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Conceptual Fuel Element Design Candidates for Conversion of High Flux Isotope Reactor with Low-Enriched Uranium Silicide Dispersion Fuel*

Chandler D.[1], Betzler B. R.[2], Bae J. W.[2], Cook D. H.[1], and Ilas G.[2]

Oak Ridge National Laboratory
[1]NScD Research Reactors Division
[2]NSED Reactor and Nuclear Systems Division
1 Bethel Valley Road, Oak Ridge, TN, 37831 U.S.A.
chandlerd@ornl.gov

ABSTRACT

Engineering design studies are underway to assess the feasibility of converting the High Flux Isotope Reactor (HFIR) to operate with low-enriched uranium silicide dispersion (LEU_3Si_2-Al) fuel. These studies are supported by the U.S. Department of Energy National Nuclear Security Administration's Office of Material Management and Minimization. A systematic approach employing neutronic and thermal-hydraulic analyses has been performed with the ORNL Shift and HFIR Steady State Heat Transfer Code tools, respectively, to predict reactor performance and thermal safety margins for proposed LEU_3Si_2-Al fuel designs. The design process was initiated by generating an optimized design with fabrication features identified from previous studies that result in excellent performance and safety metrics. The approach continued by substituting a single fabrication feature anticipated to be difficult to manufacture with another feature expected to perform an analogous function to that of the removed feature. Four conceptual fuel element design candidates, with various fabrication features, for conversion of HFIR with 4.8 gU/cm^3 LEU_3Si_2-Al fuel have been generated and shown to meet pre-defined performance and safety metrics. Results to date indicate that HFIR could convert with the subject fuel system and meet performance and safety requirements if, among other considerations, fabrication of the specific design features are demonstrated and qualification of the fuel is complete under HFIR-specific conditions.

KEYWORDS: HFIR, LEU, Neutronics, Silicide, Thermal-Hydraulics

1. INTRODUCTION

In collaboration with the U.S. reactor conversion program, Oak Ridge National Laboratory (ORNL) has been performing engineering evaluations on the conversion of its High Flux Isotope Reactor (HFIR) from high-enriched uranium (HEU) to low-enriched uranium (LEU) fuel since 2005. The U.S. has had a reactor conversion program since 1978 and has undergone several reorganizations [1]. Established in 2015, the U.S. Department of Energy (DOE) National Nuclear Security Administration's (NNSA) Office of Material Management and Minimization (M^3) continues to reduce the risk of HEU through, among other means, its

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reactor conversion mission. For over a decade, the program has pursued conversion of the remaining U.S. high-performance research reactors with a U-10Mo monolithic fuel. However, due to fabrication concerns with the complex fuel design needed to convert HFIR, M^3 requested ORNL to evaluate LEU U_3Si_2-Al (LEU_3Si_2-Al) dispersion fuel in the summer of 2017 for risk mitigation purposes.

Viability studies documented in [2] and [3] indicate that conversion of HFIR with LEU_3Si_2-Al (19.75 wt.%) fuel with 4.8 gU/cm^3 is feasible if, among other requirements, the active fuel zone length is increased from 50.80 cm to 55.88 cm, the proposed fabrication features and tolerances can be met, and the fuel can be qualified for HFIR-specific conditions. The studies described herein are a continuation of the feasibility studies described in [2] and [3] and seek to optimize the HFIR core design with 4.8 gU/cm^3 LEU_3Si_2-Al fuel. Four conceptual fuel element design candidates, with various fabrication features, have been generated and shown to meet pre-defined performance and safety metrics.

2. HIGH FLUX ISOTOPE REACTOR

HFIR is a versatile, multi-mission research reactor that is operated at ORNL for the U.S. DOE Office of Science. With world-class capabilities, it serves a variety of national missions including cold and thermal neutron scattering, isotope production, materials irradiation research, neutron activation analysis, gamma irradiation research, and fundamental physics research. HFIR is an 85 MW pressurized, light-water cooled, light-water moderated, beryllium reflected, flux-trap-type research reactor. The reactor core assembly design consists of a series of concentric regions, each about 61-cm in height, and includes, from the core centerline outward: (1) a flux trap target region, (2) an inner fuel element (IFE), (3) an outer fuel element (OFE), (4) a control element region, and (5) a beryllium reflector (Figs. 1 and 2).

