Design and fabrication of an axial neutron flux profile measurement assembly for the Advanced Test Reactor Critical Facility

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Abstract— **Real-time characterization of irradiation facilities improves the utilization of the core capabilities of test nuclear reactors. The ability to observe how the local neutron flux (level and spectrum) changes as control elements and experiments change will fundamentally transform our understanding of the underlying physical phenomena that govern the operation of present and advanced nuclear reactors, ultimately providing valuable information for the nuclear energy industry. The objective of this research was to demonstrate how advanced sensors could be used to significantly reduce the time and cost of experiments, improve our understanding of experimental environments, and enable verification and validation of simulation and modeling methods. This was accomplished by designing and fabricating a dedicated real-time instrument test train for the Advanced Test Reactor Critical (ATR-C) facility. The first year of this project focused on the design and modeling of real-time axial neutron flux monitors, leveraging proven technologies pioneered at the Idaho National Laboratory, to characterize the transient that occurs in the Small-B positions at the Advanced Test Reactor and the Advanced Test Reactor Critical Facility. We found that the flux amplitude in those positions can fluctuate as much as 380% depending on the outer shim control cylinder position. The engineering design of the test fixture and flux monitor instrumentation was the objective of the 2nd project year. New capabilities were established to electrodeposit enriched uranium for fission chamber development at the Idaho National Laboratory and trials were begun to characterize the process. The final year included the fabrication of the test fixture and instruments for Advanced Test Reactor Critical Facility. The fabrication process was delayed by supply chain and personal availability caused by the COVID-19 pandemic. However, we were still able to deliver this unique capability to Advanced Test Reactor Critical Facility that will enable future instrument testing and scientific experiments.**

Keywords — **ATR-C, Fission Chamber, MPFD, Real-Time Neutron Flux Measurement.**

I. INTRODUCTION

The Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL) in the USA is a prominent thermal test reactor designed to facilitate a wide range of nuclear experiments. With a typical operating full power of approximately 100 MWth, the ATR operates using Outer Shim Control Cylinders (OSCCs) to vary lobe powers, illustrated in Fig. 1. This versatility accommodates an array of high fluence tests that can simulate end-of-life conditions for reactor component materials (including fuel and structural materials) after only a few years of sustained irradiation.

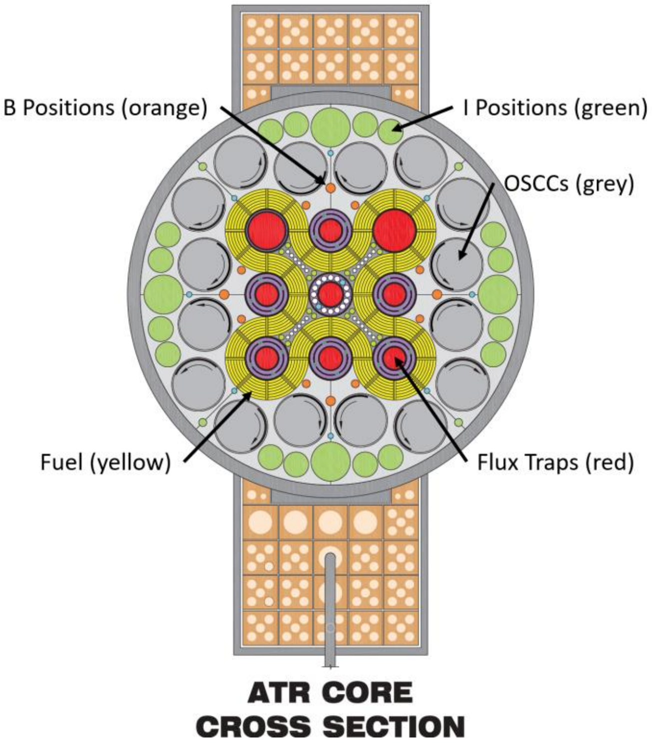

Fig. 1. The ATR core power can be tailored by rotation of the OSCCs (grey) to enhance or suppress neutron flux in different regions of the reactor [1].

The ATR is renowned for its numerous test positions, each offering unique capabilities, including in-pile tubes (red), A- (white), B- (orange), and I- (green) positions illustrated in

Fig. 1. These heavily utilized positions provide essential insights into the behaviors of materials in nuclear environments. The neutron environment within the ATR is highly heterogenous, illustrated in Fig. 2. Furthermore, the neutron flux distribution is not static throughout the nominal 60-day operating cycle, posing a challenge to reactor operators who aim to maintain stable power levels during experiments and experimenters as they interpret irradiation results.

