maximum Safe Water Volume as a Function of Fuel Assembly Pin Pitch, and Flux Trap Gap for a Single Damaged BWR TAD Canister with a Close-fitting Full-thickness Stainless Steel Reflector

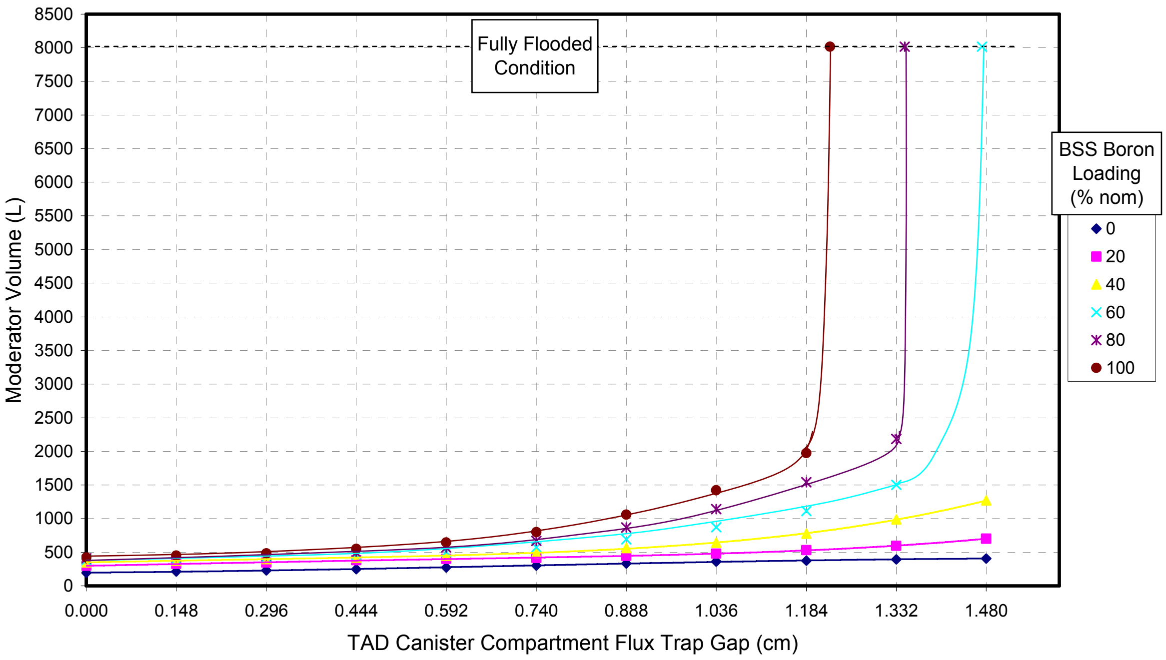
The k_{eff} sensitivity calculations examined the impact of fixed neutron absorber on system reactivity as a function of other relevant parameters to determine the minimum neutron absorber characteristics (e.g., loading) necessary to maintain subcriticality and the extent to which neutron absorber needs to be controlled. In these calculations, the fixed neutron absorber is modeled as being either present, partially or totally replaced by void, replaced by unborated stainless steel, or modeled with a reduced boron density to represent a range of possible off-normal conditions. In accordance with NUREG-1567 (NRC 2000 [DIRS 149756], Section 8.4.1.1), only 75 % credit was conservatively taken for the nominal quantity of fixed neutron absorbers. For the maximum pin pitch allowed by the fuel basket, Figure 22 and Figure 23 illustrate the effect of the amount of fixed neutron absorber by showing the maximum safe quantity of moderator in a PWR and BWR TAD canister, respectively, as a function of a) borated stainless steel (BSS) content in the absorber plates and b) flux trap gap. For details of these parameter variations, see Section 6.3.2.1.1 of BSC 2007 [DIRS 182099].

It can be seen that the need for fixed neutron absorber control depends upon the control of moderation. Therefore, initiating events and event sequences that impact neutron absorbers for dry CSNF operations need to be identified, quantified, and categorized only if there are Category 1 or Category 2 event sequences that result in introduction of moderator into a CSNF container.



Source: Adapted from Figure 31, BSC 2007 [DIRS 182099].

Figure 22. Maximum Safe Water Volume as a Function of Canister BSS Panel Boron Content and Flux Trap Gap for a Single Damaged PWR TAD Canister with a Close-fitting Full-thickness Stainless Steel Reflector



Source: Adapted from Figure 32, BSC 2007 [DIRS 182099].

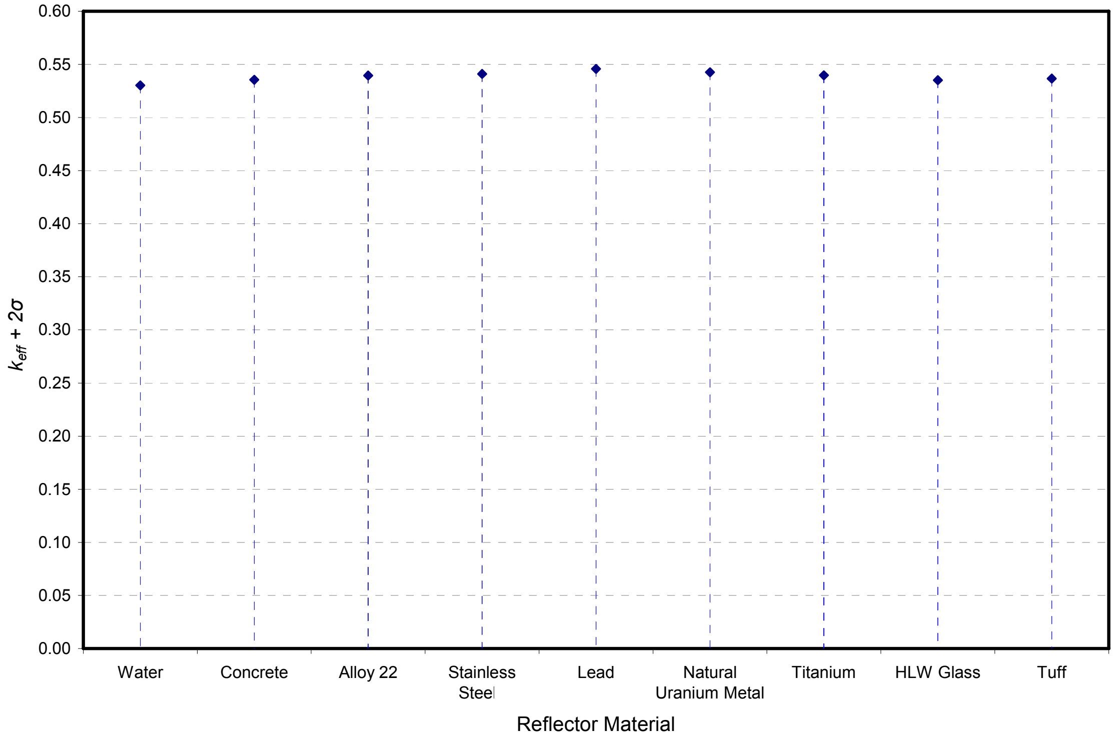
Figure 23. Maximum Safe Water Volume as a Function of Canister BSS Panel Boron Content and Flux Trap Gap for a Single Damaged BWR TAD Canister with a Close-fitting Full-thickness Stainless Steel Reflector

2.3.2.1.4 Interaction for Commercial SNF Dry Operations

The k_{eff} sensitivity calculations examined the impact of interaction of containers of CSNF with containers of the same or other waste forms (that may be present or handled in the same facility) on system reactivity as a function of other relevant parameters to determine the extent to which interaction must be controlled.

The models for TAD canisters and DPCs include infinite hexagonal planar arrays of close-fitting units, which are conservative models that effectively bound interaction between these units.

In the absence of moderation, CSNF is subcritical regardless of interaction. This is illustrated by Figure 24, which gives k_{eff} as a function of axial reflector material for an infinite planar array of undamaged TAD canisters containing intact, undamaged CSNF.



Source: Adapted from Figure 26, BSC 2007 [DIRS 182099]

Figure 24. k_{eff} for an Infinite Planar Array of Undamaged Dry PWR TAD Canisters Containing Intact CSNF, in Close-packed Triangular Pitch Configuration with Close-fitting Full-thickness Axial Reflectors

Based on the results presented in Figure 24, it is seen that little difference in the k_{eff} values is observed as a function of reflector material for an infinite planar array of PWR TAD canisters. Because there is a significant margin of subcriticality for all reflector materials for PWR TAD canisters, a stainless steel axial reflector was used in the model of an infinite planar array of BWR TAD canisters, for which the results are presented in Table 4, along with the equivalent case for the PWR TAD canister. It can be seen that under normal (i.e. dry and undamaged) conditions, substantial margin exists between the computed peak k_{eff} value and the USL of 0.93.

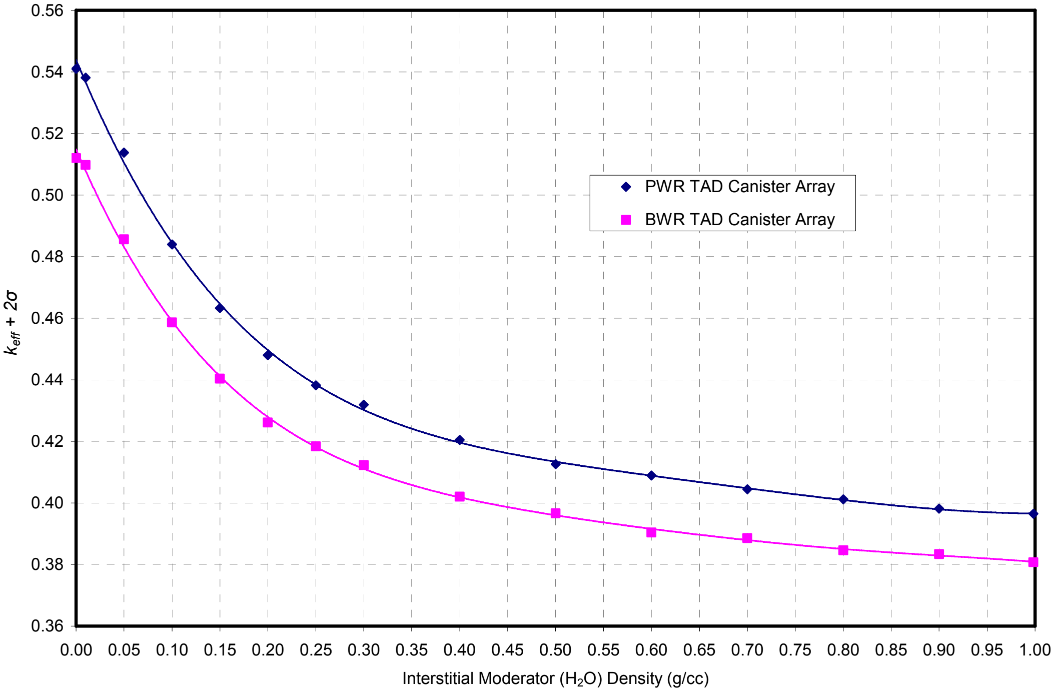
Table 4. k_{eff} for an Infinite Planar Array of Undamaged Dry PWR And BWR TAD Canisters in Close Packed Triangular-Pitched Configuration with Full Stainless Steel Axial Reflector

TAD Canister Variant	**Close-fitting 30 cm Thick Axial Reflector Material**	**TAD Canister Surface-Surface Spacing (cm)**	**$k_{eff} + 2\sigma$**
PWR	Stainless Steel	0.0	0.54104
BWR	Stainless Steel	0.0	0.51201

Source: Table 25, BSC 2007 [DIRS 182099]

Given that transportation casks and DPCs contain the same waste form with similar basket structure and fixed neutron absorber characteristics, in the absence of moderation, interaction is also bounded between all of these units.

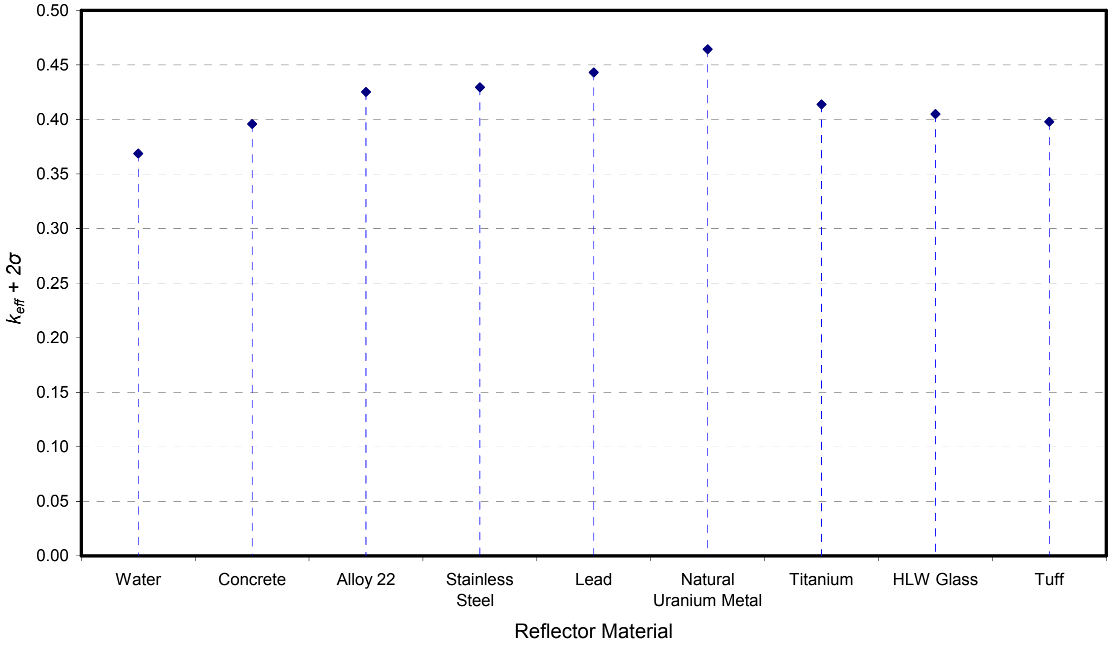
To confirm the expectation that the presence of moderator in the interstitial space between the TAD canisters in the canister infinite planar array configuration would reduce the calculated peak k_{eff} value, a series of calculations were performed with variable density water in between the TAD canisters. From the trend established in Figure 25, it is seen that the presence of moderator external to and between the TAD canisters results in a decrease in the system k_{eff}.



Source: Adapted from Figure 27, BSC 2007 [DIRS 182099]

Figure 25. k_{eff} for an Infinite Planar Array Of Undamaged Dry TAD Canisters In Close Packed Triangular-Pitched Configuration with Full-Thickness Stainless Steel Axial Reflector, Intact CSNF, and Variable Density Water in the Interstitial Space Between the Canisters

Interaction between CSNF waste packages containing the same waste form in an emplacement drift is bounded by the use of mirror boundary conditions applied to the axial ends of close-fitting, radially reflected TAD canisters (Figure 26). There is no statistically significant difference between the k_{eff} for a single waste package (fully reflected TAD canister) (Figure 19) and the k_{eff} for a waste package (fully radially reflected TAD canister) with mirror boundary conditions at the axial ends of the waste package. Note that the same trend holds true for DOE SNF codisposal waste packages as shown in Section 2.3.2.3.4. Therefore, a waste package containing CSNF is always effectively infinite in length, so that its interaction with other waste packages (of commercial or DOE SNF) in an emplacement configuration is bounded. From Figure 26 (for PWR TAD canister waste packages) and Table 26 of BSC 2008 [DIRS 182099] (for BWR TAD canister waste packages), it can be seen that in the absence of moderation, subcriticality is maintained for interaction of waste packages containing commercial SNF in an emplacement configuration with a maximum k_{eff}, including calculational uncertainty, less than 0.50.



Source: Adapted from Figure 28, BSC 2007 [DIRS 182099]

Figure 26. k_{eff} for an Infinitely Long Row (Drift) of Undamaged Dry PWR TAD Canisters Containing Intact, Undamaged CSNF, with Close-fitting Full-thickness Reflectors

To conservatively represent the interaction of containers of CSNF and DOE SNF during surface operations, the various types of DOE SNF canisters were modeled as being surrounded by a close-fitting 30-cm-thick UO_2 reflector with 5 wt% ^{235}U enrichment. As discussed in Section 2.3.2.3.4, with the most reactive DOE standardized SNF canister, the maximum k_{eff}, including calculational uncertainty, for this configuration is less than 0.84 (BSC 2008 [DIRS 182100], Attachment 3, Tab “Ref Thk Data” of spreadsheet “Ancillary Results.xls”).

In the absence of moderation inside CSNF containers, subcriticality is maintained for interaction of containers (transportation casks, DPCs, TAD canisters, and waste packages) of CSNF during surface and subsurface operations. Therefore, initiating events and event sequences that impact interaction for dry CSNF operations need to be identified and quantified only if there are Category 1 or Category 2 event sequences that result in moderation inside a CSNF container.

2.3.2.1.5 Reflection for Commercial SNF Dry Operations

The reflectors considered in the analysis of transportation casks, DPCs, TAD canisters, and waste packages include all materials that could be present during dry operations (i.e., stainless steel, concrete, lead, depleted uranium, water, Alloy 22, HLW glass, titanium, and tuff). Depleted uranium was conservatively modeled as natural uranium (BSC 2007 [DIRS 182099], Section 6.2.2.3.4), and all further reference to depleted uranium as a reflector for dry CSNF operations in this report will discuss natural uranium. Reflector materials were modeled as close-fitting reflectors that are effectively full-thickness, that is, the thickness is greater than or equal to any dimension that may be encountered during dry operations or the thickness is sufficient to be considered neutronically infinite. Note that 30 cm of close-fitting reflection by stainless steel, concrete, water, Alloy 22, HLW glass, natural uranium, and tuff is effectively infinite (BSC 2008 [DIRS 182100], Attachment 3, Tab “Ref Thk Data” of spreadsheet “Ancillary Results.xls”). For lead and titanium, 30 cm is expected to bound any thickness of either of these two materials used in the surface and subsurface facilities as well as in any transportation cask. As noted in Section 6.3.1.1 of BSC 2008 [DIRS 182099], CSNF canisters are modeled both as fully-reflected single canisters and as axially reflected infinite hexagonal planar arrays.

Therefore, reflection is considered bounded for CSNF and no event sequences involving reflection need to be identified.

2.3.2.2 Criticality Control Parameters for Commercial SNF Wet Operations

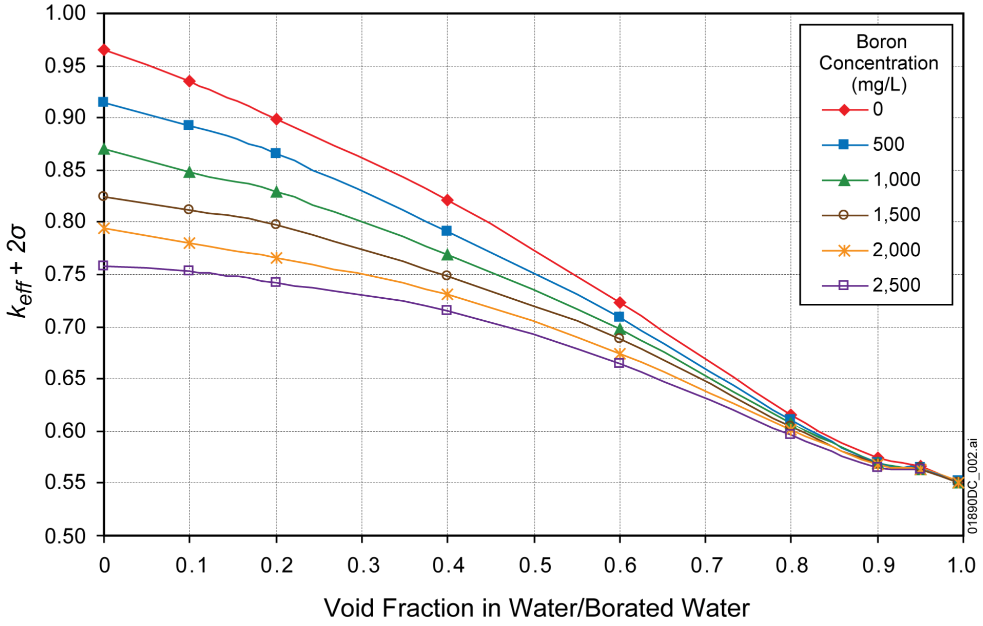
2.3.2.2.1 Waste Form Characteristics for Commercial SNF Wet Operations

For CSNF, the k_{eff} calculations for wet operations use the waste form parameters given in Section 2.3.1.1.1, just as for dry operations. Because these waste form parameters are considered bounding, no event sequences involving misloads of CSNF need to be identified.

2.3.2.2.2 Moderation for Commercial SNF Wet Operations

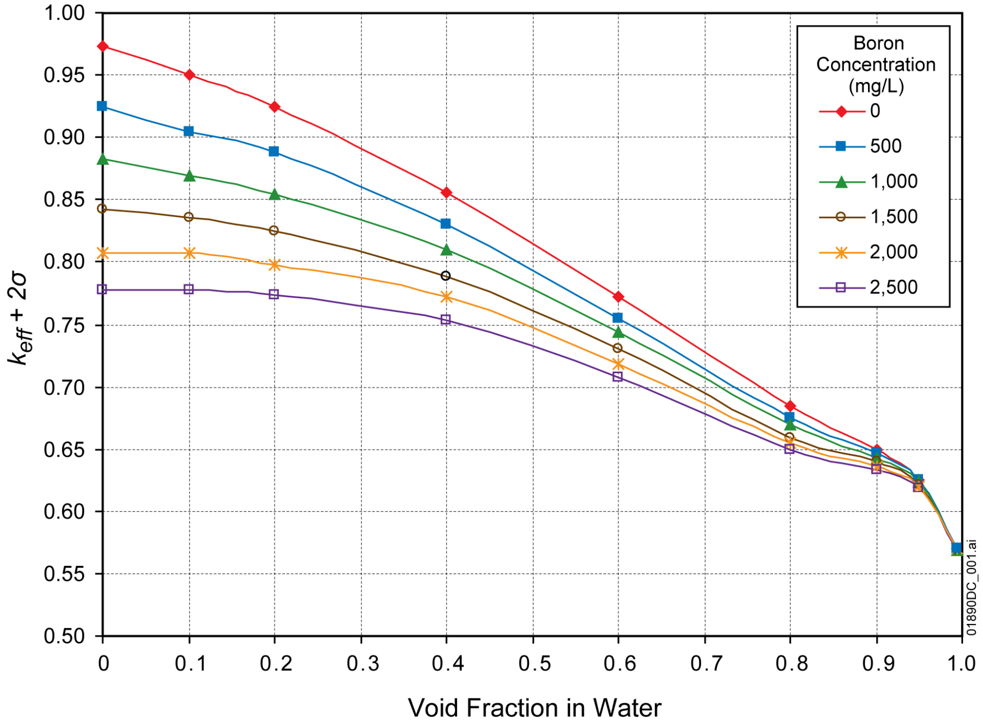
Control of moderation is not applicable to wet operations with CSNF; therefore, water moderation is not limited or controlled.

Figure 27 and Figure 28 show the effect of variable water density (i.e. void fraction) on k_{eff} for undamaged PWR and BWR DPCs for varying concentrations of soluble neutron absorber. It can be seen that full density water is bounding at all boration levels. Therefore, initiating events and event sequences that result in reducing the density of water for CSNF operations (e.g., boiling) do not need to be identified.



Source: Adapted from Figure 73, BSC 2007 [DIRS 182101]

Figure 27. k_{eff} for a PWR DPC Containing B&W 15×15 Fuel Assemblies as a Function of Void Fraction in Water/Borated Water



Source: Adapted from Figure 80, BSC 2007 [DIRS 182101]

Figure 28. k_{eff} for a BWR DPC Containing GE 7×7 Fuel Assemblies as a Function of Void Fraction in Water/Borated Water

2.3.2.2.3 Soluble Neutron Absorber for Commercial SNF Wet Operations

The k_{eff} sensitivity calculations for wet operations involving CSNF examined the impact of soluble neutron absorbers on system reactivity as a function of other relevant parameters to determine the minimum soluble neutron absorber characteristics (e.g., concentration) necessary to maintain subcriticality and the extent to which neutron absorber must be controlled.

Soluble neutron absorber in the form of orthoboric acid, H_3BO_3, is present in the WHF pool and in transportation cask/DPC fill water. The soluble boron concentration required to maintain subcriticality is dependent upon the limiting conditions and/or control of other parameters important to criticality safety. Therefore, the soluble boron sensitivity calculations are discussed in conjunction with fixed neutron absorber, geometry, and interaction in Section 2.3.2.2.4, which indicates that a soluble boron concentration of 2500 mg/L of boron enriched to 90 atom % ^{10}B is sufficient to maintain subcriticality with bounding geometry, neutron absorber, and interaction conditions for normal operations and potential event sequences.

Because soluble neutron absorber is required to maintain subcriticality, event sequences that dilute the concentration of soluble boron in the WHF pool and transportation cask/DPC fill water need to be identified, developed, quantified, and categorized.

2.3.2.2.4 Fixed Neutron Absorber, Geometry, and Interaction for Commercial SNF Wet Operations

Because event sequences involving CSNF in the WHF pool will likely impact fixed neutron absorber, geometry, and interaction at the same time, the k_{eff} sensitivity calculations considered these three criticality control parameters collectively.

