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Criticality Scoping Calculations for a Multi-Function Dissolver Insert

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INTRODUCTION

As one of its missions, the Savannah River Site seeks to be a leader in the safe and productive disposition of special nuclear materials. One of the premier programs is the disposition of used nuclear fuel (UNF), primarily from research reactors, through dissolution, purification, and down blend into low enriched uranium for commercial power reactors. Prior to use, this fuel contained highly enriched uranium (HEU). In an effort to advance this expertise, this study has been performed to demonstrate the feasibility to disposition a number of special geometry HEU fuels. These fuels come from a number of different domestic and foreign research reactors which had geometries considerably different from round or square bundles of plates or rods. As such, they cannot be dispositioned in current H-Canyon dissolver inserts so a new, multi-function dissolver insert may be considered. While this is not a current mission, it is believed that this study's scoping calculations demonstrate the feasibility of the site taking such a mission.

At the H-Canyon facility, a dissolver is a large stainless steel pot, loaded with a nitric acid solution into which uranium-alloy fuel is dissolved. The dissolver uses a device called an insert to feed the fuels to the acid solution in a controlled manner. Most fuel forms fit into one of the existing inserts which include one with ten ~5-inch diameter circular wells, one with four ~4.5 inch by ~15 inch slab wells, and one specifically designed for the Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR).

This study considered five bounding fuel candidates for scoping the potential new insert. The fuels include a generic annular plate fuel (APF), the Tower Shield Reactor (TSR) fuel elements, the Reactor A Haute Flux (RHF) core, Knolls Atomic Power Laboratory (KAPL) reactor fuel, and SLOWPOKE cores. These are expected to bound a range of proposed fuel candidates. Scoping studies were made to establish geometric restrictions for the new dissolver insert and to determine if these fuels could safely be dissolved. Homogenous models were used for the scoping study due to time constraints.

Computational modeling was performed using KENO-VI in the SCALE 6.1 code package.

DESCRIPTION OF THE WORK

General Modeling and Assumptions

The dissolution of the fuels considered was modeled as three regions: 1) the fuel element, 2) the insert well, and 3) the dissolver. Dissolution was modeled in five steps: 0%, 25%, 50%, 75%, and 100% of the fuel element dissolved into the well solution and the dissolver solution.

The APF was modeled as a solid ring which decreased in thickness with each successive dissolution step. For the other fuels considered, the fuel element region was modeled as a homogenized mixture having the outermost geometry of the fuel element being considered. This geometry included void space that was filled with the well solution. The geometry of the fuel element region was maintained throughout all partial dissolution steps. For each dissolution step, a fraction of the uranium and aluminum content was removed from the fuel element region. This loss in volume was replaced by well solution and the region re-homogenized to reflect this new condition. At 100% dissolved the well solution and fuel element geometry have the same composition. At 0% dissolved the well region and the bulk dissolver region have the same composition.

The lowest acidity assumed was 0.5M which gave the most conservative multiplication factor. The highest acidity the dissolver would charge is assumed to be 10.4M which gives the lowest multiplication factor. A median acid of 4M was also modeled in some cases. The fuels are either U-Al or U-Mo alloy both of which readily dissolved in nitric acid. Note that molybdenum is difficult to maintain in solution and will precipitate at both high and low acid, co-precipitating with uranium at low acidity. Dissolution campaigns with molybdenum require the terminal acid concentration in the dissolver to be 3 to 6 M (Ref 1.). Aluminum precipitates at a lower acidity.

No burnup is credited; bounding fresh isotopics are used. This bounds any plutonium build up in the fuel. The dissolver is assumed to be 8 feet in diameter and a constant volume of 5000 L of solution is modeled. The dissolver vessel was conservatively replaced with reflective boundary conditions. All fuel types are dissolved into fresh acid solution. All fuel types are dissolved one item at a time except for APF which is dissolved two plates at a time. Some fuels may contain stainless steel components that do not dissolve, would have to be retrieved and which are not modeled. The stainless steel components of the dissolver insert are not explicitly modeled to conservatively increase the interaction between the fuel and the solution. The main effect of the stainless steel n the insert is parasitic absorption in the iron and nickel. Each fuel type examined is modeled with an assumed size of the dissolver insert well into which it was inserted. The well is generally a close fitting geometry around the fuel element. This is assumed for modeling purposes only; the width and thickness may be similar in reality but actual well heights will be ~20 feet.

