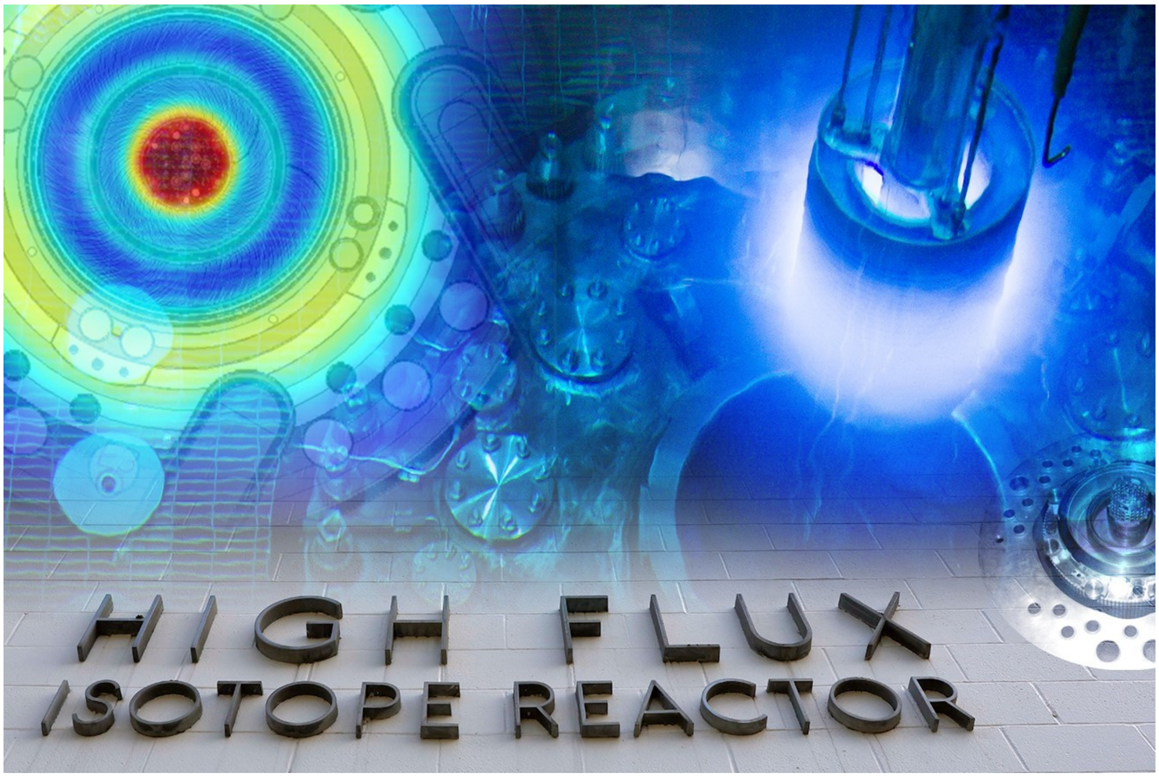
ORNL/TM-2022/2691/V9

Volume 9: Critical Facility with Add-On Ion Beam

HFIR Futures – Enhanced Capabilities Series



Gale Hauck
Doug Bowen
David Chandler
Zain Karriem
Jeff Powers
Yanwen Zhang

January 2023

OAK RIDGE
National Laboratory

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ORNL/TM-2022/2691/V9

HFIR SENSE LDRD

CRITICAL FACILITY WITH ADD-ON ION BEAM

VOLUME 9 OF THE HFIR FUTURES – ENHANCED CAPABILITIES SERIES

Gale Hauck
Doug Bowen
David Chandler
Zain Karriem
Jeff Powers
Yanwen Zhang

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
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ABBREVIATIONS

AIM1	Austenitic Improved Material #1
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
ATRC	Advanced Test Reactor Critical
BESAC	Basic Energy Sciences Advisory Committee
CEF	Critical Experiment Facility
CSA	concentrated solid-solution alloy
DOE	US Department of Energy
ENDF	Evaluated Nuclear Data File
EU	European Union
FBRs	fast breeder reactor
GEMMA	Generation IV Materials Maturity
HALEU	high-assay low-enriched uranium
HB	horizontal beam
HEA	high-entropy alloy
HEU	highly enriched uranium
HFIR	High Flux Isotope Reactor
HFIRCE	HFIR critical experiment
HFIR-C	HFIR Critical Facility
HFR	high flux reactor
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IBA	ion beam analysis
ICSBEP	International Criticality Safety Benchmark Evaluation Project
IEPI	intermediate energy proton irradiation
LDRD	Laboratory Directed Research and Development
LEU	low-enriched uranium
LPCF	Low Power Critical Facility
M3	Office of Materials Management and Minimization
M&S	modeling and simulation
MCNP	Monte Carlo N-Particle
NCERC	National Criticality Experiments Research Center
NE	Office of Nuclear Energy
NNSA	National Nuclear Security Administration
ORNL	Oak Ridge National Laboratory
PKA	primary knock-on atom
PTP	peripheral target position
R&D	research and development
RPV	reactor pressure vessel
SC	Office of Science
SENSe	Sustaining and Enhancing Neutron Science
SPR/CX	Sandia Pulsed Reactor / Critical Experiments
SST	stainless steel

SUNRISE	Southeast Universities Nuclear Reactors Institute for Science and Education
VXF	Vertical Experiment Facility

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ABSTRACT

Completion of the originally planned critical facility has been considered as part of the High Flux Isotope Reactor (HFIR) Sustaining and Enhancing Neutron Science Initiative at Oak Ridge National Laboratory (ORNL). A working group of ORNL staff members was formed to develop the idea and to recommend one or more configurations to best support future HFIR operations and scientific capacities. 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 planned critical facility was to measure the subcritical worth of fresh fuel elements to support startup requirements. However, the Y-12 National Security Complex already housed a critical facility that was used for this purpose. This report presents the working group's efforts, including determination of the proposed critical facility's high-impact benefits. A generic low-power critical facility would be employed for reactor physics measurements, code and data validation, reactor operator and staff training, and education. This facility would be instrumental in supporting current HFIR operations, conversion of HFIR to low-enriched uranium, existing light water reactor operations, and advanced reactor development and deployment.

1. BACKGROUND OF THE HIGH FLUX ISOTOPE REACTOR FUTURES – ENHANCED CAPABILITY 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 focused on continuing HFIR 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, Oak Ridge National Laboratory (ORNL) funded an initiative to provide a critical assessment of the 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. The report by Bryan and Chandler [Bryan 2022] provides more information regarding HFIR, the BESAC report recommendations, the HFIR-SENSe Initiative, and the goals of the three LDRDs.

The effort to brainstorm nonscattering scientific enhancements at HFIR was a "blue-sky" engagement with researchers across ORNL and has yielded both incremental improvement ideas, as well as new transformational 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
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

1.1 HFIR CRITICAL FACILITY

In the 1960s, a low-power critical facility pool was designed at HFIR for criticality experiments to support the design and operation of a HFIR HEU core [Bowen 2021, SUNRISE 2013]. Specific intended operational support activities included water-immersed and water-reflected reactivity worth measurements to ensure shutdown margin and to verify fuel characteristics such as uranium and boron loading. The critical facility was also envisioned to speed up restarts from mid-cycle shutdowns by burning samarium (Sm) out of the HFIR fuel elements at low power.

However, the HFIR critical facility pool was never used for its original purpose because the Critical Experiment Facility (CEF) at the Y-12 National Security Complex was available to serve this purpose in support of HFIR design and startup operations. However, CEF has been decommissioned for several decades this capability is no longer available. Critical experiments performed at the Y-12 CEF measured the important physics parameters to support HFIR startup [Bowen 2021, Cheverton 1971]. Y-12 CEF reactivity worth measurements supported the first ~400 cycles of HFIR operations. Four critical experiments (HFIRCEs) were performed and are summarized below [Bowen 2021, Cheverton 1971, Bowen 2012]:

- HFIRCE-1 was a solution critical experiment focusing on exploring the characteristics of the central flux trap geometry.
- HFIRCE-2 was a complete mockup of an HEU core, including the fuel elements, control rods, and beryllium reflector. Measurements included power distributions using foils.
- HFIRCE-3 replicated some of the HFIRCE-2 measurements for a new HFIR design with increased fuel loading, revised radial distribution of fuel and poison, and a revised control rod design.
- HFIRCE-4 used the HFIRCE-3 fuel elements with a new control rod design and filled in gaps in experimental data. Measurements included radial and axial power distributions, differential and

integral control rod worths, shutdown margins, reactivity coefficients, and simulated plutonium target worths.

