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USHPRR Fuel Development Flow Testing Overview

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ABSTRACT

Hydraulic flow testing is an integral part of experiment characterization in nuclear research and development. Using flow tests, mechanical forces can be measured or predicted, velocity measurements used to support the calculation of experiment-specific heat transfer coefficients, and using accelerometers or strain gauges, the dynamic response of the experimental apparatus can be assessed. These metrics support safety analyses for insertion as well as programmatic predictive and post-irradiation analysis. This paper presents a brief summary of historic test reactor flow testing activities, which leads into a discussion of USHPRR Fuel Development flow testing efforts, both completed and pending. The AFIP-7, MP1-Large B, MP1-CDIPT, EMPIrE, and FSP-1 experiments have all undergone flow test characterization and are in different stages of finalization. Select examples of the data collected, its analysis, and its application are presented herein. [INL/CON-16-39834].

Introduction

Hydro-mechanical characterization of nuclear components (including experiments for research reactors) via flow testing has historically been considered a recommended method for establishing the integrity of new components and flow configurations. The Atomic Energy Commission (AEC) Regulatory Guide 2.2 states the following guideline for developing technical specifications for experiments in research reactors, “Prototype testing under experiment conditions should be employed to demonstrate the ability to withstand failure.”[1] This approach was adopted by the Advanced Test Reactor (ATR), which requires a detailed analysis of experiments showing conformability to the reactor safety requirements prior to insertion. While flow testing is not specifically called out, analysis with experimental validation carries more weight than analysis alone.

Historically, hydro-mechanical testing has been a part of fuel-development programs for all US research reactors. MITR performed experimental testing to validate finned fuel as a means to improve heat transfer for the compact core in 1969 [2]. HFIR was extensively studied analytically and experimentally due to the complexity of the involute plates, with analytical and experimental recurrences throughout its ongoing lifetime, primarily associated with insight gained during the design of the ANSR. [3]

MITR and HFIR aside, the other reactors fuel assemblies are generally related, tracing their fuel element designs back to the Materials Test Reactor (MTR) and subsequent Engineering Test Reactor (ETR). These fuel elements were the result of years of iterative design that included initial element failure at design velocities [4, 6], and testing of alternative configurations that lead to successful designs [5, 6]. One conclusion from these early tests was a recommendation that, "[A]ll design changes, no matter how small, must be fully evaluated prior to acceptance for reactor operation."[6] This advice was accompanied by a description of the MTR fuel acceptance tests which included hydraulic testing to 140% of operational conditions of 25 of a new fabricator, a new fabricator technique, or a modified design, then a 1 in 10 test for follow-on pieces.

Following the early research reactors, there are two distinct paths – adoption of the flat-plate ETR elements, or evolving the curved-plate MTR-type elements. Worldwide, many research reactor fuel elements emulate the MTR element, as was the case for the National Bureau of Standards Reactor (NBSR) – again necessitating hydraulic testing and characterization for the upgraded design. MITR has (essentially) flat plate fuel like the ETR, although the flow regime necessitated the ribbed surface that provides strength as well as increased heat transfer. Finally, MURR fuel elements have distinct similarities to ATR elements, although the plate number is increased and the plate thickness reduced. [3]

MTR evolution was also the path for the ATR element; the complexities of the configuration again necessitated an extensive hydraulic testing campaign. The initial fuel qualification effort of the ATR had hydraulic loading and testing components in each of its three pillars – experimental, analytical, and repeatability [3]. The experimental campaign included many out-of-core hydraulic tests, followed by in-core instrumented testing. These tests led to design improvements, most notably, the side-channel vents for pressure equalization between channels. Even after the fuel was established, the first decades of operation of the ATR saw all incoming fuel elements qualified for operation via flow tests. In 1996, after the design had been proven via years of operation, manufacturing specifications well defined, and operational envelope of the reactor adjusted to compatible flow rates, the flow test requirement for every element was removed [3]. It is likely that the USHPRR-derived LEU elements will be subjected to the same types of pre-insertion qualification tests.

