Fuel Conversion Efforts at the High Flux Isotope Reactor – a 2020 Status Update[1]

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INTRODUCTION

The High Flux Isotope Reactor (HFIR) provides one of the world's highest steady-state neutron fluxes in the world for neutron scattering experiments focused on impactful scientific discovery, as well as materials irradiation studies and production of medical, industrial, and research isotopes. Efforts are ongoing to convert HFIR from high-enriched uranium (HEU) to low-enriched uranium (LEU) fuel while maintaining or enhancing current performance and safety margin, thus sustaining HFIR's mission portfolio and reactor-based neutron science leadership. This paper presents a status update on the HFIR fuel conversion efforts.

HIGH FLUX ISOTOPE REACTOR

HFIR is a US Department of Energy (DOE) Office of Science User Facility that is operated at the Oak Ridge National Laboratory (ORNL). The reactor design, construction, and full-power operation activities commenced in 1959, 1961, and 1966, respectively. The unique core design of HFIR consists of a series of concentric regions, including a flux trap target, an inner fuel element (IFE), an outer fuel element (OFE), control elements, and a beryllium reflector. A mockup of the core, which is contained in a pressure vessel and surrounded by light water coolant, is illustrated in Fig. 1.

HFIR is fueled by 10.1 kg of HEU (~9.4 kg ^{235}U) and currently operates at 85 MW for 23 – 26 day cycles. The IFE and OFE are composed of 171 and 369 involute-shaped fuel plates, respectively, which are constructed of U_3O_8-Al dispersion fuel and Al filler, with ^{10}B burnable poison in the IFE filler, encased in Al cladding. The fuel meat is contoured along the arc of the involute (i.e., the width of the pre-curved plates) to reduce radial power peaking. Each fuel plate is 60.96 cm in length and the active fuel zone is in the middle 50.80 cm plate region.

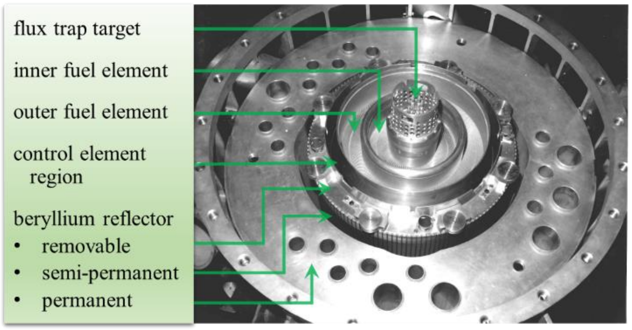

Fig. 1. HFIR reactor core mockup.

FUEL CONVERSION PROGRAM

The US DOE National Nuclear Security Administration's (NNSA) Office of Materials Management and Minimization (M^3) pursues conversion of the remaining five US high-performance research reactors (USHPRR) as part of their mission to minimize and, to the extent possible, eliminate the use of HEU in civilian nuclear applications. The five USHPRRs include HFIR, the Advanced Test Reactor, the National Bureau of Standards Reactor, the Massachusetts Institute of Technology Research Reactor, and the University of Missouri Research Reactor.

HFIR Conversion Strategy

The general LEU project strategy involves development/testing of a LEU fuel product, establishment of commercial LEU fuel manufacturing capability, preparation/approval of safety basis documentation, and LEU conversion execution. The following guiding principles govern LEU fuel design [1]:

1. Fuel should be qualified for use through appropriate irradiation testing and examinations.
2. Fuel should be designed such that it preserves existing reactor performance and safety margin.
3. Fuel should be commercially available at an acceptable cost.
4. Fuel should be acceptable to reactor operators and regulators.

The HFIR LEU conversion strategy seeks to achieve project goals via a five-phase approach, which is illustrated in Fig. 2. HFIR is currently executing Phase 1 of its strategy; a reference safety basis will summarize the work performed in this phase and detail to what extent the existing HFIR Safety Analysis Report (SAR) will be impacted by the transition to the proposed LEU fuel product.

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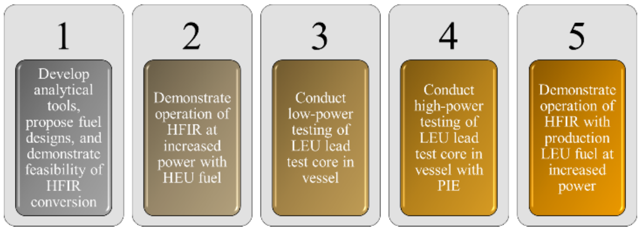

Fig. 2. Phased HFIR conversion strategy.

