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LEU CONVERSION ACTIVITIES AT THE HIGH FLUX ISOTOPE REACTOR: SIMPLIFYING THE FOIL DESIGN, PREPARING THE REACTOR

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ABSTRACT

A reference, low enriched uranium (LEU) fuel has been developed based on the assumption that the thickness of the metal foil can vary as a function of span along the plate and axial position on the plate. The characteristics of the reference design, both performance and geometry, are provided to the reader. Program criteria established by the Reduced Enrichment for Research and Test Reactors are reviewed and the status of achieving those criteria with the reference fuel are presented. The use of finite element methods for thermal hydraulic analysis should simplify the LEU foil design. A schedule for implementing the conversion of HFIR to LEU fuel by 2016 has been developed and the activities planned for the next year will be briefly discussed.

1. Introduction

The High Flux Isotope Reactor (HFIR) is a light-water-cooled, beryllium-reflected flux-trap-type reactor. The core is composed of two elements, the inner element having 171 aluminum-clad plates and the outer element containing 369 plates. The fuelled height is 50 cm and the outer diameter of the annular core is 42 cm.

Over the past four years, the staff at Oak Ridge National Laboratory (ORNL) has studied the conversion of the HFIR from high enriched uranium (HEU) fuel (93 wt. % ^{235}U) to low enriched uranium (LEU, 19.75 wt. % ^{235}U) fuel [1-5]. While the current, HEU fuel is a ceramic/metal mixture - U_3O_8 in aluminum - the LEU fuel will be a metal alloy of 90% uranium and 10%

molybdenum. This change in fuel form is required in order to maintain the current performance of the reactor to all users.

A reference LEU fuel has been developed based on the assumption that the thickness of the metal foil can vary as a function of position along the plate (span) and axial position on the plate. The design has been shown to maintain the flux performance of the reactor at the same level as is currently achieved with HEU fuel.

2. Reference design for LEU fuel

A dispersion fuel similar to the current HEU oxide but fabricated with LEU-Mo particles does not provide sufficient density in the HFIR geometry for the reactor to achieve the same cycle length at 85 MW as is achieved with HEU [3]. A monolithic, metal alloy foil is required to achieve needed uranium density. The presence of ^{238}U – a neutron absorber – in LEU increases the critical mass of ^{235}U in the HFIR geometry by a factor of 2.7. With the reduction of the enrichment from 93 wt. % to 19.75 wt. %, the amount of *uranium* in the core increases from 10.1 kg of HEU to 128 kg of LEU.

Being designed as an isotope production reactor, the HFIR core has significant neutron leakage to the central target region and to the reflector surrounding the core. Due to thermalization of neutrons occurring outside the reactor core in the surrounding beryllium reflector, the thermal neutron flux will be highest at the outside edge of the reactor core, and to a lesser extent, at the inner edge of the HFIR annular core (due to coolant water in the central target region). As with any reactor, obtaining the highest operating power requires minimizing the peak-to-average power density ratio. To obtain the highest operating power with consequent highest flux for isotope production, the HFIR fuel thickness varies significantly over the span of the fuel plates as shown in Fig. 1 from [6]. The current, HEU fuel is fabricated from U_3O_8 powder and thus a continuously graded fuel distribution can be formed from a suitably shaped die-and-punch. The same physical phenomena – peaking of the thermal flux in the reactor at the edges of the core – must be mitigated in the LEU fuel design.

HEU fuel, being formed from a powder, is amenable to the continuous grading profile that results from reactor physics calculations to flatten the power density profile. Metal foils, especially the thin ones that would be used in HFIR LEU fuel (around 350 microns), are not so easily formed into contours such as those shown in Fig. 1. “Straight edge” profiles, such as knife edges or razor edges, are commonly manufactured shapes. Calculations performed at ORNL showed that the replacement of smoothly contoured zones with “straight edge” zones did not result in a significant penalty in power density distribution. After iterative calculations – both beginning-of-life and over the entire fuel cycle – LEU radial fuel profiles were developed and are shown in Fig. 2. Note that the bases of the fuel plates are flat.

