Reference Fuel Development for Non-Aluminum Spent Nuclear Fuel Management

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ABSTRACT

The Savannah River Site (SRS) L Area Facility provides for the safe receipt, storage, handling, and shipping of spent nuclear fuel (SNF) and has received more than 47,000 SNF assemblies since 1964. In order to consolidate receipt and storage analysis, L Area criticality safety has historically used several aluminum-clad "reference fuels" to establish bounding storage, handling, and cask loading limits and then applied a reactivity comparison approach to demonstrate that candidate fuels may be processed under the reference fuel limits. Currently, only aluminum-clad SNF from off-site research reactors are transferred on-site. The Accelerated Basin De-Inventory (ABD) program will begin the removal of bundled Non-Aluminum Spent Nuclear Fuel (NASNF) from the L Area disassembly basin for dissolution and disposition, which has driven the need for a non-aluminum reference fuel.

This paper discusses the process and results of creating a new fictional homogenous NASNF highly enriched uranium reference fuel, "MITZ," to be used in nuclear criticality safety evaluations for upcoming SNF disposition operations. Data demonstrating the relationship between neutron multiplication behavior and fuel spacing is generated for the new reference fuel MITZ as well as existing reference fuels representing several types of SNF assemblies.

Key Words: Spent Nuclear Fuel, Reference Fuel,

1 INTRODUCTION

The L Area disassembly basin, referred to as L basin, consists of seven interconnected, chemically controlled water-filled basins with depths ranging from 17 feet to 50 feet. The bulk of the SNF inventory in the L Area Facility is stored underwater in L basin. The large inventory of SNF in L Area is representative of the DOE's effort to consolidate fuel irradiated in a variety of domestic and foreign research reactors in addition to a smaller volume of legacy SRS reactor assemblies and from other DOE facilities.

The ABD program is intended to significantly accelerate the disposition rate of SNF stored at SRS. At present, the only authorized disposition path for SNF stored in L Area is specific to an aluminum-clad subset of the total SNF inventory. Currently approved aluminum-clad fuels will be sent with greater frequency to H Canyon for chemical dissolution under ABD. Criticality safety work pursuant to the authorization of a NASNF disposition path wherein the NASNF inventory in L basin is transferred to H Canyon for electrolytic dissolution is ongoing and presents numerous challenges.

The L basin inventory of SNF is unique in that it represents a wide range of fuel forms (e.g., tubular assemblies, annular assemblies, fuel plate assemblies, fuel pin assemblies, etc.), enrichments, cladding materials, fuel compositions, and other such fuel characteristics. This fuel has typically been received in or packaged into long storage containers, referred to as bundles. The most common type of bundle, and the type considered in this evaluation, is a thin-walled aluminum tube with approximately 5-inch outside diameter. The number of fuel assemblies allowed in a bundle is dependent on fuel type and is determined by a fuel specific nuclear criticality safety evaluation (NCSE). The bundles are used to geometrically constrain the SNF assemblies and allow for the storage of highly varied fuel types in the L basin rack storage system of modular aluminum racks containing vertical bundles of fuel assemblies in a square array.

L Area criticality safety engineering has historically used several “reference fuels” to establish bounding storage, handling, and cask loading limits for bundled fuel and then applied a reactivity comparison approach to demonstrate that bundled candidate fuels may be processed under the reference fuel limits. Due to the degree of variability between bundles of SNF, this process significantly reduces the complexity and time required to perform evaluations that would otherwise need to be performed for each fuel type.

The cask loading limits developed for aluminum clad fuels are not applicable to the NASNF slated for transfer to H Canyon during early ABD campaigns. Unlike underwater storage where moderation conditions are constant and fuel is spaced in a regular array, conditions during the loading and transferring of an onsite cask are dynamic. The potential normal, or credible abnormal, conditions associated with this operation may result in configurations of fuel, moderator, and system reflection sensitive to characteristics NASNF not captured by the currently used aluminum reference fuel. The need to develop a new reference fuel with neutronic properties comparable to NASNF inventory in L basin was identified to support the authorization of the ABD NASNF disposition path.