The HFIR critical facility pool is 8 feet in diameter and 25 feet deep. It is lined with 0.25-inch thick stainless steel and is filled with stagnant water, but some piping exists. The HFIR critical facility pool is not currently in use. The pool's location in the reactor bay is shown in Figure 1, and a photo of the pool is shown in Figure 2.

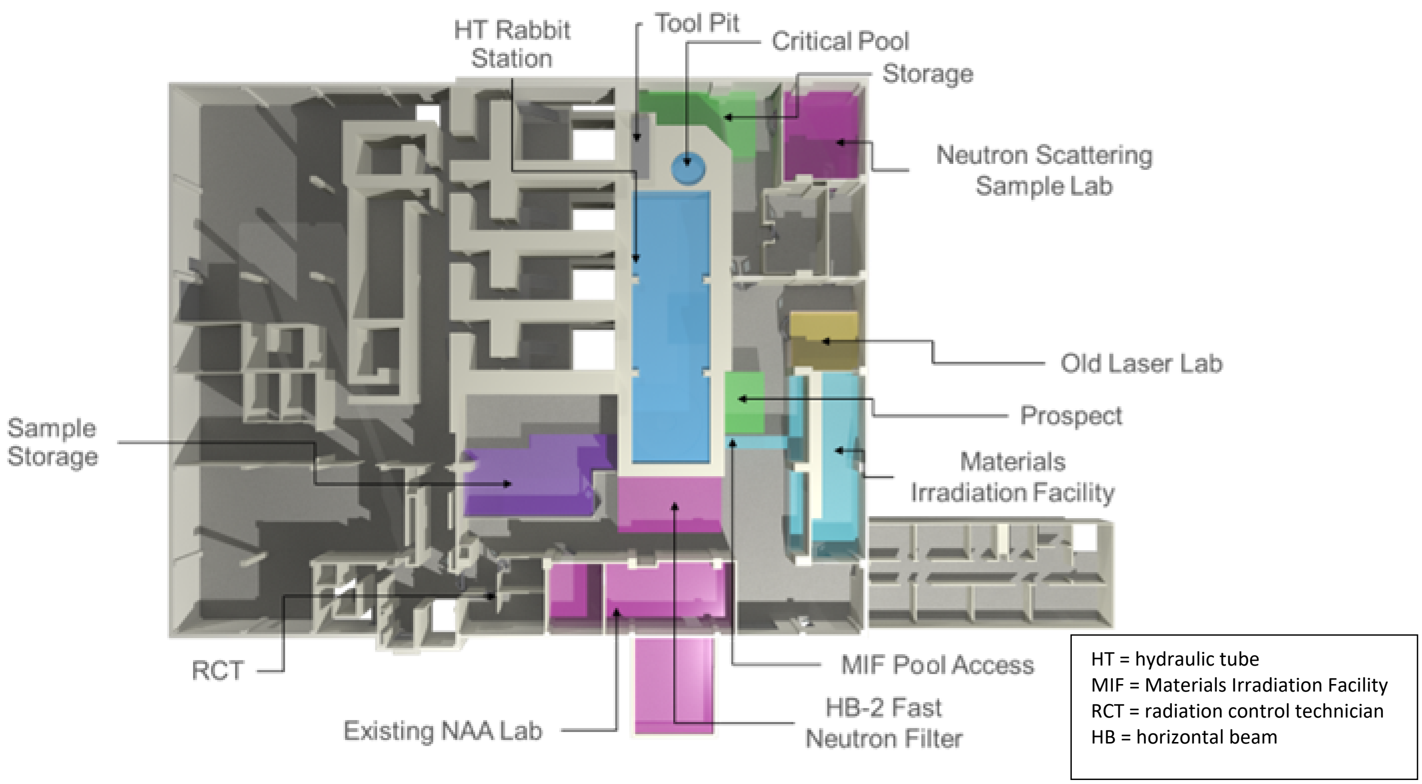


Figure 1. Layout of the HFIR facility with critical pool indicated.

Figure 2. HFIR critical pool.

2. WORKING GROUP OBJECTIVES AND GOALS

2.1 DESCRIPTION OF WORKING GROUP

The Critical Facility working group was created to generate options for completing the originally planned HFIR Low Power Critical Facility (LPCF). The scope of the working group included identifying refurbishment activities, potential operational configurations for the facility, and projected uses of the facility. The purpose of the LPCF is to support and enhance HFIR operations and research capabilities available for the broader scientific community.

2.2 SIGNIFICANCE OF WORKING GROUP

As illustrated by its original inclusion in the HFIR design and construction concept, a critical facility at HFIR could be extremely useful and impactful for HFIR and would broaden ORNL's neutron and nuclear research and development (R&D) capabilities. Key significant benefits can be categorized into four main areas: Research and Development, Education and Training, Technology Demonstration, and Fuel Qualification [Bowen 2021].

A new HFIR critical facility could support LEU conversion activities and qualification efforts. In addition, it could provide more capacity and bandwidth for critical experiments in the United States, which is increasingly important because many US research reactors and critical facilities have been retired. There are currently only two criticality experiment research facilities in the United States: the Sandia Pulsed Reactor / Critical Experiments (SPR/CX) critical facility at Sandia National Laboratories, and the National Criticality Experiments Research Center (NCERC) in the Device Assembly Facility at the Nevada National Security Site. ORNL provides project management support for all integral experiments performed at these facilities. A new capability is needed at ORNL/HFIR to support programs outside the National Nuclear Security Administration (NNSA) with experimental research reactor cores or to provide non-NNSA sponsors with a means to perform needed experiments. Currently, the two open critical facilities have limited bandwidth and cannot support DOE-SC Office of Nuclear Energy (NE) and many other missions.

Lastly, a new HFIR critical facility could advance educational, given that the shutdown of research reactors and critical facilities in the United States has disproportionately impacted the university community, leaving them with a shortage of facilities that can be used in education and training. The Southeast Universities Nuclear Reactors Institute for Science and Education (SUNRISE) Consortium [SUNRISE 2013] developed a plan to collaborate with DOE/ORNL on educational tasks. The growth of domestic nuclear capabilities having flexible design and advanced instrumentation and control (I&C) is needed to ensure that the next generation of nuclear engineers and scientists will be available to support the nuclear industry, government programs, universities, and research institutes.

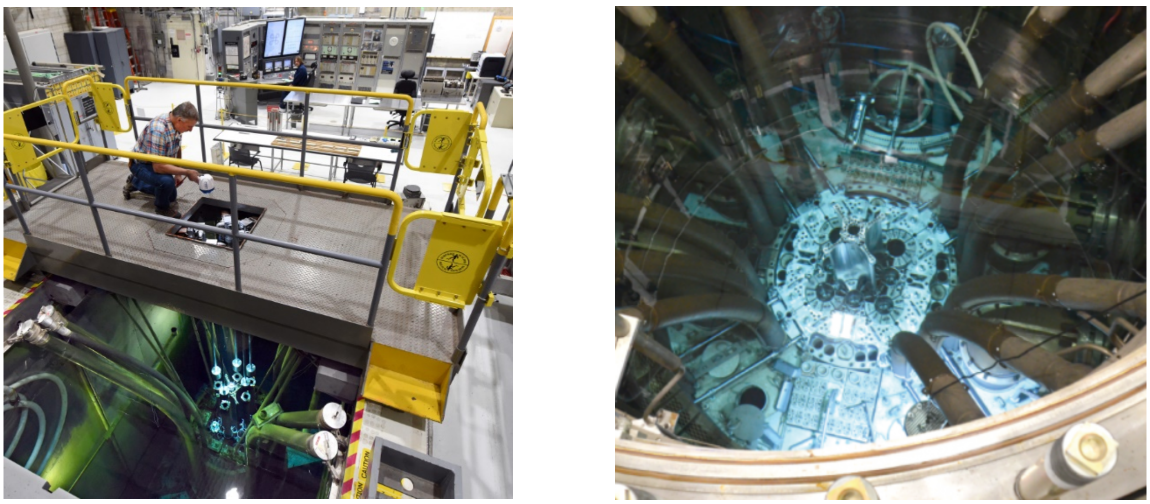
3. CONCEPTUAL DESIGN DEVELOPMENT

3.1 MULTIPURPOSE CRITICAL FACILITY

3.1.1 Description of the Multipurpose Critical Facility

The envisaged purpose of the HFIR critical facility is to support current HFIR cycle operations, as well as current and future irradiation and research activities. The proposed design concept should therefore be flexible from a physical configuration perspective. That is, it should be able to reflect the current HFIR core configuration while allowing for variable fuel (composition), flux trap and reflector, and experimental configurations to accommodate future operations.

