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On the Criticality Safety of Transuranic Sodium Fast Reactor Fuel Transport Casks

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ABSTRACT

This work addresses the neutronic performance and criticality safety issues of transport casks for fuel pertaining to low conversion ratio sodium cooled fast reactors, conventionally known as Advanced Burner Reactors. The criticality of a one, three, seven and 19-assembly cask capacity is presented. Both dry "helium" and flooded "water" filled casks are considered. No credit for fuel burnup or fission products was assumed. As many as possible of the conservatisms used in licensing light water reactor universal transport casks were incorporated into this SFR cask criticality design and analysis. It was found that at 7-assemblies or more, adding moderator to the SFR cask increases criticality margin. Also, removal of MAs from the fuel increases criticality margin of dry casks and takes a slight amount of margin away for wet casks. Assuming credit for borated fuel tube liners, this design analysis suggests that as many as 19 assemblies can be loaded in a cask if limited purely by criticality safety. If no credit for boron is assumed, the cask could possibly hold seven assemblies if low conversion ratio fast reactor grade fuel and not breeder reactor grade fuel is assumed. The analysis showed that there is a need for new cask designs for fast reactors spent fuel transportation. There is a potential of modifying existing transportation cask design as the starting point for fast reactor spent fuel transportation.

Key Words: transport cask, sodium fast reactor, transuranics, fuel cycle

1. INTRODUCTION

A fundamental infrastructure option for the future deployment of Sodium cooled Fast Reactors (SFR) to transmute transuranics (TRU) is whether or not to reprocess the SFR spent fuel on-site or a centrally located facility. One of the factors for the viability of centralized reprocessing is the transportability of this kind of SFR fuel. Design and licensing of transportation casks for Light Water Reactor (LWR) fuel is well established. However, the composition and geometry of SFR fuel is significantly different than that of LWR fuel. First, the enrichment of fissile material, namely plutonium isotopes, is much higher in SFR fuel. Secondly, the inter-pin spacing is significantly smaller in SFR fuels lending to a much smaller moderator-to-fuel ratio. In fact during normal operation in a SFR, the coolant (i.e., Na) is chosen to be a poor moderator to ensure that neutron energies constitute a fast spectrum. In the event that a cask is flooded, such as in an accident scenario, it is important to analyze the criticality of this tight lattice filled with a strong moderator (i.e, H_2O).

This work investigates the criticality margins for a conceptual SFR cask carrying TRU bearing SFR fuels. The fuel assembly design of this fuel corresponds to that for the Advanced Burner Reactor (ABR), or more generically, the Advanced Recycling Reactor (ARR). Some cask criticality design and analysis for SFR fuel transportation has been conducted for LMFBR transport, mainly for the Clinch River Breeder Reactor program [1]. However, the ARR fuel design differs from the generic Liquid Metal Fast Breeder Reactor (LMFBR) with regards to the isotopic makeup of the fissile material. Unlike a breeder reactor, the ARR does not breed its own self-sustaining source of fissile material. Instead, the ARR requires that TRU from reprocessed LWR Spent Nuclear Fuel (SNF) must be blended with the reprocessed driver TRU in order to reconstitute the fresh fuel's excess reactivity. This SNF grade TRU contains a higher concentration of non-fissile minor actinides (MA) than LMFBR fuel which decreases the reactivity worth of the TRU, especially when moderated. In addition, the concentration of fissile isotopes in the plutonium component of SNF TRU is also less than for LMFBR. Therefore, it is postulated that a cask with ARR fuel will have a greater criticality margin or conversely a greater fuel capacity based on criticality limits than LMFBR fuel.

The oxide fueled version of ARR with a conversion ratio of CR=0.5 is used as the reference fuel design [2]. The reference fuel cycle for this study is a two-tier scenario where UO2 Spent Nuclear Fuel is first reprocessed and irradiated as LWR MOX before being reprocessed again into SFR fuel [3]. This is important because the fissile quality of MOX-SNF TRU is less than that of UO2-SNF. Similarly, the fissile quality of UO2-SNF TRU is less than that created in a SFR blanket assembly.