The HFIR fuel assembly consists of an integral two element configuration composed of the IFE and OFE, which contain 171 and 369 involute-shaped fuel plates, respectively. The HEU (~93 wt.% ^{235}U) U_3O_8-Al fuel meat and Al filler regions are encapsulated in Al-6061 clad. Approximately 2.6 and 6.8 kg of ^{235}U are respectively loaded into the IFE and OFE (9.4 kg ^{235}U total). The fuel is contoured along the arc of the involute plate to reduce edge power peaking, and the IFE's filler region, which is adjacent to the fuel meat, contains B_4C poison for reactivity hold-down and edge power suppression purposes. The U_3O_8-to-Al mass split differs between the IFE and OFE fuel plates; 30 wt.% U_3O_8 in the IFE and 40 wt.% U_3O_8 in the OFE. For both plate types, the fuel plus filler region thickness is 0.762 mm and the clad thickness is 0.254 mm. Each fuel plate is 60.96 cm in length and the active fuel zone length is 50.80 cm.

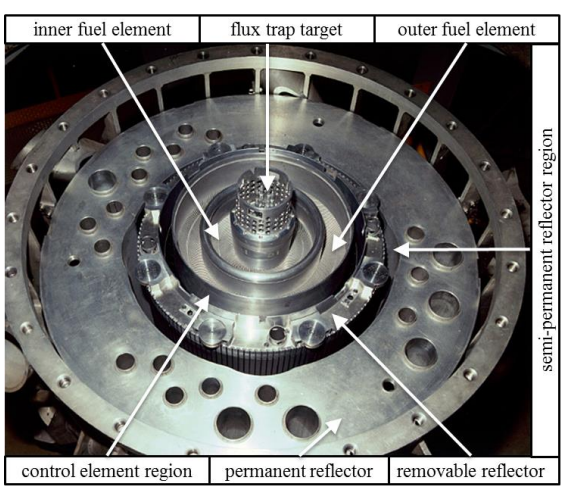

Figure 1. HFIR core mockup.

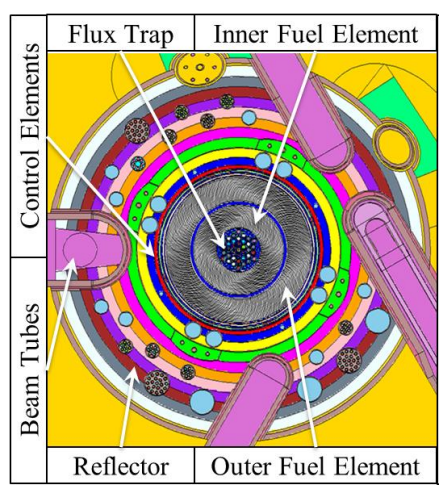

Figure 2. HFIR neutronics model.

Down-flowing coolant enters the pressure vessel through two inlets above the reactor (inlet temperature and pressure of 48.89 °C and 3.33 MPa), passes through the core (ΔT and ΔP of ~20 °C and 0.76 MPa), and then exits the vessel through an outlet below the core. Approximately 0.82 m^3/s of the total 1.01 m^3/s coolant flow passes through the fuel elements and flux trap region.

3. CONCEPTUAL FUEL ELEMENT DESIGN STUDY

Like the studies performed in [2] and [3], this work considers 4.8 gU/cm^3 U_3Si_2-Al dispersion fuel with an assumed LEU enrichment of 19.75 wt.%. Because of the low ^{235}U density (0.948 $g^{235}U/cm^3$-U_3Si_2-Al), it is necessary to increase the active fuel zone length from 50.80 cm (current HEU design) to 55.88 cm to load enough fuel into the core to power HFIR for an approximate 26-day-long cycle. Also, as concluded in [2] and [3], a nominal power of 95 MW is required for a LEU_3Si_2-Al to perform at the same level as the 85 MW HEU core; thus, 95 MW is considered for all conceptual designs discussed.

3.1 Design Method and Metrics

A systematic approach employing neutronic and thermal-hydraulic analyses has been performed with the ORNL Shift Monte-Carlo based neutron transport and depletion tool [4, 5] and an updated version of the HFIR Steady State Heat Transfer Code [3, 6], respectively, to predict reactor performance and thermal safety margins for proposed LEU_3Si_2-Al fuel designs. Key performance metrics [7] including cycle length, cold neutron flux in the cold source moderator vessel, ^{252}Cf production, and fast neutron flux in material irradiation facilities, are computed as a means of capturing data essential for HFIR's primary missions and are used to assess the impact of conversion. The reactor nominal full power full flow safety limit (SL) calculations for flux-to-flow are analyzed because this condition is typically limiting for HFIR steady-state heat transfer analyses. With the flux-to-flow ratio at its SL (1.36), all other variables at their limiting control settings (T_{inlet} = 57.2 °C and P_{inlet} = 2.41 MPa), and all uncertainties in the technical knowledge of the process resolved unfavorably (i.e., conservatively), no hot spot burnout can occur.