One critical aspect of ATR experiments is burnup, the depletion of fuel over time. The reactor also accommodates a host of experiments simultaneously, spanning diverse areas of nuclear research. To manage and optimize these experiments, precise control mechanisms are essential. Currently, the ATR relies primarily on integral dosimetry measurements to determine neutron fluence rates during irradiations, a practice that has some limitations. Dosimetry is employed throughout the reactor, although it is often not specific to the experiment at hand. In the interpretation of experiment results, most teams adopt this conventional approach. However, real-time neutron flux monitors can also be used. Calibration of conventional real-time monitors is typically conducted within a thermalized neutron field, compared to the integral fluence in the field that is determined using dosimetry techniques. This approach yields results "per nv" a unit typically valid for similarly thermalized fields. This methodology, while widely used due to its applicability in various scenarios, presents a challenge. The response of most sensors is intricately linked to the neutron energy spectrum, which can significantly vary (especially in ATR).

The ATR's unique characteristic lies in its heterogenous nature, particularly in positions of utmost interest (in-pile tubes). These positions, characterized by the highest neutron flux, tend to also be the least thermalized. This inherent property complicates the straightforward application of conventional dosimetry methods. As a result, experiment teams working within the ATR must grapple with the intricacies of interpreting results and accounting for the complex neutron energy spectral shifts both in space and time.

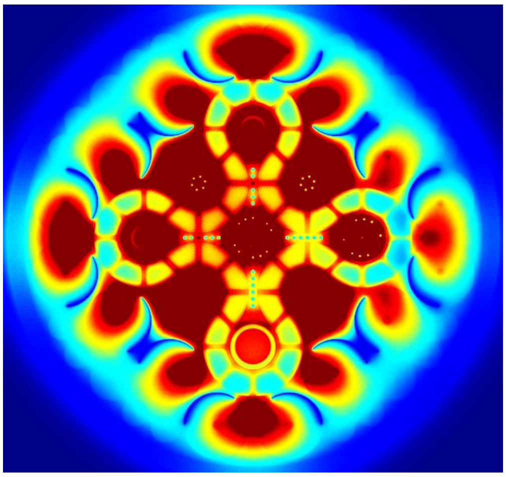

Fig. 2. The unique design of ATR creates an extremely heterogenous neutron flux distribution throughout the core, illustrated in this reproduced heat-map [2].

II. IRRADIATION AND TEST PLAN

The present research proposed an intriguing experiment conducted within the Advanced Test Reactor's Critical (ATR-C) facility. An irradiation test train was designed and constructed to utilize a Small-B position in ATR-C, strategically situated near the fuel and the OSCCs. The potential impact of OSCC rotation on the thermal neutron field within the Small-B position was investigated through modeling and simulation. These models characterized the influence such rotations wield on experiments which manifest dramatic shifts in both amplitude and spectral shape of the neutron flux. Specialized real-time neutron flux monitors were constructed based on prior research to be installed alongside conventional neutron flux monitors and passive dosimetry. A test plan was developed but operational and fabrication delays spurred by the COVID-19 pandemic prohibited the execution of the irradiation.

A. *Irradiation Plan*

The critical configurations of the ATR-C core were modeled to determine the expected neutron flux levels for the irradiation experiment. An ATR-C model was developed in MCNP [3], that could facilitate different OSCC. Critical core configurations were determined which had OSCCs adjacent to the Small-B position of interest at the nominal core critical position of 58.55° as well as the two most extreme positions which are allowed under the operating envelop of 5.73° and 150.1°, illustrated in Fig. 3. These represent positions where the OSCCs are turned completely inward and outward such that the hafnium absorbers have the greatest and least impact respectively on the irradiation position.

