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Reducing Uncertainty in Hydrodynamic Modeling of ATR Experiments Via Flow Testing, Validation, and Optimization

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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 impacts 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/hydrodynamic 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 interrelated 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 creates a scenario where the neutronic/thermomechanic/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 paper explores the efforts of the U.S. High-Performance Research Reactor program to thermomechanically/hydromechanically characterize the program's 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*

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heat transfer characteristics that would have been missed using historical methods, which allows for more accurate and representative postirradiation assessments.

Keywords — *Hydraulic testing, nuclear fuels characterization, fluid-structure interaction.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The U.S. High-Performance Research Reactor Fuel Qualification Project (USHPRR-FQ) mission is to support the National Nuclear Security Administration's (NNSA's) Office of Material Management and Minimization (M^3) in developing 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, USHPRR-FQ goals are to develop the technical means needed to use low-enriched uranium (LEU) instead of HEU in U.S. 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.

The USHPRR-FQ task is complex due to the variety of U.S. research and test reactors that are targeted for conversion to LEU. These include the ATR, the Massachusetts Institute of Technology Reactor (MITR), the National Institute of Standards and Technology's (NIST's) Neutron Beam Split-Core Reactor (NBSR), the University of Missouri Columbia Research Reactor (MURR), and the Oak Ridge National Laboratory's (ORNL's) High Flux Isotope Reactor (HFIR). As can be seen in Fig. 1, the geometries of the various fuel elements are very different, as are the power and neutron flux requirements of the fuel, as shown in Fig. 2. Because of this extreme variation in the neutronic performance space of the fuel, multiple experiments are required. These range from small mini-plate (MP) experiments, which entail a variety of coupons irradiated at select ATR reactor positions, elevations, and durations, to large, full-sized-plate (FSP) experiments that represent singular plates of fuel, which are subsampled 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.

Flow testing of experimental hardware provides valuable information about the hydromechanical behavior of uranium-molybdenum (U-Mo) monolithic fuel. It is also used to qualify the hydromechanical 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]

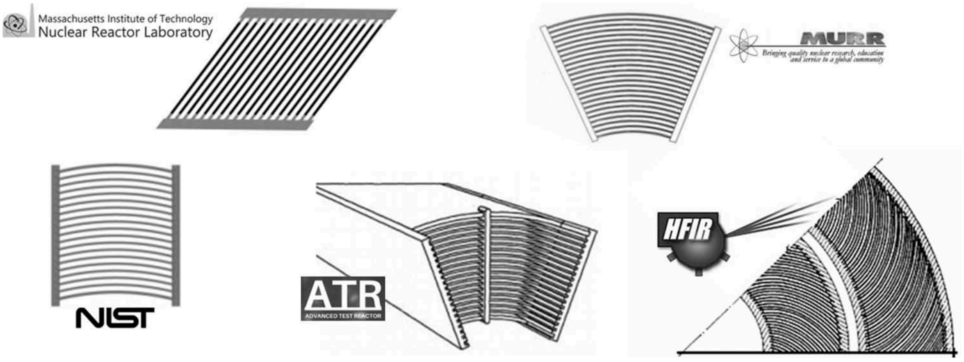

Fig. 1. Fuel element geometry from U.S. high-power research reactors.

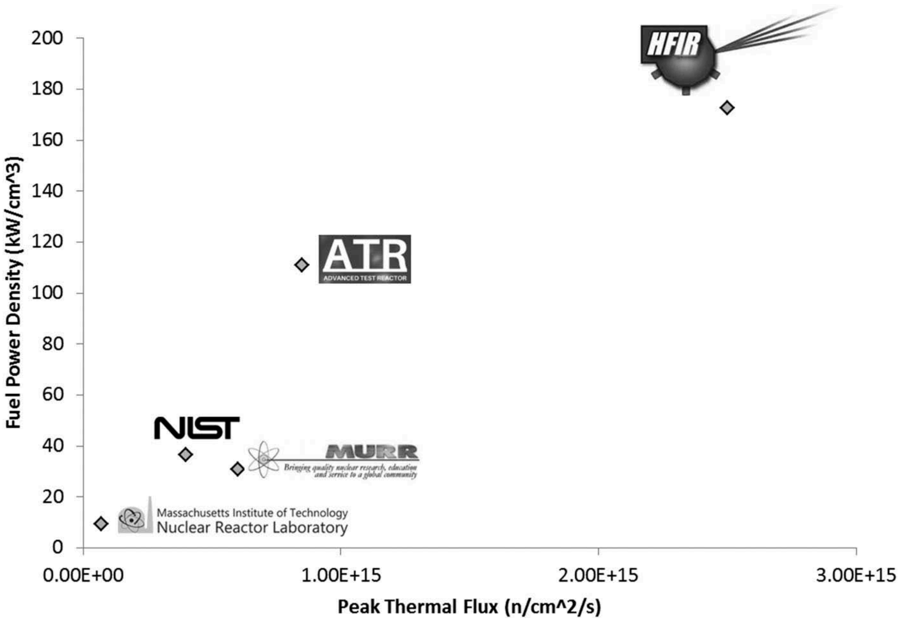

Fig. 2. Fuel power density versus peak thermal neutron flux for U.S. high-power research reactors.

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, accuracy of the analytical methods currently employed, and/or validation data for new computational techniques. The MP-1 experiments located in both the Large-B and south flux trap (SFT) positions in the ATR (Ref. 3), the FSP-1 experiment, and most recently the ATR FSP in-center flux trap position-7 (AFIP-7) experiment (Ref. 3) have each contributed to the program's understanding of the flow fields affecting the fuel plates under in-pile conditions.

II. 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 (1-D) codes and analytical formulas 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 are measured. The data from the flow test are then analyzed, 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[11] (SAR). The next sections will describe various ways flow testing has been employed to improve the scientific output of the USHPRR-FQ campaign.

III. EXPERIMENTAL FACILITIES

The flow experiments were performed in Oregon State University's (OSU's) Hydro-Mechanical Fuel Test Facility (HMFTF). The HMFTF is a large-scale thermal-hydraulic separate-effects test facility located in the Advanced Nuclear Systems Engineering Laboratory at OSU (Ref. 12). The facility operates under an American Society of Mechanical Engineers 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 that 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-ft) total length (shown in Fig. 3).

OSU has been tasked by the USHPRR-FQ 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 the high-enrichment fuels currently in use. These data will also be used to validate the 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 United States while operating under subcooled conditions. The primary loop is rated to 41.37 bars (600 psig) and 237.8°C (460°F) and has the capability to operate with net measurable flow rates ranging from 3.0 L/s [40 gallons per minute (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 upflow or downflow through the test section. The experiments discussed in this paper 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 are measured through the use of accelerometers and strain gauges strategically placed on test elements that are connected to a National Instruments (NI) PXI-express chassis for data acquisition. Pitot tube assemblies are used to measure the static and total pressure within each subchannel of the test elements to allow for characterization of flow bias within the assembles under test. This system allows for data collection at rates up to 5 kHz for short periods of time (typically 5 s) over all connected instruments to allow for characterization of the frequency of test element vibrations.