Section 2 gives the cask design model description, assumptions, and calculation method. Section 3 presents the results of a series of dry and flooded cask scenarios for different cask designs of increasing number of assemblies. Also, in light of the high thermal load of TRU SFR fuels, an all aluminum basket is envisaged as an alternative to the aluminum support disks common to LWR casks. The criticality of one, three, seven and 19-assembly cask capacity is presented. A comparison of criticality margin for the two-tier ARR, one-tier ARR and LMFBR is made. The criticality margin gained by the use of BORAL™ is investigated for a 7-assembly cask. Reactivity credit of MA is investigated for a 19-assembly cask. A most reactive scenario where all the cask fuel tubes and fuel assembly pins are hypothetically compacted into physical contact is evaluated. Section 4 gives summary and concluding remarks.

2. Design and Methodology

2.1. Description of Physics Tools

MCNP is a general purpose Monte Carlo N–Particle (MCNP) code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport [4]. MCNP simulates particle transport using the Monte Carlo method in arbitrary geometry, continuous energy, and continuous angle. MCNP is used by this work to calculate the critical eigenvalue of the cask geometry described in the following section. MCNP was selected for this work for its ability to model arbitrary neutron energy spectra. Given that the fuel assembly lattice spacing and enrichment is designed for fast spectra but will be modeled with a strong hydrogenous moderator, water, it was important to accurately capture the physics without prior knowledge of the neutronic behavior. For this critical eigenvalue calculation the MCNP KCODE with KSRC cards were used to represent 10,000 neutron histories per neutron life-cycle. A total of 1000 k-cycles were used with the first 150 k-cycles (i.e., source cycles) being discarded.

2.2. SFR Cask Design

This preliminary SFR Cask design is founded on the Universal MPC (Multi-Purpose Canister) System® (UMS) for rail transportation [5]. The transportation component of the UMS is the Universal Transport Cask (UTC) which contains a Transportable Storage Canister (TSC). The TSC consists of a canister and basket that is licensed to be loaded with either UO2-SNF or Greater Than Class-C waste (GTCC). The TSC is then loaded into the UTC. The UTC consists of neutron and gamma shields, structural steel annuluses and impact limiters. A picture of the UTC taken from SAR-UMS 71-2970 is given in Figure 1. For the purpose of the following discussion, it will be assumed that the UTC, TSC and basket are part of the same integral design represented by the MCNP model.

The MCNP model contains detailed geometry features including impact limiters, neutron and gamma shields and some structural layers of the UTC. The TSC is modeled as a steel shell surrounding a repeating lattice of BORAL^{TM} fuel tubes (neglecting the BORAL^{TM} cladding). Each fuel tube is designed to hold an ARR fuel assembly. The ARR fuel assembly duct, fuel pins, axial shield and gas plenum are explicitly modeled. Table 1 gives the pertinent UTC, fuel tube and lattice, fuel assembly and pin-lattice dimensions. In the UMS design, each BORAL^{TM} fuel tube is supported within the TSC using approximately 60 steel and/or aluminum disks. These rings and the fuel tubes comprise the basket. These support disks are not modeled in the MCNP model and the empty space is filled with helium only. The exception to this rule is: (1) a solid aluminum basket is considered for enhancing heat dissipation in a trade study, (2) a helium filled basket flooded with water is considered in the safety analysis.

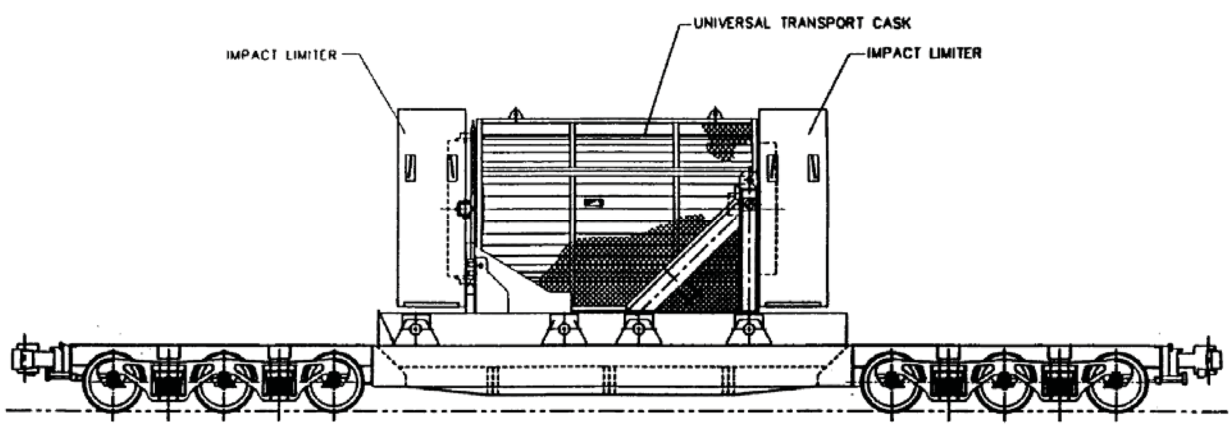

Figure 1. Transport configuration of the Universal Transport Cask [5]

