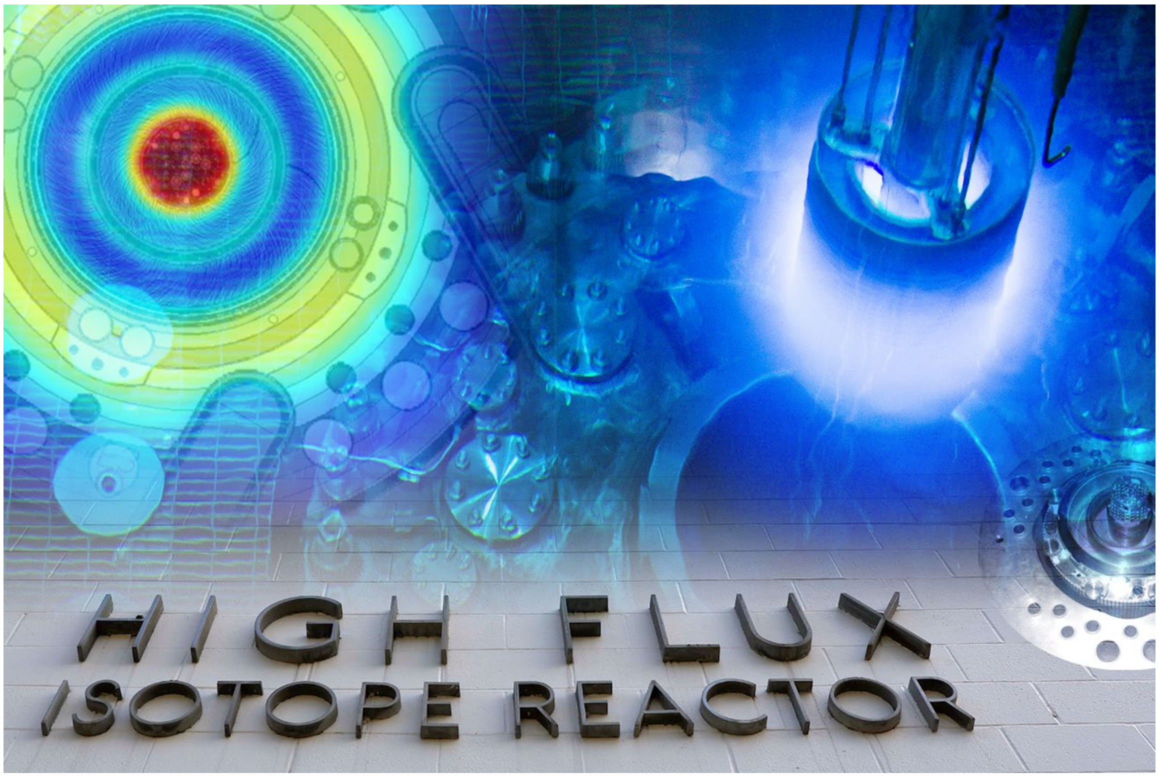
ORNL/TM-2022/2691/V1

Volume 1: Introduction

HFIR Futures – Enhanced Capabilities Series



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April 2023

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ORNL/TM-2022/2691/V1

INTRODUCTION TO THE HFIR FUTURES – ENHANCED CAPABILITIES SERIES

VOLUME 1 OF THE HFIR FUTURES – ENHANCED CAPABILITIES SERIES

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April 2023

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ABBREVIATIONS

BESAC	Basic Energy Sciences Advisory Committee Subcommittee
CE	control element
CRAP	control rod access plug
DOE	US Department of Energy
EF	engineering [slant tube] facility
FTT	flux trap target
GIF	Gamma Irradiation Facility
HALEU	high-assay low-enriched uranium
HB	horizontal beam
HEU	highly enriched uranium
HFIR	High Flux Isotope Reactor
HFIR-SCIENCE	[HFIR] - Scientific Excellence through Neutron Capabilities Enhancement
HFIR-SENSe	[HFIR] - Sustaining and Enhancing Neutron Science) Initiative
ID	inner diameter
IFE	inner fuel element
ILL	Institut Laue-Langevin
LDRD	Laboratory Directed Research & Development
LEU	low-enriched uranium
LWR	light-water reactor
M&S	modeling and simulation
MIF	Materials Irradiation Facility
NAA	neutron activation analysis
NNSA	National Nuclear Security Administration
OD	outer diameter
OFE	outer fuel element
ORNL	Oak Ridge National Laboratory
PB	permanent beryllium
PROSPECT	Precision Reactor Oscillation and Spectrum Experiment
PT	pneumatic tube
RB	removable beryllium
RPV	reactor pressure vessel
SC	Office of Science
SPB	semi-permanent beryllium
USHPRR	US high-performance research reactor
VXF	vertical experiment facility

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ABSTRACT

Since it began operating at full power in 1966, the High Flux Isotope Reactor (HFIR) has contributed unparalleled neutron science capabilities to research on neutron scattering, isotope production, materials and fuels irradiation, and neutron activation analysis. HFIR is a high-performance, multi-mission research reactor operated on behalf of the US Department of Energy (DOE) at the Oak Ridge National Laboratory (ORNL). In 2020, a DOE Basic Energy Sciences Advisory Committee Subcommittee (BESAC) published a report recommending that DOE make significant investments in HFIR to enable continued operations beyond the year 2100 while also enabling new research and isotope production capabilities. ORNL organized an initiative to investigate how to specifically address the report's key recommendations, including enabling long-term operation, brainstorming future scientific research needs, and outlining the infrastructure required to realize these future research capabilities. A multivolume series of reports has been developed to document the nonscattering enhancements. This volume, the introductory report, provides an overview of HFIR and the initiative.

1. INTRODUCTION TO HFIR FUTURES – ENHANCED CAPABILITIES SERIES

The High Flux Isotope Reactor (HFIR) Futures – Enhanced Capabilities series is a 13-volume set of reports describing nonscattering scientific capability enhancements developed by 12 Oak Ridge National Laboratory (ORNL) working groups (Volumes 2–13). Neutron scattering enhancements will be addressed in a separate report series or a single comprehensive report. The Enhanced Capabilities Series is introduced by this document, Volume 1. For reference, the volumes in this series are listed in Table 1.

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
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

This report is the HFIR-Scientific Excellence through Neutron Capabilities Enhancement (SCIENCE) Volume 1 report that provides an overview of HFIR, the HFIR-Sustaining and Enhancing Neutron Science (SENSe) initiative, and the HFIR-SCIENCE LDRD. It establishes a baseline understanding of HFIR, the scope of work that was performed from 2020–2022, and some overarching concepts that provide context to the subsequent volumes.

2. BESAC REPORT SUMMARY

HFIR provides neutron capabilities in support of the US Department of Energy (DOE) missions in science, energy, environment, and national security. As HFIR enters its sixth decade of operations, its long-term future requires careful thought and planning. Therefore, the US DOE Office of Science (SC) chartered a Basic Energy Sciences Advisory Committee (BESAC) subcommittee review to assess the scientific justification for a domestic high-performance reactor–based research facility and to provide specific recommendations on the long-term strategy concerning HFIR (BESAC 2020). The subcommittee was composed of 20 highly qualified members with technical expertise in applicable neutron science areas. The charge to the subcommittee, which was written in March of 2019, included the following questions:

1. What is the merit and significance of the science that could be addressed by a high-performance, steady-state reactor, and what is its importance in the overall context of materials sciences and related disciplines?

2. What are the capabilities of other domestic and international facilities, existing and planned, to address the science opportunities afforded by such a domestic research reactor?
3. What are the benefits to other fields of science and technology and to industry of establishing such a capability in the United States? In particular, consider applications such as isotope production, materials irradiation, neutron imaging, dark matter research, and neutron activation for trace element analysis.
4. What are the strengths and limitations of a steady-state research reactor compared to those of a pulsed spallation neutron source for science, engineering, and technology? What functions currently performed by research reactors can be assumed by spallation neutron sources?
5. Are there feasible upgrade paths for HFIR to provide world-leading capabilities in serving the Office of Science missions well into the future? What can we learn from the experience at the Institut Laue-Langevin (ILL)?
6. Can low-enriched uranium (LEU) and high assay LEU (HALEU) fuels (defined as <20% enriched ^{235}U) replace highly enriched uranium fuels in research reactors while preserving the needed characteristics of neutrons produced by steady-state reactors? What R&D would be needed to support LEU and HALEU fuels development?

The BESAC report (BESAC 2020) thoroughly answers the questions listed above and provides specific recommendations for HFIR. Additionally, it provides a detailed overview of the science that can be performed at a powerful neutron source, and it also provides a comprehensive justification for a domestic high-performance reactor–based research facility. The scientific case section of the report is organized into subsections that address neutron scattering, industrial applications of neutron scattering, fundamental physics at reactors and spallation sources, isotope production, and materials irradiation. Furthermore, informative sections detail the program to convert highly enriched uranium (HEU) to low enriched uranium (LEU), major US neutron facilities, and international neutron facilities.

The committee recognized HFIR as a unique and critical resource with world-leading capabilities; but they also identified several prospective problems that threaten HFIR's continued availability, as summarized below:

1. Decades of radiation bombardment on the reactor pressure vessel (RPV) is causing embrittlement of the steel, so the RPV must be replaced within the next two to three decades, or else HFIR must eventually be shut down.
2. The United States and other nations are committed by treaty to stop using HEU fuel as an international security measure. Because conversion to LEU will involve significant changes to HFIR, the committee recommends that the conversion be combined with RPV replacement if possible.