3.2 Conceptual Fuel Element Design Study

The primary design features explored include ^{235}U loading, fuel thickness contouring along the arc of involute, fuel zone location within plate, fuel zone axial contouring, filler region burnable poisons, and a borated pocket below the active fuel zone. Except for the fuel plate internal regions (i.e., fuel, filler, and poison regions encapsulated within clad), the LEU cores are assumed identical to the current HEU core.

Because of HFIR's high power density and unique design, featuring plates whose lateral ends face the core moderator/reflector regions, the fuel thickness must be contoured along the plate's arc and may also need to be axially contoured to meet thermal safety margin requirements. The location of the fuel zone within the plate also has a large impact on thermal margin. If the fuel zone is centered and symmetric about the fuel plate thickness centerline, the conduction paths out to the two adjacent coolant channels are equivalent and a three-pour compact is required (filler, fuel, and filler). However, if the fuel zone is off-centered and asymmetric, one side of the plate will be hotter than the other, but fabrication becomes less complicated because the process only requires a two-pour compact (fuel and filler). Axial contouring refers to the thinning down of the nominal fuel thickness profile in the bottommost region of the fuel zone to a constant bottom edge thickness. This feature results in reduced power peaking and increased safety margins. These complex features are necessary to compensate for the power increase required to maintain performance.

The design process was initiated by generating an optimized design with fabrication features identified from previous studies with LEU-10Mo fuel [8] and LEU_3Si_2-Al [2, 3] that result in excellent performance

and safety metrics. The approach continued by substituting a single fabrication feature anticipated to be difficult to manufacture with another feature expected to perform an analogous function to that of the removed feature. For example, an axially contoured fuel zone could be substituted with a neutron poison pocket underneath the fuel zone to reduce axial power peaking. Iterations between neutronic and thermal-hydraulic analyses were performed until the design met performance and safety requirements. A flowchart is illustrated in Fig. 3 to explain the process established to develop the four conceptual designs.

The design process seeks to maximize the burnout margin and key performance metrics. Depending on the design features modeled, more emphasis may be placed on improving the thermal-hydraulic performance than the neutronics performance because thermal safety margin is difficult to attain, as the minimal fuel plate interior volume limits the designers' ability to contour the fuel [2]. An approach taken to increase the safety margin consists of analyzing previous designs' radially dependent fuel thickness and maximum local-to-critical heat flux ratio profiles that indicate regions where margin is needed or can be sacrificed. The fuel thickness profiles, which vary with the distance along the arc of the involute, are illustrated for the four conceptual designs in Fig. 4. A comparison of the design features is provided in Table I.

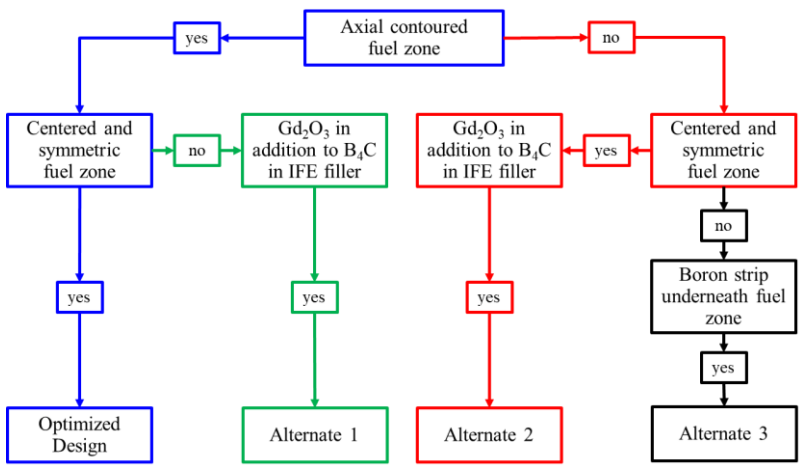

Figure 3. Conceptual design feature flowchart.

