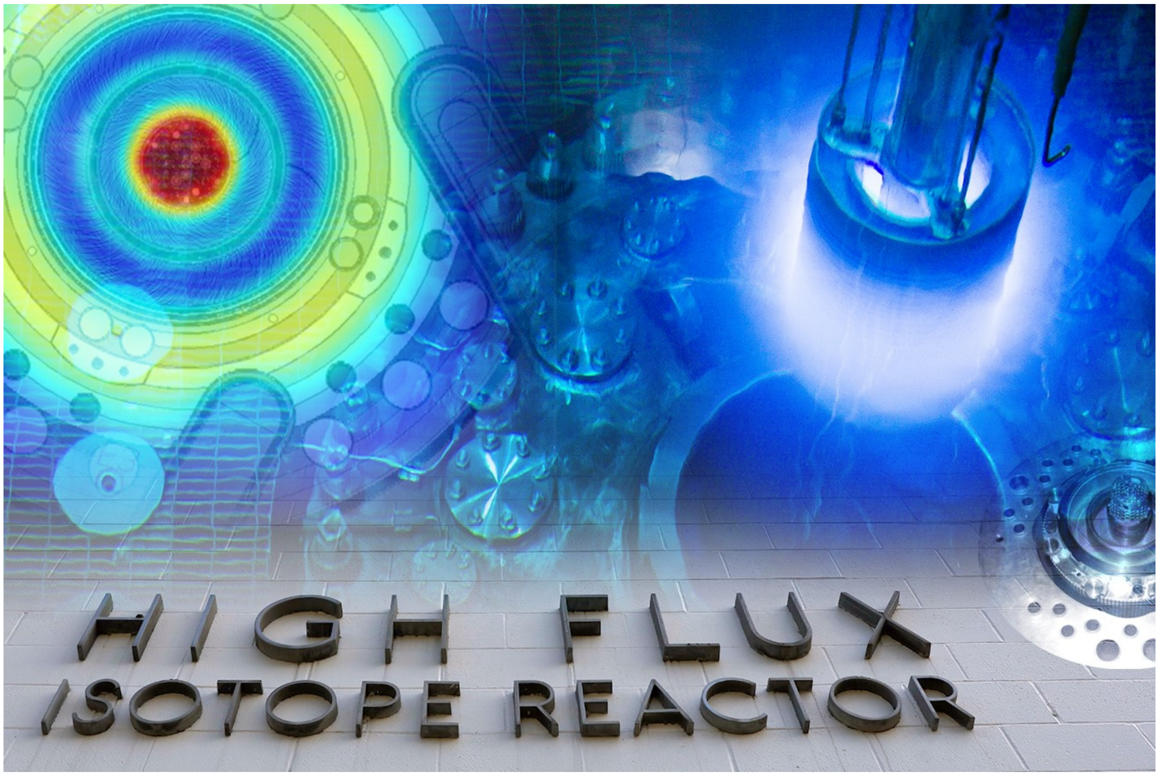
ORNL/TM-2022/2691/V10

Volume 10: Flow Test Facilities

HFIR Futures – Enhanced Capabilities Series



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January 2023

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ORNL/TM-2022/2691/V10

HFIR SENSE LDRD

VOLUME 10: FLOW TEST FACILITIES
HFIR FUTURES – ENHANCED CAPABILITIES SERIES

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ABBREVIATIONS

ATR	Advanced Test Reactor
ATRC	Advanced Test Reactor Critical Facility
BESAC	Basic Energy Sciences Advisory Committee
CAD	computer-aided design
CFD	computational fluid dynamics
CIC	core internal change-out
DOE	US Department of Energy
EFPD	effective full-power day
FSP	full-size plate
gpm	gallons per minute
HB	hydraulic beam
HEU	highly enriched uranium
HFIR	High Flux Isotope Reactor
HIFI	HFIR Irradiation Facility Improvement
HMFTF	Hydro-Mechanical Fuel Test Facility
hp	horsepower
HSSHTC	HFIR Steady State Heat Transfer Code
INL	Idaho National Laboratory
LCS	limiting control setting
LDRD	Laboratory Directed Research and Development
LEU	low-enriched uranium
M3	Material Management and Minimization
MITR	Massachusetts Institute of Technology Reactor
MP	mini-plate
MURR	Missouri University Research Reactor
NBSR	National Bureau of Standards Reactor
NEFCD	Nuclear Energy and Fuel Cycle Division
NNSA	National Nuclear Security Administration
NRC	US Nuclear Regulatory Commission
NQA-1	Nuclear Quality Assurance Level 1
ORNL	Oak Ridge National Laboratory
OSU	Oregon State University
PALM	powered axial locator mechanism
psi	pounds per square inch
psia	absolute pressure
psid	pressure differential
PVC	polyvinyl chloride
RPV	reactor pressure vessel
SC	Office of Science
SENSe	Sustaining and Enhancing Neutron Science
SL	safety limit
SS	stainless steel
TDH	total dynamic head
USHPRR	US High Performance Research Reactor
VXF	vertical experiment facility
WFL	water flow loop

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ABSTRACT

Adding additional flow testing facilities has been considered as part of the High Flux Isotope Reactor (HFIR) Sustaining and Enhancing Neutron Science (SENSe) Initiative at Oak Ridge National Laboratory (ORNL) to support HFIR operations and experiments. This prospect has prompted many ideas and discussions regarding potential features, configurations, locations, and applications for the facilities. A working group of ORNL staff members was formed in fiscal year 2022 to recommend one or more configurations to best support future HFIR operations and scientific capacities and to develop order-of-magnitude cost estimates and timing. The ideas discussed in this report include options ranging from upgrading existing small-scale testing facilities to building a full-scale HFIR mockup for detailed thermohydraulic testing and fuel assessment.