The USHPRR LEU fuel development program is a complicated endeavor, as the FD researchers are developing fuel within the constraints of the current fuel assembly footprint. This geometric restriction imparts complications, from matching power production, swelling performance, and even maintaining equivalent or better mechanical strength throughout the fuel's lifetime. The perception that a LEU fuel bundle should be identical to its HEU predecessor is a persistent challenge to both FD and RC efforts; for, as each physical evolution of MTR fuel (for example) necessitated characterization and conformance testing (i.e., MTR-NBSR-ATR-MURR), the same holds true for the HEU-LEU conversion. Additionally, while both FD and RC are concerned with the strength of the final fuel assemblies, FD flow testing has the additional burden of supporting the fuel development effort by establishing flow conditions as representative as possible for pre-assembly testing (mini-plate, full-sized-plate), and meeting ATR safety requirements for the unique test apparatuses associated with the preliminary testing.

Another benefit of hydraulic testing is in the assessment of fuel performance in post-irradiation examination (PIE). The characteristic velocities determined during flow testing are used to provide more accurate heat transfer coefficients for the analysis, in turn providing better surface and centerline temperatures, which ultimately yield improved applied conditions for determining the response of the prototypic fuels in comparison with models for parameters such as oxide growth or swelling. Additionally, for some assemblies, accelerometers are included in the testing to assess the movement of the experiment under flow. This is an attempt to pre-detect and avoid any type of flow-experiment resonance condition at operational flow velocities.

The final aspect of flow testing is concerned with the determination of the response of the new fuel configurations (layups), monolithic or dispersion, to the current HEU fuel configuration. The primary experiment for this comparison is the Generic Test Plate Assembly (GTPA) experiment, which applies hydrodynamic loading to first baseline aluminum plates, then to surrogate monolithic and dispersion plates, and compares the response of each to the others. The goal of the GTPA testing is to empirically determine whether each LEU fuel plate configuration bounds (is as strong as, or stronger than) the base 6061-O, which was used to establish the performance of the ATR fuel assemblies in the aforementioned ATR fuel assembly development program.

HMFTF

To perform hydraulic testing across the FD and RC campaigns, the USHPRR program commissioned the development of the Hydro-Mechanical Fuel Test Facility (HMFTF) at Oregon State University (OSU). The Pressure vs. Temperature design envelope is shown in Figure 1, along with the operational envelopes of the various HPRRs [8].

FD Flow Testing Campaign

To support the USHPRR fuel development effort, FD developed a series of flow tests that compliment the experiment design process and capitalize on the availability of OSU's HMFTF and its associated American Society of Mechanical Engineers (ASME) NQA-1 quality assurance program. These flow test experiments are part of the preliminary design process for an FD experiment, providing experimental feedback to the design team in order to verify flow rate and fuel-cooling parameters and to allow accurate determination of fuel-test operating conditions. Fuel Development flow testing and analyses reduces the risk of irradiation-experiment failure and are an integral part of irradiation-experiment design and fuel-performance data evaluation. To date, flow testing, at minimum, was performed to characterize hydraulic performance of irradiation vehicles to support design, safety basis, and as-run analysis of all irradiation experiments. [9]

