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Idaho National Laboratory
Idaho Falls, Idaho 83415

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W.F. Jones[a], W.R. Marcum[b,a], A.W. Weiss[b], C.B. Jensen[a], G.L. Hawkes[a], P.E. Murray[a], D.S. Crawford[a], J.W. Herter[a], J.C. Kennedy[a], N.E. Woolstenhulme[a], J.D. Wiest[a], D.B. Chapman[a], T.K. Howard[b], G.D. Latimer[b]

[a] Idaho National Laboratory, Nuclear Science and Technology, Experiment Analysis,
2525 Fremont Ave., Idaho Falls, ID 83415, United States
b Oregon State University, School of Nuclear Science and Engineering,
116 Radiation Center, Corvallis, OR 97331, United States

Corresponding Author Contact Information:

Warren Jones
Nuclear Science and Technology
Idaho National Laboratory
2525 Fremont Avenue MS 3818
Idaho Falls, ID 83415-3818
Phone 1 (208) 526 9016
Fax 1 (208) 526 2930
E-mail warren.jones@inl.gov

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ABSTRACT

The development, characterization, and qualification testing of nuclear fuel at Idaho National Laboratory's Advanced Test Reactor (ATR) requires extensive design and analysis activities prior to the insertion of an irradiation experiment in-pile. Significant effort is made in the design and development phase of all in-pile experiments to ensure that the maximum feasible impact of all necessary experimental requirements are satisfied. The advancement of fuel, cladding, and in-reactor materials technology in recent years has introduced complexities associated with the design and construct of in-pile experiments necessitating deeper understanding of boundary conditions and increasingly comprehensive observations resulting from the experiment. Each unique experiment must be assessed for neutronics response, thermal/hydraulic/hydro-dynamic performance, and structural integrity. This is accomplished either analytically, computationally, or experimentally, or some combination thereof, prior to insertion into the ATR. The various effects are inter-related to various degrees, such as the case with the experiment temperature affecting the thermal cross-section of the fuel, or the increased temperature of the experiment's materials reducing the mechanical strength of the assemblies. Additionally, the feedback between the experiment's response to a reactor transient could alter the neutron flux profile of the reactor during the transient. Each experiment must therefore undergo a barrage of analyses to assure the ATR operational safety review committee that the insertion and irradiation of the experiment will not detrimentally affect the safe operational envelope of the reactor. In many cases, the nuclear fuel being tested can be double-encapsulated to ensure safety margins are adequately addressed, whereas failed fuel would be encased in a protective capsule. In other cases, the experiments can be inserted in a self-contained loop that passes through the reactor core, remaining isolated from the primary coolant. In the case of research reactor fuel, however, the fuel plates must be tested in direct contact with the reactor coolant, and being fuel designed for high neutron fluxes, they are inherently power-dense plates. The combination of plate geometry, high power density, and direct contact with primary coolant create a scenario where the neutronic/thermo-mechanic/hydrodynamic characteristics of the fuel plates are tightly coupled, necessitating as complete characterization as possible to support the safety and programmatic assessments, thus enabling a successful experiment. This article explores the efforts of the USHPRR program to thermo/hydro-mechanically characterize their wide variety of experiments, which range from stacks of mini-plate capsules to full-sized, geometrically representative curved plates. Special attention is given to instances where the combination of experimental characterization and analytical assessment has reduced uncertainties of the safety margins, allowing experiments to be irradiated that would otherwise not have passed the rigorous qualification process for irradiation in the ATR. In some cases, the combined processes have exposed flow and heat-transfer characteristics that would have been missed using historical methods, which allows for more accurate and representative post-irradiation assessments.

keywords

Hydraulic Testing

Nuclear Fuels Characterization

Fluid-Structure Interaction

1 INTRODUCTION

The U.S. High Performance Research Reactor Fuel Qualification Project (HPRR-FQ) mission is to develop the technology needed to reduce, and eventually eliminate, worldwide use in civilian applications of highly-enriched uranium (HEU) or other weapons-grade materials. In particular, HPRR-FQ goals are to develop the technical means needed to use low-enriched uranium (LEU) instead of HEU in research and test reactors, to accomplish such without significant penalties in reactor performance, economics, or reactor safety, and to generate data of sufficient quality to support qualification for research and test reactor fuel [1]. The Advanced Test Reactor's (ATR's) role in this endeavor is twofold – first, it supports the development of LEU fuel and the down-selection of fabrication processes through various fuel-qualification experiments, and later, it is equipped with the very LEU fuel it helped develop as driver fuel for its new role as a LEU research reactor.

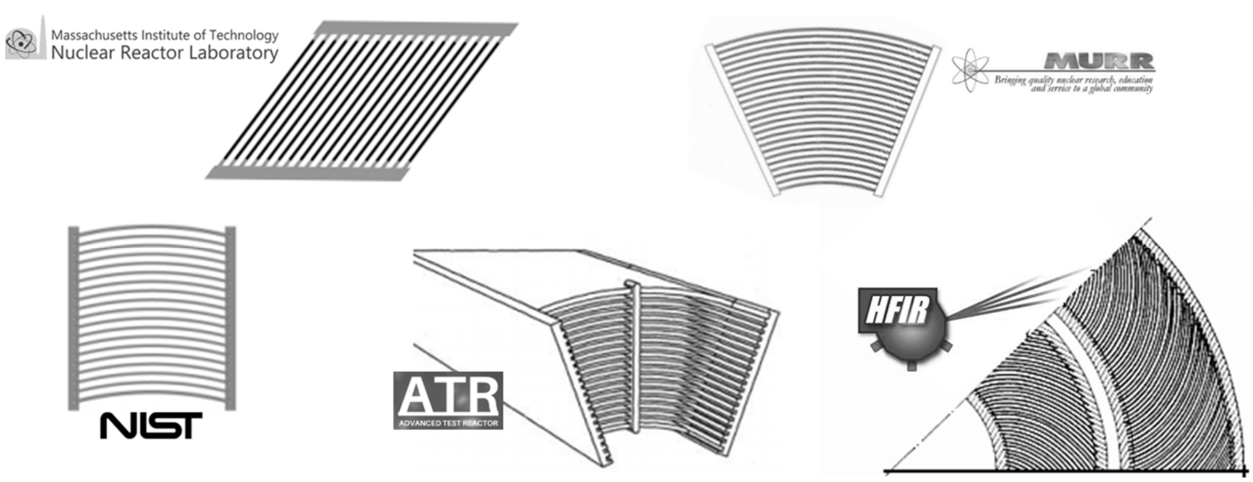


Figure 1. Fuel element geometry from U.S. High Power Research Reactors

The HPRR-FQ task is complex due to the variety of U.S. research and test reactors which are targeted for conversion to LEU. These include the ATR, Massachusetts Institute of Technology Reactor (MITR), National Bureau of Standards Reactor (NBSR), University of Missouri Columbia Research Reactor (MURR) and High Flux Isotope Reactor (HFIR). As can be seen in Figure 1, the geometry of the various fuel elements are very different, as are the power and neutron flux requirements of the fuel, as shown in Figure 2. Due to this extreme variation in the neutronic performance space of the fuel, multiple experiments were required. These ranged from small ‘mini-plate’ experiments which entailed a variety of coupons irradiated at select ATR reactor positions, elevations, and durations, to large, ‘full-sized-plate’ experiments that represented singular plates of fuel, which had to be sub-sampled to gather information representative of a given reactor. The Fuel Qualification experiments will next progress through ‘Design Demonstration Elements’ which represent driver fuel elements of the various reactors, and finally, the LEU will be fabricated into the fuel elements for the various reactors and used in either a singular fuel position or, in some cases, the entire core fuel loading.

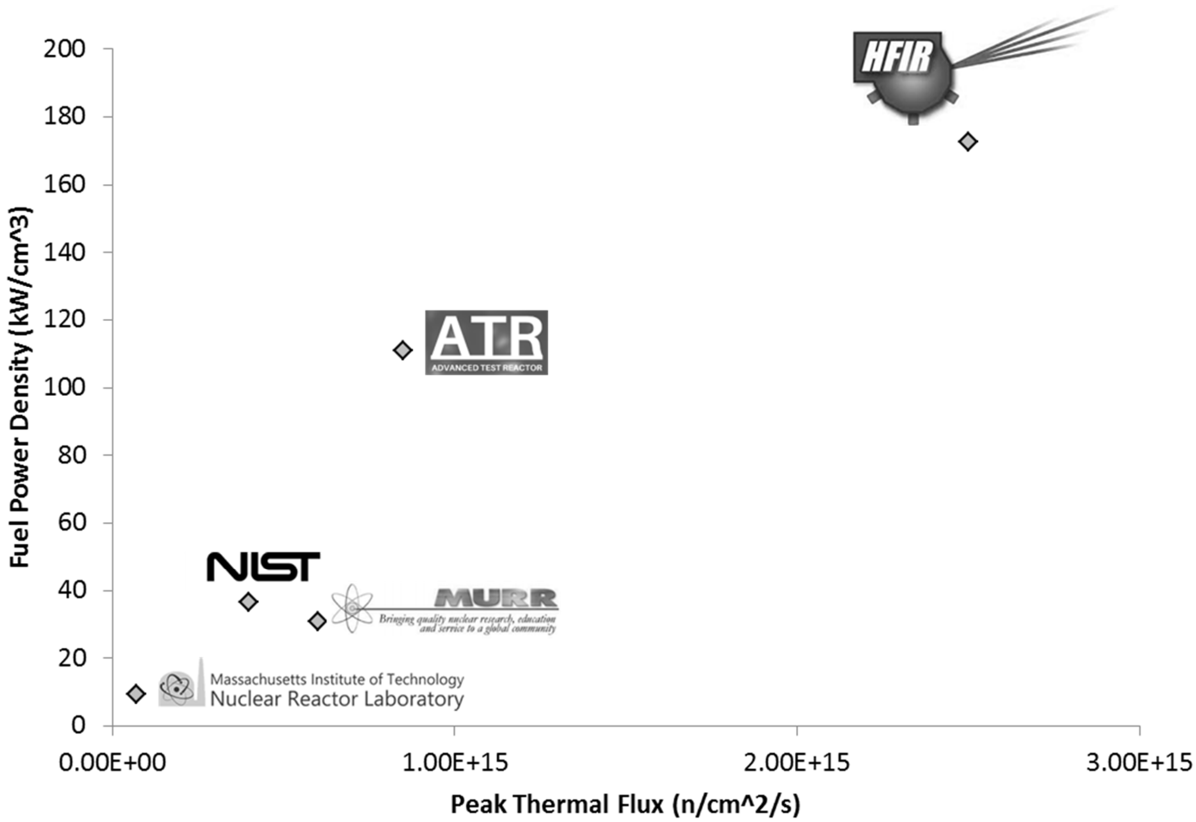


Figure 2. Fuel Power Density Vs. Peak Thermal Neutron Flux for the U.S. High Power Research Reactors

Flow testing of experimental hardware provides valuable information about the hydro-mechanical behaviour of uranium-molybdenum (U–Mo) monolithic fuel. It is also used to qualify the hydro-mechanical performance of irradiation experimental hardware prior to installation in the ATR. Flow testing of irradiation-test hardware and fuel plates prior to reactor insertion provides an opportunity to quantify flow characteristics of experimental hardware for validation of computational modeling, with the intent of identifying potential issues, avoiding in-reactor failures, and providing the highest accuracy characteristic to the fuel development programs for predictive and as-run analyses [2].

The unique and varied geometries of the fuel development tests each provide opportunities to glean useful information about the performance of fuel plates, experimental assemblies, the accuracy of the analytical methods currently employed, and/or validation data for new computational techniques. The mini-plate-1 (MP-1) experiments located in both the Large-B and South Flux Trap positions in the ATR [3]; the Full-Sized Plate-1 (FSP-1), and most recently, ATR Full size plate In-center flux trap position-7 (AFIP-7) [3], have each contributed to the program's understanding of the flow fields affecting the fuel plates under in-pile conditions.

