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Template Criticality Analyses To Qualify DOE Fuels For Repository Acceptance

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Abstract – *The variety in the physical dimensions and fissile enrichment values of the U.S. Department of Energy (DOE) spent nuclear fuels, in contrast to commercial PWR and BWR fuels, requires a modified approach to criticality analyses toward acceptance for disposal in the national repository. The initial approach for ensuring criticality safety segregated these various fuels into nine distinct groups based on their fuel matrix composition. A baseline fuel type was then selected from each group to bound, for purposes of criticality analysis, all other fuels in that group. After these initial analyses, it will be necessary to demonstrate how all the fuels in the DOE inventory are bounded by the nine distinct groups.*

I. INTRODUCTION

The nine initial analyses,[1] using the Monte Carlo N-Particle (MCNP) 4B code and known fuel matrix compositions specific to each fuel type, led to conceptual development of a variety of compartmented baskets for disposal. Some of these baskets required the addition of neutron absorbers to ensure long-term criticality safety in the event of water intrusion and any subsequent degradation inside a failed waste package. The current approach to fuel packaging proposes using a limited number of basket designs for the great variety of fuels. A recent study[2] identified which of the "other" fuels in the U.S. Department of Energy (DOE) inventory will be inserted into any given basket configuration. It is now necessary to determine if these other fuels are bounded by the baseline analyses.

I.A. Objective

The National Spent Nuclear Fuel Program (NSNFP) associated with the Idaho National Laboratory has completed criticality analyses for a postclosure repository environment[3] based on the selection of the Advanced Test Reactor (ATR) fuel as both the baseline fuel in the aluminum group and as the bounding case fuel within that grouping. This proposed template analysis[4] is intended to demonstrate how ATR fuels bound other aluminum fuel types. This is accomplished by calculating k_{eff}s within a common basket design, but with varying masses of fissile materials based on the individual fuel characteristics and their combined fissile loading inside a DOE standardized canister. Confirmation is reflected in the comparison of calculated k_{eff}s for canisters loaded with these other fuels against ATR fuels in various but comparable configurations using a common Type 1a basket design (see Figure 1). In all cases with reference to any k_{eff} value, it is always implied to mean $k_{eff}+2\sigma$.

Results of this analysis evaluated the Type 1a basket proposed to accommodate aluminum-based fuels. This basket design has 10 compartments; the baskets will generally be stacked two or three high (depending on the length of the fuel) inside a DOE standardized 18-in.-diameter/10-ft-long canister.[5] The compartment walls of these particular baskets will be fabricated from a new material[6,7] developed by the NSNFP, in conjunction with others, that consists of a high-nickel alloy containing 2 wt% gadolinium. This weight percent loading of gadolinium in a 2-stack basket configuration inside a 10-ft canister equates to ~7.21 kg of gadolinium. The basket base plate and metal shroud on the outer perimeter of the basket will use a 300 series stainless steel.

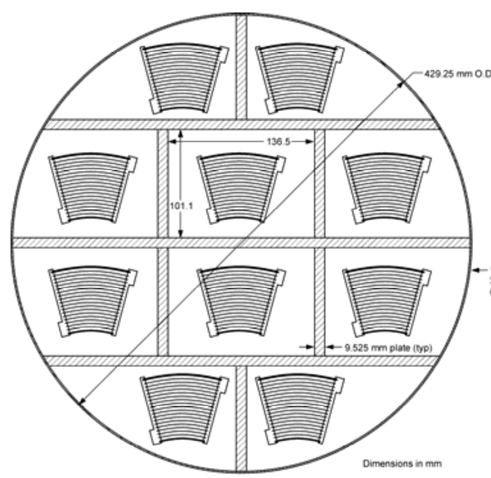

Figure 1. Cross-section of a Type 1a aluminum-fuel basket w/ ATR assemblies.