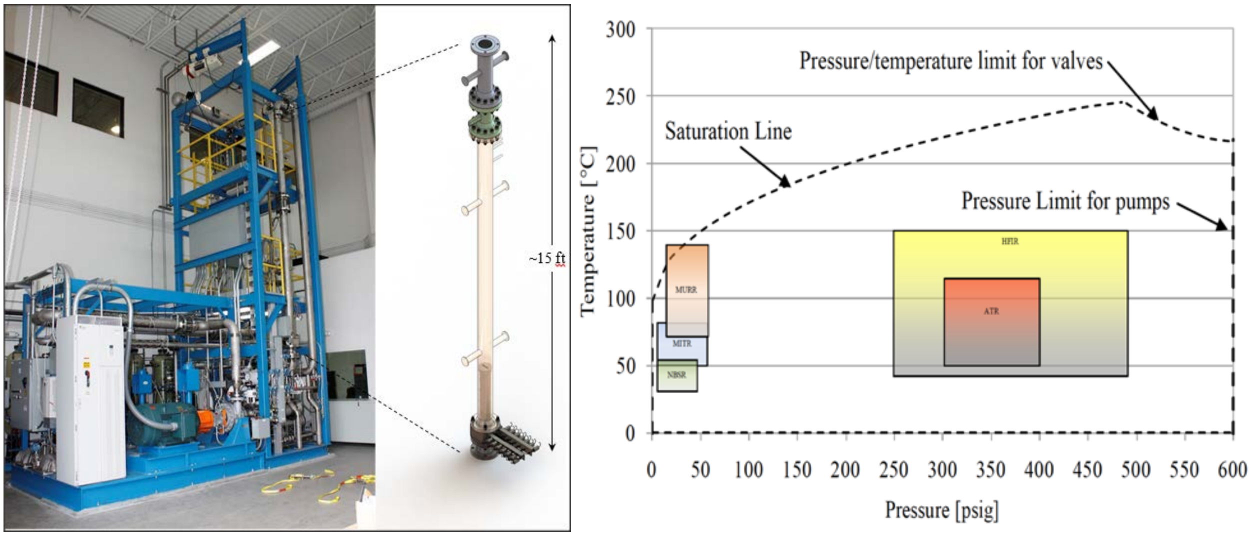

Figure 1. HMFTF and its design envelope with HPRR operational envelopes

Experiment Designs

MP-1 Large B [10] **–** The mini-plate experiment for low-power assessment of fuel resides in ATR's 'Large B' positions, located outboard of the N,S,E,W lobes, but inboard and nearly abutting the outer shim cylinder control drums. Figure 2 shows the MP-1 Large B experiment assembly, along with a 'Large B' position emulator that allows for the suspension of the experiment vehicle from the upper 'shelf', and bypass flow to enter the annulus around the vehicle at a lower 'shelf'. Incorporating this replication of the in-reactor installation provided the opportunity to collect vehicle motion data with various accelerometers placed on the upper and lower extents of the vehicle. Determining the flow rate across the plates was critical to the thermal safety analysis [17], as the close proximity of the shim cylinders, accompanied by the superposition of conservative power amplification factors necessitated a very large multiplier on the plate power for required transient analyses. The flow tests enabled high confidence in the assessed velocities and allowed the experiment to pass the restrictive safety cases.

MP-1 CDIPT [11] **–** The medium- and high-power mini-plate experiments are drop-in experiments in the ATR's south flux trap, with the experiment vehicle suspended from the top edge of the 'Chopped Dummy In-Pile Tube' (CDIPT). The flow test hardware consisted of the appropriate configuration of aluminum plate dummy capsules inserted into a representative vehicle, which is, in turn, inserted into a mock-up of the CDIPT. Various tests were performed with appropriate configurations of spacers and capsules, with the lower-most spacer being a flow-throttling spacer of variable diameter. A number of tests were performed to assess the effectiveness of this spacer to throttle the flow. Additionally, for a number of tests, the capsules were positioned such that static/dynamic pitot tube assemblies could measure the flow in the channels of the lowermost capsule. Again, the increased confidence in the velocity measurements allowed the experiments to pass the thermal safety cases associated with the ATR SAR. Figure 3 shows the high power configuration of a MP1 CDIPT test.

