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Combining RHF and HFIR Disposition Campaigns – Analysis, Opportunity, and Lessons Learned

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INTRODUCTION

Savannah River Nuclear Solutions has tasked its H-Canyon facility to prepare for disposition of used Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR) cores. HFIR cores consist of an inner and outer assembly of highly enriched uranium fuel plates. The two elements are annular, nest inside each other, and the fuel form is a curved plate held between two collars. H-Canyon has a dissolver insert specifically designed for HFIR cores and has performed this type of campaign before between 1976 and 1988. 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. The mission will be to dissolve a number of HFIR cores, purify the uranium, and down blend it to low enriched uranium suitable for commercial power reactors.

HFIR has a sister core. A French high flux research reactor, called Reactor A Haut Flux (RHF), has nearly the same geometry as the outer element of HFIR. The annulus is only slightly smaller and the RHF active fuel height is ~97 cm while the HFIR active fuel height is only ~51 cm. SRNS is currently storing RHF cores (repatriated through circa 2003) awaiting a path for disposition. There is now an opportunity.

This work is the result of an initiative to propose appending the RHF cores to the anticipated HFIR campaign. Geometry and chemistry differences are evaluated and criticality safety assessed. The RHF cores were semi-explicitly modeled in various stages of dissolution. Normal and credible abnormal conditions were assessed. RHF was shown to be bounded by the dissolution of a complete HFIR core in both neutron multiplication and dissolver chemistry.

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

DESCRIPTION OF THE WORK

Modeling of the RHF Element

Table I presents the pertinent modeling information for the RHF element as taken from Ref. 2 and Ref. 3. This is compared against the HFIR core elements from Ref. 1. Element as used here denotes a single item. In the case of RHF, an element is the whole core. In the case of HFIR, the core is composed of two elements, one of which fits inside the other.

The RHF is modeled semi-explicitly using radial layers to approximate the collars and radial segments of the fuel assembly. This was akin to the approach used to model the HFIR elements in Ref. 1. The inner annulus of the RHF was assumed to be filled at all times with the dissolver bulk fissile solution and the collars assumed to be solid aluminum. The fuel was divided radially and the volume of each radial segment available for bulk fissile solution was calculated by subtracting the fuel volume from the total volume. A unique KENO composition was created for each radial segment based on the composition and volume of fuel and the bulk fissile solution in that segment. Dissolution of the RHF was modeled in seven stages, dissolving successive radial layers. The dissolution of the radial layers model 0%, 12.5%, 25%, 50%, 75%, 87.5% and 100% of the fuel dissolved. With each step, the dissolved material was assumed to disperse into the bulk fissile solution and the composition of the bulk fissile solution was recalculated. The compositions of the remaining radial layers were then readjusted to account for the new composition of the bulk fissile solution component.

RHF, like HFIR, is an undermoderated core, so increasing the $H/^{235}U$ increases multiplication. Since the model is not further discretized into axial sub-segments, it is conservative to smear the U over the overall height of the RHF element as opposed to smearing the axial non-fuel aluminum into the active fuel height. This locally distributes the U in each radial layer and thus increases the $H/^{235}U$ ratio in each layer. This is a localized effect as the $H/^{235}U$ of the entire dissolver-plus-core system remains the same. This results in a slightly higher value for the neutron multiplication.

This analysis assumes RHF elements are fed to only fresh acid such that there is no trace plutonium in the dissolver, which could occur in recycled acid. Fresh fuel isotopics are assumed which bound Pu built up in the system since the average burnup has decreased the U enrichment from ~93 wt.% to ~84 wt.%. The HFIR insert geometry was taken from Ref. 1 The insert is ~20 feet tall and contains two wells sized specially for the HFIR inner and outer elements. The dissolver insert has holes for cross flow which allow for dispersion of the dissolved material into the bulk fissile solution. These holes comprise at most 15% of the volume of the well insert, which is therefore modeled as homogenized 85% stainless steel and 15% bulk fissile solution to account for the holes.

To further maximize the multiplication factor, only the nitrate bonded to the uranium and aluminum is modeled. Assuming 0M excess nitric acid is conservative at it increases multiplication by removing some parasitic absorption and in reality the system would never be operated at this low acidity. The 0M excess acid assumption

maintained when bulk fissile solution is re-homogenized after every dissolution step.

Like Ref. 1, this analysis seeks to alleviate the need to credit fixed burnable absorber in the insert, so this absorber material is neglected in the modeling.