1. BACKGROUND OF THE HFIR FUTURES – ENHANCED CAPABILITIES SERIES REPORTS

In 2019, the US Department of Energy (DOE) Office of Science (SC) chartered a Basic Energy Sciences Advisory Committee (BESAC) to assess the scientific justification for a domestic high-performance reactor–based research facility. This committee delivered a report, including specific recommendations for the High Flux Isotope Reactor (HFIR) focused on continuing operations beyond the year 2100, enabling future additional scientific capabilities and conversion to low-enriched uranium (LEU) [BESAC 2020]. The review determined that HFIR will have a critical role in the future of US neutron science research and recommended the immediate pursual of scientific enabling enhancements, including replacement of the reactor pressure vessel (RPV), conversion to LEU fuel, enhanced capabilities for in-core irradiations and neutron scattering research, modifications to the fuel assembly, and restoration of the flux intensity of the original 100 MW highly enriched uranium (HEU) operations.

In response to the BESAC report, an Oak Ridge National Laboratory (ORNL) funded initiative was established to provide a critical assessment of hardware, systems, and infrastructure required to sustain and enhance HFIR capabilities. The HFIR-Sustaining and Enhancing Neutron Science (SENSe) Initiative consists of three Laboratory Directed Research and Development (LDRD) projects assessing (1) infrastructure enabling operation past 2100, (2) non-neutron-scattering scientific capability enhancements and planning, and (3) neutron scattering scientific capability enhancements and planning. Refer to the report by Bryan and Chandler (Bryan, 2022) for more information regarding HFIR, the BESAC report recommendations, the HFIR-SENSe Initiative, and the goals of the three LDRDs.

The effort to brainstorm non-scattering scientific enhancements at HFIR was a “blue-sky” engagement with researchers across ORNL and has yielded both incremental improvement ideas, as well as transformational new capabilities. Thirty-five concepts were grouped into 13 separate working groups; the goal of each group was to further develop the concepts, build a scientific justification, identify potential sponsors, and estimate costs and schedules for each concept. This effort culminated in this multi-volume series of documents summarizing these efforts and ideas. Table 1 itemizes these volumes.

Table 1. Summary of the HFIR Futures – Enhanced Capabilities Series

Volume	Report number	Volume title
1	ORNL/TM-2022/2691/V1	Volume 1: Introduction to the HFIR Futures – Enhanced Capabilities Series
2	ORNL/TM-2022/2691/V2	Volume 2: Hot Cells Connected to the Reactor Pool
3	ORNL/TM-2022/2691/V3	Volume 3: Online Insertion and Removal Facilities
4	ORNL/TM-2022/2691/V4	Volume 4: Detection Systems and Ultra-Cold Neutrons

Table 1. Summary of the HFIR Futures – Enhanced Capabilities Series (continued)

Volume	Report Number	Volume Title
5	ORNL/TM-2022/2691/V5	Volume 5: Flexible Flux Trap Configurations
6	ORNL/TM-2022/2691/V6	Volume 6: Experiment Facility Spectrum Tailoring
7	ORNL/TM-2022/2691/V7	Volume 7: Cryogenic Facility
8	ORNL/TM-2022/2691/V8	Volume 8: Epithermal and Fast Neutron Radiography Facility
9	ORNL/TM-2022/2691/V9	Volume 9: Critical Facility with Add-on Ion Beam
10	ORNL/TM-2022/2691/V10	Volume 10: Flow Test Facilities
11	ORNL/TM-2022/2691/V11	Volume 11: Modeling & Simulation
12	ORNL/TM-2022/2691/V12	Volume 12: Flow Loop Facilities
13	ORNL/TM-2022/2691/V13	Volume 13: Neutrino Facilities

2. FLOW TEST FACILITIES WORKING GROUP DESCRIPTION AND SIGNIFICANCE

2.1 DESCRIPTION OF WORKING GROUP

The Flow Test Facility working group was created to generate options for flow testing facilities to support and enhance HFIR operations and research capabilities and to support broader applications beyond HFIR. Several types and configurations of flow test loops and facilities could be useful to support HFIR operations and scientific capabilities, including:

- Flow testing of core components and multi-component configurations
- Full-length partial fuel element flow testing at normal operating flow and pressure
- Full-scale fuel element flow testing at partial flow and pressure
- Full-scale fuel element flow testing at normal operating flow and pressure
- Flow testing of a full-scale HFIR mockup facility

2.2 SIGNIFICANCE

Flow testing is essential for characterizing component performance and ensuring that computational models accurately reflect the true behavior characteristics. Increasing the quality and quantity of flow testing data can allow for reduced uncertainties in codes and simulation, permitting increased performance and greater operational flexibility. For example, the flow test data for fuel and components can be used to validate computational software, operational data and correlations, and models. This leads to high confidence in methods based on strong agreement between measurements and calculations. Additionally, flow testing methods can be used to test planned operations or to simulate actual operations to confirm modeling code performance. Again, having high confidence in modeling codes requires the application of fewer uncertainties, and the result is better characterization of operations and increased thermal safety margins. This is discussed in more depth in Volume 11, "Modeling and Simulation."