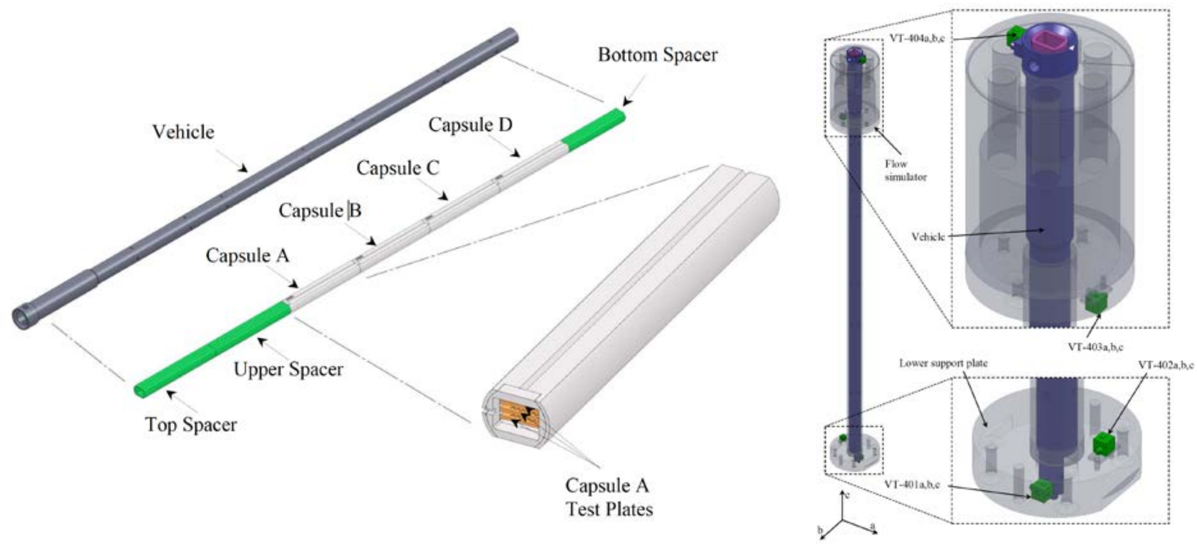

Figure 2. MP-1 Large B Experiment and Position Simulator

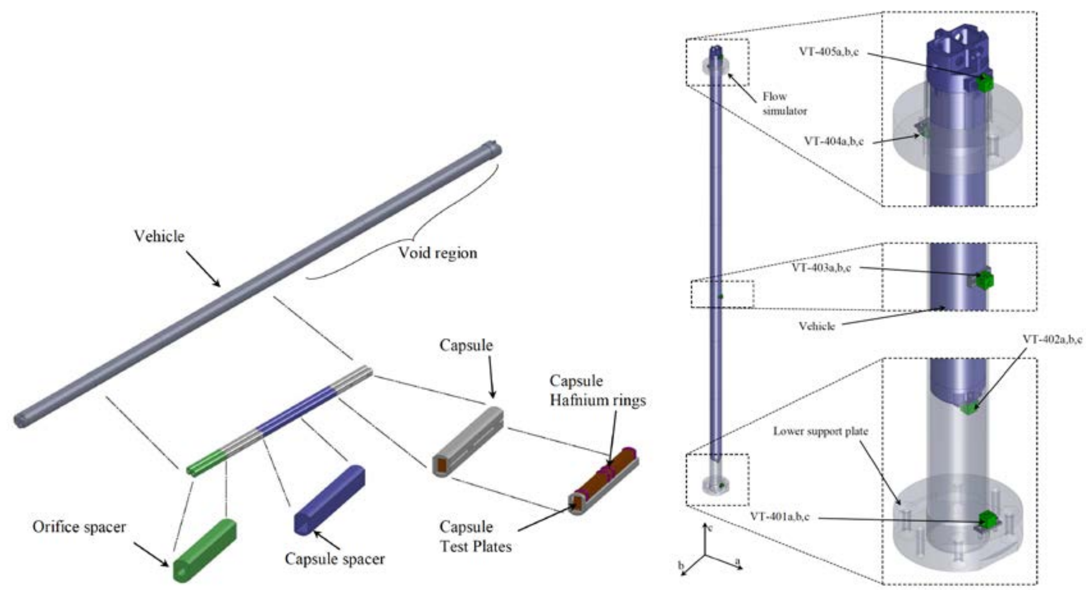

Figure 3. MP-1 High Power Experiment and CDIPT position simulator

MP-EMPIrE [12] **–** The EMPIrE mini-plate test is housed in the same vehicle and position as the medium- and high-power MP1 tests. The main difference in this test is the configuration of the fuel plates in the capsules. The EMPIrE capsules have two lateral plates, where the MP-1 capsules have four. This leads to larger flow channels in the EMPIrE experiment, and ultimately, a different choice for the orifice spacer diameter. To enable the appropriate choice of spacer diameter, various orifice diameters were tested in the EMPIrE flow test series. The channel velocities were not measured in the EMPIrE experiment. Figure 4 shows the difference between the EMPIrE capsule (left) and the MP-1 capsule (right). The EMPIrE experiment also had fuel in all four vertical capsule positions (similar to the low-power test), unlike the medium- and high-power tests, which only had fueled capsules in two vertical locations (middle for high-power, top/bottom for medium-power). Again, flow test results were critical in establishing a credible flow rate and allowing the experiment to pass thermal safety criteria [18] and performing programmatic analysis [19].

FSP-1 [13] **–** The Full-Sized Plate – 1 experiment used flow testing to establish a correct orifice size for the targeted flow velocity. Designed to emulate full-size plate fuel down-selected from the MP-1 experiments, the FSP-1 experiment consists of six flat plate fuel elements housed in an inner basket, placed in an outer basket, which is subsequently inserted into a position simulator. Figure 5 shows the hardware associated with the FSP-1 flow