Additionally, the demand for access to beamlines is between 3 and 7 times greater than can be accommodated, depending on the instrument, so high-impact research could be delayed or may not be performed at all. Furthermore, the demand is high to produce crucial radioisotopes such as those needed for national security. The committee recommends that more beamlines/experiment stations and enhanced isotope production capacity/capabilities be added during the RPV replacement shutdown to enable a significant expansion of neutron science-based research.

Based on their review, the subcommittee provided the following three recommendations:

1. Operate HFIR as-is, converting to LEU per the program schedule.
2. Replace the lifetime limiting RPV, and if possible, coordinate replacement with the conversion to LEU fuel to minimize shutdown time. Concurrently enhance capabilities for in-core irradiation and neutron scattering research.

3. Perform a scoping design study for a green field LEU-fueled reactor optimized to perform neutron scattering and isotope production.

The first option was considered least acceptable by the subcommittee and was considered because if adopted, HFIR and US DOE SC would fall far short of meeting the needs of the neutron science community. Option 1 also presents an unacceptable risk that HFIR would be shut down earlier than expected, resulting in the termination of current and future crucial neutron science-based research being performed.

The subcommittee recommended that the second option be pursued immediately and that the third option be pursued in parallel. A new research reactor would likely take several decades to design, approve, construct, and commission, so it would be prudent to begin the process now. Designing an innovative, very high flux research reactor with optimized performance to current and future neutron science needs while simultaneously optimizing the fuel design and manufacturability would allow time to evaluate options and proceed with future planning and approvals to ensure future availability of high flux research in the United States.

The review determined that HFIR will have a critical role in the future of US neutron science research, the second option is recommended, which includes the following recommendations:

1. Replace the RPV to prevent a premature and possibly an unexpected long-term or permanent shutdown and redesign the RPV to enable enhanced science capabilities.
2. Convert to LEU fuel, and if possible, coordinate the conversion and the RPV replacement so that a single shutdown would accomplish both RPV replacement and LEU conversion.
3. Enhance in-core irradiation capacity and capabilities, such as improved access for isotope production and materials irradiation experiments.
4. Enhance beamline capacity and capabilities, such as including additional instruments like a second guide hall, larger beam tubes, an improved cold source, advanced instrumentation, and reduced background.
5. Modify the fuel assembly to make it more manufacturable and less expensive.
6. Combine RPV replacement and LEU conversion to allow for a power increase to restore the flux intensity of the original 100 MW HEU operations.

3. HFIR SUSTAINING AND ENHANCING NEUTRON SCIENCE (HFIR-SENSE)

In response to the BESAC report, ORNL established a lab-directed, funded initiative comprising multiple individual internally funded research projects. The ORNL initiative, called *HFIR-SENSe*, included four LDRD projects: (1) integration, (2) Critical Reactor Improvements Towards Increased and Continued Advanced Lifetime (CRITICAL), (3) SCIENCE, and (4) Neutron Scattering Enhancements. This document series covers LDRD initiative 3, HFIR-SCIENCE.

The primary focus of the entire initiative was to assess the potential for replacement of the HFIR pressure vessel while enabling simultaneous and future scientific enhancements for neutron scattering and nonscattering missions. The RPV is HFIR's life-limiting component, and because of its increasing radiation damage with age, it is prudent to plan for its replacement. RPV replacement includes removal and disposal of the current vessel, as well as installation of a new pressure vessel, piping flanges, and other internal components. RPV replacement also presents a unique opportunity to redesign the new vessel using material less susceptible to radiation embrittlement, such as stainless or low-alloy steel, to (1) enable future increased power and pressure operations, (2) improve access to experiment facilities, and (3) develop new and enhanced scientific capabilities. Current planning activities indicate that RPV replacement could be implemented as soon as 2037. Additionally, several infrastructure-related enhancements have been identified and are being investigated by other working groups:

1. Permanent beryllium reflector lifetime extension
2. Pressure vessel specification and pre-conceptual design
3. Vessel head preconceptual design
4. Underground assessment for new buildings and beam tube tunnel
5. Reflector preconceptual design
6. Evaluation of possibility to direct horizontal beam (HB)-2 slightly southwest
7. Redesign of experiment room and planning
8. Development of a plan for seismic upgrades and compliance
9. Updated safety basis
10. Improved cost estimates for internal assemblies
11. Waste disposal paths and planning for disposal of vessel and other components
12. Fire protection system upgrades

This infrastructure work will be documented in a separate report series or single comprehensive report.

3.1 SCIENTIFIC EXCELLENCE THROUGH NEUTRON CAPABILITIES ENHANCEMENT (SCIENCE) LDRD

The HFIR-SCIENCE LDRD includes analysis of the short- and long-term future of nonscattering scientific capabilities at HFIR. This “blue-sky” engagement with researchers across ORNL has yielded incremental improvement ideas, as well as transformational new capabilities in the form of 35 enhancement concepts presented by these leading scientists and engineers. Another goal is to develop these concepts sufficiently to identify specific features in the HFIR core, vessel, head, pool, and building that should be engineered and incorporated into an RPV replacement outage. Selected concept reactor physics studies were documented in the paper by Chandler and Bryan (Chandler 2022). The 35 concepts were grouped into 12 separate working groups, with the goal of each group being to develop the concepts, build scientific justifications, identify potential facility sponsors, and estimate costs and schedules for each concept group. The following describes volumes 2–13.

3.1.1 Volume 2: Hot Cells Connected to the Reactor Pool

The prospect of adding remotely operated hot cell capabilities inside the HFIR building elicited interest from multiple programs related to isotope production, materials, and fuels irradiation testing, as well as forensics and physics. A working group of fourteen ORNL staff members representing these research areas was organized to further develop concepts, capabilities, and configurations to recommend one configuration.

3.1.2 Volume 3: Online Insertion and Removal Facilities

Since 1966, HFIR has enabled remarkable materials science research and radioisotope production with its world-leading neutron flux. For most of that time, the reactor included a unique, hydraulically driven facility for inserting and removing irradiation capsules at will during operation. With significant growth in radioisotopes for medicine and industry, as well as a growing number of materials science initiatives, the need to add facilities for online insertion and removal is well established. This working group conceptualized numerous ideas for systems that access different parts of the HFIR core through various methods.

3.1.3 Volume 4: Detection Systems and Ultra-Cold Neutrons

The idea of additional detection systems to support HFIR operations, as well as further scientific research, has prompted many concepts and discussions regarding potential features, configurations, locations, and applications. Multiple concepts were developed to address the established needs, along with potential locations and configurations to maximize the value of these new facilities.

3.1.4 Volume 5: Flexible Flux Trap Configurations

The flux trap is the central region in the reactor core, and it offers the highest sustained thermal and fast neutron flux in the Western Hemisphere. These neutrons have multiple uses, including materials damage testing, fuels testing, and isotope production. Since the reactor's inception, flux trap components and configurations have remained largely the same, with some small changes being implemented around the year 2000. Looking forward to the potential for 100 years of future HFIR operation, this working group considered alternative configurations to the current HFIR flux trap to enable irradiation research not possible in the current configuration.

3.1.5 Volume 6: Experiment Facility Spectrum Tailoring

HFIR has a unique mix of thermal and fast neutrons in the core's beryllium reflector region. Certain research missions require that very specific neutron energies be delivered to the subject samples, and in some cases, HFIR cannot meet this need in its current configuration. Several concepts were developed that could enhance irradiation experiment conditions by implementing specific neutron spectrum tailoring methodologies. Additionally, ion irradiation of materials is explored in this volume.

3.1.6 Volume 7: Cryogenic Facility

The addition of a cryogenic facility at HFIR would allow scientists to study the effects of radiation on samples maintained at cryogenic temperatures (e.g., 4 K) while being bombarded in a high neutron flux. Several challenges must be overcome to implement this capability without compromising the sample's integrity or the safety of workers in the laboratory. Several designs and configurations have been developed and described are that could bring such a capability to HFIR.

3.1.7 Volume 8: Epithermal and Fast Neutron Radiography Facility

The creation of an epithermal and fast neutron radiography station on the HB-3 would provide the capability to image highly radioactive specimens such as irradiated nuclear fuel rods, isotope production targets, or spallation neutron target materials. Caveats and cautions associated with this concept are explored, along with potential configurations to provide practical access while maintaining worker and reactor safety.

3.1.8 Volume 9: Critical Facility with Add-On Ion Beam

HFIR was designed with a critical pool in the reactor bay that was projected to be outfitted as a critical facility. The primary purpose of the critical facility would have been to measure subcritical worth of fresh fuel elements to support HFIR startup requirements. However, a critical facility existed at the Y-12 Nuclear Security Complex that was used for this purpose. High-impact scientific benefits are possible with the addition of an ORNL critical facility. A generic low-power critical facility could be used for reactor physics measurements, code and data validation, reactor operator and staff training, and education. This facility could be instrumental in supporting current HFIR operations, conversion of HFIR to LEU, existing light-water reactor (LWR) operations, and advanced reactor development and deployment.