ATR fuel (shown in Figure 2) was selected as the baseline fuel for the aluminum fuel group because of its fissile mass with 1085 g U^{235}/assembly. Three other aluminum fuel types with the next highest fissile loadings within the aluminum fuel group also use this common

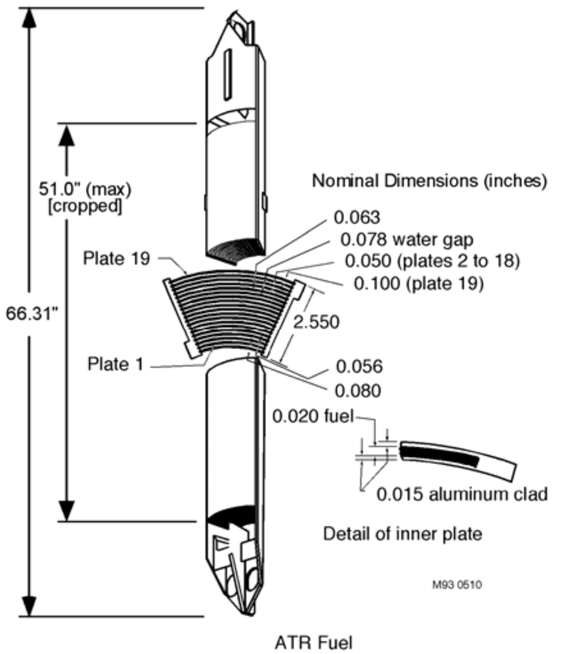

Figure 2. ATR fuel schematic.

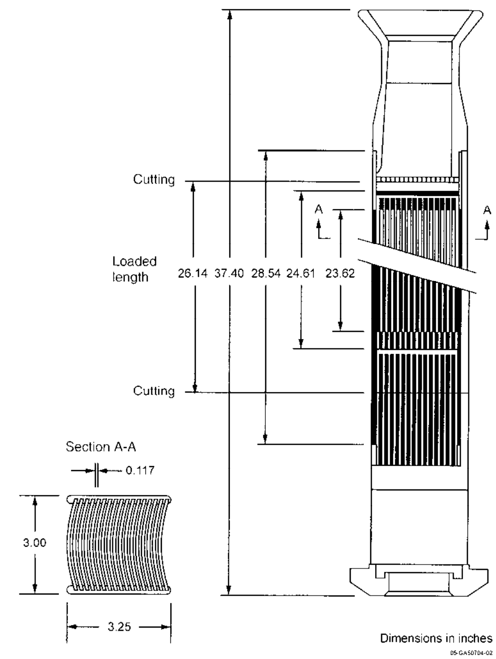

Figure 3. ORR fuel schematic.

basket design. Some of the details for these other fuels are portrayed in Figures 3, 4, and 5.

Ideally, the desire was to create a standard basket model within the MCNP code and then be able to insert simplistic fuel shapes with their attendant fissile loadings for the criticality calculations. The goal of a template analysis was to demonstrate that the only key parameter of any significance was some measure of the fissile loading in the canister. This approach would save having to develop and certify discrete shapes and configurations for internal fuel details, e.g., plate thickness, fuel matrix composition or condition, or void fractions.

To accomplish this task, a "smeared" case model was created using fuel assembly materials and moderator. They were blended within an intact fuel shape or footprint inside each basket compartment and reflected with water outside the fuel shape.

The "homogenized" case model was created by mixing the fuel assembly materials of a given fuel with water inside each basket compartment. This latter model is considered to be an extreme fuel degradation case. In both cases, the mass of the cladding, uranium, and its alloying aluminum matrix material along with the water is preserved, but its distribution within the fuel shape or basket compartment is varied.

The homogenized distribution is only hypothetical, considering that these uranium concentrations per

