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Conceptual Design of Neutron Sensor Qualification Device

September 2024

Changing the World's Energy Future

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Idaho National Laboratory

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Advanced Sensors and Instrumentation Program

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ABSTRACT

The Advanced Sensors and Instrumentation Program at Idaho National Laboratory has been formulating strategies to qualify sensors for use in nuclear environments, particularly in irradiation experiments and advanced reactors. When qualifying neutron sensors for use in high-temperature environments, the wide range of neutron flux levels and representative energy spectra presents significant challenges. This paper discusses the development of the Neutron Sensor Qualification Device (NQD), which is designed to test neutron sensors in high-temperature controlled environments with known neutron spectra, addressing the spatial and spectral complexities of neutron fluxes in reactor cores.

The proposed NQD will be situated in the exposure room at the Armed Forces Radiobiology Research Institute, thus affording a unique capability to expose sensors to high neutron and gamma fluxes. To achieve thermal control, the device will utilize a radiation-hardened tube furnace, accommodating multiple sensors and neutron activation dosimetry wires. Titanium, iron, and cobalt dosimeter wires are chosen from the American Society for Testing and Materials and International Reactor Dosimetry and Fusion File libraries as references for providing energy-dependent fluence measurements. The design ensures precise sensor positioning to minimize mutual shielding and flux perturbation, which are evaluated via Monte Carlo N-particle Transport Code (MCNP) simulations. These simulations have informed the development of guidelines on sensor placement within the NQD.

The NQD is essential to the qualification of neutron sensors for advanced reactor technologies. It enables controlled testing of a statistically significant number of sensors, thereby supporting assessments of sensor performance across various neutron flux levels and temperatures. This paper highlights the detailed planning for the NQD prototype, along with its inaugural irradiation (scheduled for fiscal year [FY]-2025). The results from this initial testing will be fundamental in evaluating the device’s performance and establishing measurement uncertainty for in-pile neutron sensor measurements.

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ACRONYMS

AFRRI	Armed Forces Radiobiology Research Institute
FC	Fission Chamber
INL	Idaho National Laboratory
MCNP	Monte Carlo N-Particle
NQD	Neutron Sensor Qualification Device
SPND	Self-Powered Neutron Detector
TRIGA	Training, Research, Isotopes, General Atomics

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Conceptual Design of the Neutron Sensor Qualification Device

1. INTRODUCTION

In recent years, the Advanced Sensors and Instrumentation Program at Idaho National Laboratory (INL) has been formulating strategies to qualify sensors for use in irradiation experiments and advanced reactors. Development of these devices and their corresponding methodologies has been steered by the *Guidelines for Developing and Qualifying Instrumentation Systems at Idaho National Laboratory* [1]. Sensor performance requirements and the level of rigor for qualification of these sensors largely depend on the intended end use. The highest level of rigor is required for sensors that serve a nuclear reactor safety function or support the licensing of new reactor technologies. The Temperature Sensor Qualification Device was the first sensor qualification device designed and prototyped at INL in fiscal year (FY)-2024, and its first irradiation is scheduled for FY-25 in the Advanced Test Reactor gamma facility, under a Nuclear Science User Facility Rapid Turnaround Experiment Proposal. Such efforts have set the stage for development of the Neutron Sensor Qualification Device (NQD).

Compared to temperature sensors, qualification of neutron sensors is significantly more challenging, due to the spectral nature of neutron energies, the wide dynamic range of neutron fluxes, and the difficulty in establishing a known flux. Low neutron flux levels calibration can be performed directly at the National Institute of Standards and Technology facility, or by irradiation testing with a neutron source that offers National Institute of Standards and Technology traceability [2]. However, qualification of sensors for high neutron flux levels and a representative energy spectrum (e.g., in-core locations within irradiation experiments and proposed advanced reactors) is much more difficult. The neutron flux levels of interest—specifically ones exceeding 10^8 n/(cm^2·s)—are typically generated by fission nuclear reactors, which feature unique neutron spectra that can vary spatially within the reactor and may fluctuate with changes in reactor power and operating temperature. Moreover, neutron sensor sensitivity, which is dependent on their design, is influenced by the neutron energies to which they are exposed.

This poses an intriguing challenge in regard to quantifying and qualifying the performance of in-pile neutron sensors. Neutron sensors installed as part of reactor facilities are typically calibrated using the heat balance method, which provides a correlation between the sensor output and the reactor thermal power output. While this technique is valuable for reactor control calibrations, it offers limited information for validating reactor models against experimental results.

Furthermore, many proposed advanced reactors operate at temperatures significantly exceeding those of conventional light-water reactors. Thus, high-temperature neutron sensors will be necessary for in-core measurements, whether for reactor control or model validation. The unique neutron spectra expected in these advanced reactor designs further complicates sensor qualification. As a result, assessing neutron sensor performance in reactors that differ from the typical light-water reactor applications will be hindered unless their performance relative to these unique temperatures and neutron spectra is evaluated.