A notable example of a critical facility constructed to support reactor operation is the Advanced Test Reactor Critical facility [Campbell 2021], "a full-size nuclear replica" of the Advanced Test Reactor [DOE-NE 2022] at Idaho National Laboratory. Figure 3 shows the ATRC and ATR side by side. Unlike the ATR, the ATRC is an open pool facility with a normal operating power of 100 W and a maximum power of 5 kW. The ATRC's main purpose is to experimentally evaluate (measure) the reactivity effects of actual experiments prior to irradiation in the ATR. The ATRC also provides the ability to measure various nuclear engineering parameters important for both reactor physics and irradiation experiment purposes. These quantities include control and experiment reactivity worth, reactivity coefficients, fission rate distributions, thermal and fast neutron flux distributions, gamma heat rates, and several other important parameters.



(a) **(b)**

Figure 3. (a) The Advanced Test Reactor Critical [Campbell 2021] and (b) the Advanced Test Reactor [DOE-NE 2022].

The initial proposed concept of a HFIR Critical Facility (HFIR-C) resembles that of reactor duplication: as in the case of the ATRC, it is a proven concept. HFIR-C would support existing HFIR operations through reactor physics measurements, including the evaluation of new HFIR irradiation experiments and reactor applications.

The need to irradiate new materials in HFIR is growing. Materials science research has an increasing demand to irradiate larger sample sizes that more closely resemble full-sized components [Bryan 2022]. The space needed to irradiate these larger sizes is not currently available in HFIR. In the field of radioisotope production, larger amounts of isotopes are needed, which in turn requires irradiation of larger quantities of feed material, which in turn may challenge experiment reactivity safety limits, as well as experiment coolability. All of these novel experiment needs should be accommodated in the HFIR-C design, thus supporting future HFIR operations through experimentation prior to irradiation.

HFIR differs from ATRC in several geometric respects: it has two fuel elements, whereas ATRC has 40 elements, and it has fewer reflector components, thus allowing for easier reconfigurability. In principle, these differences would allow HFIR-C to easily accommodate a reconfigurable center flux trap and reflectors, along with variable experiment sizes and positions to accommodate testing of the applications described above. The capabilities to accommodate a variable center flux trap experiment and reflector configurations have also been considered in this initiative for future HFIR applications. The flexible flux trap concept is described in Volume 6 [Bryan 2022]. Figure 4 shows the current HFIR core layout. Irradiation positions would be reconfigured in the center (orange) and reflector regions (purple, inner blue, and green).

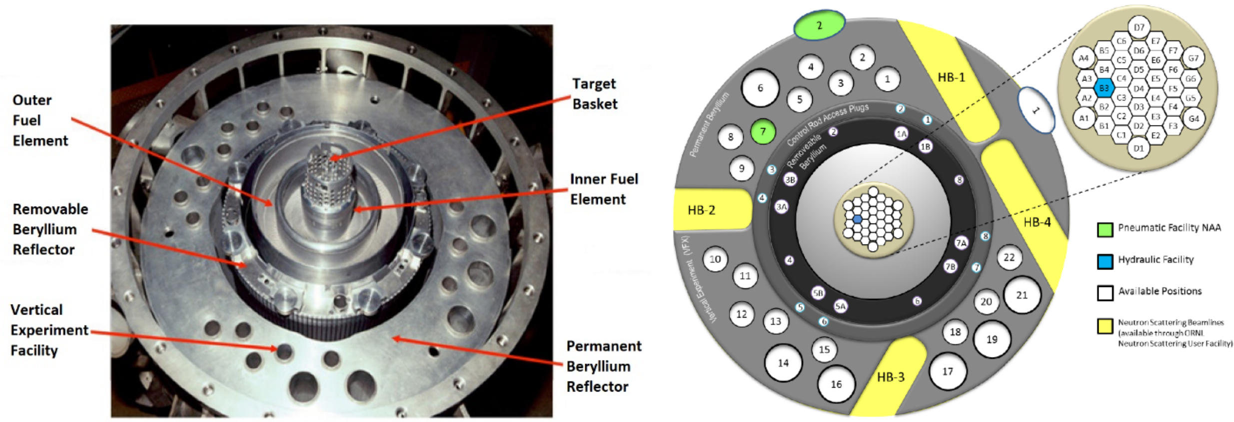


Figure 4. Current HFIR core configuration [ORNL 2015].

There is a need for HFIR-C to enable zero-power integral benchmark experiments at delayed critical to generate high-quality critical benchmarks for the International Criticality Safety Benchmark Evaluation Project (ICSBEP). These experiments are crucial for validating computational methods such as MCNP or SCALE to ensure that nuclear criticality safety (NCS) limits are accurate. These experiments will also support nuclear data testing activities for a variety of program sponsors. Zero-power measurements are crucial for operator training, hands-on training for fissile material handlers, process supervisors, and NCS staff members working in nuclear facilities with significant quantities of fissionable materials. The designs of these experiments can vary significantly, and their configuration depends on the nature of the experiment and the needed experimental data. These types of experiments can be performed in the HFIR pool. This capability is highly sought after by domestic and international sponsors at the other two critical experiment facilities.

3.1.2 Design Requirements

At a high level, the purpose of the critical facility will be to support HFIR's current and future operations and applications. The scope of the facility will include but not be limited to:

1. **HFIR fuel testing / excess reactivity measurements** for LEU conversion and high-assay low-enriched uranium (HALEU, enrichments 5–20% ^{235}U) to ensure sufficient reactivity for operations to include verification of fuel assembly manufacturing

2. **Reactor physics experiments** to support existing and future HFIR operation and utilization

3. **Irradiation experiment testing** to support existing experiments and future development of new irradiation positions and conditions in HFIR

4. **Reactor/radiation instrumentation development** to support development of novel radiation detection and monitoring instruments

5. **General purpose zero power critical experiments** for a variety of DOE and NNSA sponsors to support integral benchmarks and nuclear data testing activities for the NCS and Advanced Reactor programs

6. **Hands-on NCS training** to augment this critical need in the United States

To accommodate the various applications, the facility should contain various systems, instruments, and components to support its function and should also be configurable for the specific application. Figure 5 presents a conceptual design layout of HFIR-C, showing the systems and features that would be required in the facility. These include but are not limited to:

1. **In-pool core and experiment support structures** for use in conducting experiments and operations, indicated as a supported grid plate at the pool bottom

2. **Transfer infrastructure**, indicated as a gate connecting the facility and the reactor pool to be used to transfer experiments between the two facilities or to move larger components in and out of the facility

3. **Ring supports** to accommodate experiment and facility monitoring systems, equipment, and instruments

4. **A working platform** for installing and conducting experiments

5. **Piping** for instrumentation, facility operation and experiments

6. **Component storage** to accommodate multipurpose efforts, providing access to essential components and tools (not shown)

7. **Facility control room** (not shown)