2 METHODS

Any given fuel qualification experiment entails a series of design activities that create the necessary hardware for installation into the ATR and subsequent irradiation. The design process calls for initial scoping assessments to determine feasibility of the experiment relative to programmatic objectives and safety requirements. Computational and analytical models are used to evaluate the performance of the experiment [4-9]. In general, one dimensional codes and analytical formula are employed at this stage. Upon determining feasibility the experiment moves into the design phase, in which the hardware is detailed and the computational predictions are refined. During this phase, flow test hardware that mimics the reactor position is also designed so that a representative flow test can be performed on hardware of similar design to that which will be irradiated. Flow tests are performed to quantify the flow characteristics of the experiment, which typically includes Reynolds number sweeps where pressure drop, velocity, and sometimes acceleration is measured. The data from the flow test is then analysed and the experimentally-derived characteristics are then used to calibrate the computational or analytic models of the experiment [10]. Finally, these models are used for various predictive uses, from determining whether the experiment will achieve programmatic goals to whether the experiment will pass the various safety scenarios required by the ATR's safety analysis report (SAR) [11]. The next sections will describe various ways flow testing has been employed to improve the scientific output of the HPRR-FQ campaign.

3 EXPERIMENTAL FACILITIES

The flow experiments were performed in Oregon State University's (OSU's) Hydro-Mechanical Fuel Tests Facility (HMFTF). The HMFTF is a large-scale thermal-hydraulic separate effects test facility located in the Advanced Nuclear Systems Engineering Laboratory (ANSEL) at OSU [12]. The facility operates under an American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance-1 (NQA-1) compliant program per Idaho National Laboratory's (INL's) quality supplier program. The facility is designed such that any element which can fit within the inner vertical height of the test section region may be tested. This is limited to a component of 4.57 m (15 foot) total length (shown in Figure 3).

OSU has been tasked by the United States Department of Energy's Global Threat Reduction Initiative Fuels Qualification Program to design, construct, and utilize a thermal hydraulic experimental test facility. The primary objective is to produce a database of information to support the qualification of the new prototypic U-Mo, low enrichment fuel forms to be utilized in high performance research reactors to allow conversion from high enrichment fuels currently in use. This data will also be used to validate computational tools used to model fluid-structure interactions. This database of information is to include fuel plate and element plastic and elastic deformation and vibration as a function of operating system pressure, temperature, and flow rate.

The HMFTF was designed to cover the operating envelope of all high performance research reactors in the US while operating under subcooled conditions. The primary loop is rated to 41.37 Bar (600 psig) and 237.8 °C (460 °F) and has the capability to operate with net flow rates ranging from 7.58 l/s (100 gpm) to 121.23 l/s (1600 gpm). Operators are able to maintain conditions within ± 0.56 °C (± 1 °F), ± 0.138 Bar (± 2 psig), and ± 0.126 l/s (± 2 gpm) during testing. In order to recreate the thermal-hydraulic conditions in reactors, the loop can be configured for up or down-flow through the test section. The experiments discussed in this report were all run at simulated ATR conditions of 2.48 MPa (360 psig), and an assumed coolant temperature of 65.5 °C (150 °F), with the exception of the FSP-1 test which was performed at 2.76 MPa (400 psig) and 79.4 °C (175 °F).

Plate vibration and deformation is measured through the use of accelerometers and strain gages strategically placed on test elements which are connected to a National Instruments PXI-express (PXIe) chassis for data acquisition. Pitot tube assemblies are used to measure the static and total pressure within each sub-channel of test elements to allow for characterization of flow bias within assembles under test. This system allows for data collection at rates up to 5 kHz for short periods of time (typically 5 seconds) over all connected instruments to allow for characterization of the frequency of test element vibrations.

Figure 3. OSU's Hydro-Mechanical Fuel Test Facility (HMFTF)

Uncertainty within the campaign of experiments detailed herein was thoroughly assessed from sensor to signal. All instruments utilized as a part of the experimental study were calibrated to direct NIST traceable standards including the data acquisition system. Herein, differential pressure, flow rate, and acceleration were used as figures of merit when comparing against the numerical simulations, these measured quantities' respective component uncertainties and total compounded uncertainties are detailed within Table I. National Instruments (NI) data acquisition system hardware was used in combination with Rosemount differential pressure transmitters and vortex flow transmitters; PCB Piezotronics Accelerometers were used to acquire dynamic motion of the experiment under hydraulic loading.

Table I. Sources of Measurement Uncertainty

Measurement	Instrument Uncertainty			Reference Value	Total Uncertainty
Diff. Pressure	Measurement Uncertainty	A/D Calibration	NI Module PXI 6229 (±5V Range)	300 psi	± 0.883 psi
	Transmitter Accuracy	Percent Span Error	Absolute Error		
	0.15% of span	0.25%	1620 µV (0.0405% Range)		
	± 0.45 psi	± 0.75 psi	± 0.1215 psi		
Flow Rate	Measurement Uncertainty	A/D Calibration	NI Module PXI 6229 (±5V Range)	420 gpm and Measured (∂)	± (1.064 + 2 gpm
	FIT	Percent Span Error	Absolute Error		
	2.0% of Rate	0.25%	1620 µV (0.0405% Range)		
	± (2.0% of ∂) gpm	± 1.05 gpm	± 0.1701 gpm		
Acceleration	Accelerometer	NI Module PXI 4497		6000 hz and Measured (f)	± (10% of f) Hz
	Instrument Accuracy	Timebase Error	Offset Error (±5V Range)		
	10% Measurement at 6000 Hz, 5% up to 5000 Hz	60 ppm or external time base	50 mV (1% Range)		
	± (10% of f) Hz	---	---		

In addition to bulk hydraulic characteristics, select tests utilized pitot tubes within the coolant channels to acquire total and static pressure; through application of Bernoulli's theorem one may approximate the local superficial velocity from these two quantities. All bulk instruments were located sufficient distance from the test elements so as not to impact the hydraulics of the experiment; however, for those tests which utilities pitot tubes, it was not feasible to remove their influence or bias from the experiment therefore two experiments were performed for each case were a pitot tube was chosen to be utilized. The first experiment was performed as the reference test with no pitot tubes – bulk pressure drop was acquired with reference to a respective flow rate; the pitot tubes were added to the geometry through locating them within an experiment's subchannels and the second test was performed – bulk pressure drop was acquired in addition to the local pressure measurements within each respective channel. The difference between the bulk pressure losses across the element for a respective flow rate when comparing the reference test to the second test provided an explicit measurement of bias in hydraulics for which these instruments influence the outcome of the experiment. This bias was then taken into account when synthesizing all data.

4 EXPERIMENT DESCRIPTION

The following experiments were designed with input from flow testing: MP-1 Large B, MP-1 SFT/CDIPT, FSP-1, and AFIP-7[i]. In each case, flow testing contributed significantly to the final experiment design and its analysis. This section will describe the geometry of the experiments and their associated flow testing hardware, and later sections will explain the use of the data and its contribution to each experiment.

MP-1

The MP-1 experiment consists of three separate experiments to accommodate the various power/fluence scenarios presented in Figure 2. This was accomplished with three experiments: a 'Low Power' experiment which, in turn, was three separate baskets irradiated in 'Large-B' positions of the ATR, the 'Medium Power' experiment, irradiated in the south flux trap of the ATR with capsules located in the top and bottom (lower neutron flux) regions of the core, and the 'High Power' experiment, of the same configuration as the 'Medium Power', but with the capsules located in the vertical center of the basket, at the peak of the neutron flux profile of the

[i] The AFIP-7 design was completed without flow testing, but flow testing was performed post-irradiation to assess thermal/hydro-dynamic characteristics to improve as-run assessments.

ATR [3]. To accommodate these various power-based experiments, two sets of flow tests were required, one for the Large-B position, and another for the South Flux Trap position.

MP-1 Large B

The first mini-plate experiment flow tested at OSU was a drop-in basket experiment for the 'Large B' positions of the ATR [4,6]. The experiment consists of four capsules (A – D), each housing three to four mini-plates in a 4 x 2 plate array. These plates are fitted into grooves in the internal side walls of the capsules and then a stopper is welded into place. In some experiments, hafnium plates are inserted into the walls of the capsule to reduce edge peaking effects. The MP-1 basket, capsules and spacers are shown in Figure 4.

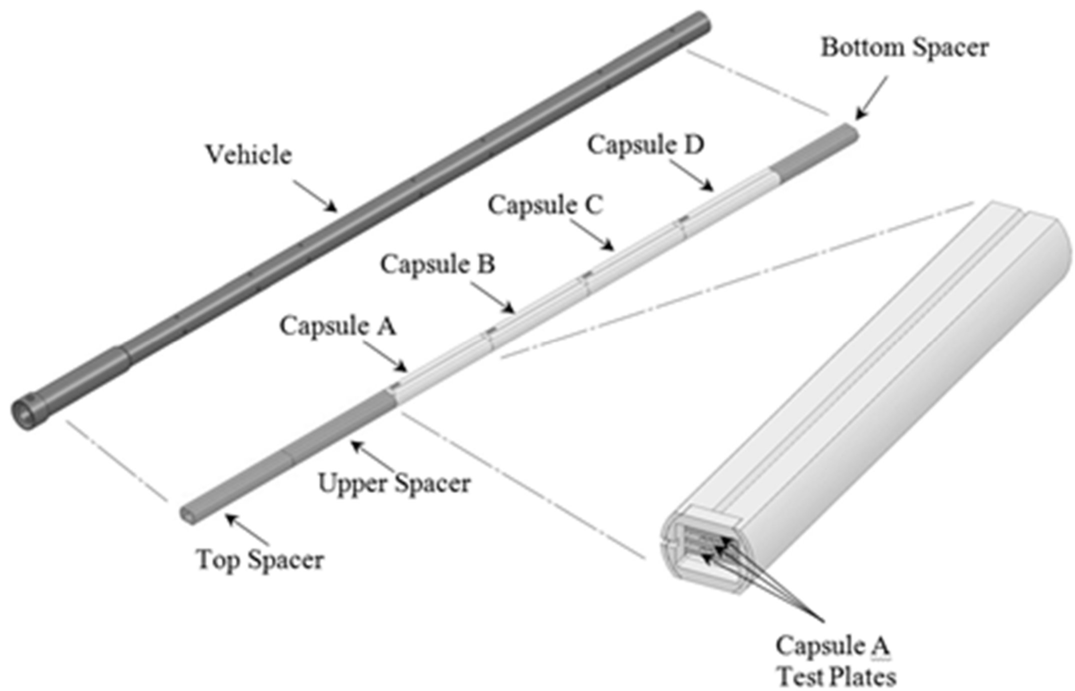


Figure 4. MP-1 experiment hardware

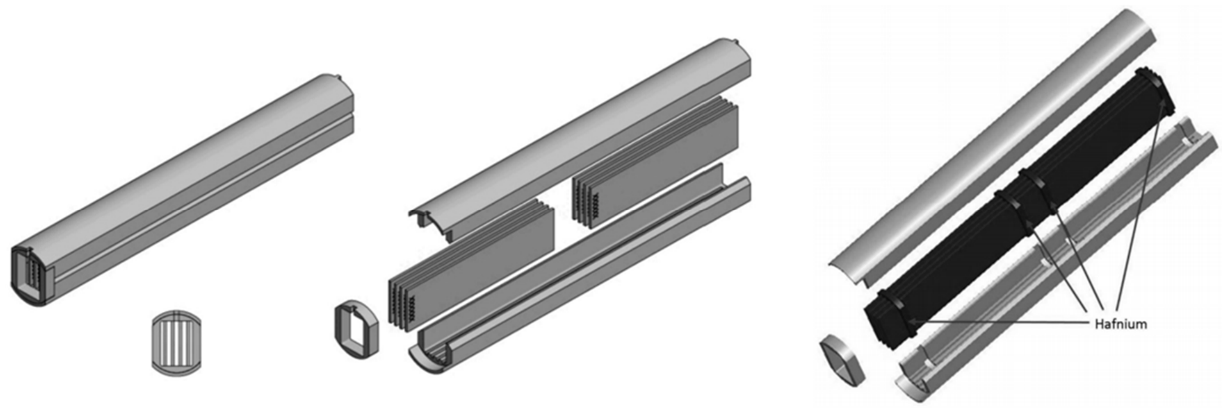


Figure 5. MP-1 capsule assembly (hafnium filter shown in purple)

OSU's HMFTF was fitted with a 'Large B' position emulator, into which the basket was inserted. The position emulator is shown in Figure 6, which also shows the basket inserted and the locations of the accelerometers.