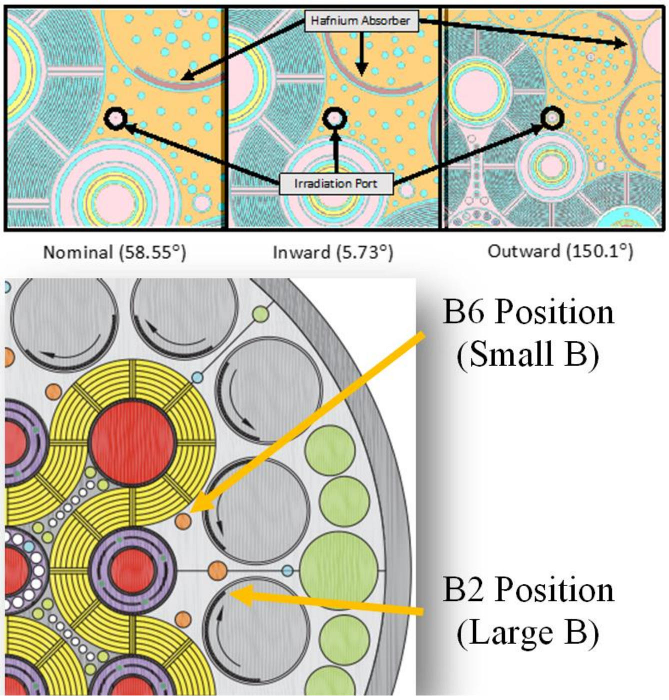

Fig. 3. The Small-B positions in ATR-C experience similar transients from OSCC rotation (illustrated above) as the Large-B positions (illustrated below) [4].

Neutron energy spectra were captured for each of 70 axial zones at these 3 positions. The normalized neutron energy spectra, comparing the neutron flux at the centerline axial position for each OSCC position, are shown in Fig. 4. Simulations revealed that even a slight shift from an inward position to the nominal setting brings about a discernible change in the thermal neutron environment. However, the most remarkable revelation stems from the transition from the nominal to an outward OSCC position, where a significant and pronounced transformation in the thermal neutron field is observed, shown in Fig. 4. These findings underscore the intricate interplay between reactor geometry and neutron behavior, shedding light on the dynamic and complex nature of nuclear systems. The variation in neutron flux can be explained by the greater local absorption of thermal neutrons when the outer shim control cylinder is turned inward (the 5.73° position) coupled with the greater neutron multiplication from the beryllium reflector when the outer shim control cylinder is turned out (the 150.1° position). These results confirm one hypothesis that was the basis of this research, that the neutron energy spectrum amplitude and shape are substantially perturbed by the position of the local outer shim control cylinders, demonstrating that there are penalties to experiments in ‘B’ positions that necessarily limit irradiation capabilities.

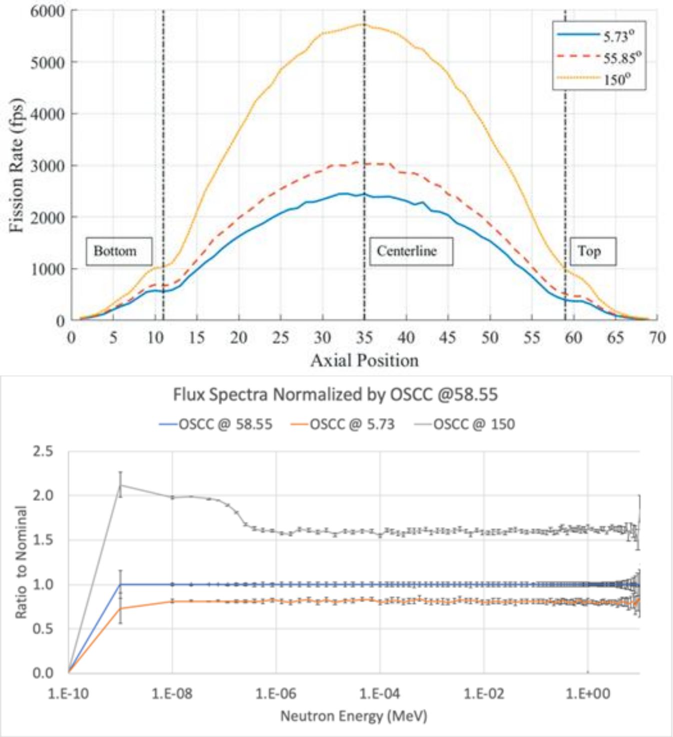

Fig. 4. Simulations of the neutron energy amplitude (above) and energy profile (below) demonstrate the dramatic shift that can occur nearby the OSCCs as they rotate from inward to outward positions [4].

The objective of the present research was to observe these spectral shifts in real-time by the installation of numerous neutron flux monitors in the Small-B position in ATR-C.