Such challenges make it essential to quantify neutron sensor performance in heated neutron irradiation environments featuring known neutron spectra. To qualify a neutron sensor design for a specific application, a statistically significant number of sensors must be tested. However, this introduces further complications, as neutron sensors can cause significant local neutron perturbations. Installing sensors close to each other in-core can lead to inaccurate readings. This issue is exacerbated by the fact that most in-core irradiation positions in test reactors are only 2–3 cm in diameter. While the sensors could be separated axially along the reactor core to prevent mutual shielding, they would then be exposed to different neutron flux levels as a result of any axial flux variations.

The following section discusses the proposed irradiation facility to be used for neutron sensor qualification. It also gives an overview of the conceptual design of the device, along with the modeling results that support the device's feasibility.

2. IRRADIATION FACILITIES AND DEVICE DESIGN

As mentioned in the Introduction, significant space is required to prevent neutron sensors from substantially perturbing the neutron flux. Also, to test sensors at elevated temperatures, substantial heaters are needed, as well as insulation to protect the reactor from the heat, further limiting the available space for sensor placement. Moreover, the need to irradiate a statistically significant number of sensors in the same neutron flux essentially rules out in-core irradiation positions, leaving only the core-adjacent locations as viable options.

Some pool reactors have exposure rooms located adjacent to the pool wall. By positioning the reactor next to the exposure room, a high neutron and gamma flux can be achieved within the room. This unique capability is only available at a select few facilities. (The two such facilities of which the authors are aware are the Armed Forces Radiobiology Research Institute [AFRRI] and the Texas A&M University reactor.) The design and analysis covered in this report focuses on use of the AFRRI exposure room, a diagram of which is given in Figure 1. [3] The figure also provides a diagram of the NQD installed within.

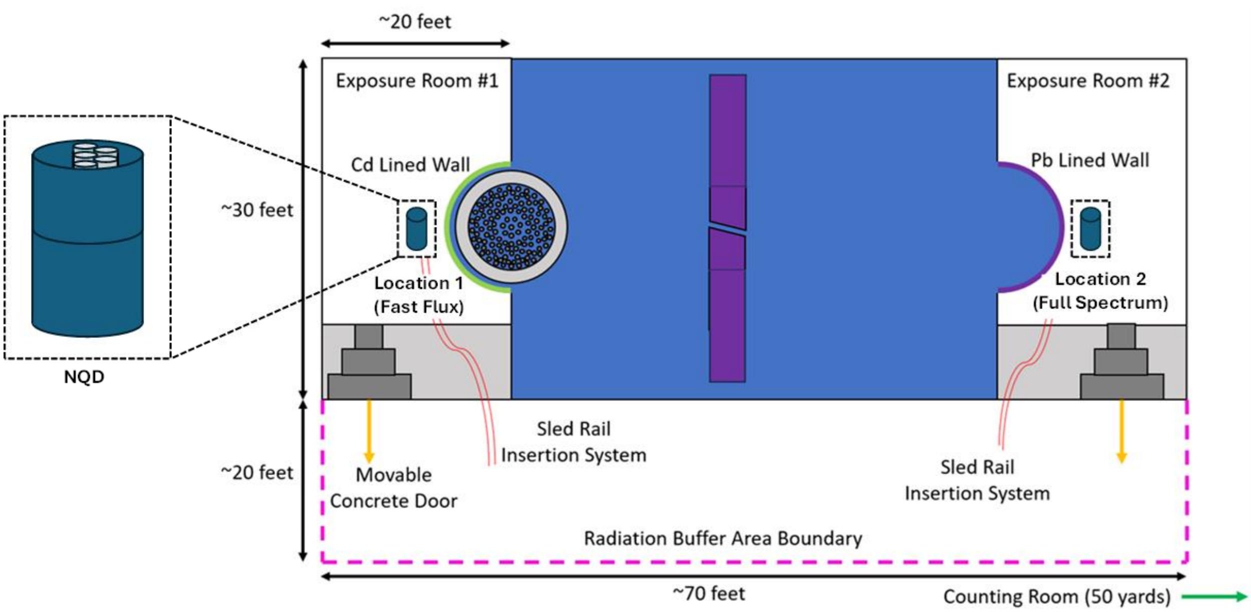

Figure 1. Diagram of the NQD device installed in the AFFRI exposure room.

The NQD conceptual design consists of a temperature-controlled environment capable of housing multiple neutron sensors and neutron activation dosimeter wires. Neutron activation dosimetry provides the energy-dependent neutron fluence reference against which to compare the neutron sensor readings. Details on the specific dosimetry package to be used in this device are given in the following section. The size of the exposure room allows for experimental configurations typically reserved for laboratory environments. To achieve thermal control, the NQD will utilize a modified, radiation-hardened tube furnace. Inside this furnace is a set of tubes that help homogenize the temperature and locate the neutron sensors and dosimetry packages. These locations must be precisely controlled to prevent the neutron sensors from shielding each other—a main topic of discussion in the subsequent sections.