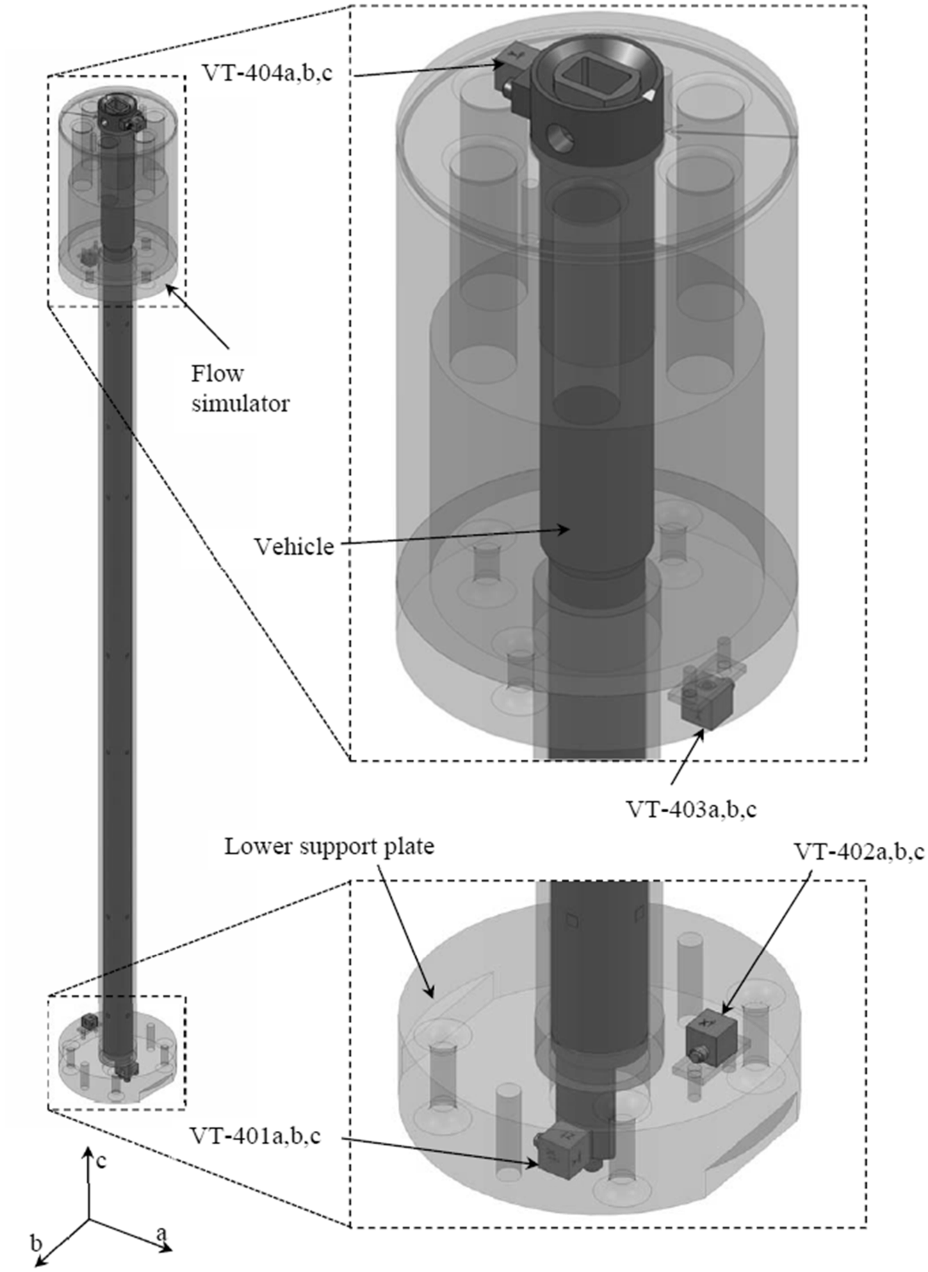


Figure 6. Large B position emulator (grey) with basket (blue) and accelerometers (green)

<u>MP-1 SFT/CDIPT</u>

The second experiment flow tested at OSU was the MP-1 South Flux Trap / Chopped Dummy In-Pile Tube (MP-1 SFT/CDIPT) experiment, which is a drop-in basket that will be irradiated in the south flux trap of the ATR [5-7]. The chopped dummy in-pile tube is the hardware in the ATR SFT to which the basket mates. The MP-1 SFT/CDIPT experiment basket has two bore holes into which capsules and spacers are inserted. At the bottom of the stack of capsules is a throttling capsule, which passively controls the flow rate through the experiment. The hardware for the MP-1 SFT/CDIPT experiment is shown in Figure 7, and the SFT/CDIPT position emulator is shown in Figure 8.

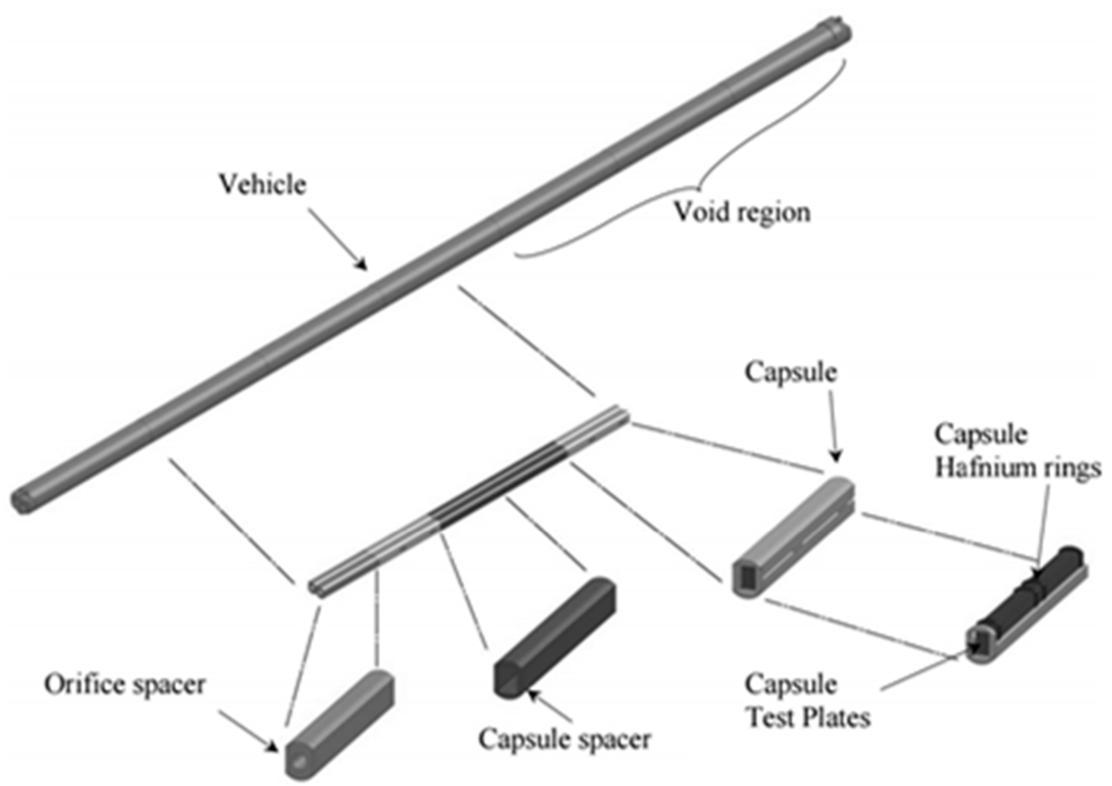


Figure 7. MP-1 SFT/CDIPT experiment hardware

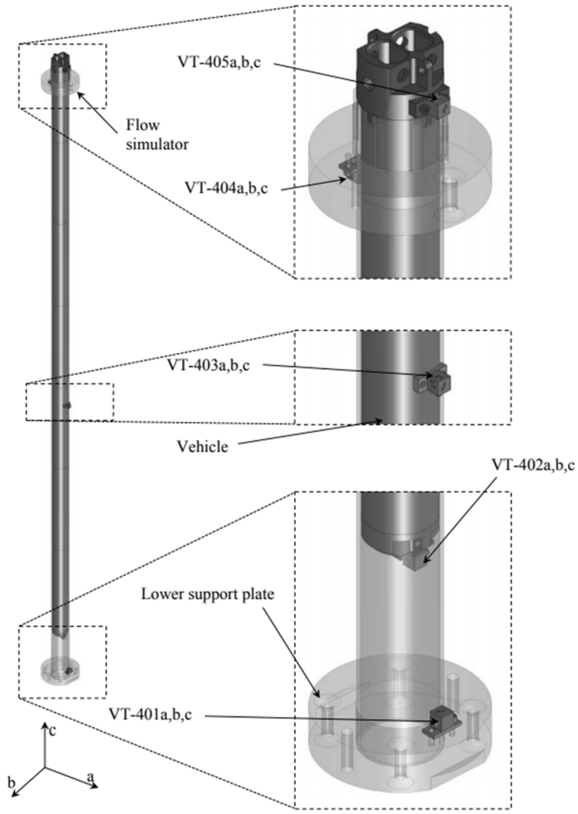


Figure 8. South Flux Trap/Chopped Dummy In-Pile Tube emulator (grey) with experiment installed (blue) and accelerometers (green)

FSP-1

The FSP-1 experiment is a full-sized plate experiment designed to investigate the performance of the fuel with a plate that is more representative of the final plate geometry [8,9]. This reduces the influence of edge peaking on the interior of the plate and allows for the evaluation of the fabrication process of the various configurations. The fuel plates in FSP-1 were fabricated with depleted uranium for the monolithic fuels and steel pellets for the dispersion fuel. The experiment configuration is a inner/outer basket geometry, where the inner basket houses six simulated flat fuel plates, and the outer basket houses the inner basket. This is all inserted into the north-east (NE) flux trap of the ATR. The experiment geometry and NE flux trap adapter are shown in Figure 9.

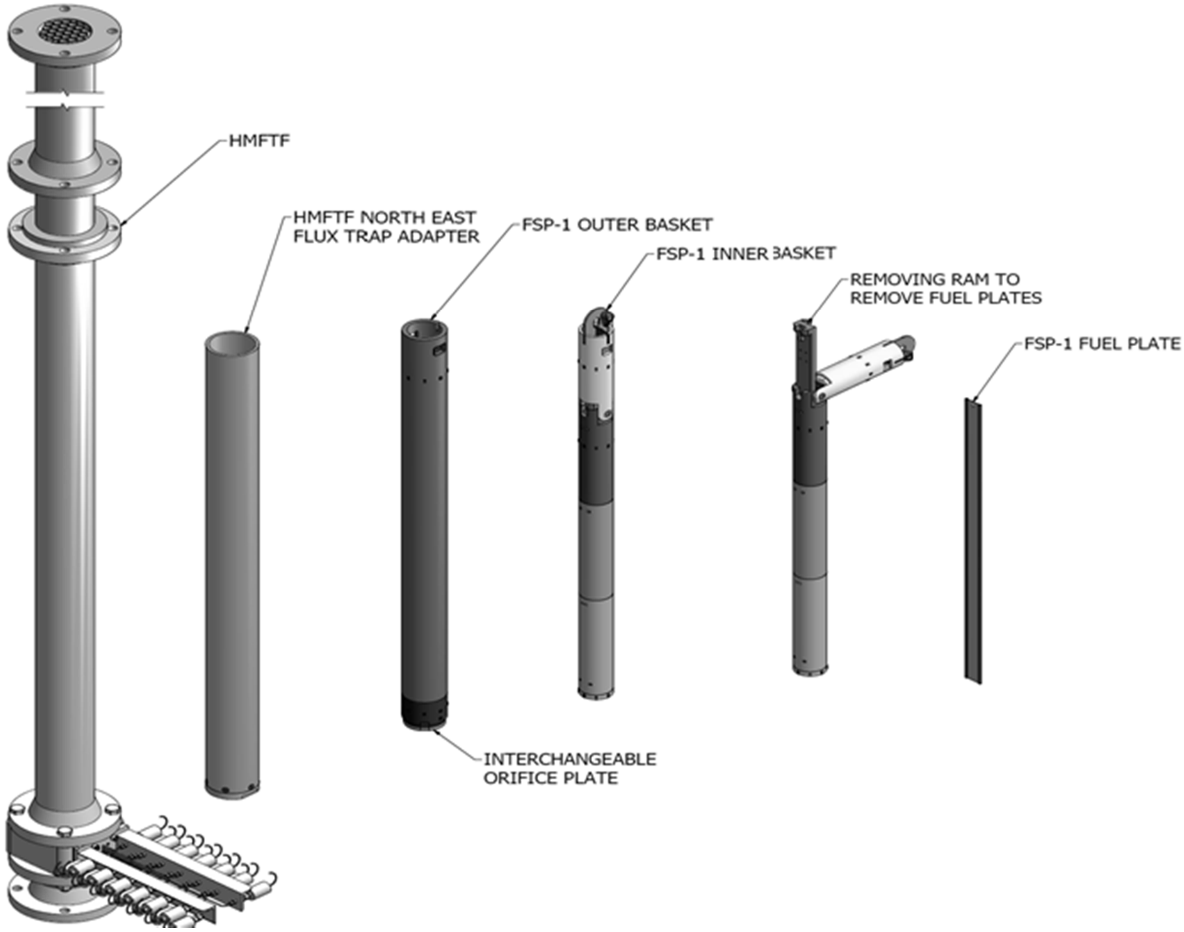


Figure 9. FSP-1 experiment, with NE flux trap adapter and HMFTF tests section shown

