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Reactor Performance Improvement Options to Sustain High Flux Isotope Reactor Leadership into the Future*

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ABSTRACT

The mission of the Neutron Sciences Directorate (NScD) at the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL) is the undertaking of high-impact research into the structure and properties of materials across the spectrum of biology, chemistry, physics, materials science, and engineering. NScD operates two world-leading neutron scattering facilities: the High Flux Isotope Reactor (HFIR) and the Spallation Neutron Source. HFIR achieved full power in 1966, and over a half century later, it continues to serve a variety of national missions. HFIR provides one of the highest steady-state neutron fluxes of any research reactor in the world to support scientific missions including cold and thermal neutron scattering, isotope production, and materials irradiation research. To sustain leadership in neutron sciences into the future, ORNL is exploring areas in which HFIR can be improved to enhance its performance. Many improvement areas are being explored including upgrading the cold source and neutron scattering facilities. The improvement areas discussed herein include replacing the reactor pressure vessel, upgrading the neutron reflector, and ensuring that reactor performance is maintained or enhanced after converting from high-enriched uranium to low-enriched uranium fuel.

KEYWORDS: HFIR, LEU, neutron science, pressure vessel, reflector, research reactor

1. INTRODUCTION

The High Flux Isotope Reactor (HFIR) is a U.S. Department of Energy (DOE) Office of Science User Facility that is operated at the Oak Ridge National Laboratory (ORNL). HFIR is a unique, high-performance research reactor that offers world-class capabilities and serves a variety of national missions and a broad range of science and technology communities. Its original mission of heavy actinide production has evolved over the years to include cold and thermal neutron scattering, isotope production, materials irradiation research, neutron activation analysis (NAA), gamma irradiation research, and fundamental physics research. Progression in neutron sciences and updates to HFIR's design and facilities since it reached full power in 1966 have resulted in HFIR's versatile mission portfolio. To enhance its scientific contributions and sustain leadership into the future, ORNL is exploring performance improvement areas.

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1.1 Historical Overview

Glenn Seaborg, the codiscoverer of plutonium, californium, and other heavy elements, recognized that a new domestic very high-flux reactor capable of producing substantial weighable quantities of heavy elements (e.g., berkelium, californium, einsteinium) was required to progress the field of transuranium element research. He wrote a letter to the Atomic Energy Commission (AEC) chairman in 1957 declaring this need, and following a series of meetings and reviews, it was recommended that a new high-flux reactor be designed, built, and operated at ORNL. ORNL submitted a proposal to the AEC in March of 1959 and a preliminary design report, spearheaded by Richard Cheverton, just a few months later in July.

HFIR achieved criticality in August of 1965 and 100% design power (100 MW_{th}) in September of 1966. In 1989, following a 2.5-year outage due to pressure vessel embrittlement concerns, HFIR was de-rated to 85 MW_{th} and the operating pressure was reduced from 5.27 to 3.33 MPa. HFIR was designed for the sole purpose of isotope production but beam tubes were included in its beryllium reflector to allow for neutrons to be delivered to experiments outside of the pool wall shielding. Pneumatic tubes were installed in 1970 and 1987 to enable and enhance NAA capabilities. Also in 1987, the number and size of material irradiation facilities were expanded. Horizontal beam tube 2 (HB-2) was increased in size in 2000 to triple the thermal flux on sample. Additionally, HB-4 was converted into a cold source beamline and it has been delivering a continuous high-brightness source of cold neutrons to the instruments in the cold guide hall since 2007.

1.2 Core Description

HFIR is an 85 MW_{th} pressurized, light-water cooled, light-water moderated, beryllium reflected, flux-trap-type research reactor. The reactor core assembly design consists of a series of concentric regions, each about 61 cm in height, and includes, from the core centerline outward: (1) a flux trap target region, (2) an inner fuel element (IFE), (3) an outer fuel element (OFE), (4) a control element region, and (5) a beryllium reflector (Figs. 1 and 2). The reactor core assembly is axially and radially reflected by light water and is contained in a pressure vessel, which itself is in a pool of light water.

