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Changing the World's Energy Future

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ABSTRACT

The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) is one of five high power research reactors will be converted from using highly enriched uranium (HEU) fuel to using low-enriched uranium (LEU) fuel by the Office of Material Management and Minimization (M^3) Program, Office of Conversion. This effort stems from the primary objective within the U.S. Department of Energy (DOE) National Nuclear Security Administration (NNSA) to achieve permanent threat reduction by minimizing, and when possible, eliminating weapon-usable nuclear material around the world. Under M^3's Office of Conversion, the U.S. High Performance Research Reactor (USHPRR) Project is pursuing fuel qualification and licensing of the high-performance reactors to operate with LEU fuels. All high-performance reactors except HFIR will be converted to LEU monolithic uranium-molybdenum alloy fuel. HFIR will be evaluated for conversion to LEU using a uranium silicide fuel, namely, U_3Si_2-Al dispersion fuel.

The mission of the USHPRR Project is to develop the technology needed to reduce, and eventually eliminate, worldwide use of HEU in civilian applications. The goal is to develop the technical means needed to use low enriched uranium (LEU) instead of HEU fuel in research and test reactors without significant penalties in performance, economics, or safety of the reactors. The USHPRR Project has four major elements, called pillars: Fuel Qualification (FQ) managed at Idaho National Laboratory (INL), Fuel Fabrication (FF) managed at Pacific Northwest National Laboratory (PNNL), Reactor Conversion (RC) managed at Argonne National Laboratory (Argonne), and Cross-Cutting (CC) managed at Savannah River National Laboratory (SRNL). FQ is responsible for the qualification of the fuel type. RC is responsible for supporting reactor conversion analysis and overseeing licensing submittals leading to conversions of domestic reactors to LEU fuel. For the FQ effort, FQ (INL) worked in collaboration with RC (Argonne) and ORNL to develop the plan for the uranium silicide fuel qualification for HFIR.

The resulting HFIR Fuel Qualification Plan provides the general approach for the USHPRR team to move the selected uranium silicide fuel design for HFIR conversion through qualification. Authorization and use in HFIR will be approved through the DOE's Office of Science. Uranium silicide fuel was previously qualified in NUREG-1313 at an approximate maximum heat flux of 1.4 MW/m^2 and a maximum fuel section temperature of about 130°C. In addition to the different regulator processes utilized by DOE, these upper limits will be exceeded in HFIR; therefore, further testing will be necessary to ensure the fuel can meet HFIR qualification requirements. The HFIR fuel loading may exceed 4.8 g U/cm^3 which was determined in the NUREG-1313 safety evaluation to be acceptable for use in non-power NRC-licensed reactors provided there exist no other safety considerations. In addition, the uranium silicide fuel will need to be qualified in a HFIR-specific design. This plan includes the currently available information from the USHPRR Project Functions and Requirements document and expands these requirements to ensure that planned tests have traceable results providing evidence that the requirements have been met. Data collection methods are discussed as well as the process to show that the requirements have been met. This document is designed to provide a pathway for researchers to obtain data necessary and at the appropriate quality level for HFIR fuel qualification.

INTRODUCTION

The Office of Material Management and Minimization (M^3) Program's primary objective within the U.S. Department of Energy/National Nuclear Security Administration is to achieve permanent threat reduction by minimizing and when possible, eliminating weapon-usable nuclear material around the world. As part of this effort to reach this objective, the U.S. High Performance Research Reactor (USHPRR) Project is pursuing a fuel qualification and licensing to convert high-performance research reactors in the United States from using highly enriched uranium (HEU) fuel to using low-enriched uranium (LEU) fuel. The USHPRR Project will qualify high-density LEU fuels, commercialize the fuel fabrication processes and inspection methods, and support the codes and methods used in analyzing reactor safety in support of licensing, or authorization for use. The project also will procure the initial conversion cores to ensure successful conversion.

Five high power reactors are being converted; however, only the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) is being evaluated for conversion to LEU using a uranium silicide fuel—namely, U_3Si_2-Al dispersion fuel. The LEU silicide fuel was found acceptable for use through NUREG-1313, "Safety Evaluation Report Related to the Evaluation of Low-Enriched Uranium Silicide Aluminum Dispersion Fuel for Use in Non-Power Reactors" [1]. The U.S. Nuclear Regulatory Commission (NRC) does not have a role in the fuel qualification for HFIR since this reactor is regulated by US DOE Office of Science (DOE-SC). However, the same general processes are being followed as those for NRC-regulated reactors. Two qualification efforts for LEU research reactor fuels provide historical precedence and a general guide for qualification of the proposed fuel.

