RERTR 2015 – 36TH INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

OCTOBER 11-14, 2015
THE PLAZA HOTEL
SEOUL, SOUTH KOREA

Design of Irradiation Tests for Monolithic Fuel Qualification

N.E Woolstenhulme*, I. Glagolenko, K.K. Holdaway, and B.H. Rabin
Idaho National Laboratory
P.O. Box 1625, Idaho Falls, ID 83415 – USA
*Corresponding Author, Nicolas.Woolstenhulme@inl.gov

ABSTRACT

The US fuel development team is focused on developing and qualifying the uranium-molybdenum monolithic fuel. Several previous irradiations have demonstrated the favorable behavior of the monolithic fuel. The overall irradiation program strategy was recently revamped to provide an opportunity to test, examine, and select the most advantageous fabrication processes for producing monolithic fuel. Specimens fabricated by the selected processes are planned to be irradiated in a series of tests in order to populate the data set needed for fuel qualification through the Nuclear Regulatory Commission. This paper summarizes the overall irradiation testing plan with an emphasis on the rigorous approach to design, analysis, and requirements for qualification tests. The recently designed Full Size Plate 1 irradiation test is also summarized as an example of this strategic approach to qualifying monolithic fuel.

1. Background

The United States (US) High Power Research Reactor (HPRR) fuel development team has selected an alloy of uranium with 10wt% molybdenum (U-10Mo) for further maturation and qualification. Unlike conventional dispersion fuels this alloy is used as a monolithic foil bonded between the aluminum alloy Al-6061, typically by Hot Isostatic Pressing (HIP) in order to form a fuel plate. A thin zirconium interlayer is typically used to enhance the interaction stability between U-10Mo and the aluminum cladding. The monolithic foil itself can vary in thickness to adjust fuel loading. The monolithic foil is normally a constant thickness within the plate creating a rectangular fuel cross section referred to as the base monolithic design [1]. Some specialized applications may call for graded thickness foils or burnable absorbers within the plate [2] referred to complex monolithic designs. The monolithic design is needed to maximize fuel density in order to enable HPRR's to convert to Low Enriched Uranium (LEU) while maintaining core performance. Figure 1 displays the different cross sections of these fuel designs.

