Fuel Conversion Efforts at the High Flux Isotope Reactor – a 2023 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.

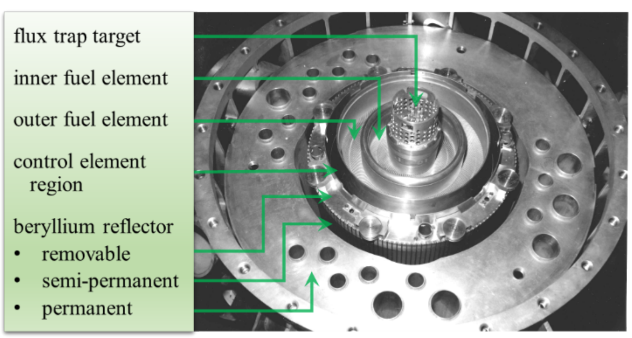

Fig. 1. HFIR reactor core mockup.

FUEL CONVERSION PROGRAM

The US DOE National Nuclear Security Administration's (NNSA) Office of Materials Management and Minimization (M^3) mission is to convert, remove, and dispose of vulnerable nuclear material located at civilian sites worldwide. As part of its mission, M3's Office of Conversion works around the world to convert research reactors and isotope production facilities to non-weapon-usable nuclear material both domestically and abroad. The five US high-performance research reactors (USHPRR) 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 suitable for each reactor such that it meets the operating and performance requirements of the existing reactor licenses or authorization basis including both nuclear capability 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.

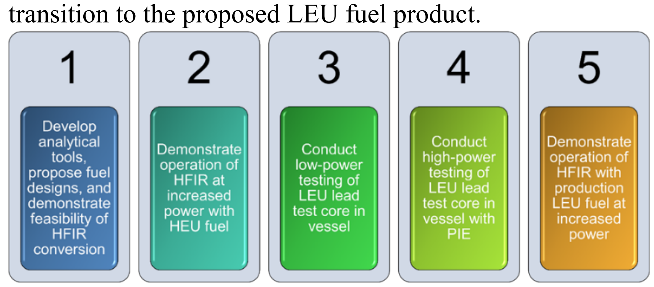

Fig. 2. The Five phases of HFIR conversion strategy.

HFIR Fuel Conversion History

ORNL has been performing engineering evaluations on the conversion of HFIR since 2005, with HFIR conversion design assumptions and criteria 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. 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. Silicide designs with various fuel fabrication features and fuel densities are documented by Bae et al. [3,4] and Betzler et al. [5].

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 [6].

Core Design Studies

Updates to the fuel design, depletion, and experiment performance are discussed in detail in [7] and summarized herein.

Core design studies make use of an objected-oriented Python framework called the Python HFIR Analysis and Measurement Engine (PHAME) [8]. The set of data obtained from all the calculations are organized and transferred to the HFIR LEU RELAP team for transient safety calculations.

A thorough set of fuel cycle depletion validation and code-to-code verification studies were completed [9]. HEU Fuel cycles were simulated at 85, 95, and 100 MW operations, as well as LEU fuel cycles operating with 95 MW with U_3Si_2-Al and U-10Mo. The results show excellent agreement between all three code depletion tools: HFIRCON, Shift, and VESTA.

Fuel inhomogeneity refers to the deviation between the as-built distribution and the nominal distribution. Analyses were performed to determine the uncertainty caused by LEU fuel inhomogeneity [to be documented in 10]. Preliminary studies demonstrate that performance metrics were reduced by less than 0.5% due to fuel inhomogeneity and could be considered negligible.

Nuclear data uncertainty was quantified in [11]. The developed workflow comprised Shift to calculate sensitivity coefficients to generate k_{eff} uncertainties due to cross sections. The sensitivity analyses revealed that ^{1}H, ^{10}B, ^{16}O, ^{27}Al, ^{235}U, and ^{238}U reactions are the greatest sensitivity contributors. The similarity assessment indicated that ~200 of the 3,690 considered critical experiments could be leveraged for the HFIR LEU validation efforts.

HFIR's experimental abilities is of primary concern to LEU conversion. To understand the impact of changing fuel enrichment, a series of analyses were performed. Neutron scattering comparisons were characterized using MCNP in [12], a study investigated the impacts of nuclear data and conversion on ^{252}Cf production [13] and, results documented in [14] further indicate that conversion will not impact HFIR's ability to produce other key isotopes such as ^{63}Ni, ^{75}Se, ^{89}Sr, ^{117m}Sn, ^{133}Ba, ^{177}Lu, ^{188}W, ^{227}Ac, and ^{229}Th. Additionally, [14] indicates an increase in HFIR's operational power from 85 MW to 95 MW would increase experiment displacements per atom.

RELAP Studies

The RELAP5 1-D transient code [15] 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.

Recent efforts involve methodology developed to assess the nuclear performance of LEU fuel designs with respect to selected accident events from the HFIR SAR, in order to inform future down-selection of LEU U_3Si_2-Al designs. Methods are generated and implemented to update fuel material properties, core heat deposition rates (or power distributions), post-shutdown decay heat tables, and reactor kinetics parameters and feedbacks.

These methods are applied to two LEU designs: the optimized low density (4.8 gU/cm^3) U_3Si_2-Al design [16] and the optimized high density (5.3 gU/cm^3) U_3Si_2-Al design [17]. Five accidents from the HFIR SAR are selected: three primary coolant system accidents with bounding thermal safety performance and two reactivity-initiated accidents with bounding power excursion performance.

Accident analysis results for the LEU optimized low density U_3Si_2-Al design indicate increased safety margins in reactivity-initiated accidents due to increased negative fuel temperature (Doppler Broadening) feedback and a decrease in thermal safety margins due to increased reactor power and fuel power distribution (particularly in the inner fuel element at the beginning of the HFIR operating cycle) [16]. The LEU optimized high density U_3Si_2-Al design show similar results [17].

COMSOL Studies

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 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). An evaluation of popular turbulence models ($k-\epsilon$ and $k-\omega$,) using three commercial codes—ANSYS CFX, COMSOL Multiphysics, and Simcenter STAR-CCM+—with the use of wall functions for heat transfer calculations relevant to involute plate reactor designs was conducted in [20].

Additional thermal-hydraulic work includes direct numerical simulation (DNS) of the entire spanwise HFIR channel [21]. A turbulence database has been developed and will be used to inform low order models like Reynolds-Average Navier-Stokes (RANS) and the 1D HSSHTC. DNS method allows for further HFIR flow exploration like heat-transfer, entrance effects of longer plates, and more.

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-selection 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. The plan to qualify new fuel for HFIR has been developed. 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. New shipping package internals 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_3Si_2-Al designs, given the conversion assumptions and constraints. Development of consistent HEU and LEU U_3Si_2-Al RELAP models is complete and transient analyses performed with these models determined the proposed fuel designs are acceptable. Additional design iterations are required once the fuel fabrication R&D data is available. 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) fabricate U_3Si_2-Al fuel, 3) qualify U_3Si_2-Al to HFIR-like irradiation conditions, and 4) 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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