ATRC Neutron Detector Testing Quick Look Report

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1. INTRODUCTION

As part of the Advanced Test Reactor (ATR) National Scientific User Facility (NSUF) program, a joint Idaho State University (ISU) / French Alternative Energies and Atomic Energy Commission (CEA) / Idaho National Laboratory (INL) project was initiated in FY-10 to investigate the feasibility of using neutron sensors to provide online measurements of the neutron flux and fission reaction rate in the ATR Critical Facility (ATRC). A second objective was to provide initial neutron spectrum and flux distribution information for physics modeling and code validation using neutron activation based techniques in ATRC as well as ATR during depressurized operations. Detailed activation spectrometry measurements were made in the flux traps and in selected fuel elements, along with standard fission rate distribution measurements at selected core locations. These measurements provide additional calibration data for the real-time sensors of interest as well as provide benchmark neutronics data that will be useful for the ATR Life Extension Program (LEP) Computational Methods and V&V Upgrade project. As part of this effort, techniques developed by Prof. George Imel will be applied by Idaho State University (ISU) for assessing the performance of various flux detectors to develop detailed procedures for initial and follow-on calibrations of these sensors. In addition to comparing data obtained from each type of detector, calculations will be performed to assess the performance of and reduce uncertainties in flux detection sensors and compare data obtained from these sensors with existing integral methods employed at the ATRC.

The neutron detectors required for this project were provided to team participants at no cost. Activation detectors (foils and wires) from an existing, well-characterized INL inventory were employed. Furthermore, as part of an on-going ATR NSUF international cooperation, the CEA sent INL three miniature fission chambers (one for detecting fast flux and two for detecting thermal flux) with associated electronics for assessment. In addition, Prof. Imel, ISU, has access to an inventory of Self-Powered Neutron Detectors (SPNDs) with a range of response times as well as Back-to-Back (BTB) fission chambers from prior research he conducted at the Transient REActor Test Facility (TREAT) facility and Neutron RADiography (NRAD) reactors. Finally, SPNDs from the National Atomic Energy Commission of Argentina (CNEA) were provided in connection with the INL effort to upgrade ATR computational methods and V&V protocols that are underway as part of the ATR LEP.

Work during fiscal year 2010 (FY10) focussed on design and construction of Experiment Guide Tubes (EGTs) for positioning the flux detectors in the ATRC N-16 locations as well as obtaining ATRC staff concurrence for the detector evaluations. Initial evaluations with CEA researchers were also started in FY10 but were cut short due to reactor reliability issues. Reactor availability issues caused experimental work to be delayed during FY11/12. In FY13, work resumed; and evaluations were completed.

The objective of this "Quick Look" report is to summarize experimental activities performed from April 4, 2013 through May 16, 2013. This report documents the data and observations obtained while completing these activities, allowing ISU and other interested organizations, such as CEA, the opportunity to evaluate the performance of detectors included in this program. Previous work and documentation related to testing are discussed in Section 2. The observations for the most recent testing campaign are described in Section 3. Conclusions, recommendations, and proposed future work are summarized in Section 4. References are listed in Section 5.
2. BACKGROUND

Understanding neutron flux in a nuclear reactor is critical for safe operation of the reactor as well as for evaluating experiments in MTRs. Recently, it has become increasingly clear that further research into real-time flux sensors are needed to evaluate operating conditions as well as fuels and materials tests in ATR. Several activities were planned to research real-time detectors. As documented in Reference 1 and 2 (see Table 1), four specific activities were envisioned to be completed in this project. Each activity has 3 experimental configurations associated with the detector evaluations (see Figure 1). All of these activities were completed except Activity 4B. It is anticipated that Activity 4B will be completed at the end of FY-13.