Figure 2 depicts a conceptual SFR cask design for transport of one, three, seven and 19-assemblies, respectively. It is important to note that the maximum number of assemblies may not be constrained by cask criticality alone. The thermal heat dissipation, neutron and gamma dose as well as weight are also factors to consider in the overall cask design.

In each MCNP model, the thickness and relative dimensions of the UTC are preserved for each assembly loading. The radial dimensions of the MCNP model are adjusted to hold radial thicknesses constant while allowing the overall cask radius to change to accommodate each assembly loading design. These radial thicknesses would be dictated primarily by the cask shield design which is not considered by this work.

The shield thickness would have some impact on neutron reflection but are not considered to be a dominating parameter. The thickness of the neutron and gamma shields were assumed based on preliminary calculations performed at Sandia National Laboratory [6].

Table 1. Important geometry details of the SFR Cask

Fuel Pellet Diameter (cm)	0.4896
Fuel Pin Cladding Inside Diameter (cm)	0.5310
Fuel Pin Cladding Outside Diameter (cm)	0.6580
Fuel Pin Hexagonal Lattice Flat-to-Flat Pitch (cm)	0.8054
Fuel Assembly Duct Inside Flat-to-Flat (cm)	14.922
Fuel Assembly Duct Outside Flat-to-Flat (cm)	15.710
BORAL™ Liner Inside Flat-to-Flat (cm)	16.142
BORAL™ Liner Outside Flat-to-Flat (cm)	16.853
Fuel Tube Hexagonal Lattice Flat-to-Flat Pitch (cm)	19.393
TSC Inside Wall Diameter "Single-Assembly" (cm)	20.738
Thickness Between Inside TSC Wall and Gamma Shield (cm)	3.300
Lead Gamma-Shield Thickness (cm)	15.000
Thickness between Gamma Shield and Neutron Shield (cm)	3.050
Neutron Shield Thickness (cm)	11.430

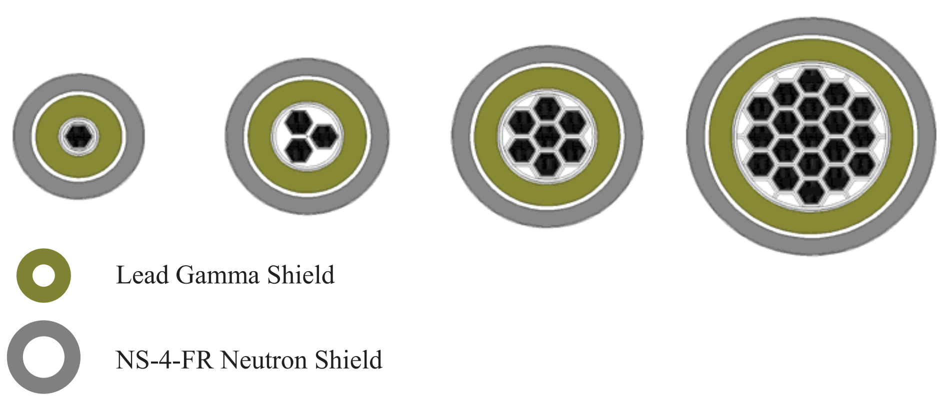

Figure 2. MCNP model of conceptual SFR Cask with a 7-assembly capacity

2.3. Design Assumptions and Conservatisms

As many as possible of the conservatisms used in the UMS SAR were incorporated into the SFR cask criticality design and analysis.