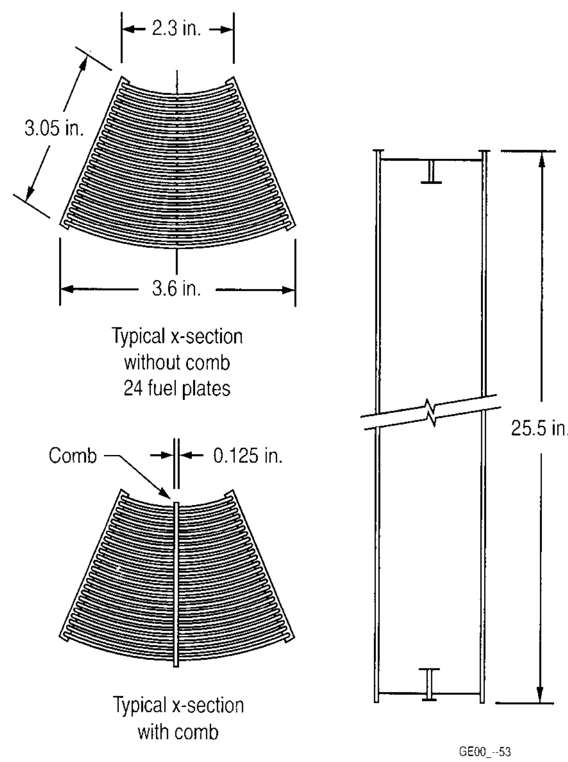

Figure 4. MURR fuel schematic.

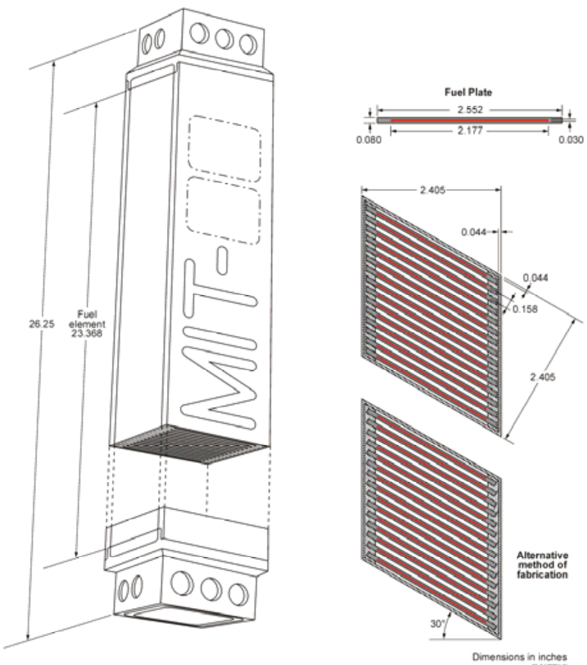

Figure 5. MIT fuel schematic.

compartment cannot be achieved either by suspension of particles in water (because of density differences) or uranyl (UO_2^{+2}) ion as solute in water (because of solubility issues). But the homogenized approach does eliminate any specific fuel geometry dependencies.

Experience with previous analyses of the other fuel groups[1] has shown that within the confines of a standard canister, it is generally the more homogenized, fully flooded condition that provides the highest calculated k_{eff}.

To demonstrate that this effect is consistent between different fuels within the aluminum fuel grouping, the Type 1a basket design was analyzed for fissile loading both as a percentage against the baseline fuel and also for two pseudo-degraded fuel (smeared and homogenized) conditions for each fuel type.

II. BASES AND CALCULATIONS

Table 1 provides the basic fissile load limit and enrichment of each fuel analyzed in this template analysis. This information was further expanded into fissile loads per canister in terms of total fissile mass (kg U^{235}/canister), linear fissile loading within the canister (g/cm), and a macroscopic (canister) fissile atom-density (atom/b-cm). Each of these parameters was then compared to the corresponding value for the baseline (ATR) fuel as a percentage. This summary portrays how each proposed canister load for these other fuels compared to the selected baseline (ATR) fuel.

Comparisons showed that the MURR fuel type had a fissile loading per fuel element that was only 72% of the baseline ATR fuel. However, the proposed MURR canister loading resulted in a kilograms fissile load per canister that was 107% of that proposed for ATR fuel, with similar percentages for linear loading and atom-density values. This added fissile per canister occurred because of using a 3-stack basket for the MURR fuel when the ATR packaging only required a 2-stack basket.

