University of Missouri Research Reactor LEU Fuel Element Flow Test Conceptual Design

Nuclear Science & Engineering Division

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prepared by

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Executive Summary

As part of the U.S. National Nuclear Security Administration's (NNSA's) mission to eliminate or minimize the civilian use of weapon-grade highly enriched uranium (HEU) fuels, the NNSA Office of Material Management and Minimization (M³) Conversion Program is collaborating with six U.S. High Performance Research Reactors (USHPRR), including one critical facility, to convert from the use of HEU to low-enriched uranium (LEU) fuel. The M³ conversion objectives for the USHPRR are to develop LEU fuel-element designs that will ensure safe reactor operations, as well as maintain the existing experimental performance of each facility. The work is being conducted through many interrelated activities that are being completed by stakeholders across organizations.

Within the Reactor Conversion (RC) Pillar of the USHPRR Project, four of the USHPRR, including the University of Missouri Research Reactor (MURR®), have progressed through preliminary element design using the proposed monolithic alloy of uranium-10 wt% molybdenum (U-10Mo). Preliminary fuel element design and safety analyses have been completed for MURR. This work has relied on preliminary data for properties, performance, and fabrication tolerances for the fuel systems that have been documented by the Fuel Qualification (FQ) and Fuel Fabrication (FF) Pillars.

The HEU fuel elements have been operating within the MURR for several decades with excellent performance history. MURR LEU fuel elements have been designed to include 23 fuel plates (one less than the HEU element). The thickness of the MURR LEU fuel plates has been reduced from 0.050 inch for all HEU plates to 0.044 inch for plates 1 to 22 and 0.049 inch for plate 23 (the outermost plate with the largest span). Five different fuel core thicknesses have been designed within these plates. Due to the change in the fuel system, to maintain equivalent performance for the reactor facility, the power of the proposed LEU core is increased to 12 MW, which is 2 MW higher than that of the HEU core. The nominal coolant flow rate for the LEU core remains the same as for the current HEU core.

In preparation for licensing, a hydraulic performance evaluation of the MURR LEU fuel element will be performed by the Reactor Conversion (RC) Pillar at the Hydro-Mechanical Fuel Test Facility (HMFTF) at Oregon State University (OSU). The purpose of this evaluation is to test a prototypic commercially fabricated LEU fuel element, to determine whether any failure modes are observed in the fuel element, including significant deformations such as plate bending, twisting, or plate detachment from the side plate under selected safety-basis limits for reactor flow conditions. The evaluation will be performed by a combination of out-of-pile flow test and supporting analyses.

This report describes the activities completed during the conceptual design of the MURR LEU fuel element flow test. Three goals have been identified for the flow test conceptual design:

1. Review the hydraulic reactor design parameters and identify the most limiting conditions for the fuel elements,
2. Review and select the methods and sensors for monitoring various hydraulic and mechanical characteristics of the flow tests, and
3. Perform a conceptual design of the testing vehicle to be used in the flow test.

The design parameters for hydraulic testing of the LEU fuel element were reviewed and documented in a separate report. These relate to the design needs of the reactor and, are therefore referred to as reactor design parameters since they do not take into account design margins required for the experimental test design and other purposes. Here, only a summary of that review containing the information affecting the design of the flow test is included. The normal operating conditions of the

MURR LEU core, including the coolant flow rate, temperature, system pressure, and coolant chemistry specification, are summarized (see Section 3 for details).

The most limiting plates from the perspective of flow-induced deflections in the MURR LEU fuel element are plates 22 and 23, which have the largest span of all the fuel plates in the element. The expected behavior of these plates in the MURR LEU fuel element has been evaluated based on the prior experimental work and preliminary fluid-structure interaction analysis for the MURR LEU fuel plate 22. The flow tests for the MURR LEU fuel element will be executed at conservative flow rates for the MURR core (from the hydro-mechanical performance perspective). For these flow rates, the coolant channel flow velocities are a fraction of Miller's critical velocity. Hence, pressure-induced quasi-static deflection is the expected type of response of the MURR LEU fuel plates to the hydrodynamic load of the flowing coolant (vibrations of negligible magnitude are expected). The maximum deflections that are expected to occur at the leading edge of the plate are predicted to be in the order of 25 micrometer (~ 1 mil, a mil is 0.001 inch). This behavior has a direct impact on the selection of the sensors for monitoring the plate's deflections during the flow test (see Section 3.3 for details).

Based on the historical experiments, prior experimental work under USHPRR Project, and the needs of the currently designed flow test, sensors for monitoring the fuel element, and in particular plate deflections, have been reviewed. Most of the past experiments used strain gauges installed on the surface or embedded in the plates to measure the deflections indirectly from strains. This technique was proven to work for the detection of static deflections as well as dynamic flutter. However, the past experiments mainly were focused on characterizing the response of the plates to significant coolant flow rates, reaching or even exceeding Miller's critical velocity. Sensors that are potentially able to resolve the small deflections expected during the flow test of the MURR LEU fuel element have been identified and will be evaluated under dry and wet conditions to demonstrate their capabilities beforehand. The demonstration tests are planned for the preliminary design of the flow test at OSU (see Sections 2 and 4 for details).

A conceptual design of the testing vehicle (basket) has been completed and is also described in this report. The external dimensions of the basket allow for its insertion into the HMFTF flow loop. The internal dimensions of the basket represent the most limiting configuration on the MURR LEU fuel element in the core. The access to the most limiting plate through the basket walls will be adjusted based on the final selection of the sensors used for visualization and deflection measurement. The design of the basket also considers different measurements and individual tests, referred to in this report as "stages of the flow test", which will be conducted as a part of the overall flow test campaign. It takes into account constraining the element for some stages of the test to prevent lateral and axial motion of the tested fuel element so the displacements of the plates due to the hydrodynamic load can be decoupled from the motion of the fuel element within the basket. The basket design also allows for inspection of the channel gap thicknesses with a channel gap probe between different stages of the flow test (see Section 5 for details).

Finally, activities conducted in preparation for the flow test preliminary design have also been briefly discussed in this report (see Sections 4.5 and 6 for details).

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Acronyms and Abbreviations

Argonne	Argonne National Laboratory
CFD	Computational fluid dynamics
CGP	Channel gap probe
DDE	Design Demonstration Element
EFL	Endurance Flow Loop
F&RD	Functions and Requirements Document
FF	Fuel Fabrication
FQ	Fuel Qualification
FSI	Fluid-structure interaction
GTPA	Generic Test Plate Assembly
HEU	Highly enriched uranium
HMFL	Hydro-Mechanical Flow Loop
HMFTF	Hydro-Mechanical Fuel Test Facility
LEU	Low-enriched uranium
LSSS	Limiting Safety System Setting
LVDT	Linear variable differential transformer
M ³	Office of Material Management and Minimization
MITR	Massachusetts Institute of Technology Reactor
MU	University of Missouri
MURR	University of Missouri Research Reactor
NNSA	U.S. National Nuclear Security Administration
OSU	Oregon State University
RC	Reactor Conversion
SAR	Safety Analysis Report
U-10Mo	uranium-10 wt% molybdenum
USHPRR	U.S. High Performance Research Reactor

Definition of Terms

Best estimate	Parameter value that is determined with the best available methods and/or models without including uncertainty.
Bounding	A parameter value that has been technically determined to not be exceeded under given conditions, such as, for example, normal operating conditions.
Conservative	Method, or resulting parameter value, that is not best estimate and includes uncertainty or margin whether discretionary or due to conservative assumptions.
Experiment design margin	The difference between an experiment target test value and a reactor design parameter value. The experiment design margin is increased (or decreased) on a discretionary basis or due to conservative assumptions.
Fuel core	The uranium-bearing region of each fuel plate.
Fuel foil	Metal uranium alloyed with molybdenum and bonded on the facing sides with zirconium diffusion barrier layers.
Fuel qualification	The process of designing, conducting, and evaluating experiments to ensure that the fuel is capable of performing without failure during reactor operations up to reported performance limits. Fuel qualification also includes measurements and reporting of fuel properties that can be used in performance and safety modeling.
Limiting safety system setting	Limiting values for settings of the safety channels by which point protective action must be initiated. The LSSSs are chosen so that automatic protective action terminates the abnormal situation before a safety limit is reached. The calculation of the LSSS shall include the process uncertainty, the overall measurement uncertainty, and transient phenomena of the process instrumentation.
Nominal	Value of a parameter under normal operating conditions.
Prototypic condition	Conditions that are considered representative of normal operating conditions and matching key aspects of the fuel design geometry.
Prototypic fuel	Fuel produced with a commercial-scale process consistent with the final specifications used for fabrication of fuel plates and elements.
Reactor design parameter	Best estimate value from reactor analysis used as a basis in experiment design for fuel qualification and licensing tests. Each reactor stakeholder in RC Pillar activities identifies and documents reactor design parameter values.
Regime appropriate	A set of conditions representative of reactor operations for which the value(s) does not have an impact on phenomena within a known range. For example, irradiation-induced creep in U-10Mo fuel at USHPRR operating conditions is not correlated to temperature, and therefore temperatures at which thermally induced creep does not occur can be referred to as “regime appropriate.”
Safety basis	A SAR, referenced supporting information, and other regulatory materials that provide the basis for safe operation of a reactor facility.
Safety margin	The difference between a regulatory limit and an appropriate value, that is either calculated or measured. Calculated values may include uncertainties to increase the conservatism of the safety margin.

Target test value	The goal value based on a reactor design parameter to be achieved during testing, such as during an irradiation experiment to support fuel qualification or fuel demonstration. The FQ, or other, Pillar identifies, and documents target test values in collaboration with other Pillars based on the reactor design parameters.
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1 Overview

1.1 University of Missouri Research Reactor and Fuel Element

The University of Missouri Research Reactor (MURR®) in Columbia, Missouri, is a multi-disciplinary research and education facility providing a broad range of analytical and irradiation services to the research community and the commercial sector. MURR is a 10 MW light-water-cooled reactor using highly enriched uranium (HEU, ≥ 20 wt% U-235) fuel [1].

MURR is one of five U.S. High Performance Research Reactors (USHPRR), plus one critical facility, that actively collaborates with the National Nuclear Security Administration (NNSA) Material Management and Minimization (M³) Reactor Conversion Program to convert to the use of low-enriched uranium (LEU, < 20 wt% U-235) fuel. A new type of LEU fuel with a very high density, based on an alloy of uranium and 10 weight percent molybdenum (U-10Mo), is expected to allow the conversion to LEU of USHPRR [2] that have been found to be unable to be converted with previously qualified uranium silicide-aluminum (U₃Si₂-Al) dispersion fuel. A detailed description of the MURR LEU fuel element design can be found in [1], [3], [4], and [5].

MURR is designed with downward flow from a single inlet plenum. The core's eight curved wedge-shaped elements are of identical design and are arranged in a circle to form an annulus, as shown in Figure 1.1. The arc angle of the fuel plates is approximately 45°. The reactor core is contained inside a pressure vessel. The pressure vessel is located near the bottom of an open pool of water, which provides shielding. A single flux trap is located in the hole in the center of the reactor core. Forced flow of water from the reactor pool is used to cool the flux trap, the control blades, and the reflectors (not shown in Figure 1.1), which are positioned outside of the pressure boundary.

Figure 1.1. Cross-sectional view of MURR.

Each of the HEU elements consists of 24 curved fuel plates that are 25.5 inch long. The fueled portion of each fuel plate is 24 inch long and centered within the length of the plate. The LEU plates retain these dimensions, but there are 23 plates per element instead of 24 (see Figure 1.2 for illustrations of the LEU fuel element). To maintain the performance of the HEU core, the power is increased to 12 MW for the LEU design. The nominal coolant flow rate for the LEU core remains the same as the current HEU core. The Limiting Safety System Setting (LSSS) flow rate and coolant inlet temperature for the LEU core are 3300 gpm and 145 °F, respectively, compared to 3200 gpm and 155 °F for the HEU core. The changes to these LSSS values are needed to maintain safety margins equivalent to those in HEU core.

Figure 1.2. An isometric view of MURR fuel element (left); cross-sectional view (right).

In the HEU element, all the fuel plates have nominal thicknesses of 0.050 inch, 0.020 inch for the fuel core, and 0.015 inch for each cladding, which is AA6061. The nominal spacing between HEU fuel plates is 0.080 inch. By contrast, each LEU plate has one of five nominal uranium-molybdenum (U-10Mo) alloy fuel core thicknesses – 0.009, 0.012, 0.016, 0.017, or 0.020 inch – in order to flatten the radial heat flux profile and improve safety margins. The first three thicknesses apply to each of the inner (closest to the flux trap) three plates within an element. The plate furthest from the flux trap (plate 23) has a fuel core thickness of 0.017 inch. The other 19 plates have a fuel core thickness of 0.020 inch. All the LEU fuel plates have a nominal thickness of 0.044 inch except for the one furthest from the flux trap (plate 23), which has a thickness of 0.049 inch. The fuel core thickness is centered within the plate thickness. The cladding for the LEU fuel plates is made of AA6061. The cladding thickness is dependent on the plate number, varying from 0.011 to 0.0165 inch as detailed in Table 1.1. A 0.001-inch-thick interlayer of zirconium (Zr) is present on each side of the fuel core, and serves as a diffusion barrier to eliminate or minimize fuel-cladding interaction. The first four inner coolant channel gaps from the two ends of the LEU fuel element have a nominal gap thickness of 0.093 inch. The other 14 channel gaps in the LEU element have a nominal gap thickness of 0.092 inch. The nominal thickness of the most inner (channel 1) and most outer (channel 24) is 0.0805 inch. A comb is attached to the bottom and the top of the fuel plates to enhance the stability of the plates at the leading and trailing edges of the plates. The other portions of the element construction (e.g., side plate length, width, and thickness; end fittings; and inner and outer rollers) will be identical to the HEU fuel element. A comparison of geometrical characteristics of the MURR HEU and the MURR LEU fuel elements is listed in Table 1.1.

Table 1.1. Comparison of geometrical characteristics of the MURR HEU and the MURR LEU fuel elements.

	MURR HEU fuel element	MURR LEU fuel element
Number of fuel plates	24	23
Interior channel thickness	0.080 inch	0.092 or 0.093 inch
Plate total thickness	0.050 inch	plate 1 to 22, 0.044 inch, plate 23, 0.049 inch
Fuel core thickness	0.020 inch	plate 1, 0.009 inch, plate 2, 0.012 inch, plate 3, 0.016 inch, plate 4 to 22, 0.020 inch, plate 23, 0.017 inch
Zirconium interlayer thickness	N/A	0.001 inch
AA6061 cladding thickness	0.015 inch	plate 1, 0.0165 inch, plate 2, 0.015 inch, plate 3, 0.013 inch, plate 4 to 22, 0.011 inch plate 23, 0.015 inch
Plate length	25.5 inch	25.5 inch
Fueled portion length	24 inch	24 inch

The HEU fuel elements have been operating within the MURR for several decades with excellent performance history. However, the MURR LEU fuel plates are thinner than the HEU plates, which leads to a reduced bending stiffness compared to the HEU plates. Due to the reduction of the number of plates within the fuel element, the average coolant flow velocity in the channels is lower than that in the HEU fuel element. The combination of these changes leads to different hydrodynamic conditions from those of the HEU core, potentially influencing the integrity of the MURR LEU element and stability of the fuel plates under operating conditions.