Neutron sensor performance will be evaluated across a range of temperatures and neutron flux levels. For each flux level, a new set of dosimeters is required for establishing the neutron flux, under the assumption that the furnace temperature does not affect the neutron flux experienced by the sensors. Reactor power will be adjusted accordingly to assess sensor performance at varying neutron flux levels, thus necessitating a new set of dosimeters for each power level. In addition, the exposure room's cadmium- and lead-lined walls can, if desired, be used to filter the neutron flux so as to further refine the evaluation of the neutron sensors.

3. REFERENCE DOSIMETRY

Various dosimeter standards are commonly used for measuring neutron fluxes at different neutron energy ranges. Of the available materials and reaction types, the most widely used dosimeter materials at INL are titanium, iron, and cobalt (in the form of 99.5/0.5% w/o Al-Co alloy). These three materials are aligned with the American Society for Testing and Materials standards for determining neutron fluence, as well as with the International Reactor Dosimetry and Fusion File, which contains high-quality nuclear data for metrological applications [4], [5]. In application, the three wires include reactions that cover the Training, Research, Isotopes, General Atomics (TRIGA) reactor spectrum (see Figure 2). Additional dosimeters can easily be included if further neutron spectrum information is desired for qualifying the neutron sensors of interest, but these three will adequately serve as the base dosimetry package.

As shown in Table 1—which lists the three materials' relevant isotopic abundance, and product half-lives—only Fe-56 (n,p) Mn-56 and Ti-48 (n,p) Sc-48 have short turnaround requirements (irradiation and activation counting)—specifically, about 1 day and 2 weeks, respectively. While these two reactions can provide additional verification of the fast neutron energy range, an onsite counting facility would be required. However, the remaining reaction types still afford similar neutron spectrum coverage and are adequately long-lived to support turnaround times of a month or greater.

Dosimeters wires planned for the NQD will be ≤1-mm-diameter wires encapsulated in a 2-mm-diameter vanadium tube. Length variations on the wires and vanadium capsules are determined on an individual basis to ensure measurable activities from the irradiation (typically ~2.5 cm long). The vanadium capsule contains the dosimeters and affords a calibrated packaging for high-temperature environments in which the dosimeters may melt.

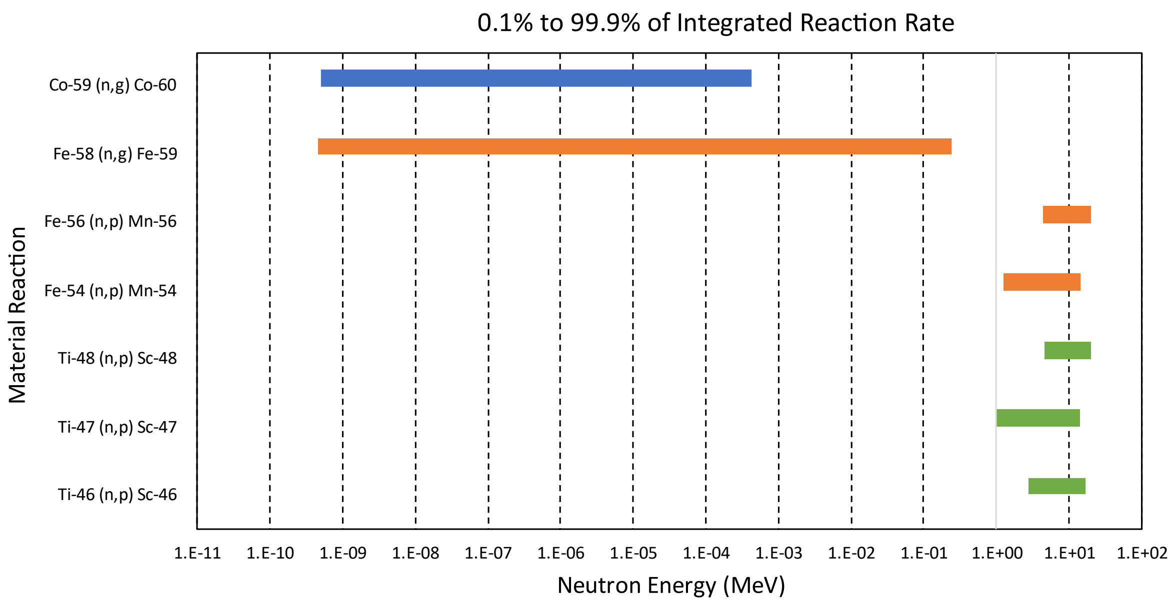

Figure 2. INL dosimeter neutron energy sensitivity range for a TRIGA reactor neutron flux spectrum.

Table 1. Titanium, iron, and cobalt's relevant reactions, isotopic abundance, and the product half-lives used for dosimetry.