Table I. Pertinent RHF Parameters Compared to HFIR.

Parameter	RHF Element	HFIR Outer Element	HFIR Inner Element
Fuel Plate Height (cm)	90.3	60.96	60.96
Fuel Plate Width (cm)	8	8.1	9.21
Fuel Plate Thickness (cm)	0.127	0.13	0.13
Fuel Meat Height (cm)	81.3	80.8	50.8
Fuel Meat Width (cm)	6.7	7	7.79
Fuel Meat Thickness (cm)	0.051	0.08	0.08
Fuel Meat U (g/plate)	32.9	19.8	16.3
Fuel Meat U-235 (g/plate)	30.6	18.44	15.18
Fuel Meat Al (g/plate)	65.4	57.6	65.9
Fuel Meat O (g/plate)	0	3.6	2.96
Clad Thickness (cm)	0.038	0.03	0.03
Clad Mass (g/plate)	179.6	96.1	111.2
Plate Mass (g/plate)	277.9	177.1	196.4
Plates/assembly	280	396	171
Total U (g/element)	9212	7316.6	2791
Total ^{235}U(g/element)	8568	6804.4	2595.8
Al Mass (g/element)	100760	84283.4	44209
Overall Height (cm)	97	79.1	76.84
Outer Collar ID (cm)	39.76	--	--
Outer Collar OD (cm)	41.36	43.6	29.8
Inner Collar ID (cm)	26.08	28.5242	12.863
Inner Collar OD (cm)	27.38	--	--
Al/U Ratio	10.94	11.52	15.84

Normal Conditions

The normal condition, shown in Fig. 1, is one RHF element loaded into the well for the HFIR outer element, and dissolving in fresh nitric acid solution. (A comparable image for HFIR may be seen in Ref. 1). Note that each dissolver well has a central stainless steel post on which the inserted element is to rest/align. Since there are only four RHF elements in storage to dissolve, the starting concentration of the normal condition assumes the first three are already dissolved in the bulk fissile solution. The bulk fissile solution is normalized to a bounding low normal volume of 13500 L. The solution concentrations before the 4th core is added to the solution are 1.904 g ^{235}U/L and 0.830 M Al. The terminal concentrations after the 4th core is dissolved are 2.539 g ^{235}U/L and 1.107 M Al, well below the uranium criticality safety limit of 11.5 g ^{235}U/L and the aluminum precipitation limit of 2M. In the model, excess solution is added so that the top of the RHF element is covered up to 2.54 cm. This adds about 1200 L of the bulk fissile solution to the normal condition model (or at 1.904 g ^{235}U/L, ~27% of an RHF's worth of ^{235}U).

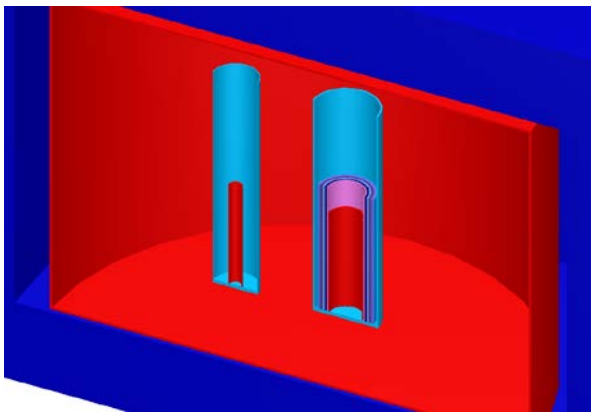

Fig. 1. RHF in the outer element position of the HFIR dissolver insert. Solution has been hidden from view to enhance detail.

Credible Abnormal Conditions

Three credible abnormal conditions were identified to be evaluated as leading to potential inadvertent criticality scenarios. These include 1) over massing the system, 2) overconcentration of the system, and 3) accumulation of undissolved solids.

Since the RHF element will only fit in the HFIR outer element well of the HFIR dissolver insert, the only credible way to over mass the system is the place a second RHF element on top of one already in the well. This upset was conservatively modeled by assuming the solution was initially at the same 1.904 g ^{235}U/L and 0.830 M Al as the normal condition and a second RHF added to the well. For additional conservatism, the solution properties were calculated at 13500 L of bulk fissile solution but then the entire dissolver and the well were filled with bulk fissile solution to the top of the second RHF element. This adds ~9000 L of additional solution, which at 1.904 g ^{235}U/L would be ~2 additional RHF element's worth of fissile material. Ultimately, seven RHF elements would be needed

to achieve the configuration modeled and only four are available. This abnormal condition is shown in Fig. 2.

