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Irradiation Tests Supporting LEU Conversion of Very High Power Research Reactors in the US

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ABSTRACT

The US fuel development team is developing a high density uranium-molybdenum alloy monolithic fuel to enable conversion of five high-power research reactors. Previous irradiation tests have demonstrated promising behavior for this fuel design. A series of future irradiation tests will enable selection of final fuel fabrication process and provide data to qualify the fuel at moderately-high power conditions for use in three of these five reactors. The remaining two reactors, namely the Advanced Test Reactor and High Flux Isotope Reactor, require additional irradiation tests to develop and demonstrate the fuel's performance with even higher power conditions, complex design features, and other unique conditions. This paper reviews the program's current irradiation testing plans for these moderately-high irradiation conditions and presents conceptual testing strategies to illustrate how subsequent irradiation tests will build upon this initial data package to enable conversion of these two very-high power research reactors.

1. Introduction

The United States High Power Research Reactor (HPRR) fuel development effort is proceeding with development and qualification of fuels based on uranium molybdenum alloys (U-Mo). In particular, an alloy containing 10wt% molybdenum (U-10Mo) is being pursued in the form a monolithic foil, coated in thin zirconium interlayers, and clad in aluminum alloy 6061 to form plate-type fuel. The high density nature of the U-10Mo monolith will enable five US HPRRs to convert to use of Low Enriched Uranium (LEU) while maintaining core performance. The zirconium interlayer mitigates formation of large uranium-aluminum interaction layers which could impede heat transfer from fuel meat to cladding; especially for fuel plates experiencing elevated temperature histories and/or high burnups. The aluminum cladding enables the fuel to be compatible with existing plant infrastructure and practices for coolant chemistry control. The resulting fuel plate can be shaped to a prescribed curvature by plastically deforming the cladding with special tooling. Fuel plates are roll-swaged or welded into non-fueled aluminum hardware “side plates” to constitute fuel element assemblies that are compatible with existing HPRR core support structures. The fuel assembly’s outer dimensions remain unchanged from existing high enriched uranium (HEU) designs, but in some cases the number of fuel plates, their thicknesses, and placement within the fuel assembly must be modified slightly in order to achieve adequate thermal hydraulic performance in the LEU design. Since the monolithic fuel cannot be blended at different fuel-to-matrix ratios as is typical for dispersion type fuels, the fuel loading of monolithic designs must be affected by adjusting the physical thickness of the monolithic foil. This adjustment is necessary to compensate for local power peaks arising from plate-to-plate self-shielding and each HPRR’s unique spatial flux distribution. This adjustment typically takes the form of different foil thicknesses that are constant within, but unique to, each fuel plate in the assembly. This rectangular cross-section fuel design is hereafter referred to as the “base” fuel design. For one HPRR, however, the foils thickness may need to be graded within the fuel plates themselves; creating a variable-thickness monolithic foil hereafter referred to as a “complex” fuel design. See Figure 1. Additionally, the potential need for burnable absorbers embedded within the fuel assembly [3] are also design features considered to be within the complex fuel category.

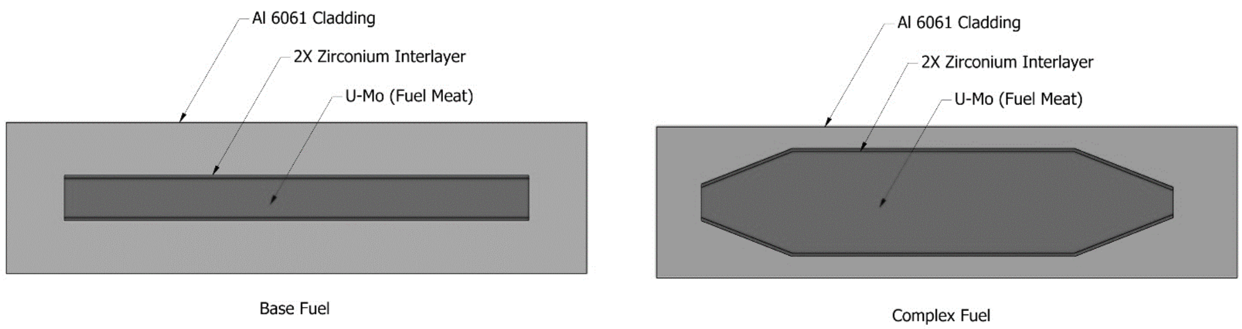

Figure 1: Cross Section of Fuel Designs

The LEU conversion designs for these five US HPRRs have commonalities in their use of U-10Mo, aluminum-clad, plate-type fuel. Despite these commonalties, each of these five HPRR designs exhibit different design geometries, thermal hydraulic conditions, and required fuel burnups. Three HPRRs are regulated by the US Nuclear Regulatory Commission (NRC) including the Massachusetts Institute of Technology Reactor (MITR), University of Missouri Research Reactor (MURR), and National Bureau of Standard Reactor (NBSR). The remaining two HPRRs are regulated by the US Department of Energy (DOE) including the Advanced Test Reactor (ATR and its low-power critical assembly ATR-C) and the High Flux Isotope Reactor (HFIR). Like the NRC-HPRRs, these two DOE-HPRRs have unique LEU fuel designs. See Figure 2, Figure 3, and Figure 4.