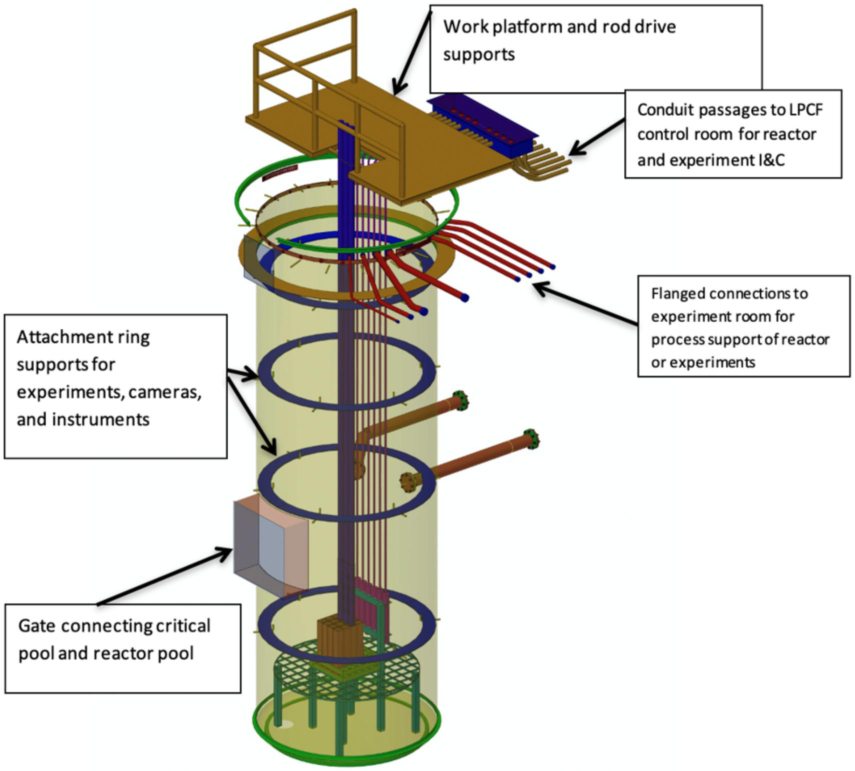


Figure 5. Critical facility preconceptual design configuration [SUNRISE 2013].

3.1.3 Limitations/Challenges

HFIR is a DOE-regulated Category 1 nuclear facility with a thorough nuclear safety basis in place and staff experienced in design, safety, maintenance, operations, radiation protection, NCS, materials handling (e.g., waste), and security. Thus, HFIR provides a suitable foundation for the design and deployment of a critical facility, especially considering that it already includes a critical pool. HFIR and the critical facility will be coupled to some degree. Although the critical facility may require its own safety analysis report, the HFIR safety basis and criticality safety controls must be updated to incorporate the critical facility. The significant criticality safety issues regarding a new critical facility are related to transportation, storage, and handling of fissile material. Therefore, the critical facility licensing processes and safety bases will follow the highest standards.

The critical pool is located in the reactor bay adjacent to the reactor and spent fuel pools, so training and procedures related to radiation protection and NCS would need to be incorporated into the existing HIFR protocols. Although this could limit visitor access to the bay, personnel could remain in the control room to support their experiment. Furthermore, having the training and procedures established to enter the reactor bay serves as a good justification for having a critical facility in the bay.

The critical facility will have a control room that would require staffing full time. This control room could be integrated with the main HFIR control room to minimize the need for additional staff. Furthermore, Operations will be responsible for setting up, monitoring/operating, and dismantling critical experiments. It will be necessary to hire and train operators dedicated to the critical facility or additional HFIR operators who are trained to work on the critical facility to ensure that the facilities' operations and maintenance do not conflict.

Adequate space and infrastructure will be necessary to support present and future applications. Additional space, concrete penetrations, or housing for additional equipment and instrumentation may be required. Modern technologies such as miniaturization of electronics and instruments allows for installation of various general or multi-purpose experiments within limited space, as implemented at NCERC [NNSS, n.d.].

3.1.4 Supporting Calculations

An MCNP [X-5 Monte Carlo Team 2003] model of the critical facility was developed to emphasize the importance of such a facility. The base model includes a 244 cm (8 ft) diameter pool of light water with a 0.635 cm (0.25 in.) thick stainless-steel liner surrounded by reinforced concrete. An SST table was modeled with a HFIR HEU fuel assembly on top of it. The fuel assembly model is based on the explicit model documented in the literature [Chandler et al. 2020, Ilas et al. 2015]. Figure 6 illustrates the fuel assembly in the critical facility, and the primary characteristics of the modeled fuel assembly are provided in Table 2.

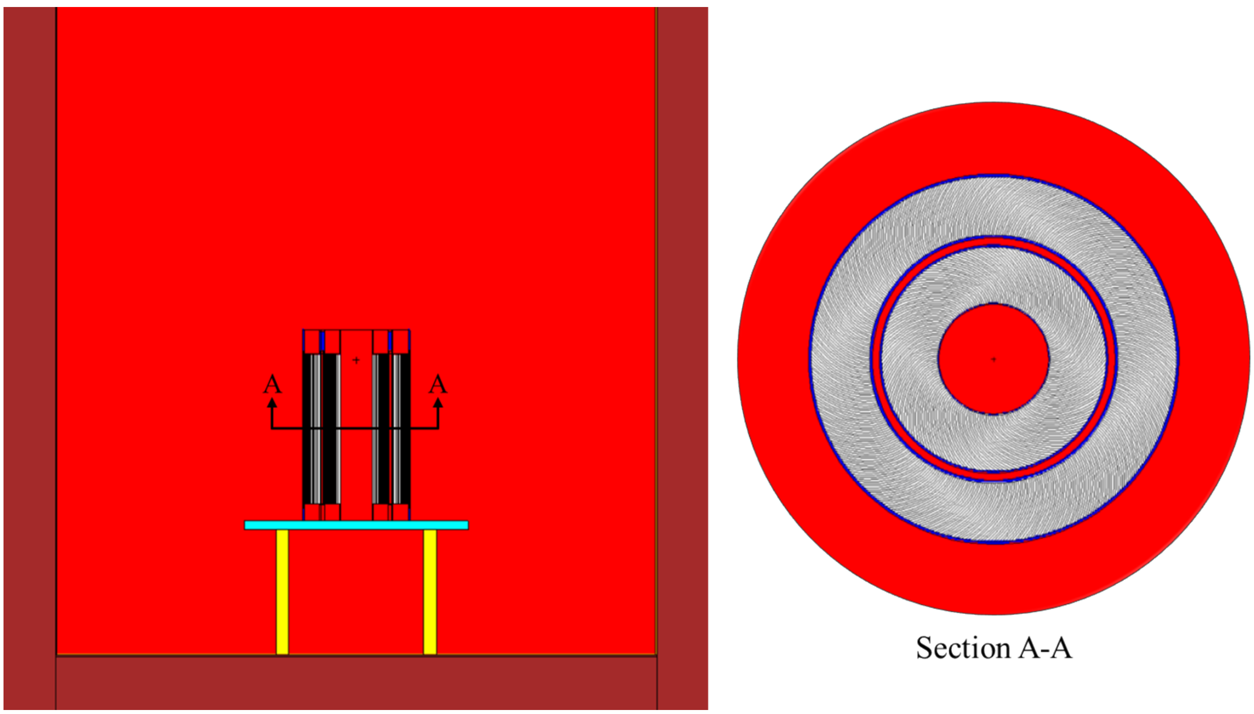


Figure 6. MCNP model of the critical facility with a HFIR HEU fuel assembly.

Table 2. Primary characteristics of the modeled HEU fuel assembly

Parameter (units)	Inner fuel element	Outer fuel element
^{235}U (kg)	2.608	6.834
^{10}B (g)	2.709	-
Average coolant channel (mm)	1.270	1.270

The cross sections used are based on Evaluated Nuclear Data File (ENDF)/B-VII.0 data, and all cross sections are considered at a temperature of 300 K, with water thermal scattering data at 293.6 K. The water density is assumed to be 0.984 g/cm^3 based on an assumed pool temperature of 35 C (95 F), which corresponds to the design basis reactor pool temperature [HFIR SAR 2021]. The calculated water-immersed and water-reflected reactivity worth of the fuel assembly is -\$2.29 (k_{eff} = 0.98397 ± 0.00009), which is about 34¢ more reactive than the -\$2.63 worth predicted via the statistical correlation developed in the analysis of HFIR fuel reactivity [Rothrock 1992] and the fuel assembly characteristics listed in Table 2. A delayed neutron fraction, β_{eff}, of 0.0071, was used to be consistent with Rothrock's analysis [Rothrock 1992].