Table 1. Summary Description of the Planned Experimental Activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I A.</td>
<td>Install and perform mechanical tests of Experiment Guide Tube (EGT) positioning devices for the N-16 positions with the ATRC in a shutdown configuration.</td>
</tr>
<tr>
<td>I B.</td>
<td>Experimentally evaluate potential radiation hazards to personnel due to neutron streaming to the surface of the ATRC water tank up the EGT assemblies. This is done via a series of low-power ATRC runs with the guide tube assemblies and dry tubes installed, but without instrumentation in place.</td>
</tr>
<tr>
<td>II A.</td>
<td>Perform NW Flux Trap activation foil and wire irradiations for each of three critical shim positions at 600 watts, beginning with the balanced configuration.</td>
</tr>
<tr>
<td>II B.</td>
<td>Perform core flux wire irradiation with U/AL and Cu/Au wires for the balanced critical shim position at 600 watts.</td>
</tr>
<tr>
<td>III</td>
<td>Test SPND detectors in the ATRC N-16 guide tubes in the positions of interest shown in Figure 1, with three different critical configurations of the outer shim cylinders. For each configuration, ascend to 600 watts with at least four intermediate power levels beginning at approximately 1 milliwatt. With each configuration at the maximum power, measure the axial flux profiles in the 6 N-16 locations shown in Figure 1.</td>
</tr>
<tr>
<td>IV A.</td>
<td>Test SPND and fission chamber detectors in the ATRC N-16 guide tubes in the positions of interest shown in Figure 1, with three different critical configurations of the outer shim cylinders. For each configuration, ascend to 600 watts with at least four intermediate power levels beginning at approximately 1 milliwatt. With each configuration at the maximum power, measure the axial flux profiles in the locations shown in Figure 1.</td>
</tr>
</tbody>
</table>

Figure 1. ATRC In-core Sensor Locations
2.1. Previous Work and Supporting Documentation

Initial work performed in FY-10 included Activity 1A/1B. Activity 3B was started, but not completed due to reactor reliability issues. Activity 1A was completed in TP-2-10, “N-16 Experiment Guide Tube Mock-up fitment in ATRC.” Activity 1B was completed, and activity 3B was started in TP-4-10, “N-16 Experiment Guide Tube Testing.”

Activity 2A/2B was performed under test plan TP-3-10, “Flux Runs for Activation Foil Measurements” and test plan TP-3-12, “Activation Foil Measurements - Irradiation 5” with results detailed in INL/EXT-10-19940 and INL/EXT-11-23348, "Advanced Test Reactor Core Modeling Update Project Final Report for Fiscal Year 2010" and "Advanced Test Reactor Core Modeling Update Project Final Report for Fiscal Year 2011." In addition, previous work of interest for validation purposes includes the flux run 12-8 for core loading 12-13 performed in TP-4-12, “SE-192 Reactivity and Axial Flux Measurements” with results detailed in ECAR-2089, “RML Data Package Flux Run 12-8 TP-4-12”.

2.2. Test Plan Details

An ATRC test plan governs the operation of ATRC and must be written to meet the experimental objectives. The test plan describes the ATRC Facility core changes and operations to be performed to test in-core neutron detectors in 4 Experiment Guide Tube (EGT) assemblies in the 4 inner lobe and 2 Center Flux Trap (CFT) N-16 locations. As outlined in Table 2, the first test will insert the in-core neutron detectors to test signal response at various power levels up to 600 watts and test the vertical movement of the EGT/dry tube/detector assemblies at 600 watts. The second test will evaluate the in-core detectors at various power levels up to 600 watts with the in-core detectors at core mid-plane and then measure the axial flux profile of the core at 600 watts. The third test will place the in-core detectors at core mid-plane and measure the power split for 3 outer shim configurations, balanced, un-balanced toward NW, and un-balanced away from NW. The fourth, fifth and sixth tests will remove the installed in-core detectors and insert different in-core neutron detectors that are capable of measuring fast and thermal neutron fluxes. The fourth test will repeat the tests performed in tests 1, 2, and 3 as well as perform a measurement of the ratio between the response for the thermal in-core detector and the fast in-core detector for a balanced Outer Shim Control Cylinder (OSCC) configuration. The fifth test will repeat the tests performed in tests 2 and 3 as well as perform a measurement of the ratio between the response for the thermal in-core detector and the fast in-core detector for an unbalanced core toward the northwest lobe OSCC configuration. The sixth test will repeat the tests performed in tests 2 and 3 as well as perform a measurement of the ratio between the response for the thermal in-core detector and the fast in-core detector for an unbalanced core away from the northwest lobe OSCC configuration. The seventh, eighth and ninth tests will repeat the tests performed in tests 1, 2, and 3 with different in-core detectors. Test objectives from the test plan are detailed.
2.3. Experimental Details

Several types of neutron detectors were evaluated to understand the operational characteristics needed for use in ATRC and for ATR experiments. Details related to the design, operation and evaluation of each type of sensor is discussed in the following sections.