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 data acquisition system hardware was used in combination with Rosemount differential pressure transmitters and vortex

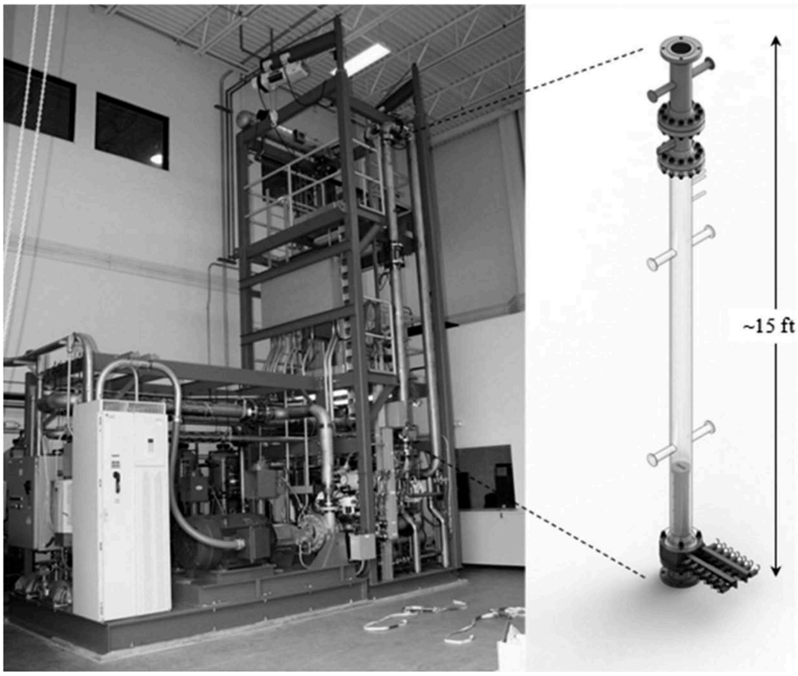

Fig. 3. OSU's HMFTF.

TABLE I

Sources of Measurement Uncertainty

Measurement	Instrument Uncertainty			Reference Value	Total Uncertainty
Differential pressure	Measurement uncertainty	Analog-to-digital calibration	NI Module PXI 6229 (±5-V 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	Analog-to-digital calibration	NI Module PXI 6229 (±5-V range)	420 gpm and measured (∂)	±(1.064 + 2.0% of ∂) 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	Time-base error	Offset error (±5-V 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	—	—		

flow transmitters; PCB Piezotronics Accelerometers were used to acquire dynamic motion of the experiment under hydraulic loading.

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 a sufficient distance from the test elements so as to not impact the hydraulics of the experiment. However, for those tests that utilize pitot tubes, it was not feasible to remove their influence or bias from the experiment; therefore, two experiments were performed for each case where a pitot tube was chosen to be utilized. The first experiment was performed as the reference test with no pitot tubes, and bulk pressure drop was acquired with reference to the 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 the respective flow rate when comparing the reference test to the second test provided an explicit measurement of the bias in hydraulics whereby these instruments influence the outcome of the experiment. This bias was then taken into account when synthesizing all data.

IV. EXPERIMENT DESCRIPTION

The following experiments were designed with input from flow testing: MP-1 Large B, MP-1 SFT/chopped dummy in-pile tube (CDIPT), FSP-1, and AFIP-7.[a] In each case, flow testing contributed significantly to the final experiment design and its analysis. This section

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[a] The AFIP-7 design was completed without flow testing, but flow testing was performed postirradiation to assess thermal/hydrodynamic characteristics to improve as-run assessments.

will describe the geometry of the experiments and their associated flow testing hardware, and later sections will explain the use of the data and their contribution to each experiment.

IV.A. MP-1 Experiment

The MP-1 experiment consists of three separate experiments to accommodate the various power/fluence scenarios presented in Fig. 2. This was accomplished with three experiments: a low-power experiment that, in turn, was three separate baskets irradiated in Large-B positions of the ATR; a medium-power experiment, irradiated in the SFT of the ATR with capsules located in the top and bottom (lower neutron flux) regions of the core; and a high-power experiment, of the same configuration as the medium-power experiment but with the capsules located in the vertical center of the basket, at the peak of the neutron flux profile of the ATR (Ref. 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 SFT position.

IV.B. MP-1 Large-B Experiment

The first MP experiment flow tested at OSU was a drop-in basket experiment for the Large-B positions of the ATR (Refs. 4 and 6). The experiment consists of four capsules (A through D), each housing three to four MPs in a 4 × 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. The MP-1 basket, capsules, and spacers are shown in Fig. 4. In some experiments, hafnium plates are inserted into the walls of the capsule to reduce edge peaking effects (Fig. 5).

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

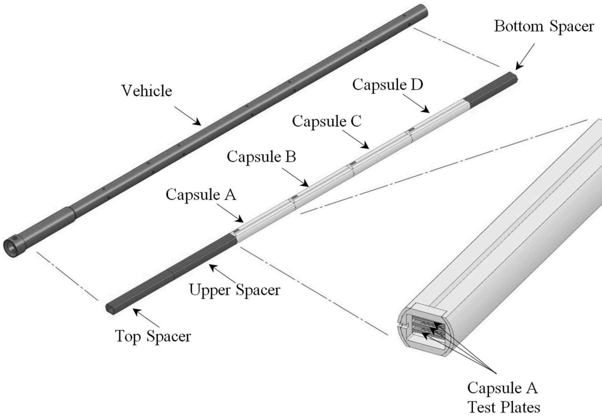


Fig. 4. MP-1 experiment hardware.

IV.C. MP-1 SFT/CDIPT Experiment

The second experiment flow tested at OSU was the MP-1 SFT/CDIPT experiment, which is a drop-in basket that will be irradiated in the SFT of the ATR (Refs. 5, 6, and 7). The CDIPT is the hardware in the ATR SFT to which the basket mates. The MP-1 SFT/CDIPT experiment basket has two boreholes 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 Fig. 7, and the SFT/CDIPT position emulator is shown in Fig. 8.

IV.D. FSP-1 Experiment

The FSP-1 experiment is a FSP experiment designed to investigate the performance of the fuel

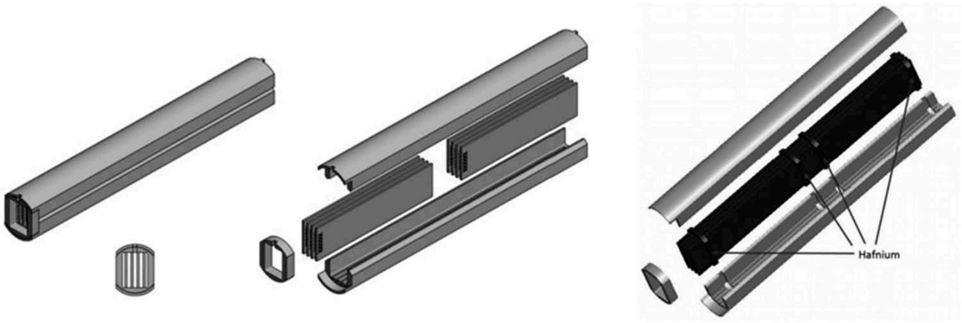


Fig. 5. MP-1 capsule assembly: assembled (left), without (center), and with (right) hafnium filters.