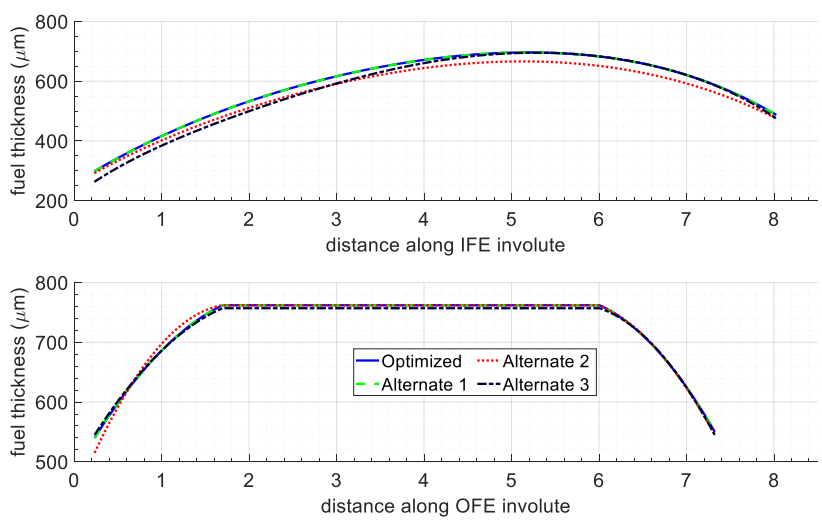

Figure 4. Conceptual design fuel thickness profiles.

Table I. Conceptual design feature descriptions.

Feature	Optimized	Alternate 1	Alternate 2	Alternate 3
^{235}U loading [kg] (IFE, OFE, Total)	4.076, 9.877, 13.953	4.076, 9.877, 13.953	3.947, 9.989, 13.936	4.014, 9.940, 13.954
^{10}B loading in IFE filler [g]	2.203	2.203	2.441	2.316
Gd loading in IFE filler [g]	0.000	1.009	1.118	0.000
Fuel zone location about plate thickness centerline	Centered and symmetric	Off-centered and asymmetric	Centered and symmetric	Off-centered and asymmetric
Axial fuel contour	Yes	Yes	No	No
Axial contour length [cm]	1	1	N/A	N/A
Axial contour thickness at bottom edge [μm]	200	200	N/A	N/A
^{10}B loading in borated pocket [g] (IFE, OFE)	N/A	N/A	N/A	0.122, 0.231

Key performance, uranium utilization, time-limiting burnout margin, and peak fission density metrics are provided in Table II. The four LEU designs meet and exceed all the performance metrics except for the Alternate 3 ^{252}Cf production rate, which is effectively the same as that for the HEU core. Additionally, all four designs meet the minimum burnout margin SL of 1.36, and the Optimized design has a better margin than the HEU core because of its axial contour and centered and symmetric design features. To exemplify the spatially dependent fission distributions, Figs. 5 and 6 illustrate the end-of-cycle (EOC) fission rate density and cumulative fission density distributions, respectively.

Table II. Conceptual design performance and thermal margin metrics.

Parameter	HEU	Optimized	Alternate 1	Alternate 2	Alternate 3
Cycle length [day]	26.2	27.5	27.5	27.1	27.1
^{252}Cf production [mg/day]	1.388	1.406	1.398	1.396	1.380
Cold source moderator vessel cold flux [10^{14} n/cm^2-s]	4.48	4.63	4.64	4.65	4.65
Reflector fast flux [10^{14} n/cm^2-s]	2.89	3.22	3.22	3.23	3.23
Flux trap fast flux [10^{15} n/cm^2-s]	1.07	1.15	1.15	1.14	1.14
Cm target thermal flux [10^{15} n/cm^2-s]	~1.62-1.65	1.64	1.64	1.63	1.63
^{235}U utilization [kg/day]	0.360	0.508	0.508	0.514	0.515
Minimum burnout margin	1.61	1.62	1.54	1.51	1.51
Peak fission rate density [10^{15} fissions/cm^3 U_3Si_2/s]	N/A	1.85	1.80	1.79	1.89
Peak cumulative fission density [10^{21} fissions/cm^3 U_3Si_2]	N/A	3.27	3.27	3.26	3.30

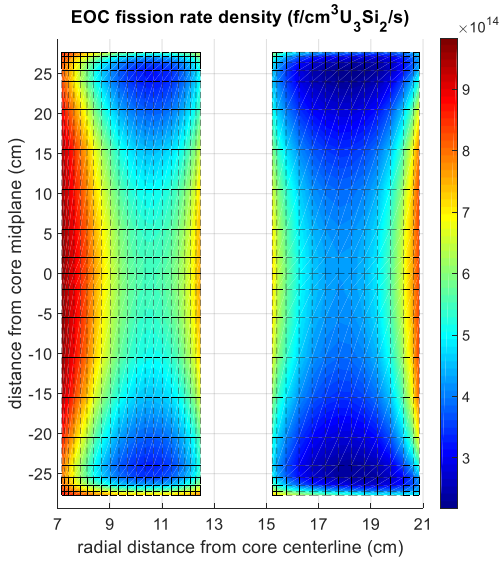

Figure 5. End-of-cycle fission rate density.