- NUREG-1313 [1], the evaluation of the safety of approved LEU silicide fuel now in use in many low power research reactors
- NUREG-1282 [2], the evaluation of the safety of approved Training, Research, Isotopes, General Atomics (TRIGA®) U-Zr hydride fuel.

Each fuel type is used in several research reactors. NUREG-1313 [1] is the most applicable for HFIR conversion because it provides a model to qualify uranium silicide dispersion fuel.

To determine if LEU silicide fuel is a viable option for HFIR, additional testing is necessary to qualify this fuel for use in HFIR because it was not tested at operating conditions representative of HFIR. The USHPRR Project is divided into four technical areas to effectively manage the work scope. The Fuel Qualification (FQ), Fuel Fabrication (FF), Reactor Conversion (RC), and Cross Cutting (CC) pillars work together to provide integrated solutions that meet all the conversion requirements. The objectives for LEU fuel-system design are:

- Fuel should be qualified for use through appropriate irradiation testing and examinations
- Fuel should be suitable for the reactor such that its performance is comparable to the operating and performance requirements of the existing reactor licenses or authorization bases including both nuclear capability and safety margin
- Fuel should be available from a commercial fabricator
- Fuel should be acceptable to the reactor operators and the reactor regulators

The HFIR Fuel Qualification Plan is one of the first steps toward these objectives to define the activities required to qualify high density, LEU silicide fuel for HFIR conversion. The plan expands on requirements from the USHPRR Project Functions and Requirements Document (F&RD) [3] and data collection methods to ensure planned tests have traceable results.

HFIR

The HFIR is a DOE-SC User Facility that is operated at the ORNL. It was completed in 1965 and operates at 85 MW. HFIR is a versatile research reactor that provides one of the highest steady-state neutron fluxes of any reactor in the world for neutron scattering experiments focused on fundamental and applied research on the structure and dynamics of matter, as well as materials irradiation studies and production of medical, industrial, and research isotopes. The HFIR core is cylindrical with a center hole that forms the flux trap for irradiation targets. The fuel region of the core consists of two concentric fuel elements: the inner element contains 171 fuel plates and the outer element contains 369 fuel plates. The fuel plates are involute to create water channels between the plates the same thickness as a plate. Additionally, the fuel meat in each plate is contoured radially and axially. Fig. 1 depicts the regions of a fuel element [4].

ORNL is funded by the US DOE National Nuclear Security Administration (NNSA)'s Office of Material Management and Minimization (M3) to perform HFIR conversion activities such as design studies presented in [5, 6] USHPRRs, including HFIR, the Advanced Test Reactor, the National Institute of Standards and Technology Research Reactor, the Massachusetts Institute of Technology Research Reactor, and the University of Missouri Research Reactor, are providing research on potential LEU alternatives in support of NNSA's nonproliferation mission.

Initial studies to convert HFIR from its current HEU dispersion fuel to LEU fuel explored uranium-molybdenum (U-10Mo) monolithic alloy fuel because of its high uranium density [7]. HFIR's proposed U-10Mo fuel design [7] consisted of radial and axial contoured fuel profiles. 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 [8].

URANIUM SILICIDE FUEL WITH BURNABLE ABSORBERS

Uranium silicide fuel is currently the highest density LEU fuel qualified and licensed for use in U.S. research and test reactors at up to 0.95 g U-235/cm^3 (4.8 gU/cm^3 at an enrichment of 19.75 wt. % U-235). The proposed design for the HFIR fuel system (Fig. 2) is uranium silicide fuel with and without burnable absorbers (boron is anticipated). The burnable absorber is separate from the fuel in the inner fuel element

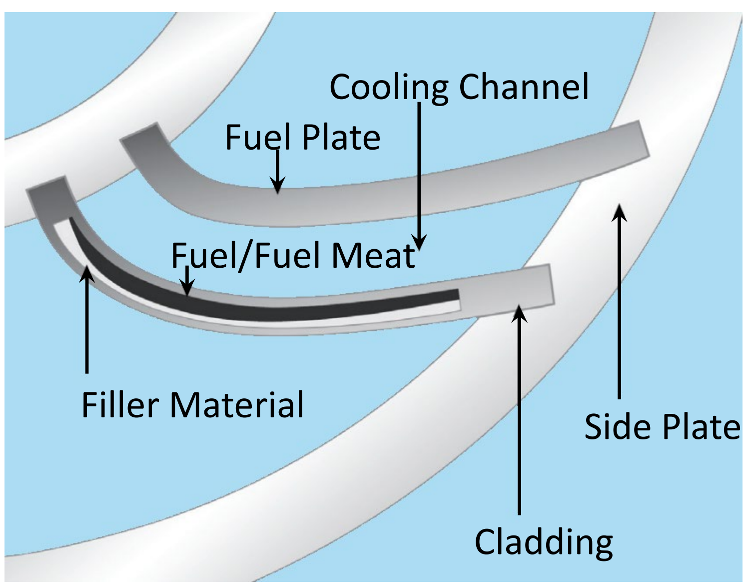

Fig. 1 Depiction of Fuel Element Regions of Current HFIR Highly Enriched Uranium Fuel Plate.