AFIP-7

The AFIP-7 experiment is, again, a drop-in basket housing a fuel plate array [13]. The plate array in this case is a swaged assembly of four curved plates, representative of plate 19 of the ATR fuel assembly. It was irradiated in the center flux trap of the ATR. Its safety basis was developed from RELAP5 simulations, and flow testing was performed post-irradiation to better quantify the flow in the experiment. The experiment and the flow simulator for the center flux trap are shown in Figure 10.

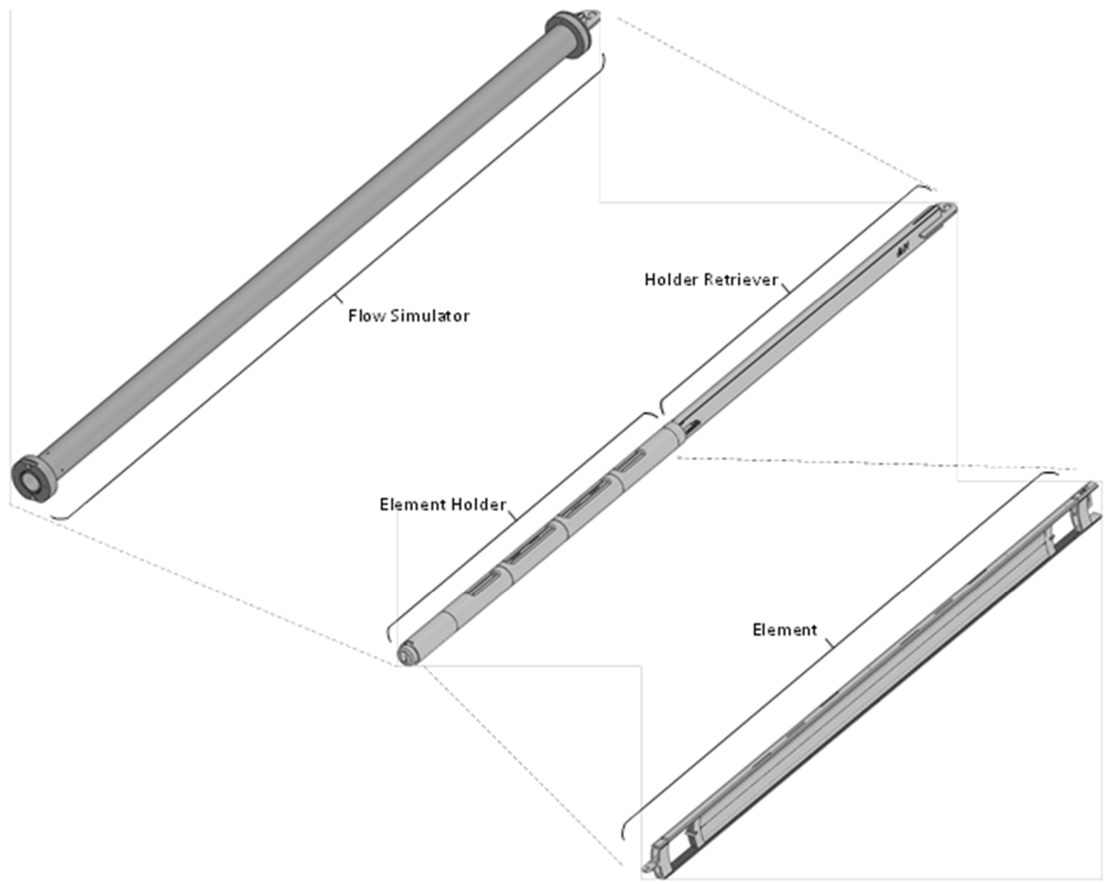


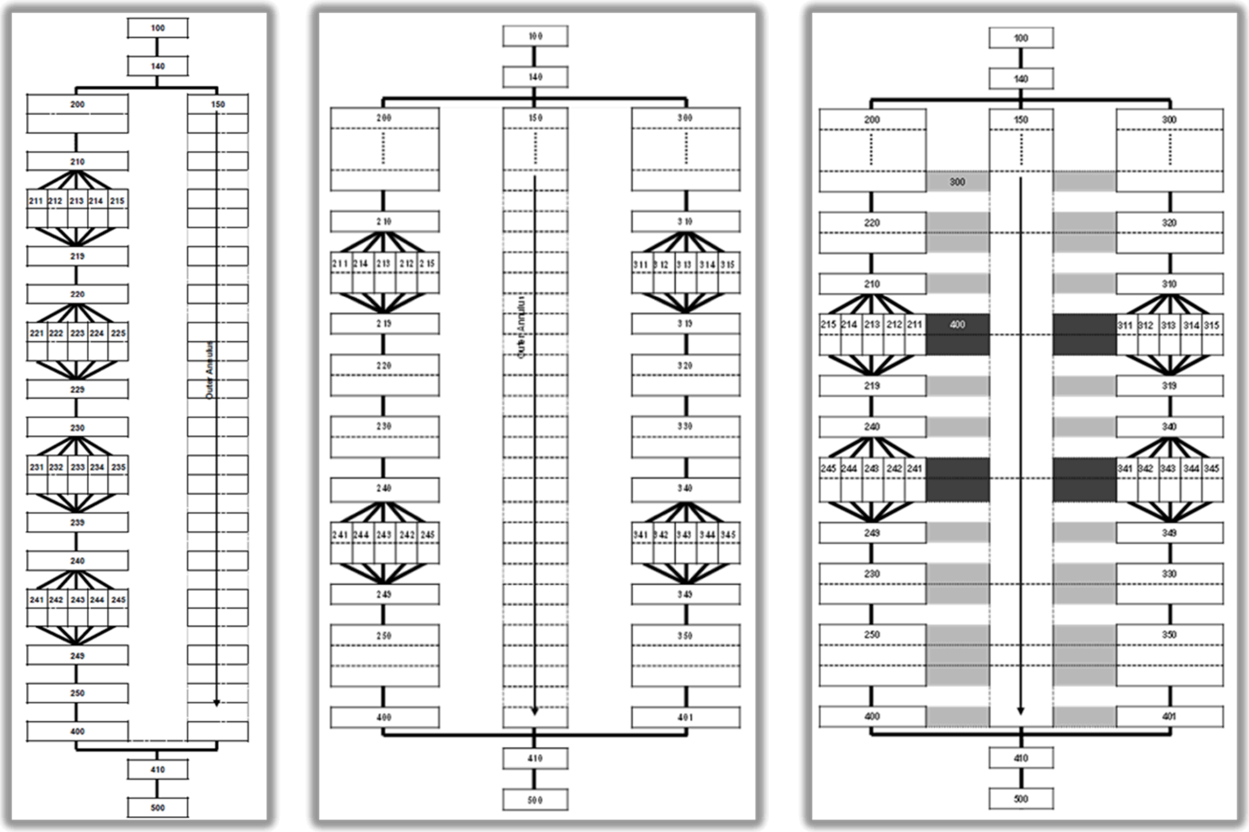
Figure 10. AFIP-7 experiment hardware and position simulator for flow tests

5 MODELING DESCRIPTION

Modeling of the various experiments was performed with a variety of software programs, methods, and applications, using a graded approach determined by the experimental needs and level of detail required to determine the various parameters in question for a given experiment. The typical methods of modeling the thermo/hydro response of an experiment are captured in INL's GDE-588, but analysts have the flexibility to choose the best method for a given task, assuming it can be verified and validated for the application. Some of the software used to model the USHPRR-FQ experiments are: RELAP5 [14], ABAQUS [15], STAR-CCM+ [16], HEEDS [17], COMSOL [18], MATLAB [19], MATHCAD [20], and EXCEL [21]. Note that the mention of a particular package does not constitute an endorsement thereof, merely a reflection of an analyst's assessment of the most appropriate computational tool based on current license availability, software capability, current Verification & Validation (V&V) status at INL, inter-operability with other software, and analyst and reviewer familiarity. The following sections will describe the computational and analytic models created for each experiment.

MP-1 Modeling

The method used for the MP-1 analysis was to build a RELAP5 model to determine flow rates in the experiment, next, derive heat transfer coefficients based on the RELAP5 results then apply those flow rates and heat transfer coefficients to the ABAQUS model [4-6]. ABAQUS modeling provides the 3-dimensional temperature field of the experiment, and allows for an assessment of localized critical heat flux (CHF) to support the safety requirements of the ATR's safety analysis report (SAR). The RELAP5 component diagram for the three MP-1 tests are shown in Figure 11, and representative ABAQUS models are shown in Figure 12 and Figure 13.