Reaction	Isotope Abundance	Product Half-Life (sec)
Ti-46 (n,p) Sc-46	8.25%	7.24E+06
Ti-47 (n,p) Sc-47	7.44%	2.89E+05
Ti-48 (n,p) Sc-48	73.72%	1.57E+05
Fe-54 (n,p) Mn-54	5.80%	2.70E+07
Fe-56 (n,p) Mn-56	91.71%	9.28E+03
Fe-58 (n,g) Fe-59	0.21%	3.84E+06
Co-59 (n,g) Co-60	100.00%	1.66E+08

4. MCNP MODELING

A sensor positioning and separation evaluation is necessary to ensure minimal local flux perturbation influences on nearby sensors. This evaluation will dictate the number and spacing of sensors in accordance with a reasonable furnace size. Therefore, modeling of detector flux perturbation was performed using a Monte Carlo N-particle Transport Code (MCNP). A semi-cylindrical surface source—30 cm in diameter and 38 cm tall—with a TRIGA reactor spectrum to mimic the AFRRI exposure room was employed to model the local flux perturbation (see Figure 4). [3] The source was placed 100 cm away from the origin where the sensors were located. The sensors were placed horizontally in the NQD positioning tubes.

The flux perturbation was focused around three energy groups: thermal (0–0.5 eV), fast (>1 MeV), and total flux. A source-only MCNP run first provided the base neutron flux distribution. Subsequent MCNP runs, in which a sensor was positioned at the origin, were divided by the source-only results to calculate the perturbation percentage.

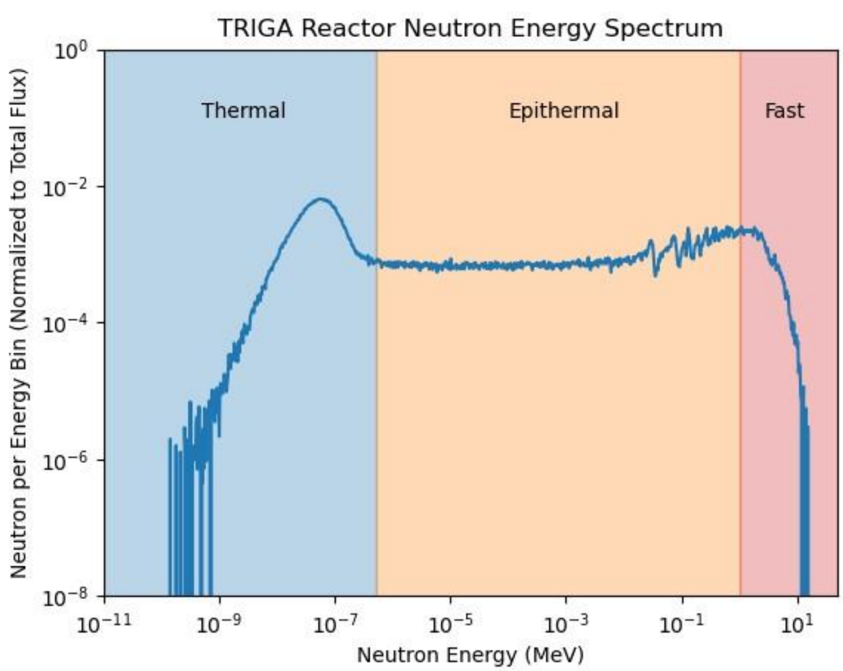

Figure 3. Plot of the typical neutron energy spectrum in a TRIGA reactor.

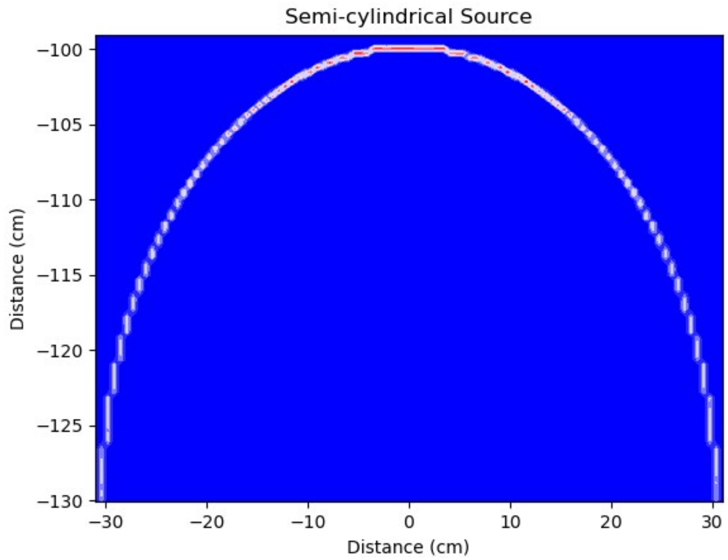

Figure 4. Semi-cylindrical surface source—30 cm diameter and 38 cm tall, with a TRIGA reactor spectrum—for modeling the local flux perturbation.

A survey of commercially available sensors was conducted for reactor power monitoring [6]. Applicable in-core fission chambers with the potential to operate in high-temperature environments (400°C and above) were chosen for evaluation. These sensors are listed in Table 2.

Self-powered neutron detectors (SPNDs) were also included in the evaluation as in-core detectors capable of withstanding high temperatures. Despite the large variety of detector geometries and emitters, the most common SPND types utilize rhodium and vanadium. Furthermore, the most common geometry utilizes a 0.16-cm-diameter probe and cable. To include past SPND evaluations performed at INL, rhodium SPNDs with an emitter length of 8.89 cm and overall diameters of 0.16 and 0.20 cm will be the primary focus [7], [8].

