U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI | Advanced Sensors and Instrumentation

# Neutron Flux

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
October 24 – 27, 2022

Nuclear Engineer: Kevin Tsai

Idaho National Laboratory

# Project Overview

Objective:

To develop and evaluate neutron flux sensor for monitoring and controlling existing and advanced reactors and to support advanced fuel cycle development.

Scope:

- Evaluating the performance of rhodium based SPNDs (Rh-SPND) for steady-state reactor operation at elevated temperatures and develop temperature compensation techniques for advanced reactor applications.
- Demonstrate commercial and developmental fission chambers and SPNDs for existing and advanced reactor power control and core monitoring.
  - Fission chambers for neutron flux and spectrum measurements
  - Elicit feedback for future evaluations

# Project Overview

FY22 Activities:

- Performance evaluation of Idaho Laboratories Corporation Rh-SPNDs at temperatures up to 800° C at Massachusetts Institute of Technology Reactor (MITR).
  - M3CT-22IN0702014, "Development of Temperature Compensation Tools for SPNDs Operating in High Temperature Environments." Due Oct. 31, 2022 (On schedule)

- Performance evaluation of Photonis fission chambers, Thermocoax Rh-SPND, and CEA fission chamber at the Ohio State University Research Reactor (OSURR) at ambient and 350ºC.
  - M2CT-22IN0702013, "Characterizing the Performance of Fission Chambers for Local Neutron Flux and Spectrum Measurement." Due Nov. 15, 2022 (On schedule)

- (Supplemental) Preliminary testing of Thermocoax Rh-SPND and Legacy B&W Gd-SPND at TREAT.
  - Performed to compare with CEA fission chambers and ion chamber.

# Project Overview

**Participants:**

- Kevin Tsai—PI for SPND development
- Michael Reichenberger—PI for Micro-Pocket Fission Detector development
- Joe Palmer—Project lead for irradiation testing work package.
- (CEA Researcher) Loic Barbot—PI for Thermocoax and Photonis sensor performance.

**Additional Acknowledgements**

- (MITR NRL Staff)--David Carpenter, Yakov Ostrovsky, and Michael Ames
- (OSURR NRL Staff)—Andrew Kauffman, Kevin Herminghuysen, Susan White, Matthew Van Zile.

# Technology Impact

The FY22 scope specifically focuses on advanced reactor applications—high temperature and fast neutron spectrum.

- Development of a temperature compensation technique for SPNDs (Rh-SPND) for steady-state reactor operation.
  - Completion of this task will identify methods to extend the operational limits of SPNDs into advanced reactor environments (up to 800ºC).

- Demonstrate commercial and developmental fission chambers and SPNDs for reactor power control and core monitoring in support of advanced reactor development.
  - Completion of this task will provide advanced reactor developers the evaluation data of commercial neutron flux sensors for measuring local neutron flux and spectrum.

# Results and Accomplishments

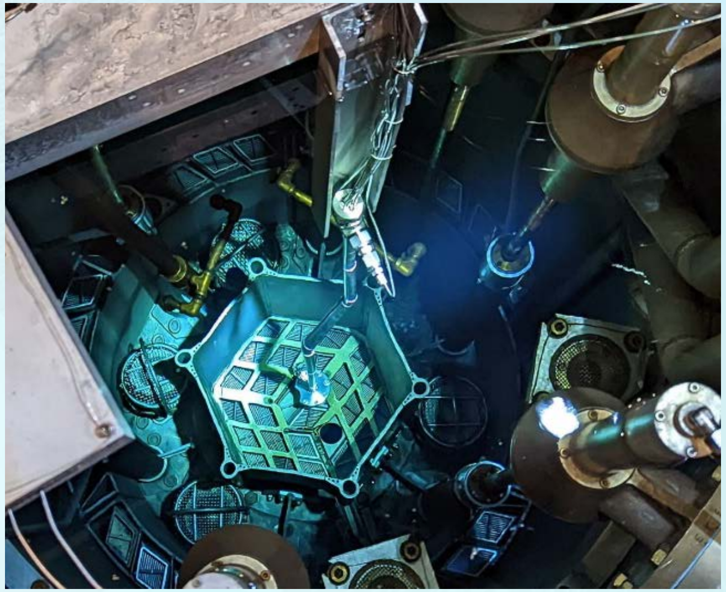
## Rh-SPND operating in high temperatures

Assessed in FY21, SPNDs have demonstrated the potential to operate in high temperature environments. However, an unknown response to temperature was observed that at 500ºC and above.

## Rh-SPND testing at MITR

Same Idaho Laboratories Corporation Rh-SPNDs were tested at MITR

- In-core A-1 position (1013 thermal neutron flux)
- Heater based on gamma heating
  - Central tungsten rod and varying gas (He/Ne) flow
- Temperature ranges from 600-800ºC at 6 MW.