test. The main component of the FSP-1 flow test was an iterative evaluation of the orifice plate directly beneath the plates on the outer basket. Initial estimates were adjusted as flow test information was received and evaluated, and over the course of five tests, the orifice dimension 'zeroed in' on the dimension that provided the target flow rate for the tests. One FSP-1 flow test was dedicated to the measurement of the velocities in the plate channels via static/dynamic pitot taps.

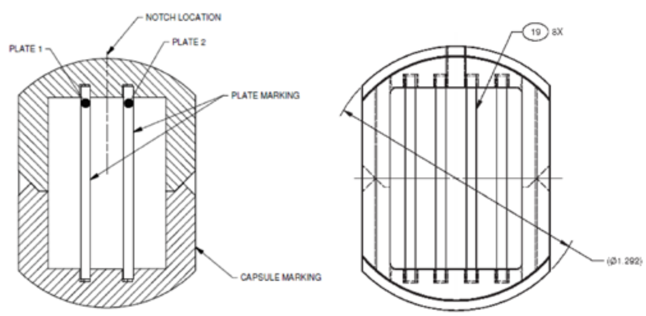

Figure 4. EMPIrE capsule configuration (left), MP-1 capsule configuration (right)

AFIP-7 [14] **–** The AFIP-7 test was unique in the campaign, as the fuel had already been irradiated in the ATR. The intent of the flow testing was to quantify the flow characteristics and velocities to support the PIE analysis and its associated assumptions. Three tests were performed, with static/dynamic pitot tubes incorporated into one of the tests. The other tests provided an opportunity to determine the amount of flow that 'bypasses' the plates in the experiment. Figure 6 shows the AFIP-7 geometry.

Experiment Results

The results from the flow tests are used in a variety of ways. Primarily, they are used to calibrate/validate models such as 1-D RELAP5 flow models or in other cases, the results are used as local calibration for 3-D CFD models. A typical example of data usage is shown in Figures 8-10, as follows: Figure 7 shows a comparison of HMFTF test data collected in the MP-1 Large B flow tests with a RELAP5 model with several parameters being varied. Notably, the surface roughness and the exit losses have been used to more closely match the flow test data [15]. The results are then applied to ATR operating conditions and the resultant flow velocities are reported in Table 1.