Table 2. Commercially available fission chambers for in-core use, with the potential for high-temperature operation.

Detector	Sensitivity	Range (nv)		Max Temp. (°C)	Max Dimensions (cm)	
		Min	Max		Diameter	Length
Exosens						
CFUE24	1×10^{-2} cps/nv	10^{2}	10^{8}	400	0.7	15.0
	1×10^{-15} A/nv	10^{8}	10^{12}			
CFUE32	1×10^{-3} cps/nv	10^{3}	10^{8}	600	0.7	15.0
	1×10^{-16} A/nv	10^{9}	10^{13}			
CFUR64	8×10^{-6} cps/nv	10^{6}	10^{11}	400	0.3	4.2
	9.2×10^{-19} A/nv	10^{12}	10^{15}			
Mirion						
WL-24132	5.6×10^{-18} A/nv	10^{10}	1.4×10^{14}	400	0.47	6.6

Neutron flux perturbation contour maps for each sensor are provided in Figure 5 through Figure 10. The dashed lines represent the threshold for 1% perturbation; the solid lines represent the threshold for 5% perturbation.

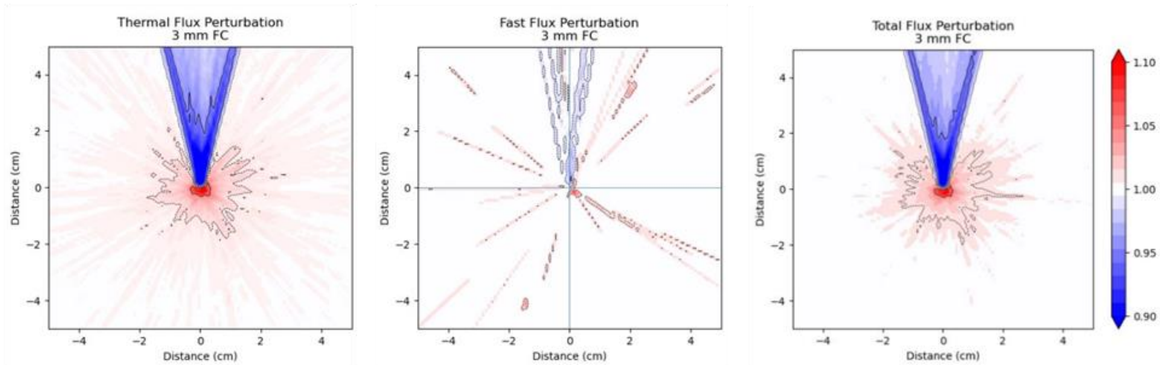

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Figure 5. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a 3-mm fission chamber (FC).

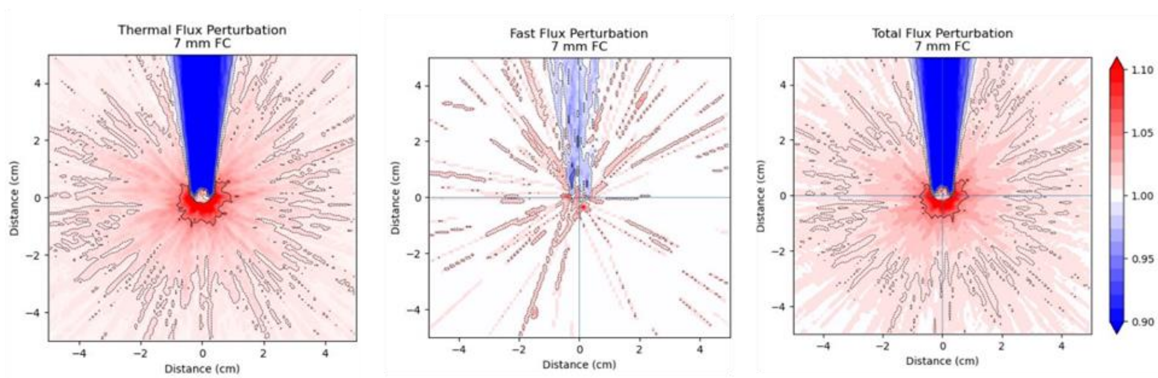

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Figure 6. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a 7-mm FC.