	Fuel Volumetric Power	End of Life Burnup	Fuel Meat Thickness	Primary Coolant	Regulator
MITR	Low	Medium	High	Light Water	NRC
MURR	Medium	Low	Medium	Light Water	NRC
NBSR	Medium	High	Low	Heavy Water	NRC
ATR	High	Medium	Medium	Light Water	DOE
HFIR	Very High	Low	High (Graded)	Light Water	DOE

Figure 2: HPRR Comparison

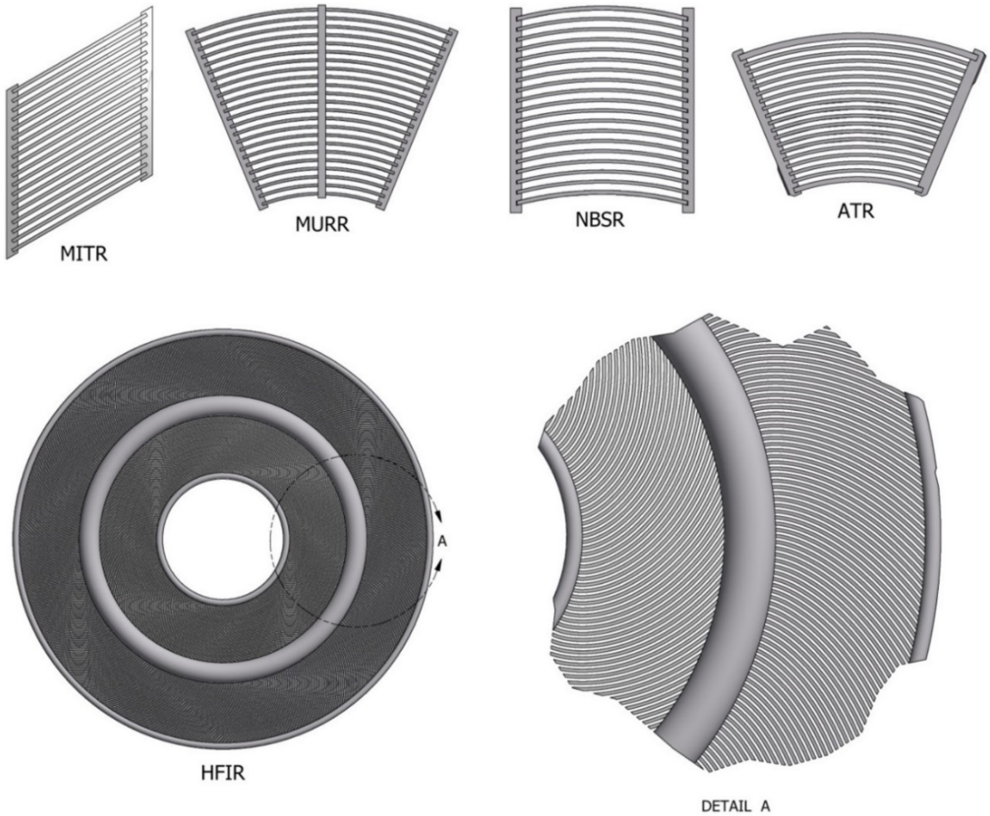

Figure 3: HPRR Fuel Assembly Designs, Top Views

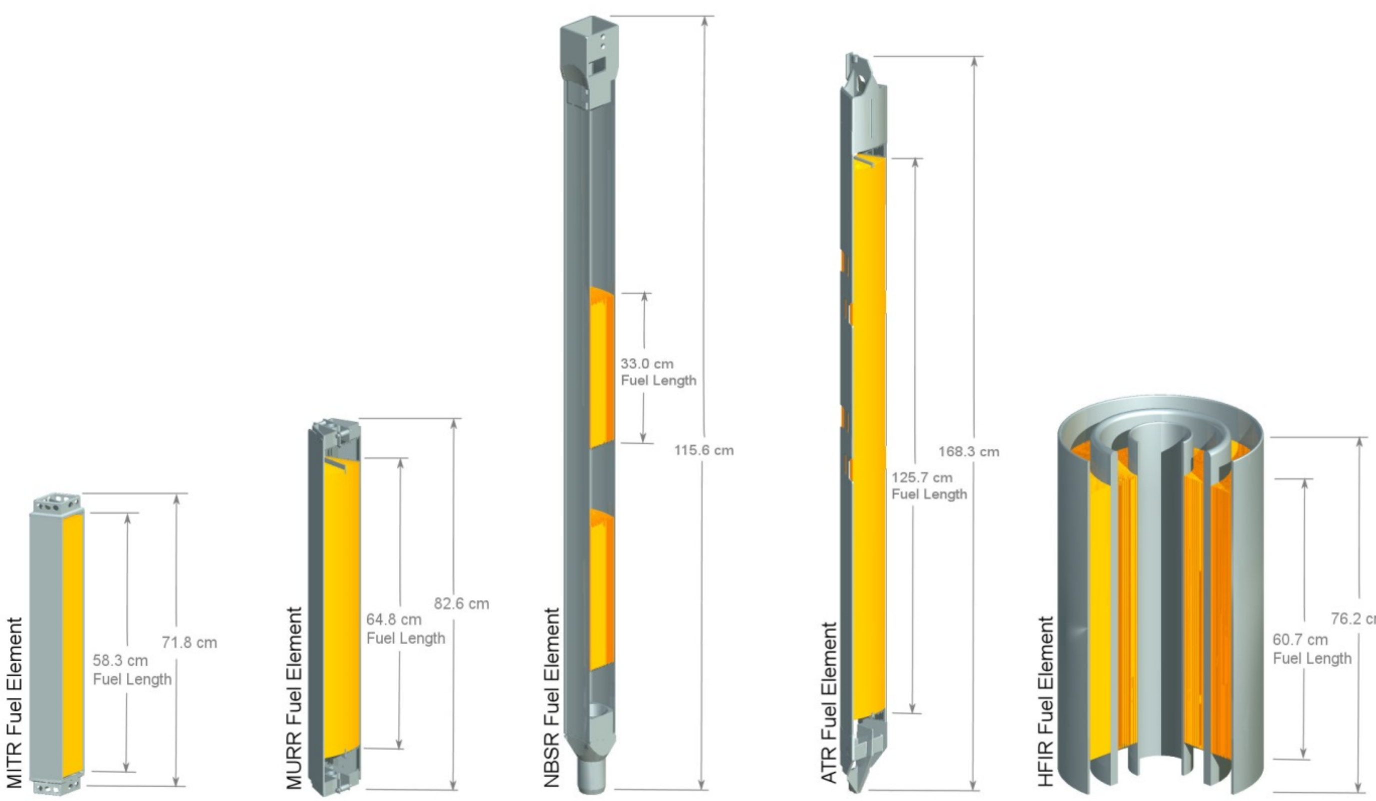

Figure 4: HPRR Fuel Assembly Designs, Isometric Views

2. HPRR Irradiation Testing Overview

The HPRR-FD program has overseen design, fabrication, irradiation, and examination of numerous tests on small-to-medium sized specimens, and one prototypic fuel assembly, containing base fuel [2]. Differences in the fabrication process for creating monolithic fuels, compared to traditional plate-type dispersion fuels, have caused the HPRR program to suspend further irradiations for a short time in order to develop, select, and demonstrate commercially viable fabrication processes. The next irradiation test, known as Mini-Plate -1 (MP-1), will be performed shortly to help facilitate final selection of the preferred base fuel fabrication processes [1]. Each of the three NRC-HPRRs, as well as the ATR, can be converted using the base monolithic fuel. MP-1 includes three distinct specimen designs purposed to separately investigate fuel performance under conditions with high power, high burnup, or high fuel meat thickness. In this way, MP-1 will help ensure that the fuel fabrication processes selected will be able to serve LEU conversion for the four HPRRs using base fuel.

A series of irradiation tests will follow MP-1 to accomplish fuel qualification for the three NRC-HPRRs. In addition to having the same regulator, the NRC-HPRRs also operate in a similar power range (less than ~250 W/cm^2 surface heat flux in normal operation [4], [5], [6]). As a result, the fuel qualification effort for these three HPRRs will be accomplished within one group of irradiation tests, hereafter referred to as the base fuel qualification package [7]. Unlike the NRC-HPRRs, ATR and HFIR can exhibit much higher operating powers (>600 W/cm^2 surface heat flux). Additionally, HFIR conversion designs indicate that complex fuel design features may be needed. The base fuel qualification package will not address the ATR/HFIR high power conditions or complex design features in order to manage the total scope and execution risk for the base fuel qualification package.