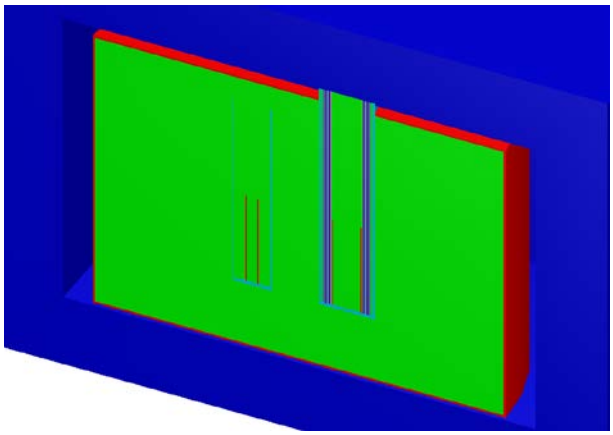

Fig. 2. Over mass of two RHF with solution filling the dissolver and the well.

Over concentration may be achieved in two manners. First, chemistry will allow dissolution of material until the acid is consumed. Ref. 5 indicates 3.75 moles of acid per mole of aluminum and 4 moles of acid per mole of uranium are consumed. The maximum capacity of the dissolver before overflow is 16523 L and the maximum acidity is 10.4 M. Each RHF element contains 3732.4 moles Al and 39.2 moles U. Therefore, no more than 12.125 RHF elements could be dissolved in the maximum volume of acid resulting in a terminal concentration 6.290 g ^{235}U/L. Returning to the 13500 L basis, dissolution is modeled for over concentration wherein an RHF element is dissolved in a solution initially 5.655 g ^{235}U/L and 2.465 M Al such that the final concentration is 6.290 g ^{235}U/L and 2.741 M Al; which is the bounding maximum ^{235}U concentration achievable. The no excess acid condition is maintained in all dissolution steps.

The second means of over concentration is through multiple, concurrent operator errors. System chemistry would allow no more than the bounding condition of 12 RHF elements dissolved in initially 10.4 M acid in a dissolver full to the overflow point. The resulting solution would then need to be concentrated by evaporation by more than 50%, *without detection*, to reach the criticality safety limit of 11.5 g ^{235}U/L. This is deemed not credible.

Finally, undissolved solids are considered though not an expected situation. In this evaluation 10% of the mass of an RHF element is assumed to accumulate in a hemisphere on the tank bottom beneath the dissolver well. This is modeled both with and without the aluminum. A low density theoretical hemisphere the same diameter of the well is modeled and a small hemisphere having the theoretical density of uranium metal is modeled. These are expected to bound any possible accumulation of undissolved solids. This situation is shown in Fig. 3.

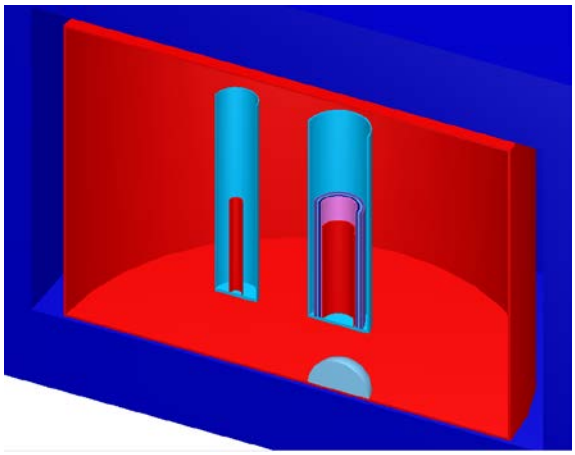

Fig. 3. RHF with undissolved solids.

Sensitivity

The system was also evaluated for sensitivity to two mechanical design tolerances. First, corrosion of the stainless steel of the dissolver insert was considered. While this is expected to be minimal, bounding cases were rerun with the steel walls of the insert removed so that no requirement needs to be placed on their thickness. Second, tolerances on the axial positioning of the dissolver insert were examined in bounding cases. The insert is a mechanical device placed in the dissolver when needed and has a tolerance on positioning (Ref. 1). The axial positioning tolerances can cause the height of the dissolver well above the bottom of the dissolver to vary between 57.528 cm and 49.493 cm, compared to a nominal height of 57.15 cm.