HFIR Fuel Conversion History

ORNL has been performing engineering evaluations on the conversion of HFIR since 2005. The HFIR conversion design assumptions and criteria were first documented in [2]. Initial HFIR studies explored uranium-molybdenum (U-10Mo) monolithic alloy fuel because of its high uranium density and its anticipated use in all USHPRRs. HFIR's proposed U-10Mo fuel designs [3,4], which meet existing performance metrics and preserve safety margin, consist of radial/lateral and axial contoured fuel profiles, resulting in fabrication complexities not associated with the other USHPRR fuel designs. The HFIR-specific U-10Mo fuel manufacturing R&D process was anticipated to be long and expensive, and it might not result in a process with adequate yields to maintain an economically viable fuel. To mitigate this high project risk, HFIR initiated fuel design studies with LEU uranium-silicide dispersion (U_3Si_2-Al) fuel in 2017 and officially re-baselined to U_3Si_2-Al in 2019.

REACTOR DESIGN AND ANALYSIS ACTIVITIES

Retrofitting a compact, high-power density, HEU fueled core with LEU is a challenging problem to solve and therefore high-fidelity modeling and simulation has been leveraged in recent years to efficiently explore the conversion design space. As discussed in the following subsections, several analysis-related activities are ongoing to generate optimal HFIR LEU designs that meet or exceed HEU 85 MW metrics, which are defined in [5].

Core Design Studies

Recent core design studies [4,6-10] make use of the Shift Monte Carlo-based neutron transport and depletion code [11] and the HFIR Steady State Heat Transfer Code (HSSHTC) [12], which are automated via the Python HFIR Analysis and Measurement Engine (PHAME) [9,10,13,14]. The reference neutronics model for these studies is the HEU representative model that includes the high-fidelity, explicit fuel plate modeling approach [15].

More recent design studies have been performed to optimize the aforementioned LEU U-10Mo designs. ORNL is actively documenting two designs: one with a 50.80 cm long fuel zone and axial contouring and one with a 55.88 cm long fuel zone and no axial contouring. Results to date show that HFIR can maintain its performance level if the U-10Mo designs operate at 95 or 100 MW, depending on the design.

Feasibility studies with 4.8 gU/cm^3-U_3Si_2-Al (i.e., low density) dispersion fuel were performed in [6] and follow-on optimization studies resulted in four designs that meet or exceed performance and safety metrics [7]. Because of the ^{235}U density (0.948 g^{235}U/cm^3) associated with low density U_3Si_2-Al, the active fuel length must be increased to 55.88 cm to maintain HFIR's current cycle length. Uranium-silicide dispersion fuel designs with a higher 5.3 gU/cm^3-U_3Si_2-Al (1.047 g^{235}U/cm^3) density (i.e., high density) have also been studied [10]. The ~10% increase in ^{235}U density slightly relaxes the design space and thus mitigates some fabrication complexities relative to the lower density fuel. All U_3Si_2-Al designs require a power uprate to 95 MW to meet performance metrics. One high density design is proposed that maintains a 50.80 cm long active fuel length, consistent with the current HEU design.

Each of the U_3Si_2-Al designs have different complex fabrication features (e.g., axial contouring, continuous or discontinuous OFE filler regions, additional Gd poison in IFE filler, centered symmetric or off-centered asymmetric fuel zones), which must be evaluated during the fabrication R&D process to help in design down-selection. Detailed technical reports are actively being written to document the design characteristics and performance parameters for these low density [8] and high density [9] U_3Si_2-Al fuel designs. These reports will serve as references for the fuel fabrication and qualification efforts.

RELAP Model Development

Full power and flow safety limit calculations are performed with HSSHTC in the core design studies to assess the steady-state thermal safety margins; however, these calculations do not envelope the entire HFIR SAR. Transient/accident analyses are required to further bound the HFIR operations envelope and help declare a specific LEU design acceptable. The RELAP5 1-D transient code [16] is used for HFIR accident analyses, such as those involving coolant channel flow blockages, loss of coolant accidents (LOCA), loss of offsite power (LOOP) accidents, and control cylinder ejection (CCE) transients.

Current efforts are primarily focused on establishing a new HEU baseline model that makes use of the neutronics data from [15] and [17] and updating from RELAP5/Mod2.5 to Mod3.3. The updated decay heat curves, spatially dependent heat deposition results, fuel peaking factors, and hot channel coolant gap thickness are being incorporated. Concurrently, a LEU U_3Si_2-Al model is being developed based on the updated HEU model by incorporating an U_3Si_2-Al design geometry, preliminary fuel meat properties, and neutronics data from [7].

Bounding events that challenge the fuel thermal safety margin will be run with the HEU and LEU U_3Si_2-Al models once they are complete for safety margin comparison purposes. The scenarios to be analyzed include, at a minimum, the LOOP, small break LOCA, CCE, and target region optimum void events.