3.1.9 Volume 10: Flow Test Facilities

Only one flow facility exists at ORNL that can support testing of HFIR experiment capsules, and no facilities exist to test larger HFIR components. The addition of facilities that could enable world-leading capabilities in the areas of reactor flow analysis could be valuable for many programs supporting LEU conversion, LWR license extensions, and unique experiments. Several configurations would support future HFIR operations and scientific capacities effectively and would also provide order-of-magnitude cost estimates and timing. These concepts include a full range of options, from upgrading existing small-scale testing facilities to building a full-scale HFIR mockup for detailed thermal-hydraulic testing and fuel assessment.

3.1.10 Volume 11: Modeling & Simulation

Modeling and simulation (M&S) plays a vital role in HFIR's safe, reliable, high-performance operation. M&S is routinely exercised to support the nuclear safety basis, support reactor startup and at-power operations, redesign and qualify core components and experiment facilities, design and analyze in-core irradiation experiments, and perform high-impact R&D aligned with ORNL's missions. A compendium of M&S enhancements capable of increasing the fidelity of methods to predict reactor performance, nuclear safety margins, and irradiation experiment conditions has been developed and is documented.

3.1.11 Volume 12: Flow Loop Facilities

Flow loops at HFIR can provide several advantages for experiments, including proving the ability to use unique and separate coolants for experiments, as well as potentially enabling isotope production in flowing liquid systems. Flow loops pose unique potential hazards to the facility and staff, so careful planning and configuration are key to developing robust, and useful systems.

3.1.12 Volume 13: Neutrino Facilities

Neutrino (and antineutrino) research is the most recent addition to HFIR's missions. With a compact HEU core and a very high power density, HFIR offers a unique point source for neutrino research. Because of these unique characteristics, HFIR has hosted several neutrino experiments in the past five years. However, this neutrino research could benefit from enhancements and additions to the existing facilities. These enhancements could open new potential scientific opportunities in fundamental physics research. Additionally, nonproliferation research has recently focused on neutrino detection as a possible method for treaty monitoring.

4. INTRODUCTION TO HFIR

HFIR is a high-performance, versatile, multi-mission research reactor operated at ORNL on behalf of DOE SC. With the highest steady-state neutron flux in the United States, this DOE user facility is critical for domestic and international neutron-based research, and it serves a broad range of science and technology communities. Fueled by HEU and operating at a steady-state power level of 85 MW thermal, HFIR typically operates for cycles that range between 23 and 26 days with a 2.5×10^{15} n/cm^2-s peak unperturbed thermal neutron flux and a 1.7 MW/liter average power density. Currently, HFIR operates 6–7 cycles per year: cycle number 501 is expected to commence in May of 2023.

HFIR's preliminary design report was submitted in 1959 and concluded that an annular, HEU-fueled flux trap-type reactor consisting of light-water coolant and a large beryllium reflector would produce a very high neutron flux capable of producing substantial, weighable quantities of heavy elements (e.g., Bk, Cf). Production of these elements was HFIR's original primary mission (Chandler 2021). Construction was initiated in 1961, and criticality was achieved just a few years later on August 25, 1965. Following a series of low-power tests, HFIR was brought to its 100% design power of 100 MW thermal in September of 1966.

HFIR operated at 100 MW with a vessel inlet pressure of 4.58 Mpa (650 psig) until 1977, when it was increased to 5.27 Mpa (750 psig) following a reevaluation of the safety setpoints. In 1989, following a 2.5 year outage caused by RPV embrittlement concerns, HFIR was derated to 85 MW, and the vessel inlet pressure was reduced to 3.33 Mpa (468 psig). HFIR currently operates at a power of 85 MW with an inlet coolant temperature of 48.89 °C (120 °F) and a pressure of 3.33 Mpa. Refer to the article by Chandler and Bryan (Chandler 2021) for more details regarding HFIR's operating history, reactor design, operating conditions, nuclear physics, and experiment capabilities and highlights.

Although HFIR's mission portfolio has evolved over the years, and its current primary mission is neutron scattering research, it retains its unique original mission/capability to produce heavy isotopes. HFIR's intense steady-state neutron flux, consistent cycle lengths, and state-of-the-art facilities enable world-class capabilities and missions spanning cold and thermal neutron scattering, radioisotope production, materials and fuels irradiation science, neutron activation analysis (NAA), nonproliferation research, and nuclear physics research. HFIR's multi-mission capabilities are attributed to its high-power density core design consisting of a series of concentric regions, each ~61 cm in height, including a flux trap target (FTT), an inner fuel element (IFE), an outer fuel element (OFE), a control element (CE) region, and a large beryllium reflector. Figure 1 provides a core mockup with descriptions.

HFIR offers unique and versatile facilities that enable world-class research, including:

- Four HB (HB) tubes penetrating the beryllium reflector and terminating in cold and thermal guide halls equipped with state-of-the-art neutron scattering instruments;
- In-core irradiation facilities in the FTT and beryllium reflector for isotope production, materials irradiation, and fuels irradiation;
- A NAA laboratory with cutting-edge detection equipment and two pneumatic tube systems connected the core;
- A Gamma Irradiation Facility (GIF) in the spent fuel pool, where spent fuel elements are used as gamma sources for gamma irradiation research; and
- Locations in the HFIR building suitable for neutrino and other types of detectors for instrumentation, detection, and fundamental physics research.

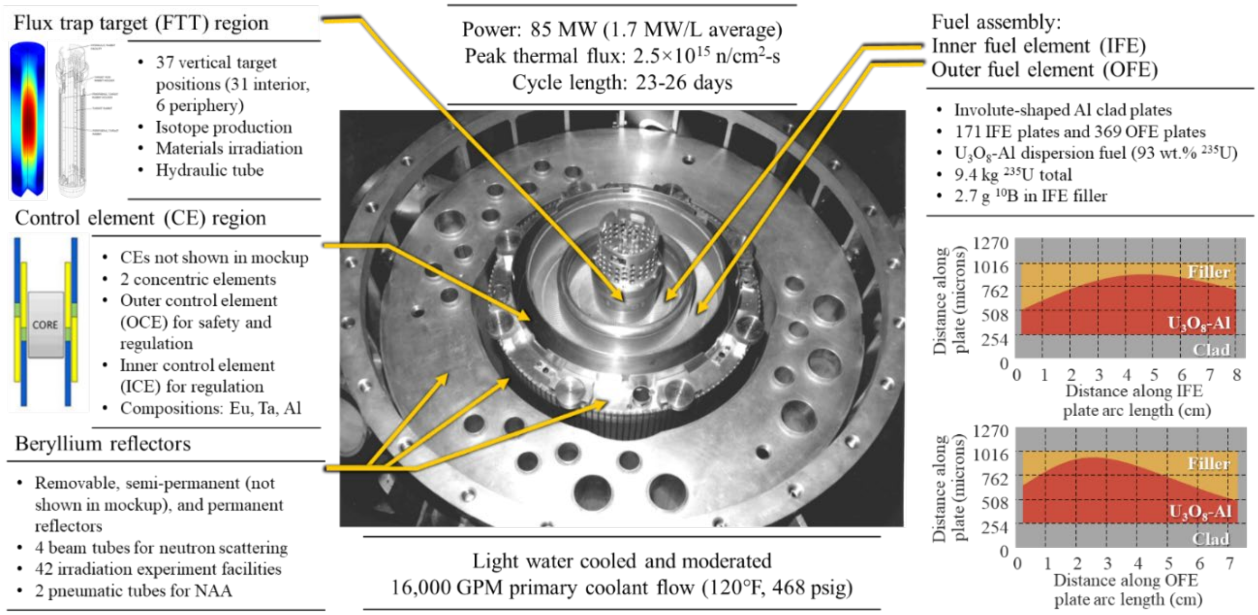

Figure 1. HFIR core mockup and description (Chandler 2022).

4.1 REACTOR DESIGN OVERVIEW

HFIR is a pressurized, light-water–cooled, light-water–moderated reactor; however, it significantly differs in design, operation, and mission from a typical commercial LWR. Commercial LWRs are much larger, operate at higher temperatures and pressures, and have the sole mission to generate electricity. In comparison, HFIR was designed to have a compact, high power density core to promote neutron leakage into experiment regions, thus enabling unparalleled neutron science–based research capabilities. Additionally, the high coolant velocity and large fuel plate heat transfer area result in low temperature operations, which in turn supports safe, reliable, efficient operations. Brief summaries of the primary core regions, progressing from innermost to outermost radial regions, are provided below. For more details on HFIR design and experiment facilities, refer to the article by Chandler and Bryan (Chandler 2021), the modeling and simulation paper by Chandler et al. (Chandler 2020b), the HFIR User Guide (ORNL 2015), and the other HFIR-SCIENCE volumes.

4.1.1 Flux Trap

HFIR was designed with a central, over-moderated FTT region (~12.9 cm outer diameter [OD]) surrounded by fuel elements because this geometry produces a very high thermal neutron flux in the FTT for heavy isotope production. Fission-born neutrons leaking from the fuel into the flux trap slow down as a result of interactions with the water moderator. Therefore, the highest accessible fast neutron fluxes are near the periphery of the FTT, and the highest thermal neutron fluxes are near the centerline of the FTT.