Rothrock's statistical correlation [Rothrock 1992] was developed to estimate the water-immersed reactivity worths of fresh fuel assemblies using as-built data and reactivity worth measurements from a sample of 40 assemblies. The minimum, maximum, and average measured reactivity worths from the 40 assemblies are -\$3.62, -\$2.13, and -\$2.56±0.28. The differences—calculated as predicted-minus-measured—vary between -59¢ and +65¢, and the corresponding standard deviation is 20¢. Therefore, the difference between the MCNP-predicted and correlation-predicted values is within 2σ of this standard deviation.

This model and the as-built data of the 40 assemblies could serve as the basis of a validation and sensitivity / uncertainty quantification study to estimate the water-immersed and water-reflected reactivity worths of fresh fuel elements. The study would enhance the understanding of impacts of as-built fuel characteristics (e.g., ^{235}U, ^{10}B, coolant channel thickness, material impurities), cross-section releases (e.g., ENDF/B-VII, ENDF/B-VII.1, ENDF/B-VIII), and model assumptions on fuel worth. The model and as-built data would also help to determine model biases providing a more refined, more accurate fuel assembly model to be used for nuclear safety, irradiation experiments, and other research analyses. Once the fuel assembly critical facility model is validated, a thorough perturbation study could be performed to explore the fuel specification-defined design space, resulting in a more accurate correlation to predict the fresh fuel assembly water-immersed reactivity. The updated correlation would be used in the startup's estimated symmetrical critical control element position calculation and would satisfy Technical Safety Requirements Surveillance Requirement 4.1.2.1 [HFIR TSR 2022].

The studies discussed above are just a few of many examples of how critical facility experiments and data have been used and could be used in the future to support HFIR nuclear safety and operations. Similar nuclear experiments and data would significantly advance the understanding of current systems (e.g., commercial pressurized water reactors and critical assemblies) and the deployment of new systems such as HFIR and other US high performance research reactor LEU cores, the Transformational Challenge Reactor, microreactors, and other advanced reactors.

3.1.5 Cost Forecasting and Estimates

Facility costs would include development of a new control room to support the HFIR LPCF, cleanup of the existing critical pool facility, and installation of additional infrastructure to support the general purpose capability. Additionally, nuclear material for the experiments must be procured. Costs to add the control room and the needed equipment in the pool will range up to \$10M, including updates needed to meet American National Standards Institute (ANSI) / American Nuclear Society (ANS) -1 standards and safety basis requirements. Equipment for general purpose application must be procured in preparation for specific experiments as sponsor costs incurred during design and experimental preparation and would not be included in up-front costs.

Ongoing costs for this type of facility are highly dependent on facility overhead rates. As a user facility, the Sandia critical experiment work costs over \$25k per week, and NCERC costs are over \$100k per week because of the security posture (Sandia – Security Category 3, NCERC – Security Category 1). Ongoing costs for the HFIR facility would likely fall between these two values and would support 1–3 experiments per week in the facility's single pool.

3.2 ION BEAM ADD-ON FACILITY

3.2.1 Description of Ion Beam Add-On Facility

Nuclear materials research and qualification needs are extensive, especially in the area of irradiation damage in materials. An onsite ion beam facility will (1) allow for material modification to a predicted neutron damage level under different operating conditions and in-service periods, (2) enable rapid evaluation of defect structures formed and evolved in a fission or fusion neutron environment at low displacements per atom (dpa) ranging up to a few tens or hundreds of dpa as necessary, (3) bridge the dose gap between HFIR's 14 dpa per year and over 200 dpa expected for many structural components in advanced reactors, (4) implant helium, hydrogen, lithium, other transmutation products, or some marker elements to analyze irradiation-induced diffusion or migration, and (5) empower rapid nuclear qualification of structural materials, nuclear fuels, and so on.

Ion and neutron irradiation facilities have been used to pursue fission and fusion applications to determine whether irradiation parameters such as damage rates, gas production, or recoil spectra are similar or relevant to those of the corresponding nuclear energy systems [Guo et al. 2016]. Because ion irradiation is the most amenable method for reaching high doses in a reasonable time, energetic ions are often used as surrogates for neutrons, greatly accelerating the R&D processes for investigating radiation effects in materials [Mayer et al. 2020, Jepeal et al. 2021, Zhang et al. 2014, and 2023, IAEA 2018] For example, using 10+ MeV protons makes it possible to combine the benefits of ion irradiation (e.g., high dose rate, flexible irradiation conditions) and reactor neutron irradiation (uniform and bulk irradiation), thus enabling reduced transmutation rate and direct engineering testing [Jepeal et al. 2021]. An onsite high-energy ion irradiation facility will expand R&D for fission and fusion applications and for new education and training opportunities.

3.2.2 Justification of Concept

Some critical needs are also reflected by some recent international conferences/workshops. The workshop on Ion and Neutron Irradiation of Nuclear Materials (November 22–23, 2021) is in the framework of the Generation IV Materials Maturity (GEMMA) project, which is dedicated to the advancement of material science of nuclear materials for Gen IV nuclear reactors. The workshop bought together experts from the United States and the European Union (EU) to discuss recent findings and major scientific issues. The objective of studying irradiation effects within GEMMA is to improve understanding of the microstructural evolution of austenitic stainless steels under irradiation. Such alloys will be used in Generation IV prototypes such as the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) for both structures (316 L[N] steels) and cladding (Austenitic Improved Material #1 [AIM1]-type steels). The International Conference on Fusion Reactor Materials (ICFRM-20, held October 24–29, 2021 in Madrid, Spain) is the EU-led premier international conference and foremost platform for materials experts studying, developing, and qualifying materials for fusion energy facilities. Whereas the structure materials will receive a low irradiation flux and dose over a long time period, the core components and fuel cladding tubes will receive very high irradiation fluences, that produce new microstructure features in the temperature range of interest (300–700°C). These features include new families of precipitates, solute segregations at structural defects, and point defect clusters and voids, leading to dimensional changes in the components (i.e., swelling). In addition, cladding materials are exposed to higher operating temperatures than structural materials, which exacerbates corrosion issues in the short term, resulting in a concomitant need for protective coatings. Swelling, corrosion and mechanical issues that limit these materials' lifetimes strongly related to their microstructures. Therefore, it important to be able to predict their microstructural evolution.

The workshop for High-Entropy Alloys (HEAs) for Nuclear Applications (held October 19–21, 2021 in Madrid, Spain) focuses on the more chemically complex alloys [Zhang, 2022]. The pursuit of alloy development with improved radiation tolerance or increased structural strength has relied on (1) incorporation of alloying elements at low concentrations to synthesize so-called dilute alloys, or (2) incorporation of nanoscale features to mitigate defects. Unlike traditional approaches, recent studies on concentrated solid-solution alloys (CSAs) or HEAs with wide elemental diversity set them apart from traditional approaches. To go beyond the current knowledge based on conventional alloys, studies are being performed to take advantage of property enhancement by tuning chemical disorder through appropriate choices of alloying elements. New knowledge on energy dissipation pathways, deformation tolerance, and the structural stability of CSAs is being revealed by exploiting the equilibrium and non-equilibrium defect processes at the electronic and atomic levels, as well as at nanoscales. Further exploration through ion and neutron irradiation studies [Zhang et al 2023] will improve understanding of the defect properties of these complex alloys and their performance in reactor environments, ultimately enabling structural alloys by design.

High-energy proton irradiation has recently been recommended for new research and engineering testing in fusion and fission research. Intermediate energy proton irradiation (IEPI) is evaluated for rapid high-fidelity materials testing for fusion and fission energy systems [Jepeal 2021]. The authors pointed out that limitations of existing facilities or methods could be addressed by IEPI using beams of 10–30 MeV protons to damage bulk material specimens rapidly and uniformly before direct testing of engineering properties.