MP-1 Low Power MP-1 Medium Power MP-1 High Power

Figure 11. RELAP5 models of the MP-1 experiments

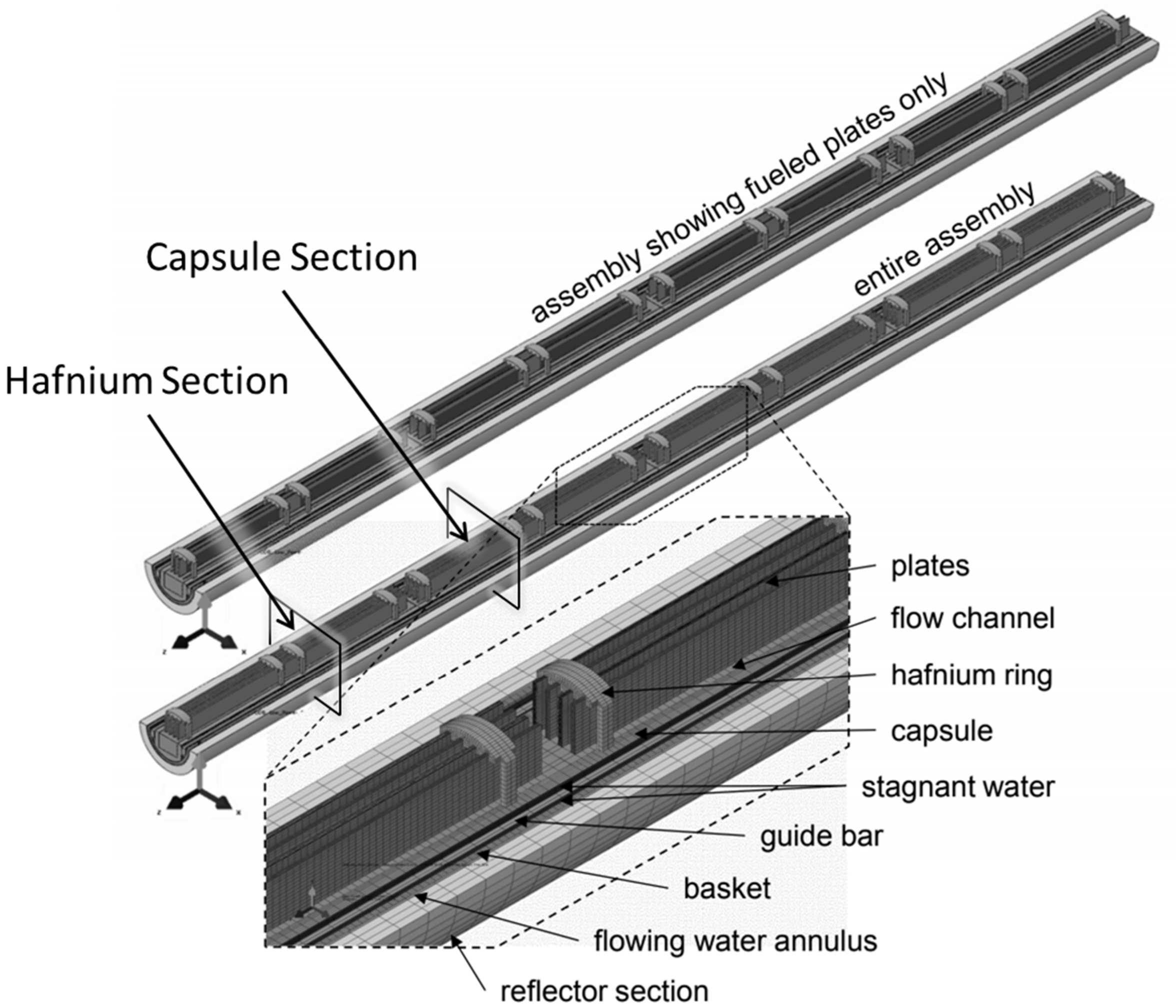


Figure 12. ABAQUS model of the MP-1 Low Power experiment with Fig. 13 section locations

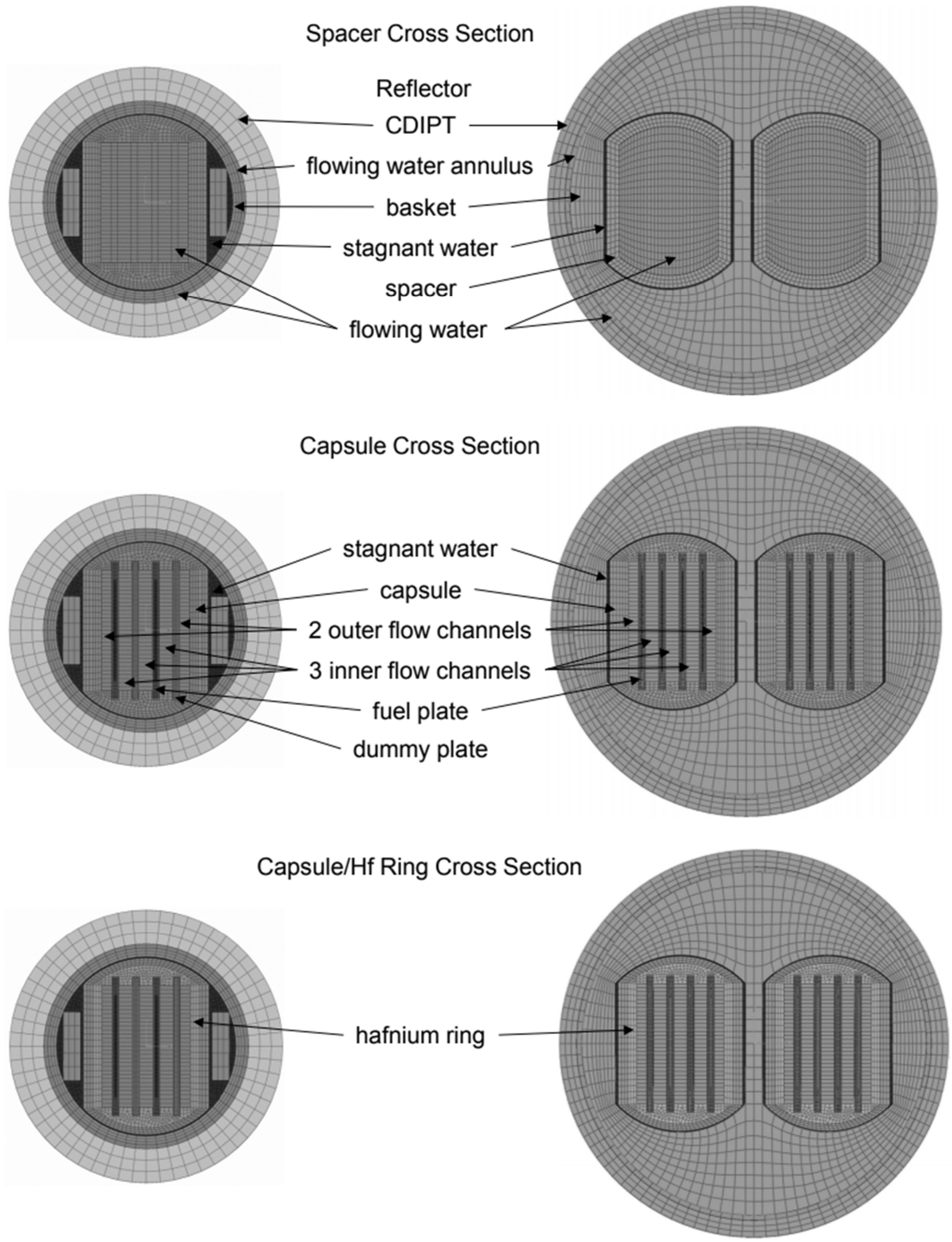


Figure 13. ABAQUS models of the Medium and High power MP-1 experiments (cross section locations from Figure 12)

FSP-1 Modeling

The method used for the FSP-1 analysis was nearly identical to that of MP-1 [8,9]: first, build a RELAP5 model to determine flow rates in the experiment, next, derive heat transfer coefficients based on the RELAP5 results then apply those flow rates and heat transfer coefficients to the ABAQUS model. The RELAP5 component diagram for the FSP-1 test is shown inFigure 14, and representative ABAQUS model is shown in Figure 15.

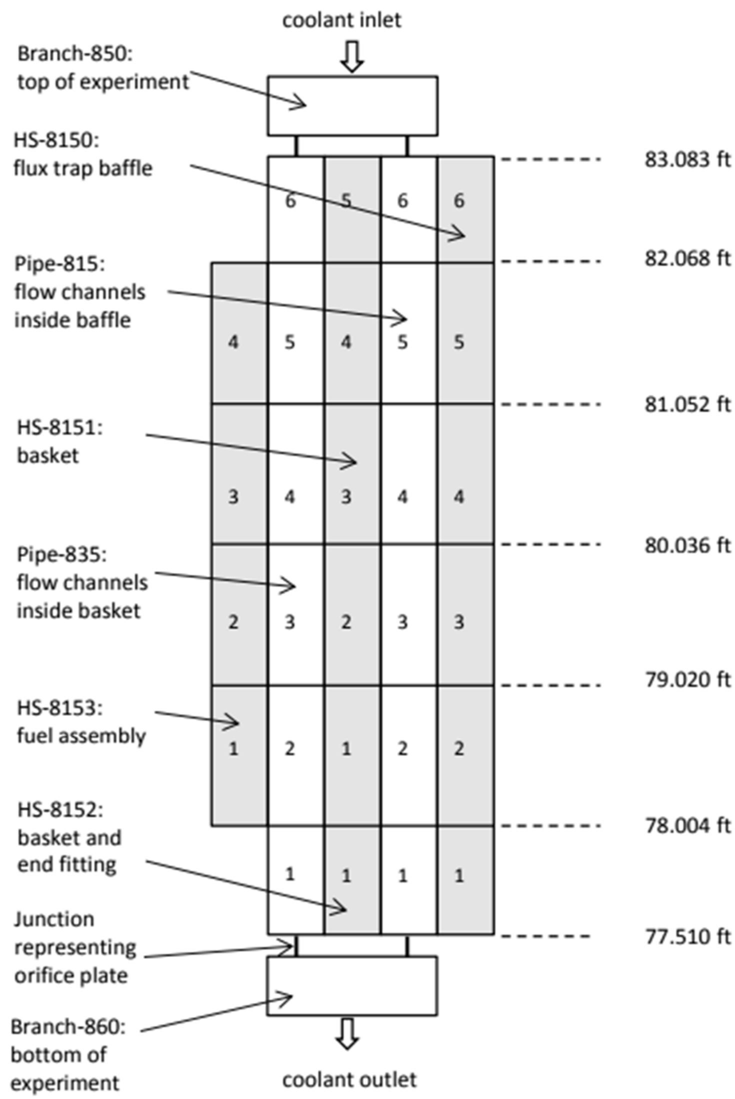


Figure 14. FSP-1 RELAP5 model

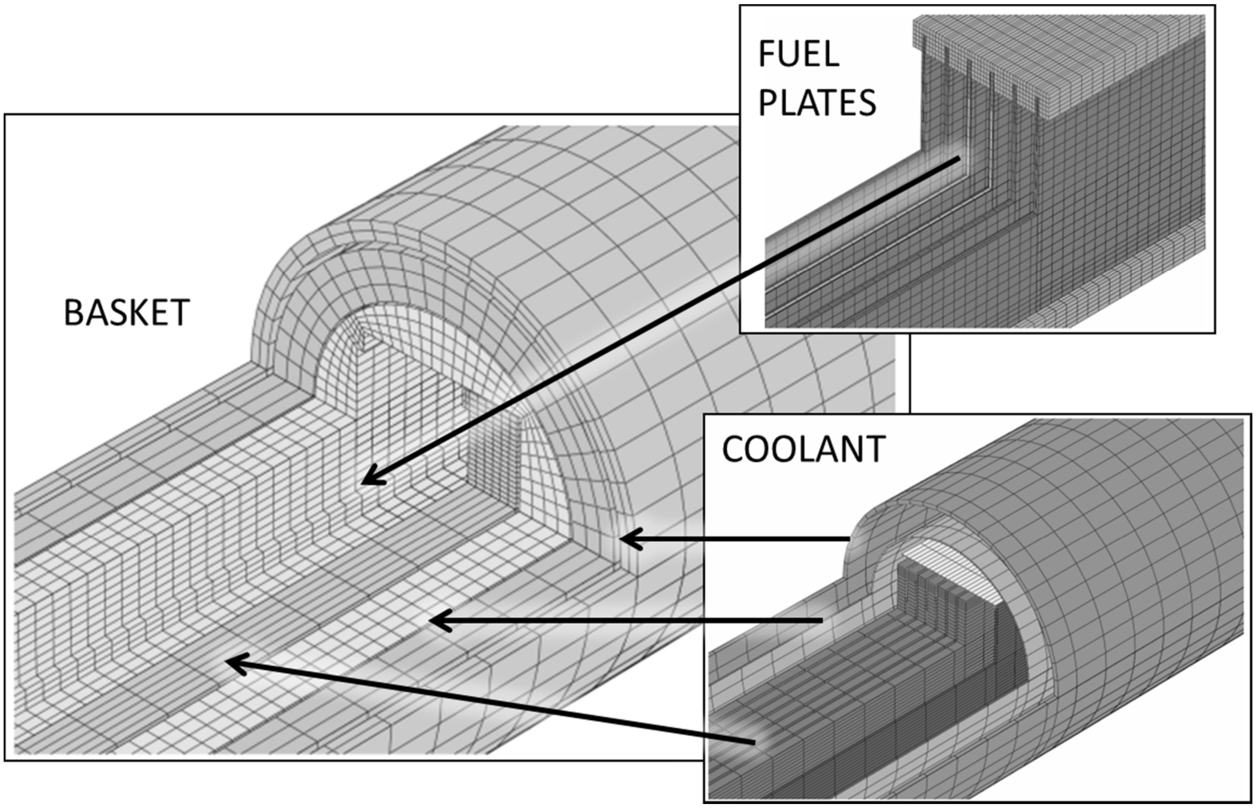


Figure 15. FSP-1 ABAQUS model (exploded view)

AFIP-7 Modeling

AFIP-7 was initially modelled in RELAP5[22], with heat structures allowing for the assessment of a natural convection scenario, shown in Figure 16. Additionally, an ABAQUS model was built to assess the safety-related transient scenarios required by the ATR, a section of which is shown in Figure 17. Finally, after irradiation was complete, a CFD model was built to gain a better understanding of the distribution of the flow in the experiment [23]. Note that the current model does not account for fuel swelling or other irradiation effects. A cross-section of the polyhedral mesh taken around the entrance of the 'fuelled' section of the experiment is shown in Figure 18.