(IFE). No burnable absorber is associated with the outer fuel element (OFE). The high-density LEU fuel consists of uranium silicide dispersed in a matrix of aluminum (U_3Si_2-Al) with a target fuel loading within 4.8 gU/cm^3 to 5.6 gU/cm^3. NUREG-1313 documents information for qualification of a uranium silicide dispersion fuel with a fuel loading of 4.8 gU/cm^3 at a maximum heat flux of 1.4 MW/m^2 and a maximum fuel-section temperature of about 130°C [1]. These approved upper bounds for fuel operating conditions and fuel loading will be exceeded in HFIR; therefore, additional testing is necessary to ensure the fuel can meet HFIR fuel qualification requirements. In addition, the uranium silicide fuel will need to be qualified in the HFIR-specific fuel design.

USHPRR PROJECT LEU FUEL QUALIFICATION STRATEGY

The USHPRR Project's fuel qualification strategy formulates requirements to provide the framework for the fuel-qualification plan. Following the fuel-qualification process (Fig. 3) and satisfying these requirements leads to fuel qualification.

Successful execution of the fuel qualification plan relies on producing fuel tests in a manner representative of the commercially viable processes that meet conversion requirements. Commercial viability implies acceptable cost and uranium-resource use. Data and analyses generated during execution of the experiment test plans will be documented and submitted to the regulator. Reactor-specific fuel-element performance will be confirmed through irradiation tests including a design demonstration element (DDE) and the lead test core (LTC) testing and then a request for reactor conversion. The primary deliverable is a qualified U_3Si_2-Al dispersion fuel design for HFIR.