- Heavy metal composition and fuel assembly dimensions corresponding to past ARR fuel cycle studies (2-tier fuel cycle scenario used as the reference) [3]
- Oxide Fuel (ρ=11.70 g/cm^3), ARR CR=0.5, TRU enrichment equals: 41 w/o [2]
- Highest enrichment fuel of the ARR design is considered (i.e., outer core fuel)
- Fuel pellet is 95% theoretical density, pellet-to-cladding gap is explicitly modeled
- No credit for fuel burnup or fission products (i.e., fresh fuel) [5]
- 75% of the nominal B-10 loading in BORAL™ in accordance with 10CFR71 guidance* [5]
- Wire-wrap or spacer grids are not modeled, cask structural support disks are not modeled
- Gamma shield modeled as pure elemental lead (Pb)
- Neutron shield modeled as NS-4-FR (borated hydrogenous synthetic polymer), UMS design
- Flooded scenarios assume water in open spaces of the cask, between fuel tube and SFR assembly duct wall, within the pin-lattice, not within the cladding†
- Flooded scenarios assume water at standard temperature and pressure (1.0 g/cm^3)
- Absolute highest allowable k-eff under any condition is taken to be 0.95

In a later section, the reactivity margin gained by incorporating reprocessed UO2-SNF and MOX-SNF is compared with a representative LMFBR composition. Table 2 gives the detailed isotopic compositions of these fuel types.

Table 2. Isotopic fuel compositions for comparison (w/o)

	LMFBR [1]	1-Tier ARR [3]	2-Tier ARR [3]
U-234	0.00	0.25	0.25
U-235	0.15	0.15	0.15
U-236	0.00	0.32	0.32
U-238	67.05	58.53	58.53
Np-237	0.00	0.89	1.25
Pu-238	0.00	1.50	2.01
Pu-239	28.36	14.89	11.84
Pu-240	3.82	12.81	12.34
Pu-241	0.55	2.72	2.50
Pu-242	0.07	3.79	4.60

* Nominal B-10 composition of BORAL is the natural (un-enriched) isotopic composition

† The scenario with every fuel pin cladding compromised with water infiltrating between cladding and pellet everywhere is considered overly conservative for this preliminary analysis.

Table 2 (Continued). Isotopic fuel compositions for comparison (w/o)

Am-241	0.00	1.42	2.09
Am-242m	0.00	0.08	0.12
Am-243	0.00	1.27	1.91
Cm-244	0.00	0.90	1.37
Cm-245	0.00	0.27	0.40

3. Analysis Results

3.1. Flooding Scenarios

A series of calculations were conducted to evaluate cask criticality as a function of water infiltration into increasing barriers of radiologic protection (cask canister to fuel pin). These sensitivities are given in Figure 3. A trade study was conducted to determine the difference in criticality performance of a mostly helium basket versus a solid aluminum basket. The cask capacity for this comparison was assumed to be for a single assembly.