# Results and Accomplishments

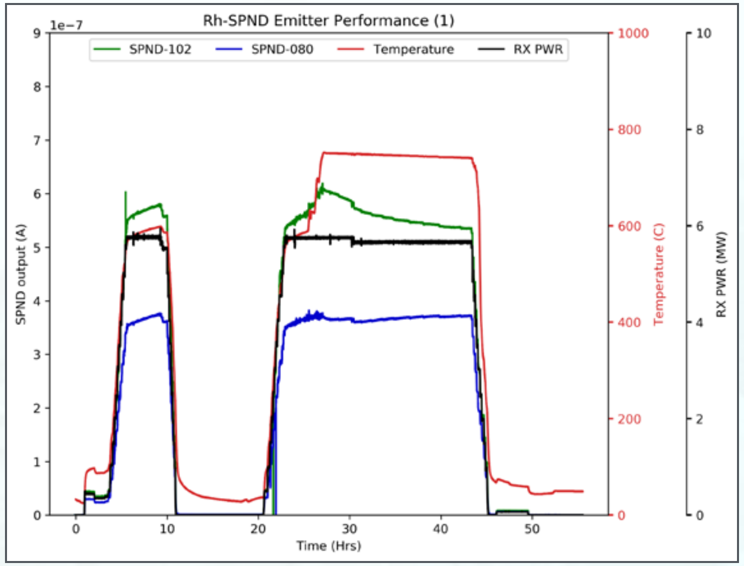
<u>Rh-SPND testing at MITR</u>

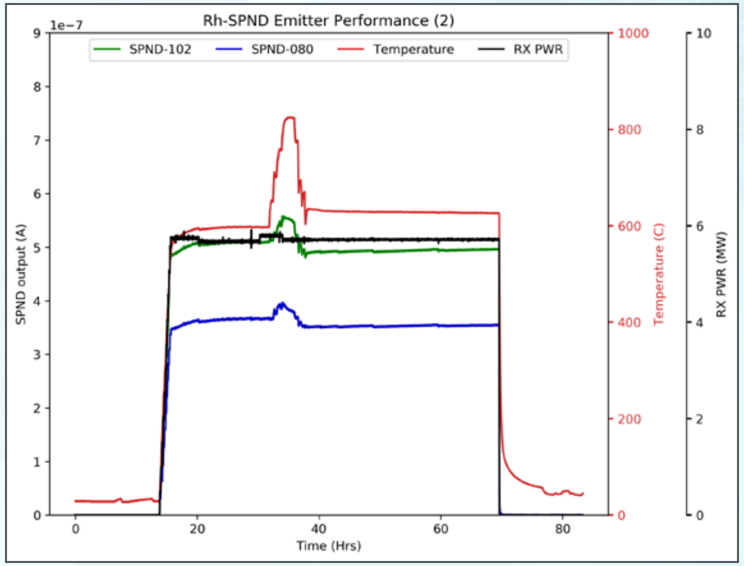
Steady-state power:

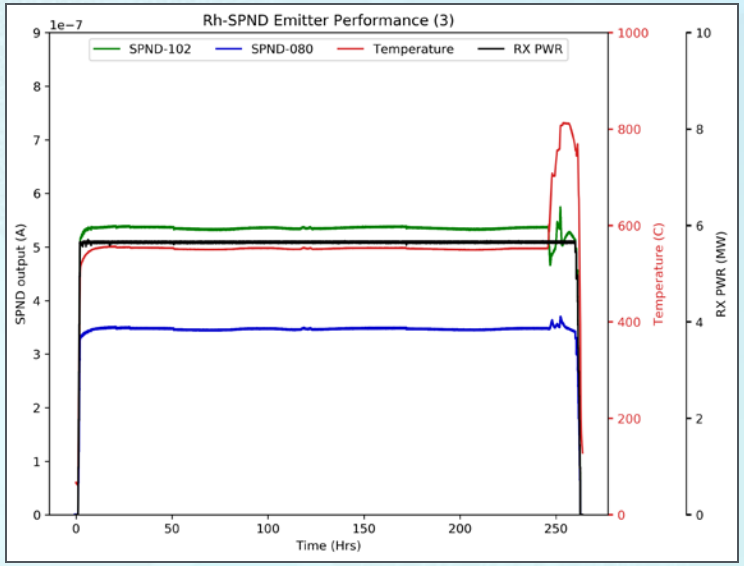
- Ramp temperature
- Step-increase and maintain temperature
- Increase and decrease temperature