Fixed neutron absorber is present in transportation casks, TAD canisters, DPCs and in the staging racks in the WHF pool. In the k_{eff} sensitivity calculations, the quantity of fixed neutron absorber is varied between its nominal value and complete omission. In accordance with NUREG-1567 (NRC 2000 [DIRS 149756], Section 8.4.1.1) only 75 % credit was conservatively taken for the nominal quantity of fixed neutron absorber present.

Geometry control is provided by the structure of the canister baskets and the pool staging racks, as well as by the structure of the assemblies themselves. In the k_{eff} sensitivity calculations, aspects of geometry such as pin pitch and flux trap gap size are varied between their nominal and most reactive or physically limiting state.

In addition, the k_{eff} sensitivity calculations examined the impact of interaction of individual assemblies and containers of CSNF on system reactivity as a function of other relevant parameters to determine the extent to which interaction must be controlled.

In order to bound geometry for normal operations and potential event sequences associated with transferring single assemblies from DPCs or transportation casks to the staging racks or into a TAD canister or from the staging racks to a TAD canister, all criticality calculations were performed with close-fitting full-thickness reflection with borated water, unborated water, concrete, stainless steel, lead, and natural uranium modeled on all six sides of an assembly (BSC 2007 [DIRS 182101], Section 6.3) with optimized pin pitch. For the limiting PWR assembly in this configuration (i.e., B&W 15x15) and the most limiting reflection conditions, no more than 15 % of the minimum required soluble boron is sufficient to maintain subcriticality

(BSC 2007 [DIRS 182101], adapted from Figure 44 based on 1500 mg/L of natural boron (i.e., $[\frac{0.199 \cdot 1500}{0.9 \cdot 2500}]$)).

For the same configuration, with the most limiting reflection conditions, BWR assemblies remain subcritical without any credit for soluble boron, with a maximum k_{eff}, including calculational uncertainty, less than 0.80 (BSC 2007 [DIRS 182101] Figures 45 and 46).

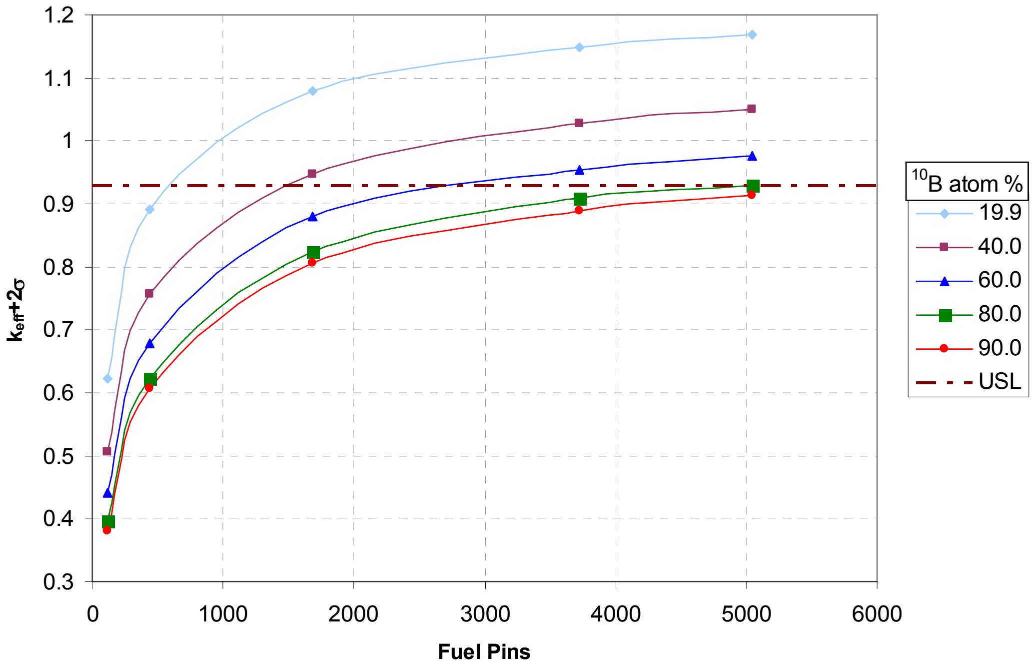
Interaction of single undamaged assemblies and the undamaged staging racks results in a maximum Δk_{eff} less than 5%, with a maximum k_{eff}, including calculational uncertainty less than 0.80 crediting no more than 15 % of the minimum required soluble boron. The maximum Δk_{eff} for interaction between an assembly and an STC containing a TAD canister or a DPC is expected to be similar based on the similarity of their neutronic characteristics to the staging racks. The conservative representation for this configuration is based on an infinite planar array of staging racks with an infinitely long assembly on top (BSC 2007 [DIRS 182101], Section 6.3.4).

Potential event sequences including drops or seismic events during operations with STCs containing either TAD canisters or DPCs associated with their transfer in and out of the pool could impact the geometry inside these canisters as well as the effectiveness of the fixed neutron absorber. Subcriticality is maintained for these operations crediting no more than 10 % of the minimum required soluble boron with the geometry control and the fixed neutron absorber provided by the canister baskets (BSC 2007 [DIRS 182101], Table 45). In order to bound geometry, fixed neutron absorber, and interaction effects inside these canisters, the canister baskets and the fixed neutron absorber are omitted. This configuration is neutronically similar to a hypothetical conservative representation in which the entire contents of a transportation cask or STC are optimally rearranged in a square pitch array outside of the confinement of the cask or STC on the bottom of the pool reflected by stainless steel or concrete and borated water. The required ^{10}B enrichment for various transportation cask/DPC capacities is shown in Table 5, as well as the corresponding maximum acceptable dilution relative to a 90 atom % ^{10}B enrichment. The results for the stainless steel reflected configurations, shown in Figure 29 through Figure 32, are statistically equivalent to those for the concrete reflected configurations (BSC 2007 [DIRS 182101], Attachment 2, spreadsheet “Simple Geometry Results.xls,” tabs “BW 15 Processed Results,” “17OFA Processed Results,” “ANF9 Processed Results,” and “GE7 Processed Results.”). It can be seen that subcriticality is maintained with a soluble boron (enriched to 90 atom% ^{10}B) concentration of 2500 mg/L for the most limiting fuel type, pin design, and reflection condition.

Table 5. Maximum Acceptable Dilution of 90 Atom % ^{10}B Enriched Boron to Maintain Subcriticality for Various Transportation Cask/DPC Capacities

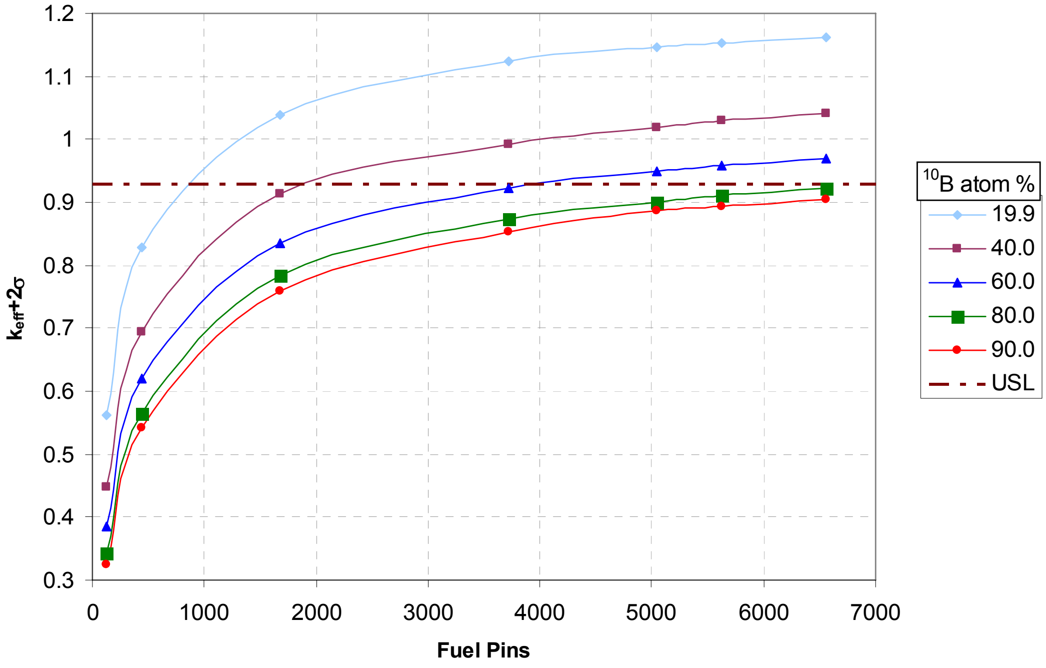
Transportation Cask/DPC Capacity (assemblies)	Number of Fuel Pins per Assembly	Total Number of Fuel Pins per Cask/DPC	Required ^{10}B Enrichment at 2500 mg/L Total B concentration (atom %)	Maximum Acceptable Dilution (%) at 2500 mg/L Concentration of 90 atom % ^{10}B Enriched Boron[f]
4 PWR	208 (15×15)	832	40[a]	55
	264 (17×17)	1056	40[b]	55
9 PWR	208 (15×15)	1872	60[a]	33
	264 (17×17)	2376	60[b]	33
21 PWR	208 (15×15)	4368	80[a]	11
	264 (17×17)	5544	80[b]	11
24 PWR	208 (15×15)	4992	90[e]	0
	264 (17×17)	6336	80[b]	11
9 BWR	49 (7×7)	441	40[c]	55
	77(9×9)	693	40[d]	55
12 BWR	49 (7×7)	588	40[c]	55
	77(9×9)	924	40[d]	55
24 BWR	49 (7×7)	1176	60[c]	33
	77(9×9)	1848	40[d]	55
44 BWR	49 (7×7)	2156	80[c]	11
	77(9×9)	3388	60[d]	33
68 BWR	49 (7×7)	3332	90[c]	0
	77(9×9)	5236	90[d]	0

[a] Source: Figure 29
[b] Source: Figure 30
[c] Source: Figure 32
[d] Source: Figure 31
[e] Source: Attachment 2, spreadsheet “Simple Geometry Results,” tab “BW 15 Processed Results,” BSC 2007 [DIRS 182101]
[f] Dilution ≡ 100 × (Initial ^{10}B enrichment – Required ^{10}B enrichment)/(Initial ^{10}B enrichment)



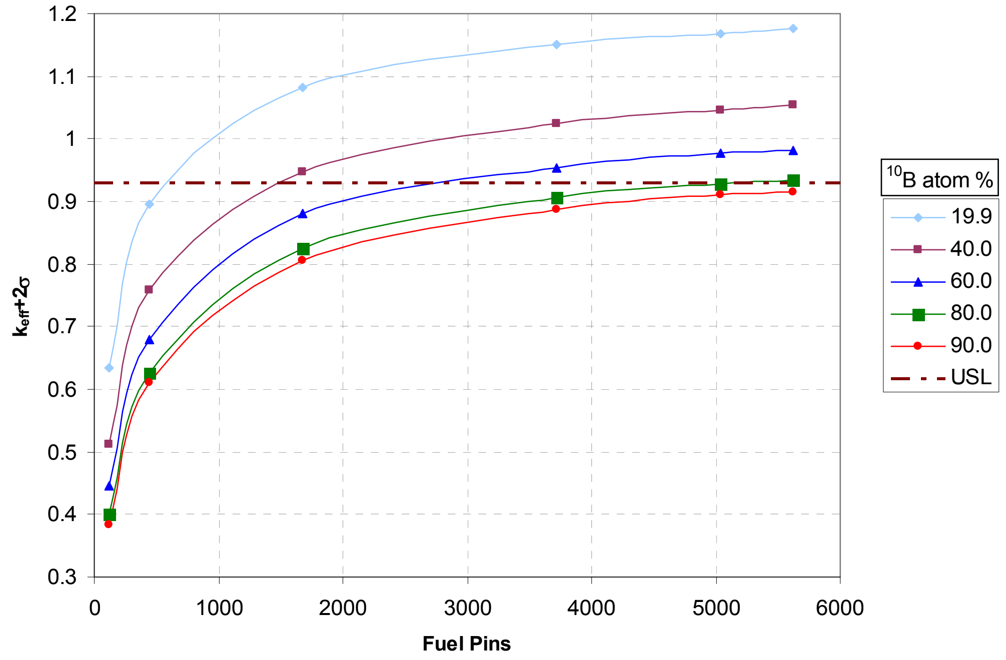
Source: Adapted from Figure 111, BSC 2007 [DIRS 182101]

Figure 29. Maximum k_{eff} versus Number of B&W 15×15 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection



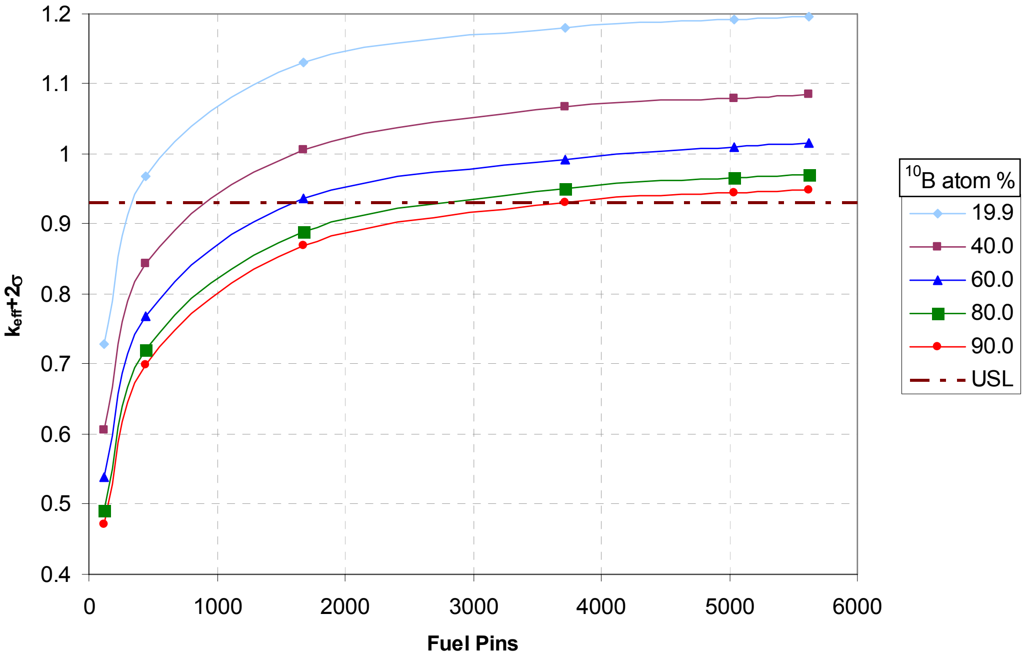
Source: Adapted from Figure 113, BSC 2007 [DIRS 182101]

Figure 30. Maximum k_{eff} versus Number of Westinghouse 17×17 OFA Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection



Source: Adapted from Figure 115, BSC 2007 [DIRS 182101]

Figure 31. Maximum k_{eff} versus Number of 9×9 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection



Source: Adapted from Figure 117, BSC 2007 [DIRS 182101]

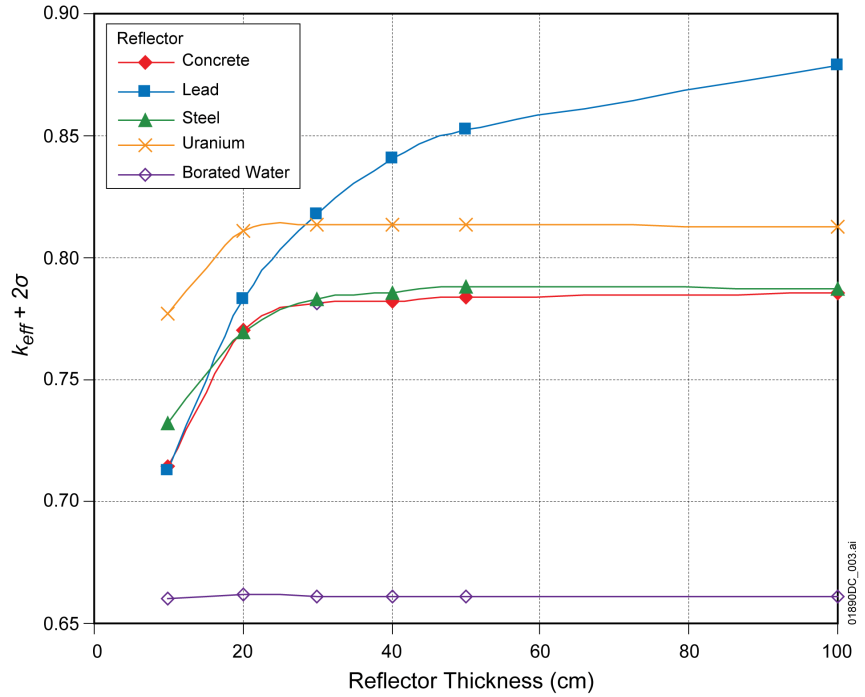
Figure 32. Maximum k_{eff} versus Number of 7×7 Fuel Pins for Various Boron Enrichments at a fixed Boron Concentration of 2500 mg/L with Steel and Borated Water Reflection

Event sequences that result in damage to the staging racks are conservatively represented with optimally spaced fuel pins within the fuel compartments, fixed neutron absorber omission, and complete flux trap gap collapse, for which subcriticality is maintained crediting no more than 30 % of the minimum required soluble boron based on the extrapolated fit in tab "BW15 Processed Results", spreadsheet "Rack Results.xls" in Attachment II of BSC 2007 [DIRS 182101].

Therefore, control of geometry, fixed neutron absorber, and interaction in the WHF pool is not required for operations with single assemblies and STCs containing either TAD canisters or DPCs unless Category 1 or Category 2 event sequences are identified that result in boron dilution sufficient to lower the concentration below 2500 mg/L of boron enriched to 90 atom % ^{10}B. In addition, because the staging racks are designed to maintain confinement of the fuel assemblies within the fuel compartments for all Category 1 and Category 2 event sequences (Assumption 1.4.6), a concentration of 2500 mg/L of soluble boron enriched to 90 atom % ^{10}B is also sufficient to maintain subcriticality without any additional control of geometry, interaction or fixed neutron absorber.

2.3.2.2.5 Reflection for Commercial SNF Wet Operations

The reflectors considered in the analysis of transportation casks, DPCs, CSNF assemblies, and TAD canisters include all materials that could be present during wet operations, i.e., borated and unborated water, stainless steel, concrete, lead, and depleted uranium. Depleted uranium was conservatively modeled as natural uranium (BSC 2007 [DIRS 182101], Section 6.2.3.5), and all further reference to depleted uranium as a reflector for wet CSNF operations in this report will discuss natural uranium. Reflector materials were modeled as close-fitting reflectors that are effectively full-thickness, that is, the thickness is greater than or equal to any dimension that may be encountered during wet operations or the thickness is sufficient to be considered neutronically infinite. As shown in Figure 33, 30 cm of close-fitting reflection by stainless steel, concrete, uranium, and borated water is effectively infinite. Whereas, for lead, 30 cm bounds any thickness of this material used in the surface and subsurface facilities as well as in any transportation cask. The trends presented in Figure 33 are similar for various configurations and various boration levels (BSC 2007 [DIRS 182101], Section 6.3.1). TAD canisters and DPCs were modeled as axially reflected infinite hexagonal planar arrays (BSC 2007 [DIRS 182101], Sections 6.1.3 and 6.1.4, respectively).



Source: Adapted from Figure 48, BSC 2007 [DIRS 182101]

Figure 33. k_{eff} as a Function of Reflector Material and Thickness for a 17x17 PWR Assembly Moderated with Borated Water

Therefore, reflection is considered bounded for CSNF and no event sequences involving reflection need to be identified.

2.3.2.3 Criticality Control Parameters for DOE SNF

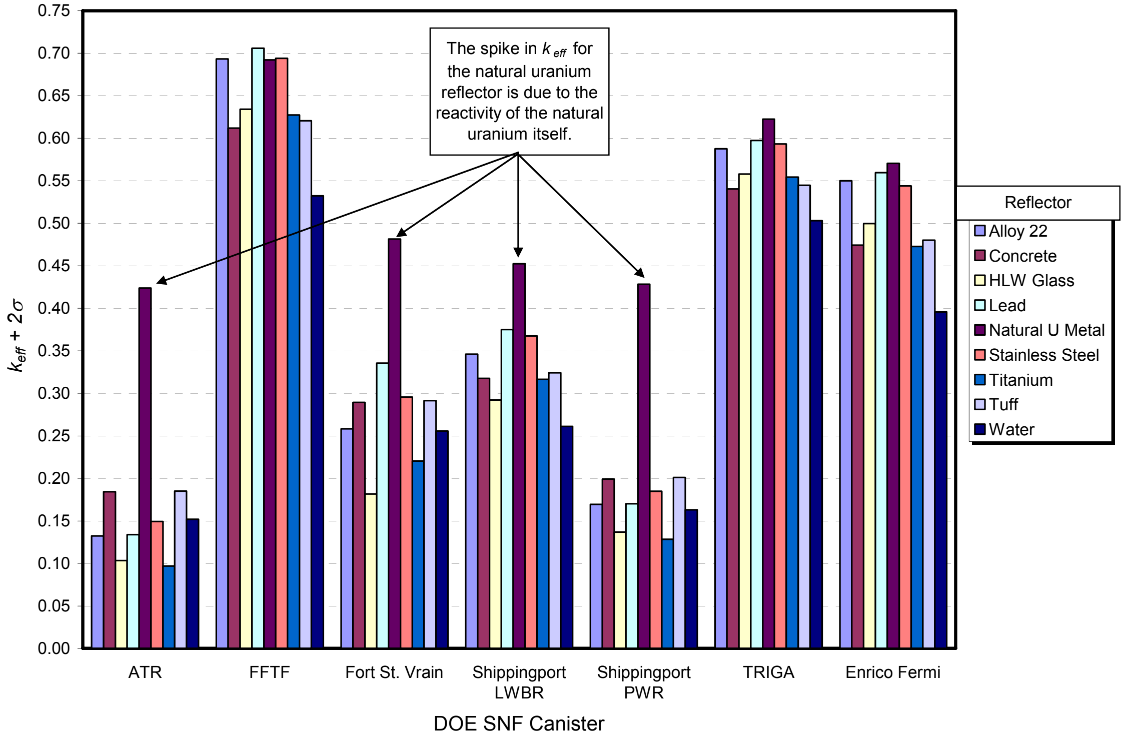
2.3.2.3.1 Waste form Characteristics for DOE SNF

The preclosure criticality safety analysis is based on the nine representative DOE SNF fuel types as described in Section 2.3.1.1.2. Consideration of waste form misload is not appropriate because the criticality safety analysis is for representative DOE SNF fuel types only and loading procedures for DOE standardized SNF canisters have not been established yet.

2.3.2.3.2 Moderation for DOE SNF

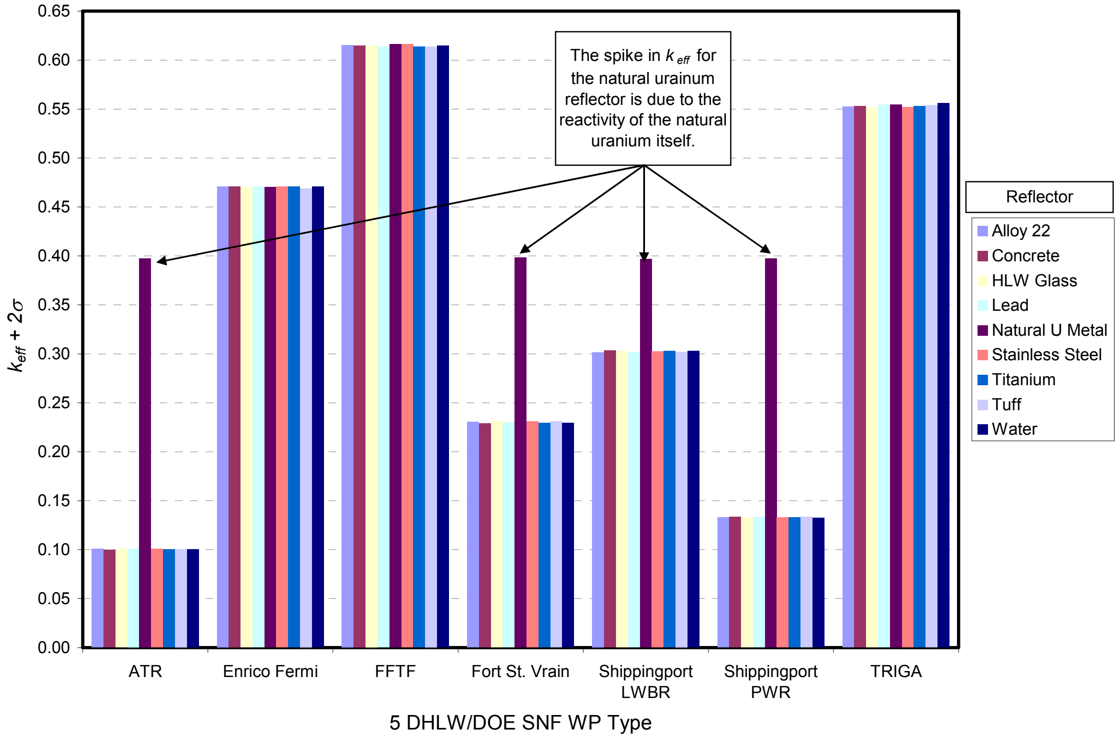
Moderation is a primary criticality control parameter for DOE SNF operations. Because moderator control is required to maintain subcriticality, event sequences related to introduction of moderator into breached transportation casks, DOE SNF canisters, and codisposal waste packages containing DOE SNF canisters need to be identified, developed, quantified, and categorized.