A basket-type assembly design provides 37 target positions, including 31 inside the basket, and six around the periphery (referred to as *peripheral target positions)*. This basket assembly is nested inside of the IFE. Figure 2 illustrates the in-core irradiation facility layout in the flux trap as well as in the removable reflector, the control rod access plugs (CRAPs), and the permanent beryllium reflector. The target tubes loaded in the peripheral target positions are routinely loaded with small capsules (also referred to as *rabbits*) containing materials irradiation specimens that require high fast neutron fluxes. The interior positions consist of a hydraulic tube in position B3, as well as 30 target tubes. Such as target rod rabbit holders. Target tubes typically bear materials for isotope production or materials irradiation. The hydraulic tube provides a means for small rabbits to be shuttled into and out of the core on demand. This also makes it possible to implement irradiations for less than a full cycle, which is ideal for short-lived radioisotope production.

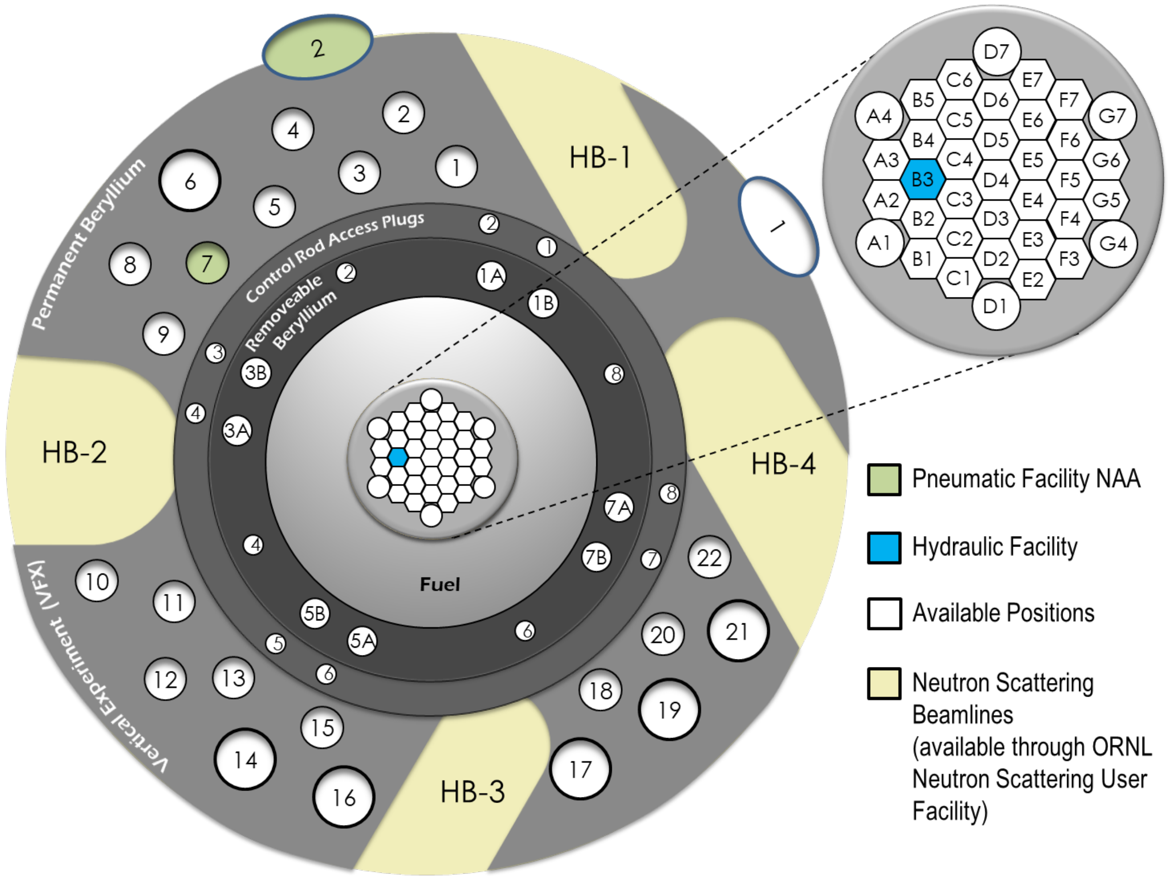

Figure 2. HFIR in-core irradiation facility layout (ORNL 2022).

4.1.2 Fuel Elements

The HFIR fuel assembly (~43.5 cm OD) consists of an integral two-element configuration in which the IFE is nested within the OFE. The IFE and OFE contain 171 and 369 involute-shaped fuel plates, respectively, and each Al-clad plate contains a filler and fuel section. The fuel section consists of HEU U_3O_8 fuel dispersed in an Al matrix. The fuel is enriched to ~93 wt.% ^{235}U, and approximately 2.6 and 6.8 kg of ^{235}U are loaded into the IFE and OFE, respectively. Thus, the total core loading is approximately 9.4 kg ^{235}U and 10.1 kg U. The fuel is contoured along the arc of the involute plate to flatten the radial power distribution. The filler section is Al, but the IFE filler section contains ^{10}B burnable poison in the form of B_4C homogeneously dispersed in Al for reactivity control and edge power suppression purposes.

The fuel plates are inserted into slots machined into cylindrical side plates and are attached via circumferential welds at every inch down the element. The fuel plates are 60.96 cm in length and have 50.80 cm long fueled regions. Each fuel plate and adjacent water coolant channel is 1.27 mm thick, so the core water–to–metal ratio is one-to-one. The IFE and OFE are separated by a water-filled labyrinth region for heat removal purposes. The nominal inlet coolant temperature and pressure are approximately 48.89 °C and 3.33 Mpa, respectively. Approximately 0.820 m^3/s of the total 1.009 m^3/s coolant flow passes through the fuel assembly and flux trap, where a ΔT of ~20 °C and a ΔP 0.69 Mpa are nominally maintained.

4.1.3 Control Elements

Two concentric CEs are located in the small water annulus (~47.9 cm OD) between the fuel assembly and the beryllium reflector. The inner CE consists of four control plates welded together that are used for reactivity control and power regulation. The outer CE consists of four independent safety/control plates that are used for reactivity control, power regulation, and fast scram purposes. Each of the eight Al-clad plates contain Al (transparent to neutrons), Ta-Al (moderate absorber), and Eu_2O_3-Al (strong absorber) longitudinal regions. When the reactor is shutdown, the Eu_2O_3-Al regions are adjacent to the fuel elements to maintain subcriticality. The CEs are axially withdrawn in opposite directions during the operating cycle by moving the absorber regions away from the core horizontal midplane to compensate for reactivity changes caused by fuel depletion, burnable poison depletion, and fission product generation. The inner CEs are driven downward, and the outer CEs are driven upward during the cycle.

4.1.4 Beryllium Reflector

The beryllium reflector (~1.09 m OD) serves multiple functions, including moderating and reflecting neutrons for increased core reactivity, housing in-vessel experiment facilities and HB tubes, and moderating neutrons for enhanced irradiation and neutron scattering experiments. The large ring of beryllium is subdivided into the removable beryllium (RB), semi-permanent beryllium (SPB), and permanent beryllium (PB) reflectors. The RB, which is closest to the core and adjacent to the CE region, houses eight large and four small irradiation facilities. The SPB, located between the RB and PB, is composed of four quadrants separated by CRAPs that are each outfitted with two small irradiation facilities (eight in total).

The PB is the largest of the three regions, housing 22 vertical experiment facilities (VXFs)—11 inner small, 5 outer small, and 6 outer large—for irradiation experiments, and four HB tubes for neutron scattering experiments. HB-1, -2, and -3 are thermal beamlines, and HB-4 contains a moderator vessel with liquid hydrogen used to produce a high-brightness source of cold neutrons. Cold and thermal neutrons travel down the beam tubes to instruments at the ends of the beamlines in the cold guide hall and thermal beam room, respectively. These neutrons are used for neutron scattering research. Additionally, two engineering slant tube facilities (EFs) graze the outer radial edge of the reflector. Two pneumatic tubes—one in the inner small VXF-7, and one in EF-2—are used to shuttle small rabbits in and out of the reactor for NAA.

4.1.5 Pressure Vessel

The core is radially and axially reflected by light water and is contained in the RPV (~2.55 m OD), which is located in a pool of water. The RPV (Figure 3) consists of an upper head, a vessel cylinder (i.e., shell), a lower vessel extension, and a flat lower head. The vessel's upper head and cylinder are carbon steel clad with stainless steel, whereas the lower extension and bottom head are stainless steel. The upper head includes a quick-opening hatch which is routinely accessed for experiment and core component changes. The vessel cylinder has many penetrations, such as those required for coolant inlet/outlet lines, HB tubes, safety/servo ion chamber thimbles, and engineering slant tube facilities. The CE drives penetrate through the bottom head and into the sub-pile room. The RPV is bolted to vessel support pedestals that are in turn bolted to the concrete floor of the pool.