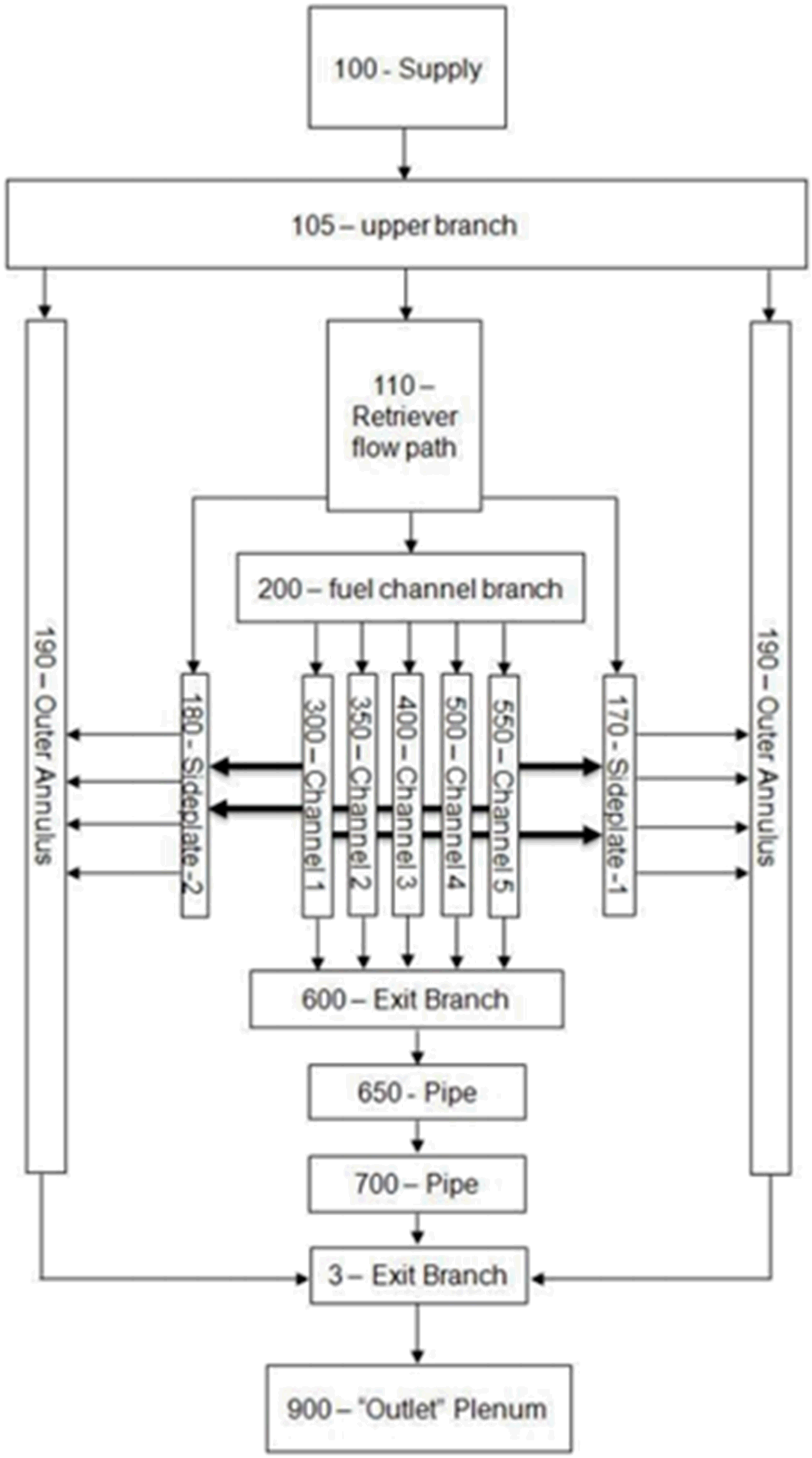


Figure 16. Original RELAP5 model of the AFIP-7 experiment

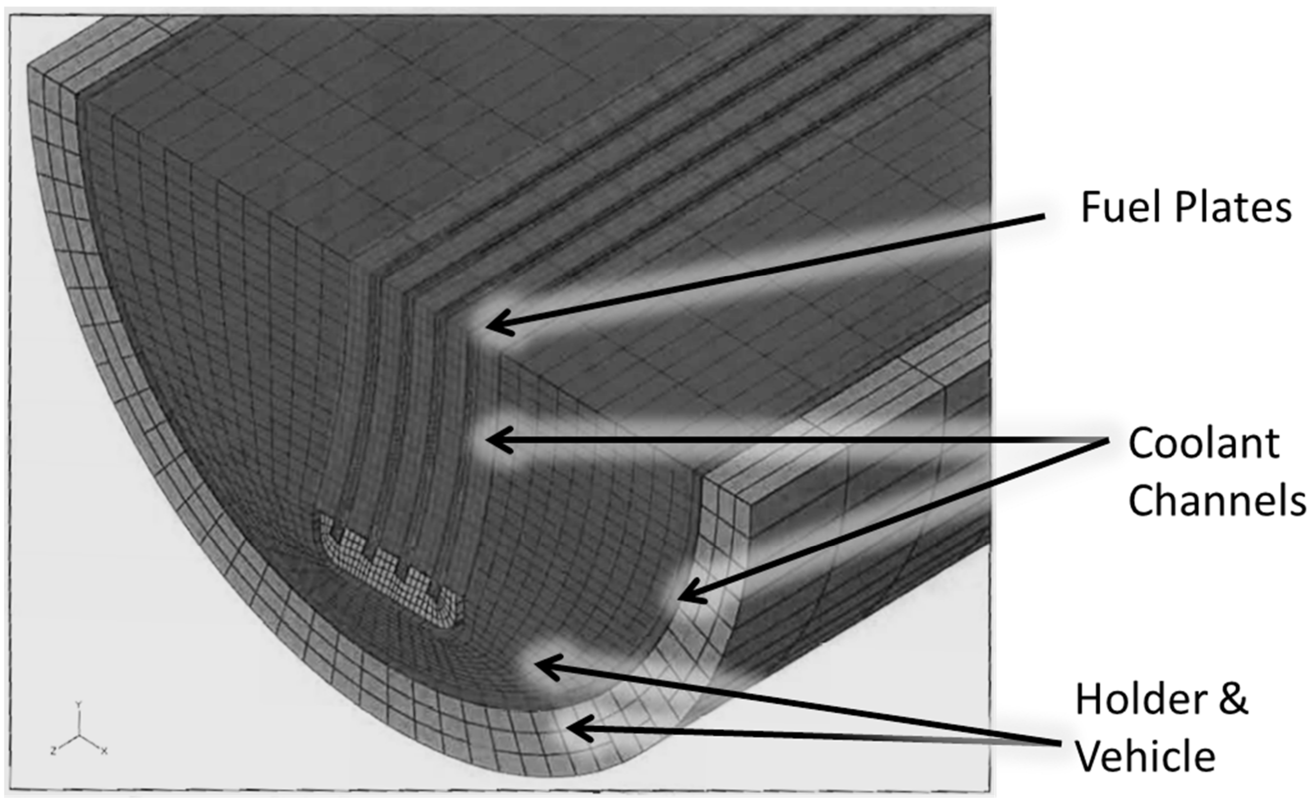


Figure 17. ABAQUS finite element model of the AFIP-7 experiment

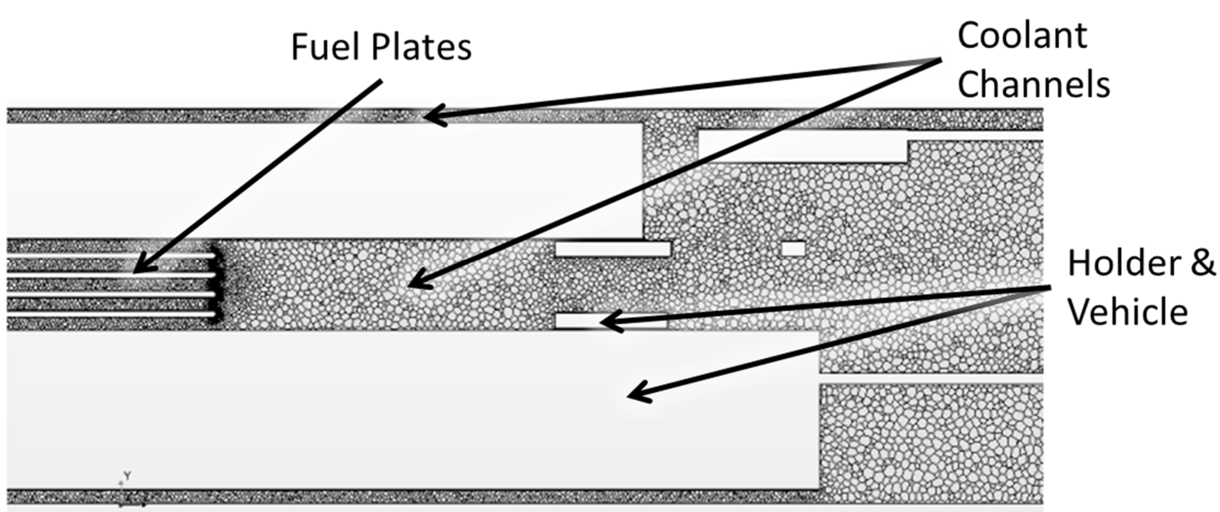


Figure 18. CFD mesh of AFIP-7 experiment - inlet of fuel assembly and outer annulus

6 RESULTS & DISCUSSION

Each experiment's flow test provided a unique opportunity to illuminate aspects of the flow field that otherwise would have been occluded in a base assumption about the given test. The contribution to each test will be discussed separately.

MP-1 Low, Medium, High Power Experiments & EMPIrE

The Large-B experiment performed for the benefit of the MP-1 Low-Power experiment, being relatively simple from a hydro-mechanical perspective, afforded the opportunity to compare the performance of RELAP5 modeling to test data [6]. Previously, RELAP5 models would be built with subject-matter-expert-derived reasonable values for parameters such as surface roughness, Reynolds-independent loss coefficients, channel aspect ratio effects, and friction factor correlation. Using a state-of-the-art commercially available optimization package (HEEDS), the flow testing team was able to optimize the RELAP5 model of the MP-1 Large-B experiment to reduce the RMS error of the modelled data vs the experimental data by an order of magnitude. This, in turn, allowed the use of high-confidence coolant velocity values for the thermal safety analysis, without which, the experiment would not have passed (due to compounded safety margins of Large-B positions). The results of the optimization study are summarized in Figure 19. Additionally, the vibrations of the basket were collected and analyzed. The response of the experiment under flow can be seen in Figure 19. The assessment of this motion increased the understanding of the motion of cylinders in parallel annular flow, and represented a higher bound on the buckling response of thin cylinders in flow [24-27].

The SFT/CDIPT experiments afforded similar opportunities, allowing for high-confidence selection of orifice spacers to optimize plate target temperatures while still achieving all safety margins for the ATR. Both the MP-1 High Power experiment and the EMPIrE experiment, without flow testing, would have been fitted with an oversize orifice for the sake of conservatism in the safety analysis, which would have resulted in cooler, less representative plates.