Control of moderation is sufficient to maintain subcriticality during dry operations with individual canisters, with a maximum k_{eff}, including calculational uncertainty, less than 0.75 for DOE SNF (Figure 34 and Figure 35).



Source: Adapted from Figure 7-1, BSC 2008 [DIRS 182100]

Figure 34: k_{eff} for Individual Undamaged and Dry DOE Standardized SNF Canisters with a Variety of Close-fitting Full-thickness Reflectors



Source: Adapted from Figure 7-5, BSC 2008 [DIRS 182100]

Figure 35. k_{eff} for Individual Undamaged, Dry and Normally Loaded 5 DHLW/DOE SNF WPs with a Variety of Close-fitting Full-thickness Reflectors

In the absence of moderation, DOE standardized SNF canisters and codisposal waste packages containing TMI-2 fuel debris will be subcritical with a maximum k_{eff} including calculational uncertainty, less than 0.36 (BSC 2005 [DIRS 173284], Table 6.2-1).

2.3.2.3.3 Fixed Neutron Absorber and Geometry for DOE SNF

The k_{eff} sensitivity calculations for DOE SNF examined the impact of fixed neutron absorber on system reactivity as a function of other relevant parameters to determine the minimum neutron absorber characteristics (e.g., loading) that maintain subcriticality and the extent to which neutron absorber must be controlled. In the sensitivity analysis, these fixed neutron absorbers were modeled as being either present, or as partially or totally absent. In accordance with NUREG-1567 (NRC 2000 [DIRS 149756], Section 8.4.1.1), only 75 % credit was conservatively taken for the nominal quantity of fixed neutron absorbers.

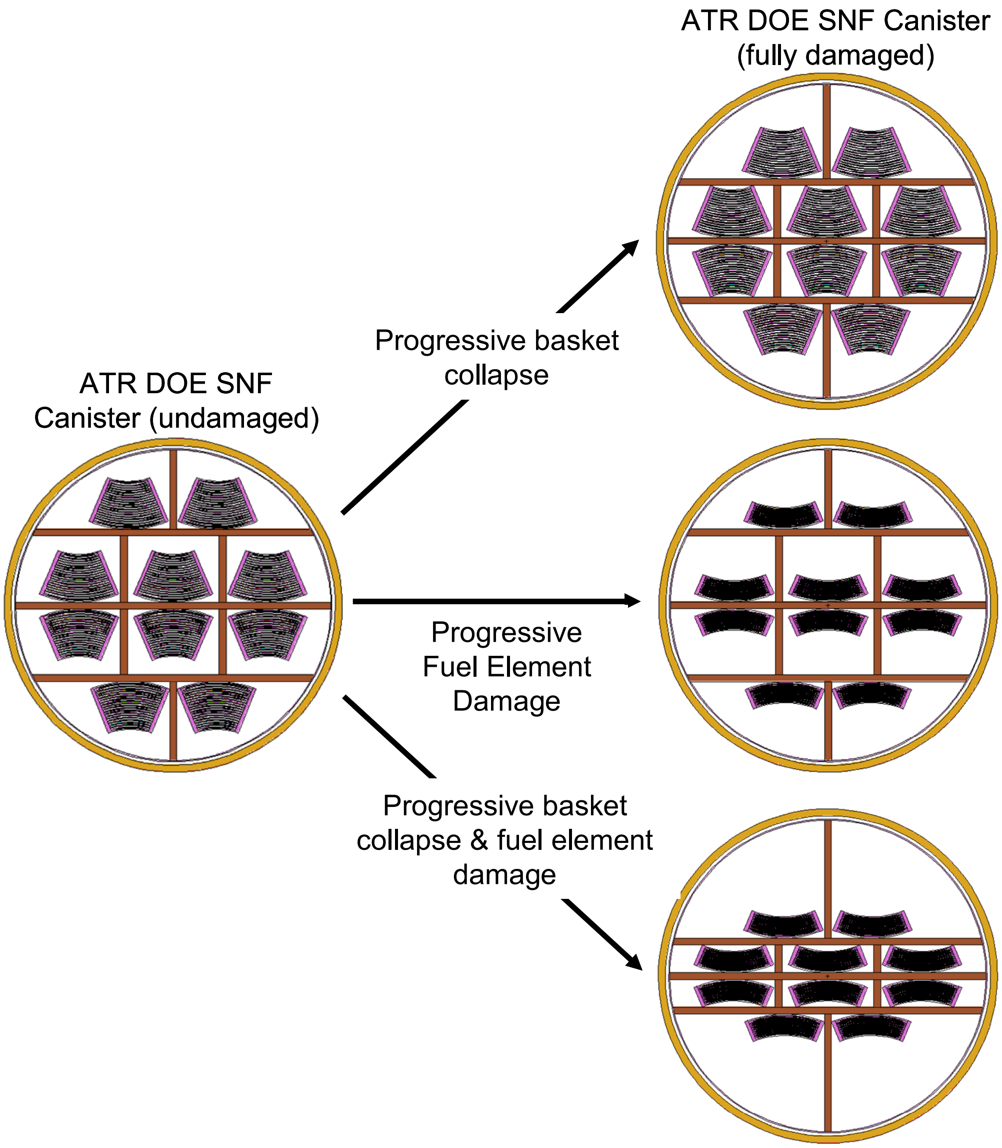
The k_{eff} sensitivity calculations examined the impact of geometry on system reactivity as a function of other relevant parameters to determine the extent to which geometry must be controlled. In the sensitivity analysis, aspects of the geometry such as pin pitch, plate spacing, and fuel damage were varied between their nominal and most reactive or physically limiting states as idealized representations of potential off-normal conditions. Details of the parameter variations considered in the sensitivity analysis are discussed in Section 6.2.2 of BSC 2008 [DIRS 182100].

Because geometry control inside several DOE standardized SNF canisters is provided by a gadolinium-bearing low-carbon high-nickel alloy, which also serves as the fixed neutron absorber, the k_{eff} sensitivity calculations examined the two parameters collectively as discussed in the following subsection for each of the DOE SNF types. Because of the variability of total fissile mass, geometry control, and fuel element matrix for the seven DOE SNF types analyzed in this section, various geometry treatments and levels of conservatism are considered for each fuel type.

2.3.2.3.3.1 Fixed Neutron Absorber and Geometry for ATR SNF

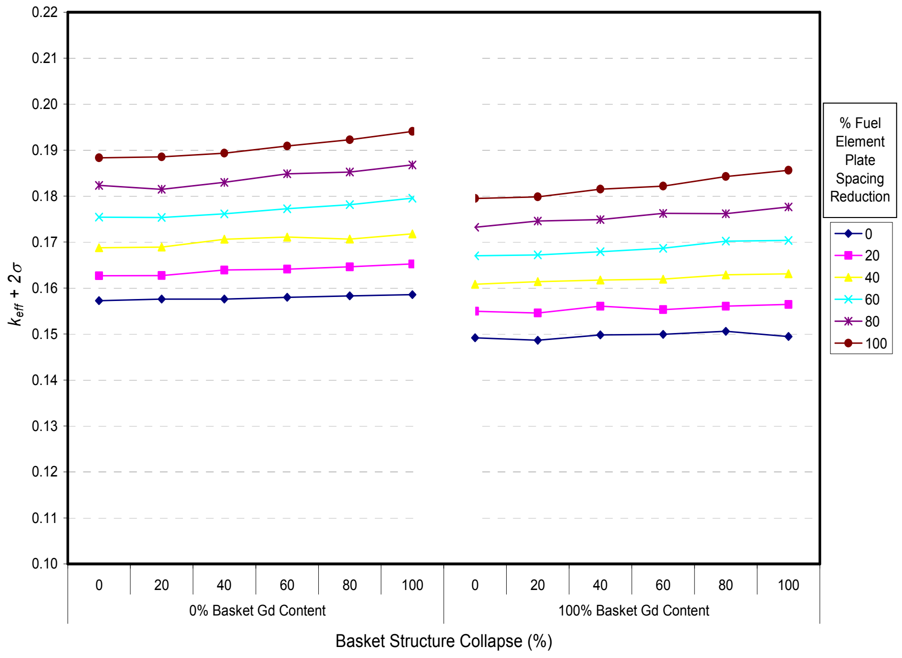
Geometry control for DOE standardized SNF canisters containing ATR SNF is provided by a basket made of a gadolinium-bearing low-carbon high-nickel alloy, which also serves as the fixed neutron absorber. The basket limits the number of ATR elements loaded in a DOE standardized SNF canister to 30 (10 elements per layer) (Figure 13).

To investigate the worth of the fixed neutron absorber in DOE standardized SNF canisters containing ATR SNF, the presence and complete omission of the gadolinium in the basket material were studied as function of geometry as illustrated in Figure 36. The results in Figure 37 demonstrate that the gadolinium for the various stages of basket collapse is worth less than a Δk of 0.01. This is due to the fact that gadolinium, which is the primary neutron absorber in the basket and filler material in DOE standardized SNF canisters containing ATR SNF, is a strong thermal neutron absorber, and its effectiveness diminishes in hard neutron spectra associated with dry conditions. Figure 37 shows that the maximum k_{eff}, including calculational uncertainty, is less than 0.20 for a stainless steel reflected DOE standardized SNF canister containing ATR SNF with complete omission of the gadolinium in the basket, maximum fuel plate collapse, and maximum basket collapse. Results shown in Figure 38 for analysis of the most reactive damage conditions based on Figure 37 demonstrate that the maximum k_{eff}, including calculational uncertainty, is less than 0.45 for the most limiting reflection condition with natural uranium.



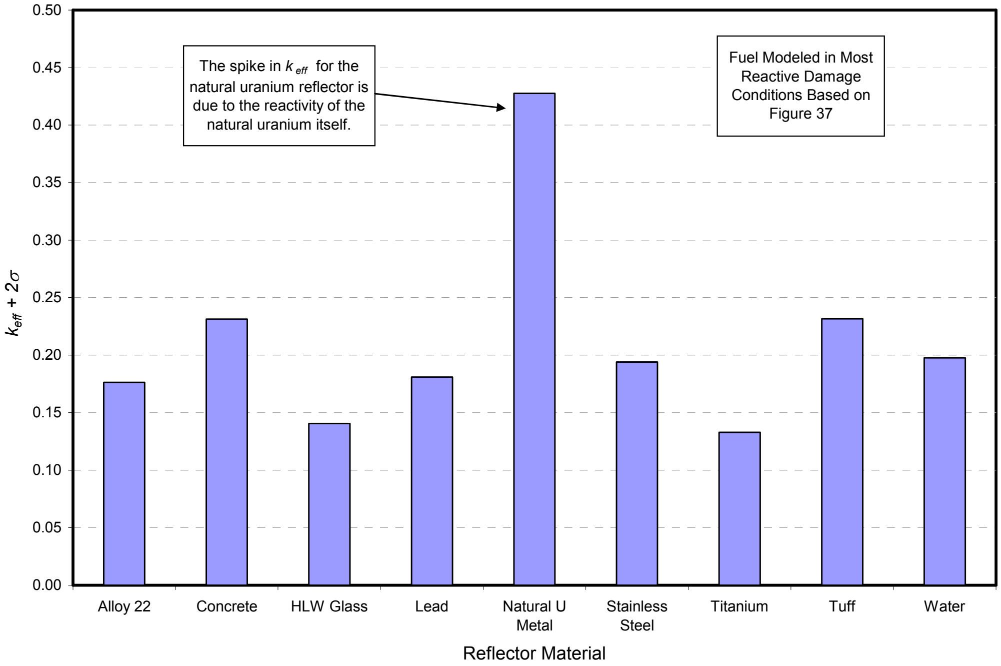
Source: Figure 6-74, BSC 2008 [DIRS 182100]

Figure 36. Radial Cross-Section Views of the ATR DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged, but Unbroken Fuel Calculations



Source: Adapted from Figure 7-16, BSC 2008 [DIRS 182100]

Figure 37. k_{eff} as a Function of Basket Structure Collapse, Basket Structure Gd Content, and Fuel Element Spacing Reduction for an Individual Dry Damaged DOE Standardized SNF Canister Containing ATR SNF with a Close-fitting Full-thickness Stainless Steel Reflector



Source: Adapted from Figure 7-17, BSC 2008 [DIRS 182100]

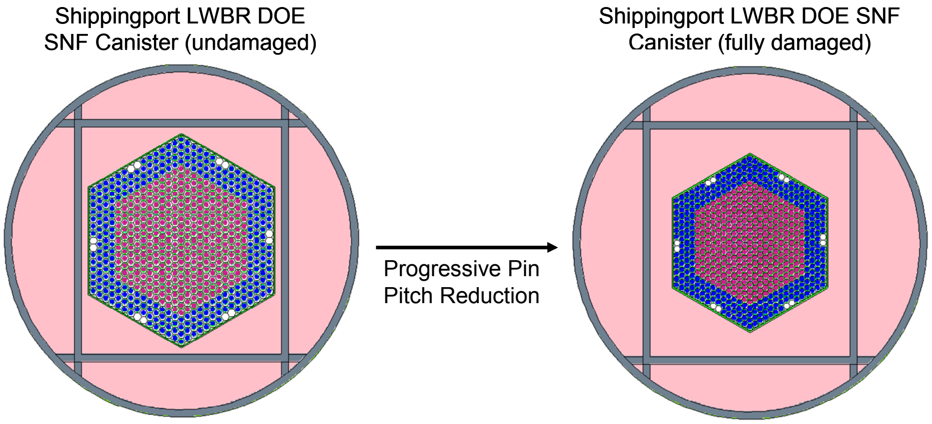
Figure 38. k_{eff} for Individual Dry Damaged DOE Standardized SNF Canister Containing ATR SNF Canister with a Variety of Close-fitting Full-thickness Reflectors

In order to bound geometry and neutron absorber effects in DOE standardized SNF canisters containing ATR SNF, which contain a limited fissile mass and a fuel basket that is a parasitic absorber, the calculation modeled a hypothetical complete separation between the SNF and the basket. The SNF was conservatively represented as rubble in a cylindrical geometry at the bottom of the canister with close-fitting reflection and variable void fraction levels. With the most limiting reflection conditions, and a 100 % non-physical packing fraction (zero void volume in the rubble), the maximum k_{eff}, including calculational uncertainty, for DOE standardized SNF canisters containing ATR SNF, is less than 0.83 (BSC 2008 [DIRS 182100], Figure 7-30). Therefore, in the absence of moderation, neutron absorber and geometry do not need to be controlled for DOE standardized SNF canisters containing ATR SNF.

2.3.2.3.3.2 Fixed Neutron Absorber and Geometry for Shippingport LWBR SNF

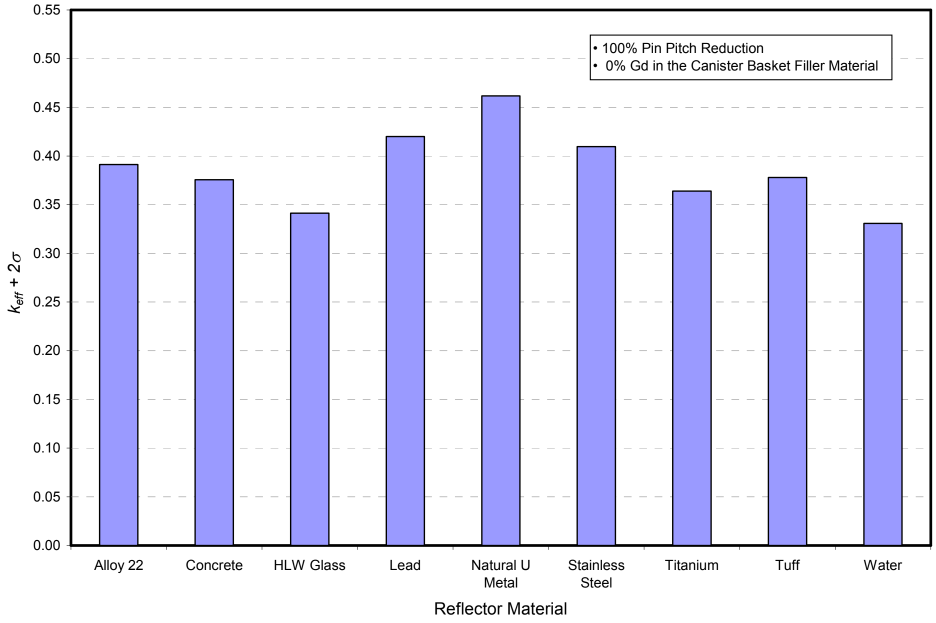
Geometry control for DOE standardized SNF canisters containing Shippingport LWBR SNF is provided by the stainless steel basket; whereas, fixed neutron absorber is provided by a gadolinium-bearing aluminum shot (Figure 9).

To investigate the worth of the fixed neutron absorber in DOE standardized SNF canisters containing Shippingport LWBR SNF, the presence and complete omission of the gadolinium in the filler material were studied as a function of geometry as illustrated in Figure 39. Figure 40 shows that the maximum k_{eff}, including calculational uncertainty, is less than 0.50 for a DOE standardized SNF canister containing Shippingport LWBR SNF with complete omission of the gadolinium in the filler material and maximum pin pitch collapse (which provides maximum reactivity) for the most limiting reflection conditions with natural uranium.



Source: Adapted from Figure 6-83, BSC 2008 [DIRS 182100]

Figure 39. Radial Cross-Section Views of the Shippingport LWBR DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged, but Unbroken Fuel Calculations



Source: Adapted from Figure 7-24, BSC 2008 [DIRS 182100]

Figure 40. k_{eff} for Individual Dry Damaged DOE Standardized SNF Canister Containing Shippingport LWBR SNF with a Variety of Close-fitting Full-thickness Reflectors

In order to bound geometry and neutron absorber effects in DOE standardized SNF canisters containing Shippingport LWBR SNF, which contain a limited fissile mass and a fuel basket/filler material that are parasitic absorbers, the calculation modeled a hypothetical complete separation between the SNF and the basket. The SNF was conservatively represented as rubble in a cylindrical geometry at the bottom of the canister with close-fitting reflection and variable void fraction levels. With the most limiting reflection conditions and a 100 % non-physical packing fraction (zero void volume in the rubble), the maximum k_{eff}, including calculational uncertainty, for DOE standardized SNF canisters containing Shippingport LWBR SNF, is less than 0.70 (BSC 2008 [DIRS 182100], Figure 7-43). Therefore, in the absence of moderation, neutron absorber and geometry do not need to be controlled for DOE standardized SNF canisters containing Shippingport LWBR SNF.

2.3.2.3.3.3 Fixed Neutron Absorber and Geometry for Shippingport PWR SNF

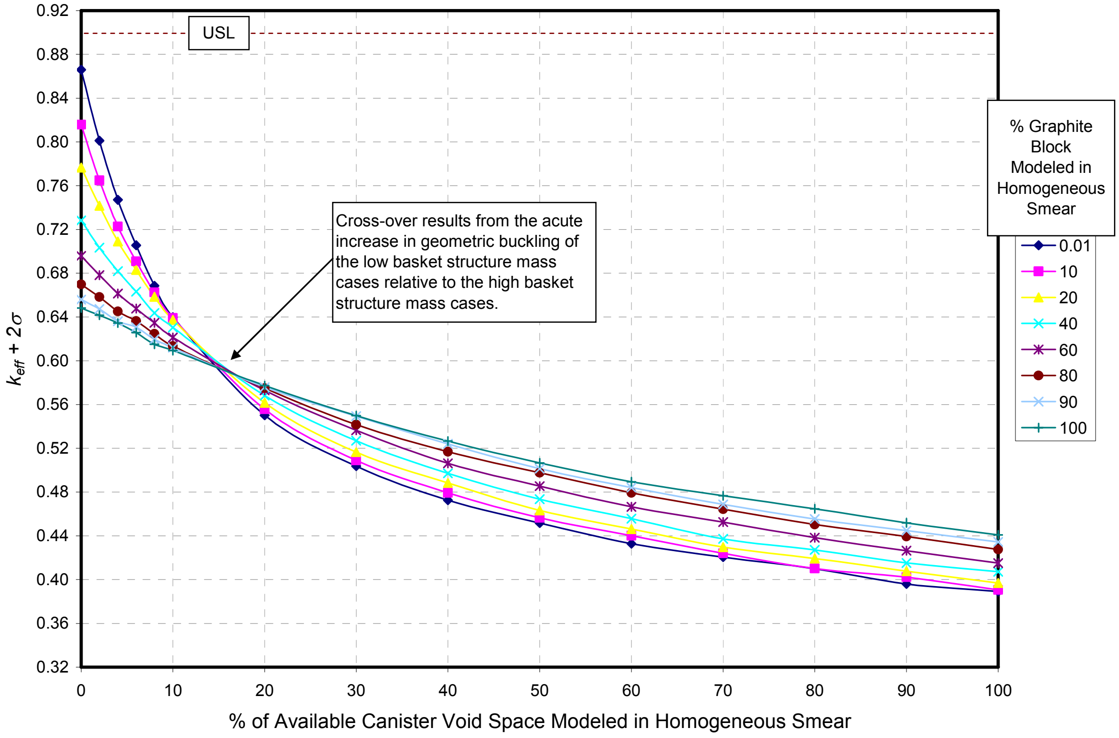
Geometry control for DOE standardized SNF canisters containing Shippingport PWR SNF is provided by the stainless steel basket (Figure 8), which also limits the number of Shippingport PWR SNF elements to one per canister. Fixed neutron absorber is not incorporated in DOE standardized SNF canisters containing Shippingport PWR SNF.

In order to bound geometry effects in DOE standardized SNF canisters containing Shippingport PWR SNF, which contain a limited fissile mass and a fuel basket that is a parasitic absorber, the calculation modeled a hypothetical complete separation between the SNF and the basket. The SNF was conservatively represented as rubble in a cylindrical geometry at the bottom of the canister with close-fitting reflection and variable void fraction levels. With the most limiting reflection conditions, and a 100 % non-physical packing fraction (zero void volume in the rubble), the maximum k_{eff}, including calculational uncertainty, for DOE standardized SNF canisters containing Shippingport PWR SNF, is less than 0.73 (BSC 2008 [DIRS 182100], Figure 7-44). Therefore, in the absence of moderation, geometry does not need to be controlled for DOE standardized SNF canisters containing Shippingport PWR SNF.

2.3.2.3.3.4 Fixed Neutron Absorber and Geometry for Fort St. Vrain SNF

Geometry control for DOE standardized SNF canisters containing Fort St. Vrain SNF is provided by the five fuel elements themselves that are loaded in a long DOE standardized SNF canister (Figure 10). Fixed neutron absorber is not incorporated in DOE standardized SNF canisters containing Fort St. Vrain SNF.

In order to bound geometry effects in DOE standardized SNF canisters containing Fort St. Vrain SNF, which contain a limited fissile mass and fuel elements that are composed of graphite (a moderator), the calculation determined the optimum packing density at the optimum moderation (graphite) in a conservative cylindrical geometry containing rubble (with 100% of the SNF mass) at the bottom of the canister with close-fitting axial graphite reflection and radial water reflection (limiting potential reflection for this configuration as demonstrated in BSC 2008 [DIRS 182100], Figure 7-41). The results in Figure 41 show that the highest k_{eff}, including calculational uncertainty, for the optimum packing density and optimum moderation (graphite) for the most limiting reflection conditions is less than 0.87. Therefore, in the absence of moderation, geometry does not need to be controlled for DOE standardized SNF canisters containing Fort St. Vrain SNF.