The flux trap region provides the highest accessible thermal and fast neutron fluxes for isotope production and materials irradiation research, respectively. As shown in Fig. 2, the flux trap contains one hydraulic tube, six peripheral target positions, and thirty additional interior positions. The fuel assembly consists of the IFE and OFE that contain 171 and 369 involute-shaped fuel plates, respectively, which are secured

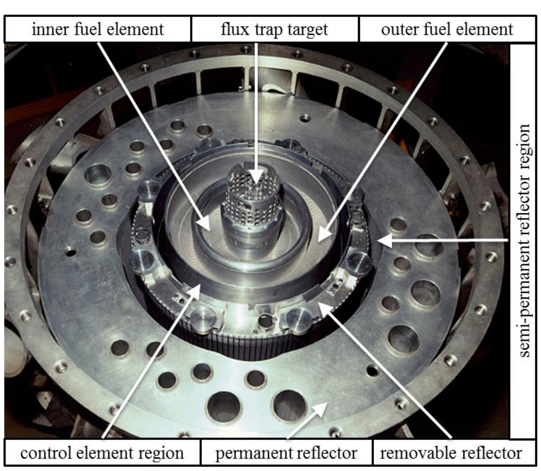

Figure 1. HFIR core mockup.

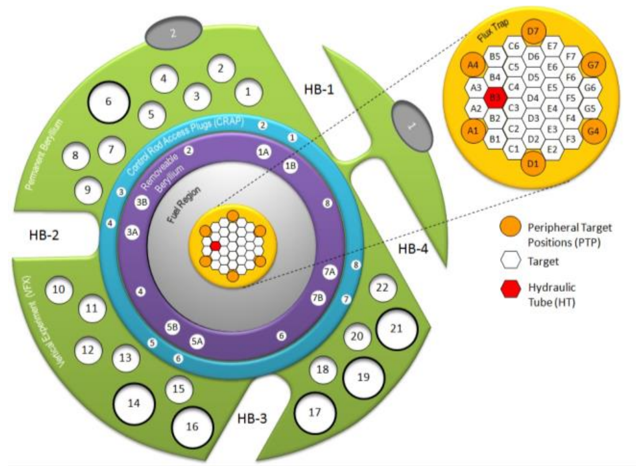

Figure 2. HFIR experiment layout.

within inner and outer cylindrical side plates. The fuel meat is high-enriched uranium (HEU) in the form of U_3O_8-Al which is collocated with a filler region within the aluminum cladding. The total core loading of ~9.4 kg ^{235}U results in cycle lengths that typically vary between 23 and 26 days at 85 MW_{th}.

Two concentric poison-bearing control elements located in the annulus between the fuel assembly and beryllium reflector are used for regulation and safety. The reflector, which is subdivided into removable (RB), semi-permanent (SPB), and permanent (PB) reflectors, is used as a neutron moderator and reflector. Additionally, the reflector houses 42 facilities for isotope production and materials irradiation purposes, four HB tubes for neutron scattering purposes, and two slant engineering facilities (one for NAA activities).

2. SELECTED PERFORMANCE IMPROVEMENT OPTIONS

Many performance improvement options are being explored such as upgrading the liquid hydrogen cold source moderator vessel to increase the brightness of the HB-4 cold beam [1] and building a new guide hall equipped with state-of-the-art instruments. However, the improvement areas focused on in this paper include replacing the reactor pressure vessel (RPV), upgrading the neutron reflector, and ensuring that performance is maintained or enhanced after converting from HEU to low-enriched uranium (LEU) fuel.

2.1 Reactor Pressure Vessel Replacement

The RPV consists of a cylinder (i.e. shell), a lower hemisphere, an upper head, and a lower head (Fig. 3). The shell diameter is about 2.39 m and is constructed of carbon steel cladded with austenitic stainless steel. The hemisphere and upper head are also carbon steel cladded with stainless while the lower head is stainless.

The RPV is HFIR's life-limiting component and has a life expectancy estimated to be 50 EFPY (100 MW) based on extensive evaluations of its structural integrity [2]. The RPV program consists of hydrostatic proof testing and an extensive surveillance specimen program. Assuming 2300 MWd per cycle, which is slightly conservative, and seven cycles per year, which is typical of current operations, the RPV may last until 2068. However, due to uncertainties in the evaluations and increased risk with age, it is prudent for HFIR to begin planning for RPV replacement.

Replacing the RPV with a new stainless steel RPV would extend the facility's life without complicated radiation damage limits, which would reduce the costs associated with maintaining the RPV basis. It would also enhance operational efficiencies by eliminating the need for periodic hydrostatic testing. Additionally, the vessel support structure could be enhanced to improve its seismic capacity.