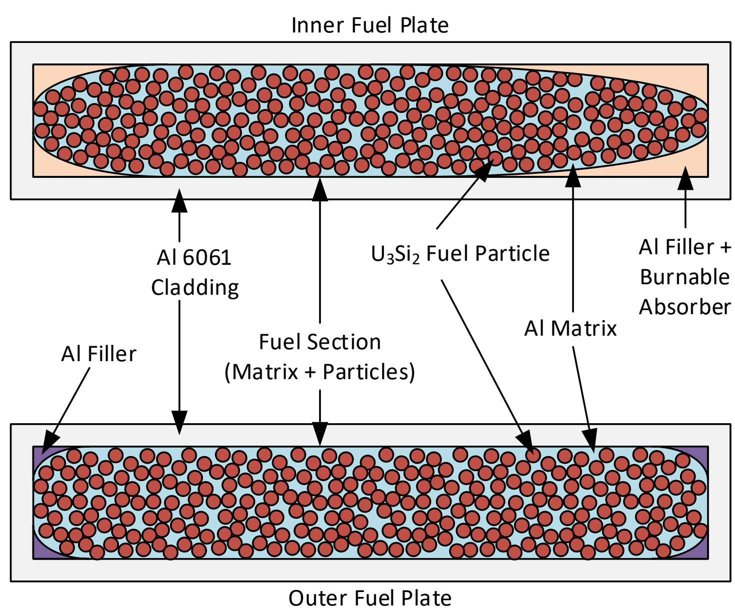

Fig. 2. U_3Si_2-Al Inner and Outer Fuel Plate Schematic Representation

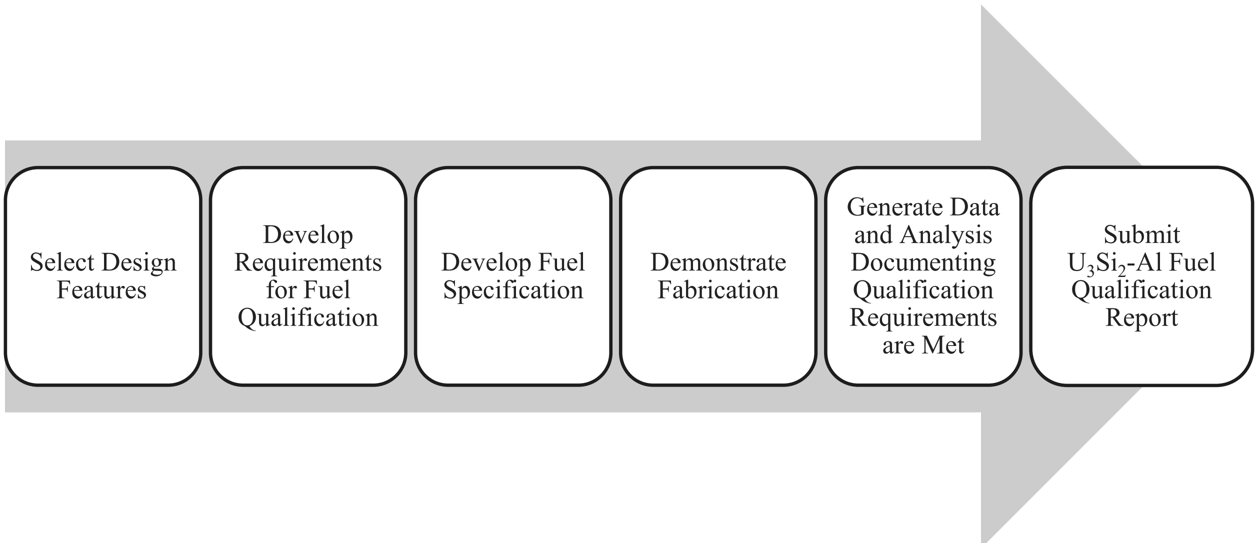

Fig. 3. Schematic showing steps for HFIR fuel qualification.

The pillars for USHPRR work together to ensure that their respective tasks occur. Each pillar could introduce requirements that can cause the other pillars to alter their planning and activities, which requires that the pillars be integrated, jointly developing requirements, and sharing test results (Fig. 4). Key documents include:

- The Fuel Fabrication Plan created by FF about the commercial-scale fabrication process for manufacturing the LEU silicide-aluminum dispersion fuel for HFIR.
- The FQ test planning and execution to collect data about and document fuel performance.
- The HFIR conversion analysis documents the conversion strategy including minimal impact on the reactor operating and experiment performance, without major modifications to the reactor structure, and little increase to operating cost of the reactor.
- The testing envelope describes requirements needed to ensure acceptable fuel performance behavior of both the IFE and OFE type plates and cores during irradiation.
- The HFIR Fuel Qualification Report will document data and recommendations for using uranium-silicide fuel at HFIR and will form the basis for the DOE review.
- A HFIR safety basis supplement (SBS) will be developed and submitted to DOE for approval.
- The updated HFIR SAR will reflect the process, hazards, and controls to protect the public, workers, and the environment in accordance with 10 CFR 830 Subpart B [9].

DATA QUALITY PLANNING AND QUALITY ASSURANCE

Formal data qualification is required for fuel-qualification data using the NQA-1 system to ensure quality. NQA-1, Part I, and applicable sections of Part II ensure uniform and more-easily enforceable standards for fuel-qualification data. These requirements apply for research/data that will be included in the HFIR fuel-qualification report or used to support the qualification of fuel. NQA-1, Part IV, Subpart 4.2, applies to scoping activities and data collected from scoping activities.

REQUIREMENTS

During the project, requirements will be formally traceable and flowed down from implementing documents beginning with the USHPRR Project Functions and Requirements [3] through execution documents and verification through documentation of objective evidence that all requirements have been met.

The plan ensures adherence to high-level requirements demonstrated through testing and analysis. Experiment execution, characterization, and post-irradiation examination (PIE) plans implement tasks and lower-level requirements. Activity-specific test plans provide the lowest level of requirements, including requirements for acceptance of test data and exit criteria.

HFIR requires a review of the fuel by DOE-SC followed by subsequent changes to the SAR. To be approved for reactor conversion, the U_3Si_2-Al fuel must meet the requirements of maintaining mechanical integrity and geometric stability and demonstrating stable and predictable behavior. The LEU fuel and cladding must perform safely under all current and relevant safety-basis conditions considered during the life of the fuel used at the HFIR reactor. HFIR operations requested the properties listed in TABLE I to meet the requirements necessary for SAR updates and reactor conversion.

Additional detail and specific lower-level requirements are defined here over the USHPRR Project set of functions and requirements. All requirements under F 1.0 (Develop and Qualify and Establish Capacity to Build LEU Fuel) apply directly to this fuel-qualification plan. Some requirements under F 2.2 (Fuel Fabrication) and F 2.3 (Regulatory Review) apply and are included in this plan.