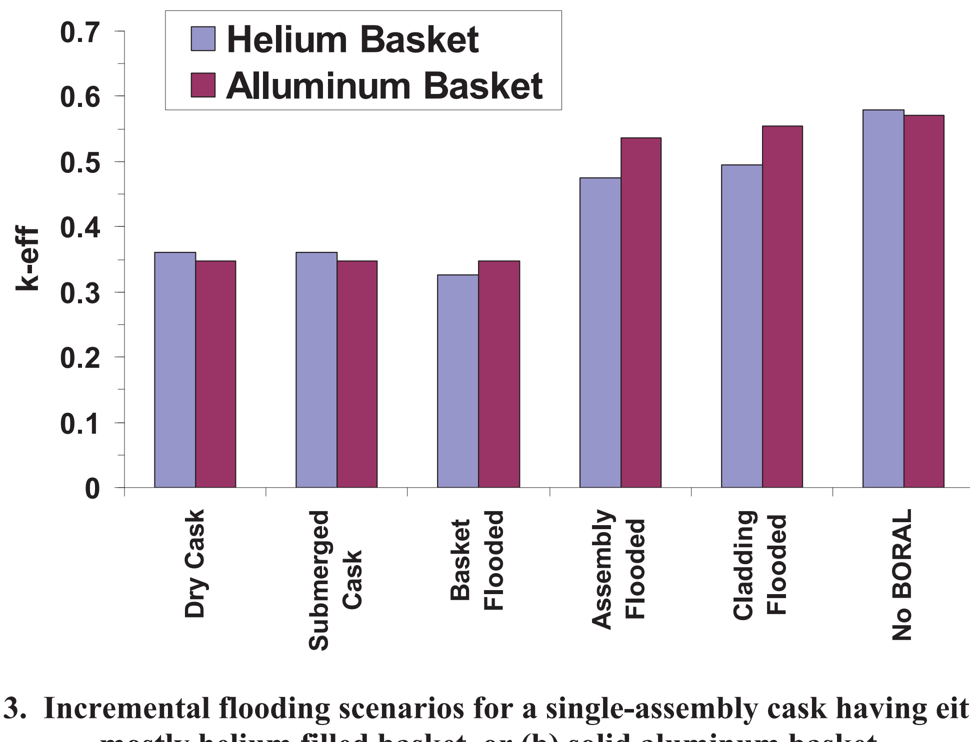

Figure 3. Incremental flooding scenarios for a single-assembly cask having either: (a) mostly helium filled basket, or (b) solid aluminum basket

In all of these single-assembly cases the criticality margin is great. This is due to the high surface-to-volume ratio of a single assembly, resulting in a high overall neutron leakage. The flux spectrum for the "Dry" and "Assembly Flooded" scenarios are given in Figure 4. Notice that the flooded sask neutron spectrum is very thermal somewhat resembling a MOX spectrum in a LWR. The dry cask neutron spectrum is much faster but still having a considerable epithermal component.

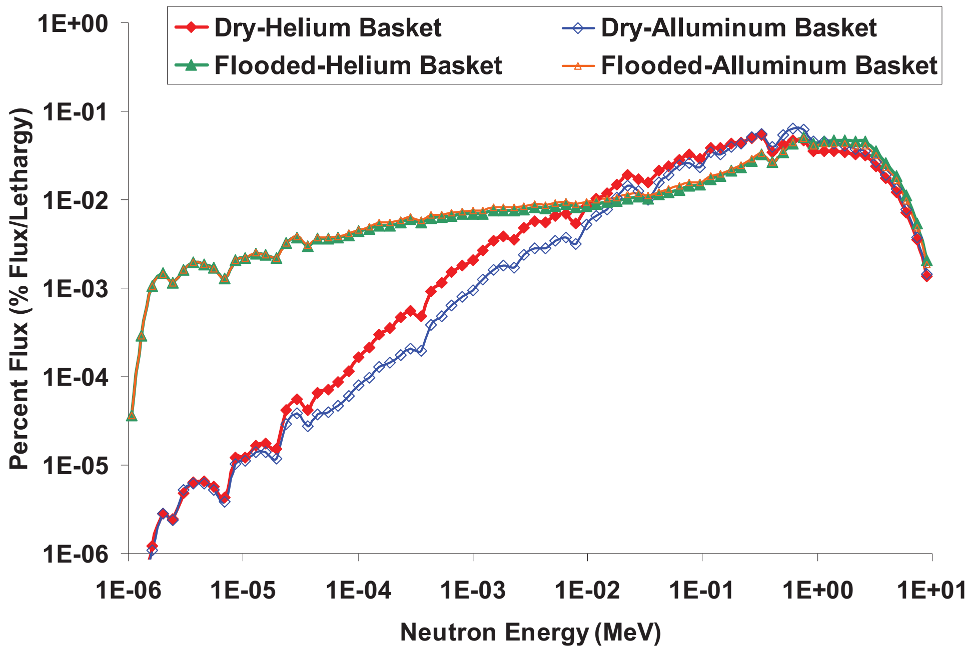

Figure 4. Flooded and non-flooded neutron spectra for: (a) mostly helium basket and (b) solid aluminum basket

Keeping these spectral characteristics in mind, the all-aluminum basket has virtually zero impact on the flux spectrum of a flooded cask. This is likely due to the fact that the neutron mean-free-path in thermalized spectra is much shorter than that for fast. Thus, the moderated case is essentially *blind* to the presence of material outside of the pin-lattice. However, for fast spectra, as is the case for un-moderated lattices, the mean-free-path is much larger. Hence, the interaction with the aluminum outside the pin-lattice is much greater. In the case of a single-assembly cask, the aluminum basket acts as a reflector that reflects neutrons back into the pin-lattice instead of allowing them to escape. The helium filled basket would be filled with water if flooded, providing a water reflector. Water is a poorer reflector than aluminum which explains the higher k-eff of the flooded aluminum cask than the flooded helium cask.