B. Sensor Selection, Design, and Fabrication

A tiered approach was used in the selection of neutron flux measurement sensors for the experiment. First, passive dosimetry was desired. This conventional approach is sensitive to the integral neutron fluence in a single position during the experiment. Therefore, an established real-time sensor was also selected to provide a scaling factor to translate the integral signal to the time-domain. Two Self-Powered Neutron Detectors were selected with hafnium emitters to provide sufficient sensitivity for the low-power ATR-C experiment. However, even SPNDs only provide a single point measurement. A multi-nodal instrument was also desired for the present research so that the axial distribution of neutrons in the experiment could be observed. Micro-Pocket Fission Detectors (MPFDs) have been developed previously which offered advantages for this experiment [5] [6] [7] [8]. Typical parameters of MPFDs were used to construct a 3-D model to assess the electric field within the sensors in an array of 4 detectors, shown in Fig. 5 (Top and Middle). Then, MPFDs were simulated in a characteristic neutron flux from the reactor-scale models. The response of sensors with various loadings of fissile ^{235}U were determined, shown in Fig. 5 (Bottom). The required fissile layer mass was determined to be between 0.5 to 1.0 µg of ^{235}U [4].

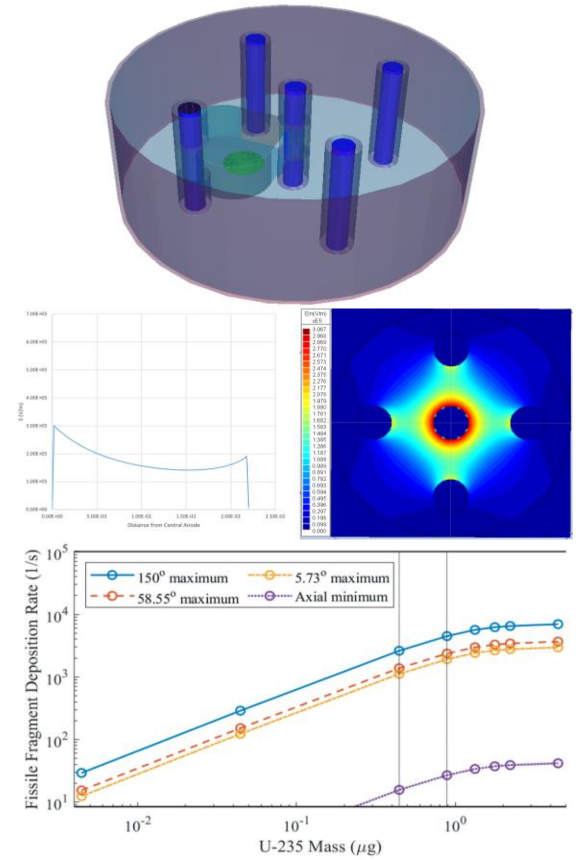

Fig. 5. A 3-D model of an MPFD (top) was developed to model the electric field characteristics (middle) within the sensor. These models were used to determine the response rate of MPFDs in the desired irradiation location (bottom) [4].

The high enrichment required for the present effort prohibited sub-contracting outside the national laboratory complex for the electroception of MPFD components. A method of electrodeposition of enriched uranium onto the small (~250 micro-meter) diameter electrodes was developed for the present research. The chemical preparation of the electrolytic solution was optimized, starting from the method developed previously [9]. Improvements to the consistency of the chemical preparation of the solution and the electrodeposition process dramatically improve reproducibility and reduced material waste compared to prior research [10]. A high-concentration enriched uranium solution was prepared from the enriched uranium dioxide source material. The chemistry and electrodeposition were performed at the Radioanalytical Chemistry Laboratory (RaCL) at ATR. The RaCL has appropriate work controls and support to facilitate safe work with both the powder uranium dioxide and liquid electrolytic solutions containing highly enriched uranium. The source solution was then diluted to prepare an appropriate amount of working solution that was pH balanced using precision pipetting for a highly reproducible system, shown in Fig. 6 (Top). The electrolytic solution was fixed under a microscope to allow the chemists to make electrical contact with the working electrode. Two electrodeposition methods were performed to deposit fissile material on the platinum substrate. Although both cyclic voltammetry and bulk electrolysis methods yielded electrodeposited uranium, the bulk electrolysis appeared to deposit more material. After the electrodeposition, the samples were cleaned, and the alpha-particle activity of the samples was measured using an alpha-particle spectrometry system at RaCL. A sample spectrum is shown in Fig. 6 (Bottom).