The vessel in many ways restricts upgrades to the reactor because it is the most permanent fixture in the facility. This performance improvement option would consider a new vessel designed to more favorably accommodate anticipated future use of the reactor such as providing improved access to experiment facilities, allowing for neutron scattering component upgrades, and permitting a potential power up-rate. A power up-rate to 100 MW_{th}, for example, would improve reactor performance by ~18% and increase the peak thermal neutron flux from ~2.5 to ~3.0×10^{15} n/cm^2-s.

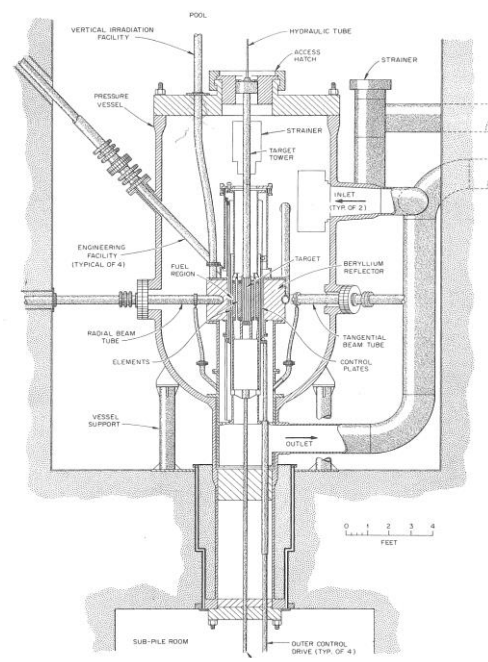

Figure 3. Reactor pressure vessel.

2.2 Neutron Reflector Redesign

The RB, SPB, and PB must be replaced periodically due to radiation damage, and their in-vessel lifespans are 83.7, 167.4, and 279.0 GWd, respectively. Assuming current operations, these exposures convert to 40, 80, and 133 cycles or approximately 5.7, 11.4, and 19.0 years. Recent studies, briefly described in the following sections, have been performed to (1) enhance the current PB design (i.e., PB no. 4) and (2) assess the feasibility of converting to a heavy water reflector.

2.2.1 Permanent Beryllium Reflector Redesign

In preparation for the PB changeout currently anticipated to be in 2024, the PB was redesigned to include six additional irradiation sites and be more versatile with respect to irradiation and scattering experiments [3]. Targets containing ^{237}Np are irradiated routinely in the PB vertical experiment facilities (VXF) to produce ^{238}Pu, which is used by NASA to fuel their radioisotope power systems.

The neutronics toolkit employed included the MCNP Monte Carlo-based transport code [4], the ADVANTG variance reduction tool [5], the SCALE ORIGEN point depletion and decay code [6], and the VESTA depletion tool [7]. A series of optimization and perturbation studies were performed to

(1) estimate potential increases in ^{238}Pu production with respect to the number of VXFs, number of targets per VXF, feed material form (cermet or oxide), bolt circle radii on which the VXFs reside, and number split between outer small VXFs and large VXFs;
(2) estimate the cycle length penalties associated with the concept designs;
(3) understand the impact of various configurations on beam tube fluxes; and
(4) calculate heat deposition distributions for use in follow-on COMSOL [8] thermal-structural (TS) calculations.

The TS calculations were performed to optimize the layout of the cooling features and reduce the number of stress-riser features. A holistic review of the neutronic and TS results, combined with discussions among the HFIR staff, resulted in the final design of PB no. 5.

The PB no. 5 design is expected to increase the annual production of PuO_2 for NASA's deep space missions by ~20-60% depending on the constraints implemented (i.e., impacts on other HFIR missions) [3]. Figs. 4 and 5 illustrate the HFIR MCNP model with PB no. 4 and 5, respectively, loaded with ^{238}Pu production targets. In addition to increasing the number of experiment positions, the new cooling hole layout enhances the temperature and stress profiles in the PB.

2.2.2 Heavy Water Reflector Feasibility Studies

Feasibility studies on converting the beryllium reflector to a heavy water (i.e., D_2O) reflector have been initiated to assess the potential benefits on HFIR's missions. This study only considers replacing or partially replacing the beryllium reflector with heavy water. Replacing the primary system light water coolant with heavy water is not studied because of the severe, resultant reactivity/cycle length penalty. More effort is needed to optimize the design and evaluate the impact on HFIR's infrastructure, systems (e.g., need for a detritiation plant), and safety basis. The toolkit used included MCNP, ADVANTG, and HFIRCON [9].