1.2 Functions and Requirements for the LEU Fuel Elements

The USHPRR Functions and Requirements (F&R) Document [6] has been issued to document the functions and requirements of the new LEU fuel systems that the USHPRR Project is developing for the conversion of the USHPRR from HEU. The functions identify what the fuel systems should do, and the requirements define the parameters for performing these functions. The F&R document also generally describes the key performance attributes that guide the development of the fuel and fabrication processes as a component of the requirements. Several of these requirements warranting flow test are outlined below.

Under function F 1.1 “Maintain Mechanical Integrity,” the following requirements, among others, are listed:

- R 1.1.2. The mechanical response of the fuel core, cladding, and any interlayers or other fuel plate components during normal operations and transients where fuel integrity is required shall be established. (Basis: NUREG-1537, Part 1, Chapter 18 and Chapter 4 Section 4.2.1. Retention of fission products capability and establishment of safety limits.)
- R 1.1.3. The fuel element shall not fail mechanically during normal operations and transients where fuel integrity is required. (Basis: NUREG-1537, Section 4.2.1, Maintain fission products and integrity of fuel element.)

Under function F 1.2 “Maintain Geometric Stability,” the following requirements, among others, are listed:

- R 1.2.3. Fuel performance and structural stability shall be maintained so that reactor coolant flow keeps fuel plate heat transfer and/or temperatures within the reactor safety analysis envelope (Basis: The ability to cool the reactor fuel must be maintained. Report ANL/RERTR/TM-11-28 on flow instability model for MURR states flow instability avoidance as a safety requirement for MURR, and NUREG-1537, Section 4.2.1)
- R 1.2.4. Plate movement caused by pressure differential shall not compromise ability to cool the fuel. (Basis: Geometry of the fuel must be stable and predictable to maintain cooling.)
- R 1.2.5. Changes in channel gap shall not compromise ability to cool the fuel. (Basis: Ability to cool the fuel during normal and transient conditions must be maintained allowing for geometry changes [volumetric swelling, twist, thermal expansion and deflection, etc.])

Under function F 1.5 “Test to Verify Design Requirements Have Been Met,” among others, the following requirements are listed:

- R 1.5.1. Verification (i.e., tests, reviews, analyses) shall be completed to demonstrate that the fuel elements are designed to accommodate expected mechanical forces and stresses,

hydraulic forces, thermal changes and temperature gradients, internal pressures including that from fission products and gas evolution, and radiation effects including the maximum fission densities, fission rates, and fuel temperatures. (Basis: NUREG-1537, Part 1, Section 4.2.1.)

1.3 Flow Test Goal

The experimental needs for qualification of the proposed design of the LEU fuel elements consist of two major components conducted at the full element level: the hydraulic performance evaluation led by the Reactor Conversion (RC) Pillar and the irradiation testing led by the Fuel Qualification (FQ) Pillar.

The purpose of the hydraulic performance evaluation of the MURR LEU fuel element designed by the RC Pillar is to test a prototypic commercially fabricated LEU fuel element, to determine whether any failure modes are observed in the fuel element, including significant deformations such as plate bending, twisting, or plate detachment from the side plate under selected safety-basis limits for reactor flow conditions. The evaluation will be performed by a combination of out-of-pile flow test and supporting analyses. Although margins to these failure modes need to be presented, the tests are not meant to be run to failure (loss of integrity or large deflections) of the fuel elements. To demonstrate the existence of such margin, the most conservative MURR core configuration (in terms of the fuel element configuration in the core) will be considered, as well as the flow rates during the test will be increased beyond the normal operation band. That core configuration and the conservative flow conditions (from the perspective of flow-induced deflection) are described in Section 3 of this report and in more detail in [7].

Another component of the hydraulic performance evaluation of the MURR LEU fuel element design comprises of computational analyses, including both computational fluid dynamics (CFD) and fluid-structure interaction (FSI), that are meant to guide certain aspects of the tests (e.g., instrumentation placement) and provide data that are complementary to the experimental observations (e.g., sensitivity study).

It is noted that separate testing will be performed within the USHPRR Project as part of the MURR Design Demonstration Element (DDE) irradiation test led by the FQ Pillar. The MURR DDE will be irradiated in a test reactor (Advanced Test Reactor [ATR]) under irradiation conditions designed to be as prototypic of the MURR LEU fuel element as possible. While the irradiation test contains an aspect of flow test, the MURR DDE end fittings have a significantly modified shape, and the flow conditions in these tests are as close to nominal as practical. MURR LEU fuel element flow test will be representative of the conservative conditions from the perspective of the hydro-mechanical stability of the fuel elements.

1.4 Flow Test Conceptual Design Goal

The first technical objective of the flow test conceptual design is to perform a review of the hydraulic reactor design parameters of MURR to represent best estimate values and account for uncertainties that may lead to more conservative values in MURR LEU core. As a part of this, there is also an evaluation of adequate additional experiment design margin which includes differences between the reactor core and the flow test. To initially analyze these systems, a flow network analysis with both a

reactor core and a single element in the basket was performed. Confirmatory CFD and FSI analyses will be performed during the preliminary design of the flow test following the proposed plan given in Section 6.1 of this report.

The second technical objective is to review the methods and sensors for monitoring various hydraulic and mechanical characteristics of the flow tests. Testing the sensors by Oregon State University (OSU) on a single plate and an all-aluminum mockup of the MURR LEU fuel element are planned for the preliminary and final design of the flow test, respectively.

The maximum static deflections of fuel plates in MURR LEU elements caused by a pressure differential in the channel gaps are expected to be in the order of 25 micrometer (~ 1 mil), see Section 3.3.2 for details. Since such small deflections are difficult to measure in fuel plates under the flow conditions, the quantification of the total deflections (elastic and plastic components) is desired but not required for successfully conducting a flow test. Quantification of the plastic (permanent) deflections is required via the analysis of pre- and post-test geometry (see Section 4.2.5 for permanent deflections measurement). Techniques for visualization, as well as measurements of the deflections near the plate's leading edge (where the deflections in the MURR LEU fuel element are expected to be the largest), are of interest during the conceptual design of the flow test. As an alternative, confirmation that the deflections are below the known accuracy of a measuring device is sufficient. In such a case, the confirmed uncertainty of the measurement must be shown to be of a similar scale as the expected maximum deflection of the MURR LEU fuel plate under the hydrodynamic load (see Section 3.3 for the estimation of that value).

The third technical objective of this work is to develop a conceptual design of a testing vehicle (basket) that will accommodate the MURR LEU element in the Hydro-Mechanical Fuel Test Facility (HMFTE) flow loop for hydro-mechanical testing. The outer dimensions of the basket must allow for insertion in the testing section of the HMFTE flow loop. The internal dimensions of the basket should represent the most limiting configuration in the core. The geometrical features of the basket must be machinable with the techniques and equipment available. The conceptual design of the basket and the evaluation of the sensors will take into consideration the accessibility of the most limiting plate in the MURR LEU element for measurements. The basket also needs to be structurally sound enough not to deform during handling, assembly, and flow tests.

The conceptual design of the flow test will also focus on other preparatory tasks to be completed later in the flow test design process, including planning for supporting numerical analyses, purchase of the sensors, and all-aluminum dummy elements for sensor testing and basket fitting.

2 Experimental Methods

2.1 Background

The original design work on U.S. research reactors was conducted in the late 1940s through the 1960s. The early experiments conducted at Oak Ridge National Laboratory by Stromquist and Sisman in 1948 indicated that at sufficiently high flow velocities, mockup flat plates were deforming plastically, and curved plates experienced a reversal of curvature (i.e., were buckling) [8]. These deformations were caused by pressure differential on the two sides of the plate due to the imbalance of the flow. As a result, one or more channels in the assembly were completely closed.

The phenomenon of plate collapse observed by Stromquist and Sisman raised a concern and triggered a series of experiments and analyses conducted in later years by many researchers. The most often cited of these was Miller, who in 1958 derived formulas for critical coolant flow velocity at which elastic plates can lose their stability and collapse [9]. Miller derived his equations for both initially flat and curved plates with a multitude of boundary conditions including built-in (fixed) and hinged (simply supported) plates (see Section 3.3.1 for calculations of Miller's critical velocity for MURR LEU plate).

Many researchers have continued the work begun by Miller. Some of the results, especially those coming from theoretical derivations, supported Miller's findings. However, a substantial group of experimental studies did not confirm the presence of the critical velocity that would mark the onset of instabilities or collapse. Instead, they reported gradually increasing deflections of the plates and/or vibrations, depending on the flow conditions.

One of Miller's original assumptions was that all channels have an equal thickness. He also assumed that the length of the plate was significantly larger than the length of the deflected region. Miller approximated the behavior of the plate using wide beam theory which simplified his derivations. In Miller's derivation, the frictional pressure drop in the deflected region is small, inertia effects in the fluid and some three-dimensional effects are ignored. Refinements of Miller's theory came from, among others, Johansson [10]. In his work, Johansson made corrections to some of the assumptions made by Miller. He accounted for flow redistribution between adjacent channels due to the plate's deflection. This caused further pressure increment acting on the plate. Also, by including axial bending in the analysis, the three-dimensional character of the deflection region was accounted for. Depending on the geometrical aspects of the plates, he predicted critical coolant flow velocity to be between 0.8 and 1.6 times that of Miller. He concluded that the addition of comb support at the leading edge locally increases the critical velocity significantly and moves the most critical region in the plate from the leading edge to about one to two spans of the plate between the supports downstream from the leading edge.

In 1962 Rosenberg and Youngdahl [11] included inertia effects in their analysis and formulated a dynamic model of the plate stability in the coolant flow. Their model confirmed Miller's finding of the presence of divergence (deflections increasing with time) at higher velocities and stable oscillations at lower velocities. Further improvements of Miller's theory were made, among others, by Scavuzzo (1965) who coupled the hydraulic equations with the plate equations to obtain non-linear integral equations describing the plate's deflection even more accurately [12].

In the late 1950s, Zabriskie studied the deflection of single and multiple plate assemblies with and without leading-edge support combs [13], relating his findings to those reported by Miller. A sudden collapse was not observed in these experiments. Instead, in all conducted tests, the deflections grew progressively with increasing velocity. However, agreement within 20% of Miller's theory was reported for most of the cases. Zabriskie used pressure taps installed along the plate axis in the side plates to characterize the pressure differentials acting on the plates. He subsequently utilized simple beam theory to correlate these pressure differentials to the deflection of the plates. The presence of the combs on the leading edge increased the stability of aluminum plates allowing for higher flow velocities.

In 1963 Groninger and Kane tested three 5-plate assemblies to examine their deflections due to the parallel flow [14]. The experiments introduced specially designed strain gauges embedded in the plate edges to measure the deflections indirectly. Flow velocities up to 190% of Miller's critical velocity were considered in these tests. The primary conclusion of this work was that the critical velocity deflection is a magnification of the initial perturbations in the fuel plates. The authors did not observe catastrophic or sudden deformations of the plates. They noticed that the adjacent plates always deform in opposite directions at high flow rates, either opening or closing the channels. High-frequency vibrations (flutter) were noticed for the highest flow velocities. The comb installed on the leading edge suppressed this behavior, but large deformations were still present away from the leading edge. Further theoretical analysis performed by Kane [15] also focused on the influence of initial imperfections in the plate geometry near the leading edge on the increase in the flow-induced deflections. Kane concluded that small differences in channel gap thickness for flow rates near the Miller's critical velocity exacerbate the deflections.

In 1968 Smissaert conducted a set of experiments on plate assemblies made of PVC to characterize the static and dynamic behavior of the plates at different flow velocities [16]. Five-, nine-, and fifteen-plate assemblies were investigated. Strain gauges were embedded along the center plate's length in the middle of the span to capture the entire profile of the deflected plate. Because of the minimum thickness needed for the installation of the pressure taps, only the assembly with the largest channel gaps (the five-plate assembly) was instrumented with them. The maximum flow rates in the test reached 3.5 times Miller's critical velocity. Smissaert identified several instabilities in the plate: static deflection of the leading edge, static deflection over the full length of the plates in the plate array, small amplitude traveling waves, and large amplitude flutter. He noticed that for low velocities, the plates deformed as a result of a static pressure differential in the channels. The flutter, consisting of traveling waves, originated at the leading edge of the plate and ran down the plate in the direction of the flow. The wavelength of the deformation was a function of the coolant velocity. High-frequency flutter instabilities, without sudden collapse, were reported for velocities close to two times Miller's critical velocity. These tests also showed that any disturbance of flow entering the channels surrounding the fuel plates has a significant effect on plate deflections. Smissaert also noticed that installing a support comb on the leading edge suppresses the high-frequency flutter and significantly reduces the deflections in the plates.

In the early 1990s Swinson, et al. conducted flow tests on involute plate assemblies in support of the Advanced Neutron Source reactor design [17], [18], [19], [20]. Five-plate assemblies were the subject of the experiments. To lower the flow velocity and pressure required for the anticipated collapse conditions, the test assemblies were constructed of epoxy. The inner three plates in the assembly were instrumented with five strain gauges placed along the center axis. Each of the gauges were located near the leading edge, at 25%, 50%, and 75% of the plate's length, and near the trailing edge. Five static pressure taps in each channel were positioned in the same cross-sectional plane as the strain gauges. The maximum deflections were measured either at the leading edge or at a three-

quarter length of the plate. The author formulated an analytical solution for the maximum involute plate deflection due to a pressure load using Castigliano's energy theorems for deformation. The deflections calculated through this analytical approach were compared with the deflections experimentally found with the strain gauges. The calculated values were a reasonable approximation of the measured values.

In 2004 Ho, et al. performed a series of experiments on two-plate assemblies to support the design of the Replacement Research Reactor for the Australian Nuclear Science and Technology Organisation (ANSTO) [21]. The plates were instrumented with strain gauges at three positions: the leading edge, the middle of the plate (in the axial direction), and the trailing edge. At each position, two strain gauges were installed on either side of the plate. To prevent the strain gauges from influencing the flow in thin channels, the gauges were epoxied into a groove milled on the plate's surface. The results showed plate collapse occurring at an average velocity of 78% of Miller's critical velocity. During the plate collapse, cavitation was observed on the leading edge of the deformed plate. The mode of collapse in these experiments appeared to be random with both plates collapsing onto each other or both deflecting away from each other.

In the early 2010's Liu et al. [22] and Li et al. [23] performed a study on FSI for single and double plate assemblies in water flow. In their experiments, Liu et al. constrained only the four corners of the plates, which significantly decreased the stiffness and increased the deflection of the plates as compared to the plates constrained along two long edges. The testing section was enclosed with plexiglass, which allowed for the utilization of a laser sensor for the measurement of the plate's deflection. Li et al. found several regimes of flow rates that resulted in different characteristic responses. At the lowest velocities, the thickness of the channel between the plates was reduced and no vibrations were present. At higher velocities, large vibrations that occurred caused both plates to oscillate in the same or opposite phases, depending on the flow rate regime. The boundary conditions selected for the tested plates did not allow for a comparison of the results with Miller's theory.