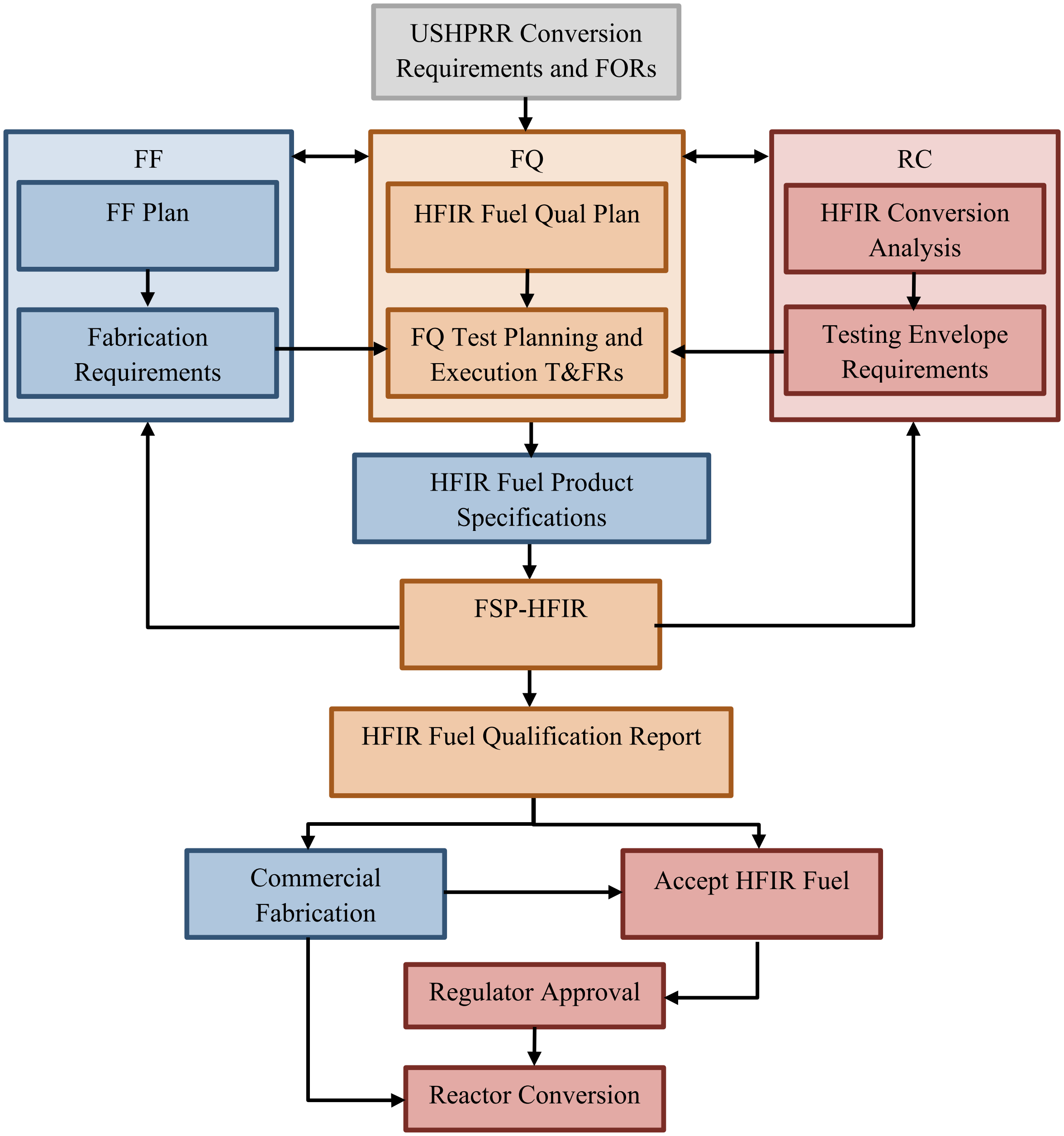

Fig. 4. The HFIR fuel qualification and reactor conversion process for HFIR conversion.

TABLE I. Fuel and cladding properties requested by HFIR to support safety basis analyses.

Fuel State	Required for SAR for Prevention	Analysis or Calculations	Properties
Unirradiated			
	Fuel damage, melt	Thermal	Latent Heat of Fusion Liquid Specific Heat Liquid Density Liquid Thermal Conductivity Boiling Point of U_3Si_2-Al fuel Heat of reaction U_3Si_2-Al Molten mixture with water Melting Temperature
	Fuel damage, melt	Thermal Structural Manufacturing related	Densities of the fuel section and filler Fuel section thickness uncertainty Fuel section length and width uncertainties Fuel Plate Thickness Uncertainty
	Fission product release	Thermal Structural Manufacturing related	Min-clad thickness Fuel Enrichment Uncertainty Fuel Homogeneity Uncertainty Fuel U-235 Plate Loading Uncertainty Fuel Grading Uncertainty Across Plate Minimum Detectable Non-Bond Area Fuel bond integrity for U_3Si_2-Al
	Fission product release	Structural Manufacturing related	Clad Bond Integrity for end and edge regions
Unirradiated End-of-cycle (EOC) irradiated			
	Fuel damage, melt	Thermal	Enthalpy threshold for fuel fragmentation[a]
Unirradiated Irradiated. 0 to end-of-life (EOL), maximum intervals of 1E21 f/cm^3 Temperature dependence from 50-350°C, in maximum intervals of 100°C (both unirradiated and irradiated)			
	Fission-product release	Mechanical	U_3Si_2-Al Yield Stress U_3Si_2-Al Ultimate Tensile Strength U_3Si_2-Al Young's Modulus U_3Si_2-Al Shear Modulus or Alternate Poisson's ratio
	Fuel damage, melt	Thermal	Specific Heat Capacities of the fuel section and the filler Thermal Conductivities of the fuel section and filler
	Fuel damage, melt	Thermal Structural Manufacturing related	Coefficients of Linear Thermal Expansion of the fuel section and filler