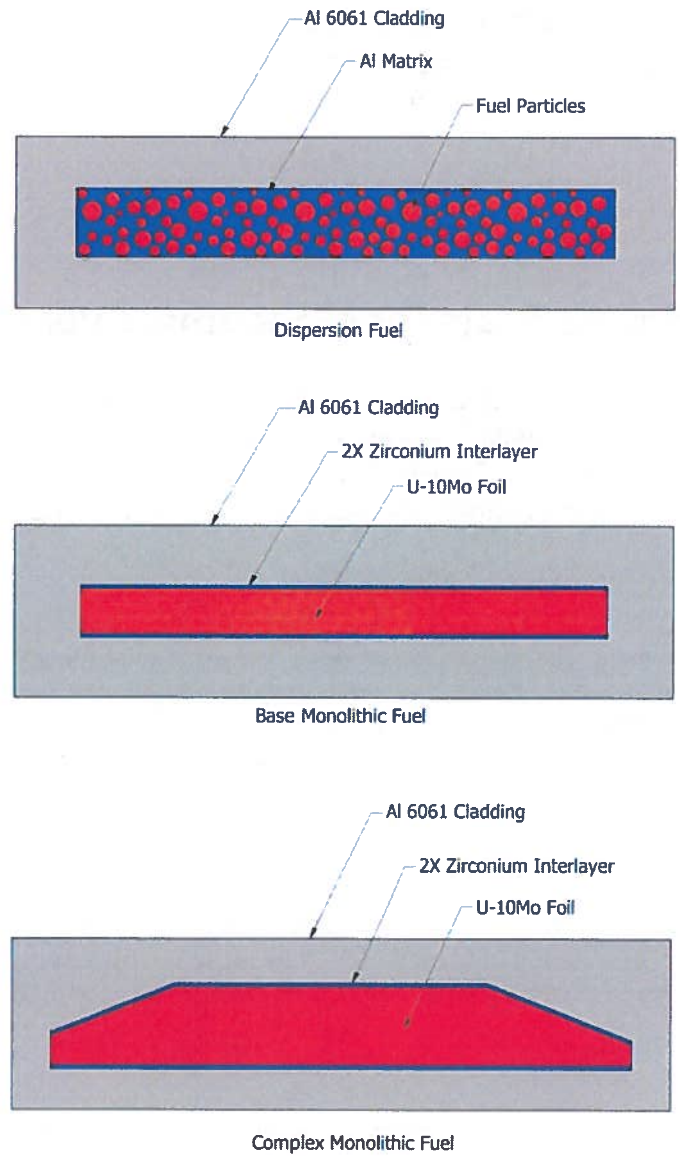

Figure 1: Fuel Design Schematics

Monolithic fuel plates can be used in a flat shape, or formed to prescribed curvatures, to be assembled into non-fueled aluminum hardware by swaging or welding in order to create reactor fuel assemblies with the needed coolant channel gaps. Five HPRR's in the US, each with its own unique fuel assembly design, are planned for LEU conversion using the U-10Mo monolithic fuel. Of these, three are regulated by the US Nuclear Regulatory Commission (NRC) including the Massachusetts Institutes of Technology Reactor (MITR), University of Missouri Research Reactor (MURR), and National Bureau of Standard Reactor (NBSR). The other two HPRR are regulated by the US Department of Energy (DOE) including the Advanced Test Reactor (ATR) and the High Flux Isotope Reactor (HFIR). The variety of geometric configurations for these five reactors is illustrated in Figure 2.

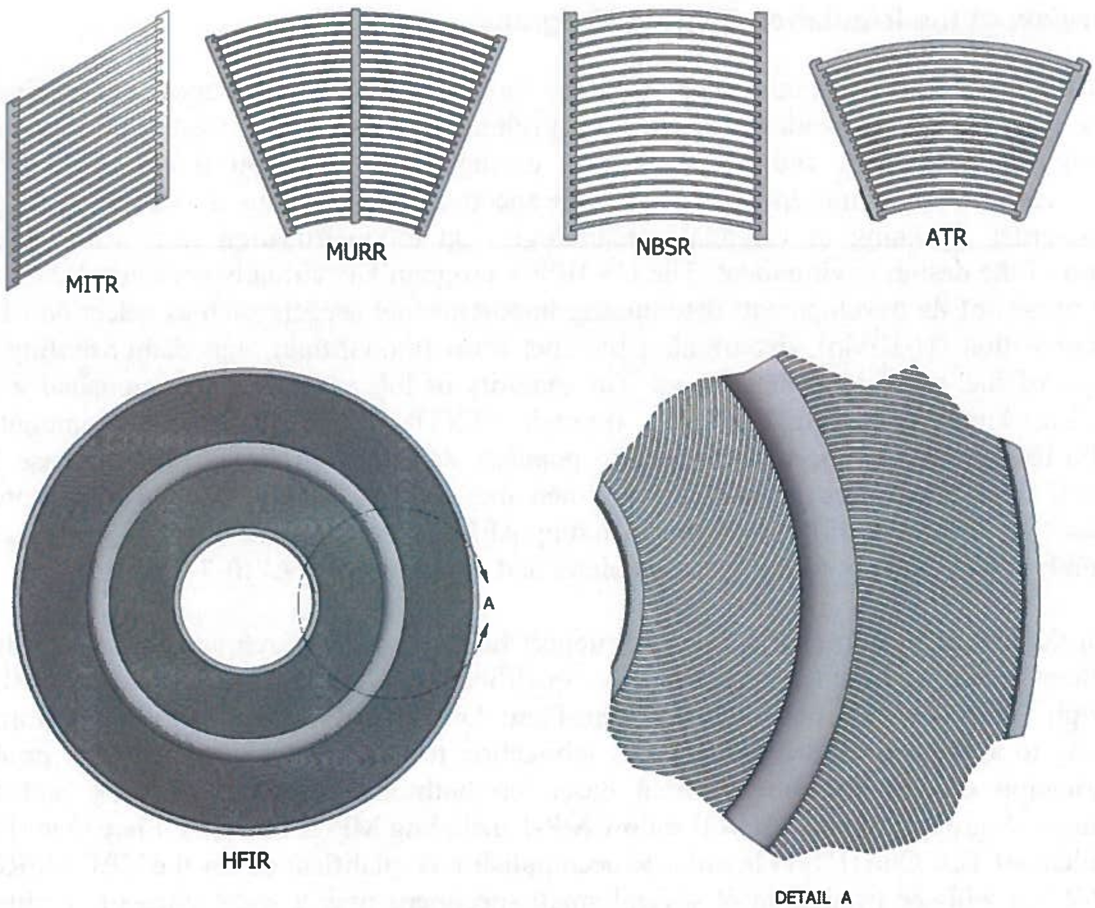

Figure 2: HPRR Fuel Assembly Designs, Top Views

Current conversion analyses and designs indicate that each of the three NRC-regulated HPRR's can be converted using the base monolithic fuel. These three reactors also operate in a similar thermal regime of less than ~250 W/cm^2 surface heat flux in normal operation [3][4][5]. Owing to their common regulator, similar operating range, and exclusive use of the base monolithic fuel, the HPRR fuel development team plans to perform the qualification effort for these three within one group of irradiation tests, with respective pre- and post-irradiation data gathering, to form the base fuel qualification package Error! Reference source not found.. Despite their similarities, each of these three NRC-regulated HPRR's has unique design features and performance attributes that must be considered in this combined approach.