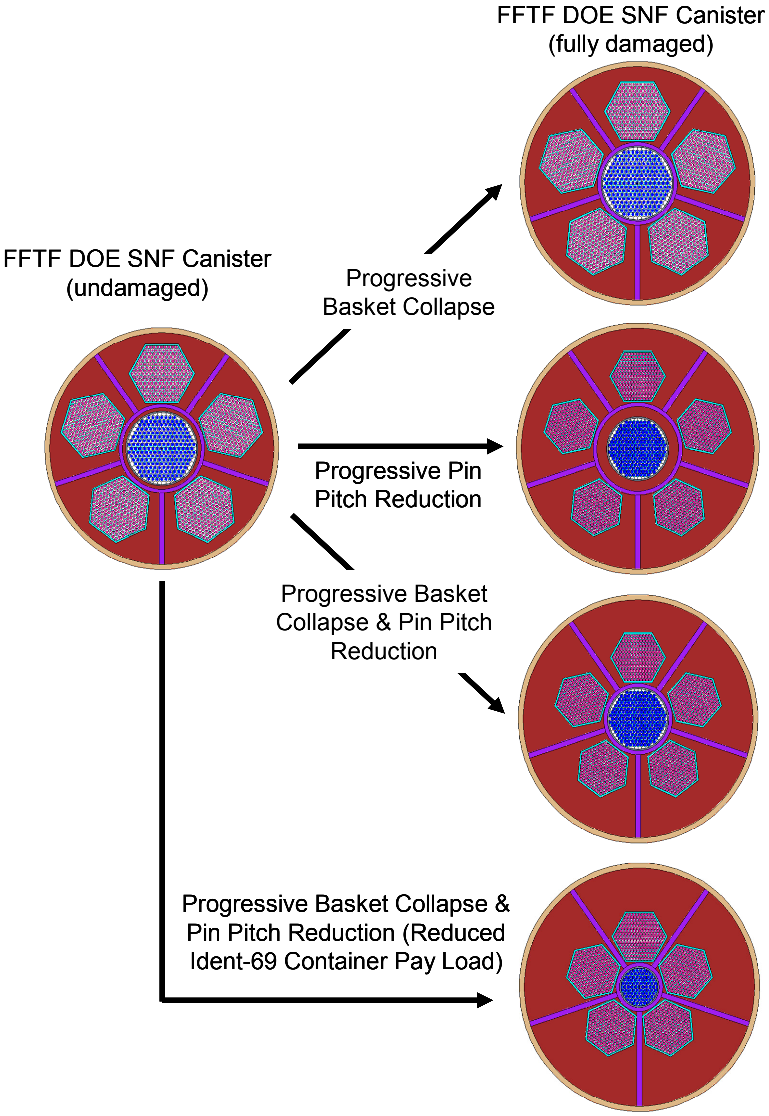
Source: Adapted from Figure 7-42, BSC 2008 [DIRS 182100]

Figure 41. k_{eff} as a Function of Void Space and Graphite Block for an Individual Dry Damaged DOE Standardized SNF Canister Containing Fort St. Vrain SNF Rubble, with Close-fitting Full-thickness Axial Graphite Reflection and Radial Water Reflection

2.3.2.3.3.5 Fixed Neutron Absorber and Geometry for FFTF SNF

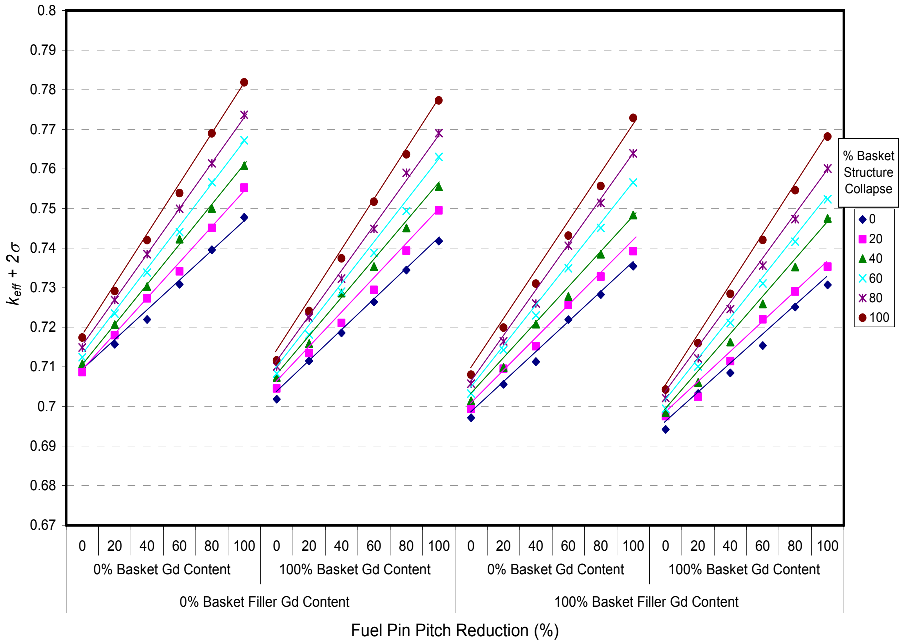
Geometry control for DOE standardized SNF canisters containing FFTF SNF is provided by a basket made of a gadolinium-bearing low-carbon high-nickel alloy, which also serves as the fixed neutron absorber. Fixed neutron absorber is also provided by gadolinium-bearing aluminum shot. The basket limits the number of FFTF elements loaded in a DOE standardized SNF canister to six (Figure 4). Only five of the six baskets will be used for any fully-loaded canister. The space not occupied by the fuel assemblies, the Ident-69 container, and the basket is filled with aluminum shot containing $GdPO_4$ that is used as a neutron absorber.

To investigate the worth of the fixed neutron absorber in DOE standardized SNF canisters containing FFTF SNF, the presence and complete omission of the gadolinium in the basket material and filler material were studied as a function of geometry as illustrated in Figure 42. The results in Figure 43 demonstrate that the gadolinium for the various geometrical configurations is worth less than a Δk of 0.01. This is due to the fact that gadolinium, which is the primary neutron absorber in the basket and filler material in DOE standardized SNF canisters containing FFTF SNF, is a strong thermal neutron absorber, and its effectiveness diminishes in hard neutron spectra associated with dry conditions. Figure 43 shows that the maximum k_{eff}, including calculational uncertainty, is less than 0.79 for a DOE standardized SNF canister containing FFTF SNF with complete omission of the gadolinium in both the basket and the shot, maximum pin pitch collapse and maximum basket collapse with stainless steel reflection. For the most limiting reflection conditions with lead, Figure 44 demonstrates that the maximum k_{eff}, including calculational uncertainty, is less than 0.80 for the most reactive damage conditions based on Figure 43.



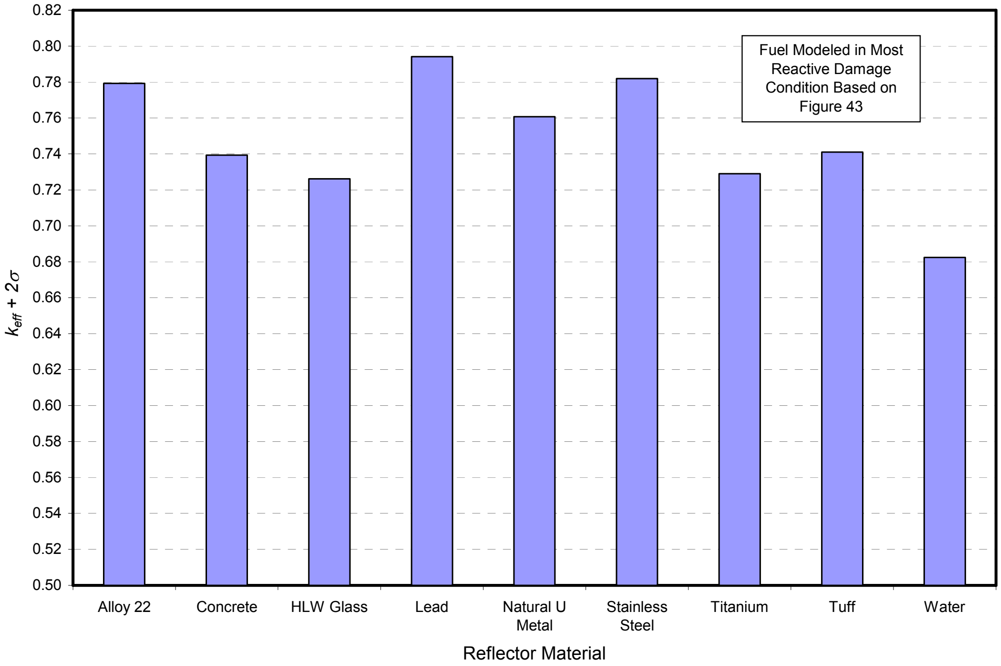
Source: Figure 6-81, BSC 2008 [DIRS 182100]

Figure 42. Radial Cross-Section Views of the FFTF DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged, but Unbroken Fuel Calculations



Source: Adapted from Figure 7-20, BSC 2008 [DIRS 182100]

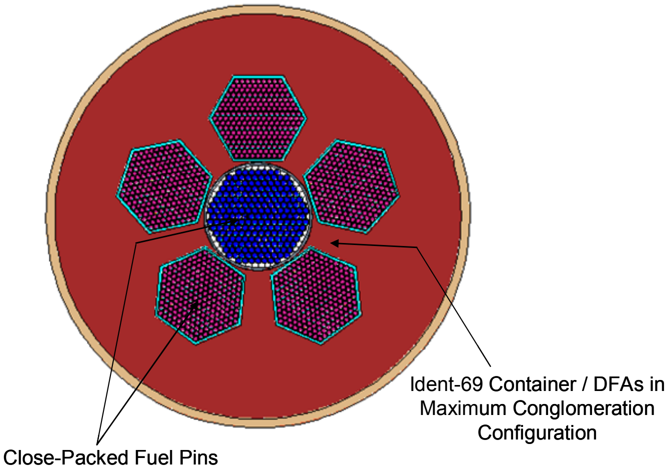
Figure 43. k_{eff} as a Function of DFA and Ident-69 Pin Pitch Reduction, Basket Filler and Structure Gd Content, and Basket Structure Collapse for an Individual DOE Standardized SNF Canister Containing FFTF, with a Close-fitting Stainless Steel Reflector



Source: Adapted from Figure 7-21, BSC 2008 [DIRS 182100]

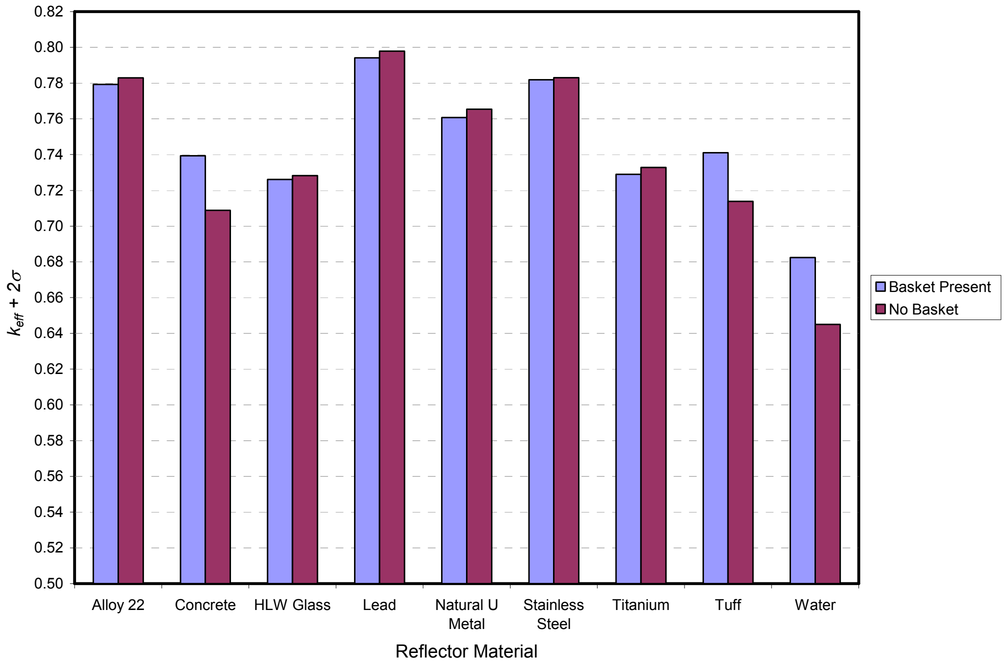
Figure 44. k_{eff} for an Individual Dry Damaged DOE Standardized SNF Canister Containing FFTF fuel with a Variety of Close-fitting Full-thickness Reflectors

DOE standardized SNF canisters containing FFTF SNF contain a relatively high fissile mass and a fuel basket that is a parasitic absorber. The canister contains up to six fuel elements in one layer (Figure 4). The first step in determining the level of geometry control required for DOE standardized SNF canisters containing FFTF SNF is to determine the extent to which the basket presence is needed to maintain subcriticality for potential geometrical reconfiguration of the basket and the SNF. Figure 45 depicts the geometrical representation used for DOE standardized SNF canisters containing tightly packed FFTF elements without a fuel basket. Figure 46 demonstrates that subcriticality is maintained for this conservative geometry with no control of fixed neutron absorber and the most limiting reflection conditions. The maximum k_{eff}, including calculational uncertainty, for DOE standardized SNF canisters containing FFTF SNF in this conservative configuration is less than 0.80.



Source: Adapted from Figure 6-91, BSC 2008 [DIRS 182100]

Figure 45. Radial Cross-Section View of a DOE Standardized SNF Canister Containing FFTF SNF Depicting the Configuration Examined for the Dry Damaged Configuration



Source: Adapted from Figure 7-21, BSC 2008 [DIRS 182100]

Figure 46. k_{eff} For an Individual Dry Damaged DOE Standardized SNF Canister Containing FFTF SNF with a Variety of Close-fitting Full-thickness Reflectors

As shown in Figure 7-38 of BSC 2008 [DIRS 182100], subcriticality for DOE standardized SNF canisters containing FFTF SNF is maintained even for the hypothetical case of complete loss of geometry control by the basket, filler material, and fuel elements. This hypothetical geometry represents complete separation between the fuel basket and the SNF, crediting only 11 % of the filler material, in which the rubble (SNF and filler material) is modeled in a cylindrical geometry with a non-physical 100 % packing fraction at the bottom of the canister with close-fitting full-thickness reflection.

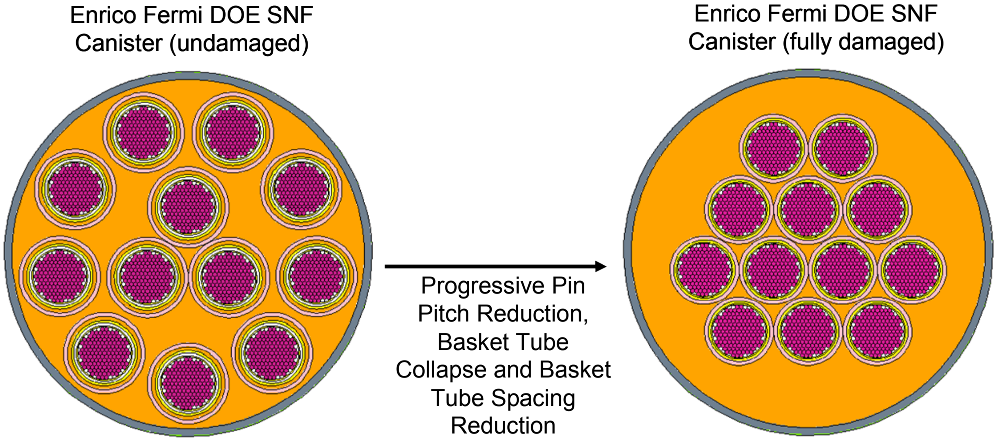
Based on Assumption 1.4.5, there is no Category 1 or Category 2 event sequence that results in a DOE standardized SNF canister breach allowing the shot to escape from the canister. Given the fact that it is not physically possible to separate the SNF from the “fluid” filler material, which is composed of fine aluminum shot, and place it in an idealized geometry, the presence of the filler material in DOE standardized SNF canisters containing FFTF SNF is considered sufficient to ensure subcriticality under any potential geometrical reconfiguration.

Therefore, in the absence of moderation, neutron absorber and geometry do not need to be controlled for DOE standardized SNF canisters containing FFTF SNF.

2.3.2.3.3.6 Fixed Neutron Absorber and Geometry for Enrico Fermi SNF

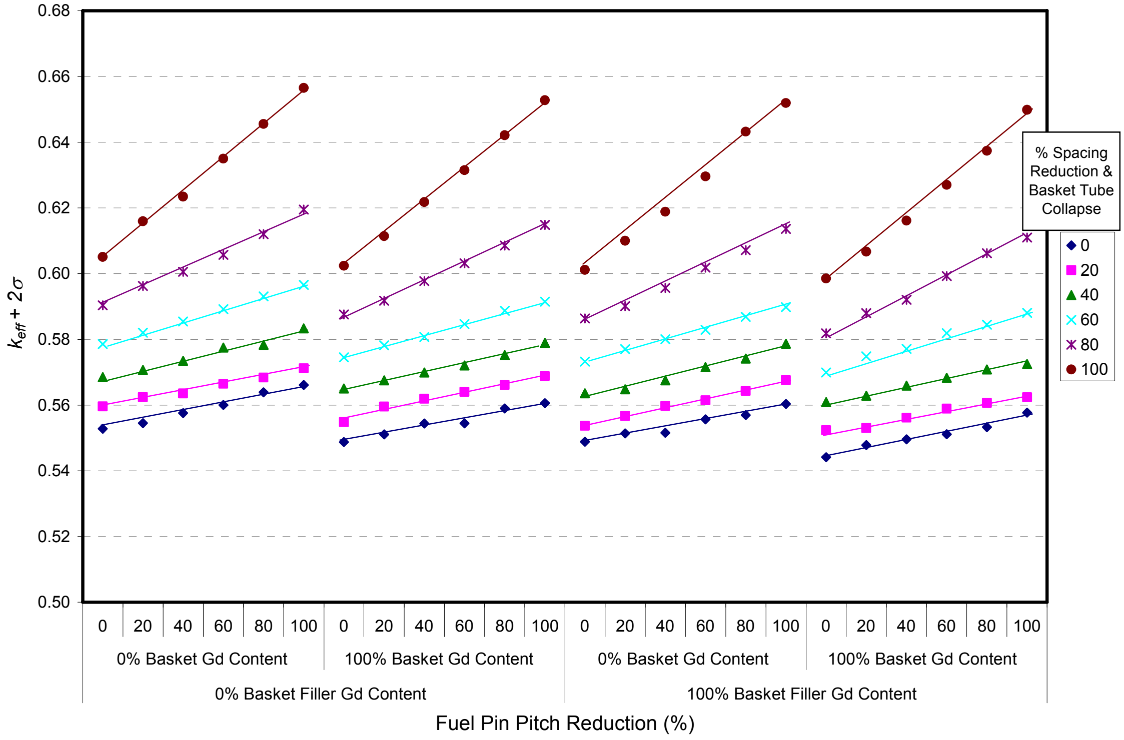
Geometry control for DOE standardized SNF canisters containing Enrico Fermi SNF is provided by the two (i.e., the -01 and -04) aluminum cans surrounding the consolidated fuel pins (Figure 5) as well as by tubes made of a gadolinium-bearing low-carbon high-nickel alloy, which also serve as fixed neutron absorber. Fixed neutron absorber is also provided by gadolinium-bearing iron shot. There are 12 locations for the concentric aluminum cans in each of the two baskets loaded in a short DOE standardized SNF canister (Figure 6).

To investigate the worth of the fixed neutron absorber in DOE standardized SNF canisters containing Enrico Fermi SNF, the presence and complete omission of the gadolinium in the basket material and filler material were studied as a function of geometry as illustrated in Figure 47. Figure 48 demonstrates that the gadolinium for the various geometrical configurations is worth less than a Δk of 0.01. This is due to the fact that gadolinium, which is the primary neutron absorber in the basket and filler material in DOE standardized SNF canisters containing Enrico Fermi SNF, is a strong thermal neutron absorber, and its effectiveness diminishes in hard neutron spectra associated with dry conditions. Figure 48 shows that the maximum k_{eff}, including calculational uncertainty, is less than 0.66 for a DOE standardized SNF canister containing Enrico Fermi SNF with complete omission of the gadolinium in both the basket and the shot, maximum pin pitch collapse and maximum basket collapse with stainless steel reflection. For the most limiting reflection conditions with lead, Figure 49 demonstrates that the maximum k_{eff}, including calculational uncertainty, is less than 0.70 for the most reactive damage conditions based on Figure 48.



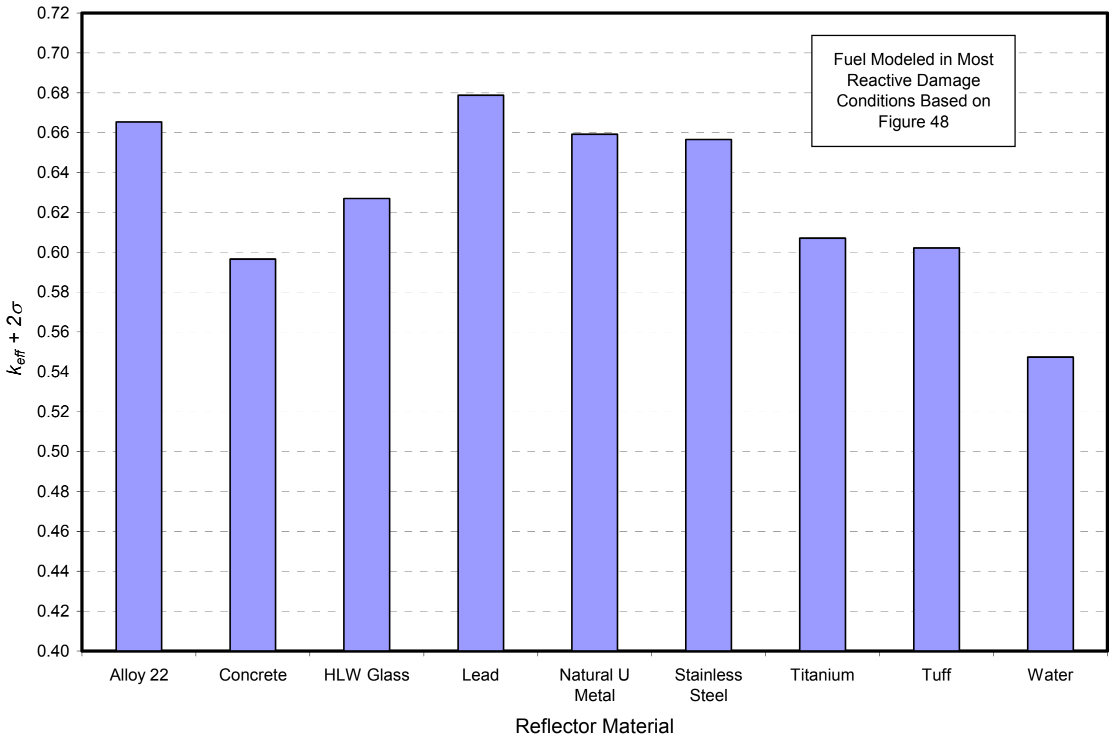
Source: Adapted from Figure 6-77, BSC 2008 [DIRS 182100]

Figure 47. Radial Cross-Section Views of the Enrico Fermi DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged, but Unbroken Fuel Calculations



Source: Adapted from Figure 7-18, BSC 2008 [DIRS 182100]

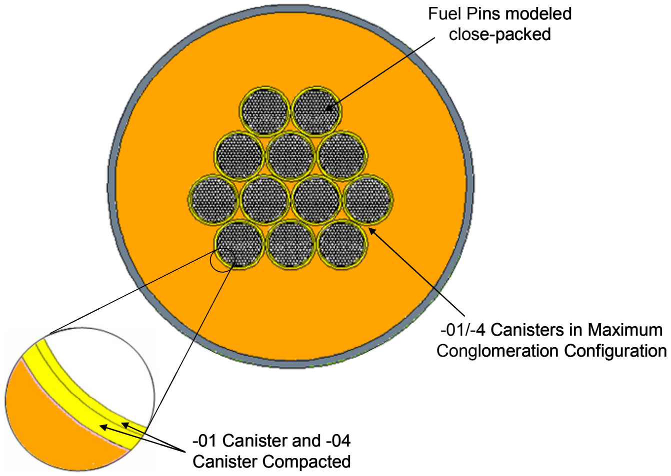
Figure 48. k_{eff} as a Function of Pin Pitch Reduction, Basket Filler and Structure Gd Content, Basket Tube Spacing Reduction, and Basket Tube Collapse for an Individual Dry DOE Standardized SNF Canister Containing Enrico Fermi SNF, with a Close-fitting, Full-thickness Stainless Steel Reflector



Source: Adapted from Figure 7-19, BSC 2008 [DIRS 182100]

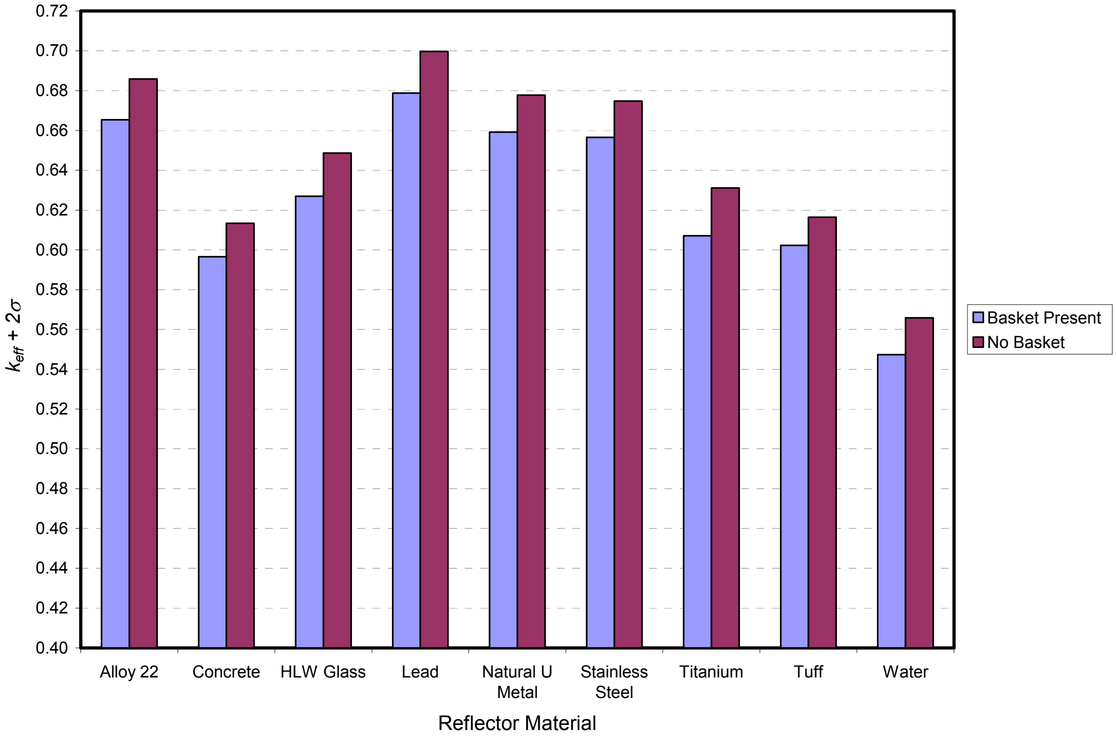
Figure 49. k_{eff} for an Individual Dry Damaged DOE Standardized SNF Canister Containing Enrico Fermi SNF with a Variety of Close-fitting Full-thickness Reflectors

DOE standardized SNF canisters containing Enrico Fermi SNF contain a relatively high fissile mass and a fuel basket that is a parasitic absorber. There are 24 Enrico Fermi cans per DOE standardized SNF canister divided into two even layers (Figure 6). The gadolinium-bearing low-carbon high-nickel alloy tubes serve the function of ensuring that only 12 cans are loaded per layer. Structural plates in the fuel basket ensure the separation between the two layers. The first step in determining the level of geometry control required for DOE standardized SNF canisters containing Enrico Fermi SNF is to determine the extent to which the basket presence is needed to maintain subcriticality for potential geometrical reconfiguration of the basket and the SNF. Figure 50 depicts the geometrical representation used for DOE standardized SNF canisters containing tightly packed Enrico SNF cans without a fuel basket but maintaining separation between the fuel layers. Figure 51 demonstrates that subcriticality is maintained for this conservative geometry with no fixed neutron absorber and the most limiting reflection conditions. The maximum k_{eff}, including calculational uncertainty, for DOE standardized SNF canisters containing Enrico Fermi SNF in this conservative configuration is less than 0.70.



