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Bounding Criticality Safety Analyses for Shipments of Unconfigured Spent Nuclear Fuel

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I. Introduction

In November 1996, a request was made to the U.S. Department of Energy for a waiver for three shipments of spent nuclear fuel (SNF) from Oak Ridge National Laboratory (ORNL) to the Savannah River Site (SRS) in the U.S. NRC certified BMI-1 cask (CoC 5957). Although the post-irradiation fissile mass (based on chemical assays) in each shipment was less than 800 g, a criticality safety analysis[1] was needed because the pre-irradiation mass exceeded 800 g, the fissile material limit in the CoC. The analyses were performed on SNF consisting of aluminum-clad U_3O_8, UAl_x, and U_3Si_2 plates, fragments and pieces that had been irradiated at ORNL during the Reduced Enrichment Research and Test Reactor Program of the 1980s. The highlights of the approach used to analyze this unique SNF and the benefits of the waiver are presented in this paper.

II. Description of Work

The criticality safety analysis was performed to demonstrate that the three separate loadings of the BMI-1 cask would be adequately subcritical with the specified pre-irradiated

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fissile mass loadings. The analysis was performed assuming that the only available data was the elemental form of the spent fuel and the mass of ^{235}U and total uranium in each canister, from which fresh fuel enrichments were determined. With this data a process was followed to determine the combination of particle size, fissile/moderator ratio, and SNF position within a canister that provided the highest neutron multiplication factor (k_{eff}) for the package under all transport conditions specified by the regulations. All of the computational analyses were performed with the SCALE code system.[2] Final k_{eff} values were calculated with the KENO V.a Monte Carlo code within SCALE.

Because the SNF fragment varied in size and shape, the first step was to assume the SNF consisted of spherical particles in a close-packed, triangular-pitched array (provides the highest fuel-to-water volume ratio). Then for each fresh fuel enrichment, the particle size and pitch were varied to determine the size and pitch that provided the highest reactivity.[3] The optimum fuel/moderator mixture for each enrichment was used to generate, using XSDRNPM of SCALE, the cell-weighted cross-sections passed to KENO V.a.

Within the physical limitations of the known masses and calculated particle sizes and pitches, various arrangements of the uranium/water mixtures at active fuel length within the canisters, including multiple mixtures per canister, were studied using a detailed KENO V.a model of the BMI-1 cask loaded with canisters. The various arrangements were studied to obtain the maximum neutron interaction between canisters in the package and to determine the highest k_{eff} value for a single package.

To meet the regulatory conditions for analysis of arrays of packages, an infinite array of packages were analyzed using the single package model that provided the maximum k_{eff} value.

Various degrees of moderation between packages were studied to obtain the maximum neutron interaction between packages and to provide the highest k_{eff} value for the array.

III. Results

The calculational results for the most reactive shipment are given in Table 1 and are representative of the type of calculations performed for all three shipments. In the table X-13, X-14, and X-15 are canister numbers with U-H_2O mixtures of 22.02%, 48.91% and 19.06%, and 19.97% average enrichments, respectively. The canister ordering is clockwise in the four holes of the basket. "Center", "minimum distance", and "close" describe the mixture positions relative to the canister, all mixtures, and a pair of mixtures, respectively.

The highest single package value k_{eff} obtained from all three shipment loadings was 0.8075 ± 0.0023. The maximum k_{eff} value for an infinite array of packages was statistically the same as the result for the single package.

The adequacy of the k_{eff} value determined by calculations was compared to an Upper Subcritical Limit (USL). The value of the USL was determined by analyzing 66 critical experiments[4] chosen for their representation of the physics involved in the actual package model. Based on a statistical assessment[5] of the calculational bias and uncertainty from analyzing these 66 critical experiments together with an additional 5% margin of subcriticality, the lowest USL value over the full range of experiment characterization parameters was 0.9161.

A parametric study to determine the effect of mixture height on reactivity concluded that the highest k_{eff} of 0.8771 ± 0.0024 was achieved at a height less than the active fuel length; the k_{eff} value was within the demonstrated safety limit. Note, no mechanism was identified that could cause such deformation. Thus, the final safety analysis was based on the use of the active fuel length.