Recent analyses indicate that the ATR conversion fuel design can be accomplished without the use of burnable absorbers within the fuel plate [7], effectively enabling the ATR to convert using the same base monolithic fuel planned for the NRC-regulated HPRR's. However, ATR's thermal operating conditions can be much higher even to exceed 600 W/cm^2 surface heat flux. For this reason, the ATR conversion bases will build upon the NRC HPRR package, but will also require dedicated irradiation tests to achieve these high power conditions. The HFIR conversion design indicates that graded thickness fuel designs may be needed and that the fuel may operate in excess of 600 W/cm^2 surface heat flux [2]. Consequently, the irradiation tests supporting HFIR build upon the NRC HPRR package, and the ATR package, but still require unique tests to address complex fuel features.

2. Overview of the Irradiation Testing Program

Much of the work performed in support of U-Mo fuel development is grouped into irradiation tests as a categorical framework for fabricating specimens, characterizing fresh fuel specimens, performing the irradiation, and gathering data during Post Irradiation Examination (PIE). Irradiation tests can serve multiple purposes in the spectrum of technology development ranging from first-order screening of candidate technologies up to qualification tests with specific simulation of the design environment. The US HPRR program has virtually completed the basic research phases of its development; determining important fuel aspects such as selection of the alloy composition (U-10Mo), determining the fuel form (monolithic), and demonstrating the advantages of fuel-to-cladding interlayers. The majority of this work was accomplished in the reduced Enrichment including RERTR-1 through RERTR-10. An considerable amount of irradiation testing has also been performed to populate data sets specifically for the base fuel design in the RERTR-12 test, to address specimen size scale up in the ATR Full-size plate In center flux trap Position (AFIP) series test including AFIP-2 through AFIP-6, and to demonstrate the assembly effects such as forming curved plates and swaging in the AFIP-7 test. [1]

Although the majority of irradiations which support fundamental research and fuel design have already been performed, one test remains before qualification tests can be performed for the base fuel design. This test has been termed Mini-Plate One (MP-1). MP-1 will be performed specifically to address several candidate fuel fabrication technologies so that the final product and fabrication process can be specified based on both manufacturing viability and fuel performance. A group of three test will follow MP-1 including MP-2, Full-Size Plate One (FSP-1), and Element Test One (ET-1) in order to accomplish fuel qualification for the NRC HPRR's. The MP-2 test will see irradiation of several small specimens over a wide range of conditions addressing the NRC HPRR condition envelope. The FSP-1 test will demonstrate the effect of size scale-up using a few larger-scale plates. Successful scale-up demonstration will give way the ET-1 test. ET-1 will exhibit the base fuel design as the fuel meat in a couple ATR driver fuel assemblies at power levels to addressing the NRC power conditions, but not enveloping the highest powers possible in ATR driver fuel. Specimens from these three tests will comprise the majority of the data in the NRC HPRR fuel qualification package. Like the preceding U_3Si_2 qualification package [8], the base fuel qualification package will be submitted to the NRC for qualification of the fundamental fuel system.

Following ET-1, a second driver fuel demonstration will be performed, termed ET-2, to bolster confidence in the base fuel by irradiating several ATR driver fuel assemblies. Follow-on irradiations specific to each NRC HPRR will be performed to support conversion licensing requests in the Design Demonstration Element (DDE) series of tests. Full size plate testing specific to ATR (FSP-ATR) will pave the way to ATR Lead Test Assemblies (LTA's), which may be combined with the ET-2 campaign, to address ATR's upper power envelope in order to facilitate its full-core conversion. Although not detailed in this paper, the complex fuel development program for HFIR will progress through a similar series of tests including miniplates, DDE's, and LTA's to facilitate its LEU conversion. The base fuel irradiation test progression, both past and future, is illustrated in Figure 3.