This paper discusses the process and results of creating a new fictional homogenous NASNF reference fuel, “MITZ” [1], to be used in NCSEs for upcoming SNF disposition operations. Data demonstrating the relationship between neutron multiplication behavior and fuel spacing is generated for the new reference fuel MITZ as well as existing reference fuels.

2 METHODOLOGY

2.1 Fuel Homogenization and SASHAY

The SRS Standardized Approach for Storage and Handling Analysis (SASHAY) methodology [2] delineates the process by which to perform reactivity comparison approach for the storage and handling of bundled fuel. Both homogenized and explicit fuel assembly models are used in the SASHAY methodology. Homogenized assembly models are generally easier to set up and are generally conservative compared to the more accurate explicit assembly models.

Homogenous mixtures representative of fuel assemblies are developed using the proportional masses of fuel, cladding, moderator, and extraneous materials contained within the assembly volume divided by the assembly volume. The assembly volume is defined as the assembly cross sectional-area (including fuel plates, side plates, and any dummy fuel plates, such as the non-fissile end plates.) times the assembly length (active fuel region). The homogenous assembly models are designed to conservatively reflect the actual fuel geometry and preserve the assembly cross-sectional area. Typically modeled using the usable length of the storage container or storage system, these homogenous models are generally sufficiently conservative to account for assembly damage, deformation, or element movement.

The homogeneous reference fuels considered in this analysis are the new reference fuel MITZ and the reference fuels currently in use in L Area based off of High Flux Beam Reactor (HFBR) fuel, Missouri University Research Reactor (MURR) fuel, and MURR-50 - a fictional fuel based on MURR fuel with an artificially lowered $H/^{235}U$ ratio. The NASNF assemblies slated for ABD are all less reactive than HFBR fuel, and the current L basin storage and shipping limits are based on MURR and MURR-50 fuel, so MITZ was designed to have a reactivity between that of HFBR and MURR/MURR-50 in order to maximize use cases.

2.2 Fuel Composition

The previously derived nuclide densities for homogeneous HFBR, MURR, and MURR-50 reference fuels are provided in Table I.

Table I. Reference Fuel Parameters and Nuclide Densities

Parameter		HFBR [3]	MURR [4]	MURR-50 [5]
Nuclide Densities [10^{-6} × atoms / barn-cm]	^{1}H	38366	36388	38718
	^{16}O	19944	18194	19359
	^{27}Al	24599	25591	24642
	^{235}U	265.36	480.20	774.36
	^{238}U	18.214	32.635	53.153
	Total	83193	80685	83547
$H/^{235}U$		145	76	50
Fuel Meat Matrix // Cladding		$U\text{-}Al_x$ // Al	$U\text{-}Al_x$ // Al	$U\text{-}Al_x$ // Al
Homogeneous Assembly Shape		square	cylinder	cylinder
Assembly Size [cm]		side = 7.6516	r = 4.6557	r = 4.6575

The homogeneous reference fuel MITZ was designed as a high enriched uranium (HEU) fuel, with a uranium enrichment of 93.5 wt.%, which bounds the uranium enrichments anticipated for the initial set of fuels comprising early ABD campaigns. Massachusetts Institute of Technology (MIT) research reactor fuel data was used as the basis for the design of MITZ. The aluminum side plates and cladding in MIT fuel assemblies were replaced with an equivalent volume of zirconium metal, and the $U\text{-}Al_x$ fuel matrix was substituted with UO_2 containing an equivalent mass of U^{235} of the same enrichment. The difference in volume after substituting UO_2 for $U\text{-}Al_x$ was modeled as water. MIT fuel is a square assembly with a side length of 6.53 cm. During development, MITZ was found to be insufficiently moderated (H/ U^{235} ratio of approximately ~62:1) to bound the reactivity of HFBR, so the side length was increased to 7 cm to enlarge the internal water volume resulting in an H/ U^{235} ratio of approximately 95. Table II details the nuclide densities developed for homogeneous MITZ.