Modeling of IEPI demonstrates that high dose rates (0.1–1 dpa/per day) can be achieved in bulk material specimens (100–300 μm) with low-temperature gradients and reduced radioactivity. The capabilities of IEPI are demonstrated through a 12 MeV proton irradiation and tensile test of 250 μm thick tensile specimens of Alloy 718, the results from which simulate or reproduce neutron-induced experiments. In a different example, the ion ranges of four common elements are shown in Figure 7. Protons above 10 MeV (due to the lowest stopping power and greatest range in materials) can penetrate more than 100 μm in typical metals. Thus, a length scale at that direct testing of mechanical properties becomes feasible. High dose rates are achievable by increasing the ion currents. For heavy ions (e.g., self-ions) with the same energy, the penetration depth (Figure 7) is only a few micrometers.

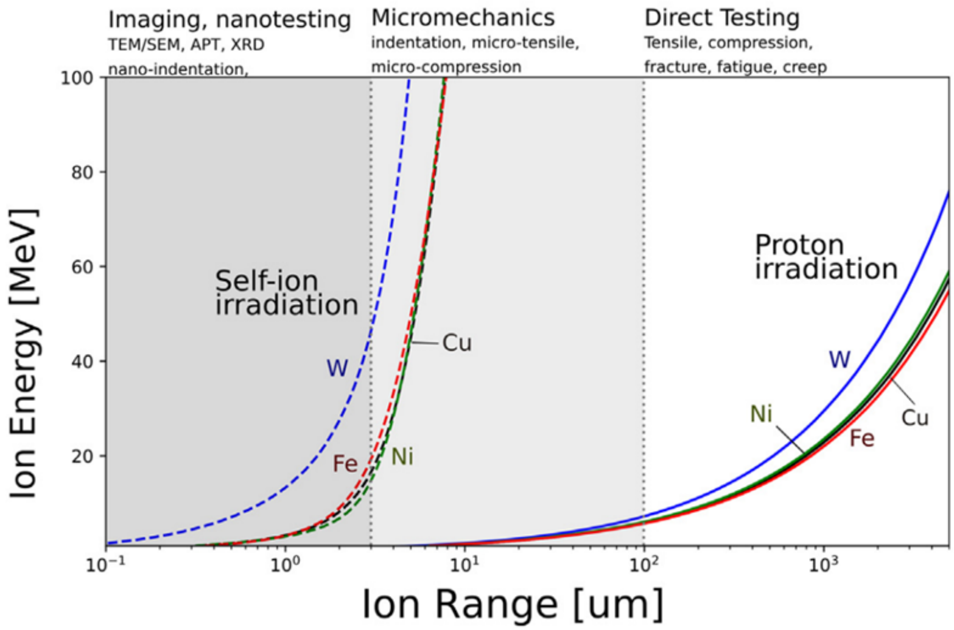


Figure 7. Ranges of intermediate energy protons in four common elements demonstrate the ability to achieve bulk penetration (right side of plot), allowing evaluation of irradiated material properties for direct testing at the macroscopic engineering scale [Jepeal, 2021]. Also shown are ion ranges (left side of plot) of self-ions with energies ranging up to 100 MeV and penetration up to a few micrometers.

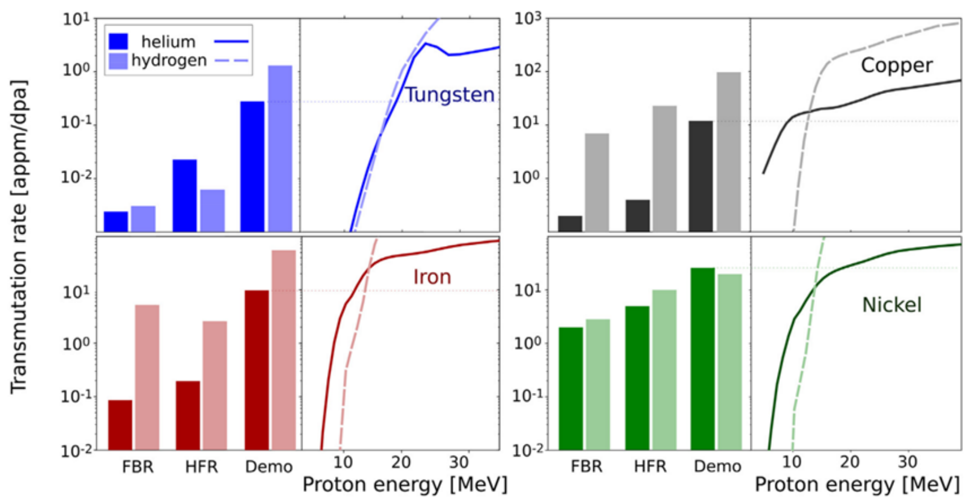


Figure 8. Transmutation calculations demonstrate that intermediate energy protons can generate fission- and fusion-relevant levels of He and H during irradiation [Jepeal 2021].

Moreover, the production of helium and hydrogen through transmutation can be controllable based on the incident proton energy and can be matched to any of the wide range of neutron environments (Figure 8), as in fast breeder reactors (FBRs), high flux reactors (HFRs), and a prototypical fusion power plant first wall (Demo) [Jepeal 2021].

This work [Jepeal 2021] emphasizes the need for IEPI capabilities, especially for fusion research, because material irradiation in a fission reactor is insufficient to reproduce the important effect of H and He accumulation found in fusion materials. IEPI differs by orders of magnitude in the production of He and H across neutron environments with a fusion power plant, typically producing one to two orders of magnitude more than either fission reactor environment due to the presence of higher energy neutrons (up to 14 MeV) from the deuterium-tritium fusion reaction. IEPI overcomes limitations, because nuclear reaction energy thresholds for generating H and He low-energy proton irradiation (below 5–10 MeV) and self-ion irradiation cannot generate fusion-relevant transmutation. Moreover, IEPI enables the tunability to produce fusion-relevant quantities of H and He transmutation gases over three to four orders of magnitude in concentration [Jepeal 2021].

In terms of fusion relevance, the combined Neutron-Ion Irradiation Strategy is the most effective way to achieve scientific understanding (through well-controlled separated ion experiments) and engineering validation (under neutron irradiation such as at HFIR). The approach of the combined Neutron-Ion Irradiation Strategy [Zhang et al 2023] may enable *nuclear screening*, a routine way to examine the credibility of candidates more quickly and to provide validation to designs and models of fusion fuel cycles and reactor systems. Neutrons and charged particles interacting with a solid will produce transient irradiation-induced processes. These processes are often referred to as athermal because there is little or only weak dependence on temperature. Although HFIR is a fission-type reactor, careful design of irradiation capsules will enable fusion-relevant information to be derived. The combined Neutron-Ion Irradiation Strategy is the most effective way to accelerate the damage evolution in a meaningful manner [Zhang et al. 2023]. New scientific perspectives include understanding and quantifying differences resulting from (1) spatial distribution of defects, (2) recoil spectrum, (3) density of cascade events on damage evolution (i.e., dose rate effect), and (4) temporal and spatial coupling of thermal and athermal defect processes by considering the athermal effect from hot electrons by ions vs. primary knock-on atoms (PKAs) produced by neutrons (note that PKAs from fusion can be several MeV).

3.2.3 Comparison of Current Capability with Similar Facilities

Some existing particle accelerators currently being used for nuclear materials research are capable of light ion implantation and damaging to a surface region up to a few µm [Mayer 2020, Zhang 2014]. Following the International Atomic Energy Agency (IAEA) Technical Meeting on Advanced Methodologies for the Analysis of Materials in Energy Applications Using Ion Beam Accelerators, a review was conducted of the status of ion beam analysis (IBA) techniques and some aspects of ion-induced radiation damage in materials for the field of materials relevant to fusion [Mayer 2020]. The article concludes that there is need for detailed material analyses and experimental simulation of radiation-induced damage. In both cases, accelerator-based ion beam techniques play prominent roles either in IBA or as tools for fast, efficient creation of radiation damage in solids for simulating certain effects connected with the impact of fast ions and neutrons.