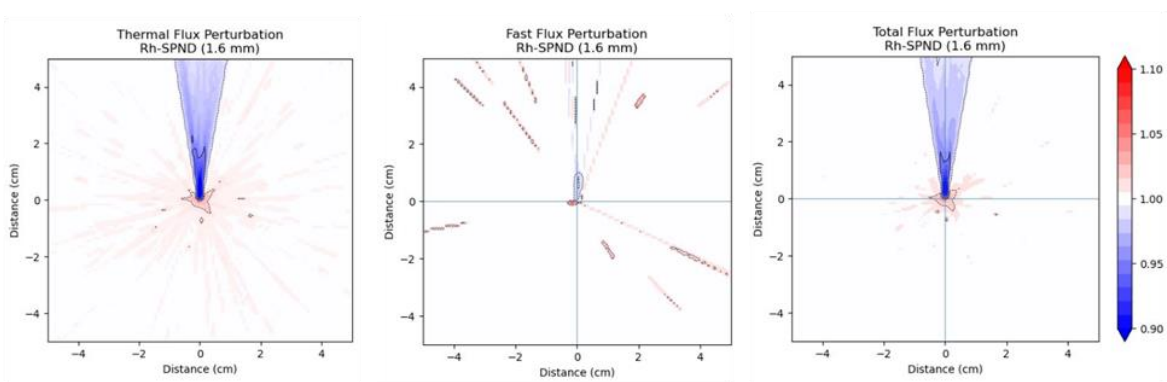

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Figure 7. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a 1.6-mm rhodium SPND.

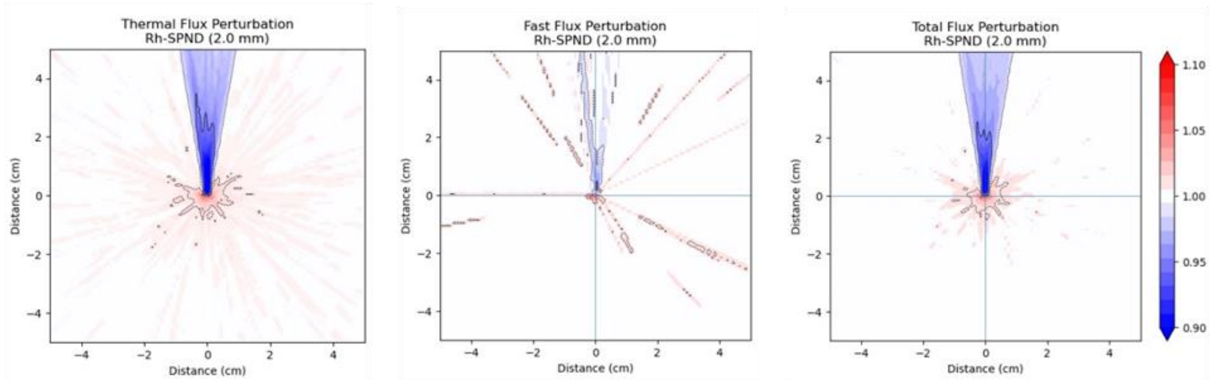

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Figure 8. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a 2-mm rhodium SPND.

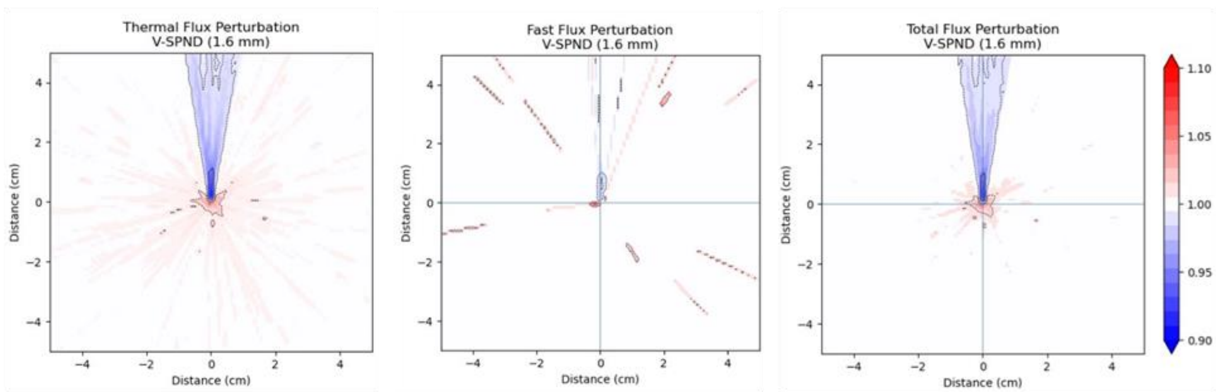

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Figure 9. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a 1.6-mm vanadium SPND.

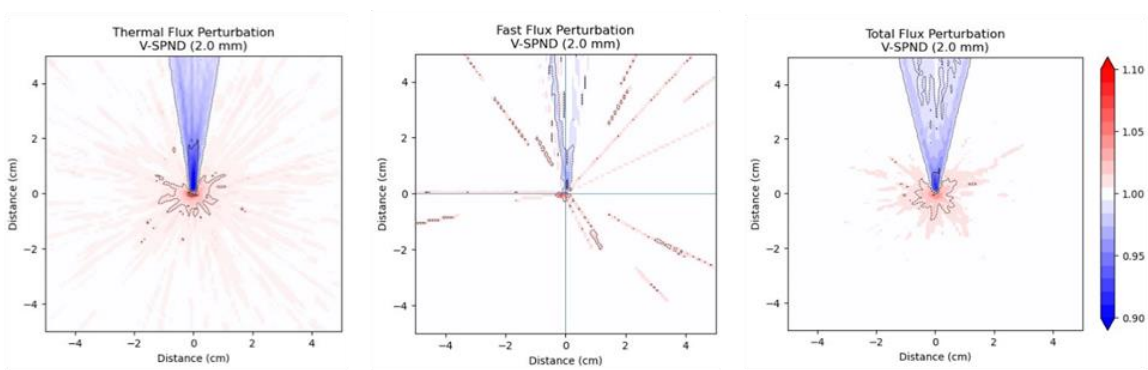

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Figure 10. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a 2-mm vanadium SPND.