Steady-state Temperature

- Decrease power



# Results and Accomplishments

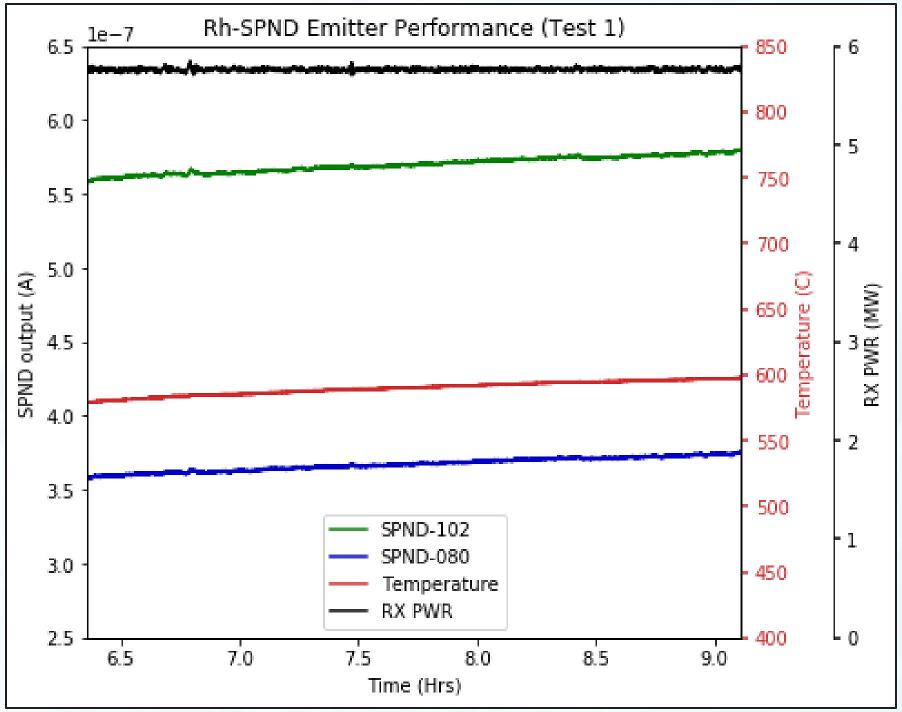
<u>Rh-SPND testing at MITR</u>

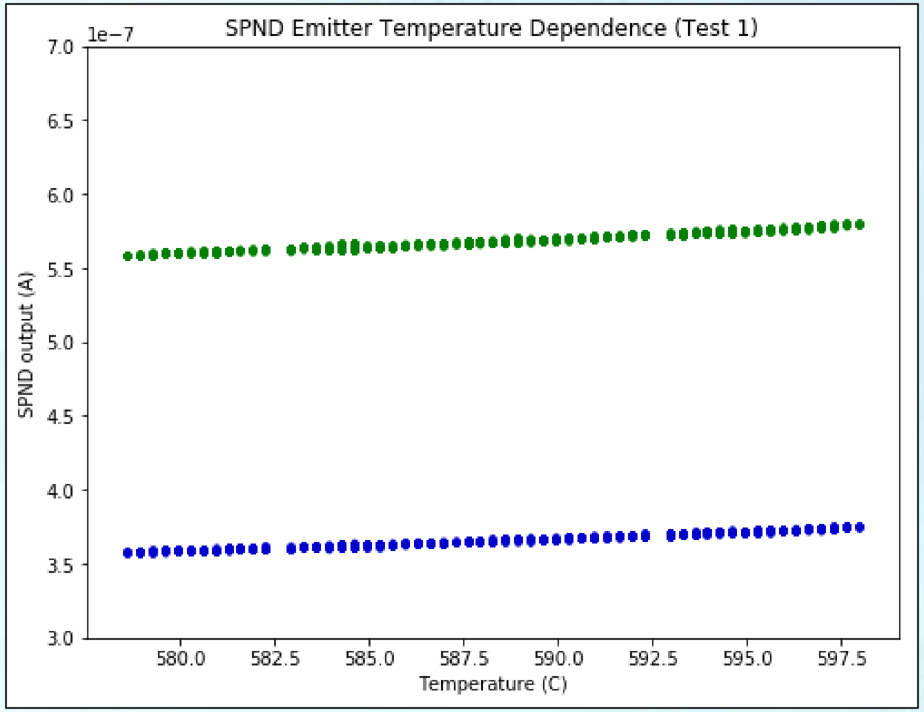
Steady-state power--Ramp temperature

- Linear relationship for small temperature changes

$$SPND102(A) = (1.054 \times 10^{-9})T(°C) - 5.205 \times 10^{-8}$$
$$r^2 = 0.9838$$

$$SPND080(A) = (8.876 \times 10^{-10})T(°C) - 1.564 \times 10^{-7}$$
$$r^2 = 0.9868$$



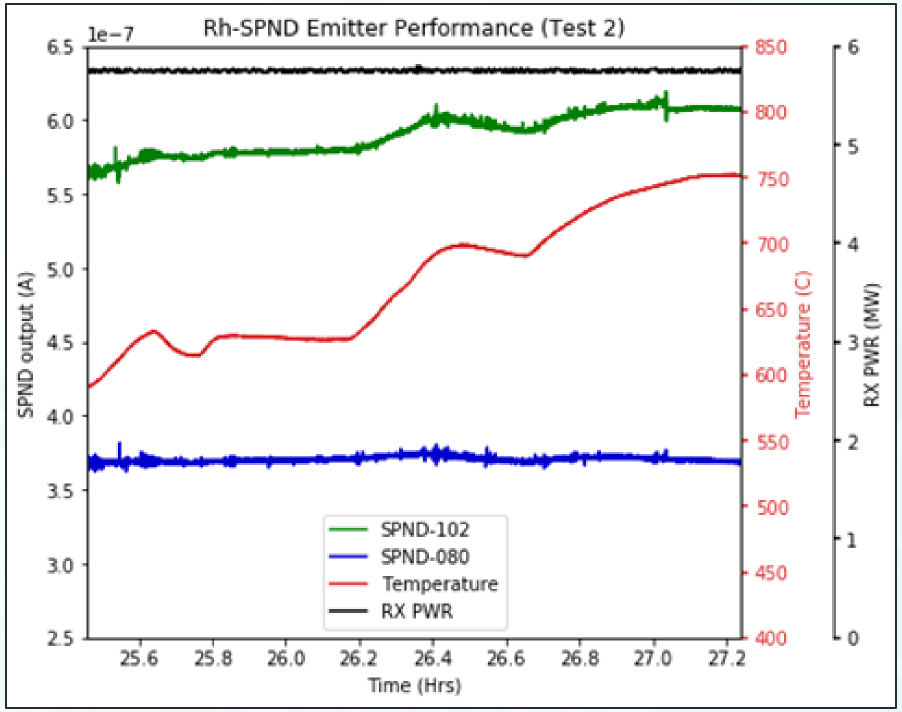
# Results and Accomplishments

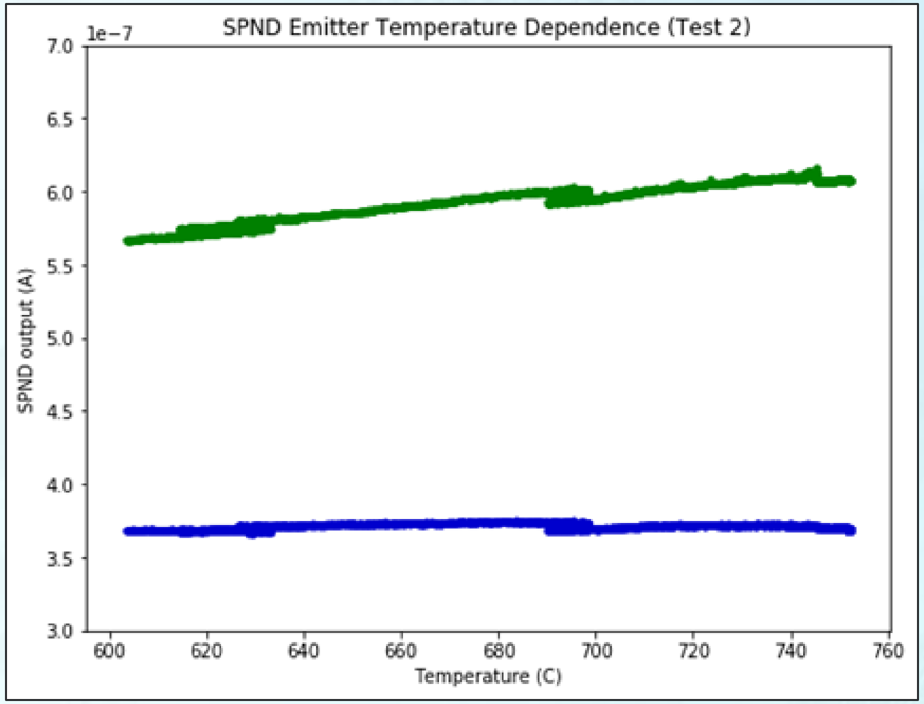
<u>Rh-SPND testing at MITR</u>

Steady-state power--**Step-increase** and maintain temperature

$$SPND102(A) = (2.685 \times 10^{-10})T(℃) + 4.094 \times 10^{-7}$$
$$r^2 = 0.9643$$

$$SPND080(A) = (1.146 \times 10^{-11})T(℃) + 3.629 \times 10^{-7}$$
$$r^2 = 0.1256$$