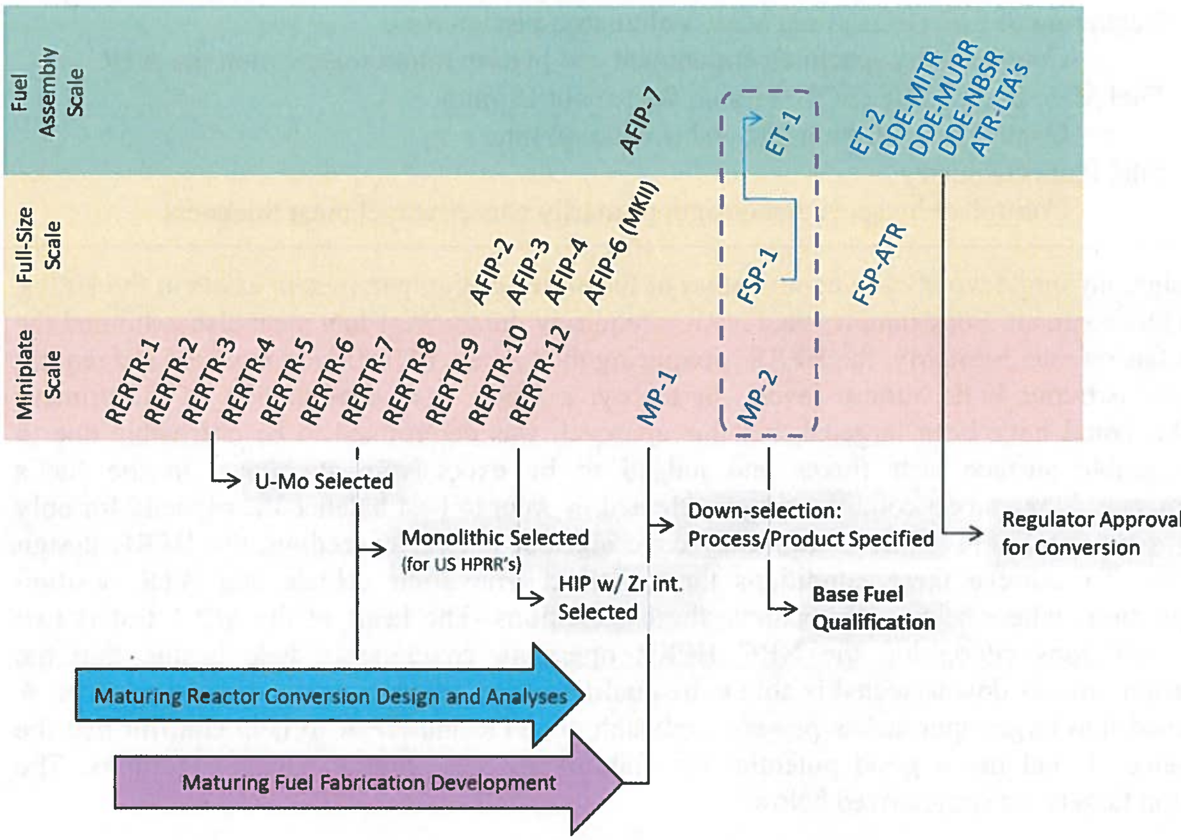

Figure 3: Overview of Irradiation Test Program for Base Fuel Qualfication

3. Irradiation Testing for Fabrication Process Downselection

The MP-1 test will be performed in the ATR and will be the next irradiation experiment to include base fuel specimens. MP-1 is the first test to be designed with input from the newly formed HPRR program experiment working group. This multi-disciplined group was formed to ensure that MP-1 test serves all program needs including fuel performance, design conditions in the HPRR environment, and viability for commercial fabrication. As a result, the MP-1 test design has emerged with specific configurations addressing HPRR conditions (e.g. power and burnup levels) and the capacity for many specimens which are fabricated by a variety of processes currently under investigation by the fuel fabrication team.

The multiple candidate fabrication processes drove the need for high specimen capacity. MP-1 also needed to provide similar conditions between specimens of different fabrication process to enable comparison between their observed performances. These objectives drove the MP-1 design to prioritize from among the myriad of operating conditions possible to just a few that were essential. The operating conditions for all five HPRR's were compiled and evaluated by the experiment working group to determine the most important irradiation conditions for the MP-1 test. The irradiation condition targets were based on fuel performance failure modes which were postulated based on performance models, innate phenomena, and that had been manifest, or at least for which precursors had been observed, in previous irradiations. These fuel performance considerations were reduced to three primary input test variables, all of which are interrelated, as outlined below:

- Beginning of Life (BOL) Fuel Meat Volumetric Fission Rate
    - Controlled by specimen enrichment and placement/arrangement in the ATR
- Fuel Meat End of Life (EOL) Fission Density or Burnup
    - Controlled by fission rate and irradiation time
- Fuel Plate Geometry
    - Controlled by specimen design, primarily concerns fuel meat thickness