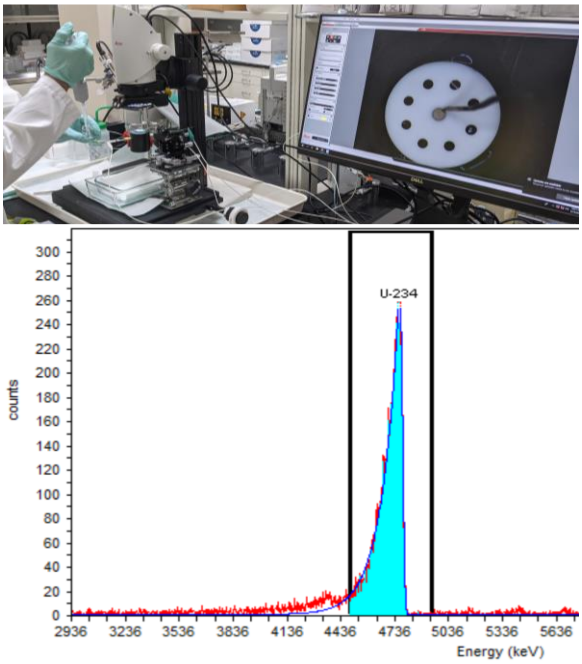

Fig. 6. An electrodeposition system (top) was developed that improved on prior research [9] [10]. The amount of U-235 was determined by measuring the activity of U-234 on the samples by alpha-particle spectroscopy.

Schematics were developed by which MPFD arrays could be constructed with proper spacing to ensure placement within the ATR-C core to align with the desired measurement locations, shown in Fig. 7 (Top). Then two MPFD arrays were fabricated using parts that were produced by laser waterjet cutting. The gas chamber, shown in the top-left of the bottom of Fig. 7, provides space for ionization from fission fragments in the MPFD. Silica spacers were used to ensure proper spacing between MPFD nodes, and the 2-ft. long MPFD array was attached to a mineral insulated extension cable by micro-tig welding inside an Ultra-High Purity Argon glove box at approximately 1 atm and a laser weld was used to seal any imperfections.

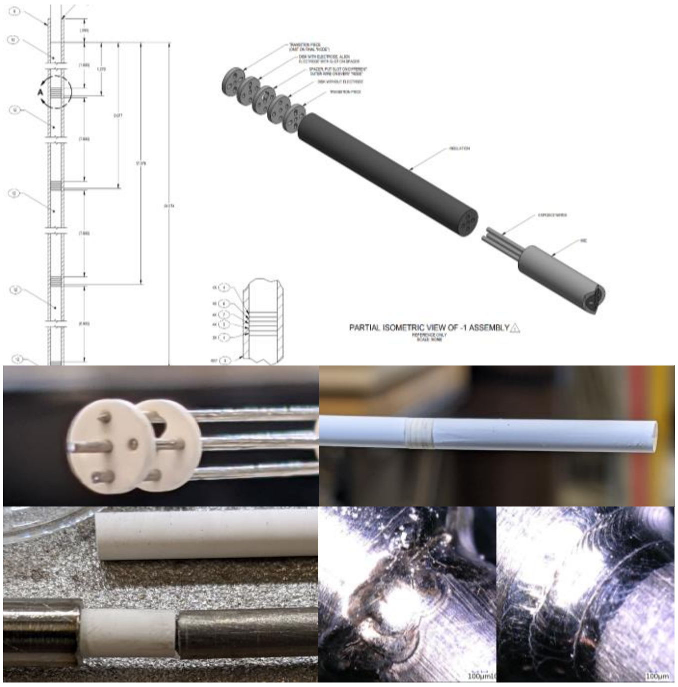

Fig. 7. MPFD arrays were constructed with 4 measurement locations separated by silica insulation and encapsulated in an Inconel sheath.

C. Test Train Design

The experiment test-train was designed to situate all the measurement devices in the proper location within the irradiation position in ATR-C. Illustrated in Fig. 8, each of the 5 sensors (2 SPNDs, 2 MPFD arrays, and 1 central dosimetry holder) were suspended in the test train with symmetry around the center of the position.

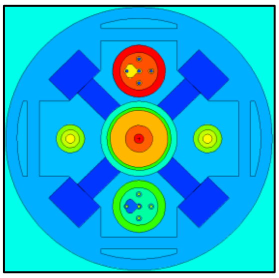

Fig. 8. The test train included support structures for two MPFD arrays (top and bottom), two SPNDs (left and right), and a central dosimetry package.