In 2017, Castro et al. [24] reported on experiments conducted on two-plate assemblies with dimensions similar to those in the fuel element of the Brazilian Multipurpose Reactor. The aluminum plates were enclosed in a testing section made of plexiglass. Strain gauges were installed near the inlet, the middle, and the trailing edge of the plate to indirectly measure the deflections. Pressure drop measurements were used as a secondary method for detecting the collapse of the plates. Collapse and plastic deformations of the plates were reported at flow velocity close to 85.5% of Miller's critical velocity. Below that velocity, the maximum deflection on the leading edge was proportional to the squared velocity.

Past experiments mentioned in this section remain an important reference in this evaluation of fuel plate hydro-mechanical performance, both in terms of designing fuel plate assemblies and in informing the selection of measurement techniques. Most of the described experiments made use of the strain gauges installed on the surface of the plate to measure the deflections. This technique was proven to work for the detection of static deflections as well as dynamic flutter. However, these experiments were mostly focused on characterizing the response of the plates to significant coolant flow rates reaching or even exceeding Miller's critical velocity. The flow tests for the USHPRR LEU fuel elements will be executed at significantly lower flow rates which are a fraction of Miller's critical velocity (see Section 3.2). Also, the deflections of the plates are expected to be at the level of a fraction of the MURR LEU element channel gap thickness see (Section 3.3). Thus, the conceptual design of the flow test is focusing on selecting the most appropriate sensors that can detect the expected deflections in the plates under the nominal and conservative MURR flow conditions.

2.2 Flow Testing Capabilities for USHPRR

To support the evaluation of the hydraulic performance of the USHPRR LEU fuel elements, the USHPRR Project commissioned the development of two experimental facilities: the Hydro-Mechanical Flow Loop (HMFL) at the University of Missouri (MU) and the HMFTF at OSU. Both facilities have hosted a series of flow-test experiments in previous testing campaigns. The outcomes of these testing efforts have resulted in an impact on the design of the current flow tests. The following sections briefly describe these two facilities and some of the experiments performed there.

2.2.1 Hydro-Mechanical Flow Loop at the University of Missouri

Initial work for the RC Pillar's hydraulic performance evaluation of the LEU fuel elements has been performed at the HMFL at MU. The flow loop and a flow path schematic of HMFL are shown in parts a and b, respectively, of Figure 2.1. This flow loop includes a National Instruments cDAQ system for data collection and control of the flow. User control and monitoring are accomplished with LabView software.

Figure 2.1. (a) The Hydro-Mechanical Flow Loop (HMFL) at the University of Missouri, and (b) schematics of the loop.

The water flow loop was designed to accommodate a wide range of test sections. So far, single flat and cylindrical aluminum plates with two surrounding channels have been tested at the facility at varying flow rates [25]. During the tests, the pressure differential between the two fluid channels was monitored with the use of Omega PX-26 differential pressure transducers. The total flow rate was measured with an in-line flow meter. To map the thickness of the fluid channels and monitor plate deflection during the flow test, two Keyence LK-G152 laser displacement sensors were used.

The test sections were built with a wider channel gap on one side of the test plate and a narrower channel gap on the other side. This represents the differences that could be encountered in USHPRR LEU fuel elements due to allowed fabrication tolerances. The flat plate was nominally 0.040 inch thick. The outer walls of the channels in the flat plate experiments were built of transparent plexiglass to allow for the mapping of the channel gap thicknesses with the motor-operated laser sensor. The laser

was also used for monitoring the deflection of the plate at several locations along the centerline of the plate. The variation in the channel gap thickness was a combination of the plate shape and the channel's wall imperfections. Sizeable imperfections that were detected before the test influenced the magnitude as well as the shape of the plate's deflections. The maximum displacements occurred at the leading edge of the plate with similar magnitude deflections near the middle of the plate in the axial direction.

Numerical models of the setup were built with the use of STAR-CCM+ software to study the behavior of the plate as a FSI problem. Pre-deforming the modeled plate using the distribution of the mapped imperfections of the channel gap thickness, allowed for obtaining results that closely matched the experimental data.

In the curved plate experiments, the outer channel walls were built of stainless-steel cylinders. The cylindrical plate was built of a 0.0159-inch-thick sheet of aluminum. In this case, the majority of the imperfections in the channel gap thickness came from the shape and the position of the tested plate between the inner and outer cylinders. Since the mapping could not be done with a laser through the opaque walls, a depth micrometer was used to measure the variation in the channel gap thickness. The displacements of the plate were measured again with the use of the laser, but only through a series of five plexiglass windows installed in the outer cylinder. Again, after including the measured imperfections in the position and flatness of the plate in the numerical models of the setup, a close match between the simulations and the experiments was found.

These experiments have proven that laser sensors can resolve small deflections of the plates (around 4 mil) with a reasonable level of uncertainty (~1 mil). Also, they have confirmed that information about the as-built geometry is required for the numerical models to match the experimental data.

2.2.2 Hydro-Mechanical Fuel Test Facility at the Oregon State University

The HMFTF (see Figure 2.2) is located in the Advanced Nuclear Systems Engineering Laboratory at OSU [26], [27], [28]. It is a large-scale thermal-hydraulic separate-effects test facility operating in conformance with the American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA-1) standard (ASME NQA-1-2008 with 2009 Addenda) [29]. The facility allows for testing a wide range of elements provided that they fit into the 15-foot-tall test section. Test section diameter is that of 6-inch Schedule 40 stainless steel (SCH40S) pipe with nominal internal diameter of 6.065 inch. The HMFTF facility was designed to envelop the flow, and pressure operating conditions of all high performance research reactors in the U.S. as well as those required for fuel qualification. The range of operation of the loop covers flow rates ranging from 100 gpm to 1600 gpm. The testing loop is rated to 600 psig and 460°F. The configuration of the loop allows for upward and downward flows through the test section.

Figure 2.2. Hydro-Mechanical Fuel Test Facility at the Oregon State University (left); test section schematic (right).

To date, multiple experiments have been performed at HMFTF supporting FQ Pillar's efforts, including the MP-1, EMPIRE, FSP-1, AFIP-7 [30], and Generic Test Plate Assembly (GTPA) campaigns. The recently published results of the GTPA experiments document many findings that are instrumental to the entire conversion effort, including experience with the sensors and methodology for monitoring the structural response of thin fuel plates to hydrodynamic load induced by coolant flowing through dissimilar channel gaps [31], [32].

The GTPA compared the response of plates made of four different compositions:

1. A homogenous hot and cold rolled AA6061-T6,
2. DU-Monolithic foil plate,
3. SS-Dispersion fuel plate, and
4. A homogenous sheet AA6061-O.

Each plate was tested within an assembly totaling six plates, with five of them significantly more resistant to bending (Comprising Hastelloy HX alloy) than the tested plate. The tested plates were 0.050 inch thick with a nominal channel gap thickness in the assembly of 0.075 inch. The center channel on one side of the tested plate was approximately 0.188 inch thick, creating a pressure differential acting on the plate.

In the experiment, standard strain gauges (providing point data), as well as fiber optic-based LUNA gauges (providing linear data), were used to monitor strains and hence deflections in the plates. While able to provide high-frequency data, the standard strain gauges were not suitable for

monitoring low-magnitude deflections of the plates because of high noise in the recorded output under the flow conditions during the GTPA tests (high flow rate, pressure, and temperature) [32], [31]. However, they were useful in exploring the dynamic response of individual plates within an element both during steady and transient flow conditions (see Section 4.2 for more information).

The GTPA experiments have shown that all four types of plates tested responded similarly in the elastic range (i.e., had similar bending stiffness) regardless of the material in the core. The tests have also shown that AA6061-O is a conservative material choice for predicting the hydro-mechanical responses of plate-type fuels as it was the first one to collapse at high flow rates. Gradually increasing plate deformations were not observed with increasing flow rate. On the contrary, a sudden collapse of the plates has been noted for all failed plates.

Because of its versatility, NQA-1 compliance, and ability to handle USHPRR LEU fuel elements, OSU HMFTF was chosen to conduct the flow tests for MURR LEU fuel element planned in this report.

2.2.3 Endurance Flow Loop at the Oregon State University

Besides the HMFTF, OSU also operates several testing flow loops used for studying separate effects in plate-type fuel elements; one of these is the Endurance Flow Loop (EFL) shown in Figure 2.3. The EFL is a parallel-system welded stainless steel flow loop designed to force a controlled volumetric rate of water over mock-up reactor fuel plates to simulate in-pile hydraulic conditions. Although compact in size, the EFL is outfitted with several different flow paths balanced by strategically placed valves to divert flow, enabling desired flow and pressure conditions to be achieved with respect to the fuel elements. All hardware and sensors on the EFL are controlled or monitored through a Data Acquisition System and displayed in a Graphical User Interface control panel on the computer [33].

The driving force for the flow in the EFL is a twin-stage 10-hp vertical in-line pump that can deliver 35 to 225 gpm and provide a differential pressure of up to 200 ft dynamic head. This pump is controlled via a variable speed drive which adjusts the rotational speed of the pump. The flow through the EFL is measured from three vortex-style Rosemount flow meters, which cover the whole operational range of the system. Pressure transmitters are placed around the facility to monitor the gauge pressure of the inlet test sections and the differential pressure across the fuel elements and the pump. Three thermocouples are located on the facility to measure the bulk coolant temperature and the differential temperature across the pump. Water quality is measured by pH and conductivity probes. The EFL is limited to a pressure of about 150 psig, and a temperature of 200 °F enveloping the flow conditions of the MURR.

A portion of the preparatory tests, including a feasibility study and demonstration of the sensors, is planned to be performed at the EFL facility. The capabilities of this facility are sufficient to perform the relevant flow tests with a significantly shorter turnaround time as compared to the large-scale HMFTF loop.

Figure 2.3. The OSU Endurance Flow Loop (left); test-section schematic (right).

3 Hydraulic Reactor Design Parameters

3.1 Most Limiting Fuel Element Configuration in the LEU Core

The magnitude of deflections in a fuel plate of a specific fuel element design is primarily affected by the following parameters: the coolant flow rate, the thickness and span of fuel plate, and the channel gap thickness disparity between the two sides of the plate. The bending stiffness of the flat plates is determined by their thickness and the material from which they are built. For curved plates, the curvature adds additional stiffness. Imperfections in the boundary conditions and the shape of the plate usually exacerbate the deflections.

In the MURR LEU fuel element, the channel gap thicknesses may differ by design or manufacturing and assembly tolerances. When the thicknesses of both channel gaps adjacent to a fuel plate are dissimilar, coolant flow velocities in these channels are different and cause pressure differential acting on such fuel plate. The plates tend to deform towards the channel with lower pressure, which is usually the thicker one. For curved plates examined in [25], under the same hydrodynamic load, a larger deflection was noted for the case with the thicker channel gap on the concave side of the plate as compared to the case with the thicker channel gap on the convex side of the plate. Additionally, for a sufficiently large pressure differential acting from the convex side of the plate, a sudden buckling of the plate may occur. Hence, the case with a thicker channel on the concave side is assumed to be the limiting one for curved plates from the flow-induced deflection perspective.

Figure 3.1 presents a cross-section through the MURR LEU fuel element with highlighted plates 22 and 23 that have the largest span. The nominal dimensions with tolerances for the LEU fuel plates and channel gaps between them are listed in Table 3.1. The thickness of plate 22 is 0.044 inch while for plate 23, it is 0.049 inch (11% difference in thickness between the plates). Both plates have the same thickness tolerances of 0.002 inch. Thus, in a worst-case scenario from the bending stiffness perspective, these plates can be 0.042 inch and 0.047 inch thick, respectively. Both plates have the same constant curvature.

Plate 22 and 23 have various fuel core thicknesses, but the influence of that variance on the bending stiffness is marginal. In fact, for the FSI analysis in the elastic range, the properties of cladding can be assumed for the entire thickness of the plate as confirmed by the recent FSI analysis for Massachusetts Institute of Technology Reactor (MITR) LEU plates [34] and the three-point bending experiments that supported the GTPA testing performed at OSU [31], [32].

The larger the span of a plate, the larger deflections can be expected in the plate. The span of plate 23 is marginally larger than that of plate 22 by about 3% based on the dimensions presented in the last row of Table 3.1.

Figure 3.1. Most limiting plates in terms of hydro-mechanical stability.

Table 3.1. LEU fuel plate nominal values and tolerances [1].

Fuel Plate Dimension	Location	Nominal Value and Tolerance
Fuel Core Thickness	plate 1	0.009 ± 0.001 inch
	plate 2	0.012 ± 0.001 inch
	plate 3	0.016 ± 0.001 inch
	plate 4-22	0.020 ± 0.001 inch
	plate 23	0.017 ± 0.001 inch
AA6061 Cladding Thickness ^a	plate 1	0.0165 ± 0.001 inch
	plate 2	0.015 ± 0.001 inch
	plate 3	0.013 ± 0.001 inch
	plate 4-22	0.011 ± 0.001 inch
	plate 23	0.015 ± 0.001 inch
Plate Thickness	plate 1-22	0.044 ± 0.002 inch
	plate 23	0.049 ± 0.002 inch
Channel Gap Thickness ^b	channel 1	0.0955 (0.067 to 0.123) inch
	channel 2-5	0.093 ± 0.008 inch
	channel 6-19	0.092 ± 0.008 inch
	channel 20-23	0.093 ± 0.008 inch
	channel 24	0.0955 (0.068 to 0.124) inch
Total span	plate 22	4.090 (4.228 – 2 x 0.069) ^c inch
	plate 23	4.200 (4.338 – 2 x 0.069) inch

^a The measured point minimum AA6061 cladding thickness ("point minclad") by ultrasonic probe inspection can be 0.0095 inch with a bulk minimum AA6061 cladding thickness ("bulk minclad") no less than 0.0107 inch. The terms "point minclad" and "bulk minclad" are defined in Reference [35].

^b For channel 1 and 24, the dimension is between the pressure vessel wall and the surface of the plate.

^c The span estimated as the total width of the plate minus the depth of the plate embedded in the groove of the side plate on both sides of the plate.

As shown in Table 3.1, the range of the thicknesses for channel gaps 1 (0.067 to 0.123 inch) and 24 (0.068 to 0.124 inch) is much larger than that of the inner channel gaps (0.084 to 0.100 inch for channels 6-19 or 0.085 to 0.101 inch for channels 2-5 and 20-23). The channel gap thicknesses of channels 1 and 24, as presented in Table 3.1, consists of two parts: 1) the distance from fuel plates (plate 1 or 23) to the roller bounding surfaces (inner or outer), and 2) the distance from the roller bounding surfaces to the pressure vessel walls, which are schematically shown in Figure 3.2 as A and B, respectively (see Figure 3.2, [1], and [36] for the definition of the outer channels). Note that dimension A in Figure 3.2 is determined by the fabrication of the fuel element. In contrast, dimension B in Figure 3.2 is determined by the position of the fuel element in the pressure vessel.