The base fuel qualification package tests will include Mini-Plate -2 (MP-2), Full-Size Plate -1 (FSP-1), and Element Test -1 (ET-1). The MP-2 test will form the foundation for base fuel performance data. Since only one fuel fabrication process will be selected for use in the NRC-qualification tests, MP-2 will be able to devote its specimen capacity to more-compressive investigation of NRC-HPRR irradiation conditions, development of continuous performance correlations (e.g. swelling vs burnup correlations), and replication for increased statistical confidence in the developed data. The FSP-1 test will occur concurrently to MP-2 with much fewer, but far larger, fuel plate specimens under similar irradiation conditions. FSP-1 will confirm that the base fuel performs at larger size scales representing HPRR designs. Finally, ET-1 will see irradiation of fuel assemblies as a demonstration of the base fuel in a prototypic end-use product.

The MP-1, MP-2, and FSP-1 test will all be accomplished in flux traps and reflector experiment positions in the ATR owing to its ability to drive specimens to the desired conditions as well as proximity to hot cell facilities at the Idaho National Laboratory. The ET-1 irradiation will also be performed in the ATR core, except using driver fuel positions, for the same reasons. ET-1 is not expressly purposed to support ATR conversion, but will have many foundational benefits for ATR-specific fuel development owing to its use of the ATR driver fuel geometry. A follow-on campaign, known as ET-2, will continue to demonstrate base fuel product in ATR driver fuel positions to further support the bases for conversion licenses. Further description of the ET-series irradiations, with description of their impact for ATR-specific data needs, are described later in this paper.

All of the irradiation testing work following base fuel qualification will branch into five different paths to support distinct characteristics for each HPRR. While MP-2 and FSP-1 will envelope fundamental fuel performance parameters for NRC-HPRRs (e.g. burnup, power), a series of three Design Demonstration Elements (DDE's) will be needed to address specific fuel assembly geometry for MITR, MURR, and NBSR. The regulatory bases for these three NRC-HPRRs does not permit them to easily test DDE's in their respective cores, hence these three DDE irradiations will be accomplished in other test reactors with specific design features to affect the most prototypic irradiation conditions achievable. The two primary candidate reactors for DDE irradiations include the ATR and Belgium Reactor -2 (BR2).

The fuel performance bases for ATR will build upon the base fuel qualification package, but will also require dedicated irradiation tests to achieve these high power conditions. The HFIR conversion design may also include complex design features. Consequently, the irradiation tests supporting HFIR will build upon the NRC HPRR package, as well as the ATR package, but will still require unique tests to address complex fuel features. The overall irradiation plan is displayed graphically in Figure 5. The remainder of this paper is devoted to describing the current plan for irradiation tests which support these two very-high power research reactors.