Source: Adapted from Figure 6-90, BSC 2008 [DIRS 182100]

Figure 50. Radial Cross-Section View of a DOE Standardized SNF Canister Containing Enrico Fermi SNF, Depicting the Dry Damaged Configuration Examined



Source: Adapted from Figure 7-19, BSC 2008 [DIRS 182100]

Figure 51. k_{eff} for an Individual Dry Damaged DOE Standardized SNF Canister Containing Enrico Fermi SNF with a Variety of Close-fitting Full-thickness Reflectors

As shown in Figure 7-33 of BSC 2008 [DIRS 182100], subcriticality for DOE standardized SNF canisters containing Enrico Fermi SNF is maintained even for the hypothetical case of complete loss of geometry control by the basket, filler material, fuel cans, and fuel elements. This hypothetical geometry represents complete separation between the fuel basket and the SNF, crediting only 32 % of the filler material, in which the rubble (SNF and filler material) is modeled in a cylindrical geometry with a non-physical 100 % packing fraction at the bottom of the canister with close-fitting full-thickness reflection.

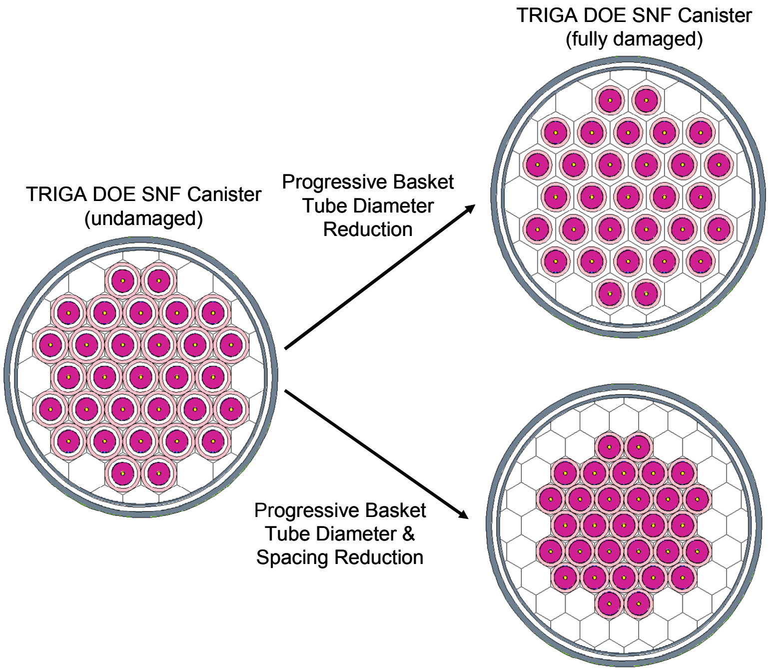
Based on Assumption 1.4.5, there is no Category 1 or Category 2 event sequence that results in a DOE standardized SNF canister breach allowing the shot to escape from the canister. Given the fact that it is not physically possible to separate the SNF from the “fluid” filler material, which is composed of fine iron shot, and place it in an idealized geometry, the presence of the filler material in DOE standardized SNF canisters containing Enrico Fermi SNF is considered sufficient to ensure subcriticality under any potential geometrical reconfiguration

Therefore, in the absence of moderation, neutron absorber and geometry do not need to be controlled for DOE standardized SNF canisters containing Enrico Fermi SNF.

2.3.2.3.3.7 Fixed Neutron Absorber and Geometry for TRIGA SNF

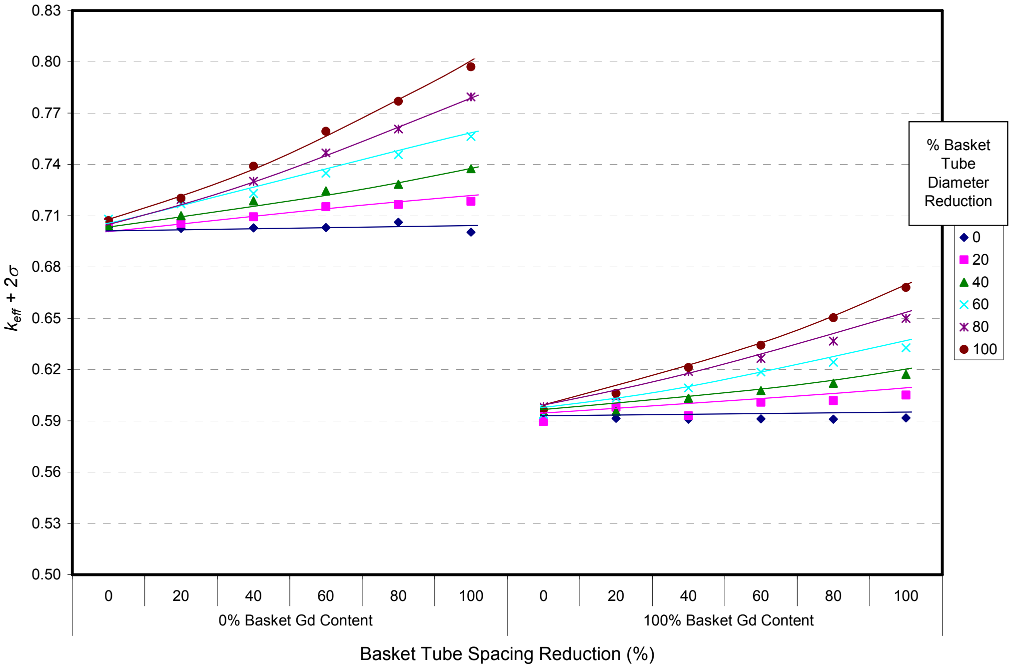
Geometry control for DOE standardized SNF canisters containing TRIGA SNF is provided by tubes made of a gadolinium-bearing low-carbon high-nickel alloy, which also serve as the fixed neutron absorber. The basket provides for three layers of 31 TRIGA fuel elements loaded in a short DOE standardized SNF canister (Figure 11 and Figure 12).

To investigate the worth of the fixed neutron absorber in DOE standardized SNF canisters containing TRIGA SNF, the presence and complete omission of the gadolinium in the basket material were studied as a function of geometry as illustrated in Figure 52. Figure 53 demonstrates that the gadolinium for the various geometrical configurations is worth more than a Δk of 0.10. This is due to the fact that TRIGA SNF is a self-moderated SNF with a zirconium-hydride matrix that softens the neutron spectrum such that the worth of gadolinium, which is a strong thermal neutron absorber, is increased. Figure 53 shows that the maximum k_{eff}, including calculational uncertainty, is less than 0.80 for a DOE standardized SNF canister containing TRIGA SNF with complete omission of the gadolinium in the basket tubes, maximum pin pitch collapse and maximum basket collapse with stainless steel reflection. For the most limiting reflection conditions with lead, Figure 54 demonstrates that the maximum k_{eff}, including calculational uncertainty, is less than 0.82 for the most reactive damage conditions based on Figure 53.



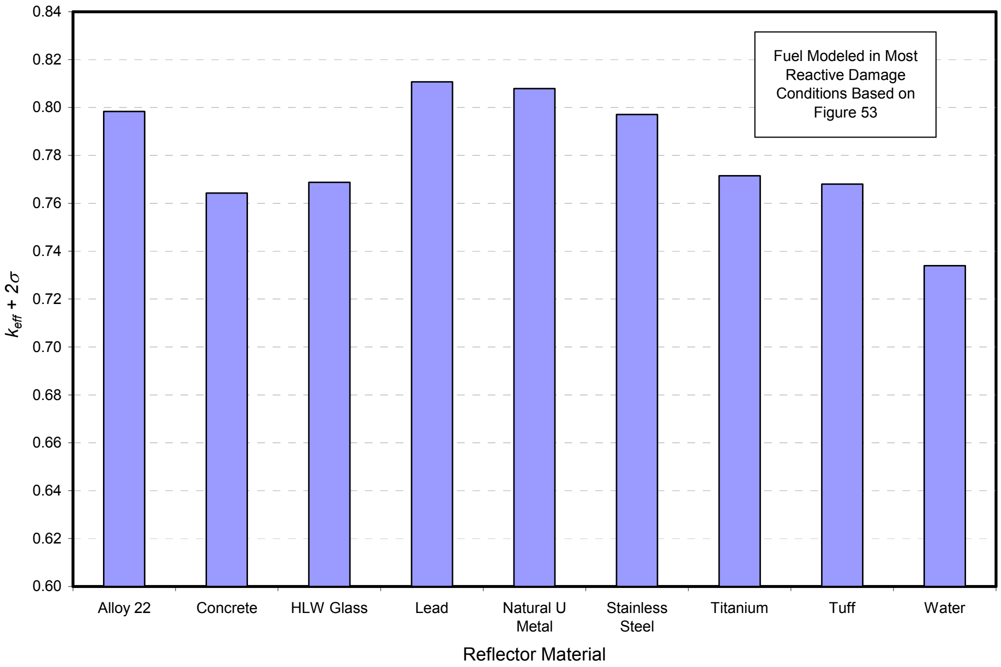
Source: Figure 6-89, BSC 2008 [DIRS 182100]

Figure 52. Radial Cross-Section Views of the TRIGA DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged, but Unbroken Fuel Calculations



Source: Adapted from Figure 7-28, BSC 2008 [DIRS 182100]

Figure 53. k_{eff} as a Function of Basket Tube Spacing Reduction, Basket Tube Gd Content, and Basket Tube Diameter Reduction for an Individual Dry DOE Standardized SNF Canister Containing TRIGA SNF with a Close-fitting Full-thickness Stainless Steel Reflector



Source: Adapted from Figure 7-29, BSC 2008 [DIRS 182100]

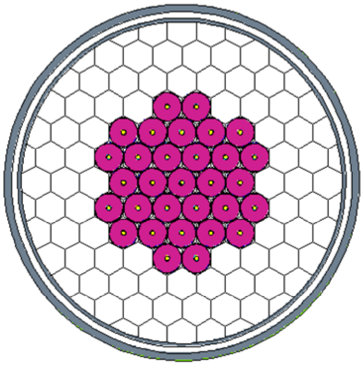
Figure 54. k_{eff} for an Individual Dry Damaged DOE Standardized SNF Canister Containing TRIGA SNF with a Variety of Close-fitting Full-thickness Reflectors

DOE standardized SNF canisters containing TRIGA SNF contain a limited fissile mass; however the fuel matrix is composed of a uranium-hydride matrix, which serves as a moderator. The TRIGA SNF elements are loaded individually into tubes made of gadolinium-bearing low-carbon high-nickel alloy, which is a strong neutron absorber. These tubes limit the number of TRIGA fuel elements to 93 elements per canister divided into three even layers stacked vertically. The first step in determining the level of geometry control required for DOE standardized SNF canisters containing TRIGA SNF is to determine the extent to which the basket presence is needed to maintain subcriticality for potential geometrical reconfiguration of the basket and the SNF. Figure 55 depicts the geometrical representation used for DOE standardized SNF canisters containing tightly packed TRIGA SNF elements without a fuel basket but maintaining separation between fuel layers. Figure 56 presents k_{eff} values for a dry damaged basket, but intact TRIGA SNF. The “basket present” values are for 100% basket tube spacing reduction, 100% basket tube diameter reduction, and no Gd in the basket structure, previously shown in Figure 52, whereas the “no basket” values are for the configuration shown in Figure 55. The results in Figure 56 demonstrate that the basket must be present to ensure subcriticality in DOE standardized SNF canisters containing TRIGA SNF; however, the basket does not need to contain gadolinium.

As shown in Figure 7-46 of BSC 2008 [DIRS 182100], subcriticality for DOE standardized SNF canisters containing TRIGA SNF is maintained even for the hypothetical case of complete loss of geometry control by the basket and fuel elements. This hypothetical geometry represents significant separation between the fuel basket and the SNF, crediting only 8% of the basket material, in which rubble (SNF and 8 % of the basket) with a non-physical 100 % packing fraction (zero void volume in the rubble) is modeled in a cylindrical geometry at the bottom of the canister with close-fitting full-thickness reflection.

Given the fact that there is no mechanistic way to separate the fuel from the basket material (each fuel rod is surrounded by a basket tube constructed of gadolinium-bearing low-carbon high-nickel alloy) and place it in a cylindrical geometry, the presence of the basket in DOE standardized SNF canisters containing TRIGA SNF is considered sufficient to ensure subcriticality under any potential geometrical reconfiguration.

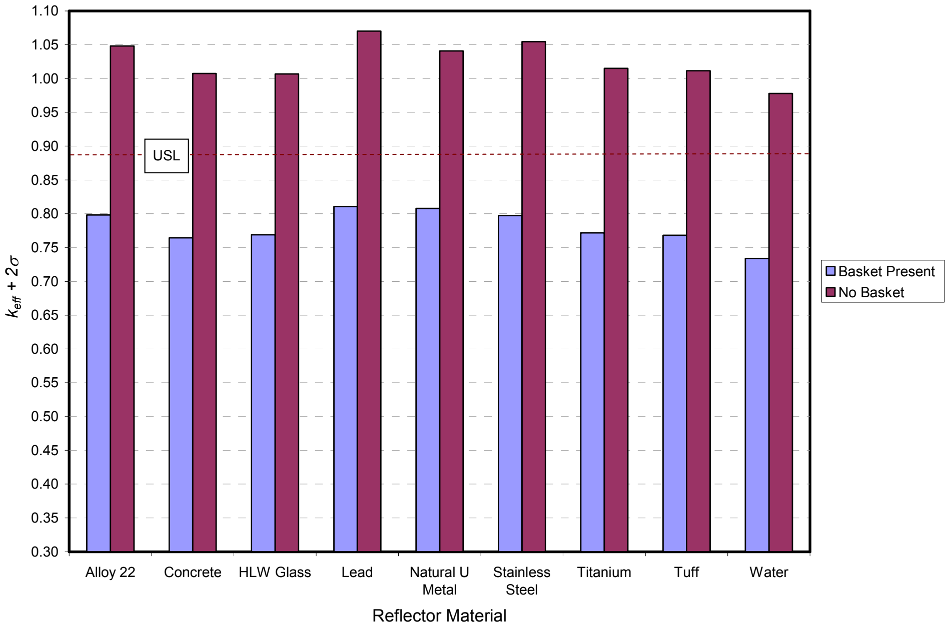
Therefore, in the absence of moderation, neutron absorber and geometry do not need to be controlled for DOE standardized SNF canisters containing TRIGA SNF.



Close-Packed Fuel Elements

Source: Figure 6-92, BSC 2008 [DIRS 182100]

Figure 55. Radial Cross-Section View of a DOE Standardized SNF Canister Containing TRIGA SNF, Depicting the Dry Damaged Configuration Examined



Source: Adapted from Figure 7-29, BSC 2008 [DIRS 182100]

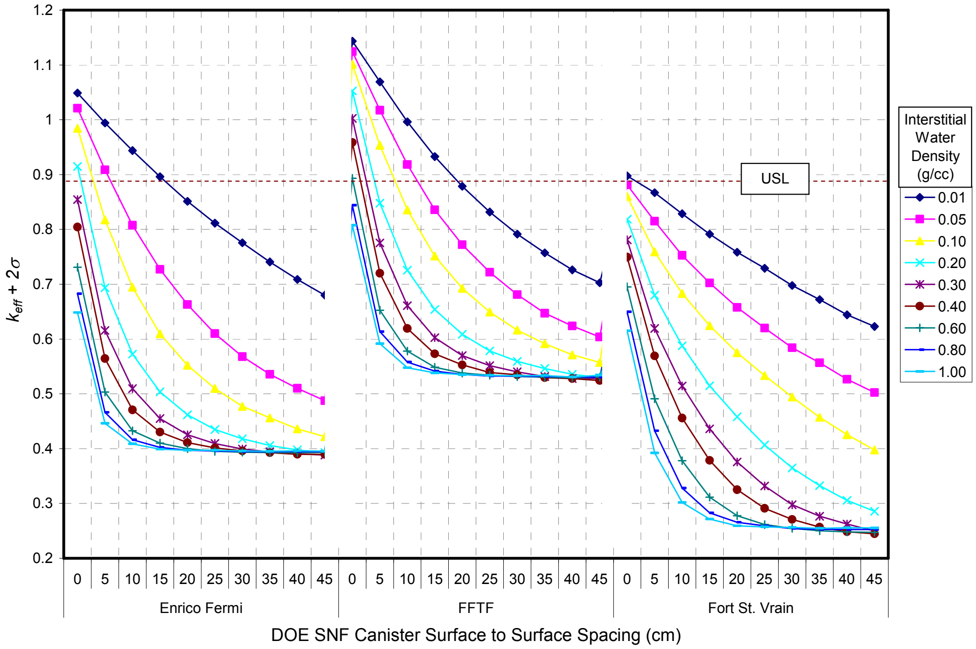
Figure 56. k_{eff} for an Individual Dry Damaged DOE Standardized SNF Canister Containing TRIGA SNF with a Variety of Close-fitting Full-thickness Reflectors

Based on the analysis performed in this section, fixed neutron absorber and geometry for operations with DOE standardized SNF canisters containing FFTF, ATR, Enrico Fermi, Shippingport LWBR, Shippingport PWR, TRIGA, and Fort St. Vrain SNF need to be controlled only if there are Category 1 or Category 2 event sequences that result in introduction of moderator into a DOE standardized SNF canister.

2.3.2.3.4 Interaction for DOE SNF

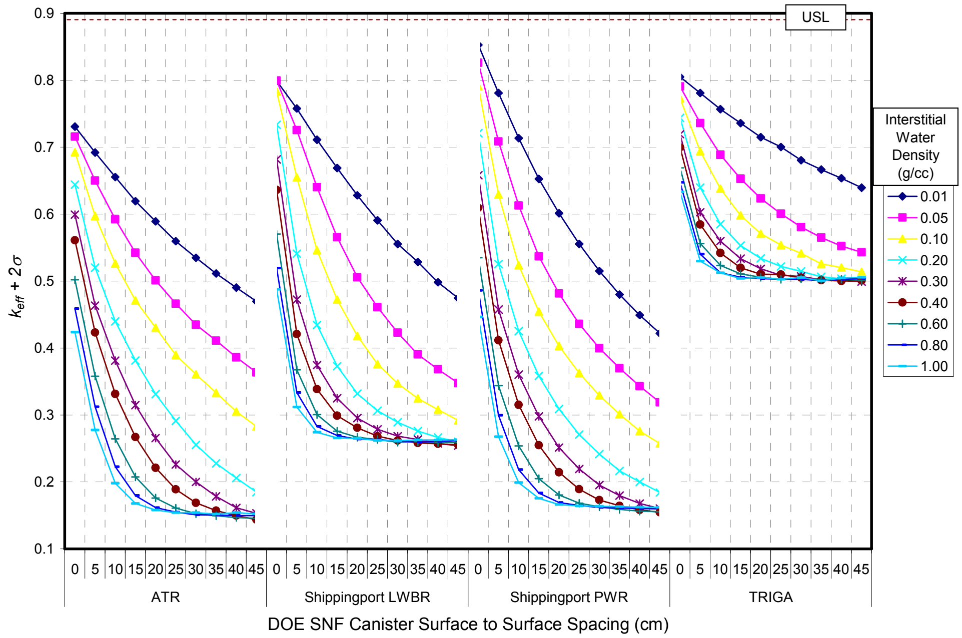
The k_{eff} sensitivity calculations examined the impact of interaction of containers of DOE SNF with containers of the same or other waste forms on system reactivity as a function of other relevant parameters to determine the extent to which interaction must be controlled.

The k_{eff} values for infinite planar arrays of DOE SNF canisters are shown in Figure 57 and Figure 58. Figure 58 shows that interaction is bounded for DOE SNF canisters containing ATR, Shippingport LWBR, Shippingport PWR, and TRIGA SNF, and that under these most reactive reflection conditions, subcriticality is maintained for those fuels with a maximum k_{eff}, including calculational uncertainty, less than 0.86. It can be seen from Figure 57 that unlimited interaction between canisters results in k_{eff} exceeding the USL (0.89) for DOE standardized SNF canisters containing Enrico Fermi, FFTF, and Fort St. Vrain SNF. The figures also demonstrate that the DOE standardized SNF canister containing FFTF is the most limiting from an interaction standpoint. Mixing DOE standardized SNF canisters containing various types of DOE SNF will not result in a higher k_{eff} than that for the most reactive type (i.e., DOE standardized SNF canisters containing FFTF), unless the neutron spectrum is shifted to maximize the ratio of fissions to parasitic absorptions. Neutron spectral changes can be thoroughly investigated by studying the trend of k_{eff} as a function of moderator density in between the DOE standardized SNF canisters, which simulates any potential spectral shift associated with moderation outside the canisters. Figure 57 and Figure 58 demonstrate that the presence of interstitial moderator for arrays of DOE standardized SNF canisters reduces the system k_{eff}. Therefore, the variable density interstitial moderation results confirm that mixing of DOE SNF canisters (which may result in neutron spectral variations) in an array will result in a lower k_{eff} than an array of the most reactive canister type.