3.2. Cask Assembly Capacity

A series of scoping calculations were conducted comparing cask criticality for a one, three, seven, and 19-assembly cask, respectively (Figure 5). These cases exhibit considerable margin to the k-eff=0.95 limit. In fact, as the cask capacity becomes larger, the effect of a water moderator enhances criticality margin. This can be explained by the cask design moving from under-moderated to over-moderated [7].

An under-moderated critical configuration will increase in reactivity as the moderator-to-fuel ratio increases. In the smaller cask designs, neutron leakages are higher than the larger casks. Therefore, the resonance escape probability (i.e., neutrons lost to neutron capture resonances) is very small. Also, the fuel utilization factor (i.e., neutrons absorbed in the fuel per overall) will dominate over the effect of the resonance escape probability. So, as moderator-to-fuel ratio increases (i.e., flooding), fuel utilization decreases as more neutrons are absorbed in the water, structure and BORAL™. The relative decrease in fuel utilization however is less than the increase in resonance absorption. Thus, the k-eff for under-moderated configurations increases as the moderator-to-fuel ratio increases.

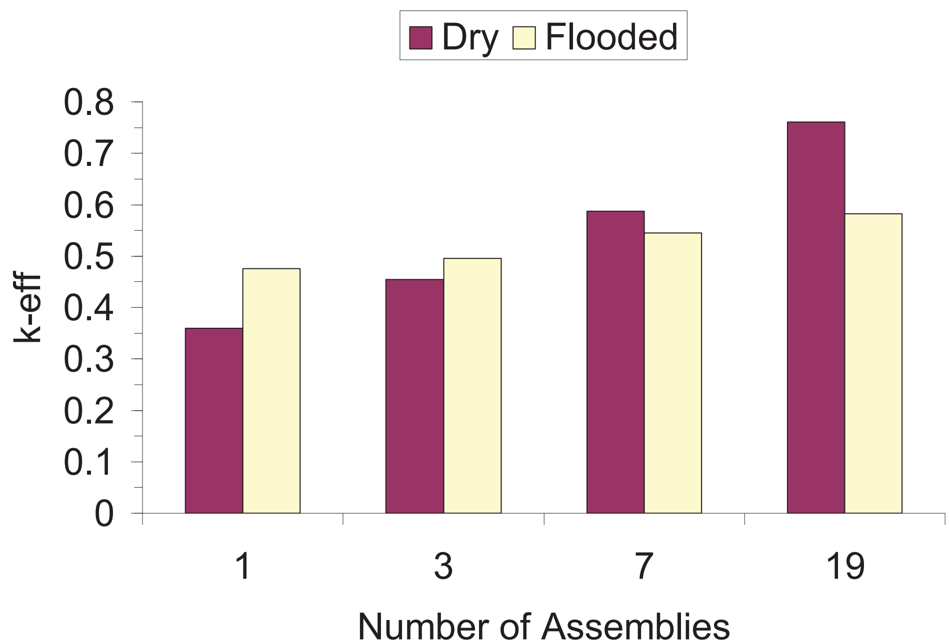

Figure 5. Dry and flooded reactivity for casks of increasing size

However in the larger casks, the leakage is less, thus allowing the resonance escape probability to be larger than the fuel utilization factor. For these casks, an increase in the moderator-to-fuel ratio causes an increase in the resonance escape probability relative to fuel utilization. This is known as an over-moderated configuration and allows the k-eff to go down as moderator-to-fuel ratio increases.

3.3. Sensitivity to Transuranic Fissile Quality

The 7-assembly cask design from Figure 6 was evaluated using the three different compositions from Table 2 to evaluate the effect of fissile grade on criticality. This geometry most closely matches the geometry of the CRBR cask investigated by Philbin and Dupree in 1978 [1]. Also, of interest was the effect on criticality by using BORAL™ as opposed to pure aluminum fuel tube liners. This evaluation assumed a flooded cask scenario since the reactivity worth of B-10 increases with decreasing neutron (i.e., moderated) energies. Similar to the Philbin and Dupree result, the flooded 7-assembly cask with *breeder* grade plutonium was slightly critical without the use of BORAL™. The *burner* grade transuranic composition gave a greatly enhanced reactivity margin by approximately 30% Δk. This criticality margin is attributed to the much higher concentration of fertile per fissile transuranic isotopes in the ARR 1-tier and 2-tier compositions. For example, the Pu-240 concentration is higher than that of Pu-239 in the 2-tier composition (Table 2).