TABLE I. Fuel and cladding properties requested by HFIR to support safety basis analyses. (continued)

Fuel State	Required for SAR for Prevention	Analysis or Calculations	Properties
Irradiated, 0-EOL, max intervals of 1E21 f/cm^3 Temperature <550°C, in 25°C increments			
	Fission-product release	Thermal	U_3Si_2-Al blister temperature vs. burnup
EOC irradiated (Testing required unless analysis concludes that 100% release fraction meets regulatory requirements.)			
	Fission-product release	Thermal	Fission Product and Actinide Release Fraction from Fuel to Coolant
Irradiated, 0-EOL, multiple measurements			
	Fission-product release	Thermal Structural	Fuel Plate Swelling

[a] Analysis or testing must be completed to address the regulatory requirement in NRC RG 1.70 [10].

Requirements for U_3Si_2-Al Fuel Qualification

Applicable high-level USHPRR functions and requirements are for HFIR acceptance of the U_3Si_2-Al fuel design. FQ Pillar has determined the key actions necessary to demonstrate that all functions are satisfied and meet the requirements. Some requirements and actions are listed here.

- Convert USHPRRs to LEU
- Develop, qualify, and establish capacity to build LEU fuel
- Maintain Mechanical Integrity - no breach in the cladding that releases fission products occurs under normal fuel operating conditions or transients.
- Maintain Geometric Stability - ensure the unrestricted passage of reactor coolant, as required by fuel element design, is maintained to prevent overheating and hot spots in the fuel, and data shall be documented for material properties that affect geometric stability (TABLE II).
- Stable and Predictable Behavior - ensures the fuel provides consistent, repeatable behavior within a range of fabrication tolerances specified in fuel-element design documentation, over the required number of reactor cycles, and over a range of power and fission densities expected during normal operation and anticipated transients.
- Establish Reactor-Mission Performance Envelope - ensure the fuel system operating envelope is established so that testing within the established envelope verifies performance equivalent to current HEU fuels.
- Test to Verify Design Requirements Have Been Met - verification of fuel behavior at the scale of integral fuel elements.

TABLE II. Material properties for the U_3Si_2-Al fuel system

Component	**Property (U_3Si_2-Al)**
Fuel Section	Melting temperature Corrosion behavior Swelling behavior Mechanical properties (strength, hardness, elastic modulus, Poisson's ratio, irradiation enhanced creep rate) Thermal properties (heat capacity, thermal conductivity, thermal expansion coefficient) Porosity
Fuel Section Matrix Material	Melting temperature Corrosion behavior Mechanical properties (strength, hardness, elastic modulus, Poisson's ratio, irradiation enhanced creep rate) Thermal properties (heat capacity, thermal conductivity, thermal expansion coefficient)
Cladding	Melting temperature Surface oxidation rate Mechanical properties (strength, elastic modulus, Poisson's ratio, irradiation hardening) Thermal properties (heat capacity, thermal conductivity, thermal expansion coefficient)
Filler Section with and without Burnable Absorber	Information on gas formation Mechanical properties (strength, hardness, elastic modulus, Poisson's ratio) Thermal properties (heat capacity, thermal conductivity, thermal expansion coefficient)
Integrated Fuel System	Blister threshold temperature Reaction enthalpy during overheating event Fuel-to-cladding bond integrity (such as bond strength, evidence of metallurgical bonding) Cladding-to-cladding bond integrity (such as bond strength, evidence of metallurgical bonding)

Requirements for Post-Qualification Fuel Acceptance

Upon meeting the previously listed requirements, a HFIR U_3Si_2-Al fuel-qualification report will be submitted to the regulator. After acceptance, the FQ pillar will continue to provide data and analysis to facilitate authorization for use of the U_3Si_2-Al fuel for HFIR. Additional requirements must be met for fabrication/manufacturing that may impact fuel qualification. These requirements are listed below.

- Fabrication process specifications and acceptance criteria for prototypic fuel elements shall be based on the results of fuel characterization and manufacturing evaluations.