Source: Adapted from Figure 7-12, BSC 2008 [DIRS 182100]

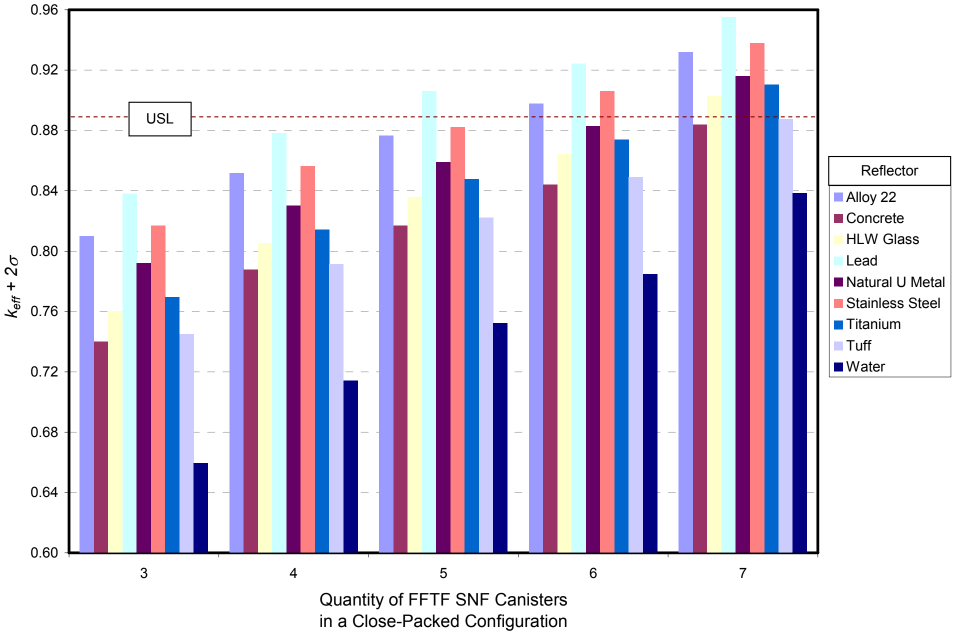
Figure 57. k_{eff} for an Infinite Planar Array of Undamaged and Dry DOE Standardized SNF Canisters Containing Enrico Fermi, FFTF, and Fort St. Vrain SNF, with Close-fitting Full-thickness Stainless Steel Axial Reflection and a Variety of Interstitial Water Moderation Conditions



Source: Adapted from Figure 7-13, BSC 2008 [DIRS 182100]

Figure 58. k_{eff} for an Infinite Planar Array of Undamaged and Dry DOE Standardized SNF Canisters Containing ATR, Shippingport LWBR, Shippingport PWR, and TRIGA SNF, with Close-fitting Full-thickness Stainless Steel Axial Reflection and a Variety of Interstitial Water Moderation Conditions

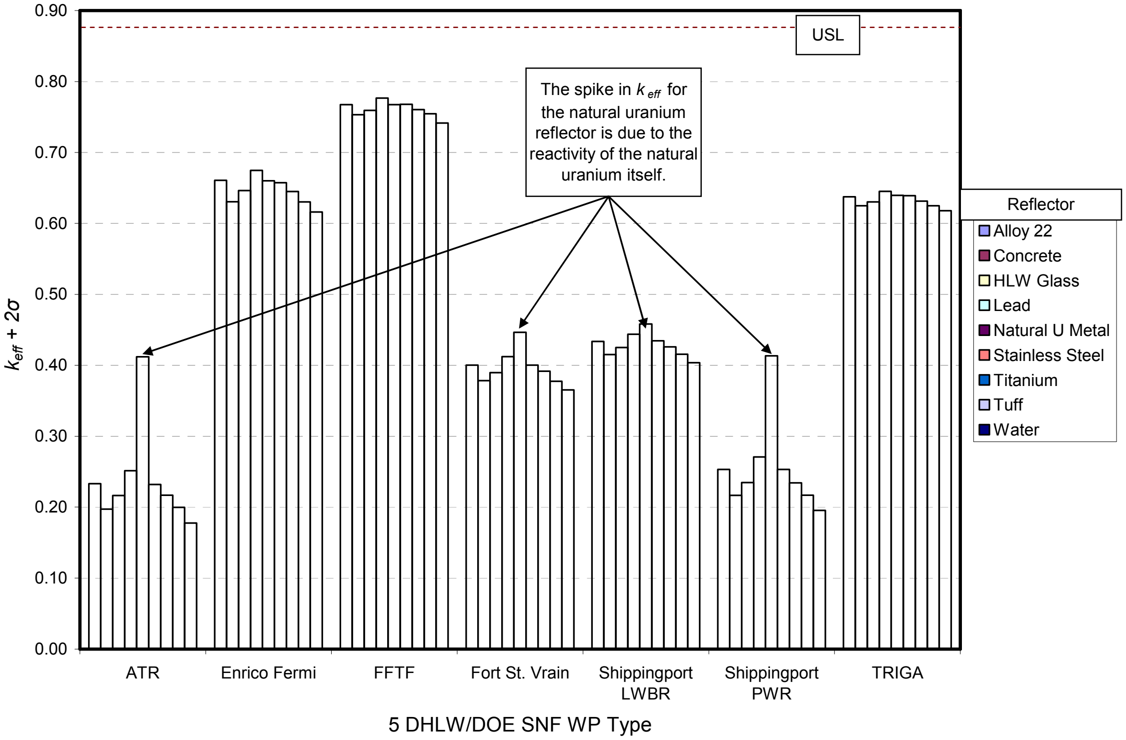
The values of k_{eff} for groupings of the most limiting undamaged canister (DOE standardized SNF canister containing FFTF) are shown in Figure 59, which demonstrates that subcriticality is maintained with a maximum of four DOE standardized SNF canister containing FFTF staged in close proximity with limiting reflection conditions. Because the fuel type contained within a DOE standardized SNF canister is not obvious from visual inspection of a sealed canister, event sequences that result in staging more than four DOE standardized SNF canisters containing any fuel type must be identified, developed, quantified, and categorized.



Source: Adapted from Figure 7-15, BSC 2008 [DIRS 182100]

Figure 59. k_{eff} for Limited Groupings of Undamaged and Dry DOE Standardized SNF Canisters Containing FFTF SNF with a Variety of Close-fitting Full-thickness Reflectors

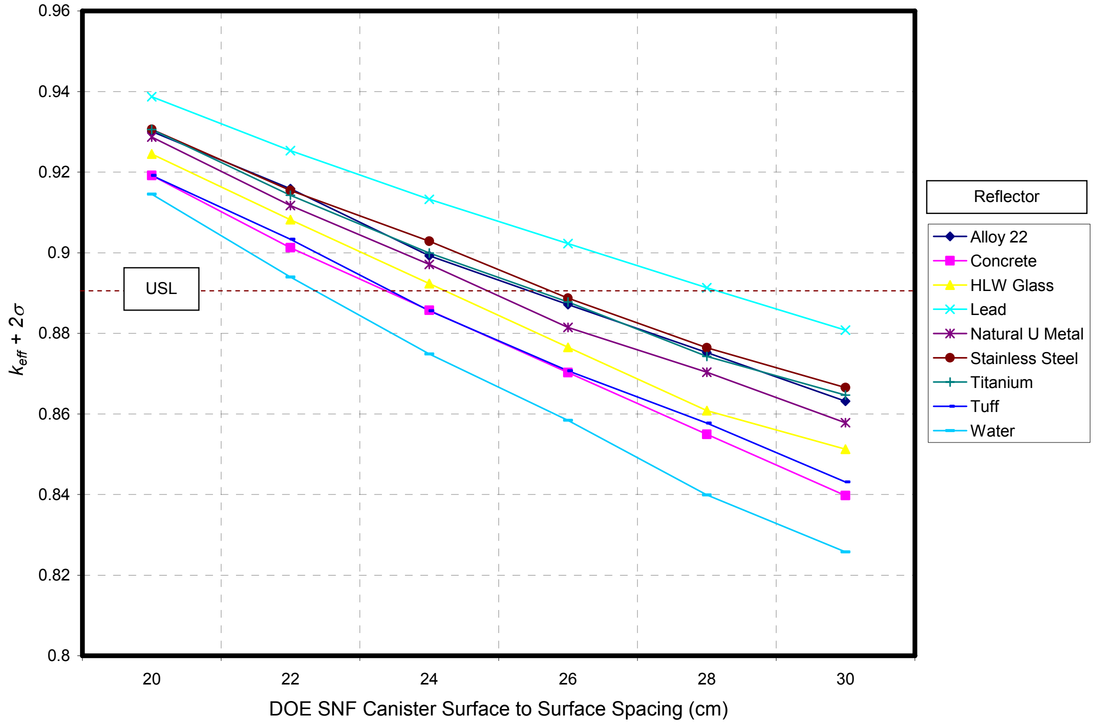
To investigate the criticality potential of misloading a codisposal waste package with more than one DOE standardized SNF canister, which is the loading requirement, six DOE standardized SNF canisters containing various types of DOE SNF were modeled closely packed within a fully-reflected codisposal waste package, in which the basket provides separation between the canisters. As demonstrated in Figure 60, subcriticality is maintained for this bounding codisposal waste package misload configuration with a maximum k_{eff}, including calculational uncertainty, less than 0.80. Therefore, inadvertent staging or misloading of DOE standardized SNF canisters in a codisposal waste package does not need to be controlled to maintain subcriticality.



Source: Adapted from Figure 7-126, BSC 2008 [DIRS 182100]

Figure 60. k_{eff} for Individual Undamaged Dry, but Misloaded 5 DHLW/DOE SNF WPs (Containing 6 DOE Standardized SNF Canisters) with a Variety of Close-fitting Full-thickness Reflectors

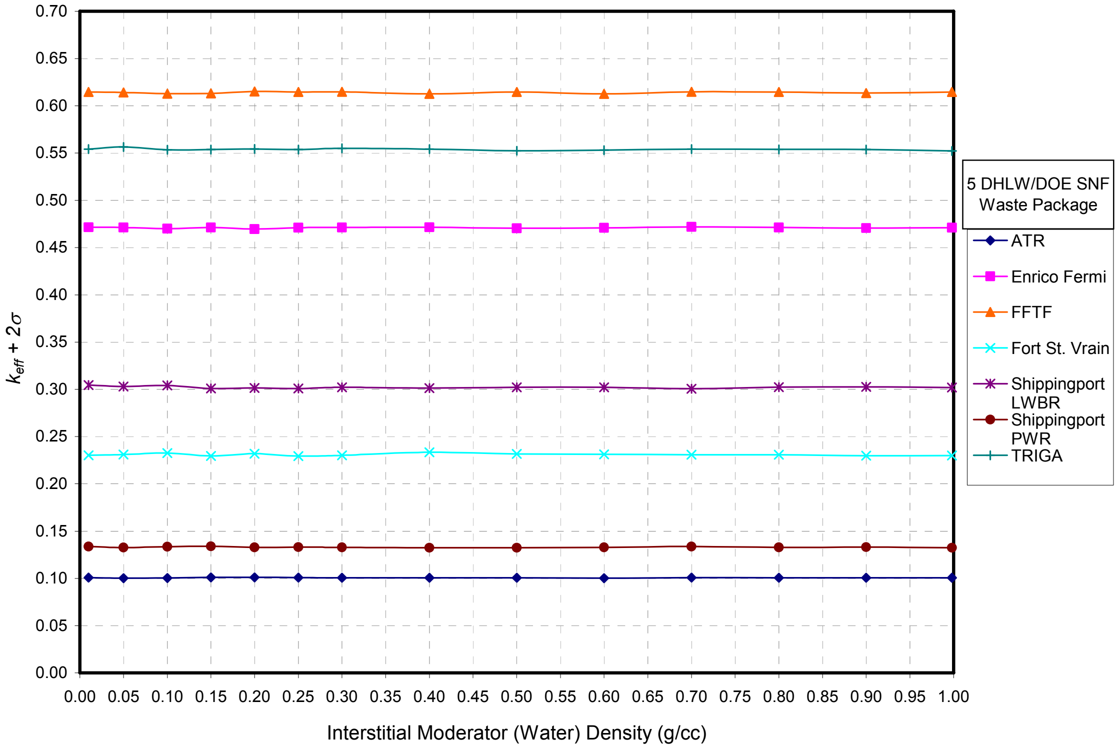
The minimum canister spacing that would ensure subcriticality for an infinite array of the most limiting canister (DOE standardized SNF Canister containing FFTF SNF) is 30 cm based on the results for lead reflection presented in Figure 61, which is significantly less than the minimum separation of 60.3 cm between canisters in the staging racks as described in Section 2.3.1.3.4.



Source: Adapted from Figure 7-14, BSC 2008 [DIRS 182100]

Figure 61. k_{eff} for an Infinite Planar Array of Undamaged and Dry DOE Standardized SNF Canisters Containing FFTF SNF with no Interstitial Moderation and a Variety of Close-fitting Full-thickness Axial Reflectors

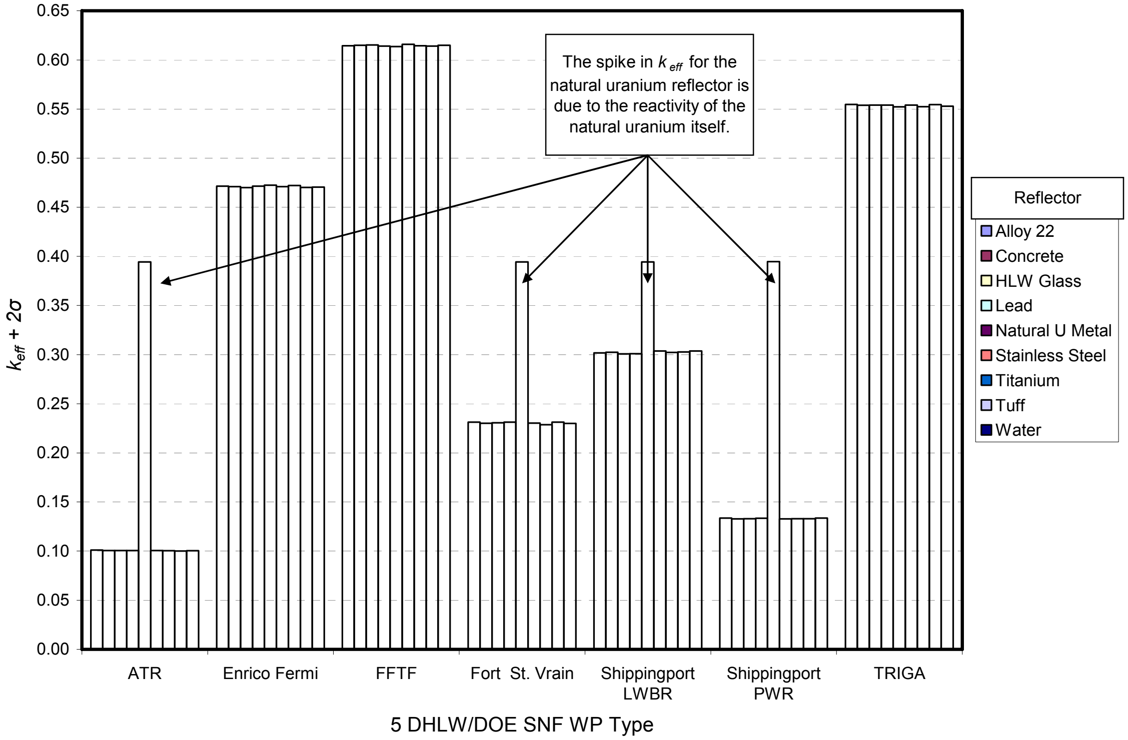
Figure 62 presents k_{eff} values for stainless-steel axially reflected infinite planar arrays of close-packed and normally-loaded codisposal waste packages. It demonstrates that subcriticality is maintained for codisposal waste packages with no restriction on interaction, and with a maximum k_{eff}, including calculational uncertainty, less than 0.65. Hence, there is no limit on how many codisposal waste packages can be staged together. Figure 62 also shows that the presence of interstitial moderator for arrays of codisposal waste packages loaded with various types of DOE SNF canisters does not affect system reactivity.



Source: Adapted from Figure 7-10, BSC 2008 [DIRS 182100]

Figure 62. k_{eff} for an Infinite Planar Array of Close-packed and Normally-loaded 5 DHLW/DOE SNF WPs with Close-fitting Full-thickness Stainless Steel Axial Reflection and a Variety of Interstitial Water Moderation Conditions

Interaction between waste packages containing the same waste form in an emplacement drift is bounded by the use of mirror boundary conditions applied to the axial ends of close-fitting, radially reflected waste packages, for which the results are presented in Figure 63. There is no statistically significant difference between the k_{eff} for a single waste package (Figure 35) and the k_{eff} for a waste package with mirror boundary conditions at the axial ends of the waste package (Figure 63). Note that the same trend holds true for TAD canister waste packages as shown in Section 2.3.2.1.4. Therefore, a waste package containing DOE SNF is always effectively infinite in length, so that its interaction with other waste packages (of commercial or DOE SNF) in an emplacement configuration is always bounded.



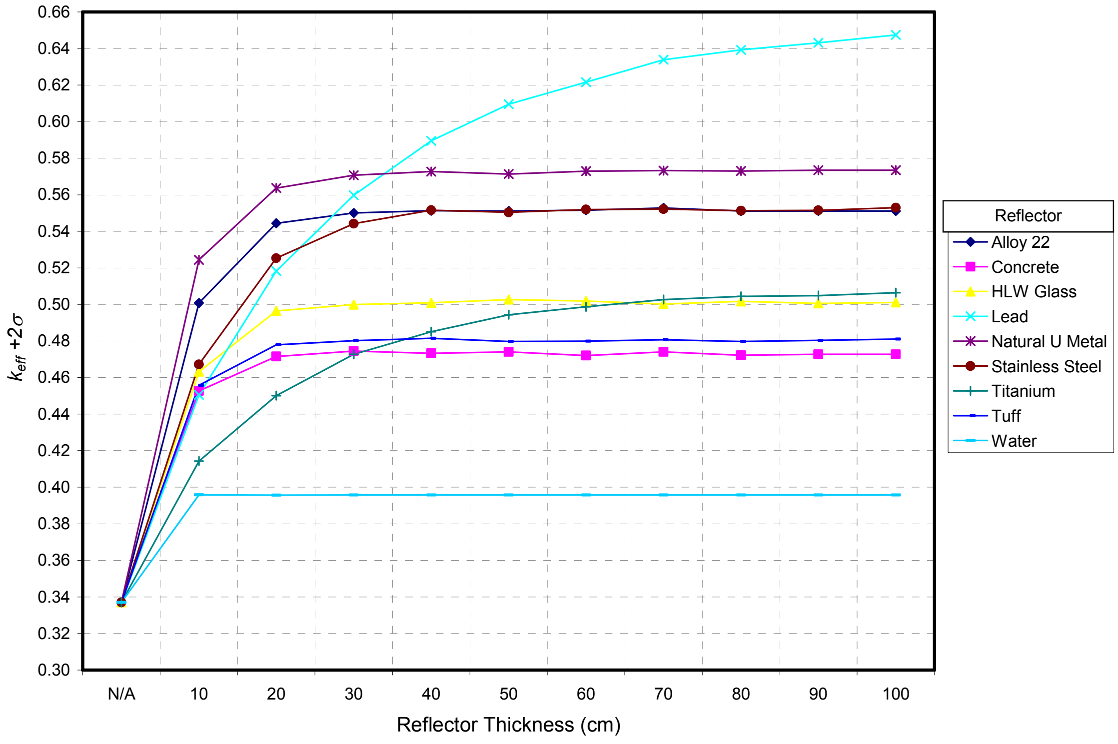
Source: Adapted from Figure 7-11, BSC 2008 [DIRS 182100]

Figure 63. k_{eff} for Undamaged, Dry and Normally-loaded 5 DHLW/DOE SNF WPs in an Emplacement Configuration, with a Variety of Close-fitting Full-thickness Radial Reflectors

To conservatively represent the interaction of containers of CSNF and DOE SNF during surface operations, DOE standardized SNF canisters containing the various types of DOE SNF are surrounded by a 30-cm-thick UO_2 reflector with 5 wt % ^{235}U enrichment, which results in a maximum k_{eff}, including calculational uncertainty, less than 0.84 (BSC 2008 [DIRS 182100], Attachment 3, Tab "Ref Thk Data" of spreadsheet "Ancillary Results.xls"). Therefore, interaction between CSNF containers and DOE SNF canisters does not need to be controlled.

2.3.2.3.5 Reflection for DOE SNF

The k_{eff} sensitivity calculations for DOE SNF examined the impact of reflection on system reactivity as a function of other relevant parameters to determine the extent to which reflection must be controlled. The reflectors considered in the analysis of transportation casks, DOE SNF canisters, and codisposal waste packages include all significant reflector materials that could be present during operations, i.e., stainless steel, concrete, lead, depleted uranium, water, Alloy 22, HLW glass, titanium, and tuff. Depleted uranium was conservatively modeled as natural uranium (BSC 2008 [DIRS 182100], Section 3.2.1), and all further reference to depleted uranium as reflection for DOE SNF in this report will discuss natural uranium. Reflector materials were modeled as close-fitting reflectors that are effectively full-thickness, that is, the thickness is greater than or equal to any dimension that may be encountered during dry operations or the thickness is sufficient to be considered neutronically infinite. For certain damaged geometry models for FFTF and Enrico Fermi SNF canisters, a nickel reflector was also considered based on its presence in the canister baskets. As shown in Figure 64 for a DOE standardized SNF canister containing Enrico Fermi SNF, 30 cm of close-fitting reflection by stainless steel, concrete, water, Alloy 22, HLW glass, uranium, and tuff is effectively infinite. For lead and titanium, 30 cm bounds any thickness of either of these two materials in the surface and subsurface facilities as well as in any transportation cask. The same trend holds true for all other DOE SNF types (BSC 2008 [DIRS 182100], Attachment 3, Tab "Ref Thk Data" of spreadsheet "Ancillary Results.xls"). Therefore, reflection is considered bounded for DOE SNF and no event sequences involving reflection need to be identified.



Source: Adapted from Tab 'EF Ref Thk Cht', Spreadsheet 'Ancillary Results.xls ', Attachment 3, BSC 2008 [DIRS 182100]

Figure 64. k_{eff} as a Function of Reflector Material and Thickness for Dry Operations with DOE Standardized SNF Canisters Containing Enrico Fermi SNF

2.3.2.4 Criticality Control Parameter for HLW Glass

The only criticality control parameter important for HLW glass is fissile isotope concentration (a waste form characteristic). As demonstrated in Section 2.3.1.1.3, criticality is not possible due to the low concentration of fissile isotopes in a HLW glass canister. No further analysis is required to demonstrate the subcriticality of individual HLW glass canisters and codisposal waste packages containing only HLW glass canisters, so they will not be discussed in the criticality safety evaluation of individual facilities other than the IHF.

2.3.2.5 Summary of Criticality Control Parameters

A summary of the criticality control parameters is shown in Table 6. For dry operations with canistered CSNF, moderation is the primary criticality control parameter and it must be controlled. Fixed neutron absorber and geometry need to be controlled only if moderator is present in CSNF canisters. For wet operations with CSNF, soluble neutron absorber must be controlled. Fixed neutron absorber, geometry, and interaction need to be controlled only if there is a boron dilution event during wet operations. For operations with DOE SNF, moderation and interaction between canisters are the primary criticality control parameters and they must be controlled. Fixed neutron absorber and geometry need to be controlled only if moderator is present in DOE standardized SNF canisters. There are no required criticality control parameters for HLW.

Table 6. Criticality Control Parameter Summary

Parameter \ Operation	CSNF (Dry Operations)	CSNF (WHF Pool and Fill Operations)	DOE SNF	HLW
Waste Form Characteristics	No[a]	No[a]	No[b]	No[c]
Moderation	Yes[d]	N/A	Yes[d]	No
Interaction	No	Conditional[g]	Yes[e]	No
Geometry	Conditional[f]	Conditional[g]	Conditional[f]	No
Fixed Neutron Absorbers	Conditional[f]	Conditional[g]	Conditional[f]	No
Soluble Neutron Absorber	N/A	Yes[h]	N/A	N/A
Reflection	No	No	No	No

[a] As described in Section 2.3.1.1, the criticality safety analysis considers bounding waste form characteristics. Therefore, there is no potential for a waste form misload.

[b] As described in Section 2.3.1.1.2, the preclosure criticality safety analysis considers nine representative DOE SNF types. Because the analysis is for representative types and loading procedures for DOE standardized SNF canisters have not been established yet, consideration of waste form misloads is not appropriate.

[c] Criticality safety design control features are not necessary for HLW canisters because criticality is not possible due to the low concentration of fissile isotopes in an HLW canister (Section 2.3.1.1.3).

[d] Moderation is the primary criticality control parameter (Sections 2.3.2.1.2 and 2.3.2.3.2).

[e] Placing more than four DOE standardized SNF canisters outside the staging racks or a codisposal waste package needs to be controlled (Section 2.3.2.3.4).

[f] Needs to be controlled only if moderator is present (Sections 2.3.2.1.3 and 2.3.2.3.3).

[g] Needs to be controlled only if the soluble boron concentration in the pool and transportation cask/DPC fill water is less than the minimum required concentration (Section 2.3.2.2.4).

[h] Minimum required soluble boron concentration in the pool is 2500 mg/L boron enriched to 90 atom % ^{10}B (Section 2.3.2.2.4).

Source: Original to this document.

2.3.3 Initial Handling Facility Evaluation

This section discusses the evaluation of preclosure nuclear criticality safety in the Initial Handling Facility (IHF). The IHF provides the SSCs to handle a portion of the DOE-managed waste stream (BSC 2007 [DIRS 182131], Section 3.1.1). The waste stream for the IHF is limited to naval SNF canisters and HLW canisters. The primary mode of receipt of waste into the IHF is rail service. In addition, the IHF is designed to receive legal-weight trucks and over-weight trucks, each of which carries a transportation cask loaded with a single HLW canister. Naval SNF canisters will be shipped by rail only, while HLW may arrive by rail or truck. Canisters received in transportation casks in the IHF are transferred directly into waste packages, which are welded closed and carried out of the IHF by the transport and emplacement vehicle (TEV) for emplacement in the repository.

The preclosure nuclear criticality safety analysis for the IHF in this report considers only the handling of HLW. As demonstrated in Section 2.3.1.1.3, criticality is not possible in HLW because the concentration of fissile isotopes in HLW is too low.

2.3.4 Receipt Facility Evaluation

The RF provides the SSCs that support receipt of transportation casks and canisters and transfer of CSNF (BSC 2007 [DIRS 182131], Section 6.1.1). It receives rail-based transportation casks containing TAD canisters and DPCs. TAD canisters and vertical DPCs are placed in aging overpacks and transferred to the Aging Facility, a CRCF (TAD canisters), or the WHF (DPCs). Horizontal DPCs inside transportation casks are placed on a transfer trailer and transferred to the Aging Facility for placement in a horizontal aging module.

2.3.4.1 Overview of Operations

The operations performed in the RF are described in *Yucca Mountain Repository Concept of Operations* (BSC 2007 [DIRS 183522], Appendix F). Prevention of nuclear criticality is considered during all operations involving fissile material as follows:

- Receipt of transportation casks containing CSNF in TAD canisters or DPCs
- Preparation, inspection, sampling, upending, and removal of casks from their conveyances; unbolting and removal of lids from casks
- Transfer of TAD canisters or DPCs to aging overpacks for movement to the WHF, CRCF, or Aging Facility; installation and bolting of lids on aging overpacks
- Transfer of horizontal DPCs in transportation casks to transfer trailers for movement to horizontal aging modules at the Aging Facility.