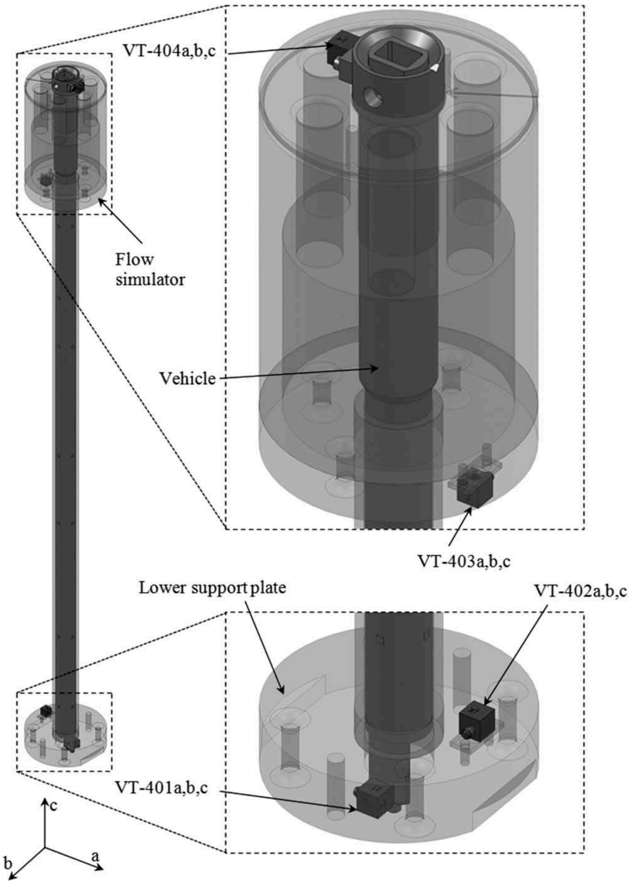


Fig. 6. Large-B-position emulator (flow simulator), experiment basket (vehicle), and accelerometers (VT-40x-a,b,c).

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 mock fuel plates in FSP-1 were fabricated with depleted uranium (DU) to emulate the performance of monolithic fuel plates. The experiment configuration is an 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 northeast flux trap of the ATR. The experiment geometry and northeast flux trap adapter are shown in Fig. 9.

IV.E. AFIP-7 Experiment

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 postirradiation to better quantify the flow in the experiment. The experiment and the flow simulator for the center flux trap are shown in Fig. 10.

V. 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 guidebook GDE-588 (Ref. 10), but analysts have

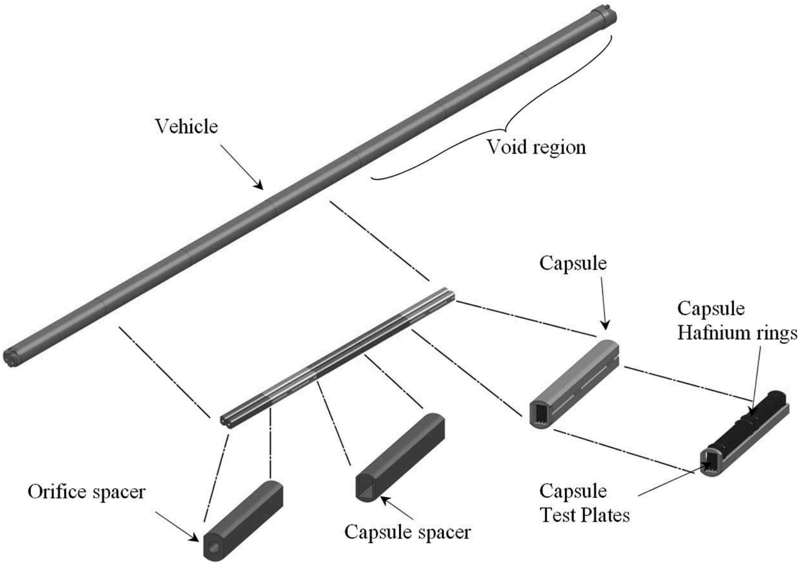


Fig. 7. MP-1 SFT/CDIPT experiment hardware.

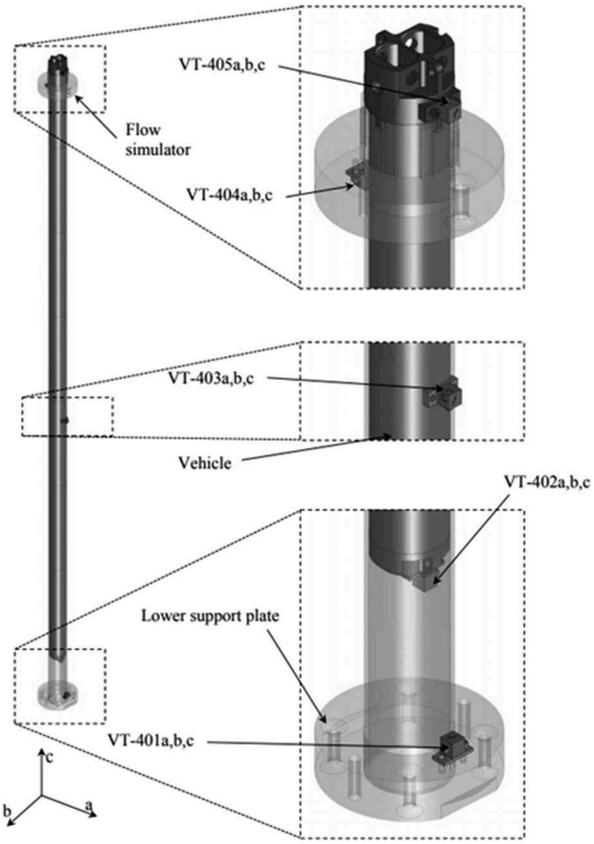


Fig. 8. The SFT/CDIPT emulator (flow simulator), “double-barrel” experiment basket (vehicle), and accelerometers (VT-40x-a,b,c).

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 (https://relap53d.inl.gov/SitePages/Home.aspx), ABAQUS (https://www.3ds.com/products-services/simulia/products/abaqus/), STAR-CCM+ (https://mdx.plm.automation.siemens.com/star-ccm-plus), HEEDS (https://www.redcedartech.com/), COMSOL (https://www.comsol.com/), MATLAB (https://www.mathworks.com/products/matlab.html), MATHCAD (https://www.ptc.com/en/products/mathcad), and EXCEL (https://office.microsoft.com/excel). 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 and validation status at INL, interoperability with other software, and analyst and reviewer familiarity. The following sections will describe the computational and analytic models created for each experiment.

V.A. 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

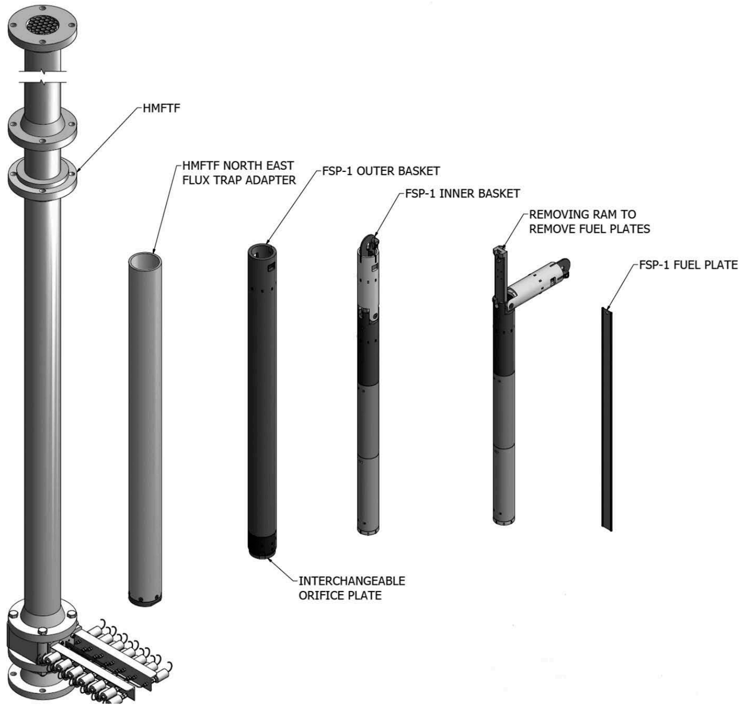


Fig. 9. FSP-1 experiment, with northeast flux trap adapter and HMFTF test section shown.