One notable addition to the calculated k_{eff}s (Table 2) for the various configurations is the comparative k_{eff} value for ATR fuel in a 10-ft versus a 15-ft canister for the intact/ flooded model. While correctly cropped ATR fuel elements now in storage would fit in a 10-ft canister configuration, there are a number of assemblies that will not fit, thereby necessitating their loading in a 3-stack basket arrangement inside a 15-ft canister. This singular comparison illustrates that, for the calculated $k_{eff} = 0.674$ for the loaded 10-ft canisters (~255 cm fuel cavity length) versus $k_{eff} = 0.676$ for the 15-ft canister, the 10-ft canisters are already at an infinite cylinder length. Comparison of the other fuels in 15-ft lengths was disregarded, because they are destined for loading in 10-ft canisters to balance against the 10-ft high-level waste (HLW) canisters in their proposed disposal configuration.[1]

The calculated k_{eff} values shown in Table 2 for the MURR fuel type demonstrate that the presumed bounding case—ATR fuel—was not bounding within the aluminum fuel grouping. The premise of loading in a 3-stack basket configuration with MURR fuel (23.48 kg) rather than a 2-stack as for ATR (21.70 kg) resulted in the increased fissile loading. In this case, the calculated k_{eff} =1.0218 for the MURR fuel loading exceeded the ATR baseline fuel values for the homogenized case. The choice for packaging this fuel then becomes either the addition of more neutron poisons to the canister, or derating the canister for this particular fuel type by blanking off one or more of the basket compartments. For this derated analysis, the two center compartments were analyzed empty of fuel, but moderator was allowed in the compartment for any potential increase in reflection. The important point of this single MURR model was the revelation of the outlier fissile loading and an unacceptable k_{eff}. Once the homogenized case revealed a calculated value significantly below any expected subcritical limit, calculating the other k_{eff} values for the derated MURR canister were of little interest and hence omitted.

In general, the increases in the calculated k_{eff}s are relatively predictable as a direct function of the fissile content inside a loaded canister. This is seen in the Figure 6 plot of $k_{eff}+2\sigma$ versus kg fissile loading in 10-ft canisters. Furthermore the tabular values generally show, as was anticipated, increased reactivity going from intact/flooded → smeared → homogenized for each fuel type analyzed.

However, there were a couple of noteworthy anomalies. The ORR moderately enriched uranium (MEU) aluminum silicide fuel experienced essentially no increase between the intact/flooded and smeared/flooded configuration. This may be a reflection of the already optimized plate configuration relative to the void space for water between the plates. The higher calculated k_{eff} for the ORR MEU fuel when compared to the ORR highly enriched uranium (HEU) fuel is easily explained with the increased fissile atom-density of the ORR MEU fuel even though the ORR HEU fuel has a greater enrichment.

The homogenized MIT fuel result is interesting in terms of its k_{eff} value of 0.9206 when compared to the k_{eff} of 0.9543 for the ATR fuel. The macroscopic H/X ratio of 293.6 is comparable to the 306.6 value calculated for the ATR fuel. Yet the ~73% of baseline fissile content in the MIT loaded canister would seem to justify a much greater difference between the two homogenized cases. If any of the calculated k_{eff}s for the MIT fuel had exceeded the corresponding ATR values, then such an anomaly would have warranted further investigation. Similarly, if any of the intact/flooded analyses raises concerns with a calculated k_{eff} greater than baseline, then analysis of the homogenized fuel condition would also require demonstration of a calculated k_{eff} less than the comparable baseline fuel result.

TABLE 1. Comparison of Aluminum Fuel Parameter Values in Poisoned Baskets

Fuel identifier →	**ATR (HEU / UAl_x)** [baseline]	**ORR* (MEU / U-Al-Si)**	**ORR (HEU / U_3O_8)**	**MIT* (HEU / UAl_x)**	**MURR* (HEU / UAl_x)**	**MURR** [derated canister load]
BOL % enrichment	93.15	20.56	93.15	93.15	93.15	93.15
Assemblies/canister	20	30	30	30	30	24
Fissile/assembly (kg)	1.085	0.347	0.300	0.525	0.783	0.783
% of baseline	100	32	28	48	72	72
Fissile/canister (kg)	21.70	10.41	9.00	15.75	23.48	18.79
% of baseline	100	48	41	73	108	86
Canister fissile linear loading (g/cm)	85.526	41.001	35.447	62.003	92.488	73.990
% of baseline	100	48	41	72	108	87
Fissile atom-density / canister (atom/b-cm)	1.45E-04	6.79E-05	6.02E-05	1.05E-04	1.57E-04	1.26E-04
% of baseline	100	48	39	73	107	86

* MURR (Missouri University Research Reactor); (ORR) Oakridge Research Reactor; MIT (Massachusetts Institute of Technology)