These velocities are then applied to an ABAQUS finite element model that determines fuel centerline temperatures, surface temperatures, thermal conductivity degradation and oxide growth for the experiment. Examples of these results are shown in Figure 8 (Fuel Centerline Temperature), and Figure 9 (Oxide Thickness in microns). The final results for the Low Power experiment are summarized in Table 2 [16].

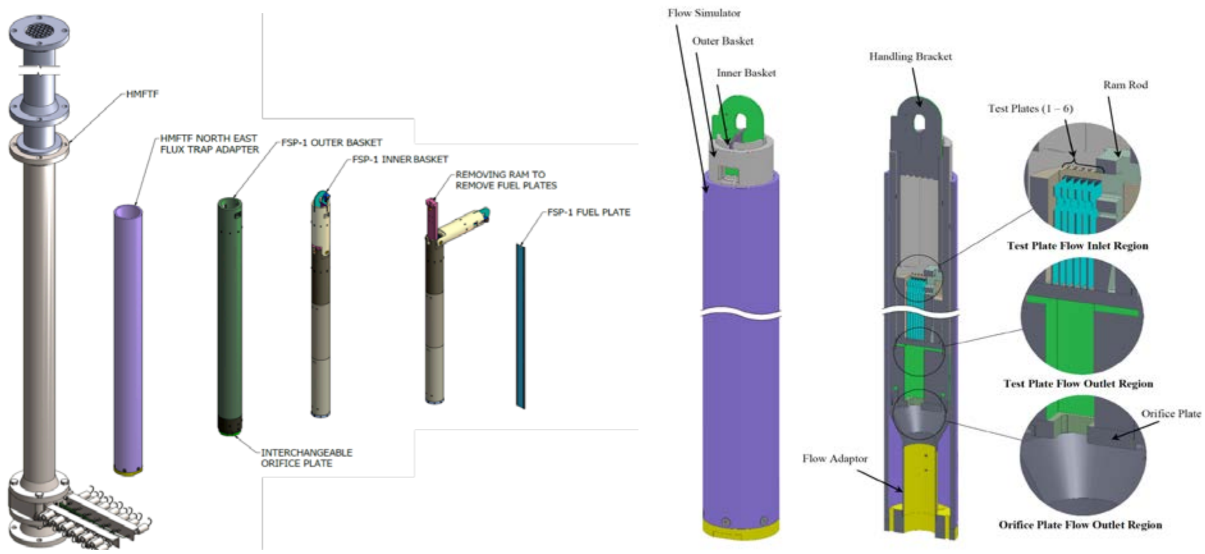

Figure 5. FSP-1 flow test hardware

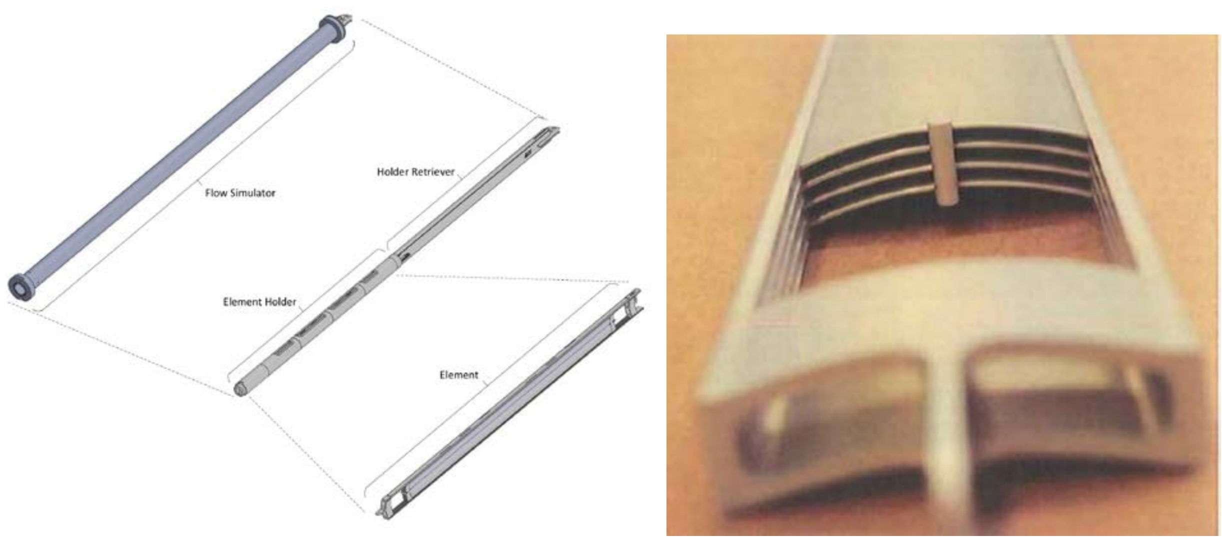

Figure 6. AFIP-7 flow test hardware