Dissolved U and Al/Mo were assumed to remain in the well until the well concentration exceeded 150 gU/L based on Ref. 2 and Ref. 3. Only then was the material assumed to disperse into the dissolver solution. It was assumed that the Al/Mo dispersed in the same fractionation with uranium as in the initial fuel form. Only the dissolution of APF provided enough uranium to require application of the dispersion assumption.

Figure 1 shows SCALE KENO 3D images of the fuels types considered, not to scale.

APF Model

The APF is a generic, idealized fuel form expected to bound several candidate fuel types. A bounding APF plate is modeled at 14 kg U (93.5 wt.% enrichment) with 10 wt.% Mo. The plate is modeled as a nominal 7.0 inch inner diameter, 11.7 inch outer diameter, and thickness of 0.795 inch. The APF well is modeled to be 12.0 inches wide and 14.0 inches high. The thickness of the well is parameterized for the study at 2.0 and 3.0 inches thick. Separation between the wells is parameterized at 6.0 and 8.0 inches face to face separation. The fuel element region was explicitly the fuel plate geometry.

TSR Model

The TSR is a unique geometry. The model is based on information from Ref. 4. The TSR is a hollow spherical reactor which disassembles into 25 components. There are 12 annular fuel elements which make up the exterior geometry and resemble orange slices. These attach to upper and lower assembly pieces which are nearly identical to each other and consist of four segments each. Each segment is a quarter hemi-shell with a quarter cylinder removed from the apex. When combined the four segments form a complete hemi-shell with a cylindrical opening. There is one cylindrical fuel plug which fits into either the lower or upper assembly opening. The remaining four pieces are half hemi-shell "lune plates," thin quarter moon shaped plates which assemble into a hollow sphere. The lune plates serve as an interior liner for the cavity formed by the other pieces.

The annular fuel element and lower/upper element will bound the lune plates and cylindrical plug by mass. The annular fuel element consists of 472.534 g U (440.18 g U-235) plus 2,578.6 g Al in the fuel, 5,291 g Al in the cladding and 411 g Al additional in the structural materials. The lower/upper fuel element consists of 378.13 g U (352.24 g U-235) plus 2,034 g Al in the fuel, 4,176 g Al in the cladding and 117 g Al additional in the structural materials. Both have stainless steel components which would need to be retrieved. There is no stainless steel in the lune plates or cylindrical plug. Using nominal densities of aluminum and uranium, approximately 76% of the annular fuel element and 89% of the lower/upper fuel element geometry is free volume. The annular fuel element is modeled as a truncated segment of a sphere as near to the actual shape as possible and retaining the volume of the actual element. The lower/upper element is modeled as a quarter hemi-shell with a semi-cylindrical opening at the bottom. The annular fuel element was assumed to remain vertical in the dissolver insert, however the lower/upper element may have to be rotated depending on the dissolver insert geometry.

The well for the annular fuel element was assumed to be a cylinder of radius 18 cm and height 70 cm. The well for the lower/upper element was assumed to be a 40 cm cube.

RHF Model

The Reactor A Haute Flux (RHF) model is based Ref 5. The RHF fuel is comparable to the HFIR outer core component in both geometry and composition. The difference is height: RHF active fuel height is 96.5 cm while the HFIR active fuel height is only 50.8 cm. RHF does not have an inner core element like HFIR.

The RHF is an annular fuel assembly consisting of an inner collar and an outer collar with curved plates between the two collars. There are 280 plates with a total U of 9,212 g of which 8,568 g are U-235. Each plate contains 65.4 g aluminum in the fuel alloy and 179.6 g aluminum in the cladding. The plate is 90.3 cm long, 8 cm wide, and 0.127 cm thick. The inner and outer radii of the inner collar are 13.04 and 13.69 cm. The inner and outer radii of the outer collar are 19.88 and 20.68 cm. The overall height is 97.0 cm. Approximately 47.9% of the assembly is free volume. The annular geometry of 13.04 cm inner radius, 20.68 cm outer radius, and height of 97.0 cm is maintained by homogenizing the fuel, cladding, and interstitial well solution over this same volume with each dissolution step.

The RHF well is assumed to be 98.0 cm in height and 43.18 cm in diameter.

KAPL Model

The KAPL fuel element model is based on Ref. 6. The KAPL fuel element is an aluminum shaft to which are attached 35 equally spaced thin disc fuel plates. The fuel assembly is placed into an aluminum can, then overpacked into an aluminum inner container, and placed into a thick carbon steel outer container. The outer container is an oversized 2R type container.