- Fuel elements for a specific reactor shall be fabricated and tested to support the development of the reactor-specific conversion safety analysis.

- Acceptance criteria used for manufacturing fuel elements shall be based on the U_3Si_2-Al fuel qualification, reactor-specific conversion safety analysis, and manufacturing evaluations.

- The DOE reactor operator, with USHPRR project support, shall provide additional safety-analysis data from demonstration tests to the DOE at a time to allow sufficient review prior to the end of the DOE's review period.

FUEL DEVELOPMENT AND QUALIFICATION DATA

In general, research-reactor fuel systems are not routinely tested to failure because of issues associated with release of fission products to the test reactor's primary coolant system. Therefore, the testing approach is to determine fuel operating requirements and test fuels under conditions providing sufficient margin to guarantee that in-service failures will not occur. Irradiation tests are designed to stop short of fuel failure and rely heavily on post-irradiation investigation for identification of failure precursors to understand failure modes in the fuel system (i.e., within the fuel core and at interaction layer and cladding interfaces). Additional testing to understand fuel-failure mechanisms has been conducted historically out of the reactor.

To gather the data needed to demonstrate that the requirements are met, well-defined test specimens are fabricated, characterized, irradiated in a test reactor, and examined to quantify irradiation effects. Unirradiated components and fuels are examined to quantify the effects of fabrication variables on fuel performance and to gather basic data on component and fuel properties in the absence of a radiation field. The tests and analyses will be conducted on test articles, and irradiation tests will be conducted.

In-Canal Examinations

In-canal examinations assess the fuel test for any anomalies or damage that may have occurred before or during irradiation. Photographs or measurements may be taken of experiment elements or plates. All fuel test plates are conducted to verify that the fuel meets fuel performance requirements. Activities include channel-gap width measurement, ultrasonic scanning, and visual examination to determine mechanical integrity, dimensional stability, the absence of debonded or delaminated, and fuel-plate damage.

Post-Irradiation Examination

PIE is conducted to verify that the fuel meets fuel performance requirements: mechanical integrity, geometric stability, and stable and predictable behavior. PIE quantifies fuel behavior such as oxidation, swelling and creep rate, warping, fission-product transport, blister-threshold temperature, and fission product release. Non-destructive PIE is typically performed on all fuel plates while destructive techniques are typically performed on approximately 50% of the irradiated plates to provide statistical confidence in the data. PIE includes:

Non-destructive examination includes radiographic inspection of fuel elements and fuel plates, oxide-thickness measurements, local plate-thickness measurements, and plate-immersion density measurements. These techniques assess the mechanical integrity and geometric stability of the fuel plates. Changes to fuel thickness result in changes to channel-gap width that can affect plate coolability. Measurements confirm the predictability of oxide growth and confirm fuel-surface temperatures were in the range expected during irradiation.

Destructive examination includes gamma scanning, analytical chemistry, microstructural examination with optical metallography and electron microscopy. Quantitatively measuring and mapping fission product inventories and the concentration of uranium and plutonium isotopes allow determination of local burnup, fission product loss, transport, and relocation. Microstructural examination provides a detailed understanding of fuel behavior and fuel failure mechanisms including the presence of large gas bubbles or voids, clad tearing, and delamination of the fuel/cladding interface. Coupled with modeling, this gains insight into conditions when fuel failures might occur enabling a determination of fuel that will not fail within bounding HFIR operating conditions.

Out-of-Pile Testing and Analysis

Understanding the links between fabrication, microstructure, properties, and fuel performance is the goal of out-of-pile testing. Tests may be conducted on fuel plates before or after irradiation. These tests include measurement of mechanical and thermophysical properties, microstructural characterization, hydraulic flow testing, and fuel performance modeling. Mechanical properties are measured before and after irradiation to assess mechanical integrity, geometric stability, and stable and predictable behavior. Measuring thermophysical properties such as thermal diffusivity, heat capacity, thermal conductivity enables determining the plate-operating temperature and developing predictions of temperature-dependent behavior. Characterization improves understanding of how fabrication processing and irradiation conditions affect the microstructure of fuel, and how the microstructure affects fuel-irradiation performance during normal and anticipated transient conditions. Flow testing provides information about the hydromechanical behavior of fuel to qualify the hydromechanical performance of the test before installation in the test reactor. Fuel performance models serve an integrating function in which individual fuel-performance phenomena are combined and evaluated in the context of the complex irradiation environment. Linking the properties and other assessments of the fuel correlates properties to fabrication process and materials and fuel behavior during irradiation which reduces risk during irradiation and increases understanding fuel failure mechanisms.