2.3.1. Fission Chambers

Fission chambers, which are ion chambers with a fissionable material deposit on the inner wall, offer a method for real-time flux measurement (see Figure 2). The fission fragments provide a very large pulse from the neutron-induced reaction and can be used in either pulse or direct current mode. Normally highly-enriched $^{235}\text{U}$ is used for the coating, which makes them sensitive to thermal neutrons. However, other deposits can be used, such as $^{238}\text{U}$, $^{242}\text{Pu}$, or $^{232}\text{Th}$, providing a higher neutron energy cutoff.

Characteristics of the miniature fission chambers included in the ATRC evaluations are listed in Table 3. Miniature fission chambers are used in pulse mode using current preamplifier electronics. Uranium coat-

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**Table 2. Test Plan TP-2-13 Details**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Experimental Configuration</th>
<th>Test</th>
<th>Description/Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>A</td>
<td>1) Detector checkout</td>
<td>Verify detector response to neutrons and set fission chamber voltages</td>
</tr>
<tr>
<td>III</td>
<td>A</td>
<td>2) Power linearity tests</td>
<td>Verify detector response to power levels</td>
</tr>
<tr>
<td>III</td>
<td>A</td>
<td>2) Axial flux profile setup</td>
<td>Measure axial flux profile to determine location for maximum flux</td>
</tr>
<tr>
<td>III</td>
<td>A</td>
<td>2) Axial flux profile measurement</td>
<td>Measure axial flux profile</td>
</tr>
<tr>
<td>IV-A</td>
<td>A</td>
<td>3) Reactor power split measurements</td>
<td>Measure detector response when OSCCs are: 1) balanced, 2) with the NW OSCCs +4 from balanced position, and 3) with the NW OSCCs -4 from balanced position</td>
</tr>
<tr>
<td>IV-A</td>
<td>B</td>
<td>4) Detector checkout</td>
<td>Verify detector response to neutrons</td>
</tr>
<tr>
<td>IV-A</td>
<td>B</td>
<td>5) Power linearity tests</td>
<td>Verify detector response to power levels when OSCCs are: 1) balanced, 2) with the NW OSCCs +4 from balanced position, and 3) with the NW OSCCs -4 from balanced position</td>
</tr>
<tr>
<td>IV-A</td>
<td>B</td>
<td>6) Axial flux profile measurement with power split</td>
<td>Measure axial flux profile when OSCCs are: 1) balanced, 2) with the NW OSCCs +4 from balanced position, and 3) with the NW OSCCs -4 from balanced position</td>
</tr>
<tr>
<td>III</td>
<td>C</td>
<td>7) Detector checkout</td>
<td>Verify detector response to neutrons</td>
</tr>
<tr>
<td>III</td>
<td>C</td>
<td>8) Power linearity tests</td>
<td>Verify detector response to power levels</td>
</tr>
<tr>
<td>III</td>
<td>C</td>
<td>8) Axial flux profile measurement</td>
<td>Measure axial flux profile</td>
</tr>
<tr>
<td>IV-A</td>
<td>C</td>
<td>9) Reactor power split measurements</td>
<td>Measure detector response when OSCCs are: 1) balanced, 2) with the NW OSCCs +4 from balanced position, and 3) with the NW OSCCs -4 from balanced position</td>
</tr>
</tbody>
</table>
ing masses were chosen in order to provide a high fission rate in ATRC flux (from $10^3$ to $10^5$ cps). To pro-
tect these fission chambers and to preclude any leakage from fission chamber components into the ATRC
coolant, chambers were placed in tinted Lucite tubes.

2.3.2. SPNDs

SPNDs have been used effectively as in-core flux monitors for decades in commercial nuclear power
reactors and materials testing reactors world-wide. SPNDs rely on interactions of neutrons and atomic
nuclei to produce a current which is proportional to the neutron flux.

A typical SPND consists of a coaxial cable containing an inner electrode (the emitter), which is sur-
rrounded by insulation and an outer electrode (the collector). In an "integral SPND," the lead cable and
detector are mated directly to each other; the insulation of both sections are identical; and the collector of
the detector section is also the outer sheath of the lead cable section (see Figure 3). Modular SPND
assemblies are made from separate detector and lead cable sections. Typically, SPND characteristics of
interest include size, material compatibility at high temperatures, sensitivity, response time, and burn-up
rate.

Characteristics of SPNDs evaluated in this project are listed in Table 3. SPNDs were also placed in
tinted Lucite tubes to prevent any unwanted leakage of component materials (if they are not leak-tight) and
to reduce unwanted noise from the SPND cables being in contact with metal surfaces. SPNDs were
inserted into the ATRC N-16 positions using the EGTs.