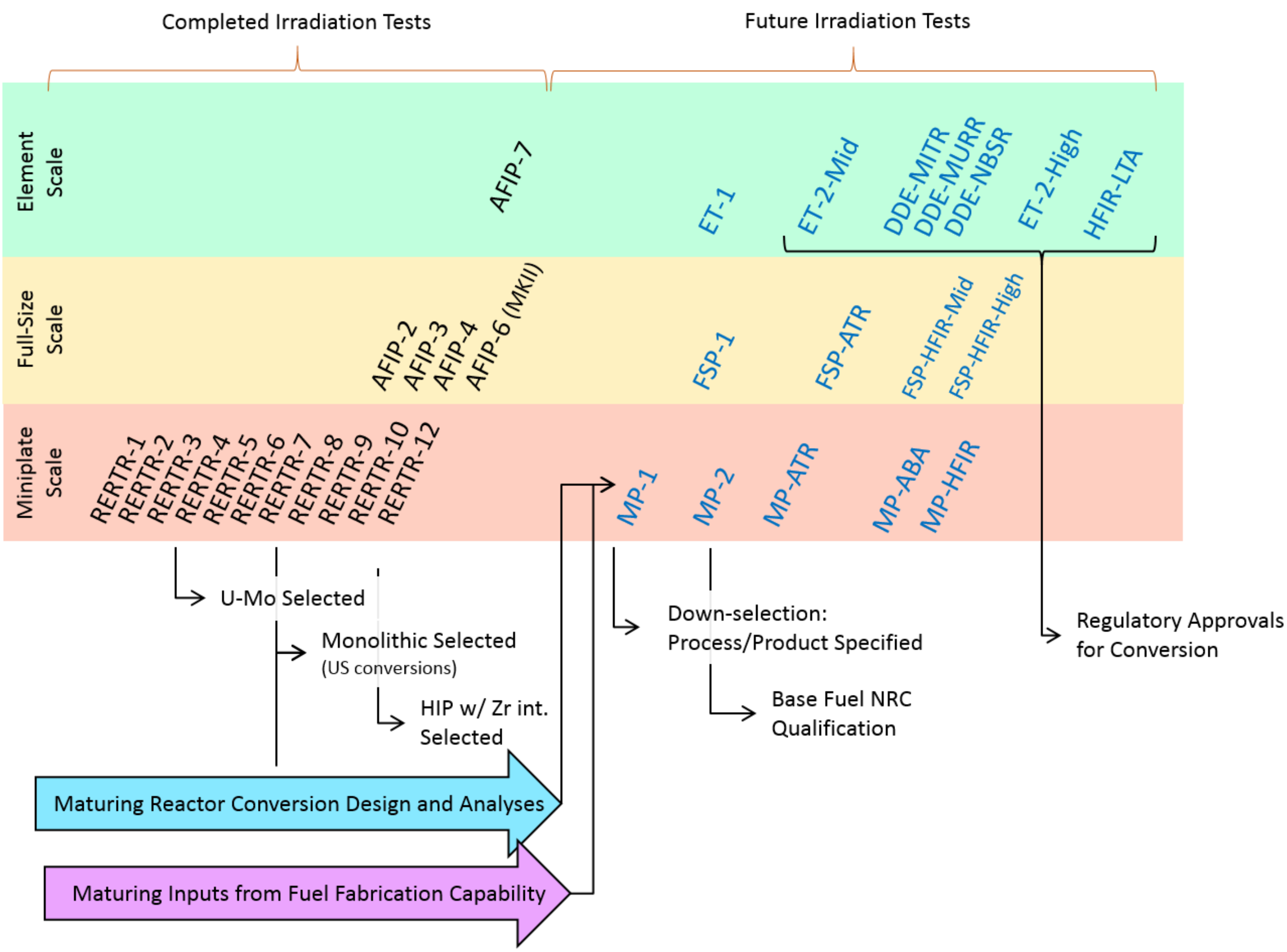

Figure 5: Irradiation Testing Plan

3. ATR-Supporting Irradiation Tests

Since the ET-1 irradiation design is that of an ATR LEU driver fuel assembly, the test may appear to directly support ATR's irradiation conditions, but this is not its express purpose. In fact, the ET-1 test is meant to be a modern equivalent for a historic precedent where U_3Si_2 research reactor fuel was qualified through the NRC which, among other things, included data from driver fuel assembly irradiations at the Oak Ridge Research Reactor (ORR) [9]. If ORR or other contemporary test reactors were operational today, then ET-1 could conceivably be accomplished elsewhere. However, due to core design and regulatory arrangements, the ATR is the only feasible option for such an irradiation in the US. Hence, ET-1 is essentially planned to use the most-current ATR-conversion design.

Despite its distinct mission, the ET-1 test will at least provide some synergistic groundwork for ATR conversion including use of updated safety analysis methods, fabrication experience with ATR driver fuel elements, and opportunities for foundational physics measurements. The majority of ATR's "normal" irradiation cycles operate for ~50 days each at powers not too dissimilar from that of MURR and NBSR. ATR occasionally operates shorter irradiation cycles, commonly referred to as PALM cycles, where the local driver fuel powers can be approximately three times greater than a normal cycle. ATR fuel only achieves its highest heat fluxes (>600 W/cm^2) in these PALM cycles. ET-1 will not be operated in PALM cycles to minimize any undue risks both for successful qualification under the NRC-HPRR condition envelope and for uninterrupted operation of mission-crucial PALM cycles; noting that high-power demonstration of the down-selected fabrication process will be limited to a few specimens from MP-1 at this point in the program.

Two additional irradiation tests will be commenced in this relative timeframe, both taking place in ATR flux traps, hereafter referred to as MP-ATR and FSP-ATR. The MP-ATR and FSP-ATR tests will be similar in purpose to MP-2 and FSP-1, respectively, in providing a comprehensive data set for fuel performance parameters using several mini-plate specimens with demonstration of phenomena scalability using a few full-size plate specimens. Unlike their base fuel qualification package counterparts, however, the MP-ATR and FSP-ATR will be designed to achieve fission powers representing PALM cycles. These two ATR-supporting tests will also employ fuel meat thicknesses and achieve burnups commensurate with ATR's LEU conversion design. Since the ATR conditions are only directly relevant for one DOE-regulated HPRR, there are no plans to include the data from MP-ATR and FSP-ATR in addenda to the NRC base fuel qualification package. Rather, the MP-ATR and FSP-ATR tests will build upon the base fuel qualification package and as part of ATR's conversion process.