Off-Normal Fuel Performance Behavior Testing and Analysis

Testing and analyses support the development of the reactor safety requirements such that margin to fuel protection criteria are maintained during off-normal reactor conditions. The margin to fuel failure has historically been determined for off-normal conditions by post-irradiation blister testing of research-reactor fuel. It is assumed the temperature at which fission gases are released from the fuel results in the fuel plate no longer meeting requirements for operation within the reactor safety basis. The HFIR safety basis drives the need for fission-product release data for the reactor and is required to update the safety basis for DOE authorization of Uranium Silicide Fuel use in HFIR LEU conversion.

FUEL QUALIFICATION AND DEMONSTRATION TESTING

Tests for U_3Si_2-Al fuel include scoping test FUTURE-HFIR, qualification tests (full-size plate (FSP) HFIR and HFIR DDE tests), and an LTC. The first step before fuel qualification and demonstration testing are the FQ scoping tests. The FUTURE-HFIR irradiation campaign is designed to evaluate performance of silicide fuel with and without burnable absorbers at irradiation conditions representative of HFIR (high power). The results of this early full-size plate test will be used to validate acceptable fuel performance for subsequent testing. The tests necessary for full conversion include fuel qualification and demonstration tests and are performed in a sequence of increasing complexity. The test program was established based on historical precedent and previously demonstrated performance of uranium-silicide fuel. Each test has a primary function that is not replicated elsewhere.

Full-size plates (FSP) are fabricated using representative equipment and processes from the downselected HFIR fuel design and fabrication processes. The FSP-HFIR test will be irradiated at test conditions to envelope HFIR normal operating conditions and to collect data for the fuel qualification report and for HFIR safety analysis report with high statistical confidence. The fuel plates will either be flat, curved, or involute plates representing the HFIR IFE and OFE fuel geometries. The number of plates tested will be dictated by the test position, size, and configuration within the experimental assembly. Multiple cycles may be required to collect statistically significant data from full-size plate testing. Testing provides proof of performance for prototypic-scale geometries in representative testing conditions at prototypic of power profiles under HFIR operating conditions. Successful FSP-HFIR testing provides confidence that fuel-element demonstration tests can be conducted with low risk of failure.

A final FQ irradiation of reactor-specific fuel-element geometries in HFIR fuel-element configurations provide a performance demonstration of the final fuel-system design and fabrication process and is necessary for fuel authorization for use. The DDE for HFIR will be a representative partial fuel element (both IFE and OFE), rather than a full element due to testing constraints, and will provide a statistically significant demonstration of the final IFE and OFE designs and fabrication processes. The DDE demonstrates performance of reactor-specific fuel designs through irradiation of prototypic element assemblies that represent key fuel-element design features. The DDE is irradiated under conditions, within a comfortable margin, designed to be as prototypic of actual reactor operating conditions as possible outside of the environment of the conversion reactor. This configuration will enable observation of engineering-scale behaviors (e.g., dimensional stability, coolant channel gaps) before inserting a LTC in HFIR. After completion of DDE testing, flow testing of conversion elements, completion of analyses required for reactor conversion, and completion of the HFIR-LTC irradiation, the USHPRR Conversion Program anticipates DOE-SC approval for LEU conversion.

The HFIR-LTCs will precede conversion because the LTC operation will have enhanced safety surveillance and will be a precursor to license for routine use of the LEU. The 540-plate test will be fabricated on a production line and irradiated in the HFIR. The vessel will be instrumented for the experiments, and modifications may be required to assure safety during and after the tests. Since the LEU fuel will be significantly heavier than the HEU fuel, the fuel handling path must be documented as either adequate for the new mass or modified to be adequate. The first LTC test will be at low power to validate the HFIR safety basis by comparison of measured and predicted system responses. Once the low-power LTC test is successfully completed, a comparison of the predicted and measured test results will be documented. These results will be compared to reactivity coefficients used in the high power LTC safety basis.

Regulatory approval must be obtained for a complete LEU safety basis for high power operation. The LTC at power will be the first opportunity for the integrated LEU system to be tested. Therefore, it will require all the rigorous analysis, review, and implementation of the conversion. Physics testing at power will include power defect measurement during ramp to power, coolant temperature coefficient at power, and verification of depletion predictions via control element/rod withdrawal during the cycle and cycle length achieved.

CONCLUSIONS

The use of uranium silicide fuel for HFIR will be the first use of the fuel in a high-power reactor with a complex fuel design. HFIR with LEU is estimated to have a peak heat flux of 4.37 MW/m^2 [11], which is well above the qualified fuel in NUREG-1313 with a peak heat flux of 1.4 MW/m^2.

The data from the HFIR Silicide Fuel Qualification campaign will be used by ORNL to prepare the reactor conversion SAR analyses and subsequent SBS to ensure that the LEU fuel will meet the key performance metrics and requirements for safe operation in HFIR.

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