TABLE 2. Calculated $k_{eff} + 2\sigma$ Values

Fuel identifier →	**ATR (HEU / UAl_x)** [baseline]	**ORR* (MEU / U-Al-Si)**	**ORR (HEU / U_3O_8)**	**MIT* (HEU / UAl_x)**	**MURR* (HEU / UAl_x)**	**MURR** [derated canister load]
Intact/dry	0.0857	0.0767	- - -	0.0904	0.1121	- - -
Intact/flooded (10-ft canister) (15-ft canister)	0.674 0.676	0.6440 - - -	0.6290 - - -	0.6135 - - -	0.787 - - -	- - - - - -
smeared**	0.7021	0.6432	0.6377	0.6446	0.8291	- - -
homogenized	0.9543	0.7524	0.6878	0.9206	1.0218	0.8592
Macro H/X ratio	306.6	486.3	555.7	293.6	209.1	277.1

* MURR (Missouri University Research Reactor); (ORR) Oakridge Research Reactor; MIT (Massachusetts Institute of Technology)
** smeared = homogenized fissile, cladding and moderator within the fuel footprint

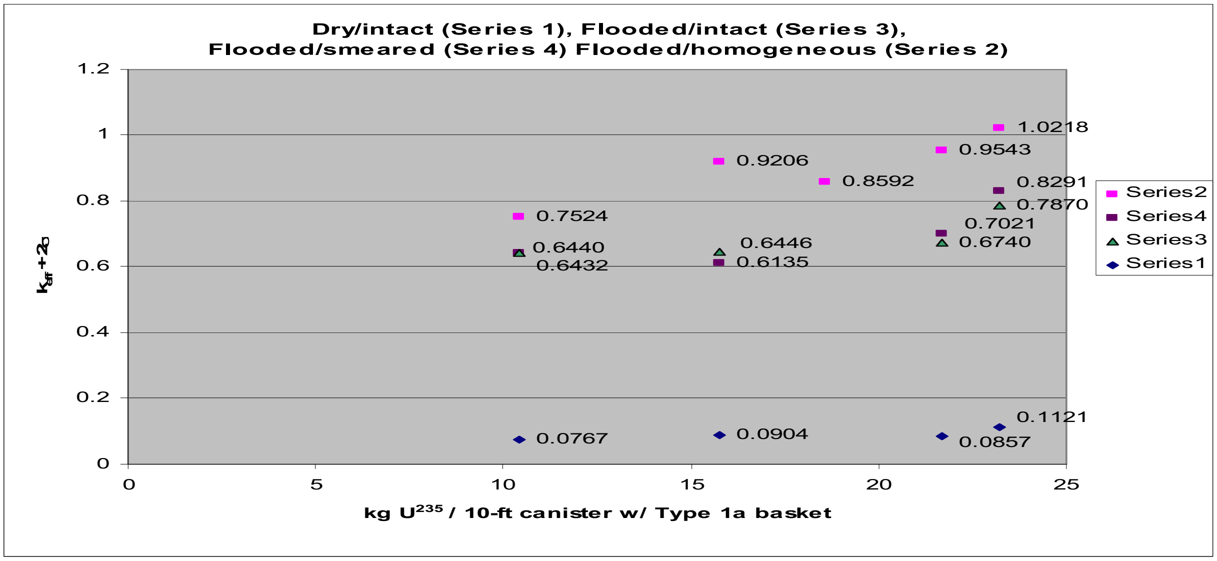

Figure 6. Graphical depiction of calculated k_{eff}s from Table 2.

Comparison of these calculated k_{eff} results for the various proposed canister loadings of these selected fuels confirms how the decreased fissile loads for other fuels should experience a predictable decrease in the reactivity. At the time of loading all other aluminum fuels, the calculated k_{eff} values (derived through criticality safety evaluations) will be needed for the intact/dry and intact/flooded conditions because of their planned reconfiguration. Such comparative analyses can also be used to address issues relative to criticality safety for transportation and repository disposal.