By design, no single worst-case combination of the above design parameters exists in the HPRR design environment. For example, the HPRR's requiring the thickest fuel meat also exhibited the lowest fission rate. Similarly, the HPRR's requiring the highest BOL fission rates did not require the most extreme EOL burnup levels. In theory, a worst case combination of all primary variables could have been targeted, but this approach was determined to be unfeasible due to unmanageable surface heat fluxes and judged to be excessively strenuous on the fuel's performance. Three target conditions were selected in order to best balance the capacity for only a few target conditions while comfortably covering, but not far exceeding, the HPRR design envelope. To achieve these conditions three distinct irradiation vehicle and ATR position configurations where selected to achieve these conditions. The heart of the MP-1 test is two target conditions addressing the NRC HPRR operating envelope to help ensure that the fabrication process downselected is able to be qualified for conversion of these three reactors. A third condition target approaches powers applicable to ATR and HFIR to help confirm that the downselected fuel has a good potential for viability in these higher power conditions. The condition targets are summarized below:

1. Specimens with Thick fuel Meat (hereafter referred to as "TM")
    a. High fuel meat thickness (0.0635 cm) and EOL burnup (3.6E21 fission/cm^3) derived from MITR interior fuel plates to give the highest fuel thickness swelling
    b. BOL fission rates (7.1 kW/cm^3, 225 W/cm^2), which are higher than those of MITR, derived from MURR plates which also use relatively thick fuel meats
2. Specimens achieving Full Burnup (hereafter referred to as "FB")
    a. Thinner fuel meat (0.022 cm) with high EOL burnup (7.2E21 fission/cm^3) derived from NBSR fuel plates to give the most fission-damaged fuel meat
    b. BOL fission rates (16.3 kW/cm^3, 175 W/cm^2), which are slightly higher than those of NBSR, derived from MURR plates which also use thin fuel meats
3. Specimens achieving High Power (hereafter referred to as "HP")
    a. Thinner fuel meat (0.022 cm) with moderate EOL burnup (5.4E21 fission/cm^3) derived from ATR conditions
    b. High BOL fission rates (ideally as high as 51.9 kW/cm^3, 560 W/cm^2, but MP-1 will likely achieve power slightly less due to thermal hydraulic constraints)

A newly-designed irradiation vehicle was created for use in ATR's east and south flux traps (EFT, SFT) to enable this variety of conditions to be met. The vehicle was designed with two channels allowing plate-bearing capsules to be arranged axially for different neutron flux levels within the ATR axial power profile. This vehicle is planned for use in the FB and HP tests. The previous irradiation vehicle used in RERTR test series will be used for the TM specimens in ATR "large-B" positions in the beryllium reflector. Altogether, these irradiation vehicle configurations and use of multiple positions in the ATR will allow MP-1 to irradiated approximately 100 specimens. Additionally, local hafnium power shaping ring features was designed into the capsules to suppress corner edge peaks in the small miniplates (fuel meat of 1.9 × 8.25 cm). The hafnium rings are used in TM and HP capsules, but not in FB capsules so that the peak burnup can be achieve in the fuel meat corner as it does in the NBSR. The burnup level is controlled by the amount of irradiation cycles performed. Capsules are open to ATR primary coolant flow. Apart from ATR's core power and hydraulic instruments, there are no instruments within the irradiation vehicle and all irradiation condition are determined by analysis and post-test exams. However, a probe is being developed to measure coolant channel thickness in the MP-1 capsules during reactor outages. See Figure 4.