Figure 3.3 is an excerpt of the technical drawing of the MURR LEU fuel element [4]. It indicates the distance from fuel plates 1 or 23 to the roller bounding surfaces is 0.0805 inch for nominal conditions [4], [7]. The lower and upper limit for the distance from fuel plates 1 or 23 to the roller bounding surfaces is 0.068 inch and 0.094 inch for channel 24, and 0.067 inch and 0.093 inch for channel 1 [4], [7]. Note that this dimension is determined by the fuel element manufacturing. The second part of the end channel gap, the distance from the roller bounding surfaces to the pressure vessel walls (dimension B in Figure 3.2), depends on the positioning of the fuel element in the pressure vessel. The distance between the inner and outer wall of the pressure vessel is 0.030 inch larger than the distance between the inner and outer roller bounding surfaces of the fuel element. For the nominal conditions (Figure 3.2 (a)), this 0.030 inch difference will contribute equally to the dimension of channels 1 and 24, namely 0.015 inch for each channel, which leads to the nominal end channel gap thickness of 0.0955 inch. For the extreme case (Figure 3.2 (b)), the roller bounding surface could contact the outer wall and the entire 0.030 inch would contribute to the inner channel gap thickness, which results in the minimum channel 24 thickness (0.068 inch) and maximum channel 1 thickness (0.123 inch). Also, minimum channel 1 dimension and maximum channel 24 dimension occurs when the roller bounding surface contacts the inner wall of the pressure vessel. When the thickness of channel 1 is maximum, the thickness of channel 24 becomes is at the minimum, and vice-versa. A summary of these values is provided in Table 3.2.

Figure 3.2 Schematic side view of MURR LEU end channel gap(a) fuel element centered between inner and outer pressure vessel wall (b) fuel element contacting the outer wall.

Figure 3.3. Drawing of MURR LEU with end channel gap (fuel plate to roller) highlighted [4].

Table 3.2. MURR LEU end channel gap thicknesses and tolerances.

Dimension of	Tolerance source	Channel	Nominal thickness (inch)	Minimum thickness (inch)	Maximum thickness (inch)
A. Plate to roller	Fuel element manufacture	channel 1	0.0805	0.067	0.093
		channel 24	0.0805	0.068	0.094
B. Roller to wall	Fuel element positioning	channel 1	0.015	0	0.030
		channel 24	0.015	0	0.030
C. Channel gap total (A+B)	Both	channel 1	0.0955	0.067	0.123
		channel 24	0.0955	0.068	0.124

Based on the analyzed dimensions and tolerances, the most limiting distribution of the channel gap thicknesses for plate 22 is 0.085 inch on the convex side and 0.101 inch on the concave side (0.093 inch $\pm$ 0.008 inch). The most limiting distribution of the channel gap thicknesses for plate 23 is 0.068 inch on the convex side (between the plate and the outer pressure vessel) and also 0.101 inch on the concave side (0.093 inch + 0.008 inch). Thus, there is a higher potential for a larger pressure differential acting on plate 23 than plate 22 under maximum channel gap thickness disparities.

Since plate 23 is thicker than plate 22 by 12%, but its span is 3% larger, and the thinner channel on its convex side can be up to 20% thinner than that of plate 22, it is difficult to determine which one of them is more limiting at this time and the flow test should focus on monitoring both of them for the largest deformations within the element. Despite the outlined differences in the geometry of plates 22 and 23 and surrounding them channel gaps, the expected behavior of these plates from the FSI perspective in the test and the reactor should be similar. The distribution of the tolerances in the thicknesses of the plates and the channel gaps around them will determine which one of them is the more limiting plate. In the design of the test, only the thickness of channel gap 24 is partially controlled. By forcing the outermost channel gap to be the smallest possible, the probability of plate 24 being the limiting one is raised.

The fuel element used for flow test at OSU will be a prototypic commercially fabricated fuel element produced to meet the specifications of the MURR LEU element with no additional modifications specific for the testing. Thus, the internal dimensions of the element (including channel gap thicknesses) will not be controlled in the flow test. However, it is planned that the design of the testing vehicle (basket) will allow controlling (in a limited range) the thickness of the outer channel gap on the convex side of plate 23 (channel gap 24). To meet the goal of the MURR LEU element flow test, the most conservative conditions for the outer channel gap thickness will be targeted in the conceptual design of the flow test (thinnest possible outer channel gap 24). Additionally, the most conservative pressure differential acting on plates 22 and 23 will be evaluated in the preliminary design of the flow test using CFD modeling. Adjustment of the flow rate in the experiment can be made based on these calculations to assure conservative values of pressure differential on the limiting plates.

3.2 Summary of Design Parameters

In preparation for the hydraulic performance evaluation, hydraulic reactor design parameters of the MURR LEU fuel element have been reviewed and documented in [7]. These relate to design needs of the reactor and, are therefore, referred to as reactor design parameters since they do not take into account design margins required for the experimental test design and other purposes. Nominal dimensions and tolerances, and other design basis conditions that may lead to more limiting requirements for the LEU fuel element hydraulic performance have been analyzed. In this section, only a summary of this review is presented.

The coolant flow rate per element was estimated based on the flow network analysis, which provides the target test value of the inlet condition for the flow test. To evaluate the flow distribution and the pressure differential on the plate under the given inlet condition, a more detailed CFD analysis, which takes into account the three-dimensional (3D) shape of the element, including the end fittings, will be performed during the preliminary design of the flow test.

The hydraulic reactor design parameters for the MURR LEU fuel element are summarized in Table 3.3. One key parameter for the flow test is the outer end channel (channel 24) gap thickness (distance between outermost fuel plate to the outer pressure vessel wall), which determines the maximum channel gap thickness disparity, and the maximum hydraulic force (induced by pressure differential) on the fuel plate. The nominal value of channel 24 gap thickness is 0.0955 inch and the range due to the tolerances is from 0.068 inch to 0.124 inch. Compared to the channel gap thickness of the adjacent channel 23 (nominally 0.093-inch-thick), the size disparity is small if the nominal channel gap thickness of 0.0955 inch is assumed for channel 24. As mentioned previously, the hydraulic pressure differential induced by channel gap thickness disparity tends to deform the plate towards the thicker channel. Therefore, the hydraulic pressure differential on plate 23 could be either inward or outward, depending on the end channel gap thickness. Given the arc-shape of plate 23, the inward force is more

limiting considering that buckling of the plate may occur at sufficiently high pressure. Thus, the minimum channel 24 gap is targeted in the flow test basket design, with the nominal value of 0.0805 inch, and may change from 0.068 inch to 0.094 inch due to the fuel element fabrication tolerance.

Another key design parameter is the flow rate per element. The primary flow rate of the MURR LEU core is 3750 gpm, which is distributed into eight fuel elements in the core. The nominal per element flow rate is 468.8 gpm, as calculated by simply dividing the total core flow rate by 8 and assuming negligible flow between elements. The upper bound of flow rate per element of 562.5 gpm is obtained using the nominal value and the uncertainty factor of 1.2. This 20.0% uncertainty is chosen by engineering judgment to conservatively envelop the core flow uncertainty (4.7%), element flow disparities due to end channel tolerance (1.3%) and burnup-related channel reduction (7.0%), see [7] for details on these uncertainties.

Temperature influences target test value selection due to the impact of water density on the pressure differential in the test. However, temperature itself is not necessarily a primary design parameter. Until the capability of HMFTF to match the desired temperature range is estimated (planned for the preliminary design of the flow test), water temperature is listed here as regime appropriate. Other design parameters, including system pressure and coolant chemistry, are also listed as regime-appropriate, but their influence on the flow test results is less significant. However, it is suggested to maintain a similar coolant chemistry property to the prototypic condition during the flow test to avoid any unexpected impact to the MURR LEU fuel element due to the flow test.

Table 3.3. MURR LEU hydraulic reactor design parameters for flow test.

Design parameters	Specification	Core condition	Hydraulic reactor design parameter	Type
Flow rate	Prototypic	3750 gpm	468.8 gpm	Primary design parameter
	Maximum	3850 gpm	562.5 gpm ^a	
Outer end channel gap	Nominal	0.0955 inch	0.0805 inch	
	Range due to tolerance	0.068-0.124 inch	0.068-0.094 inch	
Temperature	-	49°C-61°C	-	Regime appropriate
System Pressure	-	60-66 psig	-	
Chemistry	pH	5-6	-	

^a The maximum flow rate per element was calculated using the nominal value and the uncertainty factor of 1.2, see [7] for details about the uncertainty factor.

The flow rate per element was calculated using the flow network by consolidating all 24 parallel channels of an element. The predicted flow rate per element provides the target test value of the inlet flow rate for the flow test. Subsequently, the flow network analysis for a single element with all 24 channels was used to estimate the velocity of coolant in separate channels as well as the average coolant channel gap velocity. The average coolant velocity in the element for the all fresh LEU core case is 6.83 m/s. For the case considering channel reduction due to burnup, the average coolant velocity in the element is 7.31 m/s. This estimation is useful in predicting the expected structural response of the fuel plates during the flow test.

3.3 Expected Behavior of the Plates

The design of the flow tests and in particular the design of the testing vehicle, as well as the selection and placement of the sensors used in these tests to achieve the goals defined earlier, are driven by the expected type of behavior of the plates under the hydrodynamic load and the magnitude of that behavior. Deformations of a fuel plate due to its interaction with the flowing coolant can be categorized as steady-state deflections or transient oscillations. Steady-state deflections are primarily induced by a pressure differential between the two sides of the plate. Oscillations of the plate may be induced by fluctuations in the coolant flow that originate from the vortex shedding from reactor structure components, fuel element end fittings, or the plate edges exposed to the flow. Sufficiently high flow rates may lead to a plastic collapse of the plates and closure of the channels that may be preceded by gradually increasing permanent (plastic) deflections, non-negligible large oscillations, or a sudden collapse.

3.3.1 Critical Velocity Estimation

To predict the behavior of the plates, the coolant velocities in the channels (estimation presented in the previous section) have been compared to the critical velocity, a threshold velocity originally defined by Miller [9] (see Section 2.1 for background information). If the expected velocity in the coolant channels is well below Miller's critical velocity, the pressure differential is expected to be the primary driver of plate deflections. Additionally, quasi-static deflections rather than large-scale oscillations of the plates are expected. The following equations have been used for the critical velocity estimation for MURR LEU plates 22 and 23. Equation 3.1 is for a curved plate with fixed boundary conditions along the axial edges, while Equation 3.2 is for a curved plate with simply supported (or hinged) boundary conditions along the axial edges [9].

$$V_{crit_fixed} = \left(\frac{15 \cdot E \cdot t_p^3 \cdot t_w}{\rho \cdot b^4 \cdot (1 - \nu^2)} \right)^{0.5} \cdot \left(\frac{b^2 \alpha^2}{15 t_p^2} \cdot \left(1 - \frac{5 \alpha^2}{42} \right) + 1 - \frac{9 \alpha^2}{14} \right)^{0.5} \quad (3.1)$$

$$V_{crit_hinged} = \left(\frac{5 \cdot E \cdot t_p^3 \cdot t_w}{2 \cdot \rho \cdot b^4 \cdot (1 - \nu^2)} \right)^{0.5} \cdot \left(\frac{2 \cdot b^2 \alpha^2}{5 t_p^2} \cdot \left(1 - \frac{\alpha^2}{21} \right) + 1 - \frac{11 \alpha^2}{21} \right)^{0.5} \quad (3.2)$$

Where:

E – Young's modulus

t_w – channel gap thickness

t_p – plate thickness

ρ – coolant density

ν – Poisson's ratio

b – channel width (plate arc span)

2α – curved plate's arc

The Miller's critical velocity for the MURR LEU fuel plate 22 was calculated to be around 52.2 m/s using both equations for the fixed and hinged boundary conditions [37]. For plate 23, Miller's critical velocity was calculated to be around 48.1 m/s. The ratios of the estimated flow velocities from Section 3.2 to these Miller's critical velocities have been calculated and are listed in Table 3.4. The basic Miller's formulas has been developed for channels with an identical thickness on both sides of the

plate, while a channel thickness disparity for the outermost plate 23 in the MURR LEU fuel element of up to 33% is possible (thinnest outer channel of 0.068 inch versus thickest channel 23 of 0.101 inch). Also, Miller's formulas do not consider the fact that the side plates of the fuel element may deform to some extent, and thus, the assumption made regarding the fixed boundary conditions (no displacements nor rotations in the grooves) is not entirely correct. Moreover, Miller's formulas were developed for plates with leading-edge being free of any constraints (like the combs present in the MURR LEU element). Thus, the actual threshold velocity around which oscillations are more pronounced may differ from the estimations presented here. Nonetheless, the currently estimated values should provide a first-order check of the nature of the plates' behavior under the hydrodynamic load expected during the flow test and the operation of the MURR LEU fuel elements.

Table 3.4. Miller's critical velocity calculations for MURR LEU plates.

Plate #	Case	Average channel velocity v (m/s)	Critical velocity v_c (m/s)	Ratio v/v_c
22	Nominal	6.83	52.2	0.13
	With burnup	7.31	52.2	0.14
23	Nominal	6.83	48.1	0.14
	With burnup	7.31	48.1	0.15

The ratios between the average coolant velocities in the channels of the MURR LEU fuel element are 0.14 and 0.15 for the conditions with burnup for plates 22 and 23, respectively. These ratios show that the calculated velocities are far away from Miller's critical velocity. For this reason, pressure differential induced quasi-static deflections are expected to be the primary mode of the plate's response to the hydrodynamic loading expected during the operation of MURR with LEU fuel elements. Vibrations of the plates at significant magnitudes are not expected.

3.3.2 Expected Character and Magnitude of Plate Deflections

An important aspect of the sensor selection for monitoring the deflections is the location and magnitude of the expected maximum deflection along the plate. Figure 3.4 shows a typical coolant pressure distribution in the axial direction in a plate-type fuel element surrounded by two channel gaps of dissimilar thickness. Larger pressure is registered in the thinner channel. By subtracting the two curves in the plot on the left, a resultant pressure differential acting on a plate is obtained. A typical pressure differential spike is observed, which is followed by an almost linear drop of the pressure differential to near zero at the trailing edge. This behavior is common for both flat and curved plates [25], [34], [38]. If the leading edge is not constrained, this type of pressure differential almost always causes the maximum displacement to be located at the leading edge. An exception occurs when shape imperfections in the plate are substantial, or the boundary conditions are not perfect, and locally the fuel plate slips out of the grooves of the side plate.

Figure 3.4. Pressure across two channels of dissimilar thickness in a fuel element and resultant pressure differential.

Figure 3.5 presents a displacement field obtained in an initial study on FSI for MURR LEU fuel plates. An ideal MURR LEU plate 22 was modeled with fixed boundary conditions on the longer sides and no comb on the leading or trailing edge [25]. The pressure differential characterized by a curve like the one presented in Figure 3.4 caused the largest deflection to occur in the middle of the leading edge. In such a case, during the flow test, the observations should be focused on the leading edge of the plate. A more comprehensive, full fuel element FSI analysis is needed to consider exacerbating factors like the influence of the flexible side plates, or imperfections in the plate shape (slant or waviness).

Figure 3.5. Displacement field in an ideal MURR LEU plate 22 [25].