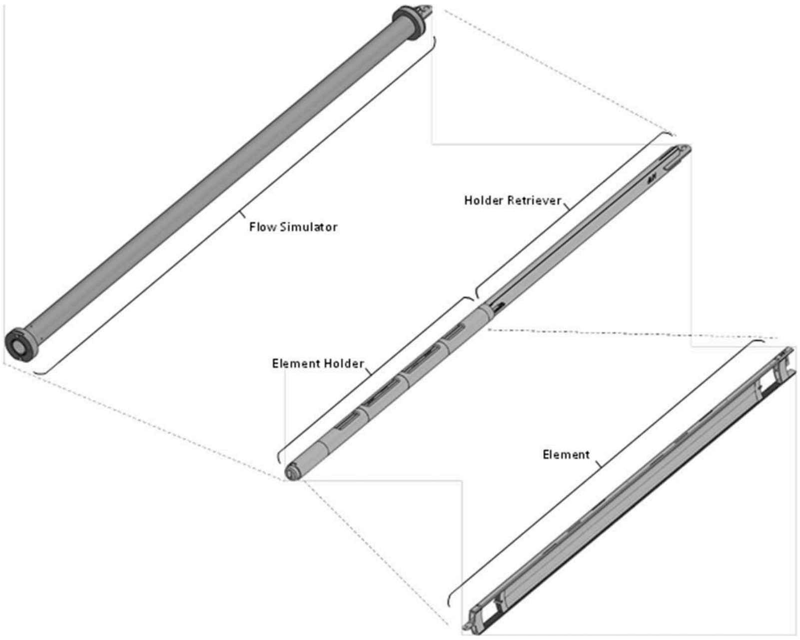


Fig. 10. AFIP-7 experiment hardware and position simulator for flow tests.

results; and then, apply those flow rates and heat transfer coefficients to the ABAQUS model.[4–6] ABAQUS modeling provides the three-dimensional temperature field of the experiment and allows for an assessment of localized critical heat flux to support the safety requirements of the ATR's SAR (Ref. 11). The RELAP5 component diagram for the three MP-1 tests are shown in Fig. 11, and representative ABAQUS models are shown in Figs. 12 and 13.

V.B. FSP-1 Modeling

The method used for the FSP-1 analysis was nearly identical to that of MP-1 (Refs. 8 and 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

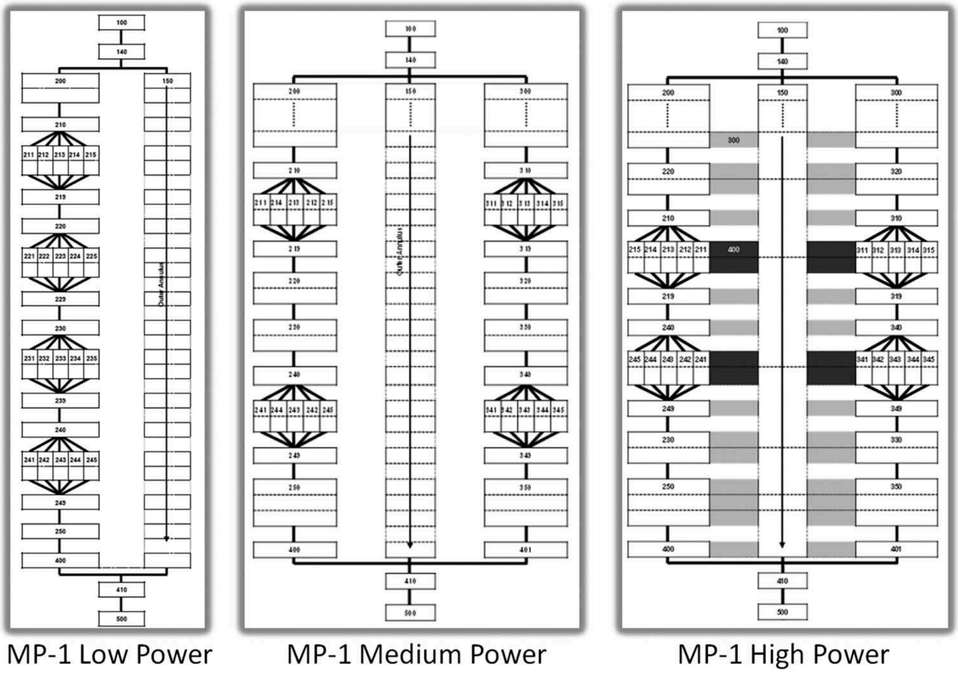


Fig. 11. RELAP5 models of the MP-1 experiments.

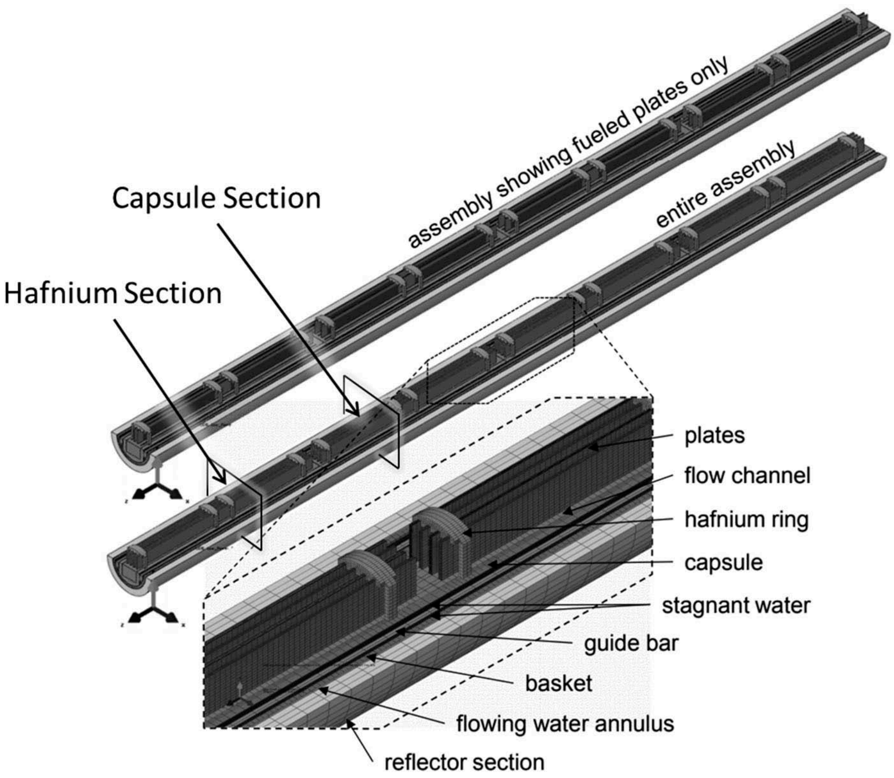


Fig. 12. ABAQUS model of the MP-1 low-power experiment with Fig. 13 section locations.