2.3.3. Flux Wires and Foils

While not evaluated during the time period covered in this quick look report, testing flux wires and
foils provide validation data to determine the neutron flux and neutron spectrum used during evaluations.
An example of the various flux wires and foils with the accompanying test hardware is shown in Figure 4.
Table 3. In-core Neutron Detector Characteristics Under Evaluation

<table>
<thead>
<tr>
<th>Detector</th>
<th>Fissile Deposit</th>
<th>Anode/Fill Gas</th>
<th>Cathode / Fill Gas</th>
<th>Extension Cable</th>
<th>Maximum Core Insertion Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEA Miniature Fission Chambers</td>
<td>Mass 30μg (deposit on anode)</td>
<td>Material: SS304L (impurities of Co 0.02%) ID: 1.6 mm OD: 2 mm Length: 14 mm Fill Gas: Argon+ 4% N₂ Pressure : 5 bars</td>
<td>Material: SS347(impurities of Co 0.2%) ID: 2.5 mm OD: 3 mm Length: 33 mm except cable Fill Gas: Argon+ 4% N₂</td>
<td>Mineral cable (1CCAc22Si50 Ohms) OD: 2.2 mm Length: 10 mm Materials Sheath: SS304L Insulation: SiO₂ (&gt;99.5%) Wires: Copper (impurities of Zirconium 0.19%) Shield: Copper</td>
<td>Detector: U-235: 30 μg SS304: &lt; 2g Fill Gas: &lt; 5E-4 g Extension Cable: SS304: &lt; 300 g SiO₂ : &lt; 12 g Cu : &lt; 8 g</td>
</tr>
<tr>
<td>Miniature Thermal Fission Chamber</td>
<td>Mass 30μg (deposit on anode)</td>
<td>Material: SS304L ID: / OD: 1 mm Length: 51.5 mm Fill Gas: Argon Pressure: 9 bars</td>
<td>Material: SS316L ID: / OD: 1 mm Length: 33.5 mm Fill Gas: Argon Pressure: 9 bars</td>
<td>Organic cable RG58BU OD: 6.15 mm ; length 10 m Materials Sheath: PVC Insulation: polyethylene (PE) Wires: copper clad steel (CCS)</td>
<td>Detector: U-235 : 30 μg SS316L : &lt; 5 g Fill Gas: 1E-2 g Extension Cable: SS304: 0 g PVC : &lt; 30 g PE : &lt; 15 g Wires: &lt; 3 g</td>
</tr>
<tr>
<td>Miniature Fast Fission Chamber</td>
<td>Mass: 1000 μg (deposit on cathode)</td>
<td>Material: SS316L ID : / OD: 1 mm Length: 51.5 mm Fill Gas: Argon Pressure: 9 bars</td>
<td>Material: SS316L ID: / OD: 1 mm Length: 33.5 mm Fill Gas: Argon Pressure: 9 bars</td>
<td>Organic cable RG58BU OD: 6.15 mm ; length 10 m Materials Sheath: PVC Insulation: polyethylene (PE) Wires: copper clad steel (CCS)</td>
<td>Detector: U-235 : 30 μg SS316L : &lt; 5 g Fill Gas: 1E-2 g Extension Cable: SS304: 0 g PVC : &lt; 30 g PE : &lt; 15 g Wires: &lt; 3 g</td>
</tr>
<tr>
<td>Hafnium</td>
<td>Hafnium (minimum 97.5% with up to 2.5% Zr) – fast response Diameter: 0.4572 mm Length: ~ 400 mm (coiled to reduce length) Mass: 0.873 g (nominal)</td>
<td>Number: Two Material: Inconel 600 Diameter: 0.203 mm</td>
<td>Al₂O₃ Purity: 99.65% Compaction: ~70%</td>
<td>Inconel 600 ID: 0.904 mm OD: 1.372 mm</td>
<td>Hafnium: 0.897 g Inconel 600: 9.02 g Al₂O₃: 0.82 g</td>
</tr>
<tr>
<td>Gadolinium</td>
<td>Gadolinium (99.7%) – fast response Diameter: 0.559 mm Length: ~25 mm Mass: 0.0508 g</td>
<td>Number: Two Material: Inconel 600 Diameter: 0.229 mm</td>
<td>Al₂O₃ Purity: 99.65% Compaction: ~70%</td>
<td>Inconel 600 ID: 0.101 mm OD: 1.575mm</td>
<td>Gadolinium: 0.055 g Inconel 600: 12.50 g Al₂O₃: 2.29 g</td>
</tr>
<tr>
<td>Rhodium</td>
<td>Rhodium Diameter – 1 mm Length – 20 mm</td>
<td>Cu</td>
<td>Acrylic ID: 1.0 mm OD: 1.5 mm Length: 20 mm</td>
<td>SS-304 ID: 1.5 mm OD: 1.9 mm Length: 100 mm</td>
<td>Rhodium: 1g SS:0.5 g</td>
</tr>
<tr>
<td>Flux Wires</td>
<td>Materials</td>
<td>Diameter</td>
<td>Maximum Length</td>
<td>Maximum Core Insertion mass</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>----------------</td>
<td>----------</td>
<td>----------------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td>U₂₃₅-Aluminum</td>
<td>1 mm</td>
<td>0.635 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper-1.55 Gold</td>
<td>1 mm</td>
<td>1.27 cm</td>
<td></td>
<td>10 grams</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. In-core Neutron Detector Characteristics Under Evaluation