Installation of a comb on the leading edge limits the displacement magnitude and changes the character of the displacement field in the plate. While FSI analysis of MURR LEU plates with a comb was not performed to date, a numerical study has been performed for curved involute plates of similar geometric characteristics as the MURR LEU plates [38]. This study examined the effect of the comb on the location and magnitude of the maximum deflection in the plate. The presence of the comb shifted that location by a length equal to approximately two widths of the plate downstream from the leading edge. This conclusion is analogous to the results of the experimental study on flat plates presented in reference [10].

The geometry of the MURR LEU element comb is presented in Figure 3.6. The thickness of the slots in the comb is 0.050 ± 0.002 inch for plates 1 to 22. These plates have a thickness of 0.044 ± 0.002 inch. Thus, the gap between the slot walls and the plate may be as large as 0.010 inch (0.052 inch – 0.042 inch) for the case with the largest slot thickness and the thinnest plate. For the outermost plate 23, which is 0.049-inch-thick, the slot width is 0.055 ± 0.002 inch. Thus, for that plate, the gap between the slot walls and the plate surface may also be 0.010 inch (0.057 inch – 0.047 inch), assuming the largest possible gap in the slot and the thinnest possible plate. On the opposite spectrum (smallest slot thickness and thickest plate), plate 23 can be as thick as 0.051 inch and the slot can be as thin as 0.053 inch.

A cylindrical pin is driven through the comb and the plates during the assembly process to hold the center of the leading edge in place during the operation of the fuel element. The pin has a diameter of 0.062 inch (with a tolerance of 0.010 inch) while the drilled hole diameter in the comb and fuel plates is 0.063 to 0.064 inch. Based on that geometrical analysis, a small shift of the plate's leading edge in the slot of the comb due to the hydrodynamic load is possible. For that reason, if the plate moves within the slot of the comb, the maximum displacement may be located at the leading edge. On the other hand, if the plate is tightly locked in the slot, the center of the leading edge will be constrained and the largest displacements due to the pressure differential will occur at some location downstream, away from the leading edge.

Figure 3.6. Drawing of the comb used in MURR LEU fuel element [4].

The methodology of the FSI analysis for the MURR LEU plate 22 reported in [25] was validated against a set of two experiments performed at MU for a single flat and a curved plate (see Section 2.2.1 for details). The predicted maximum displacement of the plate 22 was around 0.2 mil (5 micrometer). Allowing for possible uncertainties in this value, the anticipated magnitude could be expected to be in the order of 1 mil (25 micrometer). Full element FSI analysis taking into account the presence of all the plates within the fuel element, flexible side plates, and the comb on the leading and trailing edges is needed to provide a better estimation of the deflection magnitude.

Following are the implications of the discussion presented in this section on the selection of the sensors monitoring the deflection and their integration with the testing vehicle:

1. The sensors should be sensitive enough to capture deflections of magnitude in the order of 1 mil (25 micrometer),
2. The uncertainty of the measurements must be less than the maximum expected magnitude of the deflections, and
3. The sensors should be installed close to the leading edge of the plate as well as between one to two widths of the plate downstream from the leading edge to increase the chance of capturing such small deflections. (A more accurate location of maximum deflections will be determined during the preliminary flow test design.).

4 Initial Design and Conceptual Testing of Sensors

4.1 Data Gathered and Its Purpose

The sensors to be used during the flow test at HMFTF can be divided into two groups based on their primary purpose:

1. To monitor the flow conditions in the loop, and
2. To monitor the structural behavior (deflections and vibrations) of the fuel plates under the hydrodynamic load.

The sensors serving the first purpose are mostly an integral part of the HMFTF loop. These sensors were already tested at the HMFTF and proven to work during other testing campaigns supporting the USHPRR conversion [30], [31], [39], [32]. Their range of operation and uncertainties are known and previously reported by OSU [27]. For that reason, these sensors do not require further testing in preparation for this flow test. One exception is that the Pitot tube assembly will require redesign to fit the end fitting of the MURR LEU element.

Most of the sensors serving the second purpose need to be selected and acquired for further preparatory testing as the type of measurements required during this flow test is different from those of the other test campaigns conducted at OSU (characterization of small deflections of plates is of interest). Since the magnitude of the maximum fuel plate deflections are expected to be in the order of 25 micrometer, while at the same time access to the measuring locations is obstructed, the applicability of these newly selected sensors needs to be thoroughly investigated before they are chosen to be used in the actual flow test of the MURR LEU element. The exceptions in that group are those strain sensors that have been extensively tested by OSU staff during the GTPA testing campaign [31], [32]. However, the prior testing was done on flat plates only, and attachment techniques would have to be tested on the curved plates.

The applicability of sensors for the listed below measurements and observations must be demonstrated during the flow test preliminary and final designs through a single flat plate and an all-aluminum mock-up testing for:

1. Leading-edge visualization,
2. Deflection measurement,
3. Flow rate measurement,
4. Pressure drop measurement, and
5. As-built geometry measurements.

During the operation of the flow loop, the pumps generate heat that the cooling system of the facility must dissipate. The amount of generated heat varies depending on the required flow rates, and pressure drops through the tested specimens. During the GTPA tests, due to limitations on cavitation within the test loop and around the test specimen at high flow rates some tests were performed at elevated temperatures of 175°F and 250°F [32]. Based on the communication between the Argonne subject matter experts (SME) and the OSU HMFTF SME, the OSU HMFTF operating temperature could have a lower limit as high as 250°F (120°C) for the MURR LEU flow test, which is significantly higher than both the MURR core inlet and outlet coolant temperatures (49°C and 61°C, respectively).

Elevated temperature and pressure may influence the accuracy of some of the measurements or even make some sensors inoperable. Thus, the measurement capabilities, including the uncertainty levels under the flow conditions expected at the OSU HMFTF flow loop must be well understood before the LEU element testing.

A test with a surrogate system generating a similar pressure drop as the MURR LEU fuel element in the testing basket is required during the preliminary flow test design. It will allow to better understand the temperature that can be achieved in the loop in the actual tests of the MURR LEU element. Where the temperature of the coolant in the surrogate test, and hence the LEU fuel element flow test remains within the operational range of the coolant in the MURR core, no further evaluation would be required. However, if the temperature during the flow tests is higher than coolant temperatures in MURR, then the impact of these parameters on the conclusions of the hydro-mechanical evaluation of the MURR LEU fuel element must be evaluated. Modifications to the OSU HMFTF flow loop may be requested if that impact on the outcome of the test is determined to be substantial.

4.1.1 Leading-edge Visualization

As stated in Section 1.3 of this report, the goal of the flow test is to prove that integrity of the fuel element is maintained, and unacceptable deformations do not occur under the selected testing conditions that envelop the operational conditions that envelop the operational conditions of the MURR accounting for uncertainties in the flow conditions.

Since, as currently predicted, small deflections of fuel plates in these elements are challenging to measure, both visualization and measurements of the deflections of the plate's leading edge (where the deflections in the MURR LEU fuel element are expected to be the largest) are of interest for the conceptual design of the flow test. Quantification of the total deflections (elastic and plastic) in the test is desired. However, it is not required for the successful completion of the shakedown tests of the MURR LEU elements. Quantification of the plastic (permanent) deflections is required (see Section 4.2.5 for discussion of the measurement of permanent deflections).

Note that various sensors may be only applicable to selected reactor fuel elements due to different geometry of the plates and the end fittings as well as different levels of accessibility of plates of interest. As explained in Section 3.1, the outermost plates (22 and 23) of the MURR LEU element are the most limiting from the FSI perspective.

As shown in Figure 4.1 (left), a direct view from the top on the leading edge of these plates is partially obstructed by the design of the end fitting with the roller. Only an angled line of sight through the end fitting allows observing the leading edge of plates 22 (yellow in Figure 4.1) and 23 (orange in Figure 4.1).

Figure 4.1. A partially obstructed view at the outer plates through the end fitting of the MURR LEU fuel element; from the top (left) at an angle (right).

4.1.2 Deflection Measurements

While the position of plates 22 and 23 in the element makes it hard to observe their leading edge from the upstream of the flow, a side approach for direct deflection measurement sensors (i.e., for a proximity sensor, laser, etc.) is possible for plate 23. The conceptual design of the test vehicle (basket) proposed in this report takes advantage of this fact, and a side window or a smaller sensor port is currently included in the design (see Section 5.2 for more details). The final selection of the sensors as well as additional CFD analysis will guide the design of that port (or window) in terms of its exact location and size.

It is understood that each of the deflection measurement techniques faces its own set of obstacles like interference with the flow, need for external access through the loop piping walls, or difficulty of performing measurements under the selected flow conditions. These issues are further discussed in Sections 4.2 and 6 and are planned to be examined mostly later in the flow test design process.

4.1.3 Total Flow Rate and Individual Channel Flow Velocity Measurement

As explained in Section 3.1, the most conservative flow conditions are achieved for a specific distribution of the tolerances in the channel gap thickness around the most limiting plates in the MURR LEU fuel element. The element used for testing will most certainly not have these tolerances distributed in the most limiting way. The design of the basket will only allow for adjustments of the thickness of the outermost channel gap 24. For that reason, flow disparity in the channels within the element during the flow test is expected to be different from the most limiting configuration (as discussed in Section 3.1). CFD analysis will be performed during the preliminary flow test design to determine the pressure differential acting on the limiting plates for these scenarios. That specific pressure differential on the plates may be subsequently targeted during the flow test by adjusting the size of the outer channel gap 24 and the total flow rate.

Additionally, significant variations in the channel flow velocity during the test may indicate excessive plate vibrations. A sudden drop in the measured channel flow rate may indicate a plate collapse

leading to a channel gap closure. The design of the Pitot tube assembly must allow for insertion through the complex shape of the end fittings of the MURR LEU fuel element. The feasibility study must demonstrate that installation of the Pitot tube assembly is possible, and its presence does not significantly alter the flow in the coolant channels and the outcome of the flow test.

4.1.4 Pressure Drop Measurement Across the Entire Element

Proper measurement of pressure drop across the entire element is required to mimic the in-pile flow conditions. Similar to the flow rate measurements, individual channel pressure drop measurements may be used for a better understanding of the flow disparity factor within the element, as well as to detect large changes in channel gap thickness during the flow test, potentially due to the collapse of the fuel plates. Pressure taps have been used in the past to monitor pressure drops in each channel of fuel elements. However, this approach would require drilling multiple holes in the side plates of the MURR LEU fuel element. To meet the goal of this specific flow test, this data is not required. The test is designed so the most limiting conditions occur for the outermost plate. While the individual channel pressure drop was used in the past to identify the loads acting on the plates and detect collapse of the plates, in the current test the deflection monitoring of the limiting plate will be conducted with other techniques. Thus, only the overall pressure drop across the test element is currently of interest.

4.1.5 As-built Plate Thickness and Coolant Channel Profile Measurements

The channel gap measurements in the MURR LEU element must be performed for several reasons:

1. The initial as-built shape of the element will be needed to update the CFD models that will be used for calculations of flow distribution in the element.
2. The outer thin channel gap is formed by the element and the basket inner walls. The thickness of the outer channel gap must be adjusted during the assembly of the basket with the element by several set screws (see Section 5) to match the conservative size established during the review of the reactor parameters (see Section 3).
3. In case the sensors used for monitoring the leading edge during the test provide inconclusive data, the use of a channel gap probe (CGP) between consecutive stages of the flow test may provide information about any permanent flow-induced deformations, which serves the primary goal of the flow test.
4. Monitoring of any failure modes of the entire element is of interest in the flow test. CGP will be used to detect any plastic (permanent) deformations in all plates, not only the limiting one from the FSI point of view.

A feasibility study of available CGPs will be performed before the flow test on an all-aluminum mockup of the MURR LEU fuel element and early versions of the testing basket. The design of the basket must allow for inspecting of the outer channel gap thickness as well as maintaining the relative position of the element within the basket during consecutive stages of the flow test (without repositioning of the fuel element).

4.1.6 Summary

Table 4.1 contains a list of test items and the purpose of the data to be gathered during the flow test. Three roles have been designated for these quantities of interest: required (R), supporting (S), and optional (O). Measurements of the deflections of the plate away from the leading edge are optional, focus is placed on visualization (R.1) or measurements of the deflections near the leading edge (R.2) of the plate. Total flow rate measurements (R.3) are required as the total flow rate is a controlling parameter that will be adjusted to meet the required pressure differential across the most limiting (outer) plate. It is understood that the design of the end fittings may make it difficult to use Pitot tubes in the test so the role of flow rate measurements in each channel (S.2) was designated as supporting.

Table 4.1. Summary of test items and their purpose in the flow test.

Role	ID	Test item	Purpose
Required	R.1	Plate leading-edge visualization	The stability of the plates at high flow should be proven by observation (R.1) or measurement (R.2) that will determine the magnitude of elastic deformation if it occurs during the testing. A margin to plastic deformation must be proven by running one or more tests at flows beyond the MURR operating conditions.
	R.2	Plate leading-edge deflection measurement	See the purpose of R.1.
	R.3	Total flow rate	For determination of average flow test velocity
	R.4	Total flow area for the test vehicle	For determination of average flow test velocity
	R.5	Plate thickness for each plate in the as-fabricated element	To support numerical simulation and analysis
	R.6	Dimensional profile of each channel gap	Observe significant fuel element deformations such as plate bending, twisting, or plate detachment from the side plate.
	R.7	Flow area for each channel in the as-fabricated element	To support numerical simulation and analysis
	R.8	Flow area for each of the two end channels	To support numerical simulation and analysis
	R.9	Visual examination of fuel element	Observe significant fuel element deformations such as plate deflection or bending, twisting, or plate detachment from the side plate.

Role	ID	Test item	Purpose
	R.10	Water temperature	To assure prototypic coolant temperature during the flow test and to verify the pressure drop vs. flow relationship.
Supporting	S.1	Pressure drop across the fuel element	Confirmatory data to verify the average test flow velocity (R.3 and R.4)
	S.2	Flow rate for each channel	Semi-empirical Moody friction factor treatment could be confirmed; redundant confirmation of average test flow velocity (R.3 and R.4). Pressure taps or Pitot tubes will be used depending on the manufacturability of the setup.
Optional	O.1	Measurement of plate deflections (other locations than the leading-edge)	Although plate leading-edge visualization (R.1) or deflection measurement (R.2) may be sufficient, another method such as a strain or laser measurement could be used at additional locations.

4.2 Sensors Previously Used at OSU

4.2.1 Sensors Used for Monitoring the Flow

4.2.1.1 Vortex Flow Meters

The primary flow rate measurement instruments used on the HMFTF are Rosemount series 8800D vortex flowmeters. Measurement of pump net flow is provided by dedicated flow meters for each pump branch (FIT-111 for MFP-111 and FIT-211 for MFP-211), and then a flow meter is also installed in the test section (FIT-401) and the bypass leg (FIT-411) as shown in Figure 4.2. This arrangement allows for the verification of instrument operation through the comparison of the measurements (test section flow + bypass flow = net flow) as well as redundancy in case of an instrument failure by using calculated flow values instead of the direct measurement.

Figure 4.2. Flowmeter layout.

4.2.1.2 Differential and Static Pressure Instruments

Rosemount 3051 series pressure transmitters are used throughout the HMFTF for both static and differential pressure measurements (with the exception of the Pitot tubes). For quality measurements related to an experiment, both test section inlet and outlet (PIT-501 & PIT-502) static measurements are available as is a dedicated differential pressure instrument (PIT-430) across the test section. Measurement uncertainty for these instruments is presented in [27].