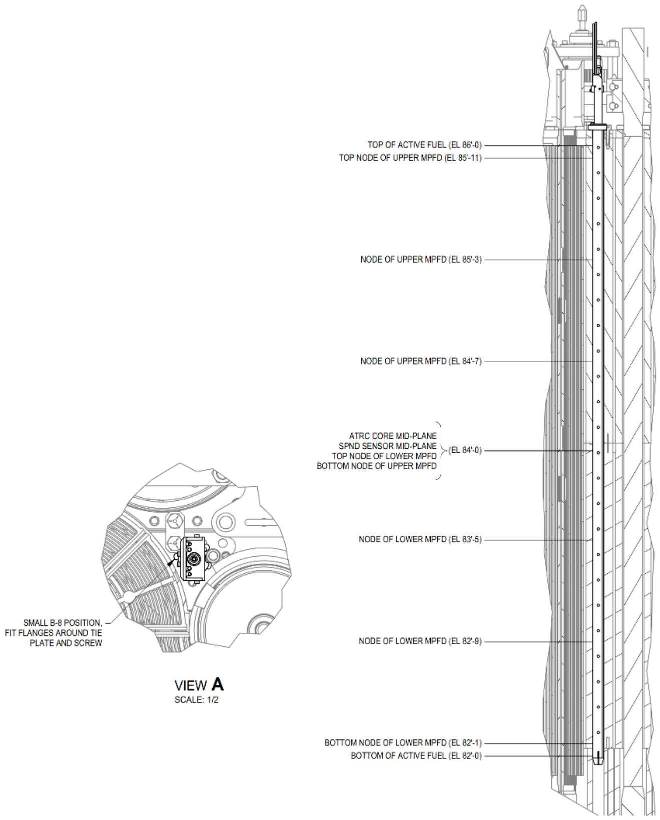

Fig. 9. The test train was designed to be inserted into the B-6 irradiation position at ATR-C without interfering with other structures while maintaining axial spacing of the neutron flux monitors.

The two MPFDs were each composed of 4 nodes. The bottom of one array overlapped with the top of the second array such that 7 independent axial positions were able to be monitored. The overlapping position, located at the core center plane, corresponded with the signals from the SPNDs and the dosimetry package where were also located on the core center plane, shown in Fig. 9. The outer sleeve of the test-train and the central support tube were constructed of 6061-T6 aluminum. However, Polyether ether ketone (PEEK) holders were fabricated to support each instrument to isolate them electrically from the reactor components. A special cruciform was designed to center the test train in the irradiation position, while a custom bale assembly was necessary to allow for the experiment to be lowered into the position and rotationally fixed. The structural integrity of the bale was assessed [11]. These efforts culminated in the publication of eight internally released engineering drawings at INL (DWG-607812 through DWG-607819). These drawings document the technical details of each component and were not only necessary to ensure the proper fabrication and assembly of components, but also as a tool to improve access to similar experiments in the future. The quality level determination for this irradiation was determined such that similar experiments could utilize many of the same features to reduce their preparation costs. Similarly, the drawings of the MPFD arrays can be further leveraged by other irradiation programs for production of these specialized instruments.

III. CONCLUSIONS

Although the irradiation associated with this project is still pending, several significant research outcomes were achieved. Future irradiations will be able to utilize the new test fixture for ATR-C to observe the difference in neutron flux in the Small-B positions at ATR-C due to different outer shim control cylinder configurations will be assessed. These results will improve irradiation capabilities by reducing uncertainties associated with experiments in these positions, improving INL's capability to meet irradiation missions. Furthermore, the new test fixture will enable experiments at ATR-C that were previously not possible, enhancing the utilization of this unique facility and producing new scientific results. The instrument design research and results developed new researcher skills by supporting two Ph.D. students and an early career scientist. This improved our capabilities to continue to meet the needs for in-core instrumentation in the future. The added capacity to perform thin-layer uranium compound electrodeposition at INL improved sensor fabrication capabilities enabling future ATR experiments to provide progressively higher fidelity measurements that will accelerate fuel cycle and advanced materials research. This research was well-aligned with the Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation (NEET ASI) real time in-core instrumentation work package that implements research and development activities to develop advanced sensors that address critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development. The new capability to perform enriched uranium electrodeposition at ATR will further benefit fission chamber development efforts at INL. Finally, the unique test fixture at ATR-C can also be utilized for simulation and modeling validation in transient reactor conditions.

IV. ACKNOWLEDGMENT

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