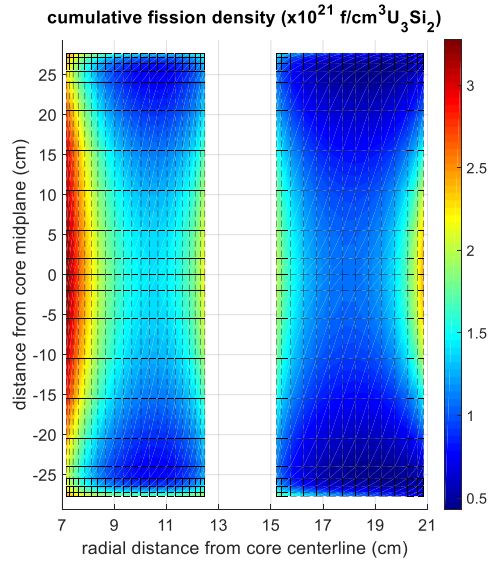

Figure 6. Cumulative fission density.

4. CONFIRMATORY STUDIES

A few additional analyses are provided in this section to confirm that the key metrics discussed previously are adequate to capture HFIR's neutron scattering mission and steady state safety envelope. Additionally, a detailed heat deposition analysis is performed to support the development of a LEU RELAP model.

4.1 Horizontal Beam Tube Flux

Four horizontal beam tubes penetrate the reflector and terminate at instruments in the beam room and guide hall where thermal and cold neutron scattering is performed, respectively. The beginning-of-cycle (BOC) and EOC neutron flux spectra resolved in 100 equal lethargy energy bins was calculated in the hemispherical regions of the three thermal beam tubes (HB-1, -2, and -3) and the moderator vessel of the cold source (HB-4) with MCNP [9]. As shown in Fig. 7, the Optimized design's cold and thermal fluxes are ~2% greater than those for the HEU core while the fast flux (i.e., instrument noise) is increased by ~9%.

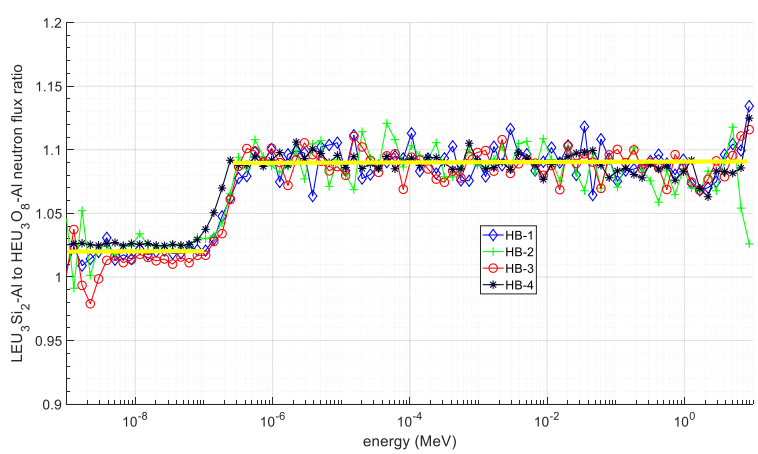

Figure 7. Comparison of end-of-cycle Optimized and HEU horizontal beam (HB) tube fluxes.

4.2 Heat Deposition

A detailed analysis was performed with MCNP to calculate the particle-dependent fission Q-values (Table III) and the heat deposition distribution throughout the reactor (Table IV) for the Optimized design. The equations described in [10] were employed for BOC and EOC evaluations. Three calculations were performed for each time point including a stochastic volume calculation, a standard heat deposition calculation, and a delayed gamma heat deposition calculation. The results are calculated on a fine spatial mesh but are coarsely reported by region. The peak volumetric power is 53.7 kW/cm^3 U_3Si_2 and this peak occurs at BOC in the IFE inner radial core midplane mesh cell. The power distribution flattens out over the course of the cycle and, at EOC, the peak volumetric power of 28.7 kW/cm^3 U_3Si_2 occurs in the IFE inner radial streak just below the core midplane. Refer to [10] for more details regarding the methodology.