Flow testing of the fresh fuel assembly is required for each cycle prior to reactor startup to ensure that no manufacturing issues would prevent the fuel assembly from maintaining a cooling geometry during full flow conditions. Currently, this flow testing is performed in the HFIR vessel because there are no external flow testing capabilities. An external flow test facility would allow flow element testing to be removed from the refueling critical path. In addition, testing in an external uncontaminated/unirradiated loop reduces operational concerns if a fuel assembly does not meet flow testing requirements.

A flow test facility outside the vessel would allow for inclusion of a suite of instrumentation to measure hydraulic parameters such as flow rate and pressure distributions. This high-quality data would further improve understanding of flow in HFIR's unique core design and could be employed for detailed hydraulic modeling and simulation validation studies. This validation could result in better quality flow correlations for use in HFIR's safety and research basis methods. Ultimately, the acquired data could be used to enhance the nuclear safety basis and to increase thermal safety margins.

Furthermore, the knowledge gained could be applied to the LEU conversion program. It would aid in the development of LEU design methods, safety basis documentation, and software quality assurance documentation. A high-fidelity validation with a 3D multiphysics finite element analysis code (e.g., COMSOL) would provide additional justification for use of such a code for safety basis. In turn, this would allow higher performing LEU core designs to be considered. Ultimately, additional flow testing capabilities at HFIR for fuel and core components will ensure the highest quality and most efficient operations possible, and it will also allow for additional scientific investigation.

3. CONCEPTUAL DESIGNS FOR FLOW TEST FACILITIES

3.1 UPGRADED SMALL-SCALE FLOW TEST FACILITY

3.1.1 Existing Facility

The Nuclear Energy and Fuel Cycle Division (NEFCD) manages and operates the current water flow loop (WFL) at ORNL. The WFL is in Building 5800, Lab D-111. A computer-aided design (CAD) representation of the WFL is shown in Figure 1. The WFL is essentially a pump and a water storage tank connected by polyvinyl chloride (PVC) pipe sections with a region for testing that can be isolated using hand valves. The loop was designed with PVC flanges at the test section to allow that region to be easily modified for testing different components. The WFL has been used to support many HFIR activities, including testing and qualifying flux trap and beryllium reflector experiment designs and redesigning and qualifying core components. Most notably, the WFL was employed for surrogate fuel plate flow testing to gain more understanding of mechanical and flow conditions under various conditions and configurations. This testing supported reactor restart after a fuel plate issue left HFIR shut down for nearly one year.

Testing in the WFL provides the real-life results associated with testing a physical system. Computational fluid dynamics (CFD) can be used to assess current performance or to predict the impact of system changes, whereas WFL flow testing validates the CFD models. The cost of WFL flow using an existing loop can be lower than CFD testing; and together, CFD modeling and WFL testing provide a very good understanding of a system. The WFL's PVC construction makes it easily modifiable for testing new components. It is common to validate CFD methods by flow testing one or more physical configurations and then performing sensitivity analyses with the CFD methods to understand the impacts on fabrication tolerances, condition changes, and other factors.

The facility uses a variable frequency controller to operate the single 40 hp TECO-Westinghouse pump capable of maximum operating pressures of 70–90 psi depending on test section geometry. The loop is made of schedule 40–80 PVC in diameters ranging from 4–6 inches that discharge to a 300-gallon water storage tank.

With the current WFL design, researchers must make conservative assumptions regarding flow performance. One limitation is the operating pressure. HFIR operates at an inlet pressure of 468 psia (absolute pressure) with a pressure drop across the flux trap of approximately 110 psid (pressure differential). The WFL exits to atmospheric pressure, so the pressure drop across the flow test section is almost equal to that of the operating pressure at 70–90 psid. Therefore, researchers must extrapolate the flow results to the required pressure drop across the HFIR flux trap. In some WFL experiments—vibration testing of HFIR components or fuel plates, for example—this extrapolation method is insufficient. These vibration tests are dependent on the pressure drop, but because the results cannot be easily extrapolated, researchers must implement other methods to achieve desirable results.

The WFL is also volume limited. HFIR experiments in the flux trap are roughly 0.5 inches in diameter, whereas experiments in the beryllium reflector can be more than 3 inches in diameter. These experiments are compatible with the 6-inch PVC piping that makes up the WFL, but experiments with HFIR components or fuel plates/elements require a much larger pipe size.