COMSOL Verification and Validation

The HSSHTC thermal-hydraulic code used for LEU core design studies and HEU safety basis calculations (e.g., SAR implementation) is a conservative 2-D R-Z channel code. HSSHTC conservatively implements physical models/correlations and makes use of 26 multiplicative factors to capture uncertainties in reactor process conditions, fuel manufacturing features, and analysis correlations. Due to inherent conservatisms and limitations of the HSSHTC approach, nominal conditions (e.g., temperatures) are difficult to assess and safety margins are more conservative than currently desired.

To take advantage of modern-day tools and computers, the COMSOL Multiphysics finite element-based tool [18] is being leveraged for high-fidelity thermal-hydraulic evaluations of HFIR LEU fuel designs [19]. Employment of COMSOL with a high-fidelity plate model and coupled 3-D physics allows for nominal, best-estimate calculations. Safety basis calculations can also be performed by incorporating the previously discussed uncertainties, resulting in increased safety margins relative to the HSSHTC approach.

COMSOL verification and validation (V&V) efforts are ongoing to provide high-confidence that it can simulate the physics required for HFIR fuel plate thermal-structural-hydraulic analyses. This is an essential step for qualifying COMSOL for regulatory acceptance and safety basis use. Key phenomena for these efforts include boundary physics (e.g., system state conditions, oxide layer, plate attachment, fuel swelling), underlying physics (e.g., plate heat transfer, channel fluid dynamics, plate structural mechanics), and coupled physics (e.g., thermal-fluid, thermal-structure, fluid-structure). Examples of previous HFIR-related COMSOL V&V studies are [20] and [21]. Documentation of the comprehensive V&V report is expected in 2020.

CONVERSION PILLAR COLLABORATION

ORNL collaborates with the M^3 Reactor Conversion, Fuel Fabrication, Fuel Qualification, and Cross Cutting Pillars to integrate the conversion work scope.

Fuel Fabrication Efforts

The LEU U_3Si_2-Al dispersion fuel fabrication process is expected to be similar to the HEU process; thus, it is more suitable than the previously proposed U-10Mo monolithic fuel for HFIR's radial contouring requirements. The fuel fabrication process is being established in phases, starting with plate fabrication and ending with the fabrication of full inner and outer fuel elements [1]. This will ensure that that feedback is integrated into the development of the HFIR LEU uranium-silicide dispersion fuel manufacturing process. Process studies evaluating the impact of manufacturing parameter (e.g., uranium loading, powder size distributions) variance on product quality and manufacturing cost will further optimize the fabrication process. Feedback from fuel fabrication development efforts will support down-selecting of proposed low- and high-density U_3Si_2-Al designs.

Fuel Qualification Efforts

Fuel qualification efforts are expanding the existing qualification envelope associated with LEU U_3Si_2-Al fuel documented in NUREG-1313 [22] in order to include the higher fission rate densities exhibited at HFIR. Planned irradiation experiments will be progressive and include FUTURE-HFIR, which will demonstrate U_3Si_2-Al survivability at HFIR conditions via flat fuel experiments; FSP-HFIR, which will produce irradiation performance data via full-sized plate specimens; and DDE-HFIR, which will further compile irradiation performance data via a partial "design demonstration element". The sum of fuel qualification activities will provide a statistical basis to support safety analyses. A summary of fuels testing and examination will be compiled in a fuel qualification report for submittal to the HFIR regulator.

Cross Cutting Efforts

Cross-cutting activities include resolution of fuel storage and shipping challenges associated with LEU fuel. Differences between the HEU and LEU cores (e.g., weight and isotopic inventory) may necessitate changes to existing storage strategies and areas. A new shipping package will be developed to transport fresh LEU fuel to HFIR. Spent LEU fuel will continue to be shipped from HFIR in the GE-2000 cask, though design modifications and revised safety analyses may be required to support LEU conversion.

SUMMARY AND CONCLUSIONS

Engineering evaluations on the conversion of HFIR to LEU fuel continue to progress at ORNL. Enhancements to core design neutronic and thermal-hydraulic methods have resulted in optimal performing U-10Mo and U_3Si_2-Al designs, given the conversion assumptions and constraints. Efforts to develop new and consistent HEU and LEU U_3Si_2-Al RELAP models are ongoing. Accident analyses performed with these models are required to determine if proposed fuel designs are acceptable. COMSOL V&V activities are also ongoing in attempt to qualify the code for safety basis fuel-related analyses and to increase the calculated thermal safety margins.

In collaboration with the M^3 program and pillars, efforts are ongoing to 1) develop a reliable manufacturing process for HFIR U_3Si_2-Al fuel designs, 2) qualify U_3Si_2-Al to HFIR-like irradiation conditions, and 3) resolve storage and shipping challenges associated with LEU.

All conversion activities are being performed in a manner to ensure HFIR sustains its mission portfolio and reactor-based neutron science leadership into the future.

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