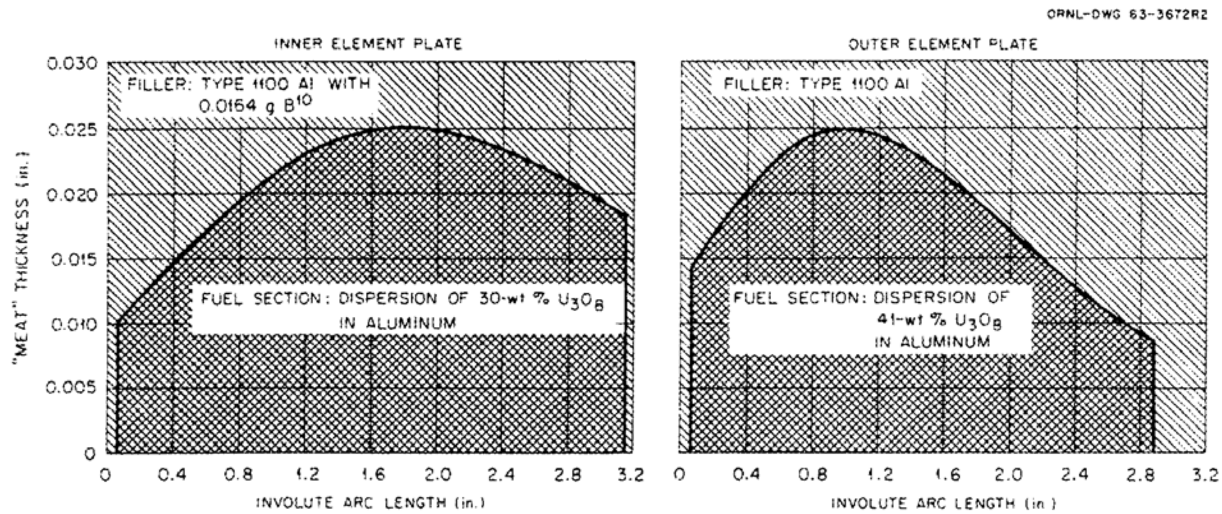

Fig. 1. Fuel thickness as a function of distance along a HFIR HEU fuel plate

Unlike HEU fuel, LEU foils must be graded (tapered) axially as well as radially in order to maintain the same margin to incipient boiling (difference between maximum, local, coolant temperature and incipient boiling coolant temperature under limiting safety setting conditions). Axial grading is needed because the edge power density of LEU fuel is greater than that of HEU for equivalent reactor performance. The phenomena is due to the increased ^{235}U atom density in LEU relative to HEU and is apparent in the reduced thicknesses of the edges of the LEU fuel regions in Fig. 2 relative to the HEU fuel region thicknesses shown in Fig. 1.

The same phenomena – thermalization of neutrons in a reflector (water) and return to the core – occurs above and below the reactor core. Local power densities at the top and bottom of an LEU core without axial grading are considerably higher than for HEU cores. Calculated inner element plate, lower edge power profiles are shown in Fig. 3. Since the HFIR is designed to reach the highest flux possible, there is no available safety margin to accommodate an LEU power density distribution that has a higher peak-to-average value than the current HEU power profile.