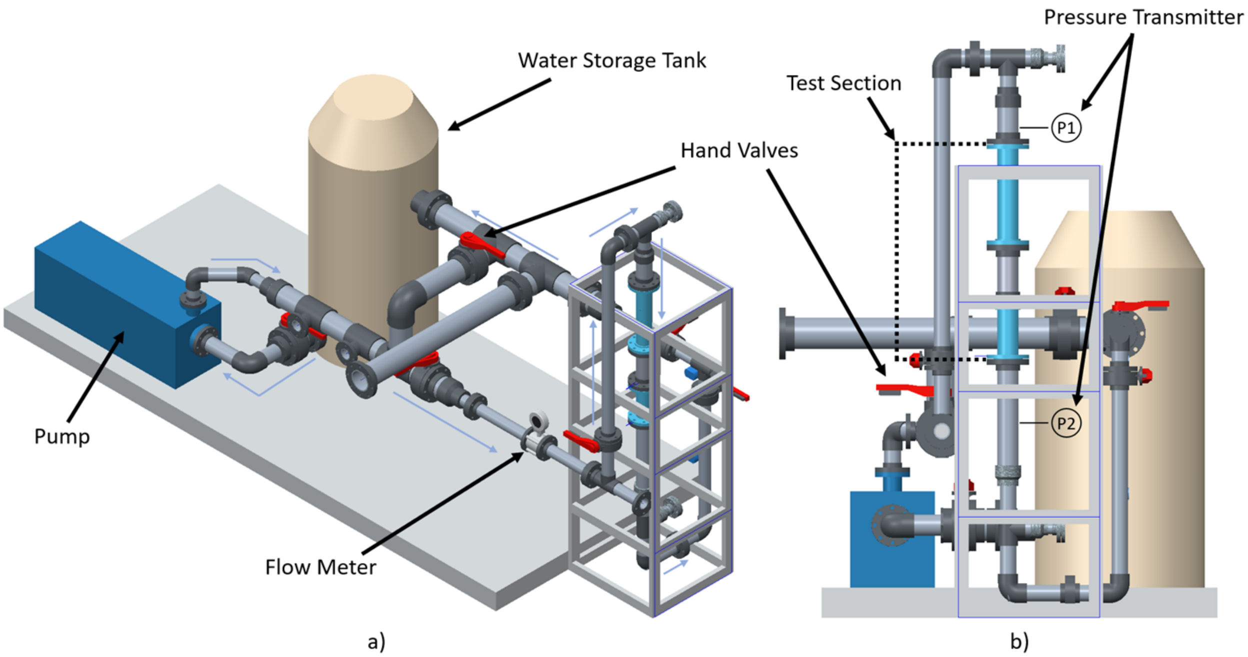

Figure 1. CAD representation of existing WFL: (a) isometric view and (b) side view.

3.1.2 Upgraded Water Flow Loop Facility

The existing WFL design has options for upgrades that could significantly increase the facility's capabilities. An upgraded facility would expand the range of testing that can be performed, thus supporting HFIR operations and serving as a more useful resource for ORNL flow testing needs.

The principal potential changes include upgrading the pump to a model with increased flow and pressure with higher and lower flow options and/or upgrading the piping from PVC to stainless steel (SS). Although these changes can be made separately, implementing both together would provide for the greatest range of flow testing conditions, including an increased range of pressures, flow rates, and pressure drops.

Upgrading the current pump to facilitate higher flow rates and to allow for test sections with larger pressure drops would better represent actual conditions in HFIR. This would enable testing of full height fuel sections and would support testing of other important HFIR components such as orifices. A pump upgrade would also provide a physical flow test facility to support ORNL user facility tests and would expand the range of potential experiments that could be tested at the WFL.

Upgrading to SS piping would allow the WFL to handle greater system pressure, supporting a maximum pressure drop of 100 psi. This level of pressure would exceed the load limit of the existing PVC piping. This upgrade would be needed to perform orifice studies for the HFIR control drums, for example.

In addition to these main upgrades, additional changes may be needed for peripheral components such as flow meters based on final flow loop specifications. Auspiciously, the upgraded flow loop facility would require minor changes to the footprint and could continue to be located in Building 5800, Lab D-111. This upgraded facility would meet the specifications described below with the anticipated costs based on engineering judgement and WFL operating experience.

3.1.3 Cost Forecasting and Estimates

High-Flow Option

For the high-flow pump replacement option, the following specifications and resource requirements would apply:

- Flow rate: 250 gallons per minute (gpm)
- System pressure: 250 psi
- Horsepower (hp): 100

The high-flow option may require upgraded power and/or flow control, and it would also require that the piping to be upgraded from PVC to Schedule 80 SS to support the increased system pressure. Upgraded instrumentation to monitor the increased flow may be needed, and temperature control may be required for continuous long periods of operation for specific experiments.

The estimated pricing for the high-flow option pump and motor package is approximately $30K. Including installation and piping replacement, the total cost is expected to be approximately $2 million. This option would allow the widest range of potential test cases and experiments to be performed.

Low-Flow Option

For the low-flow pump replacement option, the following specifications and resource requirements would apply:

- Flow rate: 150 gpm
- System pressure: 130 psi
- Horsepower (hp): 40

This option would not require any upgrades to the current WFL piping or instrumentation, but it may require implementation of temperature control. The pricing for the pump and motor package would be approximately $30K, and the total cost including installation is expected to be approximately $100K. This option would provide increased flexibility and would allow for additional experiments to be run at the WFL.

3.2 FULL-SIZE FUEL ASSEMBLY FLOW TEST FACILITY

The high heat conditions in HFIR's inner and outer fuel elements require significant cooling. Approximately 13,000 of the nominal 16,500 gpm primary coolant volumetric flow passes through the 1.5mm thick fuel plate coolant channels. The fuel's thermal-hydraulic conditions are (1) a vessel inlet pressure of 468 psig, a temperature of 50°C, a flow velocity of 52 ft./sec in the coolant channels, an outlet pressure of approximately 368 psig, and an outlet pressure temperature of approximately 70°C. HFIR's thin plate-channel design, high velocity, and high heat flux are unique compared to other research and test reactors. A proposed full-size flow test facility design would be capable of testing fuel elements individually or assembled. The working group discussions primarily included (1) pump pressure and flow capabilities, (2) power requirements, and (3) facility location. To ensure fresh fuel security and radiological safety, a facility at the HFIR complex would be practical. Achieving a 100 psid drop over the 2-foot core length and significant volumetric flow is challenging in a test loop, but these capabilities would provide data useful for HFIR operations and analysis.