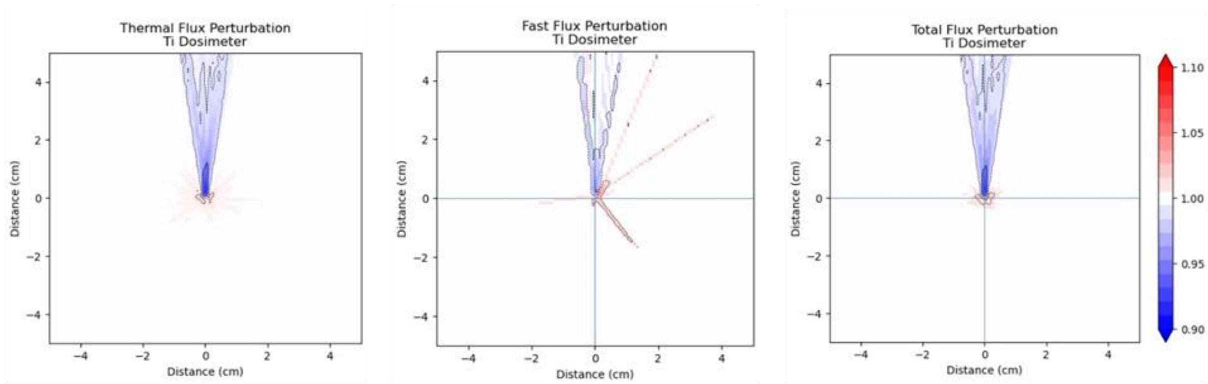

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Figure 11. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a titanium dosimeter package.

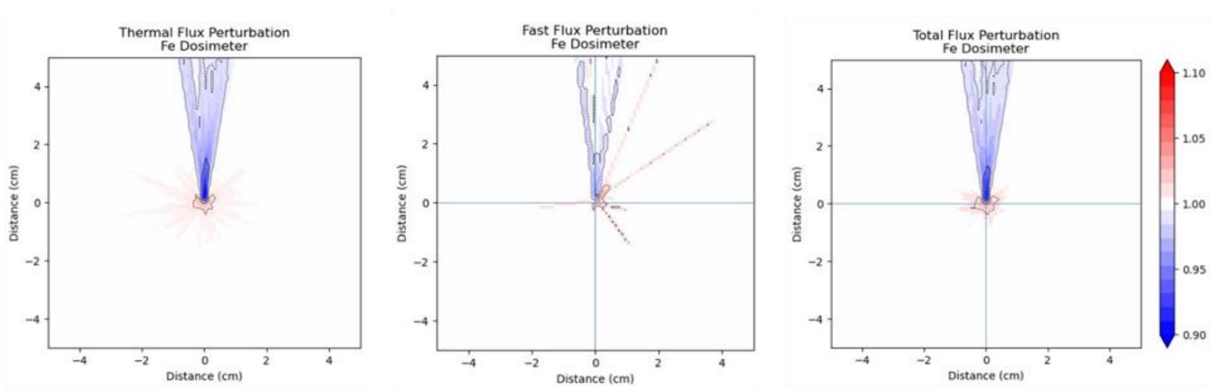

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Figure 12. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of an iron dosimeter package.

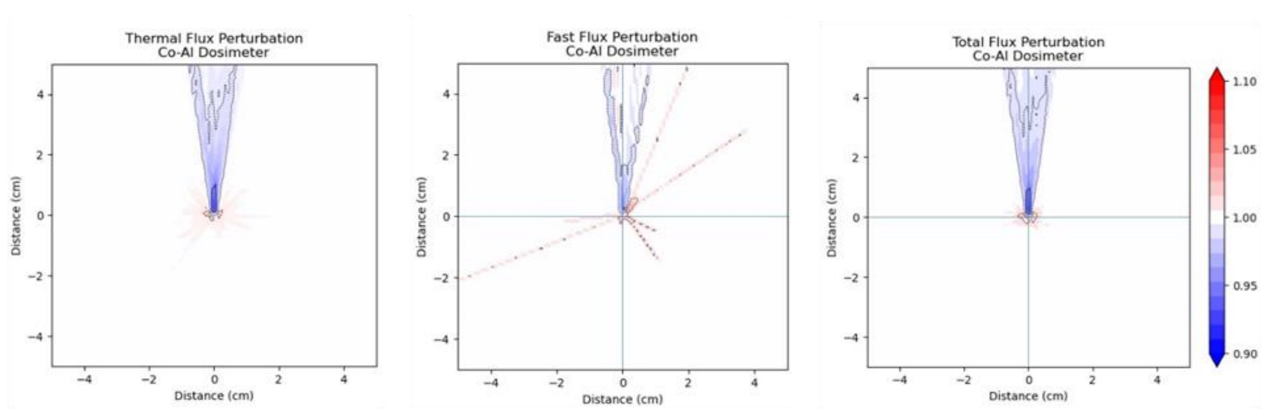

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Figure 13. Contour plots of the (a) thermal flux perturbation, (b) fast flux perturbation, and (c) total flux perturbation caused by the presence of a cobalt-aluminum dosimeter package.