Determination of k_{SAFE}

A validation for the SCALE 6.1 KENO-VI code for HEU solutions and HEU metals was examined (Ref. 4). 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

All multiplication factor values discussed below are best estimate, i.e. the calculated multiplication of the system plus two times the Monte Carlo uncertainty. Fig. 4 shows the normal condition and overconcentration results for dissolution and compares them with the HFIR data from Ref. 1. The limiting cases from the other upsets and sensitivity studies are shown in Table II. All results were below k_{SAFE}. The RHF fuel can be safely dissolved.

Like the HFIR analysis in Ref. 1, RHF has been shown to be able to be dissolved without the need for a charging plan, probing for undissolved solids, or crediting the fixed neutron poisons or the wall thicknesses of the dissolver insert. The credible abnormal conditions were shown to be subcritical in the bounding circumstances. The results should not be surprising since the aluminum and fissile

content of a single RHF element is less than the aluminum and fissile content of a single HFIR core (inner and outer element co-dissolved). Using realistic analysis and crediting chemistry, the administrative controls are eliminated. Nature of process has been shown to keep the system subcritical.

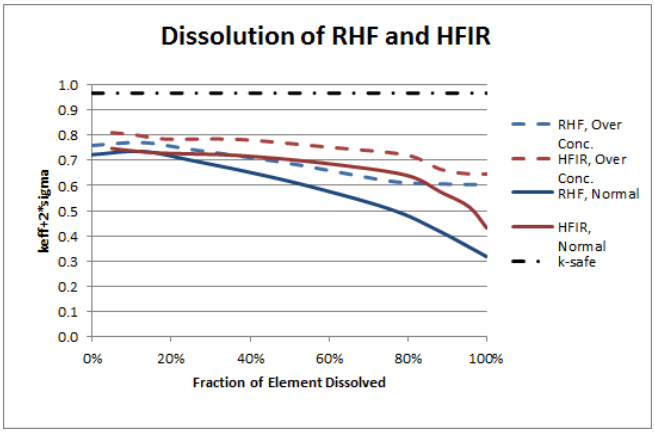

Fig. 4. Dissolution results for normal conditions and overconcentration upset.

Table II. Limiting Upset and Sensitivity Cases.

Condition	Description	k-best estimate
Over mass	Most reactive dissolution step for 2 RHF elements, dissolved filled with fissile solution	0.817
Undissolved Solids	Al and U in low density theoretical hemisphere	0.736
Undissolved Solids	U in low density theoretical hemisphere	0.738
Undissolved Solids	U in nominal density hemisphere	0.737
Corrosion	Limiting over mass case with insert well walls removed	0.852
Insert Height	Limiting over mass case, inset height at min	0.818
Insert Height	Limiting over mass case, inset height at max	0.819
Insert Height	Limiting undissolved solids case, inset height at min	0.742
Insert Height	Limiting undissolved solids case, inset height at max	0.737

HANDLING AND TRANSPORATION

Handling and transportation of the RHF element were already analyzed in Ref. 3. The RHF has its own safety significant credited transportation device to move it to H-canyon. The RHF element has been fitted with handling devices to allow it to be charged to the dissolver. Ref. 3 already analyzed the credible abnormal conditions associated with storage and transportation, including dropping the RHF during transport, and showed the element remains safely subcritical.

LESSONS LEARNED

This analysis includes a lesson learned about knowledge transfer that could have resulted in a missed business opportunity and/or mid-campaign rework.

Of the 10 HFIR disposition campaigns at H-Canyon, 7 included using the HFIR dissolver insert to disposition RHF fuel. However, the most recent HFIR campaign did not have any RHF to process at that time so the analysis performed at that time did not include RHF. It was that analysis that was used as a starting point for the new HFIR dissolution analysis. Few people who were personally involved in 1980s campaigns remain in the facility. Today, the RHF fuel was being reexamined for another campaign when it was identified as being very similar to HFIR. It was not until a senior manager happened to see that other work and recall he had a list of the campaigns H-Canyon had done since 1955. It was this record that provided confirmation that past HFIR campaigns had co-dispositioned RHF fuel in the HFIR insert. At that point the analysis would be remiss in not analyzing both fuel types for any upcoming campaign.

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