The proposed full-size facility would immediately streamline HFIR outage planning and flow testing. The HFIR fuel assembly design recently reverted to installing inlet combs on the outer fuel element, and plans are in place to approve the same design change to the inner fuel element. Combs act as fuel plate stiffeners and address observed inlet fuel plate deformations caused by hydraulic forces and thermo-mechanical stresses during operation. Before full-power operation can commence, fuel elements are installed in the vessel, subjected to full flow conditions at zero power for 24 hours, and then examined for deflection. If plate deflection is observed after the flow test, then the element must be removed from the vessel and stored in the clean pool. This process requires operator resources and can complicate outage work schedules, particularly for short outages. Minimizing downtime supports the goal to operate eight cycles per year, thus providing more neutrons per year to support beamline science and in-core irradiations. A separate test facility would avoid these critical-path logistical issues for fuel elements with bent plates or other issues and would allow elements to be tested as they are shipped to HFIR, thus building up a buffer of approved elements.

A flow test facility would also provide information about current and future HFIR fuel elements. Measurements of fresh fuel and channel track data could inform relations between average channel gap and the differential pressure across the element. This information would be useful when estimating the oxide growth on elements and reduced flow over the course of the 25-day cycle. In a contained loop, careful pH control would also provide a like-for-like element history and would address questions about the relationship between time in contact with reactor pool water and the initial oxide layer on the elements. The facility could also support longer term projects. For example, HFIR is one of the US High Performance Research Reactors (USHPRRs) in the Reactor Conversion Program pursuing conversion to LEU fuel. Several proposed designs lengthen the active uranium fuel region, which changes the entrance effects and stiffness along the fuel plates.

A significant fuel design change, such as changing the type of welding to attach the fuel plates to the cylindrical sidewalls of the element, could be supported by evaluating the mechanical strength in a flow test facility. Design changes to other core components could also benefit from the flow facility. The pressure drop across the outer shroud flanges, which feed the control and reflector regions outboard of the outer fuel element, is about 90–94 psid, with a total flow of about 2,000 gpm. To improve flow-induced vibration, future control or reflector design changes, cooling of components, or modified experiment positions may require a redesign of the outer shroud flange. Currently, a redesign of the beryllium reflector is being assessed. Flow testing using a full-size facility could help validate design and safety calculations, could qualify the new reflector before it is used in the reactor, and would inform differences in the flow phenomena compared to flow in the traditional reflector design.

The existing WFL facility is not currently able to achieve the required flow and pressure drop required for a series of full-length fuel plates. Data from the WFL did support the fuel comb design change (Howard 2021). However, the facility was limited to half of the total fuel plate length and reduced inlet pressure. Therefore, a larger test facility with higher pressure and flow capabilities will support HFIR fuel and core component design changes, operations safety and reliability, and hydraulic analysis.

4. ASSET BENEFITS

The HFIR vessel and primary piping system are outfitted with pressure taps to determine the absolute pressure and differential pressure across key core components. These components are grouped into the *Pressure Vessel Flow Monitoring system*. Live and past operating conditions are recorded by the HFIR data system ("HFIR Data System Functional Description," 2019), including:

- PT-127 pressure at vessel inlet, communicates with letdown header valve to control primary pressure
- PT-104 reactor vessel pressure at penetration RH-8
- PDT-106 total differential pressure across the strainer and reactor vessel
- PDT-103 inlet strainer pressure drop
- RP4-2 outer shroud flange pressure drop
- RP1-3 beryllium reflector/control region parallel channel pressure drop
- RP4-3 core pressure drop
- RP4-N16 fuel element pressure drop
- PDT-HB/PDT-EF hydraulic beam (HB) tube and engineering facility pressure drops (Drawing M11537OH101, "Pressure Vessel Monitoring Flowsheet," 2017).

These differential pressure drops are correlated to flow rates in the vessel by equations produced from hydraulic flow tests performed during the design of HFIR. Most pressure data measurements are updated every 30 seconds. The equations are tabulated in "Specification for Instrument Transmitter Tabulation and Ranges" (ORNL/RRD/INT-37 2021). A detailed method for calculating all vessel flows is addressed by Haack [Haack 1969]. The vessel flow distribution is incorporated when modeling the HFIR steady-state and transient thermal safety margins. Note that the HFIR core design has changed slightly since the initial data and correlations were developed. An updated set of experimental flow measurements based on the current design or any future design would support the flow characterization calculations and would allow for increased safety and/or operational margin.

Margin-to-boiling in the HFIR fuel elements is analyzed using the HFIR Steady State Heat Transfer Code (HSSHTC). The model was developed internally for original HFIR operating conditions (100 MW and 600 psi inlet pressure) and was adapted after power was downrated to 85 MW in 1989. HSSHTC results, which account for the fuel elements' nuclear, thermal-hydraulic, mechanical, and corrosion history, establish HFIR safety limits (SLs) and limiting control settings (LCSs). Therefore, the core flow and heat transfer conditions are crucial inputs. Appendix B of the HSSHTC manual [McLain et al. 1986] explains the derivation of pressure-flow equations and the model's method to determine the steady-state total fuel flow rate. Measured pressures of interest include:

- Core pressure drop RP4-RP3
- Fuel element pressure drop RP4-N16
- Outer shroud flange pressure drop RP4-RP2