A few ion beam facilities are listed below, along with details on the energy of accelerators ranging from 350 kV implanter to 14 MV tandem accelerator, and IBA analytical possibilities of samples from nuclear materials or fusion devices [Mayer 2020].

Table 3. Ion beam facility comparison [adapted from Mayer 2020]. Used with permission.

Laboratory, country	Accelerator	Available beams	Beamline	Methods available
Uppsala University, Tandem Laboratory, Uppsala, Sweden [6–12]	5 MV tandem	H, D, ^{3}He, ^{4}He, Li, and heavier ions	1	NRA (gamma & particle), RBS
			2	NRA, RBS, PIXE, μ-beam
			3	AMS tracer experiments for Be
			4	Chamber 1: RBS, NRA (gamma & particle), PIXE, TOF-ERDA; chamber 2: RBS, NRA (gamma & particle), PIXE, TOF-ERDA, large samples; chamber 3: RBS, NRA for cross section measurements
			5	Irradiation: 2 MeV to several ten MeV
			6	*In situ* growth and modification, RBS, NRA (gamma & particle), PIXE
	350 kV implanter	H, D, ^{3}He, ^{4}He, Li, and heavier ions including molecular ion beams	1	Implantation >2 keV, broad range of elements, RT—800 K
			2	ToF-MEIS with 2 PSD-detectors
			3	Low-energy HR-RBS & NRA, irradiation, cryostatic detector
	ToF-LEIS	H, D, ^{3}He, ^{4}He, Ne, Ar including molecular ion beams	1	ToF-LEIS with charge separation, AES, LEED, *in situ* growth and modification
University of Helsinki, Accelerator Laboratory, Helsinki, Finland [64–68]	5 MV tandem	H, D, Li, and heavier ions	1	NRA (gamma & particle), RBS
			2	NRA, RBS, PIXE
			3	AMS
			4	Chamber 1: RBS, NRA, PIXE, Tof-ERD; chamber 2: RBS, Stopper foil-ERDA; chamber 3: PAS
			5	Irradiation: 1 MeV—several ten MeV
	500 kV implanter	H, D, ^{3}He, ^{4}He, Li, and heavier ions including molecular ion beams	1	Implantation >100 eV, broad range of elements
			2	^{3}He NRA
			3	Low-energy RBS & NRA, irradiation
Max-Planck-Institute for Plasma Physics, Tandem Laboratory, Garching, Germany [37–42]	3 MV tandem	H, D, ^{3}He, ^{4}He, Li, and heavier ions	1	Chamber 1: RBS, NRA, ERDA (with He, Li, ^{12}C, ^{16}O beams); chamber 2: RBS, NRA, PIGE, large samples $\leqslant 300 \times 200 \times 100\,mm^3$
			2	Chamber 1: irradiation: 200 keV to several 10 MeV; chamber 2: RBS, NRA, ToF-RBS
			3	RBS, NRA for sample sizes up to $100 \times 20 \times 20\,mm^3$, glove box for Be contaminated samples, T up to 1 GBq
			4	RBS, NRA, ERDA, *in situ* irradiation and implantation with two ion sources
Los Alamos National Laboratory, Ion Beam Materials Laboratory, New Mexico, USA [56–63, 152]	3 MV pelletron tandem accelerator	H, D, ^{3}He, ^{4}He and heavier ions	1	Standard IBA techniques (RBS, NRA, ERD, PIXE, channeling).
			2	Self-ion high temperature irradiation/implantation under LN2 to 1273 K, ion irradiation and corrosion experiment
			3	He implantation to simulate material compatibility in actinides
Maier-Leibnitz-Laboratory (MLL), Garching, Universität der Bundeswehr München, Neubiberg, Germany [28–30]	14 MV tandem	H, D, ^{3}He, ^{4}He, Li, and heavier ions	1	Microprobe SNAKE: pp, dd, pd-scattering (coincidence ERDA) microscopy, high energy backscattering microscopy, transmission geometry with sample thickness 50 to 200 μm
			2	Q3D magnetspectrograph: heavy ion ERDA, high resolution ERDA
			3	AMS: high-energy AMS system with gas filled magnet system

The following recommendations were noted in the evaluation of the importance of ion-beam analysis for fusion research [Mayer 2020]:

1. IBA techniques allow full compositional analysis, including analysis of minute quantities, to understand underlying plasma surface interactions.

2. IBA techniques allow mass separation and depth profiling of special elements or isotopes such as light elements D, T, ^{6}Li, ^{7}Li, B, ^{15}N, ^{16}O, ^{18}O, and other tracers.

3. Intercomparability and standardization for future research needs should be implemented.

3.2.4 Design Requirements

Accelerators providing protons with energies above 10 MeV (and beam currents above ~1 μA) have been rare as a result of their high capital and operating costs, large physical size, electricity consumption, and staffing requirements [Jepeal 2021]. Therefore, these machines are typically too expensive for widespread materials development research and are dedicated almost exclusively to nuclear and astrophysical research or the production of isotopes for research and medicine.

3.2.5 Limitations/Challenges

One possible path forward is to consider separated and combined ion and neutron irradiation, as detailed below:

- HFIR produces high fission neutron fluxes, and over time, generates significant neutron fluence.
- There is a lack of fusion-relevant neutron energy sources to perform irradiations.
- Neutron irradiation for engineering validation via a multivariate condition, and ion irradiation for scientific understanding through single-variable experiments, are described below:
    - Neutron irradiation is multivariate. For example, in solid breeder materials, radiation damage, Li burnup, and transmutation product diffusion are entangled because of the specific neutron energy spectrum that is material dependent.
    - Ion irradiation allows separate effect studies to delineate various contributions to material degradation.

Combined ion and neutron irradiation [Zhang et al 2023] permits simulation of damage and microstructural evolution in an accelerated manner for material qualification.

1. Before neutron irradiation, samples can be modified by ion exposure to produce predicted neutron damage under different operating conditions and in-service periods.

2. After neutron irradiation, some neutron-irradiated samples can be further irradiated by ions (accelerated tests) to understand the subsequent defect and microstructural evolution, as well as the changes in mechanical behavior.

3. Such an arrangement can provide comparative information on materials response, in addition to data from the unmodified portion of the samples, thus enabling accelerated materials testing and evaluation. One example of a combined ion and neutron irradiation approach is to test critical feasibility of the solid breeding blanket concepts. The behavior of solid breeder materials after many years in a nuclear environment may be evaluated after a few hours or days of ion irradiation.

    1. Solid-state breeders must contain sufficiently high lithium density loading to ensure a tritium breeding ratio ≥1.05 within a limited space, must have good thermal, mechanical, and chemical stability with other blanket materials, must have low tritium solubility and high diffusivity, must have long-term irradiation resistance, and also must have good manufacturability.

    2. Although solid breeder materials have been studied for decades—to include thermal response, crushing behavior, hydrogen release, and pebble manufacturing—there is limited nuclear

qualification. The ion-neutron irradiation strategy can significantly accelerate scientific understanding and technical advances.

3. The accelerated path forward involves understanding and rapid evaluation of irradiation responses of solid breeder materials as follows:

    1. Breeding materials with desired grain sizes, control Li concentration, and enriched ^{6}Li materials

    2. Separated and combined ion-neutron irradiation strategies allowing for more rapid examination of materials' microstructure and mechanical properties resulting from the neutron-induced transmutation of Li to T and He

    3. Ion irradiation (before and after HFIR radiation) at controlled conditions

    4. Transmutation products to be implanted into the sample to study surface/interface diffusion and related microstructural evolution

    5. In situ or real-time ion beam analysis to monitor of H, He and Li migration and loss under real time irradiation and analysis at desirable temperatures

As an example of a study on radiation-induced gas migration pathways, irradiation-enhanced He migration and bubble formation resulting from cascade damage can be studied by He injection/implantation and self-ion irradiation in sequence with a targeted He/dpa rate. A similar study with both H and He pre-implantation can reveal synergistic effects on trapping and bubble formation. Moreover, based on redistribution from narrow H or He pre-implantation and controlled displacement damage doses with either small or large damage gradients (light or heavy ions), nonequilibrium defect dynamics of He or synergistic effects of H and He may be investigated as a function of irradiation dose, temperature, He/dpa and H/dpa rate, and distance from surface.