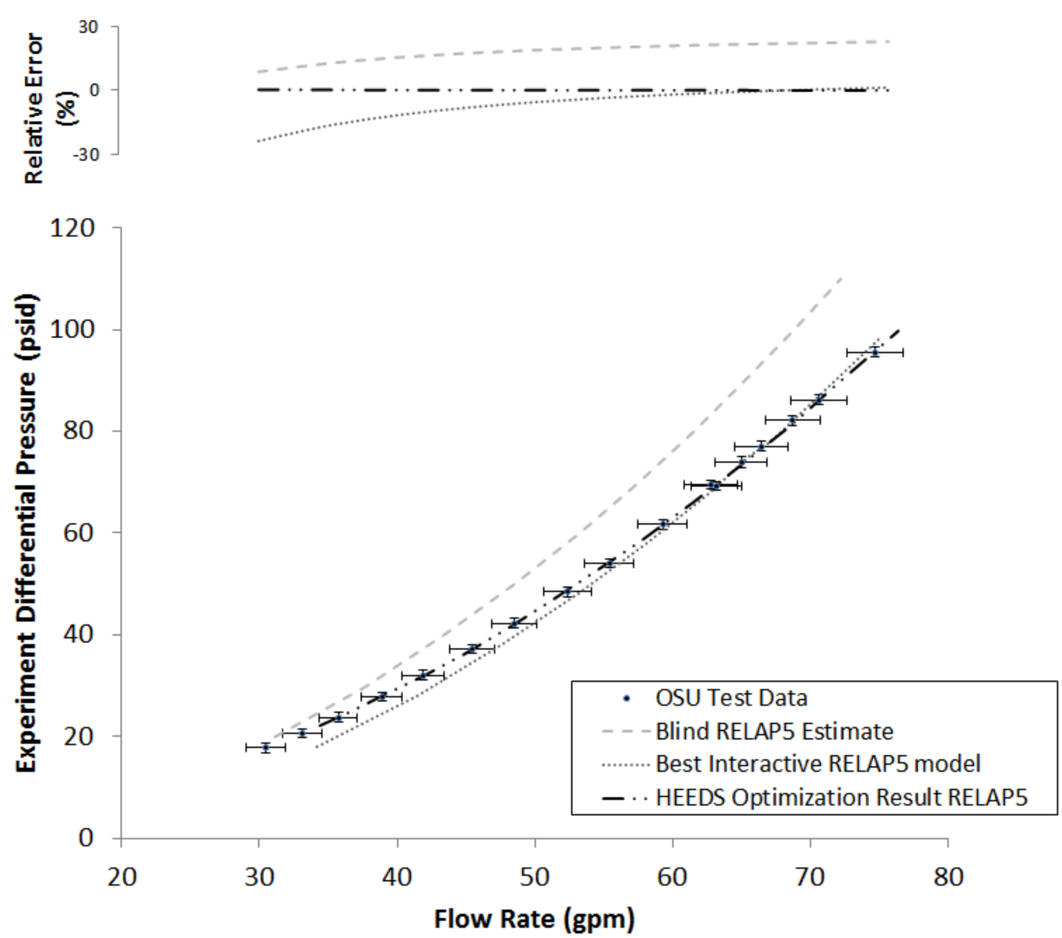


Figure 19. Results of optmization study on the Large-B Basket flow test data

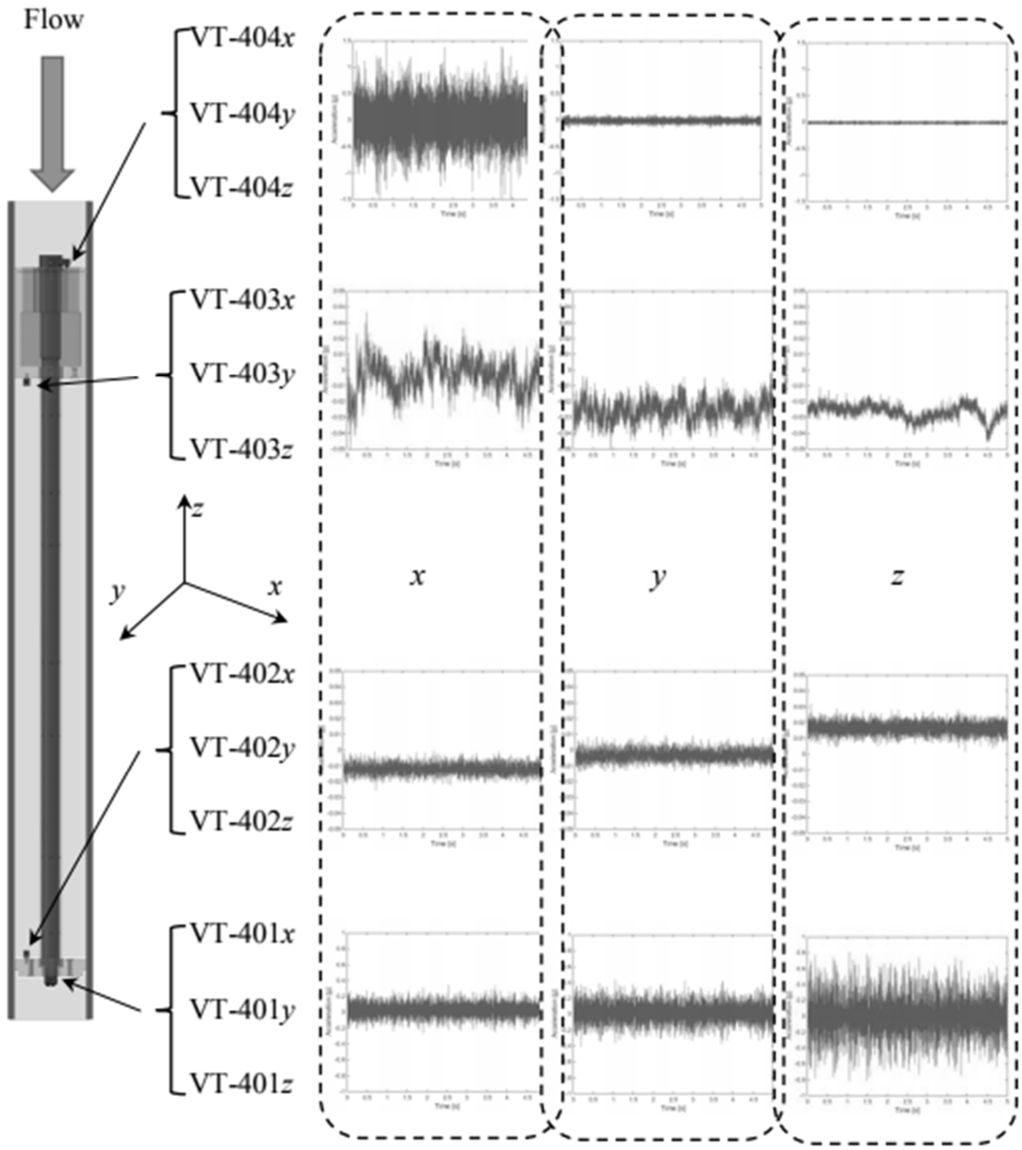


Figure 20. Tri-axial acceleration response of the MP-1 Large B experiment basket under flow.

FSP-1 Flow Test Experiment

The FSP-1 flow test campaign was used to progressively select the appropriate orifice size for the experiment outlet to achieve the targeted flow rate for the experiment [8,9]. Figure 21 shows the progression of system characteristic coolant velocity, from the initial SME 'reasonable value'-determined orifice size (1.44 inch in TEST-001) to the final orifice size (1.244 inch in

TEST-005). Inspection of the data in Figure 21 shows that if the initial orifice had been selected without flow test confirmation, the flow would have exceeded the target value by approximately 20%, based on the difference between the initial 1.44” data and the final 1.24” data at 73.3 core delta-P. Additionally, the final two FSP-1 tests were performed with depleted uranium (DU) plates fabricated exactly as the FSP-1 monolithic plates. Examination of the data shows that under all expected flow conditions, the (unheated) plates perform similarly to the surrogate aluminium plates used in the early rounds of testing. Additionally, during a high-flow excursion to extreme ATR limits of pressure differential and flow velocity, the plates experienced minimal deformation, leading to high confidence of successful irradiation in the ATR. The various orifice plates are shown in Figure 22.

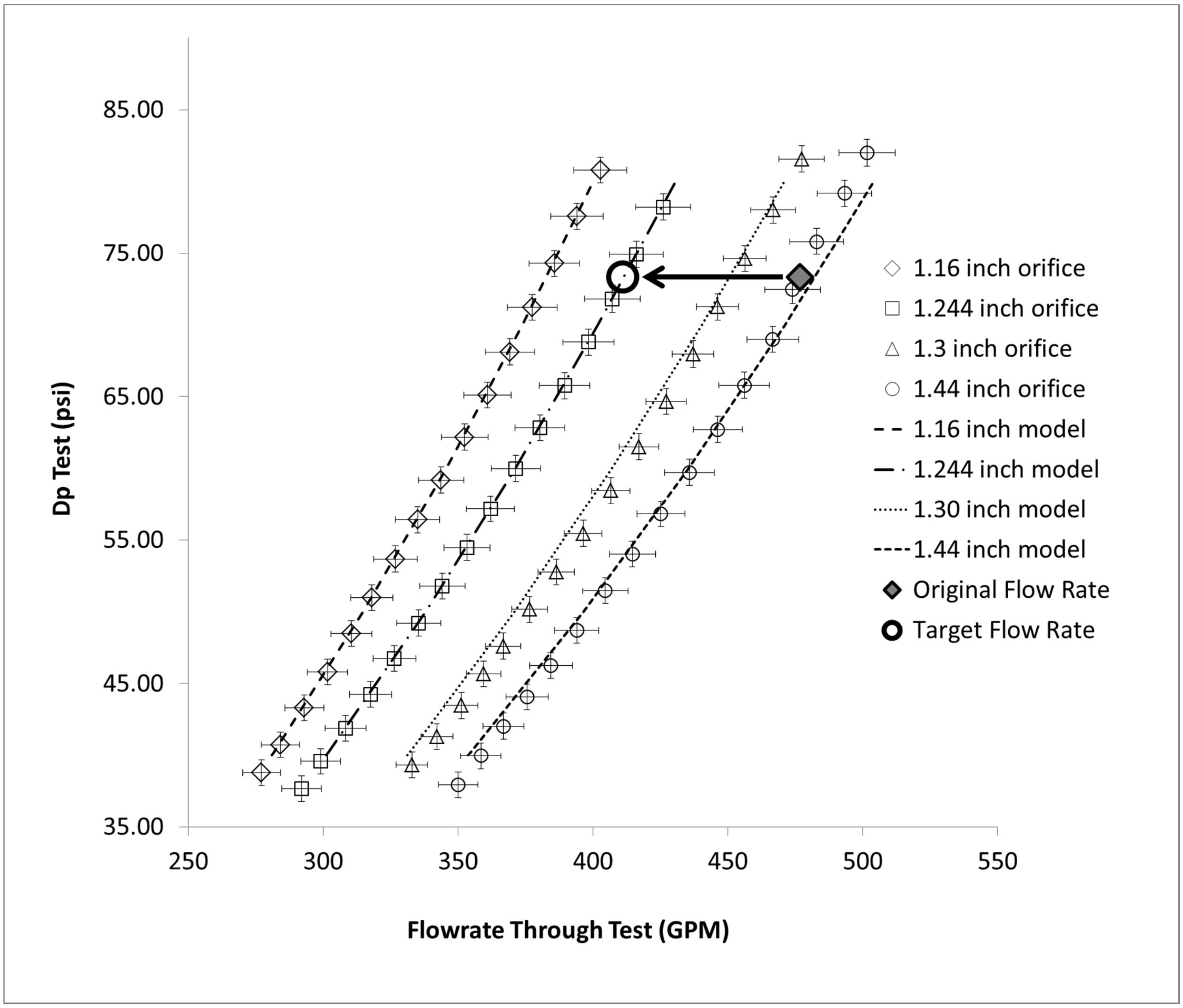


Figure 21. Variation of coolant velocity with orifice size (in) for FSP-1 tests, target rate indicated