4.2.1.3 Thermocouples

Standard k-type thermocouples are installed throughout the HMFTF to provide both required feedback for operators and quality data related to fluid temperatures during a test. In the primary coolant system, all locations that provide quality data have groupings of 3 thermocouples installed. This arrangement not only provides redundancy and the ability to verify instrument operation but also allows for the reduction in measurement uncertainty through averaging the realistic values at each location. Uncertainty data for this instrument type are presented in [27].

4.2.2 Strain Gauges

Exhaustive testing of several types of strain gauges performed at HMFTF has identified that the EK/W series of gauges from Vishay PG is the best performer found to date. A special process has been developed at OSU for installing and verifying these instruments prior to testing [40]. These instruments are paired with a PXIe-4330 data acquisition card and have been most successfully used

in a simple quarter bridge configuration. However, this card is capable of both half and full-bridge operation as well.

Due to the harsh conditions within the loop, strain gauges have proven to generally not maintain a stable enough zero signal throughout testing to be useful for quantitative characterization of deflection values. However, their very fast response and the system's ability to sample at high frequencies (up to 5 kHz, generally 2 kHz) allowed their use to explore the dynamic response of individual plates within an element under both steady and transient flow conditions during the GTPA testing campaign [32].

Since the tested element will contain LEU fuel plates, the strain gauges cannot be embedded in grooves machined in the cladding, unless these were created before the fuel plate was bonded by the Hot Isostatic Pressing (HIP) process. Thus, the only feasible method of attachment is on the surface of the cladding as described in [40]. This approach creates locally higher spots on the plates which together with the attached wiring may distort the flow in the leading-edge area of the plate.

The expected small deflections of the plate in the tested MURR LEU fuel element under the conservative flow conditions may produce a signal that doesn't allow for quantification of the strains and indirectly the deformations. Nonetheless, the strain gauges are still considered to be potentially useful, for reference purposes only, during the evaluation of the other sensors.

4.2.3 Fiber Optic Gauges

The HMFTF data acquisition system includes a LUNA ODiSI-B system for fiber optic strain measurement that is capable of sampling at up to 250 Hz, although this sample rate is reduced as the sensor length increases. To date, only 2-meter sensors bonded directly to surrogate fuel test plates have been used in the HMFTF. The LUNA system exhibited a much better zero stability when compared to the strain gauges. However, the relatively low sample rate greatly limited the system's ability to acquire dynamic data during the GTPA testing [32]. Experience has demonstrated that once a plate has begun to vibrate to a certain degree, the LUNA system is unable to acquire useful data and it has thus been useful mostly in looking for residual strain at low flow rates after exposure of the element to increased flows. For the MURR LEU, large oscillations are not expected, and these strain gauges may be useful. Another advantage of the LUNA system is that little disturbance to the flow occurs as a result of the sensors and the lead wires that can be attached to the sensors near the leading edge, where the impact on the maximum deflections of the plate is the smallest.

4.2.4 Pitot Tubes

Pitot tube assemblies like those shown in Figure 4.3 have been successfully integrated into almost all HMFTF experimental campaigns to date. These measurements have been used to estimate the flow distribution between subchannels in experiments and to estimate the pressure drop through an experiment within individual subchannels when paired with the bulk inlet pressure measurement. It should be noted that the inclusion of a Pitot tube plate in a flow test will have an impact on the hydraulics of the experiment and it is, therefore, advisable to run an identical test without the pitot tube plate to allow characterization of this impact. A bottom-up view of the Pitot tube hardware in an experiment is shown in Figure 4.4 to help illustrate the impact of the Pitot tubes on the flow. This view looks into the instrumentation housing and the outlet of the experiment, with the Pitot tube plate entering from the right and extending up into the test section.

Two separate pressure transducers are used to take measurements within each subchannel and an estimate of the superficial velocity in the subchannel can then be calculated using Bernoulli's equation. The first 14 pressure transducers (capable of measurements in 7 subchannels) are Honeywell model TJE instruments and the remaining 10 instruments are Honeywell model A-205 instruments (capable of measurements in 5 subchannels). These instruments have no internal signal processing hardware and are connected to NI PXIe-4330 Wheatstone bridge input cards. This approach allows high-frequency sampling of these channels (up to 5 kHz, normally 2 kHz) using the burst function in the HMFTF control software. Measurement uncertainty for these instruments is documented in [27].

There are two obstacles to the use of Pitot tubes for the MURR LEU fuel element flow test:

1. Because of their relatively low rigidity, Pitot tubes require the design of a support structure. A relatively complex path is required to position the Pitot tubes in the outer channels of the MURR LEU fuel element that would have to go through the end fitting. Thus, the support structure may not reach far enough. If it did, it could potentially block a significant portion of the end fitting opening.
2. The MURR LEU fuel element has 24 channels and accommodating each of them with two tubes is rather unfeasible. The Pitot tubes would have to be designed for a smaller portion of the channel gaps. However, this would unevenly affect the flow in the channels and produce spurious flow disparities in the fuel element.

Figure 4.3. Example Pitot tube plate from AFIP-7 (left) and close up of sensing end of tubes (right).

Figure 4.4. Example of Pitot tube installation in the instrumentation housing.

4.2.5 Channel Gap Probe

The CGP which allows characterizing subchannel thicknesses in an assembled element (assuming the sabre can access the measurement location). The instrument consists of 2 capacitive probes, one of which faces outward in each direction from the flat sabre, which is 36 inch long. The sabre itself is marked with the distance from the measurement points up the length to the handle down to 1/4 inch.

Data for this instrument is hand-recorded by program personnel as the vendor-supplied software does not allow matching of an insertion distance, or any other notation regarding the position of the instrument, with the recorded channel width data. To maximize the repeatability of this process, dedicated CGP guide blocks have historically been created for each experimental geometry. Guide blocks used have included wire EDM fabricated metal designs as well as 3D printed polymer designs as shown in Figure 4.5. In the past, water droplets within an experiment have also been shown to impact measurements, and it is therefore important to ensure that the experiment is thoroughly dried before taking measurements with this instrument.

The measurement uncertainty to which this instrument is held to within the HMFTF program is ± 0.0013 inch [41]. According to the specifications for CGP, it shall be capable of measuring gap thicknesses ranging from 0.050 to 0.240 inch or better. However, the CGP used by HMFTF is capable of measuring channel gaps of up to 0.500 inch. This capability will be sufficient for the target outer channel gap thickness of 0.068 inch in the MURR LEU flow test and the maximum inner channel gap thickness of 0.101 inch.

Although access to the center of several external channels of the MURR LEU element is obstructed by the design of the end fitting, the design of the basket allows for the measurements of the outer channel gap thickness between different stages of the flow test. This approach is meant to allow for detecting

any permanent deformations in the plate. Even if the position of the element in the basket shifts slightly, a permanent curvature of the plate could still be detected.

Figure 4.5. Example 3D printed (left) and wire-EDM (right) CGP guide blocks.

4.2.6 Laser Surface Scanner

The laser scanner system at OSU, shown in Figure 4.6, consists of a Gocator 2140 laser profilometer that is mounted onto a gantry stage that is suspended over a granite surface inspection plate. The laser moves along the track to scan the surface of a tested object. The system was successfully used during the GTPA testing campaign to characterize the profile of plastically deformed plates providing significantly higher resolution data than the CGP [31].

The MURR LEU fuel element can be scanned before and after the flow test to determine whether any of the following are observed: permanent deformations in the outer plates, bending or twisting of the entire fuel element, or plate detachment from the side plates.

Figure 4.6. Laser surface scanner at OSU.

4.3 Proposed Sensors Requiring Testing

4.3.1 Laser Deflection Measurements

Currently, two laser measurement systems have been selected to enable the evaluation of multiple measurement types within this instrument category.

4.3.1.1 1-D Red Laser Spot Measurement

The first laser measurement system is from the Keyence LK-G5000 series of instruments. This system consists of a head that uses a red laser to provide a spot measurement using triangulation of the reflected laser light. A separate controller allows for interaction with the sensor head configuration, setting up automated calculations or alarm set points, and output of data either to a network or to analog outputs.

The specific sensor head selected is the LK-H152 which provides a spot measurement over a diameter of 120 μm and a repeatability of 0.25 μm over a measurement range of 110-190 mm (4.33-7.48 in) as shown in Figure 4.7. The system is capable of sampling at over 10 kHz and should therefore be more than fast enough to meet this project's needs.

Figure 4.7. A schematic of Keyence LK-H152 laser measurement range.

4.3.1.2 2-D Blue Laser Profile Measurement

The second system selected is the Keyence LJ-X8000 series system with the LJ-X8200 sensor head. This system operates in the same way as the LK-G5000 system, but with a blue laser. However, instead of a point reading, it returns many discrete measurements over a line profile. With the dedicated controller OSU has selected, the system is capable of sampling at up to 16 kHz, with measurement ranges and repeatability summarized in Table 4.2 and illustrated in Figure 4.8. The nominal spacing between data points, while in the center of the measurement range, is 25 μm (0.001 inch). Included in this system is the LJ-X800A Raw Data Output Controller which will allow for outputting every sample's full 3200-point profile for storage.

Table 4.2. Keyence LJ-X8200 measurement specifications.

Measurement range	Z-axis (height)	245 mm $\pm$ 34 mm
	X-axis (width)	72 mm $\pm$ 8 mm
Repeatability	Z-axis (height)	1 μm
	X-axis (width)	3 μm

Figure 4.8: A schematic of Keyence LJ-X8200 laser measurement range.

Lasers are the least invasive measuring technique for plate deflection as the instrument itself does not protrude into the flow. However, they require a window in the basket, and due to the size of the sensors, will not fit on the basket itself. The outer pipe of the HMFTF flow loop testing section will most likely need modifications for laser access and attachment. The laser light will have to travel through several media (air, quartz in the window, water in the outer channel gap) to reach the plate and travel back to the sensor. Small vibrations of the element in the basket, the basket itself, or the outer piping may influence the uncertainty of the measurements.

4.3.2 Linear Variable Differential Transformers (LVDTs)

Linear Variable Differential Transformers (LVDTs) are a tried-and-true option for measuring displacement and so have been selected here for evaluation. Specifically, the sensor chosen is the model 0234-0000 from Trans-Tek with some customizations to allow for operation at the temperatures and pressures expected within the HMFTF. This model has a 3/8 inch housing outer diameter, a measurement range of 0.20 inch, and a non-linearity of <0.25% of full scale. Therefore, it should reliably be capable of a 0.0005 inch or better resolution.

Theoretically, due to the construction of this type of instrument, the resolution is infinite and is only limited by the data acquisition electronics used. This sensor will be paired with a PXIe-4340 displacement input module which has a 24-bit resolution and is capable of sampling at over 25 kHz. Accuracy specifications for this module are shown in Table 4.3.

Table 4.3. PXIe-4340 LVDT sensor accuracy.

Typical Accuracy ±(% reading + % full scale)	Maximum Accuracy ±(% reading + % full scale)
0.007% + 0.003%	0.025% + 0.015%

Unlike other instruments considered for the plate deflection measurements, an LVDT will need to be integrated into the flow test hardware itself in order to function. The specifications of the currently evaluated LVDT sensor are presented in Table 4.4. These instruments have a smooth outer body and will need to be fixed in place using other hardware such as set screws. A spring-loaded rod (with very small stiffness) will have to press against the plate and maintain contact with it during the test. The

presence of the rod will affect the flow and CFD analysis needs to be performed to assess the magnitude of that effect.

Table 4.4. LVDT physical specifications.

Specification	Value
Body Diameter [inch (mm)]	0.375 (9.525)
Body Length [inch (mm)]	0.95 (24.1)
Core Length [inch (mm)]	0.55 (14.0)
Core Mass [g]	0.6

4.3.3 Inductive Sensor

An inductive eddy current sensor system model eddyNCDT 3070 from Micro-Epsilon has been selected for inclusion in this program. While this is a non-contact measurement technique, it should be noted that the maximum measurement range is 0.4 mm (0.0157 in) with that range starting 0.04 mm (0.00157 in) from the face of the sensor. This means the sensor head will likely need to be installed partially protruding into the flow channel of any element under test. The influence of that protrusion on the flow and pressure acting on the plate will need to be determined via CFD analysis as well.

This measurement system has a linearity specification of $< \pm 1 \mu\text{m}$ (3.94×10^{-5} in), a resolution specification of $0.1 \mu\text{m}$ (3.94×10^{-6} in), and a sample rate of up to 50 kHz. This instrument should, therefore, be very well suited to characterizing a very slight movement of the plate whether it be a static or dynamic movement.

The sensors selected for further testing under this test plan have an externally threaded body and as such can be installed into a threaded hole in an experiment and then fixed in place with a thread locker and/or jamb nuts. However, it is likely that the instrument received by the program will be customized to some degree to account for greater operating pressures/temperatures and so may differ from that shown.

4.3.4 Contact Sensor

While contact sensors were proposed as one of the categories worth investigating, a suitable candidate has not yet been identified other than a simple resistance measurement of a closed-circuit probe. The difficulties lie in the conditions of operation expected during the test, which are beyond the range of applicability of the currently investigated contact sensors. Conditions of operations need to be clarified after conceptual design, and therefore if needed, this sensor type could be revisited where there are limitations found in other sensors. Contact sensor accessing channel 22 (channel gap on the concave side of plate 22) from the top is the desired device since access to plate 22 with other sensors may be unfeasible. Although, its presence may impact the flow distribution substantially.

4.4 Camera Systems

After researching options that could be compatible with the conditions within the HMFTF over its operating envelope, only fully externally mounted systems were selected for testing (a borescope that

can be combined with these systems is searched for). In contrast to the other systems used for measuring the deflections in this flow test, which will observe the plate from a position perpendicular to the plate surface and flow direction, the camera systems will observe the plate from a position looking at the leading edges of the plate(s), along the flow direction. Attempts will be made to quantitatively resolve the magnitude of the plate motion using camera data. However, camera data could also be used to observe qualitative motion and/or vibration or to look for phenomena such as channel collapse.

4.4.1 Machine Vision System

The first system selected is a Keyence CV-X series machine vision system. This is a fully integrated, industrial machine vision system with a separate camera, controller, and lighting modules to allow extremely versatile configurations. The camera selected is the CA-H2100M which is a monochrome 21MP camera that is capable of operating at a maximum of just under 50 frames per second. While this speed is not high enough to resolve most expected plate vibrations, the possible benefit of this system is its ability to directly output displacement measurements, whereas a high-speed camera will require post-processing of video files (and storage of those raw video files) to back out displacement data.

The camera will be paired with a CA-LHE50 lens which will allow a pixel resolution of approximately 0.001 inch when positioned with a 4 x 4-inch field of view. Therefore, resolving the desired 0.001 inch of motion will be at the limits of this system as configured. However, it is possible to change the optics on the camera for a smaller field of view as allowed by other test campaigns to achieve a higher resolution.

To provide adequate lighting, this system will include an integrated lighting controller module and a relatively simple light bar assembly. This lighting setup was selected based on the relatively simple geometry and coloring generally encountered at the leading edge of the test plates in experimental hardware tested to date in the HMFTF. If it is deemed necessary, more complicated lighting systems could be integrated in the future which may allow measurement of 3-dimensional features and/or improved measurements with surfaces of varying colors.