Like ET-1, the ET-2 test will be comprised of ATR LEU driver fuel assemblies. The primary difference is that ET-2 will irradiate an increased number of fuel assemblies compared to ET-1 (which is currently planned to irradiate two fuel assemblies). ET-2 is divided into two phases, the first phase being similar to ET-1's non-PALM conditions referred to as ET-2-Mid, and the second phase including PALM conditions referred to as ET-2-High. Like ET-1, the ET-2-Mid test is expressly purposed to demonstrate the base fuel within the NRC-HPRR condition envelope (e.g. non-PALM cycles). Also like ET-1, the ET-2-Mid irradiation will provide several synergies for ATR's eventual full-core conversion in terms of safety analysis, opportunities for model-validating physics measurements, and operational experience. It will not be until the ET-2-High test that ATR LEU driver fuel achieves PALM cycle powers specific to ATR's unique data needs. In this way, the ET-2-High irradiations are synonymous with the purpose of Lead

Test Assemblies (LTA). See Figure 6 for an illustration of the various driver driver fuel, flux trap, and reflector positions that will be used for irradiation tests.

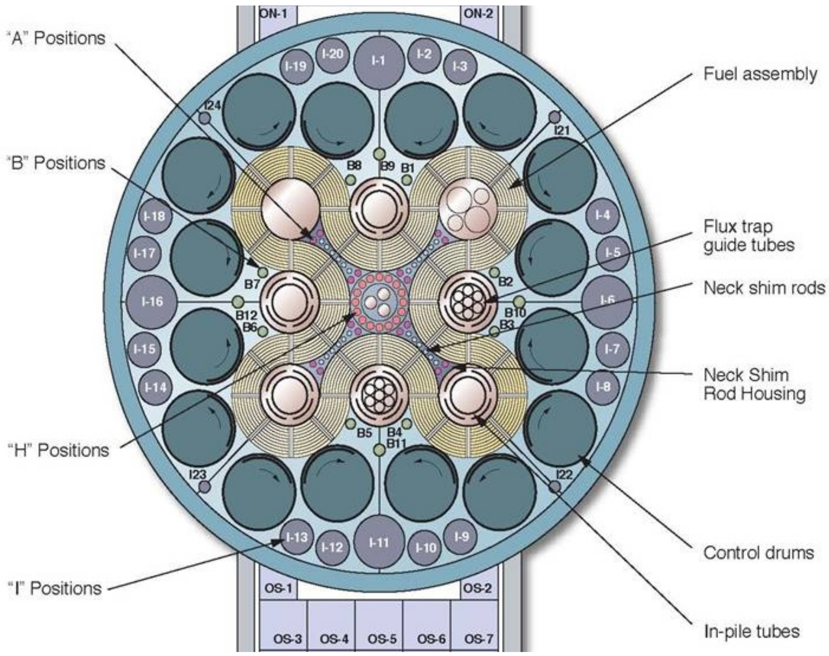

Figure 6: ATR Core Map Illustrating Driver Fuel, Flux Trap, and Reflector Positions

4. HFIR-Supporting Irradiation Tests

The HFIR LEU conversion design is arguably the most difficult to achieve in the US HPRR program. HFIR's peak conditions represent the highest surface heat fluxes (>700 W/cm^2) and the core design is based on several unique geometric aspects. The HFIR core is extraordinarily compact and composed of two annular rings referred to as the Inner and Outer Fuel Elements (IFE and OFE). Fuel plates are oriented "edge-on" to the center flux trap. As a result, the leading edges of IFE fuel meat experience extremely high volumetric fission heating. Similarly, well-moderated regions between IFE and OFE, and well-reflected regions at the trailing OFE edges, cause fission power peaking in the fuel meat edges. Constant-thickness hydraulic channels gaps are maintained across each fuel plate with involute curvatures; giving small radii of curvature in the leading-edge regions of both IFE and OFE fuel plates.

Reactors like ATR and MURR facilitate plate fabrication with uniform fuel-per-area loading while compensating for power peaking by adjusting the amount of fuel in each fuel plate (e.g. exterior plates typically contain less fuel-per-area than interior plates). HFIR's unique geometric arrangement in the HEU core, however, currently varies the fuel-per-area loading across the width of both IFE and OFE fuel plates by grading the actual fuel meat thickness within the plates.

In dispersion fuels, such as those used currently in all five HPRRs HEU cores, the desired loading can be achieved by varying fuel-to-matrix ratio in the dispersion powder blend. Fabrication of HFIR's graded-fuel HEU design is also facilitated by dispersion fuel designs where the desired contour is easily shaped into the fuel/matrix powders prior to compaction. In monolithic fuel, the fuel loading can only be affected by varying the monolithic foil's thickness. Different thicknesses of base fuel foils can be accomplished with different amount of thickness reduction in rolling mill operations, but a graded-thickness monolithic design requires development of some unique fabrication processes. The MP-1 irradiation is focused fuel fabrication techniques for base fuel only and does not address fabrication process selection for graded-thickness fuel or other complex fuel features.