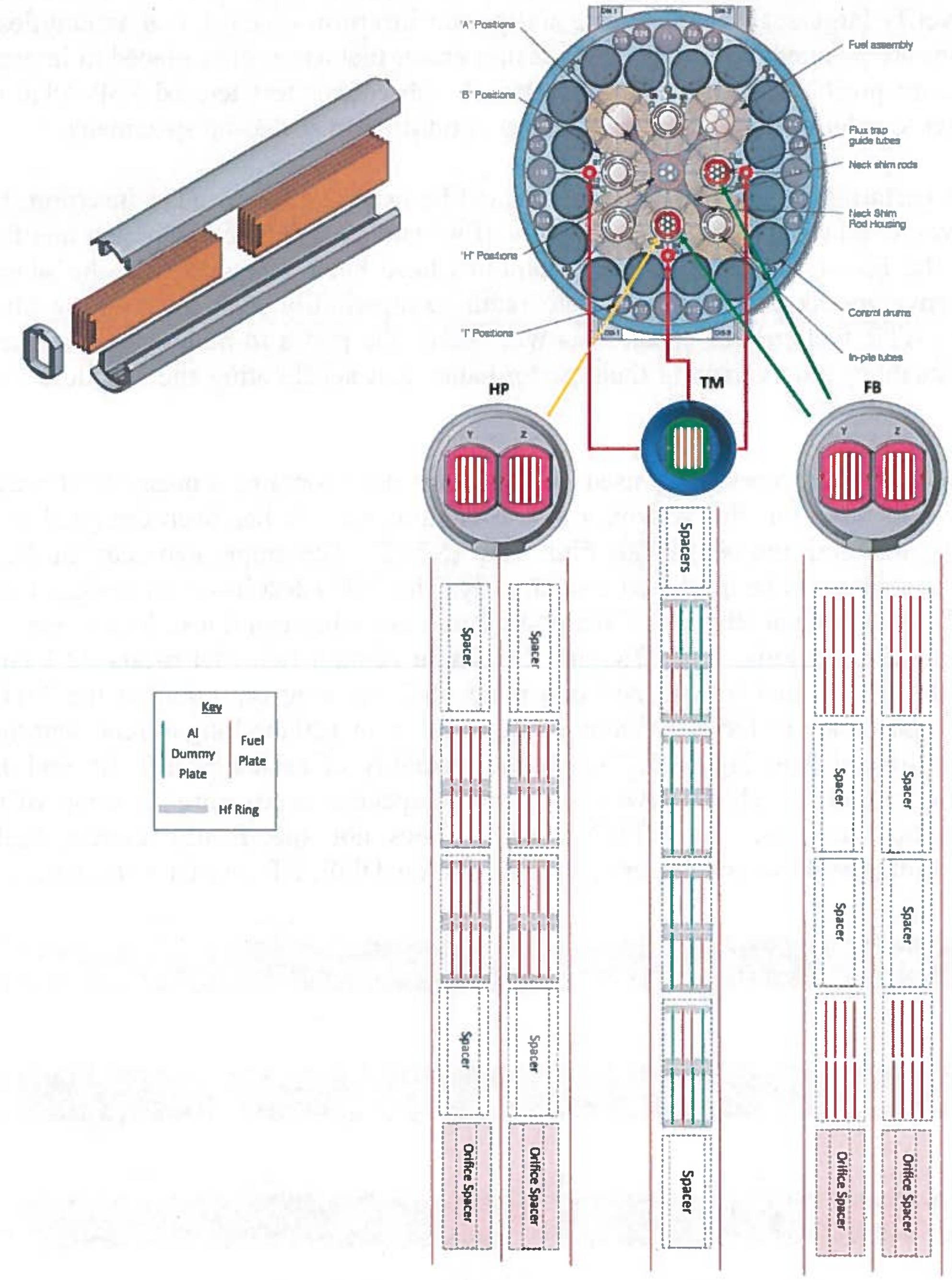

Figure 4: Overview of MP-1 Configurations

4. Irradiation Testing for Base Fuel Qualification

The three essential target conditions derived for MP-1 were highly impactful for the FSP-1 test design because the FSP-1 test, due to specimen size, had limited specimen capacity. The FB and TM conditions were targeted for FSP-1 in order to accomplish its objective of demonstrating scaled-up fuel performance to feed fuel qualification in the NRC HPRR envelope. The HP condition was modified to address an intermediate fuel meat thickness with moderate heat flux ($\geq$239 W/cm^2) for ATR LEU driver fuel interior plates. This condition is referred to as Intermediate Power (IP). This was modification was made to address FSP-1's second test objective to verify large-scale performance and permit insertion of ET-1 fuel assemblies. ET-1 fuel assemblies are planned to be ATR LEU-design driver fuel assemblies placed in intermediate power level core positions and operation cycles. A subsequent test termed FSP-ATR will be performed later to achieve the highest ATR power conditions in scaled-up specimens.

Verifying the performance FSP-1 IP specimens will be needed prior to ET-1 insertion, but this verification would delay ET-1 by several months if it included irradiated shipment and full PIE. To this end, the FSP-1 fuel plate frame assemblies have been designed with the same outer dimensional envelope as previous AFIP's to retain compatibility with the existing ultrasonic scanner in the ATR fuel storage canal. This will enable the plates to be characterized in detail following irradiation, thus verifying their performance and accelerating the schedule for ET-1 insertion.

The ATR center flux trap previously used in AFIP tests now contains a pressurized water loop with a steady user base. For this reason, a new irradiation vehicle has been designed to enable FSP-1 to be irradiated in the North East Flux Trap (NEFT). The ample geometry in the NEFT enables more specimens to be irradiated concurrently. The FSP-1 test has been designed to house up to six fuel plate frame assemblies. Each plate frame assembly can house fuel meats 3.81 cm wide and up to 120 cm long. Each TM and FB frame contain two fuel meats 27.3 cm long, representing the NBSR fuel length, and one plate 60.3 cm long representing the MITR and MURR fuel length. Each IP frame contains a single fuel meat 120 cm long to represent the ATR fuel length as illustrated in Figure 5. Two frame assembly of each type FB, IP, and TM are arranged in the irradiation vehicle, giving a total of 14 specimens covering the range of lengths considered to be "full size" for HPRR's. FSP-1 does not specifically address fuel plate curvatures or widths as these aspects will be realized in the DDE, ET, and LTA irradiations.