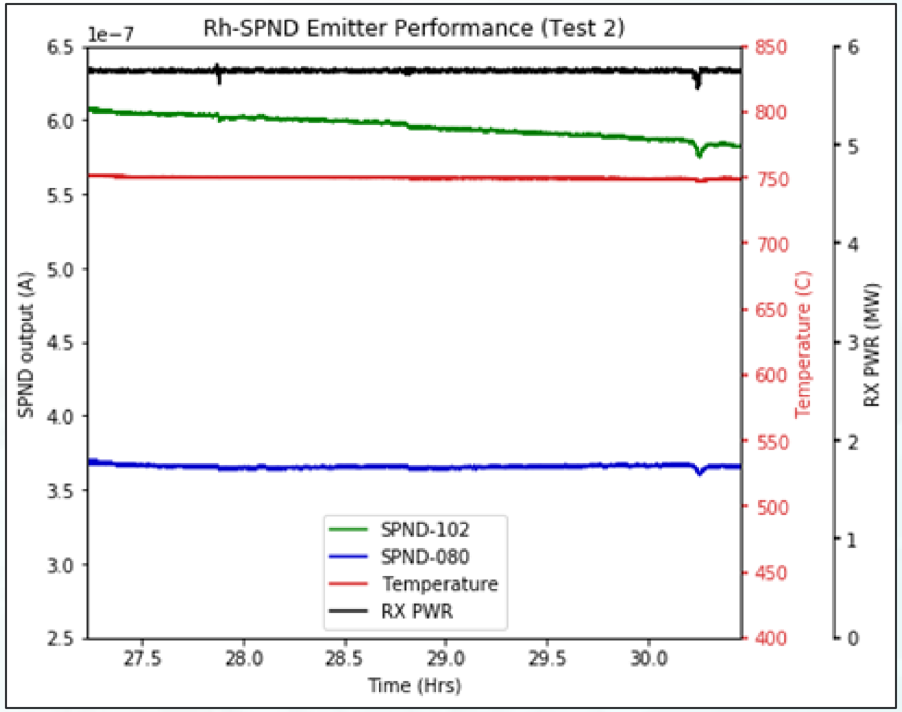
# Results and Accomplishments

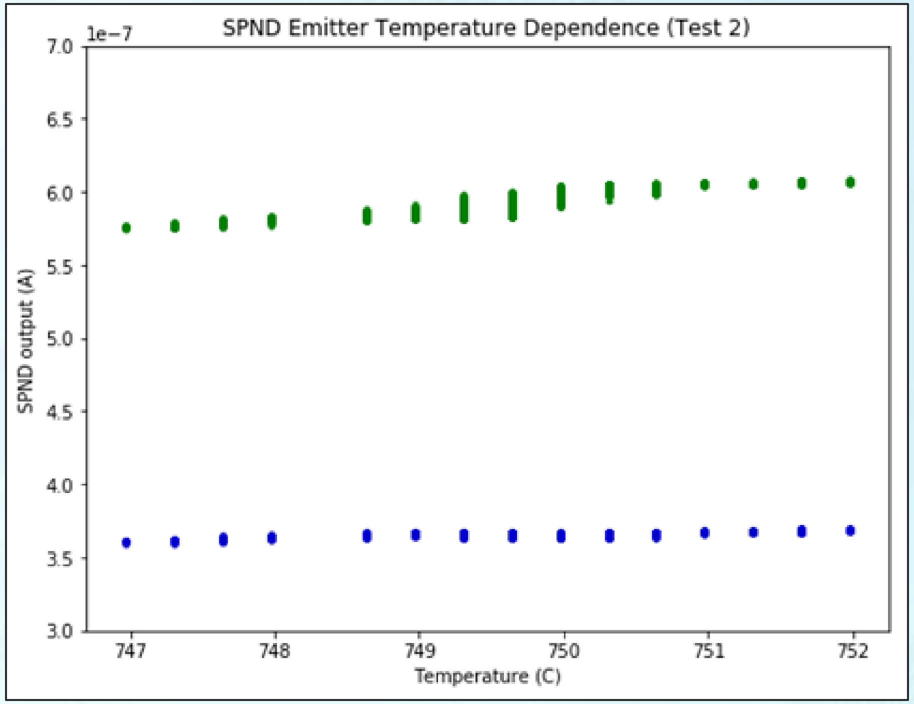
Rh-SPND testing at MITR

Steady-state power--Step-increase and **maintain temperature**

$$SPND102(A) = (9.668 \times 10^{-9})T(℃) - 6.654 \times 10^{-6}$$
$$r^2 = 0.8164$$

$$SPND080(A) = (5.357 \times 10^{-10})T(℃) - 3.605 \times 10^{-8}$$
$$r^2 = 0.1335$$