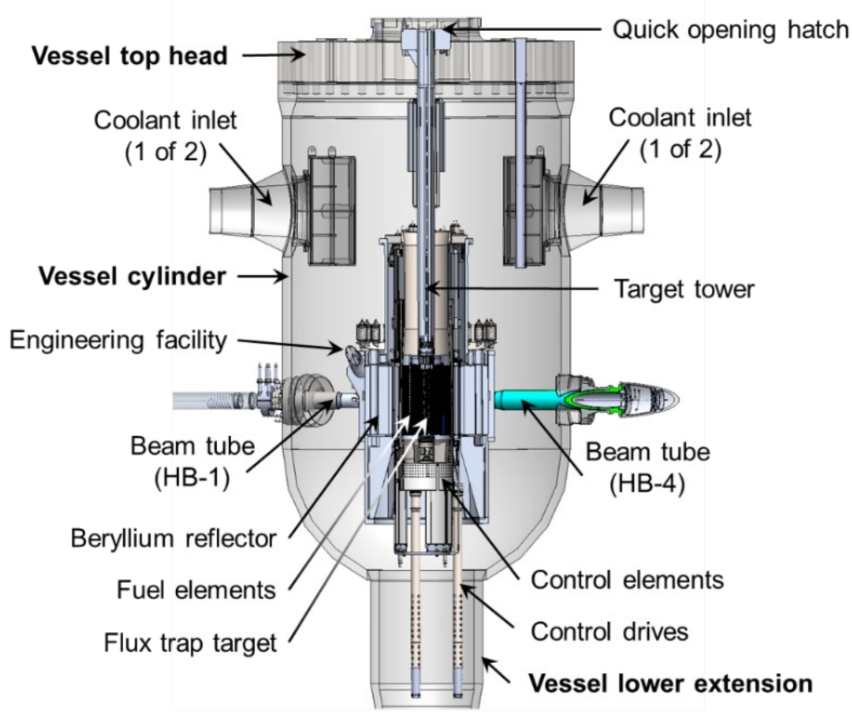

Figure 3. HFIR reactor pressure vessel.

4.1.6 Summary of In-Core Irradiation Facilities

A summary of the in-core irradiation facilities is provided below:

- Flux trap target region (37 total target positions):
  - 30 interior target positions
    - Typical Al target rod rabbit holder tube (inner diameter [ID] ~1.42 cm)
    - Target rod rabbit holder containing up to 8 irradiation capsules
  - 1 hydraulic tube in an interior position (can be replaced with a typical target rod)
    - Hydraulic tube containing up to 8 irradiation capsules
  - 6 peripheral target positions
    - Typical Al peripheral target tube, ID ~1.31 cm
    - Peripheral target tube containing up to 7 irradiation capsules
  - Generic capsules loaded into target rod rabbit holders, hydraulic tube, and peripheral target positions, ~1.10 cm OD, 6.67 cm long
  - ^{252}Cf production targets consist of Al-shrouded target tubes containing a stack of actinide-oxide dispersed in Al pellets (e.g., CmO_x/Al)
- Removable beryllium reflector region (12 total RB facilities):
  - 4 small unlined RB irradiation facilities (~1.27 cm OD)
  - 8 large Al lined RB irradiation facilities (~4.66 cm liner ID])
    - Large RB facilities, instrumented or noninstrumented
- Control rod access plugs (8 total CRAP facilities):
  - 8 small unlined CRAP irradiation facilities (~1.27 cm OD)
- Permanent beryllium reflector (22 total VXF positions):
  - 11 inner small Al-lined VXFs (~4.02 cm liner ID)
    - Concept reflector No. 5 designed with 15 inner small VXFs (Chandler 2019b)
  - 5 outer small Al-lined VXFs (~4.02 cm liner ID)
    - Concept reflector No. 5 designed with 3 outer small VXFs
  - 6 outer large Al lined VXFs (~7.20 cm liner ID)

        - Concept reflector No. 5 designed with 10 outer large VXFs
- Neutron activation analysis facilities:
    - Pneumatic tube (PT)-1 in inner small VXF-7
    - PT-2 in engineering slant facility number 2

4.2 SUMMARY OF HFIR MISSIONS

As mentioned above, HFIR is a multi-mission reactor that is critical for domestic and international neutron science-based research and serves a broad range of science and technology communities. The mission of the ORNL Research Reactors Division within the Neutron Sciences Directorate (NScD) is to provide safe, reliable, and efficient HFIR operation to support the neutron science mission. NScD works to answer big science questions about the fundamental nature of materials at the atomic scale (ORNL 2022).

In addition to research on the structure and dynamics of matter (i.e., neutron scattering), HFIR is used for isotope production, research on neutron damage to materials, fuels irradiation research, and NAA. Furthermore, HFIR provides the ability to perform gamma irradiation research with spent fuel elements and other physics-related research, such as neutrino and nonproliferation research. HFIR's primary missions are summarized in Figure 4 and are briefly described in the following subsections. For more details on HFIR's missions, refer to the article by Chandler and Bryan (Chandler 2021), the BESAC report (BESAC 2020), the NScD website (ORNL 2022), and the other HFIR-SCIENCE volumes.

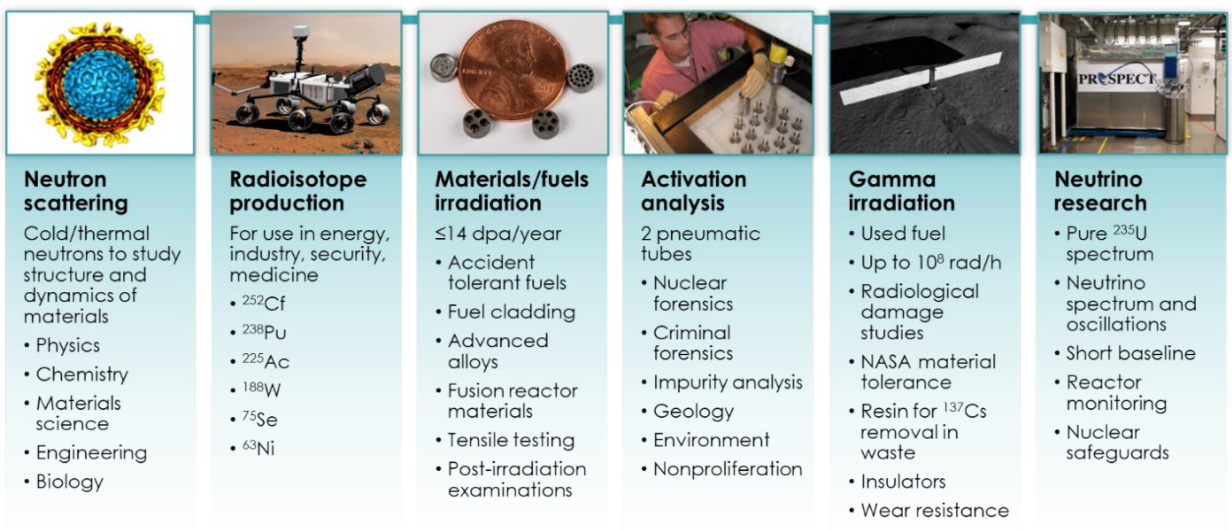

Figure 4. Summary of HFIR's neutron science capabilities.

4.2.1 Neutron Scattering

Low-energy neutrons are transported through the HB tubes from the core to instrument stations for the purpose of neutron scattering, which is HFIR's primary mission. Cold and thermal neutrons are used to study quantum materials, soft matter and polymers, physics, chemistry, materials science, engineering, biological materials and systems, environmental science, and other research areas. HB-1, -3, and -4 are tangential to the core, whereas HB-2, the largest of the four HB tubes, is "straight on" to the core (Figure 2). A powerful cold source moderator vessel located in HB-4 contains supercritical hydrogen that is nominally maintained at 17 K for the purpose of generating cold neutrons. Figure 5 provides a layout of the operating instruments in the user program and the operating development beamlines, along with descriptions of the instruments and capabilities. For additional information, refer to the referenced websites.

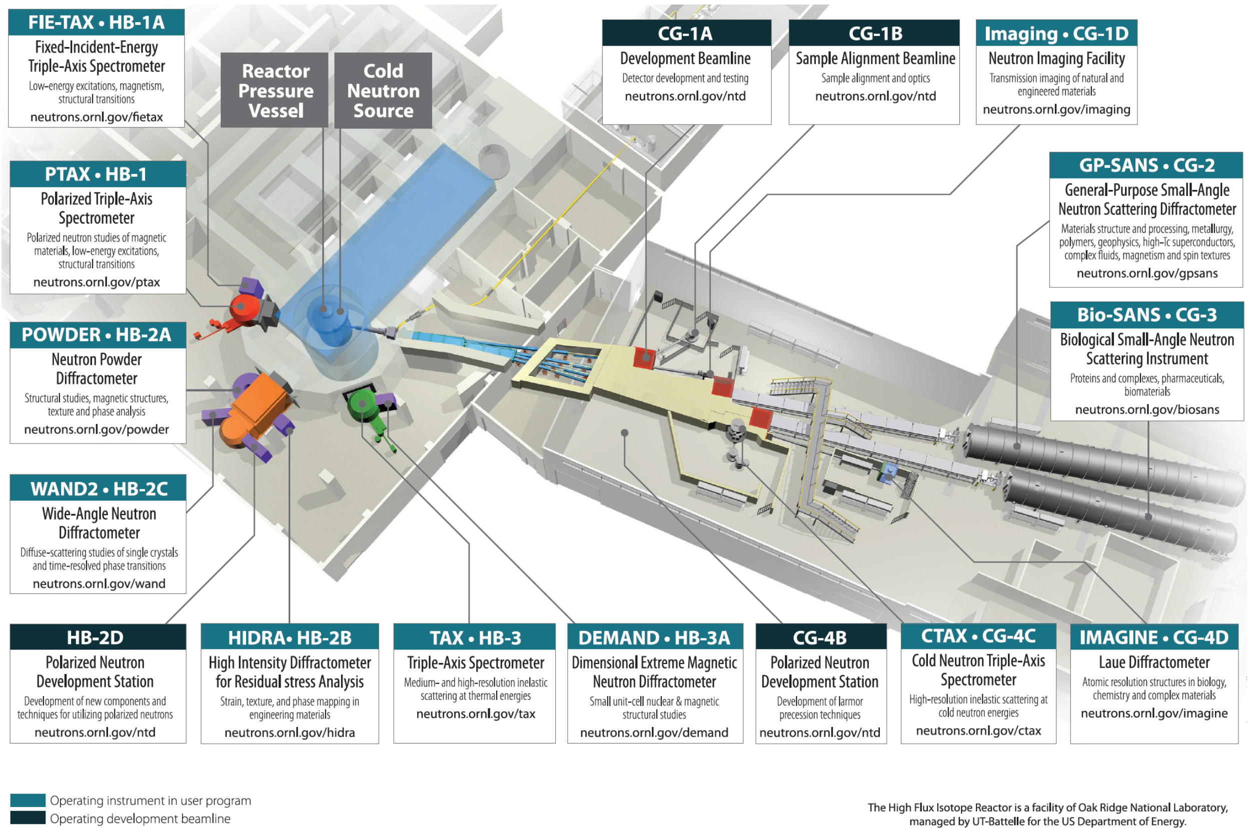

Figure 5. HFIR neutron scattering instrument layout (ORNL 2022).