2.3.4.2 Evaluation of Normal Operations

The SNF is normally dry and maintained in a sealed container (i.e., TAD canister or DPC) throughout operations in the RF. Moderation is the primary criticality control parameter during normal operations in the RF (Table 6). Control of moderation is sufficient to maintain subcriticality during those operations, with a maximum k_{eff}, including calculational uncertainty, less than 0.60 (Section 2.3.2.1.2).

2.3.4.3 Analysis of Event Sequences

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality for Category 1 and Category 2 event sequences.

- **Waste Form Characteristics** - Waste form characteristics are bounded and do not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with waste form misload.

- **Moderation -** Moderation is the primary criticality control parameter during operations in the RF (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached DPCs or TAD canisters during operations in the RF (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During operations in the RF, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached DPCs or TAD canisters, it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During operations in the RF, geometry needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached DPCs or TAD canisters, it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - Interaction (neutronic coupling) is bounded during operations in the RF and does not need to be controlled (Table 6). Therefore, it was not necessary to consider event sequences that are associated with interaction.

- **Reflection** - Reflection is bounded during operations in the RF and does not need to be controlled (Table 6). Therefore, it was not necessary to consider event sequences that are associated with reflection.

2.3.4.4 Criticality Safety Bases

The ITS SSCs relied upon to ensure subcriticality in the RF based on the event sequence quantification and categorization calculations described in Section 2.2.2.2 are summarized in a preclosure nuclear safety design bases document.

2.3.5 Canister Receipt and Closure Facility Evaluation

A CRCF provides the SSCs that support receipt of transportation casks and canisters, transfer, and packaging of CSNF, DOE SNF, and HLW canisters (BSC 2007 [DIRS 182131], Section 4.1.1). It receives truck and rail-based transportation casks containing canistered waste forms. It also receives aging overpacks containing TAD canisters from the RF, WHF, and the Aging Facility. Canisters are placed in an aging overpack and transferred to the Aging Facility or sealed in a waste package and transferred to the Subsurface Facility for final emplacement. In addition, a CRCF provides separate staging racks for DOE canisters and TAD canisters. The racks provide a capacity to hold 10 DOE canisters and two TAD canisters.

2.3.5.1 Overview of Operations

The operations performed in a CRCF are described in *Yucca Mountain Repository Concept of Operations* (BSC 2007 [DIRS 183522], Appendix D). Prevention of nuclear criticality is considered during all operations involving fissile material as follows:

- Receipt of transportation casks containing waste forms in canisters (i.e., TAD canisters, DPCs, HLW canisters, and DOE SNF canisters)
- Preparation, inspection, sampling, upending, and removal of casks from their conveyances; unbolting and removal of lids from casks
- Receipt of loaded TAD canisters inside aging overpacks from the RF, WHF, or Aging Facility
- Receipt of vertical DPCs inside aging overpacks from the RF
- Transfer of TAD canisters or DPCs from transportation casks to aging overpacks; installation and bolting of lids on aging overpacks
- Transfer of horizontal DPCs in transportation casks to transfer trailers for movement to horizontal aging modules at the Aging Facility
- Movement of canisters to and from storage racks inside the Canister Handling Machine
- Storage of canisters in the staging racks
- Transfer of canisters from transportation casks and aging overpacks into waste packages
- Installation and welding of the waste package inner lid; inspection and leak testing the inner lid weld; evacuation of the waste package inner vessel and backfilling with helium; closing and seal welding the purge port in the inner lid; inspection and leak testing of the purge port closure; installation and welding of the waste package outer lid; inspection and stress mitigation of the outer lid weld
- Inspection and relocation of the completed waste package for receipt by the TEV.

2.3.5.2 Evaluation of Normal Operations

The SNF is normally dry and maintained in a sealed container (i.e., TAD canister, DPC, DOE standardized SNF canister, or a waste package) throughout operations in the CRCF. Moderation is the primary criticality control parameter during normal operations with CSNF canisters in a CRCF (Table 6). Control of moderation is sufficient to maintain subcriticality during those operations, with a maximum k_{eff}, including calculational uncertainty, less than 0.60 for CSNF (Section 2.3.2.1.2). Moderation and interaction are the primary criticality control parameters during normal operations with DOE standardized SNF canisters in a CRCF. Control of moderation and interaction for DOE standardized SNF canisters is sufficient to maintain subcriticality during those operations, with a maximum k_{eff}, including calculational uncertainty, less than 0.75 for DOE SNF (Section 2.3.2.3.2).

2.3.5.3 Analysis of Event Sequences

2.3.5.3.1 Event Sequences for Commercial SNF

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality of CSNF for Category 1 and Category 2 event sequences.

- **Waste Form Characteristics** - Waste form characteristics are bounded and do not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with waste form misload.

- **Moderation -** Moderation is the primary criticality control parameter during operations with CSNF in a CRCF (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached transportation casks, DPCs, TAD canisters, or sealed waste packages during operations in a CRCF (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During operations with CSNF in a CRCF, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached transportation casks, DPCs, TAD canisters, or sealed waste packages, it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During operations with CSNF in a CRCF, geometry needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached transportation casks, DPCs, TAD canisters, or sealed waste packages, it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - Interaction (neutronic coupling) with TAD canisters is bounded and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with interaction.

- **Reflection** - Reflection is bounded for TAD canisters and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with reflection.

2.3.5.3.2 Event Sequences for DOE SNF

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality of DOE SNF and HLW for Category 1 and Category 2 event sequences.

- **Waste Form Characteristics** - Because the criticality safety analysis is performed for representative DOE SNF fuel types, it was not necessary to consider event sequences that are associated with waste form misload of DOE standardized SNF canisters (Table 6).

- **Moderation -** Moderation is a primary criticality control parameter during operations with DOE SNF in the CRCF (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached DOE SNF canisters during operations in a CRCF (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During operations with DOE SNF in a CRCF, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached DOE SNF canisters, it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During operations with DOE SNF in a CRCF, geometry needs to be controlled for DOE standardized SNF canisters only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached DOE SNF canisters, it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - Interaction (neutronic coupling) is bounded and does not need to be controlled for DOE standardized SNF canisters except those that contain FFTF, Enrico Fermi, and Fort St. Vrain SNF (Section 2.3.2.3.4). The sensitivity analysis established that no more than four DOE standardized SNF canisters can be placed outside of the staging racks or a codisposal waste package, in which the basket structure provides interaction control (Table 6). No Category 1 or Category 2 event sequences were identified that result in placing more than four DOE standardized SNF canisters outside the staging racks or a codisposal waste package (Assumption 1.4.3).

- **Reflection** - Reflection is bounded for operations with DOE SNF and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with reflection.

2.3.5.4 Criticality Safety Bases

The ITS SSCs relied upon to ensure subcriticality in the CRCF based on the event sequence quantification and categorization calculations described in Section 2.2.2.2 are summarized in a preclosure nuclear safety design bases document.

2.3.6 Wet Handling Facility Evaluation

The WHF provides the SSCs that support receipt of transportation casks and DPCs, transfer, and canisterization of CSNF into TAD canisters (BSC 2007 [DIRS 182131], Section 5.1.1). It receives truck and rail-based transportation casks containing uncanistered fuel assemblies, and rail-based transportation casks containing DPCs. The WHF also receives aging overpacks containing vertical DPCs from the RF and Aging Facility as well as shielded transfer casks containing horizontal DPCs from the Aging Facility. The CSNF in the transportation casks and DPCs is repackaged into TAD canisters, and the sealed TAD canisters are transported to either the Aging Facility or one of the CRCFs.

In addition, the WHF provides staging racks in the pool for PWR and BWR fuel assemblies. They provide fixed neutron absorber and geometry control (a stainless steel support structure) (BSC 2007 [DIRS 183711]). The racks are described in Section 2.3.1.3.

2.3.6.1 Overview of Operations

The operations performed in the WHF are described in *Yucca Mountain Repository Concept of Operations* (BSC 2007 [DIRS 183522], Appendix E). Prevention of nuclear criticality is considered during all operations involving fissile material as follows:

- Receipt of transportation casks containing uncanistered CSNF or DPCs
- Preparation, inspection, sampling, upending, and removal of casks from their conveyances; unbolting and removal of lids from casks
- Receipt of vertical DPCs in aging overpacks from the RF and Aging Facility; receipt of shielded transfer casks from the Aging Facility containing horizontal DPCs
- Transfer of vertical DPCs from aging overpacks to shielded transfer casks and movement to the cutting room
- Transfer of horizontal DPCs in shielded transfer casks to the cutting room
- Transfer of transportation casks containing uncanistered CSNF into the pool; removal of lid from cask in the pool
- Opening of DPCs outside the pool, followed by filling of open DPCs with borated water, and transfer into the pool inside a shielded transfer cask
- Transfer of CSNF assemblies from an open transportation cask or DPC in the pool to a TAD canister in the pool, or to a staging rack in the pool
- Transfer of CSNF assemblies from the staging rack in the pool to a TAD canister in the pool
- Removal of loaded TAD canisters from the pool inside shielded transfer casks, followed by seal welding the TAD canister inner lids outside the pool

- Draining, drying, and evacuation of the sealed TAD canisters, followed by backfilling of the TAD canisters with helium and welding the outer lids

- Transfer of sealed TAD canisters from shielded transfer casks to aging overpacks for transfer to the CRCF or Aging Facility

- Controlling contaminated waste water produced from pool operations and transferring pool cleanup filters to the Low-level Waste Facility.

2.3.6.2 Evaluation of Normal Dry Operations

For the handling of sealed containers outside the pool, the SNF is normally dry and maintained in a sealed container (i.e., TAD canister or DPC) throughout operations in the WHF. Moderation is the primary criticality control parameter during normal dry operations (Table 6). Control of moderation is sufficient to maintain subcriticality during those operations, with a maximum k_{eff}, including calculational uncertainty, less than 0.60 (Section 2.3.2.1.2).

2.3.6.3 Evaluation of Normal Wet Operations

The primary criticality control parameter for wet operations is soluble neutron absorber in the form of orthoboric acid, H_3BO_3, present in the WHF pool and in transportation cask/DPC fill water with a minimum required concentration of 2500 mg/L of boron enriched to 90 atom % ^{10}B (Table 6).

For normal operations involving the transfer of individual SNF assemblies from DPCs or transportation casks to the staging racks or into a TAD canister or from the staging racks to a TAD canister, subcriticality is maintained crediting no more than 15 % of the minimum required soluble neutron absorber concentration (Section 2.3.2.2.4).

For normal operations involving the transfer of STCs containing either TAD canisters or DPCs into and out of the pool, subcriticality is maintained crediting no more than 10 % of the minimum required soluble neutron absorber concentration (BSC 2007 [DIRS 182101], Table 45).

For normal operations involving the staging racks, subcriticality is maintained crediting no more than 15 % of the minimum required soluble neutron absorber concentration, without any credit for the fixed neutron absorber (BSC 2007 [DIRS 182101], Table 36).

2.3.6.4 Analysis of Event Sequences

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality for Category 1 and Category 2 event sequences.

2.3.6.4.1 Control Parameters and Event Sequences during Dry Operations

- **Waste Form Characteristics** - Waste form characteristics are bounded and do not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with waste form misload.

- **Moderation -** Moderation is the primary criticality control parameter during dry operations (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached transportation casks, DPCs, or sealed TAD canisters during dry operations in the WHF (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During dry operations, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached transportation casks, DPCs, or sealed TAD canisters, it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During dry operations, geometry needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached transportation casks, DPCs, or sealed TAD canisters, it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - For dry operations, interaction (neutronic coupling) is bounded and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with interaction.

- **Reflection** - For dry operations, reflection is bounded and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with reflection.

2.3.6.4.2 Control Parameters and Event Sequences during Wet Operations

- **Waste Form Characteristics** - Waste form characteristics are bounded and do not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with waste form misload.

- **Moderation** – Not applicable.

- **Fixed Neutron Absorber, Soluble Neutron Absorber, Geometry, and Interaction** – There are no Category 1 or Category 2 event sequences that result in boron dilution that will lower the soluble boron (enriched to 90 atom % ^{10}B) concentration to a value that is insufficient to maintain subcriticality (Assumption 1.4.4). A procedural safety control is relied upon to ensure that a concentration of 2500 mg/L of soluble boron (enriched to 90 atom% ^{10}B) is maintained in the WHF pool and the transportation cask/DPC fill water. On this basis, subcriticality is maintained for the following types of event sequences:

    - **Event sequences that impact individual SNF assemblies** – Subcriticality is maintained for the limiting PWR assembly with optimized pin pitch and the most limiting reflection conditions, crediting no more than 15 % of the minimum required soluble neutron absorber concentration. No soluble neutron absorber is needed to maintain subcriticality for single BWR assemblies in the same configuration (Section 2.3.2.2.4).

  - **Event sequences that impact STCs** – Subcriticality is maintained for any credible level of damage to dropped STCs in any orientation containing either TADs or DPCs including the bounding configurations in which the entire contents of the STC are rearranged outside of the confinement of the STC on the bottom of the pool, crediting 2500 mg/L of soluble boron enriched to 90 atom % ^{10}B (Section 2.3.2.2.4).

  - **Event sequences that impact the staging racks** – Subcriticality is maintained for any credible level of damage to staging racks, crediting no more than 30 % of the minimum required soluble neutron absorber concentration (Section 2.3.2.2.4). Note that the credible level of damage is limited by the requirement that the staging racks maintain confinement of the fuel assemblies within the staging rack fuel compartments for all Category 1 and Category 2 event sequences (Assumption 1.4.6).

- **Reflection** - During wet operations, reflection is bounded for all reflector materials that can be expected to be present in the WHF (Table 6). Therefore, it is not necessary to consider event sequences that are associated with reflection.

2.3.6.5 Criticality Safety Bases

The ITS SSCs relied upon to ensure subcriticality in the WHF based on the event sequence quantification and categorization calculations described in Section 2.2.2.2 are summarized in a preclosure nuclear safety design bases document.

2.3.7 Intrasite Operations and Aging Facility Evaluation

Intrasite operations and the Aging Facility provide the SSCs to support movement of waste forms between surface facilities (e.g., WHF to CRCF), to and from the aging pads, and aging of TAD canisters and DPCs (BSC 2007 [DIRS 182131], Sections 9 and 10.1.1). Transportation casks are moved from the receipt area to the buffer areas and subsequently to one of the surface facilities with the site prime mover. TAD canisters and vertical DPCs are moved to and from aging pads inside aging overpacks using a bottom-lift site transporter. Horizontal DPCs are moved to and from aging pads inside transportation casks or shielded transfer casks using a cask transfer trailer. TAD canisters and DPCs are aged in aging overpacks and horizontal aging modules.

2.3.7.1 Overview of Intrasite Operations and the Aging Facility

Intrasite operations and operations performed in the Aging Facility are described in *Yucca Mountain Repository Concept of Operations* (BSC 2007 [DIRS 183522], Appendices A and G). Prevention of nuclear criticality is considered during all operations involving fissile material as follows:

- Movement of transportation casks from the Cask Receipt Security Station to the railcar buffer area or the truck buffer area using a site prime mover

- Movement of transportation casks from the railcar or truck buffer area to one of the handling facilities (IHF, RF, CRCF, or WHF) using a site prime mover

- Movement of TAD canisters in aging overpacks from the RF, CRCF, or WHF to an aging pad, or from the WHF or an aging pad to the CRCF, using a bottom-lift site transporter

- Movement of vertical DPCs in aging overpacks from the RF or CRCF to the WHF or an aging pad, or from an aging pad to the WHF, using a bottom-lift site transporter

- Aging of TAD canisters and vertical DPCs in aging overpacks on an aging pad

- Movement of transportation casks containing horizontal DPCs from the RF or CRCF to a horizontal aging module on an aging pad, using a cask transfer trailer

- Transfer of horizontal DPCs from transportation casks supported by a cask transfer trailer to horizontal aging modules, using a hydraulic ram

- Aging of horizontal DPCs in horizontal aging modules on an aging pad

- Transfer of horizontal DPCs from horizontal aging modules to site transfer casks supported by a cask transfer trailer, using a hydraulic ram

- Movement of site transfer casks containing horizontal DPCs from a horizontal aging module on an aging pad to the WHF, using a cask transfer trailer.

2.3.7.2 Evaluation of Normal Operations

The SNF is normally dry and maintained in a sealed container (i.e., transportation cask, TAD canister, DPC, or DOE standardized SNF canister) throughout intrasite operations. Moderation is the primary criticality control parameter during normal intrasite operations and aging (Table 6). Control of moderation is sufficient to maintain subcriticality during those operations, with a maximum k_{eff}, including calculational uncertainty, less than 0.60 for CSNF (Section 2.3.2.1.2) and less than 0.75 for DOE SNF (Section 2.3.2.3.2).

Criticality is not possible during normal operations with HLW because the concentration of fissile isotopes in HLW is too low (Section 2.3.1.2.4).

2.3.7.3 Analysis of Event Sequences

2.3.7.3.1 Event Sequences for Commercial SNF

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality of CSNF for Category 1 and Category 2 event sequences.

- **Waste Form Characteristics** - Waste form characteristics are bounded for CSNF and do not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with waste form misload.

- **Moderation -** Moderation is the primary criticality control parameter during intrasite operations and aging (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached transportation casks, DPCs, or TAD canisters during intrasite operations and aging (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During intrasite operations and aging, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached transportation casks, DPCs, or TAD canisters, it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During intrasite operations and aging, geometry needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached transportation casks, DPCs, or TAD canisters, it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - Interaction (neutronic coupling) is bounded and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with interaction.

- **Reflection** - Reflection is bounded and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with reflection.

2.3.7.3.2 Event Sequences for DOE SNF

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality of DOE SNF for Category 1 and Category 2 event sequences.

- **Waste Form Characteristics** - Because the criticality safety analysis is performed for representative DOE SNF fuel types (Table 6), it was not necessary to consider event sequences that are associated with waste form misload of DOE SNF canisters.

- **Moderation -** Moderation is the primary criticality control parameter during intrasite operations with DOE SNF (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached DOE SNF canisters (inside transportation casks) during intrasite operations (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During intrasite operations with DOE SNF, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached DOE SNF canisters (inside transportation casks), it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During intrasite operations with DOE SNF, geometry needs to be controlled for DOE standardized SNF canisters only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached DOE SNF canisters (inside transportation casks), it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - Interaction (neutronic coupling) is bounded and does not need to be controlled for DOE SNF canisters in transportation casks (Table 6). Therefore, it is not necessary to consider event sequences that are associated with interaction.

- **Reflection** - Reflection is bounded for operations with DOE SNF and does not need to be controlled (Table 6). Therefore, it is not necessary to consider event sequences that are associated with reflection.

2.3.7.4 Criticality Safety Bases

The ITS SSCs relied upon to ensure subcriticality for intrasite operations and the Aging Facility based on the event sequence quantification and categorization calculations described in Section 2.2.2.2 are summarized in a preclosure nuclear safety design bases document.

2.3.8 Low-Level Waste Facility Evaluation

Low-level waste (LLW) including dry active waste and wet solid waste is collected in suitable containers in the area in which the waste is generated. It is subsequently transported to the Low-Level Waste Facility for sorting and packaging for disposal. Based on the general characteristics of the canister-based facility designs, it is not expected that the LLW will include a concentration of fissile material sufficient to have criticality potential. Nevertheless, once operations with LLW are sufficiently defined, criticality safety will be ensured by analysis, design, and/or procedural controls.

2.3.9 Subsurface Facility Evaluation

The Subsurface Facility provides the SSCs for transfer to and operations in the underground, and locations for the emplacement of waste packages, as well as interfaces with the natural barrier (BSC 2007 [DIRS 182131], Section 8.1.1). Sealed waste packages on pallets are moved from a surface facility to the underground on the waste package TEV, where they are unloaded to reside in their final locations.

2.3.9.1 Overview of Operations

The operations performed in the Subsurface Facility are described in *Yucca Mountain Repository Concept of Operations* (BSC 2007 [DIRS 183522], Appendix I). Prevention of nuclear criticality is considered during all operations involving fissile material as follows:

- Movement of a loaded and sealed waste package on a pallet to an emplacement drift using the waste package TEV

- Unloading of a loaded and sealed waste package on a pallet to its final location in an emplacement drift

- Residence of loaded and sealed waste packages in the emplacement drifts through permanent closure.

2.3.9.2 Evaluation of Normal Operations

The SNF is normally dry and maintained in a sealed container (i.e., TAD canister, DOE standardized SNF canister, or a waste package) throughout operations in the Subsurface Facility. Moderation is the primary criticality control parameter during normal operations in the Subsurface Facility (Table 6). Control of moderation is sufficient to maintain subcriticality during those operations, with a maximum k_{eff}, including calculational uncertainty, less than 0.50 for CSNF (Figure 19 and Figure 26) and less than 0.65 for DOE SNF (Figure 35 and Figure 63).

Criticality is not possible during normal operations with codisposal waste packages containing only HLW because the concentration of fissile isotopes in HLW is too low (Section 2.3.1.2.4).

2.3.9.3 Analysis of Event Sequences

This section discusses how event sequences impact criticality control parameters and the limits on those parameters necessary to ensure subcriticality for Category 1 and Category 2 event sequences.

- **Waste Form Characteristics** - Waste form characteristics are bounded for CSNF and do not need to be controlled (Table 6). Because the criticality safety analysis is performed for representative DOE SNF fuel types (Section 2.3.2.3.1), it was not necessary to consider event sequences that are associated with waste form misload of DOE SNF canisters.

- **Moderation -** Moderation is the primary criticality control parameter during operations in the Subsurface Facility (Table 6). No Category 1 or Category 2 event sequences were identified that will introduce moderator into breached waste packages during operations in the Subsurface Facility (Assumption 1.4.2).

- **Fixed Neutron Absorber** - During operations in the Subsurface Facility, fixed neutron absorber needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached waste packages, it was not necessary to consider event sequences that impact the effectiveness of fixed neutron absorber.

- **Geometry** - During operations with waste packages in the Subsurface Facility, geometry needs to be controlled only if moderator is present (Table 6). Because no Category 1 or Category 2 event sequences were identified for introduction of moderator into breached waste packages, it was not necessary to consider event sequences that are associated with geometric reconfiguration.

- **Interaction** - Interaction (neutronic coupling) is bounded between waste packages and inside codisposal waste packages, in which the basket structure provides interaction control (separation between canisters) (Table 6). Therefore, it was not necessary to consider event sequences that are associated with interaction.

- **Reflection** - Reflection is bounded and does not need to be controlled (Table 6). Therefore, it was not necessary to consider event sequences that are associated with reflection.

2.3.9.4 Criticality Safety Bases

The ITS SSCs relied upon to ensure subcriticality in the Subsurface Facility based on the event sequence quantification and categorization calculations described in Section 2.2.2.2 are summarized in a preclosure nuclear safety design bases document.

2.3.10 Criteria to Establish Subcriticality

A configuration is considered acceptably subcritical if: (1) the maximum k_{eff} plus calculational uncertainties is less than or equal to the configuration-specific USL (BSC 2008 [DIRS 185056], Section 3.4) or (2) it meets the single- or multiparameter limits established in Sections 5 and 6 of ANS/ANS-8.1-1998 [DIRS 123801]. In equation notation, the use of the USL is:

$$k_{eff} + \Delta k_{eff} \leq \text{USL} \qquad \text{(Eq. 1)}$$

where

$$\text{USL} = 1 - \text{sum of bias and uncertainties} - \text{administrative margin} \qquad \text{(Eq. 2)}$$

and

k_{eff} = calculated effective neutron multiplication factor for the system

Δk_{eff} = an allowance for: (a) statistical or convergence uncertainties, or both in the computation of k_{eff} [Note: bounds for k_{eff} values are provided at the 95% confidence level.], (b) material and fabrication tolerances, and (c) uncertainties due to the geometric or material representations used in the computational method. [Note: allowance for items (b) and (c) are obviated by using bounding representations.]

USL = an upper limit on k_{eff} characterized by statistical tolerance limits that accounts for: (1) biases and uncertainties associated with the criticality code validation process, (2) any uncertainties due to extrapolation outside the range of experimental data, or limitations in the geometrical or material representations used in the computational method, and (3) a justified administrative margin to ensure subcriticality.

The upper subcritical limit is represented in equation form as (BSC 2008 [DIRS 185056], Section 3.4):

$$\text{USL} = \text{LBTL} - \Delta k_{EROA} - \Delta k_m \qquad \text{(Eq. 2)}$$

where

LBTL = the lower-bound tolerance limit accounting for biases and uncertainties that cause the calculational results to deviate from the true value of k_{eff} for a critical experiment, as reflected over an appropriate set of critical experiments

Δk_{EROA} = penalty for extending the range of applicability

Δk_m = an administrative margin ensuring subcriticality

The largest bias and bias uncertainty for selected critical benchmark experiments applicable to moderated (with water and borated water) commercial SNF configurations is 0.012 Δk (BSC 2008 [DIRS 185090], Section 7). For added conservatism, the k_{eff} values of the analyzed configurations are conservatively rounded up to two significant digits. Continuing with the same conservative treatment, the maximum bias and bias uncertainty is also rounded up to two significant digits equaling 0.02. This maximum bias and bias uncertainty of 0.02 is conservatively applied to all commercial SNF normal and off-normal configurations.