<table>
<thead>
<tr>
<th>Detector</th>
<th>Material</th>
<th>Encapsulation Material</th>
<th>Maximum Thickness (mm)</th>
<th>Maximum Diameter</th>
<th>Maximum Core Insertion Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal-neutron Detection</td>
<td>Gold (100 %)</td>
<td>None</td>
<td>0.0127</td>
<td>1 cm</td>
<td>200 mg</td>
</tr>
<tr>
<td></td>
<td>Manganese-Copper (80%/20%)</td>
<td></td>
<td>0.0127</td>
<td>1 cm</td>
<td>100 mg</td>
</tr>
<tr>
<td>Epithermal-neutron Detection</td>
<td>Indium (&gt; 99%)</td>
<td>Cadmium Covers</td>
<td>0.0127</td>
<td>1 cm</td>
<td>200 mg</td>
</tr>
<tr>
<td></td>
<td>Gold (&gt; 99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tungsten (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cobalt (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manganese-Copper (80%/20%)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Copper (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scandium (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast-neutron Detection</td>
<td>Niobium (&gt;99%)</td>
<td>Boron Sphere</td>
<td>0.0127</td>
<td>2.54 cm</td>
<td>1 gram</td>
</tr>
<tr>
<td></td>
<td>Rhodium (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indium (&gt;99%)</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Titanium (&gt;99%)</td>
<td></td>
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<tr>
<td></td>
<td>Zinc (&gt;99%)</td>
<td></td>
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<tr>
<td></td>
<td>Nickel (&gt;99%)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Iron (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper (&gt;99%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foil Encapsulation</td>
<td>Material</td>
<td>Application</td>
<td>Thickness, mm</td>
<td>Diameter</td>
<td>Mass</td>
</tr>
<tr>
<td></td>
<td>Cadmium (&gt; 99%)</td>
<td>Epithermal-neutron Detection</td>
<td>1</td>
<td>1.27 cm</td>
<td>1 g</td>
</tr>
<tr>
<td></td>
<td>Boron Sphere (&gt;99%)</td>
<td>Fast-neutron Detection</td>
<td>2.54 cm OD</td>
<td>1.27 cm ID</td>
<td>115 g</td>
</tr>
</tbody>
</table>

Figure 3. SPNDs
A summary of the advantages and disadvantages of each type of in-core sensor is listed in Table 4.

Table 4. Standard In-core Neutron Detector Characteristics

<table>
<thead>
<tr>
<th>Option</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Foils/Wires</td>
<td>• Inexpensive</td>
<td>• Only detect thermal or fast fluence</td>
</tr>
<tr>
<td></td>
<td>• Small</td>
<td>• Requires post-irradiation analyses</td>
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<tr>
<td></td>
<td>• Accurate</td>
<td>• Not real time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Only integral measurement</td>
</tr>
<tr>
<td>SPNDs</td>
<td>• Real time</td>
<td>• Require calibration</td>
</tr>
<tr>
<td></td>
<td>• No power supply needed</td>
<td>• Only detect thermal flux</td>
</tr>
<tr>
<td></td>
<td>• Simple and robust structure</td>
<td>• Response time/lifetime/sensitivity tradeoff</td>
</tr>
<tr>
<td></td>
<td>• Small diameter</td>
<td>considerations</td>
</tr>
<tr>
<td></td>
<td>• Good stability at high temperatures and pressures</td>
<td>• Background discrimination required</td>
</tr>
<tr>
<td></td>
<td>• Generate reproducible linear signal</td>
<td></td>
</tr>
<tr>
<td>Miniature Fission Chambers</td>
<td>• Real time</td>
<td>• Only fast or thermal flux</td>
</tr>
<tr>
<td></td>
<td>• Thermal or fast neutron flux monitoring, depending on deposited fissile material</td>
<td>• Require calibration</td>
</tr>
<tr>
<td></td>
<td>• Small diameter</td>
<td>• Require power supply</td>
</tr>
<tr>
<td></td>
<td>• Reproducible linear signal</td>
<td>• High temperature survivability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High pressure fill gas</td>
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<td></td>
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<td>• Lifetime/sensitivity/flux tradeoff considerations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Gamma discrimination required</td>
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2.3.4. Experimental hardware