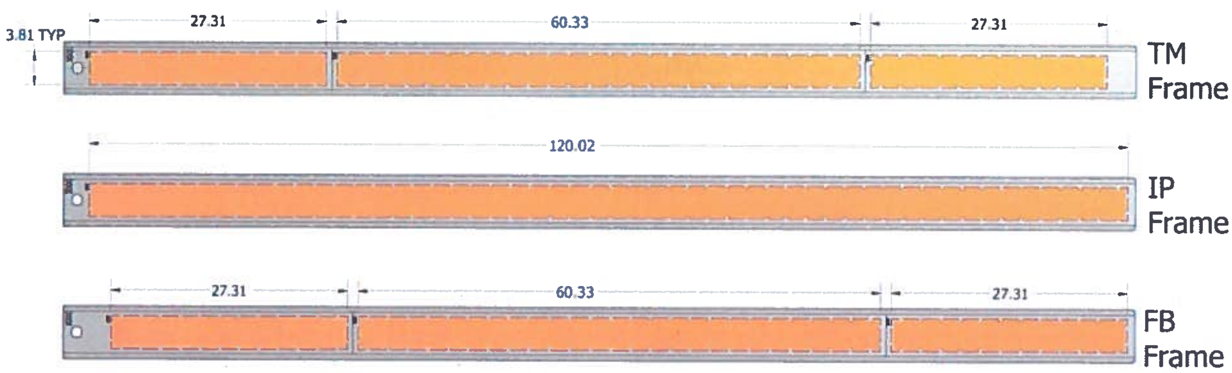

Figure 5: FSP-1 Frame Assemblies (dimensions in cm)

The NEFT's proximity to ATR control drums allows its local power to be controlled according to experimenter needs, see Figure 6. This controllability, in combination with intentional specimen-to-specimen shielding arrangements, and staged insertion/withdrawal of fueled frame assemblies during outages enables the variety of irradiation condition targets to be met simultaneously in a single irradiation vehicle. The FSP-1 test, as the first to be designed expressly as a qualification test under the new irradiation testing strategic plan, has served as a trailblazer for implementing a highly rigorous test planning process based on fuel performance requirements. In this way, the FSP-1 test itself must achieve specified conditions to be considered an acceptable test while the individual data gathering activities, each with its own test plan, must show that the fuel behaves in accordance with its fuel performance requirements. [9]

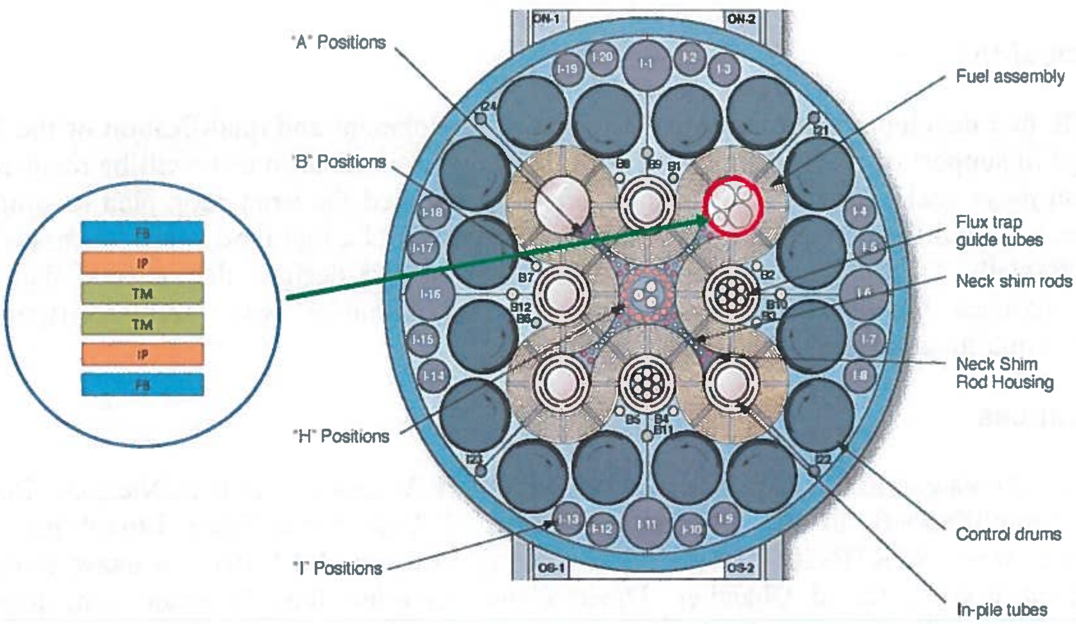

Figure 6: FSP-1 Layout

Since the thermal conditions of the fuel plate specimens are not measured directly while in-pile, these conditions must be inferred by detailed analysis. The detailed analysis, both neutronic and thermal hydraulic, is performed using as-run reactor power records. Radiochemical data obtained from irradiated fuel samples in PIE helps to confirm the results of neutronic analysis. Similarly, out of pile hydraulic flow testing is performed to help elucidate the actual hydraulic conditions for improved as-run thermal analysis. Flow testing is also performed to confirm the structural integrity of the design. The hydraulic flow tests for MP-1 have been completed and are in process for FSP-1.