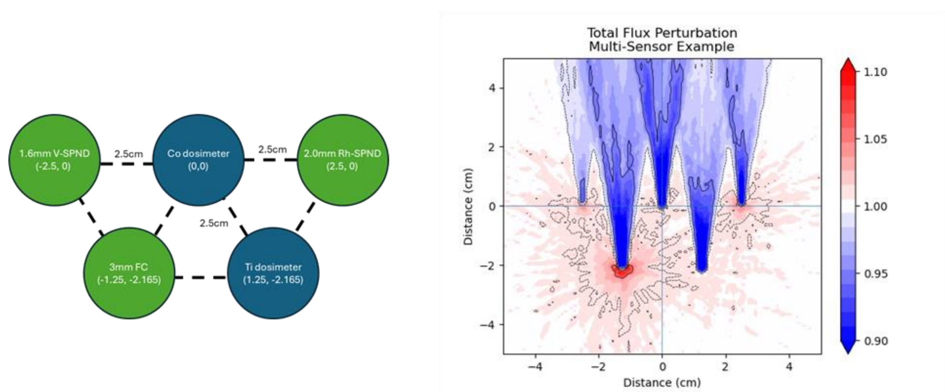
For all the detector types, the largest flux perturbation occurred in the thermal energy region and was observed to be the largest in the 7 mm FC. This was as expected, due to most materials having higher thermal neutron cross sections and the 7 mm FC having more materials. As such, detector positioning requirements are based on the thermal neutron flux perturbations.

Due to neutron capture and scattering interactions with the detectors, a flux depression (termed “detector shadowing”) was calculated to occur in a V-shaped pattern along the axial length behind the detector, at an angle of less than 10 degrees from the edge of the detector. This shadowing angle is an artifact of the source to detector placement of the model. Closer placement of the detector toward the source would result in a larger shadowing angle. Conversely, due to the neutron scattering, increased neutron flux occurs in a radial region around the detector. Thus, the requirements for detector placement within the experiment must adhere to the sensor shadowing angle as well as the minimum radius (given in Table 3).

To demonstrate with a group of sensors such as the one represented in Figure 14(a), 2.5 cm spacing in a triangular pattern (resulting in a placement angle of 15 degrees) would satisfy the requirements of both the 10 degree shadowing and 2.1 cm scattering perturbation for the 3 mm FC. The result, seen in Figure 14(b), is that each sensor is located within a region inside the 1% total flux perturbation.

Table 3. Minimum radius spacing per sensor type for less than +1% and +5% flux perturbation, due to neutron scattering.

Detector	Radius for < +1% perturbation (cm)	Radius for < +5% perturbation (cm)
3-mm FC	2.1	0.5
7-mm FC	5.6	1.1
Rh-SPND (1.6 mm)	0.7	0
Rh-SPND (2.0 mm)	1.2	0.2
V-SPND (1.6 mm)	0.7	0.1
V-SPND (2.0 mm)	1.3	0.2
Ti dosimeter	0.4	0
Fe dosimeter	0.5	0
Co-Al dosimeter	0.4	0



a b

Figure 14. (a) Configuration example of a multi-detector setup within the NQD, applying the shadowing and perturbation radius. (b) Resultant contour map of total neutron flux perturbation.

5. SUMMARY & FUTURE WORK

The Advanced Sensors and Instrumentation Program at INL has been formulating strategies to qualify sensors for use in nuclear environments, specifically in irradiation experiments and advanced reactors. The NQD is being developed to enable testing of neutron sensors in high-temperature environments with known neutron fluxes. The NQD irradiations are planned for the AFRRI exposure room. The NQD will provide a temperature-controlled environment that accommodates multiple sensors as well as neutron activation dosimetry. The baseline dosimetry package consists of titanium, iron, and cobalt in order to provide the reference neutron flux measurements. Sensor positioning and separation are critical for minimizing any local neutron flux perturbations. MCNP simulations have been employed to evaluate these effects and have fostered guidelines on the detailed design of the NQD.

The NQD is set to play a crucial role in the qualification of neutron sensors for future reactor technologies by providing a controlled environment for testing and qualifying these important instruments. Currently, the detailed design, prototype, and irradiation of the NQD are all planned for FY-25. This commissioning irradiation will provide a foundation for evaluating NQD performance to further serve as a robust test to help quantify uncertainty in neutron sensor measurements.

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