The beginning-of-cycle MCNP input [10] with the control elements fully withdrawn was used to characterize the impact the size of the heavy water reflector has on the neutron flux distribution and the fuel element fission rate density distribution. The radially dependent thermal neutron flux distributions for the base case (beryllium reflector) and cases considering replacement of the RB+SPB+PB, SPB+PB, and PB with heavy water are illustrated in Fig. 6. The thermal flux in the flux trap is slightly enhanced with the heavy water tank cases primarily because, as shown in Fig. 7, there is a small shift in power from the OFE

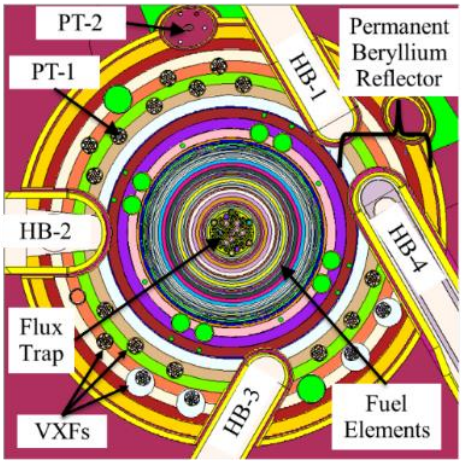

Figure 4. MCNP model with ^{238}Pu production targets in PB no. 4 design [3].

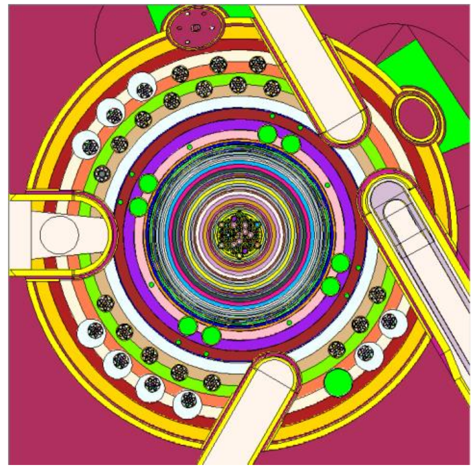

Figure 5. MCNP model with ^{238}Pu production targets in PB no. 5 design [3].

to the IFE. The peak thermal flux in the RB is decreased with the heavy water tank but, depending on the distance from the core centerline, the thermal fluxes in the PB are increased for the heavy water cases. At the origin of HB-1 (thermal beam) and HB-4 (cold source), the thermal flux for the D_2O RB+SPB+PB case is ~21% greater than that of the base case. The RB+SPB+PB case results in a maximum fission rate density decrease of ~9% at the outer radial edge of the OFE and a maximum increase of only ~2%, which is much less than that allowed by experiments in the HFIR safety basis.

The impact of the various configurations on the neutron stream traversing down the beam tubes were further studied by modeling collimators 2 m down the beam tubes, placing point detectors 3 m down the beam tubes, and only allowing neutrons from the locations of interest to contribute to the point detectors. The method discussed in [3] was employed; however, ADVANTG was not used for variance reduction, the para/ortho hydrogen split was changed to 35/65 to be consistent with [1], and a 50 interval equal lethargy

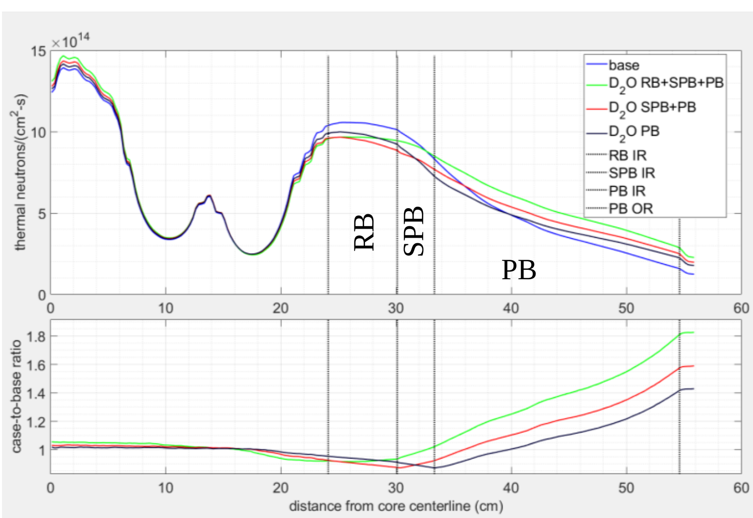

Figure 6. Radially dependent thermal neutron flux distribution comparison.