FSP-1, MP-2, and ET-1 will exclusively irradiate specimens produced by the process downselected from the MP-1 irradiation. This will enable the MP-2 test to irradiate numerous specimens for a single specimen fabrication process. In this regard, MP-2 will be the test which builds statistical confidence for input to fuel qualification. The MP-2 test will achieve the same irradiation conditions at the outermost point of the NRC HPRR operating envelope (TM and FB conditions). Additionally, MP-2 will achieve condition within the NRC HPRR envelope to determine interactions between variables and produce data sets for performance must be known as continuous functions (e.g. blister threshold temperature as a function of burnup). This will likely involve the use of lower power positions in the ATR, such as the outer "small-I" reflector positions, and phased extraction of capsules to give data for intermediate burnup levels.

The ET-1 test will represent the pinnacle of the fuel qualification package because it will represent the base fuel in its design environment (i.e. driver fuel) with test articles that are truly representative of the size-scale for its end use. ET-1 will consist of a couple of ATR driver fuel assemblies irradiated in driver fuel positions. The ATR's highest power fuel assembly positions occur when the core is operated in short-length high-power cycles under increased core cooling conditions. Although ET-1 fuel assemblies will match the ATR LEU design, the irradiation is not expressly purposed to envelope these highest power conditions. ET-1 fuel assemblies will be irradiated in power positions that represent NRC HPRR's, likely in longer-length medium-power cycles.

4. Conclusions

The HPRR fuel development program is focused on development and qualification of the base fuel design in support of reactor conversion to LEU. Several irradiation tests will be required to accomplish these goals, but the program has recently revamped the irradiation plan to simplify the approach to qualification and help facilitate downselection of a fuel fabrication processes that are commercially viable. Recent examples of irradiation test designs demonstrate that this strategic approach includes careful selection of design variables with increased rigor for submittal of qualification data to the NRC.

5. References

[1] N.E. Woolstenhulme, D.M. Wachs, M.K. Meyer, H.W. Glunz, and R.B. Nielson, "Recent Accomplishments in the Irradiation Testing of Engineering-Scale Monolithic Fuel Specimens", RERTR-2012 international meeting, October 14-17, 2012, Warsaw, Poland.

[2] David Renfro, David Chandler, David Cook, Germina Ilas, Prashant Jain, Jennifer Valentine, "Preliminary Evaluation of Alternate Designs for HFIR Low-Enriched Uranium Fuel", ORNL/TM-2014/154, June 30, 2014.

[3] Erik H. Wilson, Thomas H. Newton, Jr., Lin-wen Hu, Floyd E. Dunn, and John G. Stevens, "Conceptual Design Parameters for MITR LEU U-Mo Fuel Conversion Demonstration Experimental Irradiations", Argonne National Laboratory, ANL/RERTR/TM-12-28, June 21, 2012.

[4] J. Stillman, E. Feldman, J. Stevens, E. Wilson, L. Foyto, K. Kutikkad, J. C. McKibben, and N. Peters, "Irradiation Experiment Conceptual Design Parameters for MURR LEU U-Mo Fuel Conversion", ANL/RERTR/TM-13-1, March, 2013.

[5] N. R. Brown, J. S. Baek, A. L. Hanson, A. Cuadra, L-Y. Cheng, and D. J. Diamond, "Irradiation Experiment Conceptual Design Parameters for NBSR Fuel Conversion", Brookhaven National Laboratory, BNL-99897-2013-IR, March 29, 2013.

[6] K. Daum, Carla Miller, Brian Durtschi, "Base Monolithic Fuel: Research, Development, and Qualification Plan", INL/EXT-13-30238, December 2014.

[7] INL document TEV-1792, "Conceptual Design Parameters for ATR LEU U-Mo Conversion Demonstration Experimental Irradiations", rev 3, 1/31/2014.

[8] "Safety Evaluation Report related to the Evaluation of Low-Enriched Uranium Silicide-Aluminum Dispersion Fuel for Use in Non-Power Reactors", NUREG-1313, U.S. Nuclear Regulatory Commission, July 1988.

[9] INL Document PLN-4673, "Full-Sze Plate 1 Irradiation Campaign", Rev 1, 05/19/2014.