Table II.
Parameters and Nuclide Densities

Parameter		MITZ
Nuclide Densities [10^{-6} × atoms / barn-cm]	^{1}H	46010.44
	^{16}O	24042.22
	^{90}Zr	6376.37
	^{91}Zr	1390.53
	^{92}Zr	2125.45
	^{94}Zr	2153.96
	^{96}Zr	347.02
	^{235}U	485.20
	^{238}U	33.30
	Total	82964.49
$H/^{235}U$		94.83
Fuel Meat Matrix // Cladding		UO_2 // Zr
Homogeneous Assembly Shape		square
Assembly Size [cm]		side = 7.0

Additional conservatisms applied to fuels modeled in this calculation are as follows. The zirconium cladding incorporated in the homogeneous MITZ mixture was modeled as pure zirconium [6] to exclude the generally neutron-absorbing alloying elements (cobalt, tin, iron, and chrome) which differ in amount between zircaloy-2 and zircaloy-4. The only uranium isotopes considered in the fuel mixtures are ^{235}U and ^{238}U, and no burnable poison(s) were added to the homogenous fuel mixtures. All homogeneous fuel model compositions utilize as-reported nominal data for fresh (pre-irradiated) fuel assemblies.

2.3 Model

A reactivity comparison of an infinite planar array of bundles loaded with the new MITZ reference fuel to that of an infinite planar array of bundles loaded with other reference fuels used in L Area (HFBR, MURR, MURR-50) were performed using MCNP. All MCNP simulations were performed using MCNP6.1. The MCNP simulations utilized the ENDF/B-VII.1 cross-section library for 293.6 K (.80c), and the homogenous fuels utilized in the calculations are discussed in Section 2.2.

Bundles containing MITZ, HFBR, MURR, and MURR-50 were modeled within an infinite planar array as follows:

1. The homogenized reference fuels were modeled inside an Expanded Basin Storage (EBS) bundle. These tubes have an as modeled inner diameter of 12.436 cm, an outer diameter of 12.70 cm, and an inner usable length of 335.9 cm. The bundles are made of either 6061-T6 or 6063-T6 aluminum and are modeled as pure aluminum.

2. The bundles were fully flooded (water fills the space between fuel region and the bundle as well as the space between bundles).

3. The fuel region takes up the entire interior useable length of the EBS bundle.

4. Reflective planes are used to simulate an infinite planar array of the same type of bundle loaded with a particular reference fuel in the X and Y directions. The infinite planar array is reflected by 30 cm of water in the Z direction. Figure I shows the resulting infinite planar array for bundles of MITZ where green represents water in and outside the bundle, red represents the bundle wall, and blue is the homogenized MITZ fuel.

5. k-code calculations were performed at the following square pitches: 12.7 cm, 14 cm, 16 cm, 20 cm, 24 cm, and 30 cm.