In-core sensors were inserted into the ATRC in N-16 positions using Experiment Guide Tubes (EGTs). The EGTs are primarily fabricated from aluminum to minimize their weight. However, selected components, such as the guide tube shown in Figure 5 are made from stainless steel 304 for additional robustness. As illustrated in Figure 5, the six EGTs mechanically position detectors at a specified vertical location in the four N-16 exterior positions and two Center Flux Trap N-16 positions. The EGTs were supported above the reactor by attaching to the reactor control bridge.
The position control and detector response are controlled and measured via LabView software to allow all sensors to either individually or simultaneously move and measure the local neutron flux and provide a three-dimensional measurement of the overall neutron flux.

Figure 5. EGTs in ATRC
3. EXPERIMENTAL OBSERVATIONS

Detector evaluations were performed for a variety of operational conditions. As previously discussed, the reactor was brought to specified power levels between 0.01W and 600W. In addition, measurements were taken with the reactor shut down prior to startup and with the reactor shut down after startup. In order to assess if the detectors could be used to monitor various power splits, the reactor was purposely operated in an unbalanced condition, meaning the OSCCs in the NW lobe were positioned at +/-4 degrees from their nominal critical position. The following sections summarize the initial observations from experimental data collection and initial analysis.

3.1. Testing

As noted previously, the purpose of this project was to gain a more complete understanding of in-core sensor performance in a nuclear reactor. The response of various sensors were compared in numerous operational conditions to determine their usefulness for reactor operations and reactor experiments. Initially, the sensors were verified to be operational, then the detectors were used to track reactor power. Typical data obtained from power level testing in test 8 is shown in Figure 6.

![Figure 6. Comparison of Power Measurements Obtained from Rhodium SPNDs and a Fission Chamber from Activity III, Test 8, Experimental Configuration C](image-url)
Further testing continued by measuring the axial flux profile across the full length of travel of the EGTs. The position started outside the core above the reactor and continued until the EGTs reached the lower limit touching the bottom reactor support plate. The transition between the active region of the core top and bottom of the core seems to be the most pronounced in the center flux trap positions, H-3 and H-11. Representative data obtained from axial flux testing from test 8 is shown in Figure 7.

In addition to data collection, various insights were gained during the testing of the in-core sensors related to installation, operation, and data analysis and are summarized in the following sections.

### 3.1.1. Signal Response

Each type of detector demonstrated unique signal responses. The SPNDs displayed a current from -0.04 to 6 pico-amps. Due to the half-lives of the emitter materials, each type of SPND demonstrated a different response time for the signal to stabilize. Similarly, the decay of each type of emitter required careful consideration when monitoring power drops or recoveries from a reactor shutdown. This phenomenon can be seen on Figure 8 when the reactor was shut down during the middle of testing and the Hf-657, Hf-658, and Gd-663 signals did not return to the same values prior to shutdown.
The fission chambers displayed electrical pulses that corresponded to count rates from 0 to \(4 \times 10^6\) counts per second (cps). Unlike the response from the SPNDs, the response from the fission chambers did not have delays built into their signals. In addition, the fission chambers responded instantaneously to reactor power changes. As shown in Figure 8, the fission chamber signals returned to essentially the same value prior to a shutdown, whereas the SPND signals varied.

### 3.1.2. Power Level Linearity

The detector responses were checked at reactor instrument Log-N channel B readings of 0.00065 (shutdown) 0.02, 0.1, 1, 10, 50, 50, 100, 150 and 180 (approximately 600 W). As shown in Figure 6, all the detectors demonstrated a linear response to reactor power changes; but depending on core location, the slopes differed between the detectors in the north, south and center locations. This phenomenon was observed in all detectors. Hence, it is suspected that power in various core locations varies linearly with reactor power, but not equally with reactor power.