ABAQUS model. The RELAP5 component diagram for the FSP-1 test is shown in Fig. 14, and the representative ABAQUS model is shown in Fig. 15.

V.C. AFIP-7 Modeling

AFIP-7 was initially modeled in RELAP5 (Ref. 14), with heat structures allowing for the assessment of a natural convection scenario, shown in Fig. 16a. Additionally, an ABAQUS model was built to assess the safety-related transient scenarios required by the ATR, a section of which is shown in Fig. 17. Finally, after irradiation was complete, a computational fluid dynamics (CFD) model was built to gain a better understanding of the distribution of the flow in the experiment.[15] 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 fueled section of the experiment is shown in Fig. 18.

VI. RESULTS AND 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.

VI.A. MP-1 Low-, Medium-, High-Power Experiments and EMPIrE

The Large-B experiment performed for the benefit of the MP-1 low-power experiment, being relatively simple from a hydromechanical perspective, afforded the opportunity to compare the performance of RELAP5 modeling to test data.[6] Previously, RELAP5 models would be built with reasonable values for parameters such as surface roughness, Reynolds-independent loss coefficients, channel aspect ratio effects, and friction factor correlation, derived by subject-matter experts (SMEs). 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 root-mean-square error of the modeled data versus 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 Fig. 19. Additionally, the

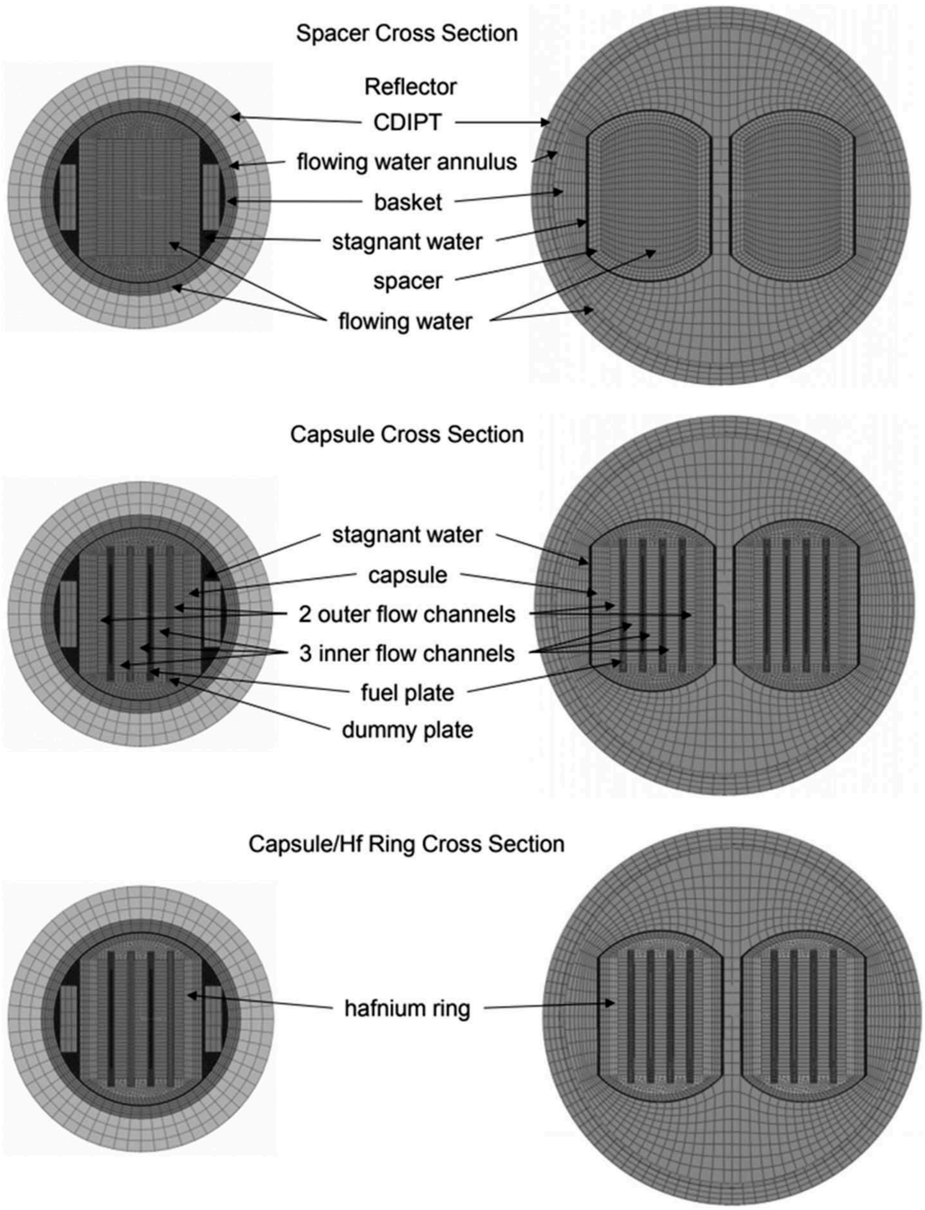


Fig. 13. ABAQUS models of the medium- and high-power MP-1 experiments (cross-section locations from Fig. 12).

vibrations of the basket were collected and analyzed. The response of the experiment under flow can be seen in Fig. 20. 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.[16–19]

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 European Mini-Plate Irradiation Experiment (EMPIrE), 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.

VI.B. 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–

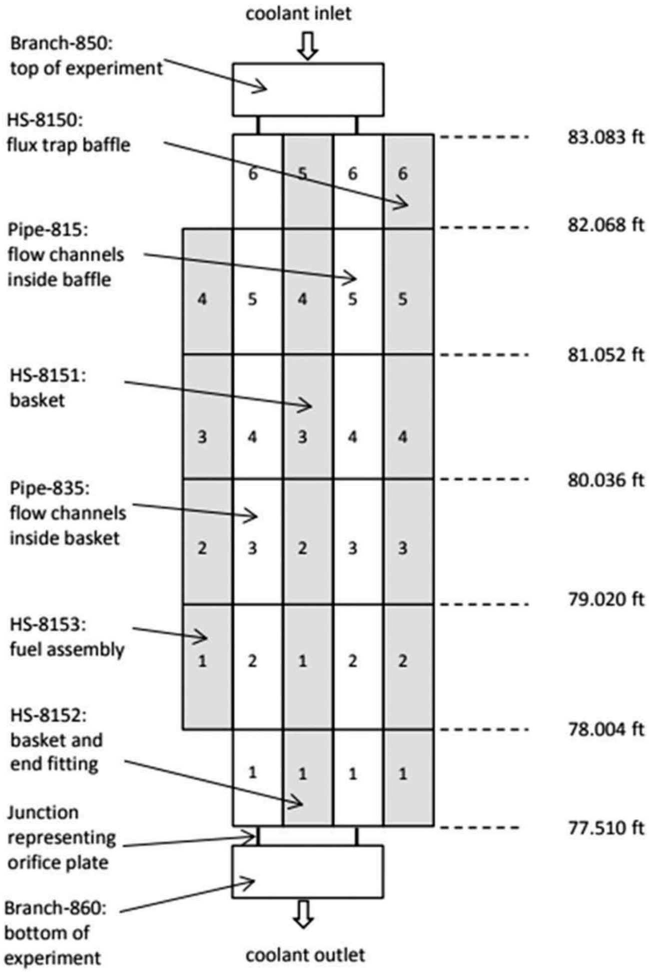


Fig. 14. FSP-1 RELAP5 model.

determined orifice size (1.44 in. in TEST-001) to the final orifice size (1.244 in. in TEST-004). Inspection of the data in Fig. 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-in. data and the final 1.24-in. data at 73.3 core delta-P. Additionally, the final two FSP-1 tests were performed with plates fabricated with DU using the same methods as monolithic fuel plates. Examination of the data shows that under all expected flow conditions, the (unheated) plates perform similarly to the surrogate aluminum 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 Fig. 22.