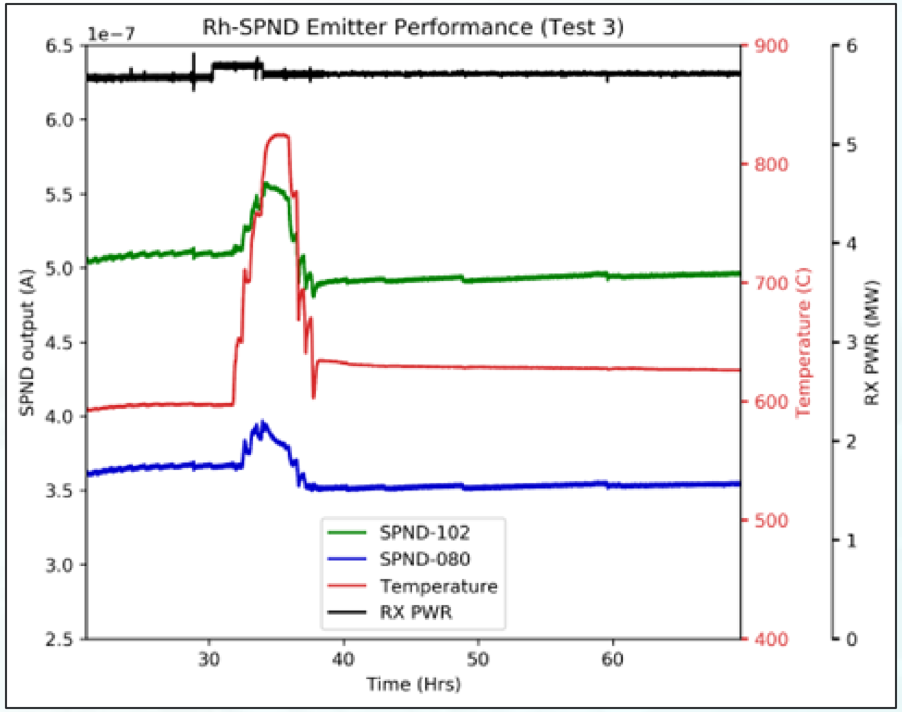



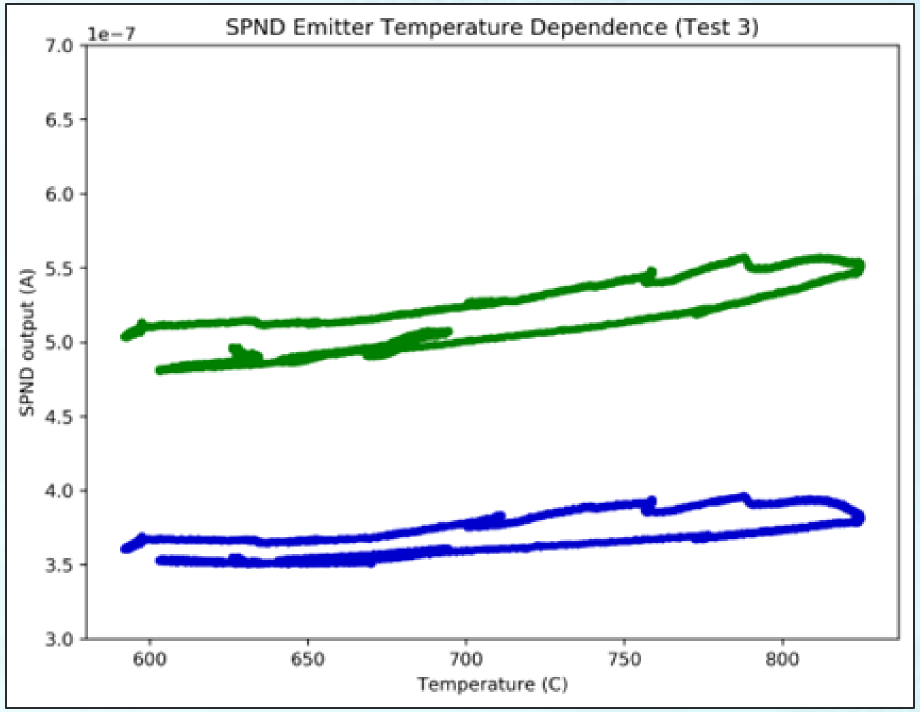
# Results and Accomplishments

## Rh-SPND testing at MITR

Steady-state power—step increase and decrease temperature

- Non-invertible behavior identified



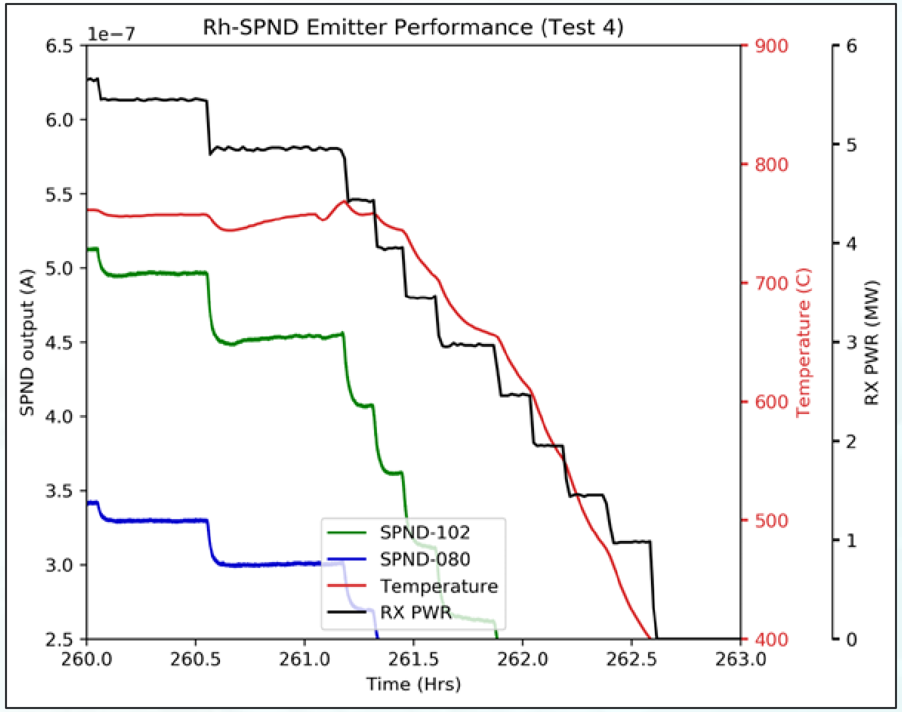



# Results and Accomplishments

Rh-SPND testing at MITR

Steady-state Temperature—decrease power

- SPND was capable of tracking power changes in steady temperature.




| | RX Power (MW) | ILC-102-RhSPND (A) | ILC-080-RhSPND (A) |
|---|---|---|---|
| Power 1 | 5.65 | 5.13E-07 | 3.42E-07 |
| Power 2 | 5.45 | 4.96E-07 | 3.30E-07 |
| Power 3 | 4.95 | 4.53E-07 | 3.00E-07 |
| Power 4 | 4.43 | 4.17E-07 | 2.76E-07 |

| % Difference | RX Power | ILC-102-RhSPND | ILC-080-RhSPND |
|---|---|---|---|
| 1 to 2 | -0.036 | -0.033 | -0.035 |
| 1 to 3 | -0.124 | -0.117 | -0.121 |
| 1 to 4 | -0.216 | -0.188 | -0.193 |