The fuel element contains a total of 206.14 g U (193.80 g U-235). The combined aluminum content for both alloy and cladding is 647.76 g. Other aluminum components of the fuel element are 109.30 g. The can is 617 g aluminum and the inner container 10,500 g aluminum. The fuel element geometry is assumed to be the outer dimensions of the inner container which is a 6.035 cm radius and 57.53 cm height. Approximately 33% of the fuel element geometry is free volume. The cylindrical fuel element geometry is maintained by homogenizing the fuel, cladding, and interstitial well solution over this same volume with each dissolution step.

The well dimensions are assumed to accommodate the oversized 2R container which is 12.09 cm in radius and

64.35 cm in height. The well is assumed to have a 6 inch radius (15.24 cm) and a 27 inch height (68.58 cm).

The dissolver and well solutions are modified for this analysis. It is assumed that the carbon steel outer container rapidly dissolves and immediately disperses. Therefore, iron and carbon content are added to both the dissolver and well solutions consistent with the dissolution of 167,375 g of carbon steel. This is based on a carbon steel density of 7.82 g/cm^3 and the steel container's volume.

SLOWPOKE Model

The SLOWPOKE model is based on Ref. 7. The SLOWPOKE fuel consists of 295 fuel pins arranged in a circular triangular pitched concentric ring lattice. The pins have an outer diameter of 0.53 cm and outer length of 22.83 cm with a 0.051 cm thick aluminum cladding. The fuel meat is 0.422 cm outer diameter. Each pin contains 3.020 g U (2.814 g U-235/pin) and 7.688 g aluminum. The lattice is held in shape by thin upper and lower aluminum plates separated by thin aluminum posts. The total assembly outer diameter is 22 cm and outer height is 23.58 cm. Approximately 82.9% of the assembly is free volume. The SLOWPOKE geometry is maintained by homogenizing the fuel, cladding, and interstitial well solution over this same volume with each dissolution step.

The SLOWPOKE well is assumed to be 35.56 cm (14 inches) in height and 35.56 cm in diameter.

Determination of k_{SAFE}

A validation for the SCALE 6.1 KENO-VI code for HEU solutions and HEU metals was examined (Ref. 8). Using the most conservative bias between the two types of systems and adding an additional subcritical margin, the k_{SAFE} assumed for this work was 0.9664.

RESULTS AND CONCLUSIONS

All reported k-best estimate values are k-calculated plus two times the Monte Carlo uncertainty.

Table I presents the results for TSR, SLOWPOKE, RHF, and KAPL fuels. The KAPL fuel had low multiplication factors computed due to its low uranium and high iron content. The SLOWPOKE fuel had results close to k_{SAFE} for the 0.5M acid cases so 4M cases were run. The TSR results were safely subcritical in all cases. The RHF exceeded k_{SAFE} in nearly all cases due to the assumption that the uranium did not disperse from the well solution and the large homogenized geometry.

Figures 2 and 3 presents the results for the APF modeling. The APF is one of the limiting fuel types for any new dissolver design. The high content of fissile material will require small slab-like dissolver wells of limited thickness. The assumption that up to 150 gU/L accumulates in the well before dispersing into the bulk solution further restricts the geometry. The results show a 2" thick well is safe under all conditions. However operations will likely need more space to handle the fuel and place it in the dissolver well. The 3" well will be safely subcritical under controlled conditions which would likely include a minimum acid concentration and minimum separation distance between the fuel plates.

This analysis showed that of the miscellaneous fuel types, all but RHF could be shown to dissolve safely subcritical under some or all of the conditions analyzed using simple homogenized models. The RHF fuel could likely be shown to also be safely subcritical provided more detailed modeling. These scoping calculations conclude that a dissolver which can accommodate the APF, TSR, SLOWPOKE, and KAPL fuels may (1) be designed to disposition these unique fuels safely subcritical and (2) accommodate other types bounded by their composition and geometry.