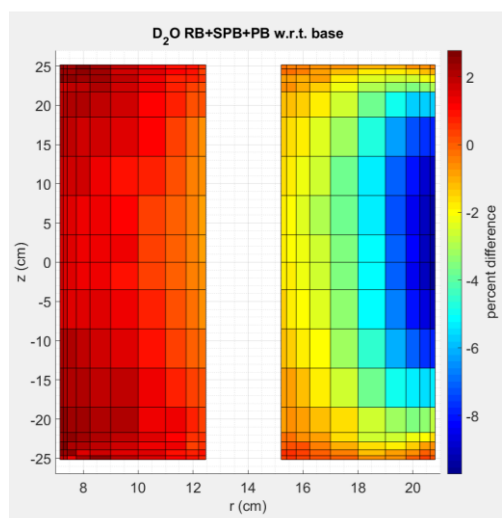

Figure 7. Fission rate density difference between base and heavy water cases.

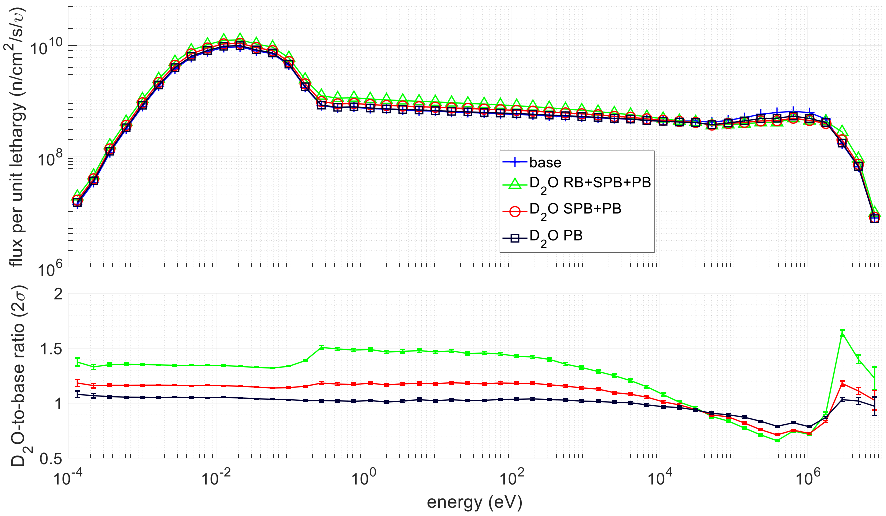

Figure 8. Neutron flux spectra comparison in the HB-4 cold source beam tube.

energy structure was used. A neutron flux spectra comparison is provided in Fig. 8 for the HB-4 cold source beam tube. Relative to the base case, the cold flux is increased by ~6, 16, and 34%, respectively, for the PB, SPB+PB, and RB+SPB+PB cases.

HFIRCON, a HFIR-specific neutron transport and depletion tool, was used to assess the cycle length penalties associated with the heavy water reflector configurations. The PB, SPB+PB, and RB+SPB+PB cases reduced the ~24-day-long base case by ~1.4, 3.4, and 12.3 days, respectively. Thus, the RB+SPB+PB configuration is not practical because it cuts the cycle length in half. Additional effort is needed to further this feasibility study such as evaluating time-dependent physics data for more complex configurations.

2.3 Conversion to Low-Enriched Uranium

The U.S. DOE National Nuclear Security Administration's (NNSA) Office of Material Management and Minimization (M^3) continues to reduce the risk of HEU through, among other means, its reactor conversion mission. ORNL supports this DOE mission by evaluating the conversion of HFIR from HEU to LEU (19.75 wt.% ^{235}U) fuel. A high-density U-10Mo monolithic alloy fuel was being evaluated for HFIR conversion until 2017 when focus was shifted to U_3Si_2-Al dispersion fuel. The U-10Mo fuel system is advantageous because it offers a density of ~3 g^{235}U/cm^3; however, fabrication of HFIR's complex fuel design has proven difficult with this fuel. Silicide fuel (~1 g^{235}U/cm^3) is now being assessed because it is expected to be easier to fabricate (the process is similar to HEU dispersion), advances in computational tools have increased the fidelity of modeling and simulation, relaxing the geometric constraints (e.g., elongating the fuel zone) have enabled increased fuel loading, and heightened interest in the European research reactor community (e.g., FRM-II, RHF, and BR-2).