For these fabrication-related reasons, current investigations are underway to determine whether HFIR can be converted to a design where monolithic foil thickness is constant within each fuel plate (i.e. base fuel design) while maintaining adequate thermal hydraulic margins at edge-peaked regions. In this scenario, management of edge peaks could require local flux suppression such as neutron poison features in non-fueled sideplates. The final HFIR LEU design is currently subject to change, but as a reasonable assumption for planning it is supposed that the final HFIR design could require graded fuel, unique neutron absorbing features, or both. Hence, irradiation testing of these complex fuel design features is currently planned. It should also be noted that the highest power ATR irradiation tests will approach, but not envelope, the very-high fission powers possible in HFIR. This unique condition will also be addressed in irradiation tests.

Figure 7 illustrates all of the non-HFIR irradiation tests and compares important parameters including U-Mo thickness, fission power, surface heat flux, and end of life burnup based on preliminary test designs and a graded-fuel HFIR concept [3]. A general observation that can be made from this comparison is that many of the salient considerations for HFIR will be addressed to some degree in the base fuel qualification package and ATR-specific irradiation tests, except HFIR's very-high fission power on the IFE leading edge. This comparison also demonstrates that HFIR's conditions are not entirely different from the other four HPRRs, but that HFIR plates are unique in the sense that this enormous spectrum of conditions are exhibited within the gradients of individual fuel plates.

	IFE							
Region	I1	I2	I3	I4	I5	I6	I7	I8
Avg U-Mo thickness (cm)	0.010	0.019	0.033	0.041	0.041	0.031	0.020	0.019
Power (kW/cm^3)	72	40	34	31	30	31	34	36
Heat Flux (W/cm^2)	350	374	563	631	611	481	347	349
Burnup (10^{21}fis/cm^3)	4.8	3.1	2.7	2.5	2.4	2.5	2.7	2.7

	OFE								
Region	O1	O2	O3	O4	O5	O6	O7	O8	O9
Avg U-Mo thickness (cm)	0.022	0.026	0.045	0.058	0.058	0.058	0.044	0.023	0.016
Power (kW/cm^3)	34	32	28	26	25	24	25	33	44
Heat Flux (W/cm^2)	369	421	623	757	728	699	553	383	351
Burnup (10^{21}fis/cm^3)	2.7	2.5	2.3	2.0	1.8	1.7	1.6	2.5	3.2

MP-1/FSP-1 Thick Fuel Plates	
U-Mo thick. (cm)	0.064
Power (kW/cm^3)	7.1
Heat Flux (W/cm^2)	225
Burnup (10^{21}fis/cm^3)	3.6

MP-1/FSP-1 High Burnup Plates	
U-Mo thick. (cm)	0.022
Power (kW/cm^3)	16
Heat Flux (W/cm^2)	175
Burnup (10^{21}fis/cm^3)	7.2

MP-1 High Power Plates	
U-Mo thick. (cm)	0.022
Power (kW/cm^3)	42
Heat Flux (W/cm^2)	460
Burnup (10^{21}fis/cm^3)	5.4

FSP-1 Intermediate Power Plates	
U-Mo thick. (cm)	0.036
Power (kW/cm^3)	13
Heat Flux (W/cm^2)	240
Burnup (10^{21}fis/cm^3)	5.4

MP-ATR/FSP-ATR Thin Fuel Plates	
U-Mo thick. (cm)	0.041
Power (kW/cm^3)	31
Heat Flux (W/cm^2)	640
Burnup (10^{21}fis/cm^3)	5.1

MP-ATR/FSP-ATR Thin Fuel Plates	
U-Mo thick. (cm)	0.020
Power (kW/cm^3)	60
Heat Flux (W/cm^2)	600
Burnup (10^{21}fis/cm^3)	5.1

*MP & FSP-ATR tests subject to change based on forthcoming ATR LEU core design

Figure 7: Comparison of HFIR Irradiation Conditions and Other Non-HFIR Tests

The initial HFIR-supporting irradiation tests will be performed on mini-plate specimens. One mini-plate test, termed MP-HFIR, will be performed in the ATR core to address both HFIR's high fission rates and the viability of graded fuel performance and/or candidate fabrication processes as needed. In the latter case, sections of full-width graded foils can be rotated 90 degrees from the normal axial direction and placed in standard size mini-plates in order to develop initial data for performance of graded monolithic fuels. Another mini-plate test, likely as a non-fueled materials test performed in the HFIR core, will address any unique data needs that may arise from the use of neutron poisons in HFIR's LEU core design. This test has been termed Mini-Plate Alternate Burnable Absorber (MP-ABA).