# Results and Accomplishments

Rh-SPND testing at MITR

Overview of results:

- The Rh-SPND have two modes of signal response to changes in temperature:
  - Direct proportionality (approximated as linear) to temperature changes
  - Exponential increase and subsequent decay at steady temperature
- The signal response to temperature are more observable in the larger diameter SPND

- The direct proportionality is theorized to be caused by decrease in insulation resistance.
  - H. Bock and J. Rantanen, "Temperature and radiation tests with Pt- and Rh-self-powered neutron detectors," Nuclear Instruments and Methods, vol. 164, pp. 205-207, 1979.
- The exponential increase and decay is theorized to be caused by displacement current in the insulation as a function of temperature.
  - M. G. Mitel'man, A. A. Kononovich, V. M. Osipov and N. D. Rozenblyum, "Effect of temperature on characteristic of self-powered detectors," At Energy, vol. 48, no. 4, pp. 263-266, 1980.

- Verification through resistance measurements at temperature is needed to test the theories proposed – planned for FY23.

# Results and Accomplishments

Commercial fission chambers for neutron flux and spectrum measurement

Fast and thermal neutron flux detection is needed for controlling and core monitoring of advanced reactor as well as supporting advanced fuel cycle development

Neutron flux sensor testing at OSURR

Commercial fission chambers and SPNDs were used

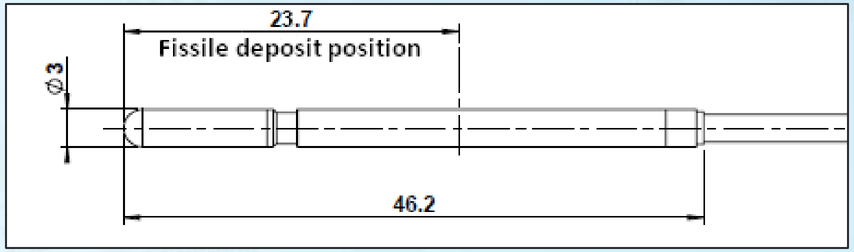
- Heated experiment rig at 6.5” dry-tube
  - 1.6E12 Total neutron flux @ 450kW
  - 1.2E12 thermal neutron flux @ 450kW
- Electrically heated to 350ºC.

# Results and Accomplishments

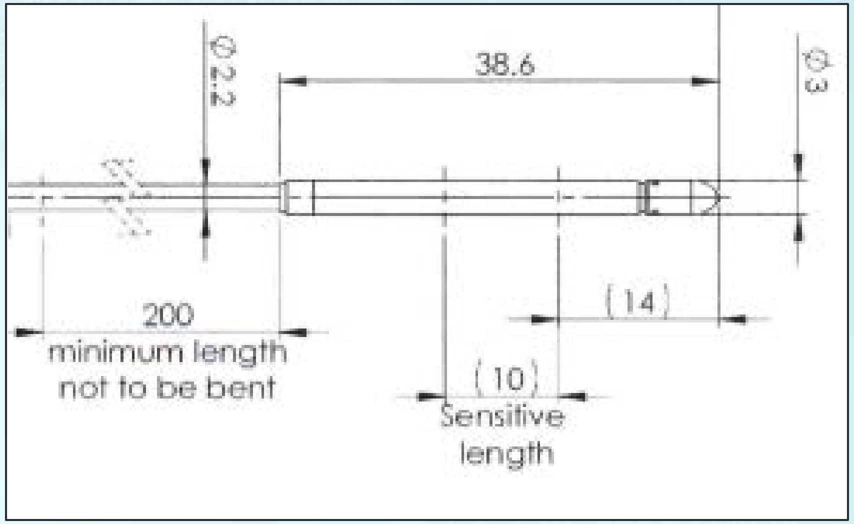
<u>Neutron flux sensor testing at OSURR</u>

- CEA: U-235 (No. 2349) Fission Chamber
  - Based on PHOTONIS CFUR64
  - 1 µg U-235 pulse mode
- CEA: THX Rhodium (T4WY/02) SPND
- INL: PHOTONIS U-235 (CFUR43 No. 204) FC
  - 140 µg U-235 current mode
- INL: PHOTONIS U-238 (CFUR43 No. 206) FC
  - 140 µg U-238 current mode