IV. Conclusions

The conclusion of the criticality safety analyses was that the largest k_{eff} value, 0.8075 ± 0.0023, of any package loading was far below the demonstrated limit of safety, 0.9161. With the demonstrated safety of the shipments and the approval of the waiver, the number of shipments was reduced from seven to three. Fewer shipments meant lower costs, less radiation exposure to ORNL and SRS staff during loading and unloading, and less risk to the public from an accident.

V. Acknowledgments

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Table 1. Calculational results of shipment one

Case	H_2O density (gm^3)	Description[a]	k_{eff}[b]
ship110	0.9982	U-H_2O centered in cans, order: X-15, X-13, X-14	0.7208 ± 0.0021
ship111	0.9982	U-H_2O min. dist. apart, order: X-15, X-13, X-14	0.7640 ± 0.0021
ship120	0.9982	U-H_2O centered in cans, order: X-13, X-15, X-14	0.7616 ± 0.0019
ship121	0.9982	U-H_2O min. dist. apart, order: X-13, X-15, X-14	0.7973 ± 0.0019
ship122	0.9982	X-14 & X-15 U-H_2O close, order: X-13, X-15, X-14	0.8075 ± 0.0023
ship123	0.9982	X-13 & X-15 U-H_2O close, order: X-13, X-15, X-14	0.7990 ± 0.0021
ship130	0.9982	U-H_2O centered in cans, order: X-15, X-14, X-13	0.7516 ± 0.0023
ship131	0.9982	U-H_2O min. dist. apart, order: X-15, X-14, X-13	0.7874 ± 0.0022
ship132	0.9982	X-14 & X-15 U-H_2O close, order: X-15, X-14, X-13	0.7970 ± 0.0021
ship133	0.9982	X-13 & X-15 U-H_2O close, order: X-15, X-14, X-13	0.7809 ± 0.0023
ship1221	0.9982	*ship122,* dry canisters and basket	0.6058 ± 0.0019
ship1222	0.9982	*ship122,* full-density H_2O in canister, dry basket	0.6938 ± 0.0019
	0.95	*ship122,* reduced H_2O density in canister, dry basket	0.6925 ± 0.0018
	0.50	*ship122,* reduced H_2O density in canister, dry basket	0.6539 ± 0.0020
	0.10	*ship122,* reduced H_2O density in canister, dry basket	0.6123 ± 0.0018
	0.01	*ship122,* reduced H_2O density in canister, dry basket	0.6017 ± 0.0018
ship1223	0.9982	*ship122,* full-density H_2O in basket, dry canisters	0.7339 ± 0.0020
	0.95	*ship122,* reduced H_2O density in basket, dry canisters	0.7301 ± 0.0018
	0.50	*ship122,* reduced H_2O density in basket, dry canisters	0.6828 ± 0.0020
	0.10	*ship122,* reduced H_2O density in basket, dry canisters	0.6195 ± 0.0017
	0.01	*ship122,* reduced H_2O density in basket, dry canisters	0.6063 ± 0.0017
ship1224	0.9982	*ship122,* full-density H_2O in basket and canisters	0.8075 ± 0.0023
	0.95	*ship122,* reduced H_2O density in basket and canisters	0.8021 ± 0.0021
	0.50	*ship122,* reduced H_2O density in basket and canisters	0.7328 ± 0.0020
	0.10	*ship122,* reduced H_2O density in basket and canisters	0.6293 ± 0.0018
	0.01	*ship122,* reduced H_2O density in basket and canisters	0.6017 ± 0.0018
ship1125	0.9982	*ship122,* canisters in contact	0.8013 ± 0.0021
ship1226	0.9982	*ship122,* infinite package array, interspersed water	0.8061 ± 0.0020
	0.0	*ship122,* infinite package array, interspersed void	0.8076 ± 0.0020
	0.0	*ship122,* infinite package array, interspersed void	0.7999 ± 0.0019[c]

[a]Uranium masses: X-13 1485 g, X-14 2915 g, X-15 4246 g.
[b]44-group ENDF/B-V cross-section library.
[c]238-group ENDF/B-V cross-section library.