As an example of an investigation on damage evolution in breeder materials, studies can include single-variable experiments to understand damage evolution and materials degradation at high temperatures by varying energies (hundreds of keV to a few MeV) and dose rates (~10^{-1} to 10^{-4} dpa s^{-1}). In addition, light ion irradiation at controlled temperatures can be used to simulate low dose-rate neutron irradiation and to produce uniform damage layers tens of microns in depth that can be readily characterized by a variety of techniques. Such controlled irradiation experiments will allow for quantification of athermal effects on damage evolution in the breeder materials and will provide an effective approach to evaluate materials performance in neutron irradiation environments.

4. IMPLICATIONS

4.1 ASSET BENEFITS

Developing the critical facility with add on ion beam at HFIR will provide many benefits to HFIR and to the broader scientific community. These benefits cover many areas, including R&D, education and training, technology demonstration, and fuel qualification.

R&D benefits include the following:

- Nuclear criticality safety
- Nuclear reactor physics

- Radiation shielding
- Nuclear forensics
- Nuclear nonproliferation and safeguards
- Radiation detection techniques and devices
- Nondestructive detection/monitoring and imaging system design
- Reactor digital control system design
- Benchmarking of radiation transport code systems
- Materials for advanced fission and fusion reactors
- Irradiation damage studies
- Benchmarking of radiation transport code systems

As previously discussed, significant opportunities for education and training would be provided by a LPCF at HFIR. These opportunities would be available for HFIR and ORNL personnel, as well as external personnel through development of a user facility. These opportunities would be developed for the following areas:

- Nuclear criticality safety
- Nuclear reactor physics
- Radiation detector development
- Nuclear material accountancy
- Reactor operations and simulation
- Nuclear nonproliferation and safeguards
- Material science
- Reactor digital control and nuclear instrumentation

The facility will provide opportunities to demonstrate new cutting-edge technologies. The LPCF will be serve as a platform for demonstrating nuclear material control and accountancy processes, radiation detection and surveillance equipment, and fuel handling operations for operations with low-enriched uranium fuels, as well as benchmarking of radiation transport and core physics codes and the demonstration of modern instrumentation and controls technologies that could be used in advanced nuclear power reactors. In addition, the facility will support the initial physics testing of low-enriched fuels intended for commercial nuclear applications and be capable of providing the initial qualification of low-enriched uranium fuels for use in research reactors that require conversion from high-enriched to low-enriched uranium or for qualification of new fuel forms.

4.2 IMPACTS

ORNL is world-leading in neutron sciences. Not only does ORNL operate two cutting-edge neutron sources, HFIR and the Spallation Neutron Source, but it is also a technically diverse institution with expertise in a variety of disciplines, including materials science, nuclear data, nuclear instrumentation, and nuclear modeling and simulation (M&S). Addition of a general purpose critical facility would enhance the scientific research performed at ORNL in all these specialties. Moreover, a critical facility would enhance the DOE Office of Science's mission portfolio.

4.2.1 HFIR LEU Conversion and NNSA Support

In addition to replacing HFIR's reactor pressure vessel and enhancing its science capabilities, the BESAC report recommends coordination with the LEU program. In support of the NNSA Office of Materials Management and Minimization (M3) nuclear nonproliferation goals, HFIR LEU fuel designs are being developed and analyzed through M&S efforts. Conversely, the HEU core was designed principally by critical experiments as previously discussed. The computation approach reduces scope, cost, and time relative to experimentation; however, high confidence in M&S results are required to ensure that safety and performance metrics are achieved. Thus, experimental determination of reactor physics metrics followed by M&S validation studies are vital for understanding core behavior and the M&S tools' range of applicability.

To ensure that the safety and performance of HFIR is maintained following conversion to LEU fuel, parameters related to NCS and reactor physics for the new fuel must be determined and verified to enable operations and benchmark predictive analyses. The reactivity worth of the proposed LEU core design and its sensitivity to as-built fuel characteristics—includes but not limited to uranium enrichment and isotopic makeup; uranium loading and distribution; boron poison loading and distribution; and coolant channel spacing data—will be critical for storage, handling, transportation, and operations. Reactivity measurements are needed to support or supplement startup critical control element position estimates and shutdown margin verification testing. Additionally, reactivity measurements are needed to confirm that the inner and outer fuel elements, separately and assembled, are subcritical when submerged in water to meet criticality safety, transportation, and storage requirements.

Furthermore, direct measurement of fission rate distributions, coolant temperature coefficients, coolant void coefficients, control element differential and integral worth data, reactor dynamics (e.g., delayed neutron fraction, prompt neutron lifetime) would be highly advantageous for ensuring nuclear safety. These data could be used in the safety analysis report and directly entered into accident analysis calculations. The results could also be leveraged as high-quality validation data to help confirm or determine biases in M&S codes and methods. Performing these measurements in a critical facility instead of in the HFIR vessel would prevent operations from being significantly disrupted for long periods of time and would also prevent the need to outfit HFIR with the I&C required to perform such measurements.

4.2.2 Experiment and Component Qualification

As described in Section 3.1.1, a critical facility could support existing HFIR operations through reactor physics measurements. Use of HFIR's in-core irradiation facilities has increased over the last several years because of HFIR's high flux, its capabilities to perform accelerated damage studies (i.e., materials irradiation research), and its capabilities to produce high-specific activities of radioisotopes. Furthermore, irradiation of fuels and materials to support current and advanced fission and fusion communities is of particular interest.

Most irradiation experiments have small-to-negligible reactivity impacts and therefore would not require specific reactivity worth measurements. However, large experiments and experiments that employ thermal poison shields (e.g., Gd, Hf) can notably reduce core reactivity and perturb the power density distribution. High-fidelity safety basis neutronics calculations are required for these types of experiments to characterize the reactivity impact for startup calculations and operations, to characterize its impact on the power density distribution, and to ensure that the impact is enveloped in the HFIR safety analysis report. Performing direct measurements could reduce the scope of the safety basis calculations and could be used to supplement and validate the calculations. Furthermore, direct measurements could reduce uncertainty in the startup critical control element position estimate calculations.

The critical facility could also support reactor core component qualification efforts. Components are sometimes redesigned to take advantage of operational and maintenance experience gained over the last 55+ years, to take advantage of advances in technology, or to manage the loss of legacy capabilities. For example, the control elements were recently redesigned with one less row of pressure equalization holes and a reduced tantalum content to help mitigate blistering. Control element worth measurements would have been excellent supplemental data to the safety basis calculations for this effort. Furthermore, fuel elements and core components are often accepted as-is with features not meeting the strict tolerances required by ORNL's Nuclear Energy and Fuel Cycle Division. Calculations and safety evaluations are often performed to justify the acceptance of these nonconforming conditions. A few examples include skewed control element absorber cores, fuel homogeneity distributions, and boron impurities in aluminum. Having the ability to evaluate fuel and core components as necessary in a critical facility would increase the safety justification to qualify and accept them with nonconforming conditions.

5. DISCUSSION

5.1 OPTIONS CONSIDERED

Different configuration options were considered by the Critical Facility Working Group to support and enhance HFIR operations and ORNL research capabilities. Basic options considered include:

- Fixed configuration based on a HFIR fuel element
- Fixed configuration based on a non-HFIR fuel element
- Flexible configuration that could support both HFIR and non-HFIR fuel element styles

Of these options, the flexible configuration was pursued further because it will provide the greatest long-term flexibility and scientific capability. The other potential options are covered by the flexible configuration option and were not seen to sufficiently minimize complexity to provide a perceived benefit over the flexible configuration option.

6. CONCLUSION

In summary, the working group recommends that the critical facility be completed to provide additional world-class scientific benefits to HFIR and the broader scientific community. With the add-on ion beam, significant materials research can be performed at the LPCF, as well as supporting R&D and training, and user facility benefits can be realized.

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