4.2.2 Isotope Production

Radioisotopes are routinely produced in HFIR's FTT and reflector for energy, medical, industrial, security, and research purposes. HFIR's original primary mission was heavy isotope production, and today, ^{244}Cm, ^{248}Cm, ^{249}Bk, ^{249}Cf, ^{252}Cf, and ^{254}Es isotopes are the most commonly produced heavy isotopes at HFIR. The ^{252}Cf isotope is used for a variety of unique purposes, such as determining fuel enrichment, serving as a reactor startup source, inspecting shipping containers, as a source in material analyzers and well-logging, and for educating university students. The ^{238}Pu isotope is used in the form of the heat source PuO_2 to power radioisotope power systems for NASA's deep-space and planetary missions. The ^{63}Ni isotope is used for national security applications, the ^{75}Se isotope is used for commercial and industrial gamma radiography, and the ^{133}Ba isotope is used monitor oil, gas, and water flow data in the oil and gas industry. A select set of medical isotopes produced at HFIR for treating conditions like cancer, arthritis, bone metastases, and restenosis include ^{14}C, ^{89}Sr, ^{166}Ho, ^{177}Lu, ^{188}W, ^{227}Ac, and ^{229}Th (Chandler 2021).

4.2.3 Materials/Fuels Irradiation Research

The irradiation facilities in the flux trap and reflector are also used to study the impact of neutron irradiation and damage to materials. Materials irradiation research provides insights on key radiation effect phenomena such as radiation hardening and embrittlement, phase instabilities and radiation-induced precipitation, and irradiation creep and growth. Materials research is performed to support life extensions of the current fleet of fission-based reactors and to evaluate materials being proposed for use in future fission-based reactors such as advanced reactors. Research on proposed fusion-based reactor materials (e.g., first wall, structural) is also performed to characterize their irradiation behavior in a reasonable timeframe. Fuels irradiation has also become an important HFIR mission and can be performed to support the design, understanding, and qualification of accident-tolerant fuel/cladding and advanced reactor development efforts. Additionally, the Materials Irradiation Facility (MIF) at HFIR allows experimenters to actively monitor and control the temperatures inside experiment capsules during irradiation via piping and electrical lines running from the MIF room adjacent to the reactor pool, through the vessel head, and down into the core and experiment.

4.2.4 Neutron Activation Analysis

Neutron activation analysis is performed at HFIR to determine the existence and quantities of major, minor, and trace elements in a material sample. Two pneumatic tube (PT) facilities, including PT-1 in position VXF-7 and PT-2 in EF-2, are used to shuttle small samples placed in plastic and graphite capsules (rabbits) into and out of the core on demand. The ability to perform nondestructive forensics analysis of evidentiary materials such as bullet fragments, gunshot residue, plastic, hair, nails, and geological materials is a major advantage of NAA (ORNL 2022). High-precision NAA at HFIR also enables nuclear material control and accountability, nuclear nonproliferation, and nuclear forensics analysis capabilities.

4.2.5 Gamma Irradiation Research

The spent fuel assembly, including the IFE and OFE, can produce peak gamma dose rates approaching 10^8 rad/h. The GIF is comprised of a sealed stainless-steel chamber which is lowered into the central region of the spent fuel and cadmium jacket assembly to study the effects of gamma radiation on the experiment material. The chamber includes an umbilical connection to gas and electrical lines in an adjacent laboratory, allowing instrumented experiments with possible inert or other cover gasses (e.g., Ar, He). Instrumentation can include thermocouples, heaters, electronic signals, and even fiber optics. Gamma irradiation research has a wide range of applications, such as the study of ion exchange resin radiation tolerances for removing ^{137}Cs from waste, radiation resistance of materials for lunar reactor environments, and radiation induced conductivity changes in high voltage insulators.

4.2.6 Fundamental Physics

Fundamental physics research is performed to investigate properties of the neutrons and neutrinos generated in the reactor. Analysis of neutrons and neutrinos is key to our understanding of the constituents and forces of matter, the properties of elementary particles, and the symmetries of nature (BESAC 2020). HFIR is a pure source of antineutrinos and is an ideal neutrino research facility because of its compact core size (i.e., point source), HEU fuel (i.e., ^{235}U spectrum), and building locations suitable for large detectors close to the core. For these reasons, the Precision Reactor Oscillation and Spectrum Experiment (PROSPECT), is performed at HFIR. PROSPECT is a short-baseline reactor antineutrino experiment with the goals of discovering eV-scale neutrinos through oscillation effect observations, testing reactor antineutrino spectrum predictions, demonstrating antineutrino detection techniques, and developing technology for nonproliferation applications (Ashenfelter 2019).

4.3 IN-CORE NEUTRON FLUX DISTRIBUTIONS

In-core irradiation experiments are performed in the FTT or the beryllium reflector. The position of an irradiation target is typically determined based on neutron flux spectrum and magnitude, volume, instrumentation, and duration requirements. The volumes of the experiment facilities are fixed, and select facilities allow for instrumented irradiations (e.g., RB positions) and insertion/removal capabilities (e.g., hydraulic tube, pneumatic tubes). The core's neutron flux distribution must therefore be well understood to support users.

To illustrate the neutron flux distribution in HFIR, the end-of-cycle MCNP (X-5 2003) model developed by Chandler et al. (Chandler 2020b) was employed to calculate multi-energy group fluxes in the core. The experiment facilities were modified to assume a clean (i.e., unperturbed) experiment loading. The flux trap is assumed to be composed of 50 vol.% water and 50 vol.% aluminum, whereas the beryllium experiment facilities are assumed to be loaded with dummy beryllium plugs. The thermal ($E_n < 0.625$ eV), epithermal (0.625 eV < E_n < 0.1 MeV), and fast ($E_n > 0.1$ MeV) neutron flux distributions on the core's horizontal midplane are provided in Figure 6. The azimuthally averaged, radially dependent flux distributions are provided in Figure 7, with the corresponding results on the core midplane illustrated in Figure 8.

As illustrated in these plots, the thermal neutron flux increases with distance into the flux trap with a peak unperturbed thermal neutron flux of about 2.5×10^{15} n/cm^2-s. Additionally, the thermal neutron flux peaks at about 2–3 cm into the removable beryllium reflector at a value of about 1.4×10^{15} n/cm^2-s. The fast neutron flux is greatest in the fuel elements; however, the highest accessible fast neutron flux in the peripheral target positions is on the order of $1.3–1.5 \times 10^{15}$ n/cm^2-s. The fast neutron flux reduces rapidly in the beryllium reflector with distance from the core centerline.

Three-energy group X–Y neutron flux distributions on the core horizontal midplane are provided for the flux trap, RB-5B, inner small VXF-13, outer small VXF-12, and outer large VXF-14 irradiation facilities in Figure 9 through Figure 13, respectively. Figure 2 shows the locations of these irradiation facilities and their orientations with respect to the fuel elements.

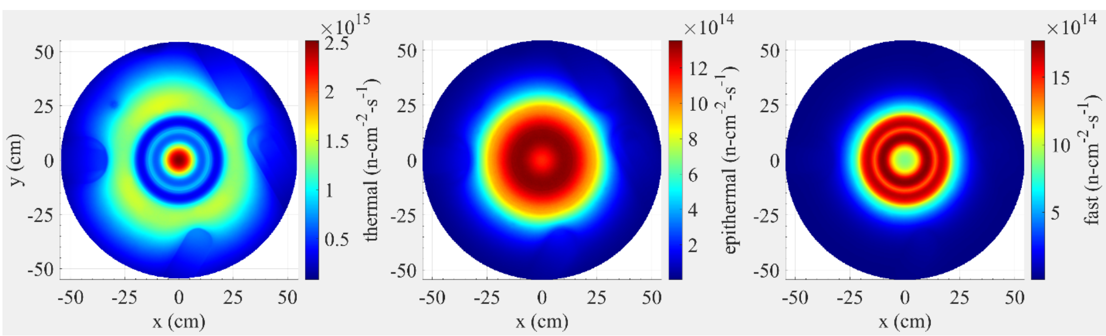

Figure 6. End-of-cycle core horizontal midplane three-energy group flux distribution.