While MP-HFIR and MP-ABA will help develop some useful phenomenological information for fundamental data and concept evaluation, the majority of HFIR's unique considerations will focus around its unique geometry-influenced conditions. For this reason, full-size plate tests are planned to follow the mini-plate tests to simulate these unique conditions. One test campaign, known as FSP-HFIR, is divided into two sequential phases for mid and high power levels. HFIR has a unique core design and fuel cycle strategy which exchanges the entire driver core with a fresh one during refueling outages; hampering its ability to perform irradiation tests of engineering-scale LEU design features without making the leap to full core conversion. As a result, these tests will be performed either in the ATR or BR2, pending further design investigations.

Due to geometric and nuclear constraints, it is not feasible to place an entire HFIR IFE and/or OFE assembly in another test reactor to drive it, forcing the FSP-HFIR test series to employ sub-size element assemblies which use full-size fuel plates. In HFIR's core all neighboring fuel plates shielded each other in a circular pattern where there are no exterior plates. Combined with the edge-on nature of plate edges towards well moderated regions in the reactor core, it becomes rather challenging to achieve all of HFIR's unique conditions throughout the plate in a sub-size fuel assembly. Conceptual investigations of the FSP-HFIR design in the BR2 [10] have indicated that reasonably representative conditions can be achieved with the use of local poisons and moderation features in the irradiation vehicle hardware, see Figure 8. Similar investigations are underway to evaluate the FSP-HFIR design if irradiated in ATR. Ultimately, successful completion of the FSP-HFIR-High irradiation will give way to irradiation of LTA's in HFIR itself, which will likely involve the irradiation of entirely-LEU IFE and OFE assemblies.

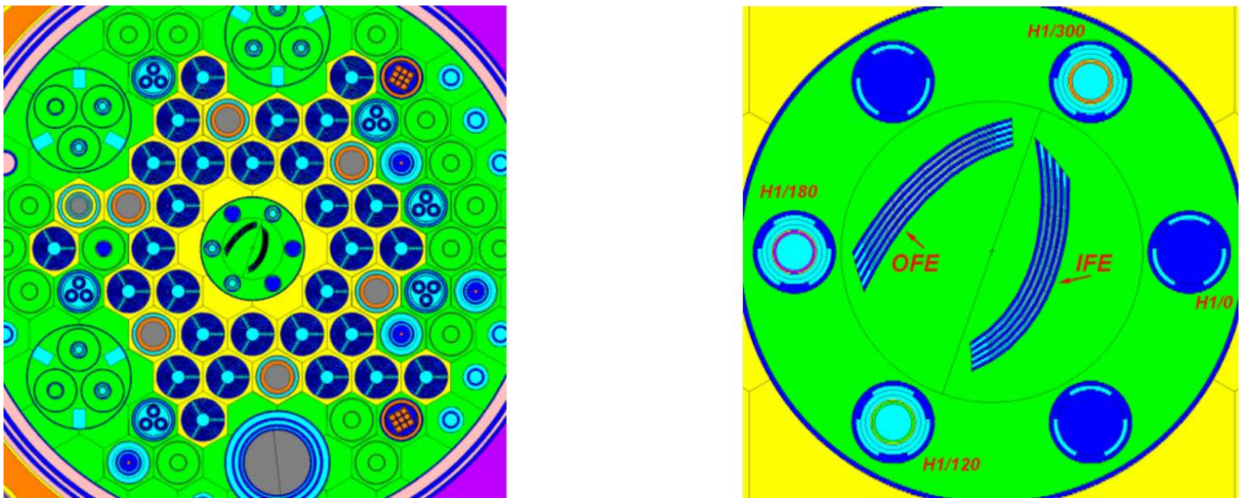

Figure 8: FSP-HFIR Design Concept in BR2 Core [10]

5. Conclusions

The US HPRR team has performed several irradiation tests to demonstrate the viability of U-10Mo monolithic fuel. The MP-1 test will help determine the most beneficial fabrication processes and enable three subsequent tests, namely MP-2, FSP-1, and ET-1, to accomplish fuel qualification for three lower-power HPRRs regulated by the NRC (MITR, MURR, and NBSR). A series of DDE tests will support licensing and conversion of these NRC-HPRRs. The two remaining HPRR's (ATR and HFIR) are regulated by DOE and operate at higher power levels. Both ATR and HFIR have distinct fuel performance conditions and design features that will be addressed in mini-plate, full-size plate, and fuel assembly irradiations. The tests performed for ATR and HFIR will build upon the NRC-HPRR qualification package to demonstrate the U-10Mo monolithic fuel and its acceptable performance for LEU conversions.

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