The calculated k_{eff}s shown in Table 2 demonstrate that modeling a smeared fuel shape is more conservative than constructing a discrete model with its attendant plate/matrix thicknesses, matrix composition, and void spaces. As increased homogenization is introduced into the criticality model, the calculated k_{eff}s produce increased values. Use of the smeared fuel model obviates the need for detailed knowledge of internal fuel assembly geometry or condition of the fuel matrix. With added mixing of the fuel and moderator, the homogenized fuel configuration is even more conservative. This approach removes the issue of the variable associated with relative positioning of fuels within the various basket compartments. The fully homogenized fuel condition inside a basket compartment simplifies the geometry dependency generally associated with the numerous parametric models typically used to identify the optimum position of intact fuels within the various basket compartments.

In retrospect, selection of the ATR fuel as the baseline case may still prove to have been a valid assumption for establishing a basket design that maximizes fissile loading in order to minimize loaded spent nuclear fuel canister counts destined for the repository. The use of this template analysis provided the identification of an outlier fuel loading and how derating the canister loading might affect an acceptable, calculated reactivity. The template analysis can also provide a simplified methodology for demonstrating maximum reactivity of other fuel loadings in a Type 1a basket, even if various aluminum fuel types are mixed within a given basket or canister. Figure 7 depicts how some of the many types of aluminum fuels can utilize the versatility of the basket in terms of basket compartment sizes relative to the fuel geometries identified for loading in a Type 1a basket.

While the Peach Bottom fuel depicted in Figure 7 is not among the aluminum fuel grouping, its geometry would allow use of this basket in a continuous (nonstacked) configuration. For that situation, the fissile loading of the Peach Bottom fuel would also have to be compared against the ATR fuel on the basis of its placement in a Type 1a basket.

All other fuels within the aluminum fuel group that are identified for loading in a Type 1a basket[2] fall below 50% of baseline fissile loading, whether based on a fissile per canister (kg), linear loading (g/cm), or fissile atom-density (atom/b-cm). Even hybrid basket loadings with various fuels such as that depicted in Figure 7 could be easily modeled with the proposed template approach.

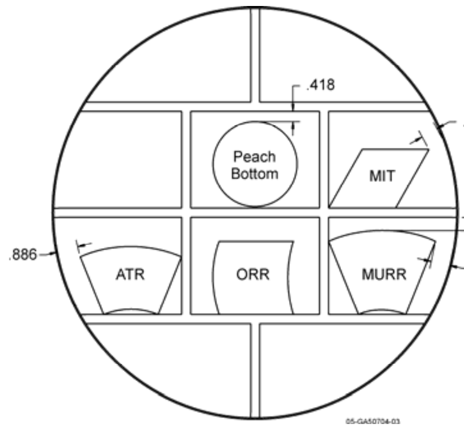

Figure 7. Type 1a basket fuel disposal with various fuels.

II. CONCLUSIONS

Previous analyses related to ATR fuels[3] analyzed those elements in a horizontal canister configuration using degraded conditions to determine the most reactive configuration, including full moderation. The need for poisoned baskets evolved from these ATR fuel packaging analyses.

The template analysis methodology has demonstrated the ability to ensure criticality safety for the baseline fuel fissile loading with ATR fuels. Subsequently, the analysis then showed that lower fissile loads, perhaps even with more optimal H/X ratios, are less reactive when using the same basket configuration for a multitude of fuel shapes with lesser fissile loads. This was demonstrated with the calculated k_{eff}s of the three next most heavily loaded of the aluminum fuel types in the aluminum fuel group.

Use of the template analysis provides a method for identifying outlier fissile loads in proposed fuel packaging. After identifying the MURR fuels as a candidate for a derated canister loading, it was possible to demonstrate a reduced and acceptable reactivity for even the most conservative fuel configuration in a canister.

In all cases, reactivity as measured by calculated k_{eff}, analyses showed trends toward lower values in direct proportion to decreased fissile loading. Use of smeared analyses can also simplify the modeling needed for all fuels if geometries or fuel matrix condition relative to the internal fuel configurations might be in doubt. The homogenized fuel configurations within the bounds of the poisoned baskets can also be used to minimize or eliminate the added analyses usually needed for the multitude of geometric positions of fuel assemblies within a basket to determine the most reactive configuration. Ancillary benefits could also include simplification of analyses needed to support hybrid packing of multiple fuel types in the same canister/basket combination.

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