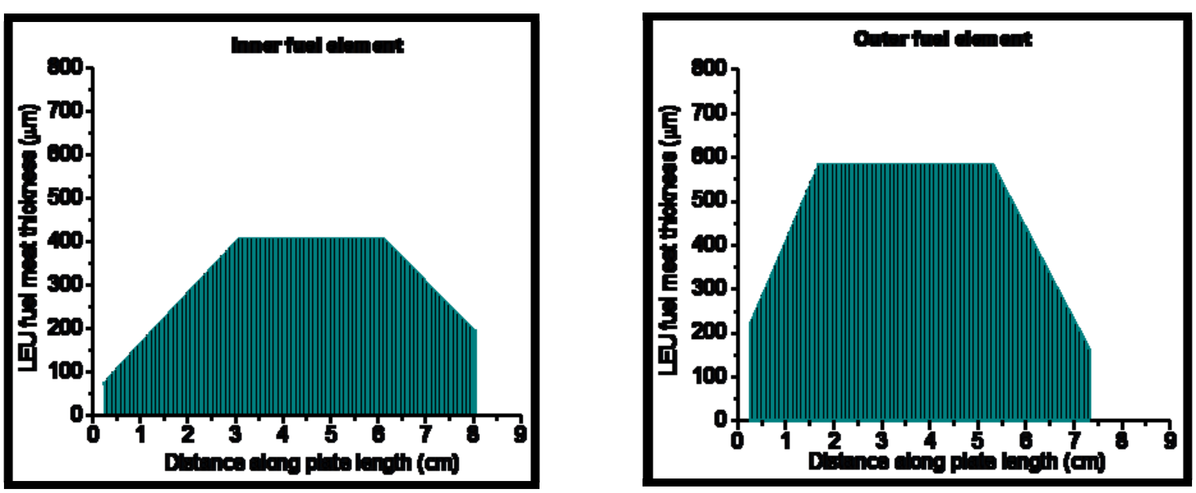

Fig. 2. Fuel thickness as a function of distance along proposed LEU fuel plates

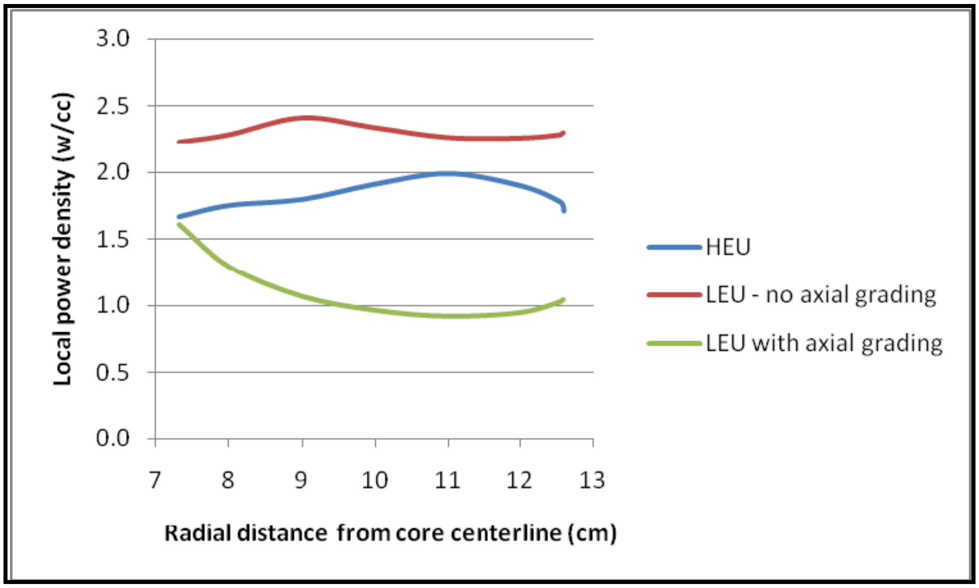

Fig. 3. Inner element fuel plate, bottom edge power density profiles

Axial grading can be used to reduce the LEU peak-to-average power profile (see Fig. 3). The grading is only needed on the bottom of the LEU core because coolant flow is downward in HFIR. The presence of a relatively high local power density at the top of the core does not yield a margin-to-incipient-boiling ratio at that location that exceeds the value at the exit of an HEU core.