VI.C. 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 postirradiation natural convection, with the realized paths illustrated in Fig. 16b. This created large variations in the velocity fields, as well as paths for relatively cooler flow to enter the experiment in the lower elevations. CFD was employed to diagnose the flows within the

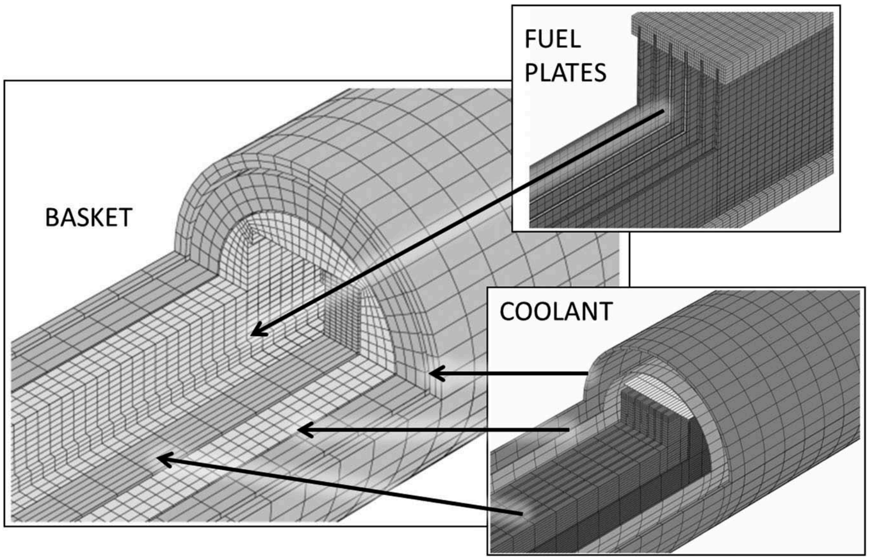
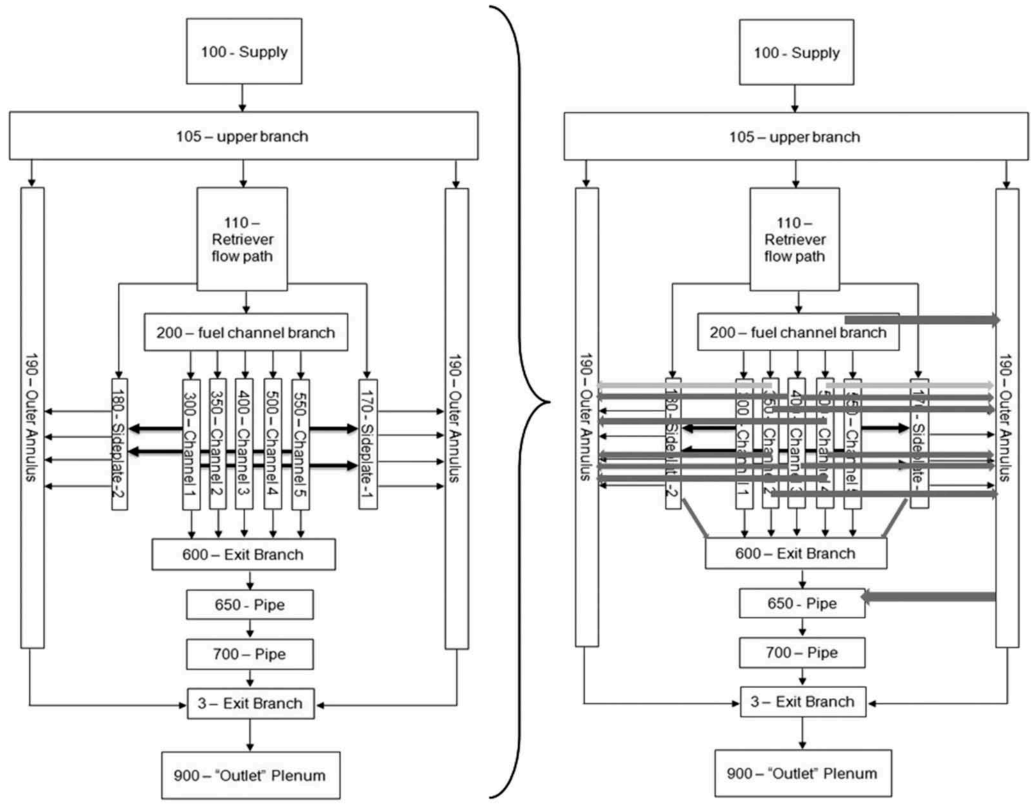


Fig. 15. FSP-1 ABAQUS model (exploded view).



(a) (b)

Fig. 16. Original RELAP5 model of the AFIP-7 experiment (a) with flow-test discovered flow connections added (b).

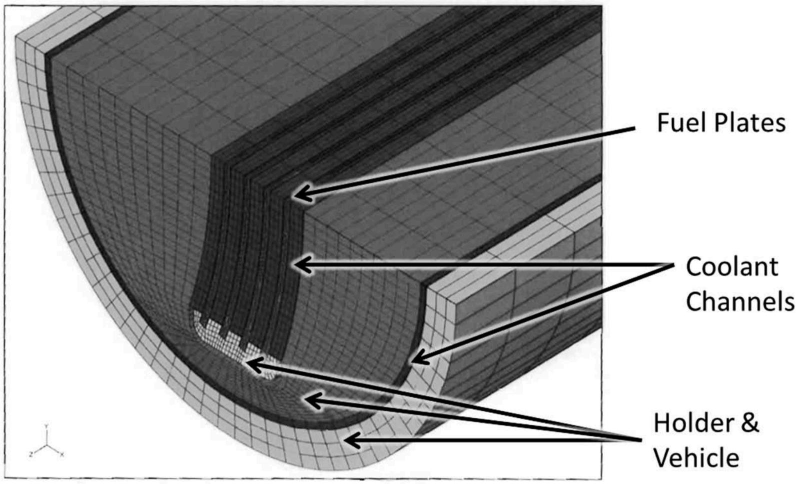


Fig. 17. ABAQUS finite element model of the AFIP-7 experiment.

channels.[15] The velocity magnitude fields for each channel are shown in Fig. 23. A streamline investigation mapping flow from the side vents in the central channels showed that the flow has a propensity not only to exit the fuel assembly but also to reenter at a lower vent, as can be seen in Fig. 24. Investigation of the effect these variations have on the plate performance is pending.

The CFD model of AFIP-7 also provided insight into the hydromechanical 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.