### 3.1.3. Detector Failures

One of the SPNDs and one of the fission chambers experienced failure during testing. Both failures were due to water egress in the dry tubes, eventually shorting the detectors that were not constructed to be leak-tight. The wet Rh SPNDs displayed a signal in the micro-amp range, which is several orders of magnitude higher than the upper value of its typical range (pico-amps). The fission chamber displayed random...
noise pulses. CEA has indicated that a thorough drying of the fission chamber and cabling would likely return the fission chamber to its previous operational condition. It is suspected the SPND would similarly benefit from a thorough drying. However, the detectors could not be thoroughly dried and retested in this series of experiments.

3.1.4. Measurement Repeatability

As previously discussed in 3.1.1 and 3.1.2, the measurement repeatability was very consistent for the fission chambers during all testing conditions and irradiation history. Due to the inherent manner in which SPNDs operate, the consistency of the measurements was closely related to their irradiation exposure. SPND response at the beginning of testing was not consistent with their response at the end of testing due to the increasing activation of the emitter during irradiation and decay of the emitter if the reactor is shut down during testing. SPND signal buildup during irradiation must be considered.

3.1.5. Sensitivity Comparisons

Detailed flux measurements using foils and wires in the N-16 positions have not been taken, so absolute sensitivities can not be determined. However, sensitivity comparisons between detectors can be determined by estimating the flux in the N-16 positions and by using cross-comparisons for each detector position.
4. CONCLUSION

Various real-time in-core flux sensors have been evaluated at the ATRC as part of a joint ISU/INL/CEA project funded through the ATR NSUF. The sensors were evaluated at various reactor power levels and at different positions throughout the core. The sensors were used to measure reactor lobe power as well as axial flux. Both fast and thermal neutron flux measurements were taken for comparison. These evaluations complete the ISU/INL/CEA project. However, the new capabilities developed from this project are available for future testing and evaluations of in-core sensors.

4.1. Experimental Setup and Testing

During sensor evaluations, it was noted that several areas of operation could be improved upon in future testing. Most notably is that the dry tubes remain dry throughout testing. The dry tubes were initially inserted into the ATRC canal in 2010, so it is unknown when the water leaked into the tube in the NW N-16 position. The Labview program developed for this project should be updated to allow for all drives to be moved simultaneously and to log data when requested.

Interfacing detector response with the reactor log count rate detectors would also aid in evaluations to verify the neutron flux remains constant throughout testing.

4.1.1. Tests Requiring Further Evaluation

The schedule to complete testing in the ATRC did not allow for appropriate drying of the fission chamber, so water ingress into the dry tube prevented further testing with the U-238 fission chamber. Further comparisons between thermal and fast flux would aid in understanding detector response between each type of detector.

Flux wire and foil measurements in the N-16 positions would be beneficial for comparisons between the real-time sensors and integral measurements.

4.2. Future Work

It is expected that in-core sensor evaluations will continue in the ATRC. The size and flexibility of the ATRC reactor core allows for alternative and advanced in-core sensors to be tested in a variety of conditions. Planned tests for future ATRC testing are identified in this section.

4.2.1. Back-to-Back (BTB) Fission chamber

BTB fission chambers, which are often called $2\pi$ fission chambers because they are designed to count almost all fission fragments emitting from a thin deposit in a $2\pi$ solid angle, provide the most accurate measure of fission reaction rates. For the ATRC evaluations, BTB chambers, developed in the Zero Power Physics Reactor (ZPPR) programs will be used. The BTB fission chambers are bisected hollow aluminum spheres, with stainless steel collector plates attached to the inside spherical surface of each half of the detector. Two stainless steel foils, coated with uranium, plutonium, or neptunium, were positioned such
that the uncoated sides are in contact. These foils act as the center divider inside the BTB chamber volume, and are kept at the same electrical potential. Each spherical half has its own purge gas (P-10, a mixture of argon and methane) supply and exhaust lines and coaxial cable signal leads.

The counting gas continuously flows through these fission chambers. This allows a chamber to be built that can be easily opened and allow fissile material deposits to be changed. There are two uses for this capability: first, one can cross-calibrate an unknown fissile material deposit to a known fissile material deposit; and second, reaction rate ratios such as spectral indices, are very accurate because the measurements of BTB fissile material deposits are made at precisely the same time. The disadvantage of this type of chamber is that it is limited in the amount of miniaturization possible. It is necessary to register all of the energy deposited by the fission fragments in order to ensure a full spectrum; and at atmospheric pressure, this range is relatively long. This requires a certain volume in the counting gas, which translates into a minimum fission chamber radius.