Figure B-9 in the HSSHTC manual [McLain et al. 1986] shows all pressure measurement locations in HFIR's primary coolant system. Calculations to find the fuel assembly flow rate (sum of inner element, outer element, and labyrinth flow rates) are outlined in Appendix B. This process involves subtracting the core periphery flow from the total vessel flow to find the target fuel region flow. The core periphery areas include the outer shroud flange, the hydraulic beam tubes, and the engineering facilities. The total control region flow rate as a function of core pressure drop (i.e., the sum of control region and outer shroud flange pressure drop) is also calculated to determine heat transfer from the outside diameter of the outer fuel element. The code chooses an initial fuel assembly flow estimate, and the core head loss is calculated. Based on the core head loss, the target region flow is calculated. The flow through the fuel assembly and target region is then iterated until the head loss across both flow paths is equal. All HSSHTC correlations are derived from the 1960s HFIR mockup flow test data. These correlations form the basis of the live plant data collection calculation and iteration in Haack's report [Haack 1969]. Therefore, the HSSHTC and the live plant data flow balances are the same.

Transient analysis is performed using the 1D nuclear systems code RELAP5 developed by the US Nuclear Regulatory Commission (NRC) and maintained by Idaho National Laboratory (INL). Analysis confirms that HFIR safety features maintain fuel and/or reactor pressure vessel integrity under accident conditions. The HFIR plant model includes primary and secondary piping, with most detail focused on the flow paths in the vessel [Morris and Wendel 1993, Griffin 2017]. Analysis assumes that total primary coolant flow is 16,500 gpm nominally with a low-to-high range from 15,840 to 17,170 gpm, depending on limiting conditions. Reference flow and pressure information is similar but not identical to the HSSHTC flow balance. The control and reflector region, vertical experiment facilities (VXFs), engineering facility / core bypass, fuel labyrinth, and HB tube cooling channels are referenced in by Sweet [Sweet 1970]. Many reported flows use the same references as the HSSHTC (identical for control region, shroud flange, and target tower). Reflector subchannel design and final flow rates using the Bernoulli equation and mockup flow tests in Jones and Kelly [Jones and Kelly 1961] are given for various pressure drops. It is assumed that the VXFs are fitted with beryllium plugs. The target region is assumed to be loaded with 31 curium rods with a flow-per-target based on a 35.5 psi pressure drop across the target holder per Ellis [Ellis 2012] and Kedl [Kedl 1965]. The remaining flow cools the inner and outer element fuel channels. Information-only "HFIR Flow Schematic [RRD drawing E-47681 2009] also serves as a helpful visual of the HFIR flow channels, particularly in the control and reflector regions.

The steady-state and transient models and HFIR data live plant flows use common references for the control and reflector regions, the outer shroud flange, the target region, HB tubes, VXFs, and engineering facilities. The primary differences are in the target region experiment loading and in capturing revised reflector region designs. Other differences are driven by differing total primary coolant flow rates and small deviations in the pressure balance across the vessel. Neither model officially captures the 1980s HFIR Irradiation Facility Improvement (HIFI) project that updated the removable beryllium designs or the newer target holders. A new Representative Core HFIR RELAP5 model that includes balancing of the target region, the VXF, and the removable beryllium is in development.

It is desired to standardize the HFIR nominal vessel flow balances in the HSSHTC and RELAP5 HFIR models, which are used for HFIR Nuclear Safety Basis analysis. New flow loop test data present an opportunity to modernize the HFIR data flow correlations and incorporate them into the HSSHTC and RELAP5 models to improve agreement between the codes and operating data. This improves understanding of the best-estimate-plus-conservative conditions, and it also provides justification for reducing conservatism in the safety basis and for increasing thermal margins. New data and model improvements also position the Nuclear Safety and Experiment Analysis Section well for making full use of HFIR's target region, removable beryllium, and permanent beryllium experiment positions. Core loading of experiments and isotope production targets such as ^{238}Pu must consider the amount of flow diverted from cooling the core and the impact to fuel thermal margins. Reduced modeling conservatism supports increased isotope and experiment throughput.

As discussed in Section 3.2 above, data from the facility and the fuel element testing can be used to streamline HFIR operations. The option to flow test fuel elements outside the HFIR core allows elements to be approved when received instead of during the reactor outage immediately before use. Operations personnel can reduce outage tasks, tolerate shorter outages, and position for operating more cycles per year. Startup tasks include estimating the control system position at which the reactor reaches criticality. The worth of the as-manufactured fuel contributes to in the critical position. The loop could also be used as a critical facility to quantify the worth of fuel elements and to correlate the worth for use in the critical position calculation.

Programs supporting extension of HFIR's lifetime and improvement of scientific capabilities can also benefit from the flow test facility. Proposals being evaluated include a new reactor pressure vessel to address lifetime radiation damage concerns. HFIR is among the USHPRRs that are redesigning their fuel to convert to low enrichment. Future core component or fuel design changes to active fuel length, combs, or welding integrity could be confirmed at full flow conditions, correlated to pressure drop, and incorporated into the HFIR data and modeling efforts. Project collaboration within ORNL that cannot be served by the current loop facilities, as well as collaboration beyond ORNL on other reactor conversion projects could lead to new scientific partnerships. Therefore, a flow test facility would benefit plant flow and pressure correlations and models and HFIR operation, it would expand future design and test capabilities.