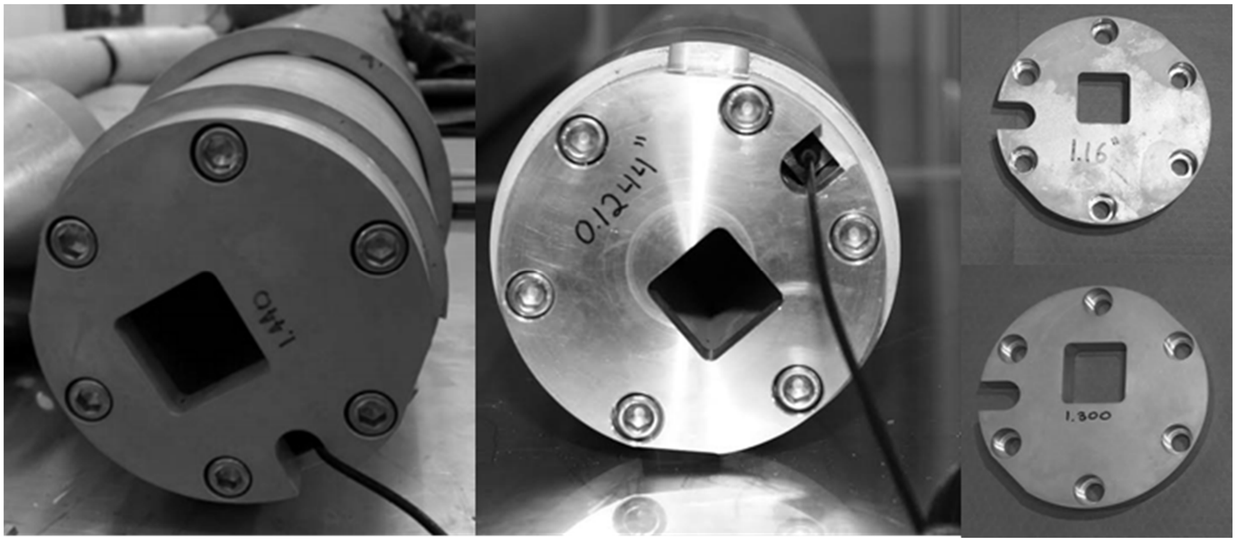


Figure 22. Initial (1.44”), final (1.244”), and interim orifice plates flow tested for FSP-1

AFIP-7 Flow Test Experiment

AFIP-7 was the most hydraulically complex experiment of the fuel qualification effort. Side vents in the fuel assembly designed to equalize pressure between channels interacted with slots in the basket designed to allow for post-irradiation natural convection. This created large variations in the velocity fields, as well as paths for relatively cooler flow to enter the experiment in the lower elevations. Computational fluid dynamics (CFD) was employed to diagnose the flows within the channels [23]. The velocity magnitude fields for each channel are shown in Figure 23. A streamline investigation mapping flow from the side vents in the central channels showed that the flow not only has a propensity to exit the fuel assembly, but also re-enter at a lower vent, as can be seen in Figure 24. Investigation of the effect these variations have on the plate performance is pending.

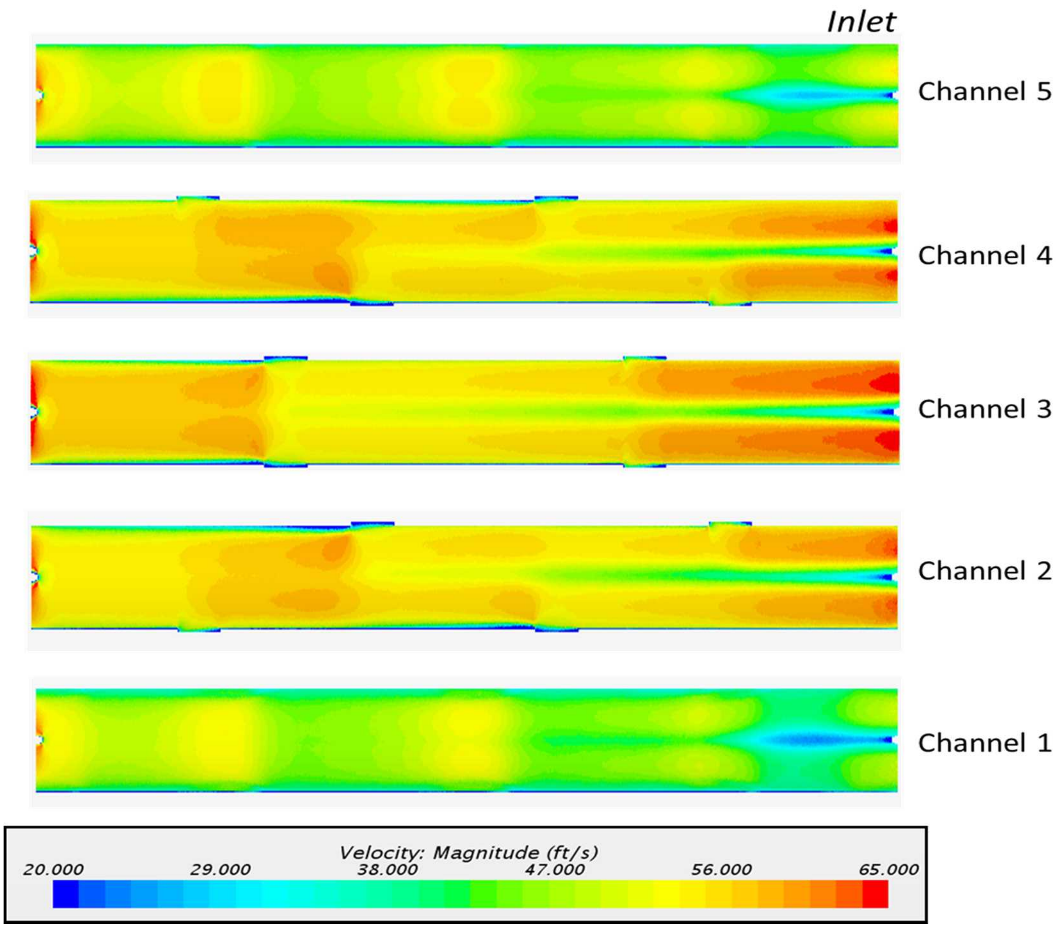


Figure 23. Flow velocity magnitude maps for AFIP-7, channels 1-5, via CFD

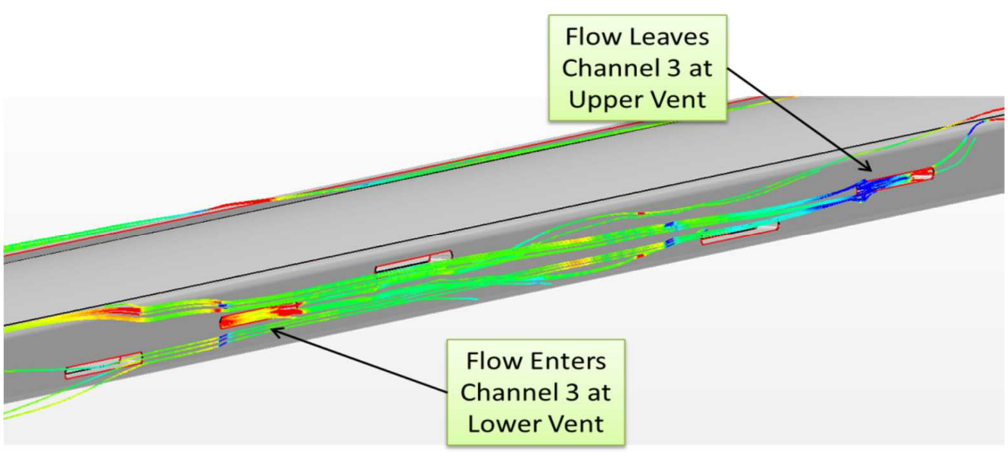


Figure 24. Streamlines from the upper vent show re-entrance of the flow into lower vents

The CFD model of AFIP-7 also provided insight into the hydro-mechanical performance of the plates themselves. Figure 25 shows the experimental measurements of the flow velocity in the middle three channels of AFIP-7, along with CFD-derived measurements of the same metric. The enveloping of the CFD by the experimental data could be attributed to the rigidity of the boundaries in the CFD. Slight deformations of the fuel plates caused by channel-to-channel pressure differentials would enhance the relative difference between the velocity of the middle channel (higher) and its neighbors (lower). While not quantifiable without a measure of deformation during the test, the data indicates that plate deformation in AFIP-7 plates is slight and has a minor effect on the channel velocities in the experiment.

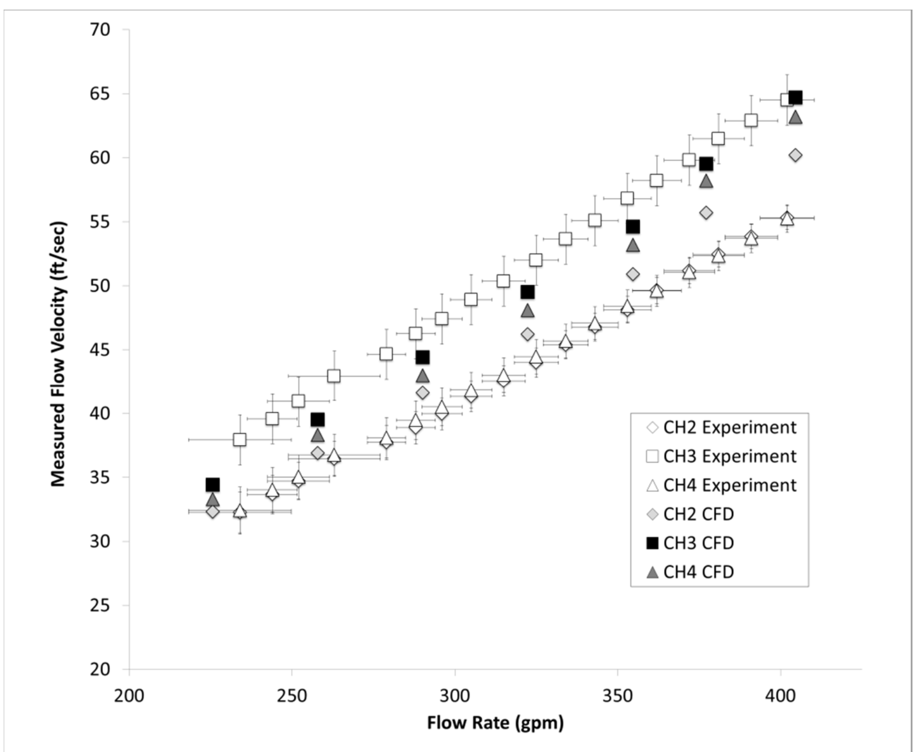


Figure 25. Experimental and computational pitot-tube flow channel velocities for AFIP-7

7 SUMMARY

The NNSA M3 USHPRR FQ program has instituted a flow test experimental verification campaign to enhance the design, safety qualification, and as-run analysis of its fuel qualification mission. Every experiment has provided important information regarding the coolant flow fields in the hardware that was either unexpected (such as in the case of AFIP-7 intra-channel flow velocity variation), or under/over-estimated from first principles and best practices (MP-1 Low Power flow rate, FSP-1 orifice size). The data collected from the flow tests was used in various ways to provide the program with higher confidence in the thermo/hydraulic parameters that contribute to safety, predictive, and as-run analyses, allowing experiments to be irradiated as planned, and alleviating any flow velocity- or heat transfer coefficient- related potential mis-conceptions about post-irradiation examination results in future years. Having high confidence, NQA-1 certified data was made possible by the foresight of INL and OSU researchers in developing the HMFTF at OSU, which was designed to be re-configurable and accommodate a wide range of thermal/hydraulic conditions and experiment geometry. The program also has the confidence generated by running endurance tests on representative hardware, to illustrate the robustness of the experimental hardware under extended reactor-like flow conditions. Finally, the viability and usefulness of applying optimization software to experimental data has been illustrated through the Large-B pressure/flow characteristic study, which allowed for confidence in the use of flow velocities that were greater than those initially predicted by first principles and 1-D codes, ultimately allowing for the irradiation of the MP-1 Low Power experiment as-designed, and avoiding a the delays and costs of a design cycle iteration.

The experiences described in this report of applying flow testing and optimization practices to the USHPRR FQ program should serve as an example of how the uncertainty arising from the complexity and non-linearity of fluid motion can be alleviated via tried-and-true experimental methods. While flow tests are expensive, the reduced uncertainty in the assessment of fuel performance in post-irradiation examination should far outweigh these expenditures.

8 ACKNOWLEDGEMENTS

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