4.4.2 High-Speed Camera

As an alternative to the machine vision system, a regular high-speed camera will also be tested. In this case, a Phantom VEO 340L will be used. When operated at the full resolution of 4 megapixels, the maximum frame rate for this camera model is 800 fps. As the operating resolution is reduced, the maximum frame rate increases as shown in Table 4.5. Note that these are just a selection of common resolutions, and many other options are available with their own corresponding maximum frame rate.

Table 4.5. Common resolutions and corresponding frame rates.

Resolution	Frames per Second
2560 x 1600	800
1600 x 1600	1190
2048 x 1080	1460
1280 x 720	3310

This camera system will allow the recording of data at a much higher rate than the machine vision system but will be operating at a lower resolution. If one considers a 4 x 4-inch field of view (a general, conservative area to fully cover the inlet of almost any experiment that would be tested in the HMFTF), the system would have a pixel resolution of 0.0025 in (0.0635 mm), and as such would not be able to resolve any plate motion below that value. To back out quantitative plate-deflection values from the data recorded by this system, post-processing of the high-speed video will be required. This procedure will increase the burden on program personnel, owing to the complexity of the experimental setup associated with image processing codes that may need to be unique to each flow element or geometry tested. If high-speed cameras, in general, were selected for full integration into the HMFTF data acquisition system, a likely recommendation would be to procure a dedicated high-speed camera system for HMFTF which could operate at higher resolutions than the VEO 340L, to resolve plate motion more finely.

4.5 Conceptual Design Sensor Testing Matrix

During the flow test conceptual design, candidate sensors have been selected that have the potential to monitor the deflections of the fuel plates in the MURR LEU fuel element during the flow test. These sensors have been briefly discussed in the previous sections of this report. Currently, a plan for a feasibility study of these sensors is being developed.

The demonstration of the sensors' capabilities should initially be performed on a single flat plate under dry conditions. Subsequently, the sensors that can resolve small deformations should be tested in submersed conditions without flow ("fish tank test"). Sensors that pass this testing stage should be tested in the EFL on a surrogate flat-plate assembly with water flowing through the assembly. Also planned is an all-aluminum mock-up element, to be procured later in the flow test design process, together with the basket for further testing in the HMFTF flow loop.

Table 4.6 lists all the types of sensors described in Sections 4.2, 4.3, and 4.4. Columns three and four of the table indicate the sensors for which dry and submersed bench testing demonstration is requested. The need for and practicality of such demonstrations can be reassessed during the flow test preliminary design. If a specific sensor from groups 1 and 2 (leading-edge visualization and deflection) shows superiority over others during the dry and wet bench tests in terms of sufficient accuracy and projected ease of use within the MURR fuel element test setup, it should be the first one tested in the EFL.

This testing will make use of the following assumptions and steps:

1. Flow tests in HMFTF with a surrogate system inducing the same pressure drop as the MURR LEU element at the flow rates planned for the flow test will be performed. This is to determine the temperature and pressure of the coolant during the flow tests of the MURR LEU fuel element. (As indicated in Section 4.1, modifications to the OSU HMFTF flow loop may be requested based on this test.)
2. All demonstration testing will use AA6061-T6 and/or -T0 flat plates of similar proportions to GTPA plates 4 inch x 24 inch x 0.050 inch with clamped boundary conditions.
3. Static dry bench testing will be performed, and measured deflections will be compared with those measured with strain gauges and LUNA fibers in two stages:
 - a. Resolve static deflections of 1 mil to confirm the ability to measure small deformations of plates.
 - b. Run a pluck test to characterize the dynamic response of the instruments.

4. Submersed bench testing (fish tank):
 - a. Resolve static deflections of 1 mil.
5. Develop calibration standards and procedures for instruments that have passed steps 3 and 4.
6. Flow testing in EFL:
 - a. Develop EFL test section with instrument wiring and optical access to test plate side and leading edge (as applicable to instruments being tested).
 - b. Comparison with deflections measured by strain gauges and/or LUNA fiber is considered

Concurrently, OSU will assemble a new data acquisition system, most likely based on a National Instruments PXIe chassis, to accommodate all the different instrument types. This system will be required to handle this range of instruments at the speed and accuracy that will be required during the flow test. The HMFTF data acquisition system is a PXIe system, so any cards used in this work scope could then be directly applied to the HMFTF flow loop if instruments are chosen for integration.

Table 4.6. Conceptual Design Sensor Testing Matrix.

ID	Measurement type	Possible sensor type (Currently assumed model for testing)	Static dry bench testing	Submersed bench testing (no flow required)	Notes
1	Leading-edge visualization	Borescope (no model identified for testing)	X	X	Data acquisition through the end fitting.
		External camera (Keyence CA-H2100M)	X	X	A side window in the basket is required.
		High speed camera (Phantom VEO 340L)	X	X	A side window in the basket is required.
2	Deflection	LVDT (TransTek series 230)	X	X	Perpendicular side feedthrough in the basket is required.
		Laser (Keyence LJ-X8200) (Keyence LK-H152)	X	X	Perpendicular side window required. Possibly mounted outside of the HMFTF flow loop testing section.
		Inductive eddy current proximity sensor (Micro-Epsilon eddyNCDT 3070)	X	X	Perpendicular side feedthrough in the basket is required.
		Strain gauges (EK/W series from Vishay PG)			Unless substantial improvements over GTPA experiment results are expected, further investigation of

ID	Measurement type	Possible sensor type (Currently assumed model for testing)	Static dry bench testing	Submersed bench testing (no flow required)	Notes
					the strain gauges' use is not required.
		Fiber optic sensor (LUNA)			Unless substantial improvements over GTPA experiment results are expected, further investigation of the fiber optic sensor use is not required.
		Contact sensor (no model identified for testing)	X	X	Perpendicular side feedthrough required. May be used with or without adjustable distances between runs.
		Ultrasonic proximity sensor (no model identified for testing)	X	X	Perpendicular side feedthrough required.
3	Flow	Vortex flow meter			No demonstration is needed.
		Pitot tube assembly for channel flow	X		Fitting testing on a dry all-aluminum mockup in the basket is required. Testing in the HMFTF flow loop is also required once the basket and an all-aluminum mockup are available.
4	Pressure	Static pressure transmitters			No demonstration is needed.
		Differential pressure transmitters			No demonstration is needed.
5	Pre- and post-test geometry	Capacitive channel gap probe (Capacitec based CGP)			No demonstration is needed.

ID	Measurement type	Possible sensor type (Currently assumed model for testing)	Static dry bench testing	Submersed bench testing (no flow required)	Notes
		Micrometer (no model identified for testing)	X		Flow channel spacing before and after flow test.
		Laser surface scanner (Gocator 2140 laser profilometer)			No demonstration is needed; Calibration is required.
6	Vibration	(not currently planned, see Section 3.3)			Although not currently planned, HMFTF has the capability for installing accelerometers on the basket to monitor the vibrations of the system.
7	Temperature	Thermocouples			No demonstration is needed.

5 Test Vehicle Design

5.1 Test Vehicle Design Requirements

To meet the goal of the flow test planned at the HMFTF at OSU, the following broad requirements have been identified for the flow test basket:

- R.1. The outer dimensions of the basket must allow for insertion to the testing section of the HMFTF flow loop.
- R.2. The internal dimensions of the basket should represent the most limiting configuration in the MURR LEU core.
- R.3. The geometrical features of the basket must be machinable with the techniques and equipment available (EDM cutting, max 20-inch segments).
- R.4. The basket must allow for the installation of the sensors as selected by OSU and Argonne and inspection of the element during the stages of the flow test,
- R.5. The basket needs to be structurally sound enough to not deform during handling, assembly, and the flow tests.

A set of design constraints based on these requirements have been defined and are listed in Table 5.1.

Table 5.1. Design constraints for the flow test basket for the MURR LEU fuel element.

Constraint ID	Requirement ID	Design constraint
C.1	R.1	The nominal internal diameter of the OSU flow test section is 6.065 inch, the tolerances (cylindricity) of the pipe manufacturing [42], [43] and tolerances of the basket assembly need to be taken into account in the design so the basket fits inside the flow loop without interference.
C.2	R.1	The basket is planned to be connected by screws going through a coupling flange to the instrumentation housing. The end caps of the basket must have mating grooves for the instrumentation housing of the HMFTF loop [44].
C.3	R.2	Gaps between the basket caps and the end fittings of the fuel element must be large enough to avoid any contact between these components during the flow test.
C.4	R.2	To recreate the most limiting geometrical conditions in the reactor, the thickness of the outer channel gap is targeted at 0.068 inch during the test.
C.5	R.2	The basket design must allow for fine-tuning of the outer channel gap thickness by controlling the position of the element.
C.6	R.2	The outer channel gap thickness on the opposite side of the MURR LEU fuel element must be within the range of dimensions possible

Constraint ID	Requirement ID	Design constraint
		for channel 1 as defined by the geometry of the fuel element and position in the core [4], [7].
C.7	R.2	The current size of all the gaps around the element within the basket is 0.020 inch unless requested otherwise (outer and inner channels are an exception here); Shells must be cut and assembled in a way so the element cannot be squeezed in the basket.
C.8	R.2	The sizes of the innermost and outermost channels is controlled only within the plated region of the fuel element (the position of the roller cannot influence the size of the channels in the test).
C.9	R.3	The basket must be machined from AA6061.
C.10	R.3	Each section of the basket cannot be longer than 20 inch due to the EDM equipment limitations.
C.11	R.3	Shells for the basket can be made each from a single 6 inch diameter billet if this allows for tighter tolerances.
C.12	R.3	The cross-section of the basket should be built of two halves with the window or sensor port entirely contained in a single part (not between separate sections).
C.13	R.4	MURR is designed with a downward flow of the coolant. Thus, the window/sensor port must be located on the top of the basket (near the leading edge of the fuel plates) and the instrumentation housing must be located on the bottom of the basket (near the trailing edge of the fuel plates).
C.14	R.4	Basket end caps should be made of a single solid piece to facilitate its removal and control of the outer channel gaps between the flow test stages.
C.15	R.4	The end fittings of the MURR LEU fuel element should be entirely covered by the basket caps, so the tolerances of fuel element assembly (end fitting to side plate riveting) do not affect the position of the element in the main portion (shells) of the basket.
C.16	R.4	One shell only has a window near the leading edge. The shape and the size will be determined in accordance with the investigation done at OSU.
C.17	R.4	Another replaceable shell is needed that instead of a window has just a ½ inch diameter hole as a placeholder for other types of sensors (contact sensor, LVDT, inductive proximity sensor, etc.).
C.18	R.4	A cutout for wires should be made, running from the window or the hole for the sensor parallel to the flow (axial direction) towards the instrumentation housing. The diameter of the cutout (currently

Constraint ID	Requirement ID	Design constraint
		about 3/8 inch) is a placeholder and will change depending on the number of wires. The cutout may be removed from the design at later stages if the selected sensors are installed through the walls of the HMFTF loop testing section.
C.19	R.4	The MURR LEU element needs to be constrained in such a way that the outer channel gap maintains constant thickness during the test (~0.068 inch) by a combination of spring-loaded set screws and regular set screws with plastic tips. Each constrained motion must have a spring-loaded set screw at least on one side of the constraint so that the thermal expansion of the fuel element does not cause large local forces on the element.
C.20	R.4	At least two cross-sections in the axial direction need to be constrained in the basket. The ability to constrain more needs to be introduced to allow for force distribution across multiple contact points.
C.21	R.4	Orientation of the basket and the fuel element within it must facilitate the installation of the Pitot tubes.
C.22	R.5	The minimum thickness of the walls in the basket should be sufficient to prevent distortions during handling, assembly, and the flow test.
C.23	R.5	Due to different coefficients of thermal expansion, the rod tying the basket sections together should be made of aluminum as well, possibly with a spring added to maintain the tension.

5.2 Conceptual Design of the Test Vehicle (Basket)

As presented in Figure 5.1, the basket has the shape of a cylinder. It is built of six major parts: four shells covering the plated region of the MURR LEU fuel element and two end caps covering the end fittings of the element. The end caps are designed as identical and are interchangeable.

Figure 5.1 presents an isometric view of the basket with a porthole for displacement monitoring sensors. Since the sensors to be used during the flow test to monitor the deflections have not been yet tested at OSU, it is expected that the shape and size of the window or the sensor port may change as the sensors are selected later in the design process. Due to their shape and size, these sensors may need to be installed outside of the testing section. In that case, the groove for the internal wiring may not be needed. However, special couplers between the basket and the testing section may be needed for wire management and positioning of the basket in the flow loop. Figure 5.2 presents an alternative design of the basket with one shell having a special window for laser access. If the lasers are proven to work under the expected flow conditions, such a window design will be further incorporated in the preliminary design of the basket. Due to possible harsh conditions during the test, a window built of quartz is desired.

Figure 5.1. Isometric view of the basket with a porthole for displacement monitoring sensors.

Figure 5.2. Isometric view of the basket with a window for laser sensors.

The basic “U” and “C” shells building the basket are presented in Figure 5.3. The length of each shell is 14.94 inch, which is within the 20-inch limit of the available EDM equipment. Two sets of “U” and “C” shells are needed for the basket. The “C” shell located closer to the trailing edge will require machining of holes for screws connecting the shells and possibly a groove for wiring from the sensor if it is entirely contained within the basket (see Figure 5.4). The “C” shell that is closer to the leading

edge of the fuel plates will require additional machining of a window (if a laser is used for the displacement monitoring) or a port (if other sensors are used) to access the outer plate. Figure 5.5 shows an example of a “C” shell with a porthole machined in it. Figure 5.6 shows an example of a “C” shell with a window machined in it.

Figure 5.3. Isometric view of the basket main “U” and “C” shells without machined features.

Figure 5.4. Isometric view of the basket main “U” and “C” shells with wiring groove.

Figure 5.5. Isometric view of the basket main shells with a porthole and wiring groove.

Figure 5.6. Isometric view of the basket main shells with a window for a laser sensor and wiring groove.

Figure 5.7 presents a close-up view of the basket end cap. Grooves are machined out from its outer edge to allow for mating with the instrumentation housing of the HMFTF (see Figure 5.8 for reference). The basket will also be bolted to the instrumentation housing by screws passing through a coupling flange, the instrumentation housing, and into the basket end cap. The exact location of these screws will be established once the orientation of the basket with respect to the Pitot tube assembly is decided upon during the preliminary design stage.

Figure 5.7. Isometric view of the basket end cap.

Figure 5.8. Installation of the basket in the instrumentation housing of the HMFTF.

The end caps are designed with a lip that reduces possible flow around the fuel element during the flow test. The lip also limits the axial motion of the element within the basket. A silicone gasket is also considered around the end fitting of the basket to further reduce the axial motion of the fuel element in the basket and reduce the flow. A cross-section view through the basket and the cap is presented in Figure 5.9.

Figure 5.9. Cross-section through a MURR LEU element installed in the testing basket.