Table 1. Large B channel velocity recommendations for various RELAP5 Models

RELAP5 Configuration	Volumetric Flow Rate in each Capsule (L/s)	Outer Channel Velocity (m/s)	Inner Channel Velocity (m/s)
Nominal	3.53	12.6	14.0
ε	3.62	13.0	14.4
ε, K	3.87	13.6	15.5

Table 2. MP-1 Large B Programmatic Results (peak values)

Low Power Experiment Position	Peak Oxide Thickness (μm)	Peak Centerline Temperature (°C)	
		BOL	EOL
B-10	25.0	134	90.8
B-11	25.8	137	91.4
B-12	23.1	124	89.9

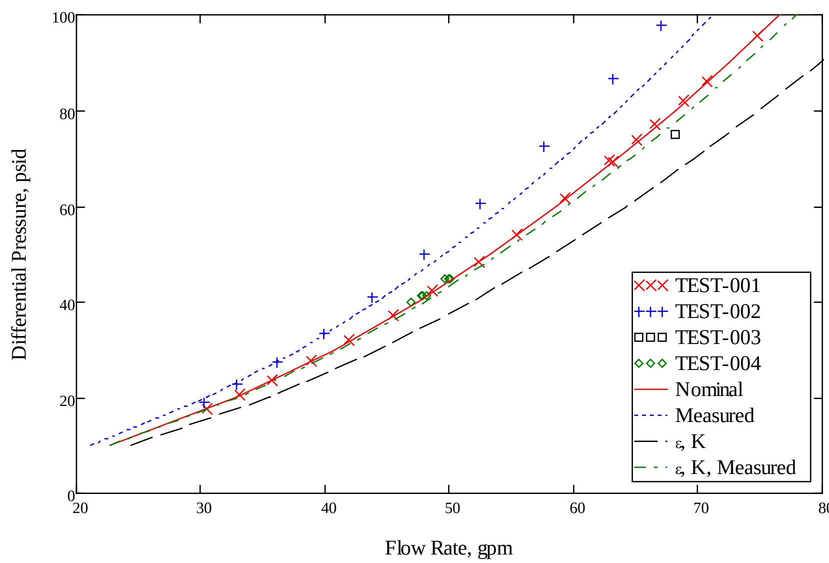

Figure 7. HMFTF Test Data comparison with 'tuned' RELAP5 models.