Table III. Fission Q-values [MeV/fission] for the Optimized core design.

	fission product + neutron	prompt gamma	capture gamma	beta	delayed gamma	total
beginning-of-cycle	174.77	6.09	6.80	6.50	6.33	200.49
end-of-cycle	175.02	6.38	7.23	6.50	6.33	201.46

Table IV. Power [%] deposited in various regions of the Optimized core design.

	flux trap	inner fuel element	outer fuel element	control element	reflector and beyond
beginning-of-cycle	0.54	38.75	56.77	1.42	2.51
end-of-cycle	0.50	33.13	62.13	0.86	3.39

4.3 Full Power and Flow Safety Limit Calculations

Full power full flow SL calculations for Case 1 (inlet temperature at SL), Case 2 (flux-to-flow at SL), and Case 3 (vessel pressure at SL) are evaluated for the Alternate 2 design, which was selected because it has the least thermal safety margin of the four conceptual designs. As shown in Figs. 8 and 9, the Alternate 2 design's margin to burnout (Fig. 8) and margin to flow excursion at SL conditions (Fig. 9), respectively, are less than those for the HEU core but are greater than their prescribed limits throughout the cycle.

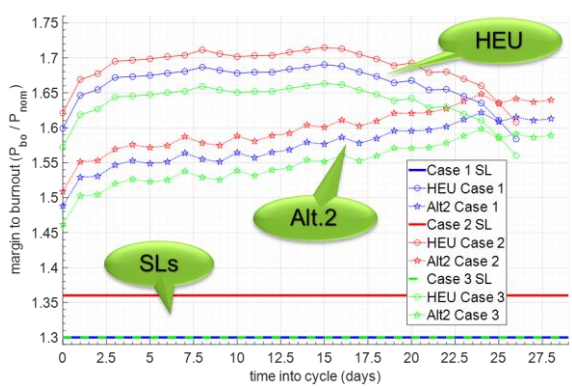

Figure 8. Burnout margin for Alternate 2.

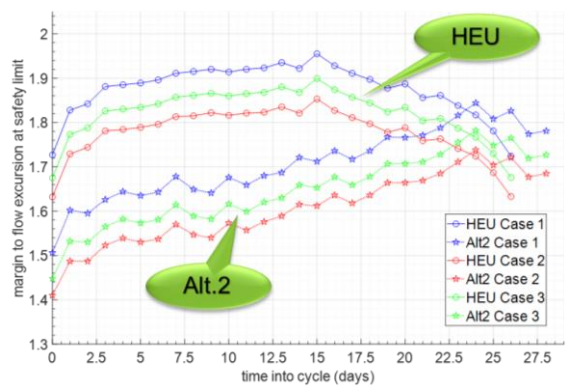

Figure 9. Flow excursion margin for Alternate 2.

5. CONCLUSIONS

Operations with LEU must meet the current HEU core's scientific performance level in a safe, reliable, and affordable manner. Four conceptual fuel element design candidates with various fabrication features were generated for conversion of HFIR with 4.8 gU/cm^3 LEU_3Si_2-Al fuel and have been shown to meet pre-defined performance (e.g., fluxes, ^{252}Cf production, cycle length) and safety (e.g., burnout margin) metrics. The studies documented in this paper do not cover the full extent of the HFIR steady-state or transient safety basis and therefore additional effort is required to ensure safe operations with the subject designs. However, results to date indicate that HFIR could convert with the subject fuel system and meet performance and safety requirements if, among other considerations, fabrication of the specific design features are demonstrated and qualification of the fuel is complete under HFIR-specific conditions. Studies with a higher density U_3Si_2-Al fuel (5.3 gU/cm^3) are being initiated in an attempt to increase performance and safety while simultaneously reducing the fabrication complexity associated with the 4.8 gU/cm^3 U_3Si_2-Al designs. Once the design studies are complete, ORNL will present the designs and metrics to the U.S. conversion program, and a fuel design down selection activity will occur to determine which fuel type (4.8 or 5.3 gU/cm^3) and design(s) should be pursued for subsequent safety/performance analysis, fuel fabrication, and fuel qualification research and development.

6. ACKNOWLEDGMENTS

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