5. DISCUSSION

5.1 OPTIONS CONSIDERED

Several types and configurations of flow test loops and facilities were considered by the Flow Test Facility working group to support and enhance HFIR operations and research capabilities. The options considered include:

- Flow testing of core components and multi-component configurations
- Full-length partial fuel element flow testing at normal operating flow and pressure
- Full-scale fuel element flow testing at partial flow and pressure
- Full-scale fuel element flow testing at normal operating flow and pressure
- Flow testing of a full-scale HFIR mockup facility

The full-scale HFIR mockup facility was not pursued because of the low cost-to-benefit ratio. This type of facility would provide more accurate measurements than a smaller scale facility, but it would be orders of magnitude more expensive to build and maintain. Historically, a mock-up facility for HFIR existed, but over time it was mined for parts. It is expected that a new full-scale facility would suffer a similar fate, making its maintenance and operation more difficult while decreasing its available operation time. This type of facility would also be limited in its applicability because it would not be easily reconfigurable for different applications. For these reasons, this option was not pursued by the working group.

Of the remaining options, the working group established that these could be covered by two separate flow test facilities: one for small-scale, high-pressure / high-flow testing of partial fuel elements and plant components in a clean loop, and one for full-scale testing for fuel elements in a separate, dedicated loop. These two facilities are discussed in detail above.

5.2 OTHER FLOW TEST FACILITIES

As part of its efforts, the working group made brief comparisons with similar facilities, or facilities that used similar equipment were investigated: the Advanced Test Reactor (ATR) and the Hydro-Mechanical Fuel Test Facility (HMFTF) at Oregon State University (OSU) [Oregon State University 2022], which was built as part of the Material Management and Minimization (M3) program within the DOE National Nuclear Security Administration (NNSA).

Information regarding the ATR at Idaho National Laboratory (INL), including the pump systems that cool the ATR, is discussed below and in Appendix A. The ATR upgrade of the primary coolant pumps is part of the scheduled core internal change-out (CIC) process. The ATR CIC process is conducted approximately every 10 years [Schoonen 2022] to perform an overhaul of key internal components, including replacement of the beryllium reflectors. During the CIC, the primary coolant pumps and associated motors, gaskets, bearings, and seals are serviced.

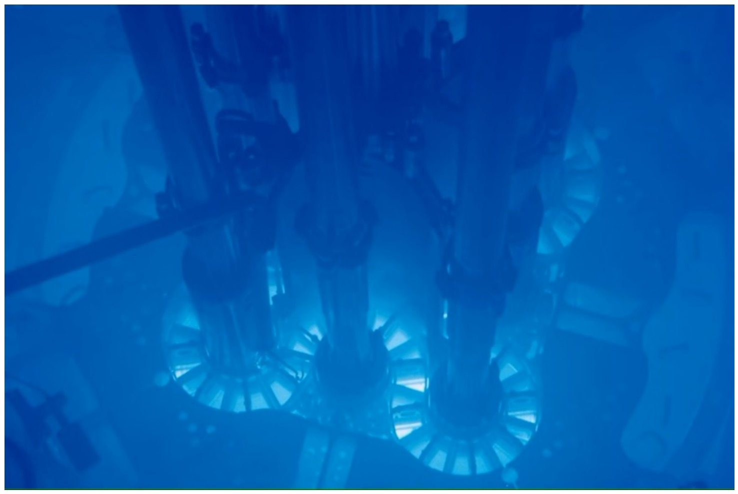

Figure 2. Advanced Test Reactor at INL [ATR n.d.].

The ATR can provide useful supporting information to guide creation of a new medium- or full-scale flow test facility for HFIR purposes. The ATR is similar to HFIR, with a few differences. The main reactor features are shown in Table 1. The information collected in this section should be viewed as a simple repository that provides reasonable background information for maintenance upkeep, possible design features to build from, and implementation of the maintenance needed to sustain a research reactor flow test facility. The key finding from this analysis is that the maintenance and efforts of the ATR staff have allowed the pumps and motors to remain in service for 25 years.

Table 2. ATR and HFIR comparison

	ATR	HFIR
Design power level	250 MW	100 MW
Nominal operating power	120 MW	85 MW
Inlet temperature	125°F	120°F
Operating inlet pressure	360 psi	468 psi
Core pressure drop	77 psi	110 psi
Flow rate *peak 3 pump flow rate	49,000 gpm*	16,000 gpm
Number of experiment locations	77	~59
Thermal / fast neutron flux	$1{\times}10^{15}$ (nts/cm^2/s) / 5×10^{14} (nts/cm^2/s)	2.3×10^{15} (nts/cm^2/s) / 2×10^{15} (nts/cm^2/s)
Typical cycle length effective full power days (EFPDs)	~60 EFPDs	22–26 EFPDs

The HMFTF at OSU can provide information to inform creation of a new medium- or full-scale flow facility for HFIR purposes. The mission of the M3 Reactor Conversion Program is to convert the remaining five USHPRRs and a critical facility from HEU to LEU. Four of the five reactors plus the critical facility will be converted to U-10Mo monolithic alloy fuel [Daum 2021], and the fifth reactor will be converting from HEU to LEU with U_3Si_2-Al dispersion fuel. The HMFTF supports the M3 program and mission by providing capability to flow test experiment assemblies before being inserted into various ATR irradiation experiment locations (i.e., flux traps) to gather Nuclear Quality Assurance Level 1 (NQA-1) flow rates. The list of reactors that will be impacted by the experiments carried out via the M3 conversion mission are:

1. The Massachusetts Institute of Technology Reactor (MITR) at Massachusetts Institute of Technology
2. The Missouri University Research Reactor (MURR) at the University of Missouri
3. The National Bureau of Standards Reactor (NBSR) at National Institute of Standards and Technology
4. The ATR and its associated critical facility, the ATR Critical Facility (ATRC), at INL
5. HFIR at ORNL

The flow rate measurements from HMFTF were used to corroborate flow rates for best-estimate as-run heat transfer models and safety analysis models created in RELAP-5/ABAQUS, Star-CCM+, and COMSOL [Jones et al. 2018]. The U-10Mo mini-plate (MP) and full-size plate (FSP) experiment campaigns benefited from the measured flow rates by providing valuable insights into improving the flow loss coefficients that are not simply implemented in a model or readily found in hydraulics handbooks or fluid flow textbooks such as the *Handbook of Hydraulic Resistance* [Idelchik 1966] or *Perry's Chemical Engineering Handbook* [Perry 1997]. The flow rates that are fed into the heat transfer prediction models and simulations were important pieces of information to be used to determine fuel performance, because temperature is one of the main drivers behind physical phenomena observed in fuel performance. The heat transfer information helped fuel performance subject matter experts to design experiments to learn more about the performance behavior of the U-10Mo monolithic fuel. Dozens of analysis documents and publications were written using the flow rates taken from the HMFTF. The HMFTF has proved to be useful as part of the overall qualification program to support the M3 program mission.

6. CONCLUSION

The Flow Test Facility Working Group discussed multiple options for upgrading resources for experimental and confirmatory testing at ORNL. The team discussed options ranging from a pump and motor upgrade at the existing WFL facility to a full-scale HFIR flow testing facility. Of these, the working group recommends that the WFL be upgraded per the high-flow option, which would replace both the pump and motor, as well as the piping, to ensure the greatest possible range of future experiments. This capability would support most of the expected testing needs to facilitate HFIR operations, and it would also allow for additional flow test experiments to support scientific needs at ORNL. In addition, the working group recommends that additional scoping be performed to develop detailed cost and schedule estimates for a HFIR fuel flow testing facility to be built and installed. This facility's location, oversight, and maintenance must also be addressed.

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APPENDIX A. ADDITIONAL ADVANCED TEST REACTOR SPECIFICATIONS

APPENDIX A. ADDITIONAL ADVANCED TEST REACTOR SPECIFICATIONS

Below summarizes the information gained from conversations with the ATR staff members David Schoonen, ATR management [Schoonen 2022], Travis Julius, ATR engineering staff [Julius 2022, and Robert Fossum, ATR Engineering Staff [Fossum 2022], the safety analysis report [INL 2015] and the ATR users guide [Campbell 2021]. The information from these sources informs the decision process for HFIR flow test facilities, describes possible maintenance processes and the dedicated work scope to be considered when creating a HFIR flow test facility and preserving this flow test facility in good working order.

Specifics to ATR cooling system, specifically the pumps, motors, and associated parts, are detailed below:

- Two- pump operation is the standard mode of operation for ATR with a few powered axial locator mechanism (PALM) cycles in which 3-pump operation is in effect.

- There are 4 redundant pumps, and the workload of cooling the ATR is evenly spread across all 4 pumps. The cycling of the pump operation is based on the number of days in operation.

- The pressure drop during 2-pump operation is 77 psi, with an inlet pressure of 360 psig.

- A single pump is rated as follows:
  - 18,000 gpm flow rate with a total dynamic head (TDH) of 400 feet
  - The pumps were originally purchased from a company named Bingham, which no longer exists
    - Bingham was part of the Sulzer company
    - More information about Sulzer [Sulzer 2022] can be found here: https://www.sulzer.com/en/about-us
    - Sulzer was reported to be responsive and provided some maintenance with a 6-month turnaround time for services. If the entire pump needed to be repaired outside of routine services, then Sulzer required a 1-year lead time
  - The motors associated with the ATR cooling pumps have the following features:
    - 2,000 hp
    - 4,165 V
    - Built by Westinghouse
    - The ATR staff looked for new motors but could not find any built as well and chose to refurbish the Sulzer motors with help from Schulz Electric [Schulz Electric 2022]
      - Schulz Electric is an NQA-1 company, and more information can be found here: https://schulzgroupusa.com/schulzelectric/index.htm
  - Refurbishing the motors required the following maintenance, and some key lessons were learned:
    - Replacement of mechanical seals and bearings and sleeve bearings
    - Roller bearings had issues and needed maintenance
    - Replacement of the rotor impeller
    - G-ring seals leaked and were worn and broken and specifically had to be replaced often
    - Motors needed to be electrically centered, which required moving the rotating elements; this was accomplished with a laser alignment of the pump
    - The issue with the uncentered motor was one reason that the seals and rings became degraded and wore out sooner than expected.
    - Electrically centering the motor reduced the maintenance frequency from bimonthly/monthly to inspections and maintenance during planned outages (note that ATR operates on a cycle of

approximately 60 days, so maintenance was reduced from by-weekly/monthly, and there was less pump cycling during operation

- It was noted that it was best to leave a pump on and running, and the cycling also affected upkeep and performance of the pump and motor

As noted above, the processes implemented by the ATR staff have resulted in the pumps lasting for 25 years of service before upgrades were addressed, and the ATR staff worked with Sulzer and Schulz Electric. A HFIR flow test facility based on a similar maintenance routine could effectively last for 25 years or more.