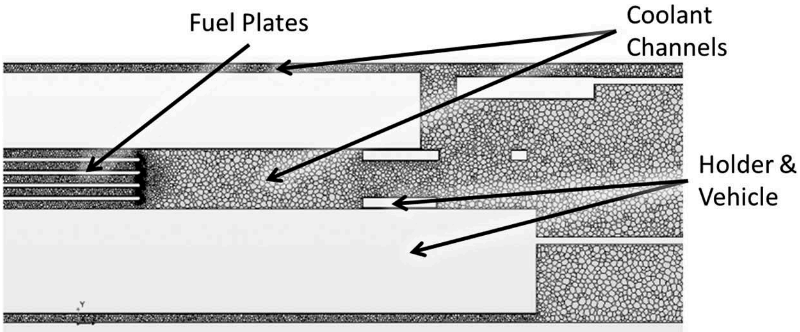


Fig. 18. CFD mesh of the AFIP-7 experiment: inlet of fuel assembly and outer annulus.

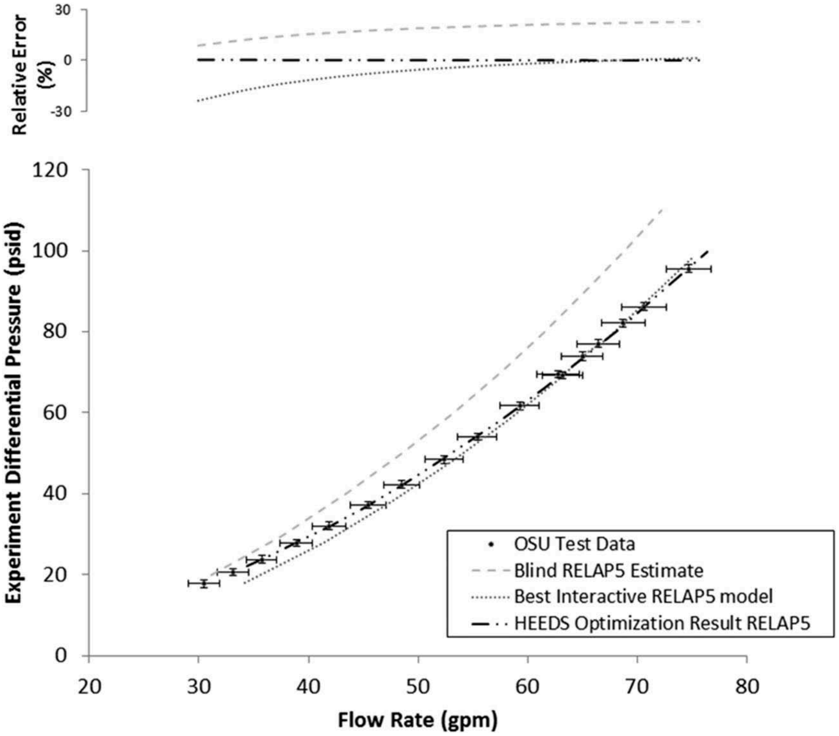


Fig. 19. Results of optmization study on the Large-B basket flow test data.

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 and its neighbors, moving the Channel 3 velocity higher and Channel 2 and 4 lower. While not quantifiable without a measure of deformation during the test, the data indicate that plate deformation in the AFIP-7 plates is slight and has a minor effect on the channel velocities in the experiment.

VII. 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 intrachannel flow velocity variation) or underestimated/overestimated from first principles and best practices (MP-1 low-power flow rate, FSP-1 orifice size). The data collected from the flow tests were 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–related or heat transfer coefficient–

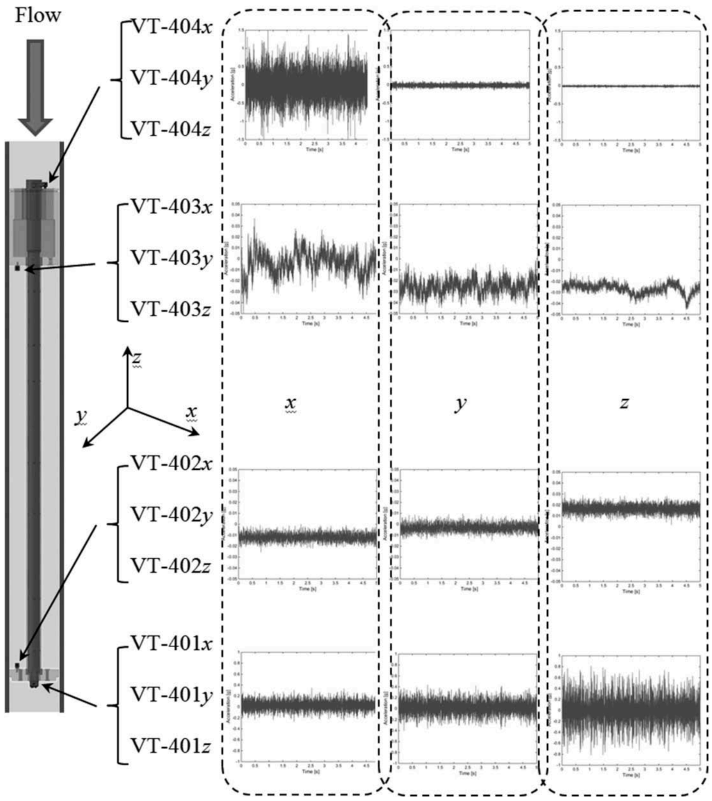


Fig. 20. Triaxial acceleration response of the MP-1 Large-B experiment basket under flow.

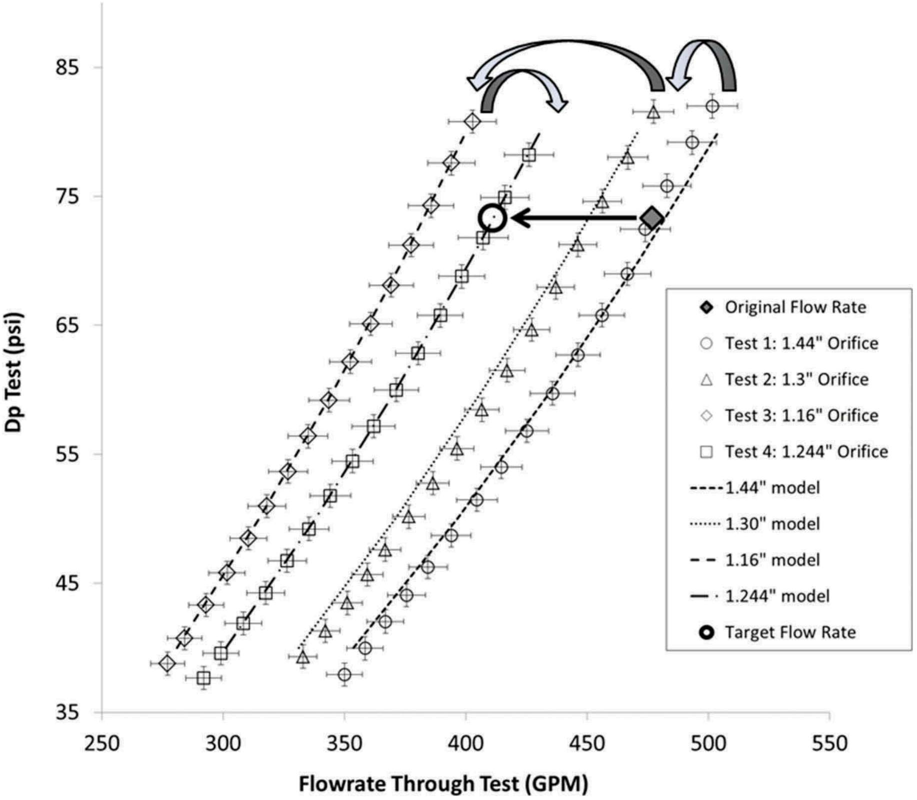


Fig. 21. Variation of coolant velocity with orifice size for FSP-1 tests, with target rate indicated (in units of inch).