In the axial direction, the end caps reach beyond the connection line between the fuel element end fitting and the side plate (see Figure 5.10 for reference). This configuration is meant to remove any influence of the fuel element assembly and tolerances around the end fitting with rollers on the thickness of the end channels gaps and overall lateral position of the fuel element within the basket. Additionally, it facilitates access to the outer channel gap for inspections between various stages of the flow test. If, for some reason, reversible (elastic) deformations cannot be traced during the experiment, the irreversible (plastic) deformations should still be observable by CGP without the need for removal of the entire fuel element from the basket in between different stages of the flow test.

Figure 5.10. Isometric view of a MURR LEU element installed in the testing basket with (left) and without (right) the end cap.

5.3 Element Constraints in the Test Vehicle

Although a detailed experiment execution plan will be prepared as a part of the preliminary design of the flow test, the stages of the flow test have already been considered in the conceptual design as they have an impact on the basket design.

Based on prior experience at HMFTF [31], [32], [39] the presence of the instrumentation required to meet the goal of this experiment in the channel gaps may influence the flow distribution, introduce vortex shedding locations and, as a result, alter the deflection of the plates. Currently, CFD analyses are planned that may help clarify to what extent the selected sensors influence the results when they are present in the flow. Lasers are the least invasive since they can be installed outside of the coolant channels and can access the surface of the plate via a window in the wall of the basket. On the other hand, the presence of the Pitot tubes, LVDTs, or strain gauges may significantly disturb the flow in the channels influencing the outcome of the test.

The MURR HEU fuel element is not fully constrained in the reactor, meaning the element can move laterally within the confinement defined by the lower grid, inner and outer pressure vessels, and neighboring fuel elements. The MURR LEU fuel element will have an identical set of constraints to the HEU element in the reactor as their outer dimensions and structure of the reactor have not changed. The thickness of the outer channel gap may change during a cycle due to the tolerances around the elements. While the flow test aims at replicating the prototypic flow conditions, the only sensors that can measure the deflections on an unconstrained fuel element that are decoupled from the motions of the entire fuel element (including plates' deflections) in the basket are strain sensors. The other methods of monitoring the deflections mentioned in Section 4.3 require that the sensors be attached to the body of the basket with a port for their wiring to exit the HMFTF test section (LVDT, proximity

sensor, contact sensor) or a window (laser) only. If the fuel element is allowed to move within the basket, the measurement registered by an external sensor (other than strain gauges) will be comprised of motion of the element and deflection of the plate, and the decomposition of these two will not be possible.

For the reasons mentioned above, the basket has been designed to constrain the fuel element in it by multiple set screws. These additional, removable (and optional) constraints on the fuel element are designed to allow for simulating various conditions in the basket, but most importantly, to control the thickness of the outer channel gap. Spring-loaded set screws acting directly on the side plates were chosen as the preferred method of constraining the element in the basket as they would allow for fine-tuning of the size of the outer channel gap. Figure 5.11 presents a view of the basket in which part of locations for the set screws is indicated.

Although the screws only need to be present in two locations in the axial direction to constrain the lateral movement of the fuel element in the basket, there are currently three proposed axial positions for the set screws in each shell of the basket (six total). These multiple locations would limit the forces exerted locally by the set screws on the side plates. The number of axial locations in which the screws need to hold the element will be determined during the preliminary stage of the flow test design.

Figure 5.11. Isometric view of the testing vehicle with potential locations of set screws for fuel element positioning.

Figure 5.12 shows a representative cross-section with the set screws for positioning of the element. All screws are acting on the side plates of the fuel element only (no point of contact with fuel plates). Due to the limitations on the minimum length of the spring-loaded set screws (red arrows in the figure), some locations can only be secured with regular set screws (blue arrows in the figure). However, along each line of constraints, there is at least one spring-loaded set screw to limit the forces exerted locally on the side plates.

Figure 5.12. Cross-section view of a MURR LEU element installed in the testing basket with the lateral constraints.

It is recognized that the preparation of the element for testing within the basket may be difficult with multiple screws requiring adjustment. This method of constraining the fuel element will be tested once the first basket is manufactured towards the end of the preliminary design stage and a surrogate all-aluminum dummy element is available for basket fitting and sensor testing purposes.

The following stages in the flow test are currently planned:

1. Constrained and instrumented element
 - a. Nominal flow rate, and
 - b. conservative flow rate;
2. Constrained element, without instruments affecting the flow
 - a. Nominal flow rate, and
 - b. conservative flow rate;
3. Unconstrained, without instruments affecting the flow
 - a. Nominal flow rate, and
 - b. conservative flow rate.

The first stage with a fully constrained fuel element is meant to allow for measurements of pressure-induced plate deflections decoupled from the motion of the element within the basket. The second stage aims to test the element without the influence of the instrumentation in the flow channels. During that stage, transient measurements of deflections will not be possible unless the strain gauges directly attached to the surface of the outer plate are used. However, between stages, the CGP

measurements could be performed to detect any permanent deformations. The third stage with an unconstrained fuel element aims to test the behavior of the MURR LEU fuel element in conditions as close to the prototypic conditions as possible.

Nominal and conservative flow rates will be used in each stage to investigate the presence of a safety margin. The duration of each stage of the flow test will be determined in cooperation with OSU later in the flow test design process.

6 Activities in Preparation for the Flow Test Preliminary Design

6.1 Planned CFD and Structural Analyses of the Fuel Element in the Basket

During the work on the conceptual design of the test vehicle and review of the sensors that could potentially be used in the flow test, a need to perform a set of simulations has been identified. While the geometry of the plate and the channels together with the flow rate are the hydraulic design parameters, it is the pressure differential resulting from these parameters that cause the deflection of the plates. Pressure differential for the nominal and the conservative values of the design parameters will be estimated in CFD analyses for the MURR LEU fuel element. This information will be subsequently used to assess the level of conservatism in the experiment with as-fabricated dimensions. The full-element FSI analysis also is needed to provide the likely location of the area with the largest deflection along the axis of the plate, where the sensors will be installed in the flow test.

Almost all the sensors that can directly or indirectly measure the deflections of the plates, as well as the Pitot tubes, will cause flow disturbances within the coolant channels. The exceptions are the lasers or cameras if they can access the leading edge of the plates via a window embedded in the testing vehicle. The influence of the other potentially used sensors (LVDT, proximity sensor, strain gauges with wiring, Pitot tubes, etc.) on the flow and, more importantly, on the deflection of the plates will be studied in a series of CFD and FSI simulations. Pitot tubes and their supports are expected to partially block the flow in the channels where they will be installed. It is rather impractical to install the Pitot tubes in all coolant channel gaps. This would require 40 tubes reaching the channel gaps through the end fitting. Thus, it is more likely that only a subset of the channels will have Pitot tubes in them. For that reason, the Pitot tubes may unevenly affect the flow in the channels. Sensors like LVDT or proximity sensors will need to partially block the outer channel gap. They also may cause local flow disturbances affecting the pressure acting on the plate surface. CFD simulations may help determine to what extent these effects are relevant for the goal of the flow test.

During the flow test, the temperature of circulating water will rise because of the heat generated by the pumps. Not all the heat can be rejected by the cooling system of the HMFTF flow loop. As indicated in Section 4.1, operating temperature could have a lower limit as high as 250 °F (120 °C) for the MURR LEU flow test. The flow rates needed for testing of MURR LEU element will be lower than those previously needed for other tests [32]. For that reason, such high temperatures may not be observed during the MURR LEU flow test. Nonetheless, thermal expansion analysis of the basket and the MURR LEU element is planned to estimate the dimensional changes of these two components. The analysis aims to assess whether the currently designed gaps between the basket and the element are sufficient to accommodate the assembly tolerances and uneven expansion rate of the tested components (the element may expand faster than the basket). The uneven expansion rate of the tested plates and the vehicle in the GTPA tests have shown to have significant effects in some cases [31], [32]. To allow for a similar magnitude of expansion of the basket and the fuel element, the fasteners for basket assembly could potentially be made of aluminum as well. Stainless steel fasteners would expand roughly half as much as aluminum due to the differences in the coefficient in thermal expansion, limiting the overall expansion of the basket.

6.2 Basket Fabrication for Fitting Purposes

As mentioned in Section 5, it is understood that positioning the fuel element in the basket may be difficult using the currently proposed method based on an array of set screws. The soft constraints provided by the spring-loaded set screws and regular set screws with plastic ball tips allow for an uneven expansion rate of the basket and the fuel element inside it. To test this method of constraining the fuel element in the basket, the plan is to machine the first version of the basket during the preliminary stage of the flow test design. Once an all-aluminum mockup of the MURR LEU element becomes available (preliminary design stage), the constraining method can be tested well ahead of the actual flow test. Additional adjustments to the design of the basket could be a potential outcome of this fitting test.

6.3 Dummy Element Procurement and Sensor Testing

While the sensor testing will be performed during the preliminary stage on a single flat plate, the demonstration of the sensor's ability to measure small deformations on a dummy element with all-aluminum plates installed in the basket must be performed ahead of the actual flow test. The challenges of using some of the sensors are unique to the testing setup required for the MURR LEU fuel element flow test. Thus, to understand the possible difficulties in the use of these sensors, as well as reduce uncertainties in the measurements, procuring an all-aluminum mockup of the MURR LEU fuel element is currently planned. Dry and submersed testing of the sensors on the all-aluminum mockup is planned to be performed during the preliminary or final stage of the flow test design (subject to availability).

7 Summary

In preparation for licensing, a hydraulic performance evaluation of the MURR LEU fuel element will be performed. Its purpose is to test a prototypic commercially fabricated LEU fuel element to determine whether any failure modes are observed in the fuel element, including significant deformations such as plate bending, twisting, or plate detachment from the side plate under selected safety-basis limits for reactor flow conditions. The evaluation will be performed by a combination of out-of-pile flow test and supporting analyses.

This report describes the activities completed during the conceptual design of the MURR LEU fuel element flow test. Three goals have been identified for the conceptual stage:

1. Review the hydraulic reactor design parameters and identify the most limiting conditions for the fuel plates,
2. Review and select the methods and sensors for monitoring various hydraulic and mechanical characteristics of the flow tests, and
3. Perform a conceptual design of the basket to be used in the flow test.

The design parameters for hydraulic testing of the LEU fuel element were reviewed and documented in a separate report [7]. These relate to the design needs of the reactor and, are therefore, referred to as reactor design parameters since they do not take into account design margins required for the experimental test design and other purposes. Here, only a summary of that review, containing the information affecting the design of the flow test, is included.

The most limiting plates from the perspective of flow-induced deflections in the MURR LEU fuel element are plates 22 and 23, which have the largest span of all the fuel plates in the element. One key dimension for the fuel element flow test design to be in the most limiting configuration is the outer channel gap thickness (between plate 23 and the outer pressure vessel). It directly affects the maximum hydraulic pressure differential acting on the fuel plates. The hydraulic pressure differential induced by channel gap thickness disparity tends to deform the plates towards the larger channel. Given the arc-shape of the fuel plates in the MURR LEU fuel element, the inward force is more limiting (buckling of the plate may occur at sufficiently high pressure differential), so for the outermost plate 23, the minimum channel 24 gap thickness of 0.068 inch is targeted in the flow test basket design. The internal channel gap thicknesses cannot be influenced by the design of the flow test, but the most limiting values for them are listed for reference to the flow network and planned CFD analyses.

Another important design parameter is the flow rate per element. The primary total flow rate of the MURR LEU core is 3750 gpm, which is distributed into eight fuel elements in the core. The nominal per element flow rate is 468.8 gpm, while the upper bound of flow rate per element of 562.5 gpm is obtained using the uncertainty factor of 1.2. The remaining normal operating conditions of the proposed MURR LEU core, including the coolant flow direction, coolant temperature, system pressure, and the coolant chemistry specification, have also been documented.

Together with the design parameters, the expected behavior of the most limiting plates in the MURR LEU fuel element has been described based on the prior experimental work and preliminary FSI analysis for the MURR LEU fuel plate 22. Because of the low value of the ratio between the calculated coolant bulk velocity in the channel gaps and the Miller's critical velocity for the limiting geometry, pressure-induced quasi-static deflection is the expected type of response of the MURR LEU fuel plates to the hydrodynamic load of the flowing coolant (oscillations of negligible magnitude are expected).

The maximum deflections that are expected to occur near the leading edge of the plate are predicted to be in the range of 25 micrometer. This behavior has a direct impact on the selection of the sensors for monitoring the MURR LEU fuel element behavior during the flow test.

Based on the historical experiments, prior experimental work under USHPRR Project, and the needs of the currently designed flow test, sensors for monitoring element behavior, and in particular, plate deflections have been reviewed. Most of the past experiments used strain gauges installed on the surface of the plate to measure the deflections indirectly from strains. This technique was proven to work for the detection of static deflections as well as dynamic flutter. However, these experiments were mostly focused on characterizing the response of the plates to significant coolant flow rates reaching or even exceeding Miller's critical velocity. The flow tests for the USHPRR LEU fuel elements will be executed at significantly lower flow rates that are a fraction of Miller's critical velocity, and hence the expected deflections are in the order of 1 mil. Sensors that are potentially able to resolve such small deflections are planned to be tested under dry and wet conditions to demonstrate their capabilities before the flow test of the MURR LEU fuel element that will be conducted at OSU. Among them are lasers, inductive sensors, LVDTs, and camera systems. Other types of sensors, like contact sensors, can also be tested if a good candidate is identified. The demonstration tests are planned for the preliminary stage of the flow test design.

A conceptual design of the testing vehicle (basket) has been performed under this activity and is also described in this report. Since the flow test will be performed at the HMFTF at OSU, the outer dimensions of the basket allow for insertion into the testing section of the HMFTF flow loop. The internal dimensions of the basket represent the most limiting configuration in the core with the thinnest outer channel gap 24. The dimensions of the components building the basket consider not only the assembly process but also different stages of the flow test, as well as the limitations of the machining techniques available. Since the final selection of the sensors monitoring the deflections will be performed during the preliminary stage, two alternative designs of interchangeable portions of the basket have been proposed. One contains a window that may accommodate laser sensors, and another contains a porthole that may be adjusted in size to accommodate other types of sensors like LVDT, or an inductive proximity sensor. The design of the basket envisions constraining the element to prevent lateral and axial motion of the tested fuel element for a portion of the test so that the displacements of the plates due to the hydrodynamic load can be decoupled from the motion of the fuel element within the basket. The removable end cap of the basket allows for inspection of the channel gap thicknesses with a CGP between different stages of the flow test.

Finally, activities in preparation for the preliminary stage of the flow test design have also been briefly discussed. The planned testing of sensors that have the potential to be used during the flow test of the MURR LEU element for monitoring the plate deflections has been described. Static dry testing, and wet bench testing, as well as flow testing in the EFL, are envisioned to demonstrate the relevant capabilities of the selected sensors. A series of numerical simulations is planned for analyzing in detail the flow distribution within the tested MURR LEU fuel element in the basket and locating the maximum deflection point in the axial direction of the plate in the case of the constrained leading edge of the plates. Also, the impact of selected sensors on the flow distribution and the plate deflection is planned to be analyzed numerically. The current plan is that the first basket will be machined during the flow test preliminary design so an all-aluminum dummy element fitting, as well as sensor testing, can be performed in advance of the flow test.

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