Studies conducted during the past year showed that grading of the LEU fuel is required only for the bottom-most 3 cm of the core. An illustration of the bottom plate profile for an outer fuel element plate is shown in Fig. 4 (a similar inner element plate configuration is used in the computational model for results shown in Fig. 3). The lowest one cm of the plate would be a flat profile having a thickness of 75 microns. For a distance between 1 and 3 cm from the bottom of the plate, the thickness of the plate would linearly increase to the values shown in Fig. 2 for both inner and outer element fuel plates.

The significant reduction in local power densities for the axially-graded LEU fuel relative to the HEU fuel implies that the grading shape shown in Fig. 4 could be studied further to continue the search for the optimal power density profile. Nevertheless, axial grading of some type will be required and input from fuel fabricators should be sought in order to conduct a faster and more informed optimization study.

Another method considered to reduce axial flux peaking would be to include a neutron absorber at the base of the fuel plate. The need for significant local reduction in power density implies that an absorber with high macroscopic cross section is needed. This would be expected to cause a reactivity penalty (shorten cycle life) requiring an increase in ^{235}U content to compensate. Since the poison would be added to each fuel plate in each core, financial cost would likely be significant (boron is not a likely candidate due to helium gas generation).

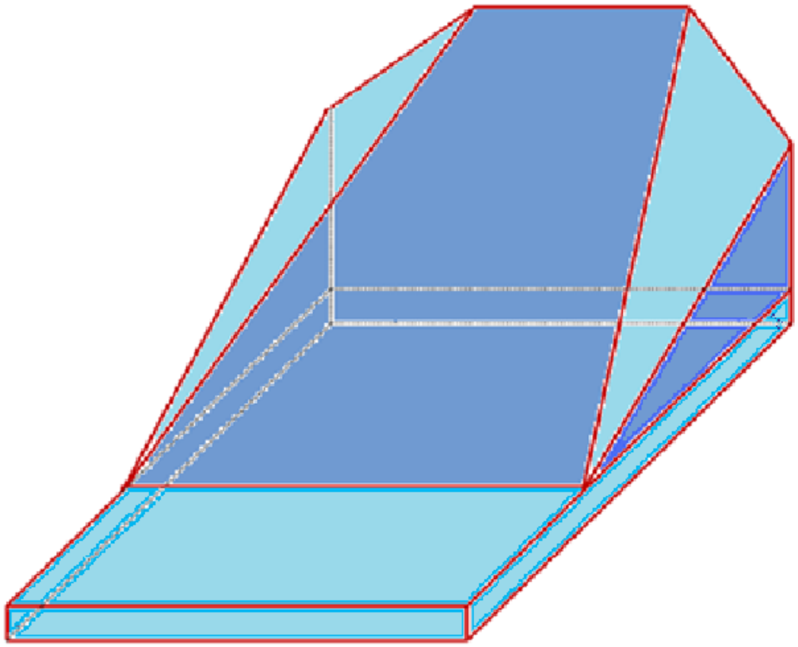

Fig. 4. Representation of axial grading on lower edge of HFIR LEU outer element fuel plate

The current manufacturing process calls for the fuel plate to be formed by rolling a relatively thick sheet or ingot into a foil (sheet if continuous rolling is used; ingot if the U/Mo ingot is encased in a shaped mold and then rolled). The foil is then covered with a zircaloy diffusion barrier, inserted in an aluminum frame, top and bottom covers applied, and then the “sandwich” pressed. Inserting a neutron poison “wire” or thin zone at the base of the plate would have to be performed concurrent with insertion of the covered foil inside the aluminum frame. This operation would be performed on every fuel plate and precise positioning of the poison “wire” would be required. The somewhat complex manufacturing procedure coupled with the expense of the poison and the reactivity penalty associated with the poison led to the option of axial grading being preferred.