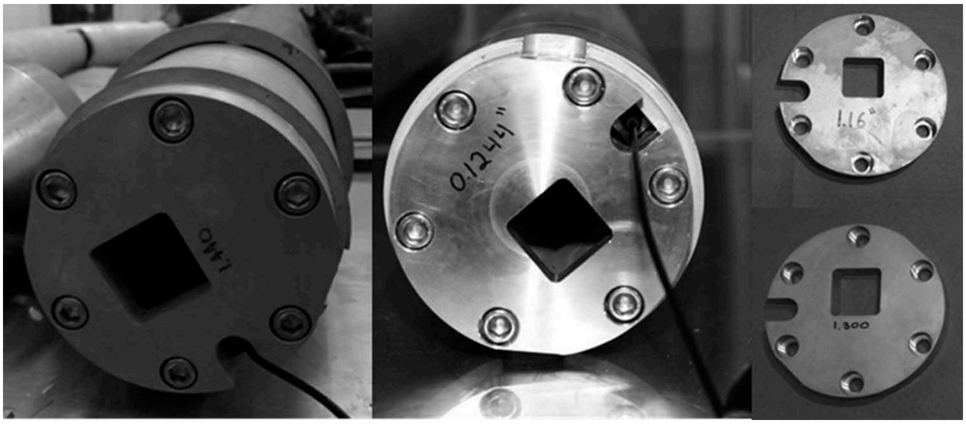


Fig. 22. Initial (1.44 in.), final (1.244 in.), and interim orifice plates flow tested for FSP-1.

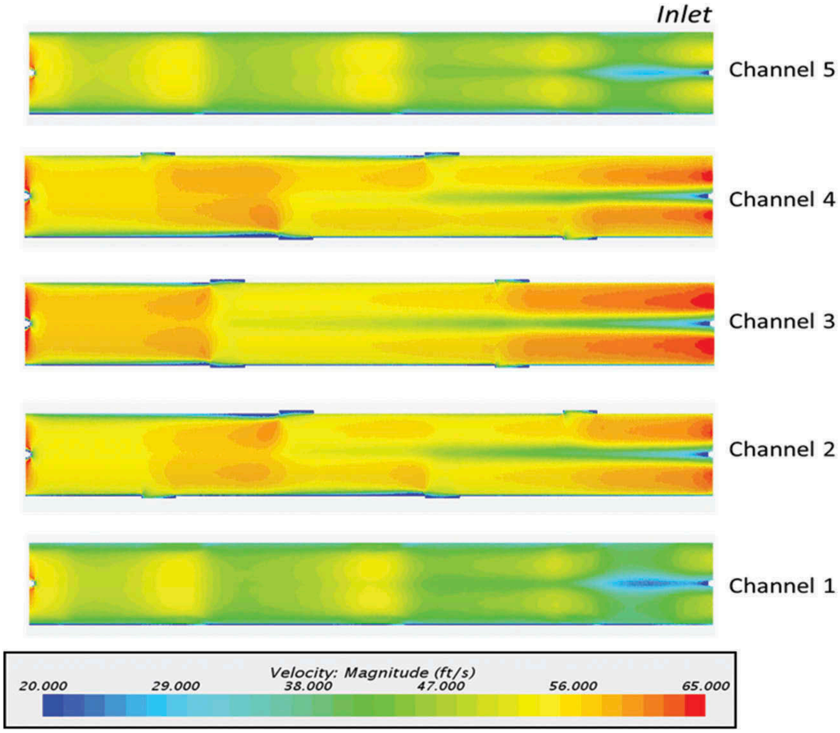


Fig. 23. Flow velocity magnitude maps for AFIP-7, channels 1 through 5, via CFD.

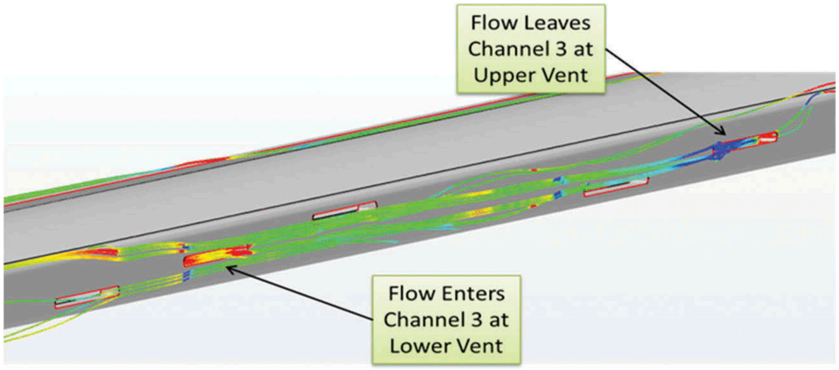


Fig. 24. Stream lines from the upper vent show reentrance of the flow into lower vents.

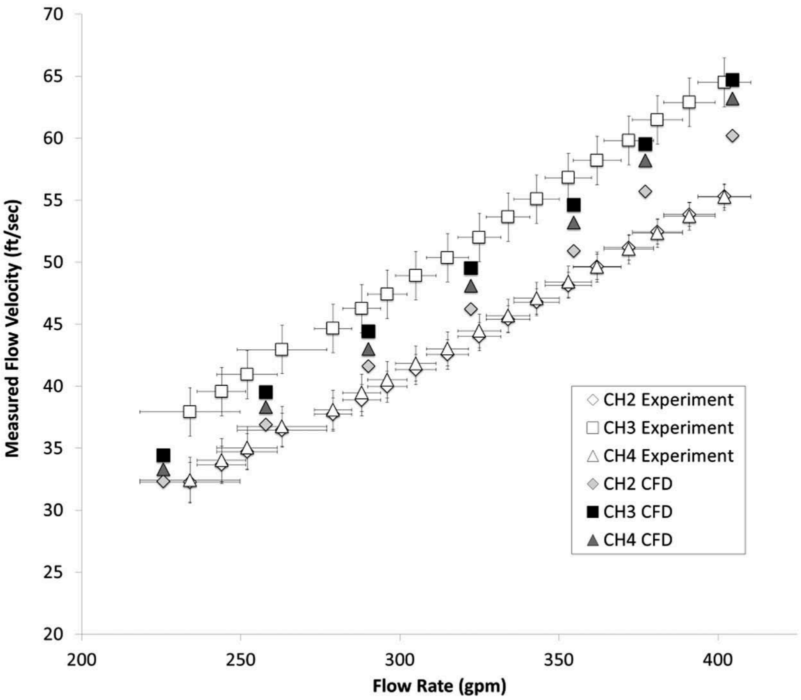


Fig. 25. Experimental and computational pitot tube flow channel velocities for AFIP-7.

related potential misconceptions about postirradiation examination results in future years.

USHPRR-FQ's high-confidence, NQA-1 certified flow test data were made possible by the foresight of NNSA-M^3 in developing the HMFTF, with the versatility to 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 have 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 the delays and costs of a design cycle iteration.

The experiences described in this paper 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 nonlinearity 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 postirradiation examination should far outweigh these expenditures.

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