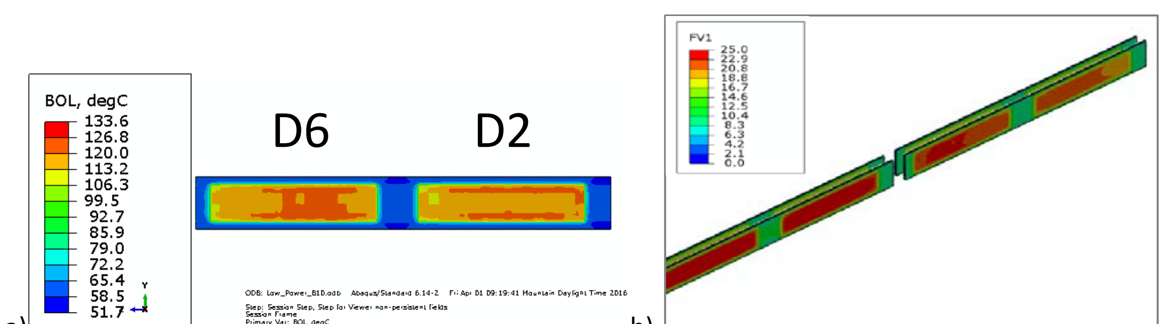

Figure 8. a) Beginning of Life fuel centerline temperature, select plates in Low Power B-10 capsules, b) End of Life Oxide Thickness (microns), select plates in Low Power B-10

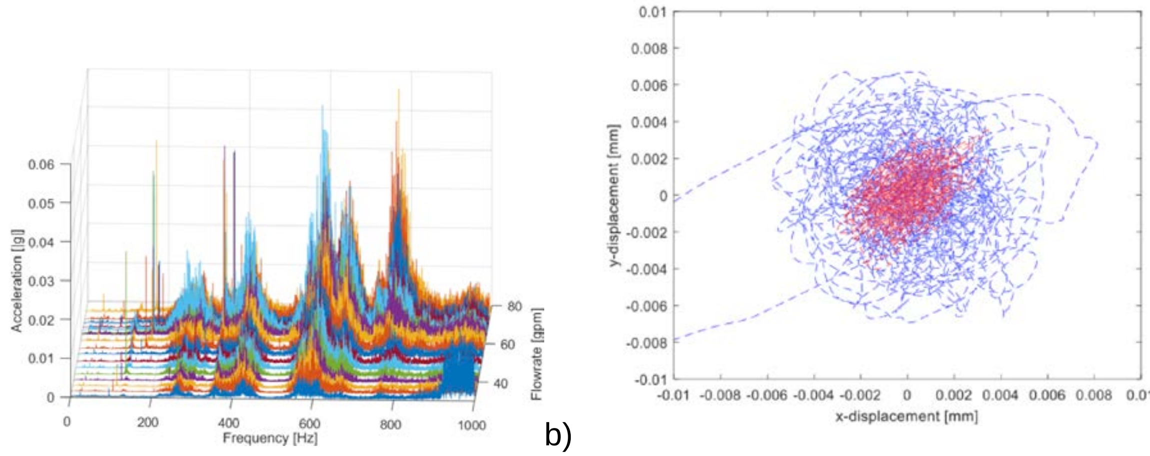

Figure 10. a) Frequency content of the Large B experiment motion as a function of flow rate, b) integrated position path cloud for basket (blue) and simulator (red)

Finally, the accelerometer data can be interrogated to determine the frequency content as a function of flow rate, or integrated to show local position of the component in time [20]. Examples of these analyses for the MP-1 Large B experiment are shown in Figure 10.

Conclusions

The USHPRR FD program has continued the longstanding practice of utilizing flow testing in the nuclear fuel development process. The tests have enabled the use of high-confidence parameters in defining hydrodynamic conditions for the analysis of thermal safety scenarios and programmatic predictions. The HMFTF has been utilized for experiment characterization, and will be used in the near future for the scientific study of the plastic response of plates under flow. OSU’s NQA-1 quality assurance program has enabled INL researchers to concentrate on planning and application of results. The supplemental data collected during the tests is being investigated to provide insight into the dynamic response of the experiment assemblies under flow. The inclusion of flow testing in the USHPRR effort is evidence of the LEU conversion program remaining mindful of the caution and diligence recommended by the early research reactors’ hydraulic test engineers, as evidenced by their thorough fuel acceptance programs and their insightful (and precautionary) conclusions.

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