Photonis CFUR 64 schematic




Photonis CFUR 43 schematic



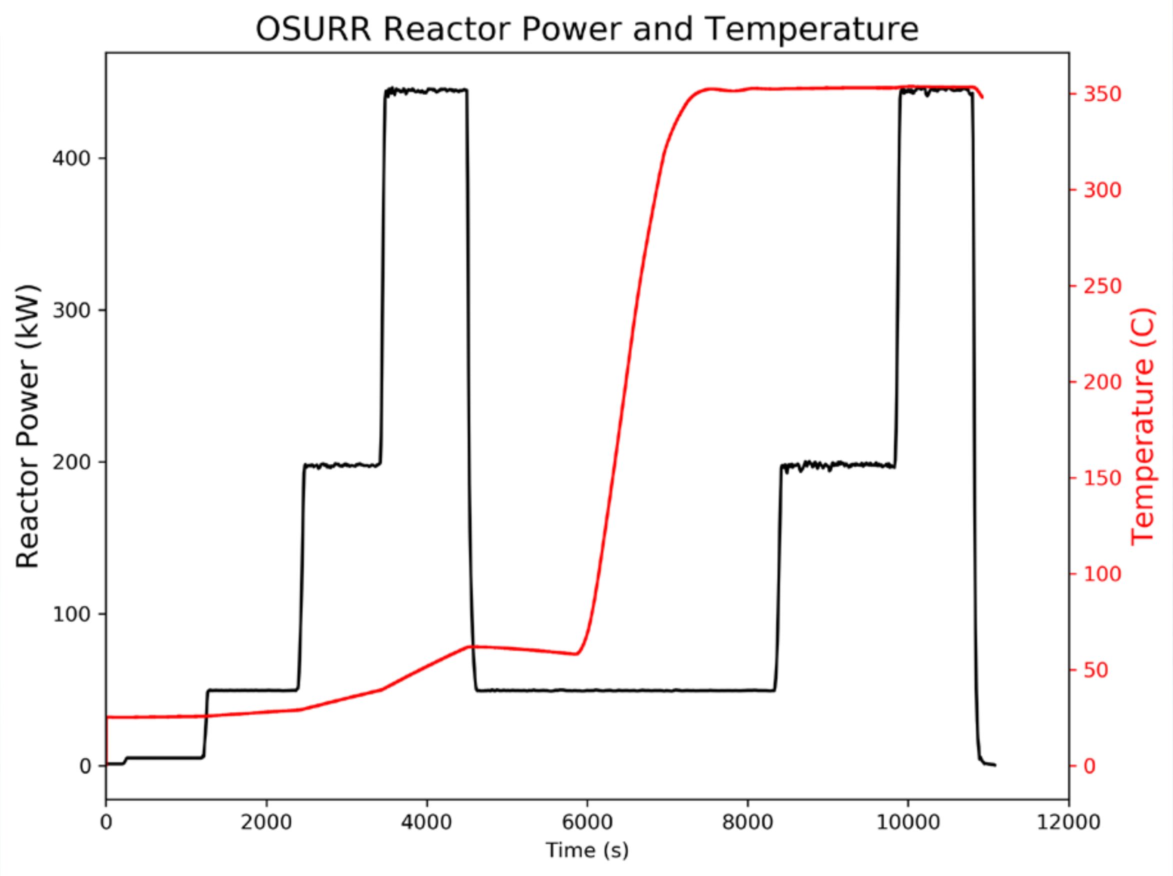

COLLECTRONS NEUTROCOAX type : 9 Rh Ac 14 / 50 mm // 1 Ac Ac 10 / 20 m / BNC MALE

| DESIGNATION | | | VALEURS Spécifiées | VALEURS Mesurées |
|---|---|---|---|---|
| 1. | <u>Contrôle des composants avant montage</u> <u>Partie sensible</u> | | | |
| a) | Emetteur: (matériau: Rh ) | longueur | 50 ± 0,5 mm | 50.36 mm |
| | | diametre | 0.50 ± 0,01 mm | 0.51 mm |
| | | poids | g | 0.1274 g |
| b) | Gaine : (matériau: Ac ) | longueur | 81±1 mm | 81.30 mm |
| | | diametre | 1.4 +0.05 -0 mm | 1.39 mm |
| c) | Cable THERMOCOAX type | 1 Ac Ac 10 | | |
| | Série : 13814 | Résistance de ligne: | / | 7.85 Ω/m |

# Results and Accomplishments

<u>Neutron flux sensor testing at OSURR</u>

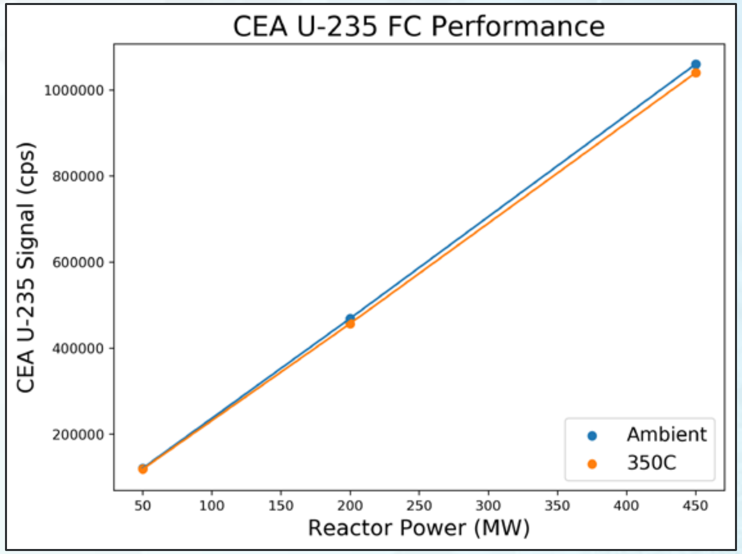
- Reactor operated at 50, 200, and 450kW for ambient temperature and 350ºC