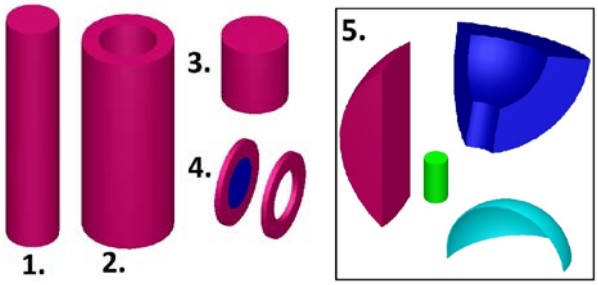

Fig. 1. SCALE 6.1 KENO-3D images of the fuel types considered. Not to scale. 1. KAPL fuel. 2. RHF fuel. 3. SLOWPOKE fuel. 4. Two APF fuel plates, left plate showing well solution in the annulus. 5. The components of the TSR (clockwise from top) upper/lower element, lune plate, plug, annular element.

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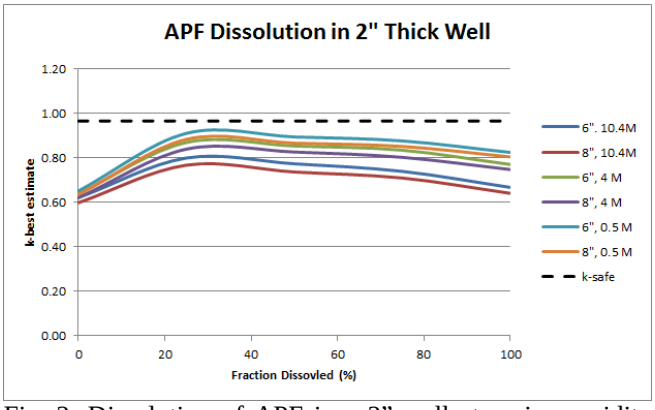

Fig. 2: Dissolution of APF in a 2” well at various acidity and separation distance between the plates.

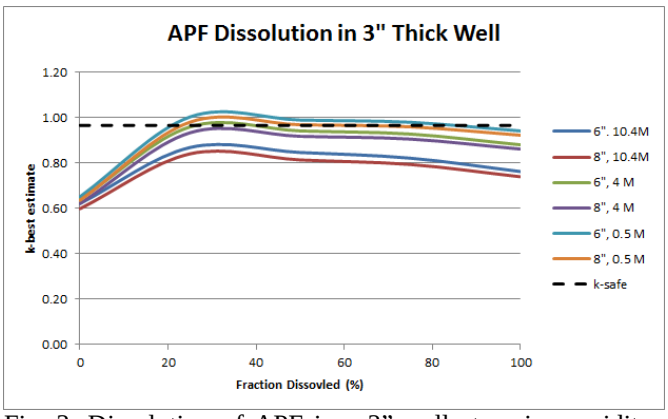

Fig. 3: Dissolution of APF in a 3” well at various acidity and separation distance between the plates.

Table I: Results for TSR, SLOWPOKE, RHF, and KAPL Fuels Under Various Conditions

Dissolved (%)	Well Conc. (gU/L)	Fresh Acid (M)	k best estimate (incl. uncert.)
SLOWPOKE			
0	0	10.4	0.686
25	6.307	10.4	0.734
50	12.613	10.4	0.762
75	18.92	10.4	0.713
100	25.226	10.4	0.720
0	0	4	0.827
25	6.307	4	0.874
50	12.613	4	0.895
75	18.92	4	0.891
100	25.226	4	0.849
0	0	0.5	0.896
25	6.307	0.5	0.943
50	12.613	0.5	0.964
75	18.92	0.5	0.957
100	25.226	0.5	0.900
RHF			
0	0	10.4	0.712
25	20.406	10.4	0.939
50	37.425	10.4	1.014
75	51.834	10.4	1.025
100	64.191	10.4	1.014
TSR, Annular Fuel Element			
0	0	10.4	0.469
25	1.658	10.4	0.499
50	3.316	10.4	0.477
75	4.974	10.4	0.431
100	6.632	10.4	0.36
0	0	0.5	0.672
25	1.658	0.5	0.67
50	3.316	0.5	0.635
75	4.974	0.5	0.567
100	6.632	0.5	0.464
TSR, Upper/Lower Fuel Element			
0	0	10.4	0.468
25	1.477	10.4	0.444
50	2.954	10.4	0.411
75	4.431	10.4	0.374
100	5.908	10.4	0.336
0	0	0.5	0.625
25	1.477	0.5	0.643
50	2.954	0.5	0.542
75	4.431	0.5	0.488
100	5.908	0.5	0.434
KAPL			
0	0	0.5	0.310
25	1.03	0.5	0.357
50	2.06	0.5	0.372
75	3.09	0.5	0.348
100	4.12	0.5	0.289