Initially, these BTB fission chambers were used for calibration of other detectors at ISU. However, specialized fixtures have been fabricated (see Figure 9) to allow a BTB fission chamber to be inserted into the ATRC NW LIPT alongside a CEA fission chamber to compare their response in near-identical flux conditions. The layout of the test fixture used to insert these BTB fission chambers into the ATRC is shown in Figure 10. Not shown is an additional insert for three in-core sensors to assess the flux gradient across the LIPT that can be used in place of the BTB fission chambers.

![Figure 9. Fabricated Back-to-Back Fission Chamber Fixtures](image)

The experimental hardware and procedures developed for this project will be available to other research programs needing to evaluate in-core sensors. Such sensors include Micro-Pocket Fission Detectors (MPFDs) for measuring thermal neutron flux, fast neutron flux and temperature simultaneously and Self-Powered Gamma Detectors (SPGDs) for measuring the gamma heating.
4.3. Recommendations

The choice of a real-time in-core flux sensor depends on the end-use requirements. For the purpose of this project, the end-use requirements are based upon the desired experimental measurements in a materials and fuels test or operational information needed to aid in reactor operation.

4.3.1. SPNDs

The simplicity of SPNDs makes them well suited for a variety of measurement conditions. They are small, robust, do not require a power source and generate a steady current while in a thermal neutron field. However, the current response is delayed and requires careful consideration if used to monitor fast power transients. Materials and fuels test are generally only monitoring for anomalies in reactor flux, so the delay
time associated with the use of SPNDs would be acceptable. However if the SPNDs are intended to be used as reactor power monitors, they will need to be supplemented with alternative fast response detectors for input into reactor safety systems. In addition, the SPNDs only operate at higher reactor powers, so they could not be used for the lower neutron fluxes encountered during a reactor startup.

4.3.2. Fission Chambers

The design of fission chambers is inherently more complicated than SPNDs; however, the fast response time associated with their operation can be a benefit for detection of neutron flux. The fission chambers also work well at low neutron fluxes, so it is expected they’d work well to monitor low level reactor power. In addition, very fast power transients would be more easily captured with fission chambers. Also, the fission chambers response does not seem to be heavily dependant on the previous irradiation history of the sensor.
5. REFERENCES

1. J.L. Rempe and D.W. Nigg, FY-10 Irradiation Experiment Plan for the ATR National Scientific User Facility - Idaho State University Project Evaluating Flux, PLN-3351, April 2010


5. Test Plan, TP-4-10, N-16 Experiment Guide Tube Testing, October 2010.

6. Test Plan TP-3-10, Flux Runs for Activation Foil Measurements, November 2010.


11. ECAR-2089, RML Data Package Flux Run 12-8 TP-4-12, November 2011.
### APPENDIX A.

**Table A-1.** Activity III, Test 2, Experimental Configuration A, Axial Measurements

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<th>SE</th>
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<th>SW</th>
<th>SW</th>
<th>NE</th>
<th>NE</th>
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<th>H-3</th>
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Table A-2. Activity III, Test 2, Experimental Configuration A, Power Linearity Measurements

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<th>U-235 FC 2253 (counts per minute)</th>
<th>Gd-663 primary (pico-amps)</th>
<th>Gd-663 background (pico-amps)</th>
<th>Hf-658 primary (pico-amps)</th>
<th>Hf-658 background (pico-amps)</th>
<th>U-238 FC 4 (counts per minute)</th>
<th>U-235 FC 2252 (counts per minute)</th>
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Table A-3. Activity IV-A, Test 3, Experimental Configuration A, Power Split Measurements

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<th>Gd-663 primary (pico-amps)</th>
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Table A-4. Activity IV-A, Test 5, Experimental Configuration B, NW Balanced, Power Linearity Measurements

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Table A-8. Activity IV-A, Test 6, Experimental Configuration B, NW Unbalanced +4, Axial Measurements

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**Table A-9.** Activity IV-A, Test 6, Experimental Configuration B, NW Unbalanced -4, Axial Measurements

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Table A-10. Activity III, Test 8, Experimental Configuration C, Axial Measurements

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### Table A-11. Activity III, Test 8, Experimental Configuration C, Power Linearity Measurements

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