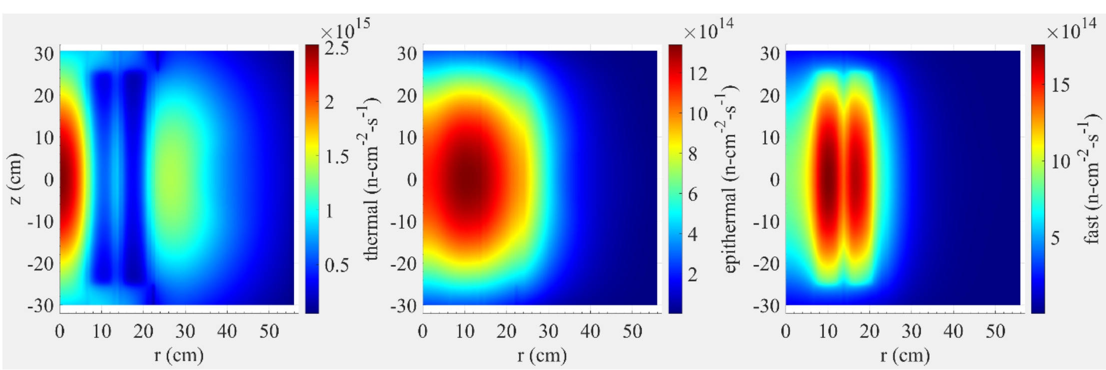

Figure 7. End-of-cycle azimuthally averaged radial three-energy group flux distribution.

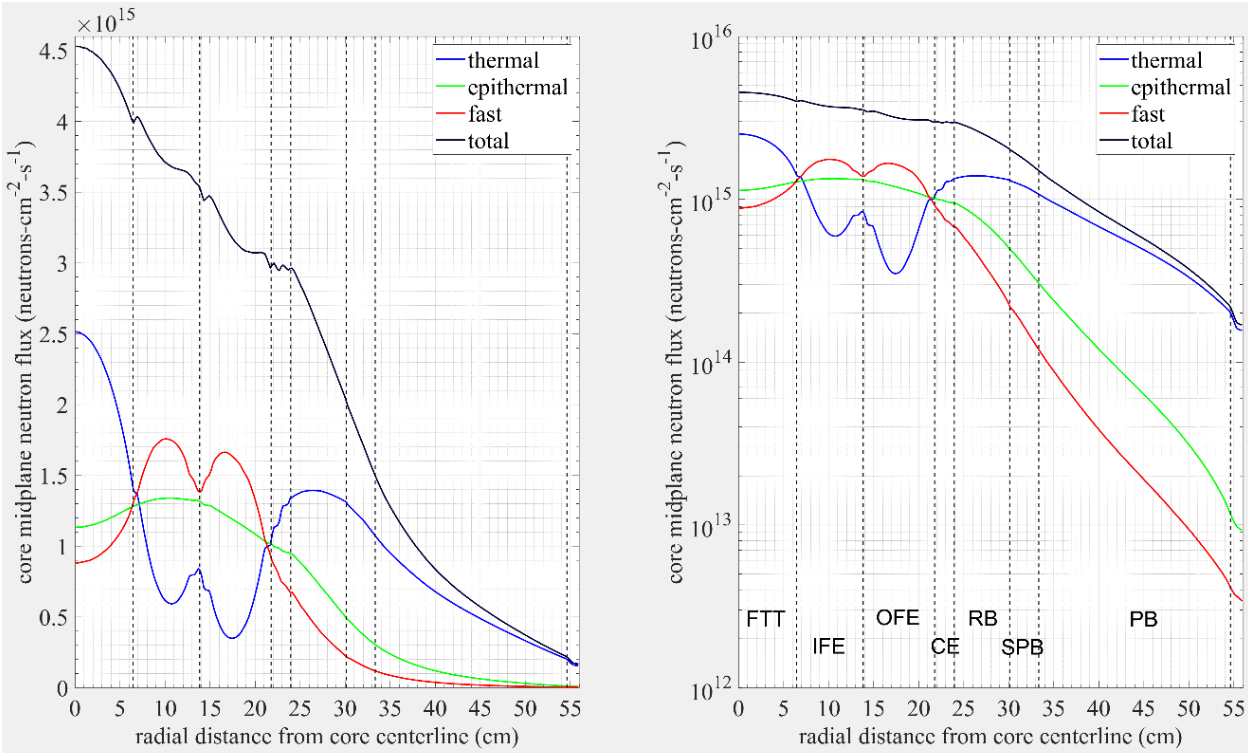

Figure 8. End-of-cycle azimuthally averaged radial three-energy group flux distribution on core midplane.

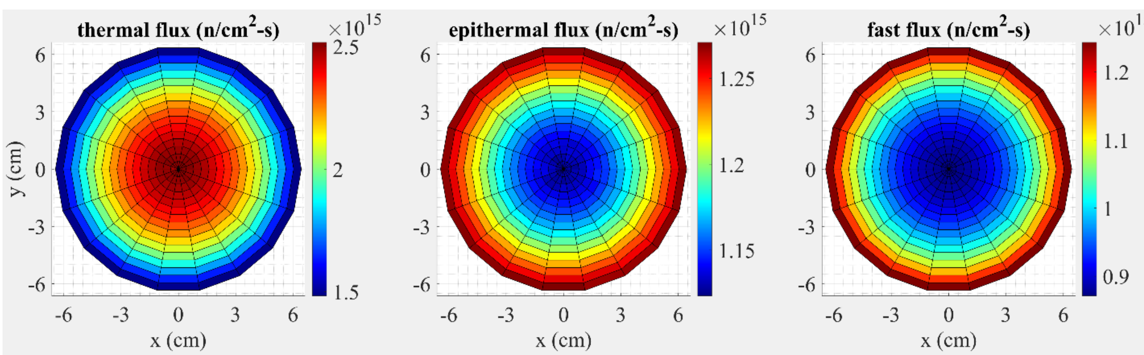

Figure 9. Flux trap end-of-cycle three-energy group flux distribution on core midplane.

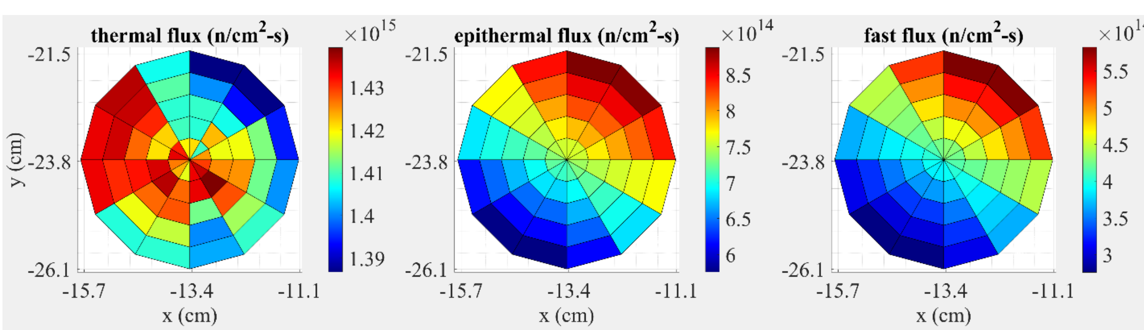

Figure 10. RB-5B end-of-cycle three-energy group flux distribution on core midplane.

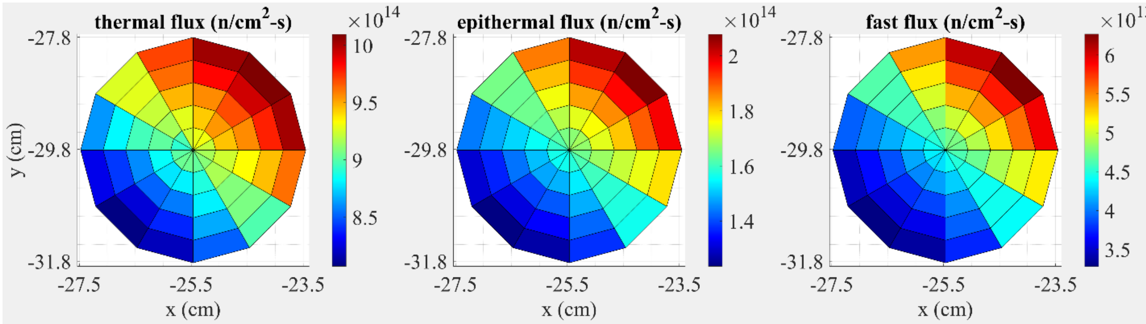

Figure 11. Inner small VXF-13 end-of-cycle three-energy group flux distribution on core midplane.

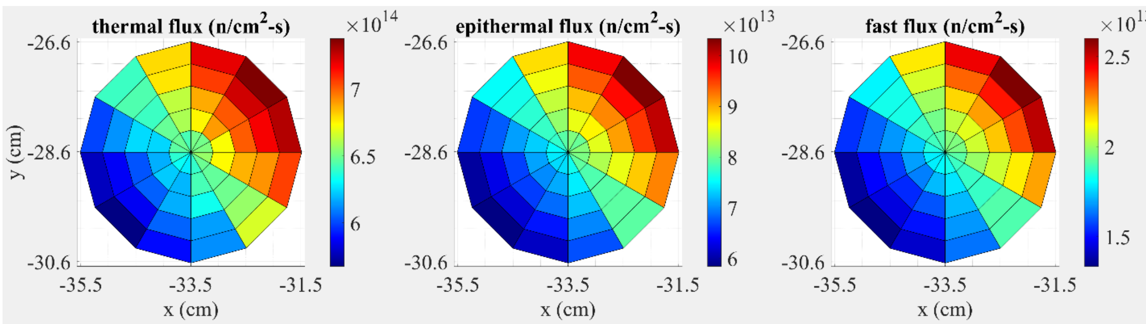

Figure 12. Outer small VXF-12 end-of-cycle three-energy group flux distribution on core midplane.