6. Consistent with the SASHAY methodology, the bundled homogenized fuel results are compared against each other.

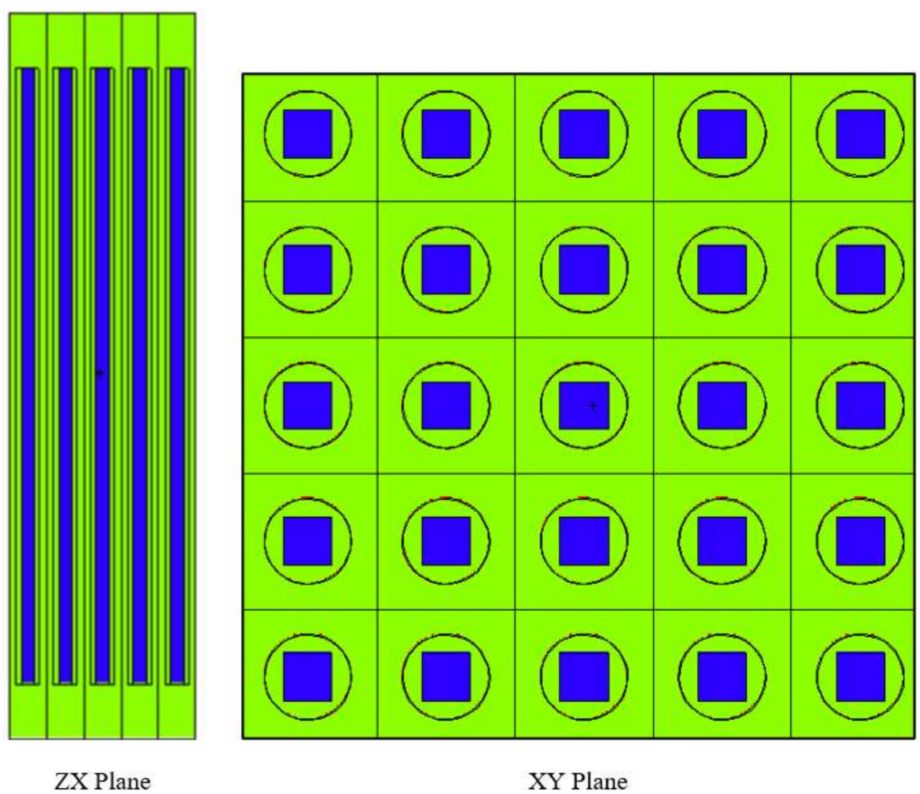

Figure I. Infinite Planar Array of MITZ in an EBS Bundle at 20.0 cm Lattice Pitch

2.4 Additional Calculations

In addition to the models and results discussed in this paper, several scoping cases were generated to examine the applicability of MITZ to the L basin NASNF inventory and new alternative bundle types. Three unique bundle types were designed for the ABD program to support proposed fuel re-bundling activities, so homogeneous HFBR, MITZ, MURR, and MURR-50 were modeled as discussed in Section 2.3 using the new bundle designs. Infinite lattice results confirmed that MITZ in the new bundle types exhibited the same reactivity behavior as MITZ in the EBS bundle. Additional models substituted 4 wt.%

of the structural material in the MITZ fuel composition with stainless steel to see the effect of extraneous material (non-zircaloy hardware) and other impurities found in some ABD candidate fuels. These tests demonstrated the introduction of impurities marginally reduced reactivity with no change to reactivity trends or reference fuel bounding. These scoping cases further confirmed the applicability of MITZ as a NASNF reference fuel and are not included in this paper for brevity.

3 RESULTS

Typically, calculated k_{eff} values for SNF are compared to an associated k_{safe} value to determine if the given configuration is safely subcritical; however, the calculations performed in this document are instead used to compare a new reference fuel to reference fuels, so k_{safe} is not defined in this calculation.

The calculated k_{eff} values and uncertainties (σ) for homogeneous HFBR, MITZ, MURR, and MURR-50 in the fully flooded infinite array of fuel in bundles across the examined separation pitches are reported in Table III and displayed in Figure II. Figure II shows k_{eff} only, as ±2σ would not be visible.

Table III. HFBR, MITZ, MURR, and MURR-50 Infinite Lattice Results

HFBR				
Pitch	k_{eff}	σ	k_{eff}-2σ	k_{eff} + 2σ
12.7	1.17921	0.00011	1.17899	1.17943
14	1.00944	0.00012	1.00920	1.00968
16	0.81278	0.00013	0.81252	0.81304
20	0.60049	0.00013	0.60023	0.60075
24	0.51817	0.00013	0.51791	0.51843
30	0.47849	0.00013	0.47823	0.47875

MITZ				
Pitch	k_{eff}	σ	k_{eff}-2σ	k_{eff} + 2σ
12.7	1.19570	0.00012	1.19546	1.19594
14	1.03288	0.00013	1.03262	1.03314
16	0.84690	0.00014	0.84662	0.84718
20	0.65024	0.00014	0.64996	0.65052
24	0.57457	0.00014	0.57429	0.57485
30	0.53802	0.00014	0.53774	0.53830

MURR				
Pitch	k_{eff}	σ	k_{eff}-2σ	k_{eff} + 2σ
12.7	1.37612	0.00011	1.37590	1.37634
14	1.19487	0.00013	1.19461	1.19513
16	0.96836	0.00014	0.96808	0.96864
20	0.70845	0.00014	0.70817	0.70873
24	0.60268	0.00014	0.60240	0.60296
30	0.55289	0.00014	0.55261	0.55317