A variety of close-fitting reflection conditions are considered for every configuration analyzed to maximize the k_{eff} of the configuration regardless of whether the presence of such reflectors is credible. These reflectors include stainless steel, concrete, lead, depleted (modeled conservatively as natural) uranium, and water. The selected benchmarks do not include all of these reflector materials for commercial SNF. However, the limiting configurations that form the basis for the criticality safety analysis (i.e., limiting minimum required boron concentration) documented in this report rely only on the reflector materials that have been validated (i.e., stainless steel, concrete, water, and borated water). In addition many of the models considered infinite planar arrays with axial reflection, which has been demonstrated to have an insignificant effect on the reactivity of commercial SNF (Figure 24). Results based on reflector materials that have not been validated (e.g., lead) are solely used to demonstrate margin and are bounding (i.e., result in higher k_{eff} values) of the results using validated and credible reflection conditions.

The largest bias and bias uncertainty for the DOE SNF fuel types considered in this report for a wide range of geometries (i.e., intact or damaged) and a wide neutron spectral range (i.e., moderated or unmoderated) is 0.052, which corresponds to intact moderated TRIGA SNF (BSC 2008 [DIRS 185105], Table 7-2). For added conservatism, the k_{eff} values of the analyzed configurations are conservatively rounded up to two significant digits. Continuing with the same conservative treatment, the maximum bias and bias uncertainty is also rounded up to two significant digits equaling 0.06 Δk. This maximum bias and bias uncertainty of 0.06 is conservatively applied to all DOE SNF types for normal and off-normal configurations.

Therefore, the lowest $\{\text{LBTL} - \Delta k_{EROA}\}$ values associated with the benchmarking and validation of the MCNP code [DIRS 163407] and the associated cross section libraries for CSNF and DOE SNF configurations are 0.98 and 0.94, respectively.

2.3.10.1 Administrative Margin and Justification

Consistent with the guidance provided in ANSI/ANS-8.24-2007, *American National Standard, Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*, [DIRS 182309], Section 6.4, and Fuel Cycle Safety and Safeguards (FCSS)-Interim Staff Guidance (ISG)-10, *Justification for Minimum Margin of Subcriticality for Safety* [DIRS 178606], the following considerations are taken into account in the justification of a conservative 0.05 administrative margin for preclosure criticality safety analyses:

- Validation results
- Conservatisms in the calculational model

- Likelihood of abnormal conditions
- System sensitivity
- Knowledge of neutron physics.

The following subsections discuss these considerations for each of the evaluated waste forms.

Validation Results—Criticality calculational method validation (BSC 2008 [DIRS 185090] and BSC 2008 [DIRS 185105]) was performed consistent with industry standards and guidance documents (e.g., ANSI/ANS-8.1-1998 [DIRS 123801], including the exception taken in Regulatory Guide 3.71 [DIRS 176331], and ANSI/ANS-8.24-2007 [DIRS 182309]). The lowest {LBTL - Δk_{EROA}} values for commercial SNF and DOE SNF (i.e., 0.98 and 0.94, respectively) are applied to normal operations and end-states of Category 1 and Category 2 event sequences.

Conservatisms in the calculational model—Preclosure criticality safety analyses for the various waste forms are based on conservative representations, including:

- Representation of all commercial SNF as fresh fuel (i.e., no burnup credit) with an enrichment of 5 wt % ^{235}U (maximum commercial SNF enrichment) and without credit for burnable poisons or the presence of ^{234}U and ^{236}U

- Evaluation of the most reactive fuel state for DOE SNF (i.e., fresh fuel for nonbreeder reactors, or calculated most reactive state for breeder reactor fuel)

- Consideration of a variety of close-fitting reflection conditions for every configuration analyzed to maximize the criticality potential of the configuration regardless of whether the presence of such reflectors is credible. These reflectors include stainless steel, concrete, lead, depleted (modeled conservatively as natural) uranium, water, Alloy 22, HLW glass, titanium, and tuff.

- Demonstration of subcriticality without credit for fixed neutron absorbers, which is primarily based on moderator control for operations with canistered SNF and soluble boron for operations with uncanistered commercial SNF.

Likelihood of abnormal conditions—The criticality safety design and operational criteria have been established such that all normal operations as well as end-states of event sequences with a mean probability of occurrence greater than or equal to 10^{-4} during the preclosure period are demonstrated to be subcritical. This goal is attained primarily on the basis of robust engineering controls with limited reliance on procedural safety controls. These controls include moderator control for dry canister operations, and soluble neutron absorber control during wet operations conducted in the WHF pool.

System Sensitivity—The results of the criticality analyses demonstrated that the waste forms are sufficiently subcritical for normal operations and all Category 1 and Category 2 event sequences important to criticality. The criticality sensitivity analysis (Section 2.3) has demonstrated that the system sensitivity to perturbation in criticality control parameters is either bounded (e.g., reflection), or controlled with a significant margin. For example, even though moderator is controlled for dry operation such that no Category 1 or Category 2 event sequence results in any moderation inside a breached canister, the criticality sensitivity analysis has demonstrated that under conservative "nonmechanistic" geometric reconfigurations (e.g., complete flux trap collapse, optimized pin pitch within the fuel compartments, separation of fuel and basket, and fuel release) with reduced credit for neutron absorbers and bounding reflection conditions, subcriticality can be maintained with a substantial amount (i.e., over 100 liters) of water inside a breached CSNF canister (Figure 22 and Figure 23).

Knowledge of Neutron Physics—Existing waste forms will be received in the GROA without the ability to alter their form to the extent that their neutron physics characteristics will be impacted. These waste forms are stable SNF from nuclear reactors whose neutronic characteristics have been well studied and extensively benchmarked.

The three fissile isotopes in commercial and DOE SNF considered in the preclosure criticality safety analysis are ^{233}U, ^{235}U, and ^{239}Pu at varying enrichments. The only neutron absorber relied upon in the criticality safety analysis is boron. The neutron moderators considered in the criticality safety analysis are hydrogen in water and in a zirconium hydride matrix as well as carbon in a limited number of canisters. The fissile isotopes at the varying enrichments, neutron absorbers, and moderators considered in the criticality safety analysis have been analyzed in numerous benchmarks with varying geometries and neutron spectra (NEA 2006 [DIRS 182629]).

Therefore, the neutron physics associated with the various waste forms and configurations considered in the criticality safety analysis are well behaved and well understood.

Upper Subcritical Limit Conclusion—Based on a conservative administrative margin of 0.05 Δk and the lowest {LBTL - Δk_{EROA}} values, the upper subcritical limits for normal operations and end-states of Category 1 and Category 2 event sequences for CSNF and DOE SNF are 0.93 and 0.89, respectively.

2.3.11 Criticality Accident Alarm System

Because 10 CFR Part 63 [DIRS 180319] contains no specific criticality monitoring requirements, guidance to determine the potential need for a criticality accident alarm system (CAAS) is taken from the applicable standard (ANSI/ANS-8.3-1997 [DIRS 176884]) and from precedents in NRC regulation (10 CFR Part 70 [DIRS 182681], 10 CFR Part 50 [DIRS 181964] and 10 CFR Part 72 [DIRS 181968]). The underlined statements in the quotes from the various referenced documents in the following subsections form the key bases for the evaluation in this section.

2.3.11.1 Compliance with Preclosure Criticality Requirement

To comply with the preclosure criticality safety requirement as described in Section 2.1.3, subcriticality is demonstrated for all preclosure operations with fissile materials for normal operations and for event sequences with a mean probability of occurrence greater than or equal to one chance in 10,000 prior to permanent closure. Subcriticality is defined as an end-state configuration whose maximum k_{eff} is less than or equal to the USL, which includes allowance for calculational bias and for a 5% Δk administrative margin. Subcriticality is demonstrated based on passive engineered systems (e.g., fixed and soluble neutron absorbers, and moderator control features such as sealed casks and canisters) with minimal reliance on administrative controls or operator intervention.

2.3.11.2 Standards Documents

ANSI/ANS-8.3-1997 [DIRS 176884], *Criticality Accident Alarm System*, Section 2 states:

> "This standard is applicable to all operations involving fissionable materials in which inadvertent criticality can occur and cause personnel to receive unacceptable exposure to radiation. This standard is not applicable to detection of criticality events where no excessive exposure to personnel is credible…."

Excessive radiation dose is defined in Section 3.3 of ANSI/ANS-8.3-1997 [DIRS 176884] as:

> "Any dose to personnel corresponding to an absorbed dose from neutrons and gamma rays equal to or greater than 0.12 Gy (12 rad) in free air"

Criticality accident alarm systems per this standard are not required in repository facilities provided either an adequate demonstration is shown that the dose consequence at personnel locations is less than 0.12 Gy (12 rad) (definition of excessive dose) or criticality accidents are demonstrated to be incredible.

Even though it has been quantitatively demonstrated that no Category 1 or Category 2 event sequence results in a configuration that violates the USL, the actual likelihood of a criticality accident is significantly lower, and thus incredible, given the following conservatisms in the analysis:

- Representation of all commercial SNF as fresh fuel (i.e., no burnup credit) with an enrichment of 5 wt % ^{235}U (maximum commercial SNF enrichment) and without credit for burnable poisons or the presence of ^{234}U and ^{236}U

- Evaluation of the most reactive fuel state for DOE SNF (i.e., fresh fuel non-breeder reactor fuel, or calculated most reactive state for breeder reactor fuel)

- Demonstration of subcriticality without credit for fixed neutron absorbers, which is primarily based on moderator control for operations with canistered SNF and soluble boron for operations with uncanistered commercial SNF

- There is a 5% Δk margin between the criterion to determine subcriticality and actual critical calculated state.

Therefore, a CAAS is not required per ANSI/ANS-8.3-1997 [DIRS 176884].

2.3.11.3 NRC Regulations

10 CFR Part 70 [DIRS 182681], *Domestic Licensing of Special Nuclear Material*, Section 70.24 states:

> "(a) Each licensee authorized to possess special nuclear material in a quantity exceeding 700 grams of contained uranium–235, 520 grams of uranium–233, 450 grams of plutonium, 1,500 grams of contained uranium–235 if no uranium enriched to more than 4 percent by weight of uranium–235 is present, 450 grams of any combination thereof, or one-half such quantities if massive moderators or reflectors made of graphite, heavy water or beryllium may be present, shall maintain in each area in which such licensed special nuclear material is handled,

> used, or stored, a monitoring system meeting the requirements of either paragraph (a)(1) or (a)(2), as appropriate, and using gamma- or neutron-sensitive radiation detectors which will energize clearly audible alarm signals if accidental criticality occurs. This section is not intended to require underwater monitoring when special nuclear material is handled or stored beneath water shielding or to require monitoring systems when special nuclear material is being transported when packaged in accordance with the requirements of part 71 of this chapter…."

Operations with fissile material in the surface (including intrasite operations) and subsurface facilities are either performed underwater or with fissile material that has been packaged in accordance with the requirements of 10 CFR Parts 71 [DIRS 181967] and/or 72 [DIRS 181968]. CSNF, DOE SNF, naval SNF, and HLW canisters are transportable containers. Their placement in an overpack, a waste package, or a shielded transfer cask does not affect the criticality control features of their packaging. Therefore, a CAAS is not required per 10 CFR Part 70 [DIRS 182681].

10 CFR 50 [DIRS 181964], Domestic Licensing of Production and Utilization Facilities, Section 50.68 States:

> "… (b) Each licensee shall comply with the following requirements in lieu of maintaining a monitoring system capable of detecting a criticality as described in 10 CFR 70.24:
>
> (1) Plant procedures shall prohibit the handling and storage at any one time of more fuel assemblies than have been determined to be safely subcritical under the most adverse moderation conditions feasible by unborated water.
>
> (2) The estimated ratio of neutron production to neutron absorption and leakage (k-effective) of the fresh fuel in the fresh fuel storage racks shall be calculated assuming the racks are loaded with fuel of the maximum fuel assembly reactivity and flooded with unborated water and must not exceed 0.95, at a 95 percent probability, 95 percent confidence level. This evaluation need not be performed if administrative controls and/or design features prevent such flooding {i.e., with unborated water} or if fresh fuel storage racks are not used.
>
> (3) If optimum moderation of fresh fuel in the fresh fuel storage racks occurs when the racks are assumed to be loaded with fuel of the maximum fuel assembly reactivity and filled with low-density hydrogenous fluid, the k-effective corresponding to this optimum moderation must not exceed 0.98, at a 95 percent probability, 95 percent confidence level. This evaluation need not be performed if administrative controls and/or design features prevent such moderation {i.e., with unborated water} or if fresh fuel storage racks are not used.
>
> (4) If no credit for soluble boron is taken, the k-effective of the spent fuel storage racks loaded with fuel of the maximum fuel assembly reactivity must not exceed 0.95, at a 95 percent probability, 95 percent confidence level, if flooded with unborated water. If credit is taken for soluble boron, the k-

> effective of the spent fuel storage racks loaded with fuel of the maximum fuel assembly reactivity must not exceed 0.95, at a 95 percent probability, 95 percent confidence level, if flooded with borated water, and the k-effective must remain below 1.0 (subcritical), at a 95 percent probability, 95 percent confidence level, if flooded with unborated water.
>
> (5) The quantity of SNM, other than nuclear fuel stored onsite, is less than the quantity necessary for a critical mass.
>
> (6) Radiation monitors are provided in storage and associated handling areas when fuel is present to detect excessive radiation levels and to initiate appropriate safety actions.
>
> (7) The maximum nominal U–235 enrichment of the fresh fuel assemblies is limited to five (5.0) percent by weight.
>
> (8) The FSAR is amended no later than the next update which § 50.71(e) of this part requires, indicating that the licensee has chosen to comply with § 50.68(b)."

Operations in the Wet Handling Facility (WHF) are similar to those in a spent fuel pool licensed to 10 CFR Part 50 [DIRS 181964] as described in Section 50.68(b). As demonstrated in Section 2.3.6, these operations meet requirements 1 through 7 listed above (requirement 8 is not applicable). In addition, radiation monitors that comply with requirement (6) above will be used in the WHF. Therefore, a CAAS would not be expected to be required per 10 CFR Part 50 [DIRS 181964].

10 CFR Part 72 [DIRS 181968], Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste, Section 72.124 states:

> "(c) *Criticality Monitoring.* A criticality monitoring system shall be maintained in each area where special nuclear material is handled, used, or stored which will energize clearly audible alarm signals if accidental criticality occurs. Underwater monitoring is not required when special nuclear material is handled or stored beneath water shielding. Monitoring of dry storage areas where special nuclear material is packaged in its stored configuration under a license issued under this subpart is not required."

Operations with fissile material in the surface (including intrasite operations) and subsurface facilities are either performed under water or the fissile material has been packaged in accordance with the requirements of 10 CFR Part 72 [DIRS 181968]. TAD, DOE SNF, naval SNF, and HLW canisters are expected to be aged, staged, and emplaced in similar configurations as those licensed under 10 CFR Part 72 [DIRS 181968]. Therefore, a CAAS would not be expected to be required per 10 CFR Part 72 [DIRS 181968].

2.3.11.4 Defense-in-Depth Evaluation

A CAAS is not needed as a defense-in-depth safety measure at the Repository. The radiation detectors as part of the radiological monitoring system are capable of detecting excessive radiation levels regardless of the cause. An unnecessary CAAS could have adverse effects on safety and operations. Accidental actuation of a CAAS due to either equipment failure or false detection resulting in unnecessary evacuations will increase worker risk and impact operations. In addition, maintenance of an unnecessary CAAS may result in hazards to workers such as exposure to radiation or accidents.

2.3.11.5 CAAS Implementation Conclusion

Based on the absence of specific criticality monitoring requirements in 10 CFR Part 63, prescriptive NRC regulations for similar applications (i.e., 10 CFR Part 50 [DIRS 181964], 10 CFR Part 70 [DIRS 182681], and 10 CFR Part 72 [DIRS 181968]), and guidance of ANSI/ANS-8.3-1997 [DIRS 176884], a criticality alarm system is not required anywhere in the GROA. This is based on the following:

- Preclosure operations with fissile materials at the Monitored Geologic Repository have been demonstrated to be subcritical for normal operations and for Category 1 and Category 2 event sequences

- Given the conservatism in the criticality analysis the likelihood of an actual criticality accident is less than 10^{-4} during the preclosure period

- All canistered waste forms are packaged in transportable containers (TAD, naval SNF and DOE canisters), for which criticality monitoring would not be expected to be required based on similar regulations

- The radiation/radiological monitoring system in the surface and subsurface facilities is designed to detect radiological releases or extreme radiation levels regardless of the cause.

2.3.12 Offsite Operations

Offsite operations are not considered as initiating events since they will be performed under an NRC accepted quality assurance program. In addition, all shipments to the repository must be loaded in accordance with the certificate of compliance for a specific transportation cask that is licensed under 10 CFR Part 71 [DIRS 181967]. Nonetheless, offsite operations and their impacts, if any, on the preclosure criticality safety control parameters are discussed in this section.

2.3.12.1 Waste Form Characteristics

2.3.12.1.1 Commercial SNF

Because the waste form characteristics for CSNF used in the criticality safety analysis are considered bounding as described in Section 2.3.1.1.1, there is no potential for CSNF misload.

2.3.12.1.2 DOE SNF

The preclosure criticality safety analysis considers the nine representative DOE SNF types listed in Section 2.3.1.1.2. Consideration of waste form misloads is not appropriate because the criticality safety analysis is only for representative DOE SNF fuel types and loading procedures for DOE standardized SNF canisters have not been established yet.

2.3.12.2 Moderation

2.3.12.2.1 Commercial SNF

Prior to receipt at the GROA, CSNF canisters will have been dried using a process similar to the one described in NUREG-1567 *Standard Review Plan for Spent Fuel Dry Storage Facilities*, Section 9.5.4.1 [DIRS 149756], which states:

> …The staff has accepted the combination of a draining procedure and a vacuum drying procedure as providing adequate assurance that the gases in the cask meet the maximum oxidizing gas criteria. The vacuum drying procedure involves a vacuum test to demonstrate that there is no water in the cask or fuel. A cask that is evacuated to less than 3 torr and, after sealing, does not have a cask pressure which increases by 1 torr over 30 minutes is considered to be free of water…

10 CFR Part 71, Subpart E, Paragraph 55(b) [DIRS 181967] states :

> (b) Except as provided in paragraph (c) or (g) of this section, a package used for the shipment of fissile material must be so designed and constructed and its contents so limited that it would be subcritical if water were to leak into the containment system, or liquid contents were to leak out of the containment system so that, under the following conditions, maximum reactivity of the fissile material would be attained: (1) The most reactive credible configuration consistent with the chemical and physical form of the material; (2) Moderation by water to the most reactive credible extent; and (3) Close full reflection of the containment system by water on all sides, or such greater reflection of the containment system as may additionally be provided by the surrounding material of the packaging. (c) The Commission may approve exceptions to the requirements of paragraph (b) of this section if the package incorporates special design features that ensure that no single packaging error would permit leakage, and if appropriate measures are taken before each shipment to ensure that the containment system does not leak.

Even with the extremely low probability event of inadequate dewatering of CSNF canisters, there is no credible potential for criticality for the following reasons:

- All CSNF canisters will have to comply with 10 CFR Part 71, Subpart E, Paragraph 55(b) [DIRS 181967] requirements as described above

- The criticality calculations documented in (BSC 2007 [DIRS 182099]) demonstrate that under the worst case damage conditions of complete flux trap gap collapse, significant fuel release, and maximum fuel pin pitch, subcriticality is still maintained with several hundred liters of water remaining in the canister

2.3.12.2.2 DOE SNF

DOE standardized SNF canisters will have been dried as described for CSNF in Section 2.3.12.2.1 prior to receipt at the GROA. Secondly, all DOE SNF canisters will have to demonstrate compliance with 10 CFR Part 71, Subpart E, Paragraph 55(b) [DIRS 181967] as described for CSNF in Section 2.3.12.2.1. Thirdly, for the purposes of postclosure criticality control, the canisters and their internals are designed to ensure subcriticality under fully flooded intact and degraded (postclosure) configurations. Therefore, even for the low probability event of inadequate dewatering of DOE SNF canisters, there is no credible potential for criticality.

2.3.12.3 Neutron Absorbers

For dry operations, neutron absorber misload is inconsequential given that the preclosure criticality safety analysis does not credit neutron absorbers in the absence of moderation. For wet operations, the soluble neutron absorber in the WHF pool is sufficient to compensate for significant reduction of fixed neutron absorbers in the analyzed CSNF canister designs (Section 2.3.6).

2.3.12.4 Geometry

The criticality calculations documented in (BSC 2007 [DIRS 182101]), (BSC 2007 [DIRS 182099]), and (BSC 2008 [DIRS 182100]) considered a wide range of geometrical reconfigurations that bound any credible potential reconfiguration due to undetected mishandling during off-site operations. Therefore, off-site operations have no additional impact on the preclosure criticality safety analysis from a geometry standpoint.

2.3.12.5 Reflection

Reflection is bounded in the preclosure criticality safety analysis and all potential reflectors that could be shipped are taken into account. Therefore, off-site operations have no additional impact on the preclosure criticality safety analysis from a reflection standpoint.

2.3.12.6 Interaction

Interaction is considered between separate units containing fissile material in the surface facilities. Therefore, off-site operations have no impact on interaction.

3. CONCLUSIONS

This technical report has presented, within the context of the regulatory requirements, a risk-informed, performance-based preclosure criticality safety analysis of waste forms (including canisters and waste packages) and repository facilities for the time period beginning with waste form receipt at the surface facility and ending with permanent closure of the Subsurface Facility. The results documented in Section 2.3 demonstrate that preclosure criticality is prevented for normal operations and for Category 1 and Category 2 event sequences. Further, it is concluded that a CAAS is not required anywhere in the surface (including intrasite operations) or subsurface facilities.

The following is a summary of the design and operational criteria that are relied upon to maintain subcriticality:

- Moderator control for all canister-based operations in the Receipt Facility, Canister Receipt and Closure Facility, Wet Handling Facility outside the pool, intrasite operations including aging, and Subsurface Facility. Moderator is controlled by ITS SSCs that are designed to prevent introduction of moderator (e.g., water and hydraulic fluid) into commercial, and DOE standardized SNF canisters for normal operations and for Category 1 and Category 2 event sequences

- Interaction control such that no Category 1 or Category 2 event sequence results in placing more than four DOE standardized SNF canisters in close proximity outside their designated staging racks or a codisposal waste package configuration

- Soluble neutron absorber control such that a concentration of 2500 mg/L of soluble boron (enriched to 90 atom% ^{10}B) is maintained in the WHF pool and the transportation cask/DPC fill water

The following is a list of key considerations on which this preclosure criticality safety analysis is based:

- Use of current facility designs and expected fuel operations

- Use of conceptual TAD canister designs described in Section 2.3.1.2.3.

- Use of representative DPC designs described in Section 2.3.1.2.2.

- Use of the nine representative DOE SNF types described in Section 2.3.1.1.2.

If the transportation cask, canister, and waste package designs, fuel characteristics, or fuel operations are not bounded by the evaluation presented in this report, an evaluation will be performed to demonstrate compliance with the criticality safety requirement in Section 2.1.3.

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APPENDIX A

DETERMINATION OF MINIMUM VOLUME OF GLASS IN WEST VALLEY DEMONSTRATION PROJECT CANISTER

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Appendix A

Determination of Minimum Volume of Glass in a West Valley Demonstration Project Canister

The dimensions used below to determine the minimum volume of glass in a West Valley Demonstration Project canister are taken from WVNS 2001 [DIRS 157559]. The justification for using these dimensions is that they are provided by the waste generator, which represents the most authoritative source of information. Therefore, they are considered suitable for their intended use in this report, i.e., to calculate the minimum glass volume.

The minimum fill volume of a West Valley Demonstration Project (WVDP) HLW canister is 80 % of the volume of the empty canister (p. 1, Section WQR-3.6, Rev. 1 of WVNS 2001 [DIRS 157559]). For the purpose of calculating glass volume, the canister is treated as a right circular cylinder, the 100% fill level is taken to be the base of the neck, which is 115.00 in. as measured from the bottom of the canister, and the glass surface at the 80 % fill level is 25.75 in. below the top of the canister (p. 2, Section WQR-3.6, Rev. 1 of WVNS 2001 [DIRS 157559]). The remaining canister dimensions are given in Table A-1.

Table A-1. WVDP HLW Canister Dimensions

Radius (R)	12.00 in. (30.48 cm)
Canister Wall Thickness (t_w)	0.135 in. (0.343 cm)
Canister Height (H_c)	117.75 in. (299.09 cm)
Canister Bottom Lid Thickness (t_B)	0.188 in. (0.478 cm)

Source: Adapted from Table 16, p. 30 of Section WQR-1.4, Rev. 2 of WVNS 2001 [DIRS 157559]

The minimum fill height is given by:

$$h_{min} = (H_c - t_B - 25.75 \text{ in.}) \tag{B-1a}$$

or

$$h_{min} = (117.75 \text{ in.} - 0.188 \text{ in.} - 25.75 \text{ in.}) \times 2.54 \text{ cm/in.} = 233.20 \text{ cm} \tag{B-1b}$$

The corresponding minimum fill volume is then:

$$V_{min} = \pi \times (R - t_w)^2 \times h_{min} \tag{B-2a}$$

or

$$V_{min} = \pi \times (30.48 \text{ cm} - 0.343 \text{ cm})^2 \times 233.20 \text{ cm} = 665400 \text{ cm}^3 = 665 \text{ L} \tag{B-2b}$$

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