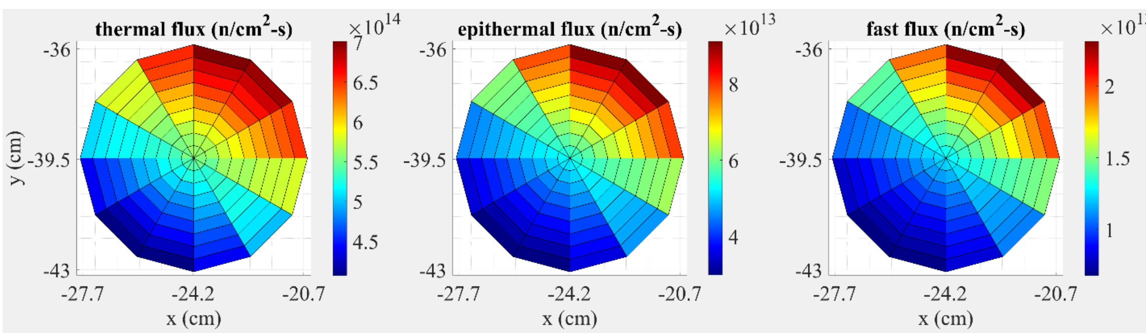

Figure 13. Outer large VXF-14 end-of-cycle three-energy group flux distribution on core midplane.

4.4 LOW-ENRICHED URANIUM CONVERSION PROJECT

The US DOE National Nuclear Security Administration (NNSA) Office of Material Management and Minimization (M^3) is pursuing the conversion of the remaining five US high-performance research reactors (USHPRRs) as part of their mission to minimize and, to the extent possible, eliminate the use of HEU in civilian nuclear applications (DOE 2022). The five USHPRRs include HFIR, the Advanced Test Reactor, the National Bureau of Standards Reactor, the Massachusetts Institute of Technology Research Reactor, and the University of Missouri Research Reactor. Of these five USHPRRs, the highest power density core and most challenging to convert is HFIR because of its unique involute-shaped plate design with lateral and axial fuel contouring requirements. Efforts are ongoing to convert HFIR from HEU to LEU fuel while maintaining or enhancing current performance and safety margins, thus sustaining HFIR's mission portfolio and reactor-based neutron science leadership.

ORNL has been performing engineering evaluations on the conversion of HFIR since approximately 2005, and the current schedule indicates conversion around 2040. The HFIR-specific conversion design assumptions and criteria were first documented in the report by Primm et al. (Primm 2006). Namely, the core geometry must be preserved, safety and performance must be maintained, and the operating conditions must be preserved (e.g., inlet temperature, pressure, and flow). The general project strategy involves design, development, and testing of an LEU fuel product; establishment of a commercial LEU fuel manufacturing capability; preparation and approval of safety basis documentation; and conversion execution.

Initial studies explored uranium-molybdenum (U-10Mo) monolithic alloy fuel because of its high uranium density (~15.32 gU/cm^3, 3.03 g^{235}U/cm^3) and its anticipated use in all five USHPRRs. Results to date show that HFIR can maintain its performance level if the U-10Mo designs operate at 95–100 MW, depending on the design. Proposed U-10Mo fuel designs (Betzler 2017, Betzler 2022), which meet existing performance metrics and preserve steady-state thermal safety margins, typically consist of radial/lateral and axial contoured fuel profiles, resulting in fabrication complexities not associated with the other USHPRR fuel designs. The HFIR-specific U-10Mo fuel manufacturing R&D process was anticipated to be long and expensive, and it might not result in a process with adequate yields to maintain an economically viable fuel. To mitigate this project risk, fuel design studies were initiated with LEU uranium-silicide dispersion (U_3Si_2-Al) fuel in 2017. Then, in 2019, HFIR officially re-baselined to U_3Si_2-Al (Chandler 2020a).

Initial U_3Si_2-Al studies performed by Chandler et al. (Chandler 2019a) considered 4.8 gU/cm^3 because NUREG-1313 (NRC 1988) concluded that "plate-type fuels suitable and acceptable for use in research and test reactors can be fabricated with U_3Si_2-Al dispersion compacts with uranium densities up to 4.8 g/cm^3." Four designs with varying degrees of fabrication complexity have been developed with the "low-density" silicide fuel form to meet or exceed performance and safety metrics (Chandler 2020c, Betzler 2021). However, several designs have thermal safety margins less than the 85 MW HEU design. Because of the low ^{235}U density (~0.95 g^{235}U/cm^3), the active fuel length must be increased from 50.80 to 55.88 cm to load enough fuel in the plates to maintain HFIR's current cycle length. This design complexity reduces the end clad length above and below the fuel zone, thus reducing the inlet length for the coolant flow to stabilize and increasing axial end power peaking.

Several "high-density" silicide dispersion fuel designs with a 5.3 gU/cm^3 (~1.05 g^{235}U/cm^3) density have also been studied (Bae 2021a, Bae 2021b). The ~10% increase in ^{235}U density slightly relaxes the design space, potentially allowing for increased performance, safety, and fabricability relative to the low-density fuel form. One proposed high-density design maintains a 50.80 cm long active fuel length, consistent with the current HEU design, and another proposed design increases the clad thickness from 0.254 to 0.305 mm.

All U_3Si_2-Al designs require a power uprate to 95 MW to meet 85 MW HEU key performance metrics, such as cycle length, ^{252}Cf production rates, and cold source flux. Additionally, each of the U_3Si_2-Al designs has one or more complex fabrication features relative to the HEU fuel design that must be evaluated during the fabrication R&D process to help with design down-selection. A few of the complex fabrication features include (1) fuel axial contouring at the bottom of the fuel zone to reduce axial power peaking, (2) fuel zones centered and symmetric about the plate thickness centerline to promote heat conduction to the coolant channels, (3) thin-to-no filler thickness in the center region of the fuel plate to load enough fuel to sustain an HEU-like cycle length, and (4) Gd poison in the IFE filler region, in addition to ^{10}B, to reduce the IFE power density for the first day of the operating cycle.

5. CONCLUSIONS

HFIR is a versatile, multi-mission USHPRR operated at ORNL on behalf of the US DOE SC. With the highest steady-state neutron flux in the United States, the DOE user facility is critical for domestic and international neutron science–based research. HFIR's intense steady-state neutron flux, consistent cycle lengths, and state-of-the-art facilities enable world-class capabilities and missions spanning cold and thermal neutron scattering, radioisotope production, materials and fuels irradiation science, NAA, and fundamental physics research. HFIR's multi-mission capabilities are attributed to its high power density core design consisting of a series of concentric regions, including a flux trap, an inner fuel element, an outer fuel element, control elements, and a large beryllium reflector.

HFIR provides neutron capabilities in support of DOE's missions in science, energy, environment, and national security. As HFIR enters its sixth decade of operations, its long-term future requires careful thought and planning. Therefore, DOE SC chartered a BESAC subcommittee review to assess the scientific justification for a domestic high-performance reactor–based research facility, including specific recommendations on the long-term strategy concerning HFIR. The subcommittee corroborated that the life-limiting component of HFIR is the RPV, because decades of radiation bombardment on it is causing embrittlement of the steel. The review determined that HFIR will have a critical role in the future of US neutron science research and thus recommended the immediate pursual of the following recommendations to ensure continued world-class operation of HFIR well into the future:

1. Replace the RPV to prevent a premature and possibly unexpected shutdown, long or permanent, and redesign it to enable enhanced science capabilities.
2. Convert to LEU fuel, and if possible, coordinate the conversion and the RPV replacement so that a single shutdown would accomplish both objectives (i.e., RPV replacement and LEU conversion).
3. Enhance in-core irradiation capacity and capabilities such as improved access for isotope production and materials irradiation experiments.
4. Enhance beamline capacity and capabilities such as additional instruments (e.g., a second guide hall), larger beam tubes, improved cold source, advanced instrumentation, and reduced background.
5. Modify the fuel assembly to make it more manufacturable and less expensive.
6. The combination of the RPV replacement and conversion may also allow for a power increase that would restore the flux intensity of the original 100 MW HEU operations.

The HFIR-SENSe initiative at ORNL was formed to address the recommendations made by the BESAC subcommittee regarding prospects for key performance and infrastructure improvements to extend world-class operation of HFIR beyond the year 2100. The HFIR-SCIENCE project within the SENSe initiative was formed to develop a compendium of preconceptual enhancement designs to support the long-term future of nonscattering scientific capabilities. Thirteen HFIR-SCIENCE working groups were formed based on categorization of 35 enhancement concepts presented by researchers across ORNL. The goal of each group is to develop the concepts, build a scientific justification, identify potential facility sponsors, and estimate costs and schedules for each concept. The HFIR-SCIENCE Working Group Series includes 13 comprehensive volumes/reports documenting an overview of HFIR and the HFIR-SENSe Initiative, which is the subject of this volume, as well as the nonscattering scientific capability enhancements presented by the working groups.

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