3.0 Performance of reference LEU fuel

The MCNP-5.1 [7] code system and associated libraries (ENDF/B-VI.8 and JENDL 3.3), coupled with ORIGEN-2 [8] via the ALEPH computer program [9] are the computational methods that have been used to analyze the performance of the reference LEU core. Validation studies of these methods have been published in a set of reports. [3, 10, 11, 12]. Flux values at key positions in the reactor are used as performance indicators. Values for the current, HEU fuel and the reference LEU fuel are shown in Table 1 (BOC = beginning-of-cycle, EOC = end-of-cycle). As noted in previous reports [3, 4, 5] maintaining the performance of the reactor at current flux following the transition from HEU to LEU requires that the operating power of the reactor be increased from 85 MW to 100 MW. The flux values for HEU fuel in Table 1 are for a reactor operating power of 85 MW; the values for LEU fuel are for an operating power of 100 MW.

	Time	Fuel	Thermal flux (n/cm^{2}s)	Epithermal flux (n/cm^{2}s)	Fast flux (n/cm^{2}s)
Central target	BOC	HEU	2.2×10^{15}	1.3×10^{15}	1.1×10^{15}
		LEU	2.3×10^{15}	1.3×10^{15}	1.1×10^{15}
	EOC	HEU	2.3×10^{15}	1.1×10^{15}	1.0×10^{15}
		LEU	2.5×10^{15}	1.2×10^{15}	1.0×10^{15}
Cold source edge	BOC	HEU	6.9×10^{14}	2.4×10^{14}	0.9×10^{14}
		LEU	8.3×10^{14}	2.9×10^{14}	1.0×10^{14}
	EOC	HEU	8.4×10^{14}	2.4×10^{14}	0.9×10^{14}
		LEU	8.5×10^{14}	2.8×10^{14}	1.0×10^{14}
Reflector r=27cm	BOC	HEU	6.0×10^{14}	6.5×10^{14}	4.1×10^{14}
		LEU	7.1×10^{14}	7.8×10^{14}	4.8×10^{14}
	EOC	HEU	8.1×10^{14}	6.6×10^{14}	4.0×10^{14}
		LEU	7.4×10^{14}	7.5×10^{14}	4.6×10^{14}

Table 1. Calculated flux values at performance indicator positions in HFIR

Two items remain to be calculated regarding the steady state performance of the LEU fuel. Staff at the Idaho National Laboratory has concluded that a zircaloy "interlayer" is required to be present between the U/Mo foil and the aluminum clad in order to prevent swelling of the fuel under irradiation. Though the impact on neutronics and heat transfer performance should be insignificant, this layer has not been included in the computational model. The second item is the re-calculation of various reactivity coefficients. These calculations were performed for an early version of the LEU fuel and are documented in [2]. The calculations must be performed again for the reference LEU design, though it is expected that the conclusions will be the same; the presence of ^{238}U in LEU serves to moderate power excursions due to reactivity accidents.

4.0 Status of achieving conversion goals

Criteria to be met during the conversion of HFIR from HEU to LEU are identified in [1]. Collecting and paraphrasing those criteria, the conversion goals and an assessment of the status of each are reported in Table 2. Advancement in HFIR conversion, with the exception of thermal hydraulic methods development, depends on the results of creating a prototypic commercial fabrication process and on the results of planned irradiation and flow tests. In regard to fresh fuel storage, current practice is to store fresh HEU assemblies at the Y-12 National

Nuclear Security Agency (NNSA) facility, not at the HFIR site. A new protocol must be established for LEU fuel.