Fuel design studies, making use of the ORNL Shift Monte Carlo-based tool [11] and an enhanced version the HFIR Steady-State Heat Transfer Code [12], are being conducted to evaluate performance and safety metrics, respectively, for U-10Mo and U_3Si_2-Al. Automation scripts for fuel design, code execution, and optimization have been deployed to increase the efficiency of the design studies that seek to balance the design features/variables (e.g., power, ^{235}U mass, fuel shape, burnable poisons) with fabrication complexity, reactor performance, and safety [13]. Proposed LEU fuel designs must maintain (or exceed) the performance of the HEU core, and a set of key metrics [14] have been defined as a means of capturing performance data essential for HFIR's primary missions.

Table I. LEU fuel design feature and performance comparisons to HEU.

Design	HEU	U10Mo-1	U10Mo-2	Silicide-1	Silicide-2
Fuel	U_3O_8-Al	U-10Mo	U-10Mo	U_3Si_2-Al	U_3Si_2-Al
Power [MW]	85	100	100	95	95
^{235}U [kg]	9.44	19.49	18.56	13.95	13.95
Fuel length [cm]	50.80	50.80	55.88	55.88	55.88
Burnable poison	^{10}B	^{10}B	^{10}B	^{10}B	^{10}B + Gd
Fuel zone location within fuel plate	off-centered	centered	centered	centered	off-centered
Axial contour	no	yes	no	yes	yes
Cycle length [day]	26.2	26.6	27.7	27.5	27.5
^{252}Cf production [mg/day]	1.39	1.51	1.39	1.41	1.40
Cold source cold flux [10^{14} n/cm^2-s]	4.48	4.87	4.55	4.63	4.64
Reflector fast flux [10^{14} n/cm^2-s]	2.89	3.35	3.20	3.22	3.22
Flux trap fast flux [10^{15} n/cm^2-s]	1.07	1.25	1.09	1.15	1.15
^{235}U utilization [kg/day]	0.36	0.74	0.67	0.51	0.51
Minimum margin to critical heat flux	1.61	1.59	1.50	1.62	1.54

An interim U-10Mo fuel design has been thoroughly analyzed [15] and U_3Si_2-Al feasibility studies have been performed [16]. Design studies are ongoing to optimize the U_3Si_2-Al designs [17]. Two U-10Mo and two U_3Si_2-Al [17] designs are presented and compared to the current HEU core in Table I. Results to date indicate that HFIR could convert and meet (or exceed) performance and safety requirements with both fuel systems. Refer to [13] - [17] for a more detailed discussion on the fabrication features discussed in Table I and the HFIR conversion project.

3. CONCLUSIONS

A few performance improvement options were presented that are being considered to sustain HFIR's leadership in neutron sciences into the future. Many improvement areas are being explored to advance the value and scientific output of HFIR in carrying out its current high-impact scientific missions and increase its preparedness for potential future missions. This paper focused on three options including (1) replacing the RPV, (2) enhancing the design of the reflector, and (3) ensuring that reactor performance is maintained or enhanced after converting from HEU to LEU fuel.

The RPV is HFIR's life limiting component that requires regular embrittlement evaluations, an extensive surveillance specimen program, and periodic hydrostatic proof testing. Replacing the RPV would reduce maintenance costs, improve operation efficiencies, and enhance performance by providing better access to experiments and allowing for a potential power uprate.

The PB was recently redesigned to include six additional irradiation sites, be more versatile with respect to irradiation and scattering experiments, and enhance the temperature and stress profiles. Feasibility studies were performed to assess the impacts that a heavy water reflector or a beryllium/heavy water reflector combination would have on reactor performance. An all heavy water reflector would result in a notable increase in thermal neutron flux outboard of the RB; however, this benefit comes at a costly cycle length penalty. A beryllium/heavy water reflector combination results in increased PB and beam tube fluxes and appears promising because the associated cycle length penalty can be minimized. Additional, higher fidelity designs and analyses are required to support this performance improvement option.

ORNL has been performing engineering evaluations on the conversion of HFIR from HEU to LEU in support of the U.S. DOE NNSA Office of M^3's mission to reduce the risk of HEU through, among other means, its reactor conversion mission. Evaluations to date indicate that HFIR could convert with a LEU U-10Mo or U_3Si_2-Al fuel type while maintaining or enhancing all its scientific missions.

4. ACKNOWLEDGMENTS

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