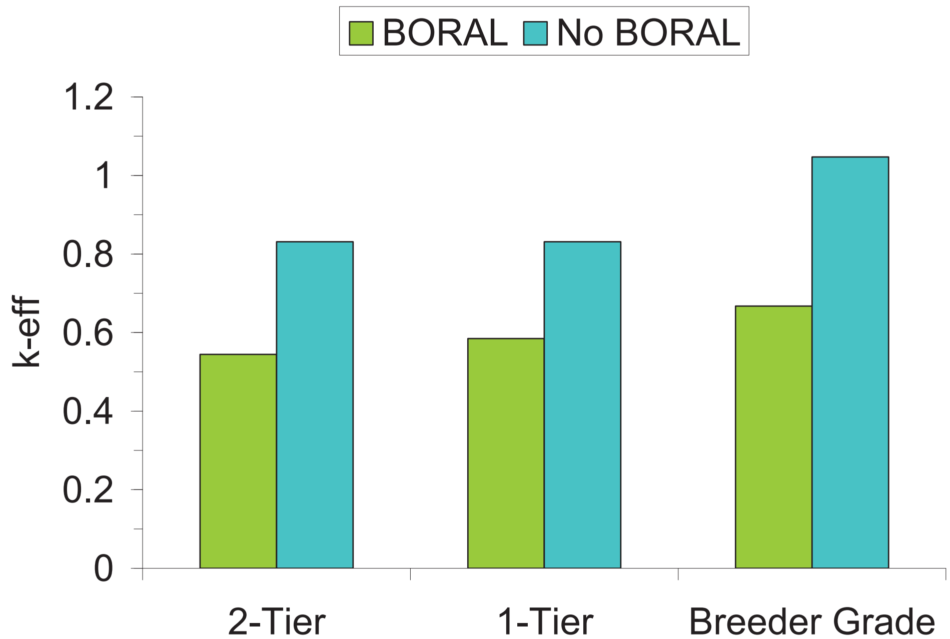

Figure 6. Flooded reactivity values with and without B-10 for fresh fuel compositions of increasing fissile worth (7-assembly)

In fact the criticality margin of burner grade SFR fuel without BORAL™ is nearly 12% Δk below the k-eff=0.95 limit. It should also be noted that the *dry* 7-assembly cask with 2-tier fuel and without BORAL™ has a k-eff = 0.6977±0.00016 which is 25% Δk below the 0.95 limit. The criticality margin with burner grade TRU does not necessarily preclude the use of BORAL™ in the cask design. It may be desired to use weapon disposition grade plutonium or highly enriched uranium as the initial startup fuel for the ARR first core. Therefore, it may be desirable to design the cask with BORAL™ liners as a standard feature to avoid requiring recertification to accommodate this option.

3.4. Minor Actinide Sensitivities

One of the fundamental differences between LMBR fuel and the ARR is the concentration of MAs in the fuel. MAs have significantly higher gamma and alpha decay activity than most uranium and plutonium isotopes, therefore the ARR cask capacity can be strictly limited by its thermal performance criteria as opposed to criticality. Hence, it may be worthwhile to separate the MAs from the ARR fuel stream in order to improve the potential cask capacity based on thermal limitations.

The sensitivity of reactivity to the presence of MAs (i.e., Np, Am, Cm, Cf) was investigated to ascertain the MA reactivity credit. Table 3 gives the k-eff values for the 19-assembly cask under dry and flooded conditions, with and without MAs. For this case, the isotopic recipe from a Pu-only version of the ARR could have been provided for this comparison. However, for this determination of reactivity credit, the all-TRU isotopic recipe was adopted with the MAs removed. Also, the density of the pellet was corrected to reflect the mass subtraction of the MAs, resulting in a reduced pellet density of 10.93 gm/cm3 as opposed to 11.70 gm/cm3. This subtraction provides an exact measure of the MA reactivity credit as compared with the all-TRU ARR fuel.