<table>
<tr><th colspan="2">Goal following conversion</th><th>Status</th></tr>
<tr><td colspan="2">Ability of reactor to perform scientific mission is not diminished</td><td>Confirmed by calculation</td></tr>
<tr><td colspan="2">Reactor has similar lifetime for fuel assembly</td><td>Confirmed by calculation</td></tr>
<tr><td colspan="2">No major changes to reactor structure or equipment</td><td>Fresh fuel storage location unresolved</td></tr>
<tr><td rowspan="5">LEU fuel meets safety requirements</td><td>Maintain safety margin; reactivity coefficients; transient behavior of fuel</td><td>Preliminary confirmation by calculation</td></tr>
<tr><td>Radial and axial grading of foil</td><td>To be demonstrated by fabrication tasks in RERTR</td></tr>
<tr><td>Zr interlayer for HFIR contoured fuel</td><td>To be demonstrated by fabrication tasks in RERTR</td></tr>
<tr><td>Involute shaped plates</td><td>To be demonstrated by fabrication tasks in RERTR; tested in flow test</td></tr>
<tr><td>Verify full-sized plate performance under irradiation at HFIR conditions</td><td>To be demonstrated by irradiation in ATR</td></tr>
<tr><td colspan="2">LEU fuel does not increase annual operating expenditure</td><td>Inconclusive; improved thermal hydraulics methods may reduce LEU fabrication cost</td></tr>
</table>

Table 2. Status of conversion goals for HFIR

5.0 Improvements to thermal hydraulic methods

The reference LEU fuel design maintains the current safety margin in HFIR – defined as the local minimum value of the margin between operating coolant temperature and incipient boiling temperature. Maintaining this margin leads to the requirement for axial grading with LEU foils.

The current steady state thermal hydraulic methodology is based on custom-designed software created by HFIR staff over 40 years ago [13]. In the computational solution, heat is transported through the plate but not along the span or height of the plate. Likewise, in calculating coolant temperature, there is no mixing of the coolant in directions other than the main direction of coolant flow (no turbulent mixing). Both of these assumptions act to overestimate the coolant temperatures at the "hot spot" and "hot channel" in the core. Preliminary studies [14] indicate that with modern computational methods (finite element analysis), it can be shown that heat generated at a hot spot is widely distributed leading to a much lower peak-to-average coolant temperature than is calculated with the current methodology. It is possible that modern methods, appropriately validated, will alleviate the need for axial grading with consequent reduction in LEU fabrication cost.

6.0 Preparing the reactor

A well documented business model, including tasks, costs, and schedules is needed to plan the conversion of HFIR. A detailed outline of the conversion program has been established and includes LEU fuel design activities, a fresh fuel shipping cask and storage building, improvements to the HFIR reactor building, and spent fuel operations. Expected costs were tabulated and are under review at NNSA. The schedule included almost 300 subtasks and will take over 10 years to complete though loading of the first LEU core in HFIR is scheduled to be accomplished by 2016. The model and schedule followed the path of the fuel from arrival at the HFIR site to shipment of spent fuel to waste disposal and illustrates the duration, start, and completion dates of each subtask to be completed.

As noted in Table 2, many of these tasks must be conducted in cooperation with the fuel fabrication facilities and experimental facilities outside of Oak Ridge National Laboratory. Preparation of a fuel specification and associated quality assurance program will be a joint effort between HFIR staff and the program fabrication task.

Having performed design and safety analyses, HFIR staff will seek to observe experimental studies noted in Table 2 and provide input as to measurements needed to confirm design and safety analyses. The improvements to the HFIR reactor building, mentioned previously, are minor but time consuming and include procurement of new fuel element handling tools (LEU elements are 30% heavier than the current HEU elements) and various safety-related analyses. While the HFIR was designed to operate at 100 MW, the return to that power level will require a review of operating systems and instrumentation.

7.0 Conclusions

With an increase in reactor operating power to 100 MW, calculations indicate that the HFIR can maintain the current level of flux performance that is achieved with HEU fuel. These calculations though, indicate that LEU fuel must be tapered (thickness varied) both radially and axially. Calculation of safety-related reactivity coefficients and design documentation will be completed during the next few months. Modern computational thermal hydraulic methods may eliminate the need for axially grading the LEU foils; that need is imposed by limitations of the currently employed analysis techniques. Continued advancement of the HFIR conversion activities requires input from experimental programs scheduled to be conducted at Idaho National Laboratory and contracted universities and input from fabrication tests, also scheduled at sites outside Oak Ridge National Laboratory.

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