MURR-50				
Pitch	k_{eff}	σ	k_{eff}-2σ	k_{eff} + 2σ
12.7	1.44355	0.00011	1.44333	1.44377
14	1.26430	0.00013	1.26404	1.26456
16	1.03412	0.00014	1.03384	1.03440
20	0.76506	0.00014	0.76478	0.76534
24	0.65622	0.00015	0.65592	0.65652
30	0.60261	0.00014	0.60233	0.60289

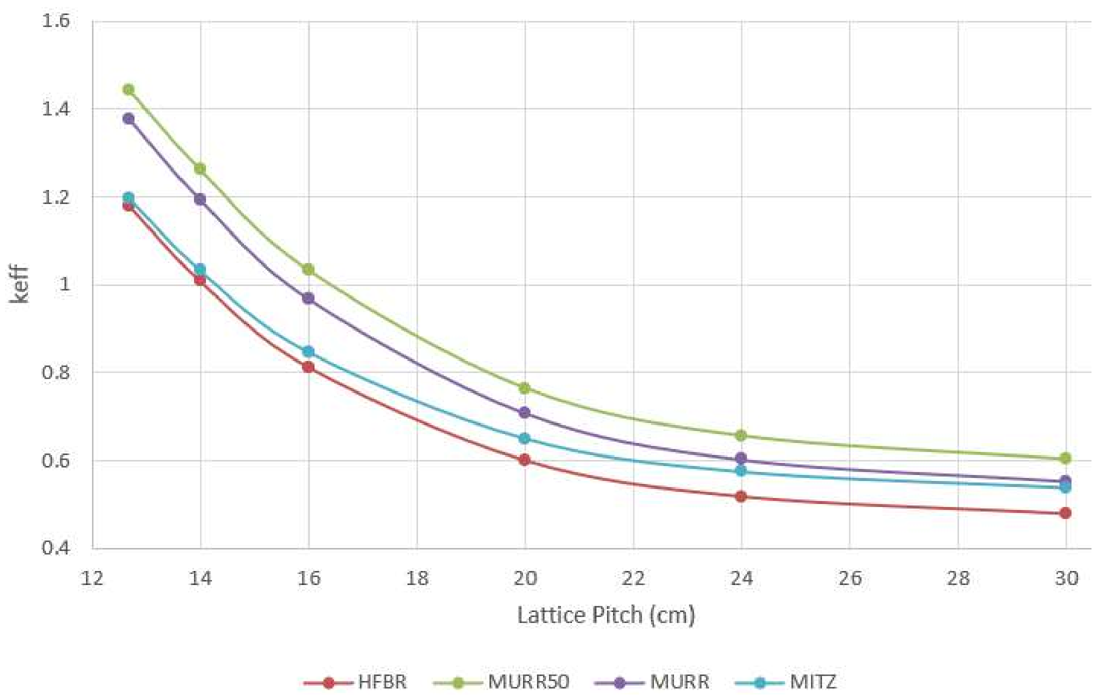

Figure II. HFBR, MITZ, MURR, and MURR-50 Infinite Lattice Results

From the results provided above, the following conclusions can be drawn. MITZ is demonstrated to be bounding of HFBR under equivalent conditions by comparing k_{eff}-2σ values calculated for MITZ to k_{eff}+2σ values for HFBR. MITZ is demonstrated to be bounded by MURR under equivalent conditions by comparing k_{eff}+2σ values calculated for MITZ to k_{eff}-2σ values for MURR. MITZ is demonstrated to be bounded by MURR-50 under equivalent conditions by comparing k_{eff}+2σ values calculated for MITZ to k_{eff}-2σ values for MURR-50.

4 CONCLUSIONS

This document defines the homogenized reference fuel MITZ and provides reactivity curves for MITZ and three existing reference fuels in aluminum bundles in a fully flooded infinite planar array. The new reference fuel was developed to have comparable neutronic properties to select NASNF assemblies currently in storage awaiting disposition in order to reduce the complexity of anticipated criticality engineering work.

5 ACKNOWLEDGMENTS

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