Table 3. Criticality credit of MAs for the 19-assembly cask

	TRU	No MA	Credit Δk (%)
Dry	0.76115	0.71612	4.5
Flooded	0.58248	0.59868	-1.6

For the flooded cask, the MAs actually provide negative reactivity credit (-1.6% Δk). This negative value results from an increase in resonance absorption in non-fissile MA isotopes (e.g., Np-237, Am-241, Cm-244) which is enhanced by a moderated spectrum. For the dry cask, removal of the MAs results in a credit of 4.5% Δk. The fast spectrum of the un-moderated cask allows the MAs to contribute fast fission neutrons. Whereas, in the thermal flooded spectrum the neutron energies do not allow for ample fast fission to occur. Thus, removal of MAs in a dry cask, removes a significant fast fission contribution to neutron multiplication.

3.5. Fuel Compaction

Finally, an absolute highest reactivity worth scenario for criticality safety of a SFR fuel is investigated. In SFR design, the worst case accident scenario is one where the sodium coolant is displaced and the fuel pins bow inwards bringing fissile material closer. This is because the over-moderated condition of fast reactors causes reactivity to go up when the moderator-to-fuel ratio decreases due to spectral hardening resulting in more fast fission multiplication. Also, as fuel is brought together due to mechanical bowing, neutron leakage via streaming through the voided space (in the absence of sodium) goes down.

It was shown earlier that the cask criticality of large casks is decreased when a moderator is added. Therefore, a cask accident scenario in the absence of moderation is considered. Also, a radial constriction at the cask midsection is considered such that causes physical contact between fuel pins (i.e., pin pitch equals outer pin diameter) in addition to physical contact between fuel tubes (i.e., fuel tube pitch equals fuel tube outer flat-to-flat)[‡]. The k-eff of this compacted geometry is 0.41643±0.00011 and 0.90353±0.00017 for the 1-assembly and 19-assembly casks, respectively. In addition, the k-eff of the un-moderated compacted 19-assembly cask, with no BORAL™, was calculated and found to be 0.99899±0.00020. In light of the fact that removal of MAs does not penalize criticality safety of the non-compacted cask, it can be expected that absence of the MAs provides a credit to a compacted cask as well. The k-eff of the MA free 19-assembly cask compacted geometry with BORAL™ is 0.85709±0.00015.

[‡] The authors are not aware of any accident condition in this type of transportation cask (Type B) that could generate this configuration. It is conceivable that a helical wire wrap would make it nearly impossible to have the intimate contact between pins. In addition, the basket structure itself is very rigid comprised of many structural disks connected by tie-rods, thus inter-assembly contact is virtually moot. If a solid aluminum basket is selected, inter-assembly compaction is completely moot.

4. Summary and Conclusions

The criticality safety of transporting SFR fuel of a transuranic burning type (i.e., ABR or ARR with oxide fuel and CR=0.50) was investigated. It was found that significantly more ARR fuel could be loaded in a cask than conventional LMFBR fuel based on criticality limiting criteria. This is due to the higher concentration of non-fissile plutonium isotopes and MAs in the ARR fuel. Based on a criticality limit of k-eff=0.95, it was found that up to 19 ARR assemblies could be shipped in one cask. Even in the most reactive configuration, dry with fuel assemblies and pins compacted into physical contact, the cask reactivity did not exceed k-eff=0.90. The use of BORAL™ in this design and its structural integrity during an accident was central to the 19-assembly capacity. It should be noted that without BORAL™, this 19-assembly design variant was found to be just critical (within standard error of k-eff=1.0) in this highest possible reactivity worth dry compacted state.

It was found that when using 1-tier or 2-tier grade ARR fuel, the cask reactivity of a 7-assembly cask did not exceed k-eff=0.85 when flooded and without BORAL™. LMFBR fuel in the 7-assembly cask gave a super-critical reactivity. The dry 7-assembly cask with ARR fuel did not exceed k-eff=0.70.

Furthermore, it was found that the 7-assembly and 19-assembly casks' reactivity goes down when flooded due to the over-moderated nature of large critical pile geometry. This can be attributed to the added importance of resonance capture in U-238 (and non-fissile TRU atoms) as well as B-10 in the BORAL™ fuel tube liner. It was also found that for un-moderated casks, separation of the MAs resulted in a decrease in reactivity. This is attributed to the removal of the MA fast fission contribution to multiplication. A slight increase in reactivity is observed for a flooded cask without as opposed to with MAs.

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