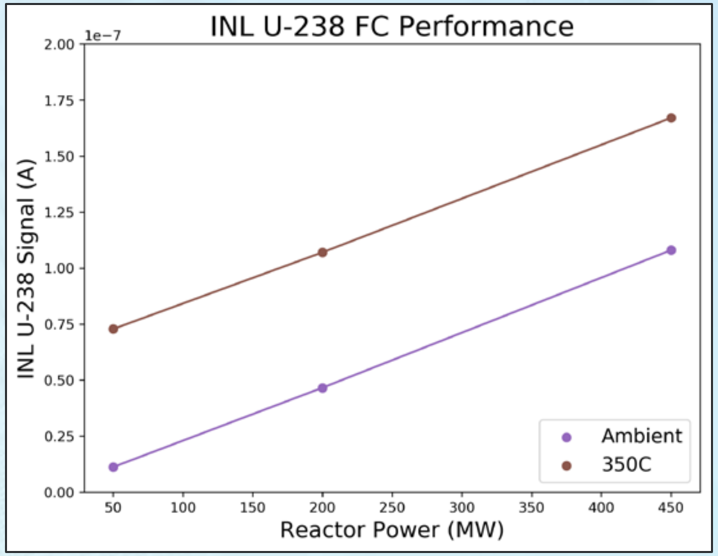


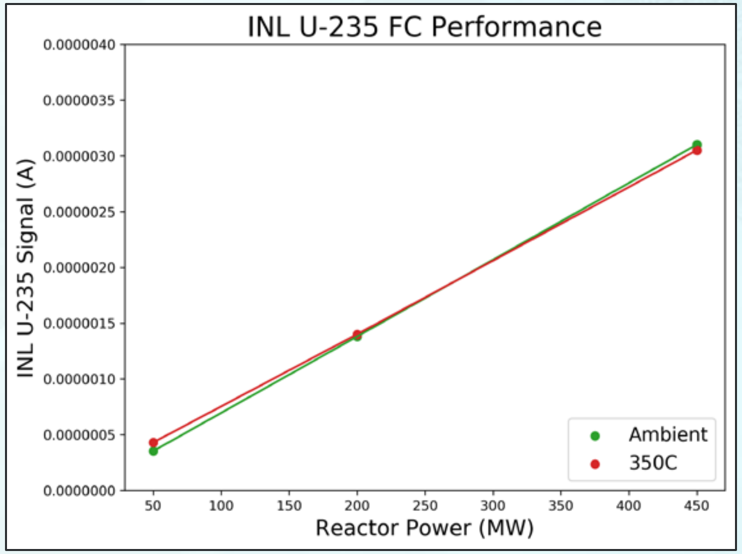
# Results and Accomplishments

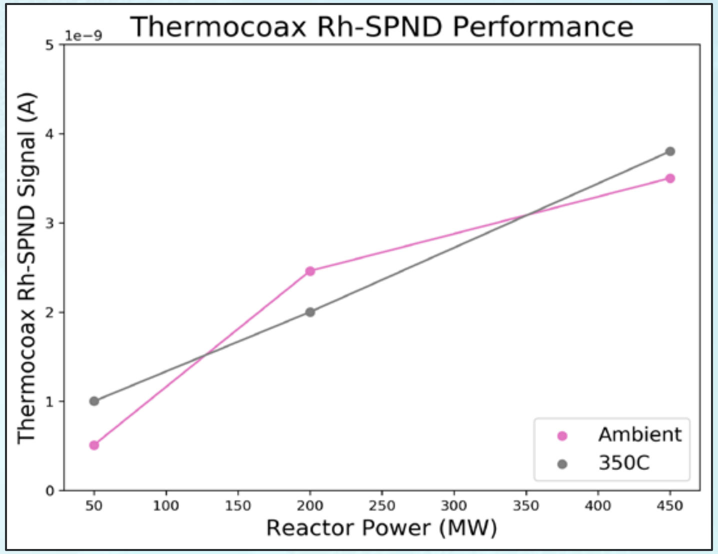
Neutron flux sensor testing at OSURR

- CEA U-235 FC (pulse mode) demonstrated the best performance with little change at 350ºC
  - Initial difficulty isolating noise
- INL U-235 FC also performed well up to 350ºC
  - Difficulty using original planned i-Tech Libera current meter.
- INL U-238 FC indicated a current offset, but maintained linearity
  - Theory: leakage currents at 350ºC.
- THX Rh-SPND has crosstalk issues at 350ºC



# Results and Accomplishments

## Rh-SPND testing at TREAT

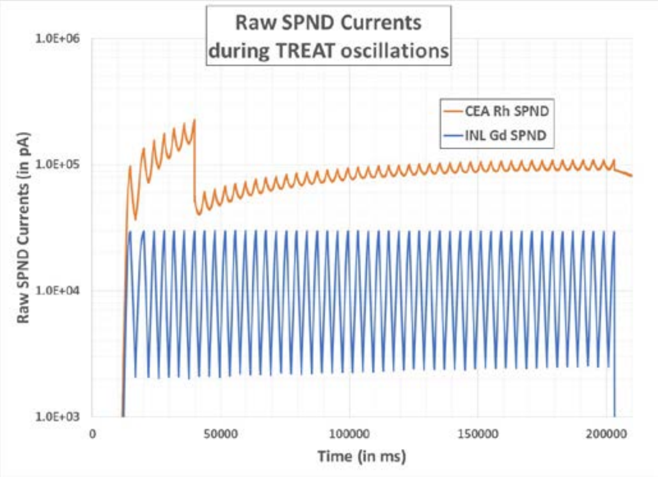
- Performed Thermocoax Rh-SPND testing in position H-16 cooling channel.
  - 80kW—SPND signal compared with MaTiSSE (CEA SPND sensitivitymodel)
  - 200s Oscillating Transient

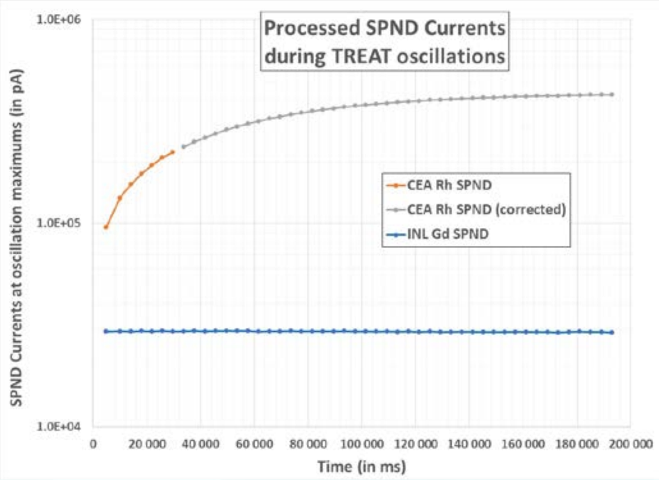
**RHODIUM**

| | | |
|---|---|---|
| Measurement | 1.218E-09 A | C/E 1.025 |
| MATiSSe | 1.249E-09 A | |

**GADOLINIUM**

| | | |
|---|---|---|
| Measurement | 9.910E-11 A | C/E 1.038 |
| MATiSSe | 1.028E-10 A | |




Dosimetry

FCs

SPNDs

| | A | B | C | D | E | F | G | H | J | K | L | M | N | O | P | R | S | T | U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.02 | 0.02 | 0.75 | 0.74 | 0.73 | 0.72 | 0.70 | 0.68 | 0.68 | 0.01 | 0.68 | 0.68 | 0.69 | 0.70 | 0.71 | 0.72 | 0.74 | 0.02 | 0.02 |
| 2 | 0.03 | 0.79 | 0.77 | 0.76 | 0.74 | 0.71 | 0.67 | 0.65 | 0.69 | 0.01 | 0.69 | 0.64 | 0.67 | 0.71 | 0.74 | 0.76 | 0.77 | 0.80 | 0.03 |
| 3 | 0.84 | 0.82 | 0.84 | 0.83 | 0.79 | 0.72 | 0.68 | 0.53 | 0.74 | 0.01 | 0.74 | 0.53 | 0.68 | 0.72 | 0.79 | 0.84 | 0.85 | 0.85 | 0.87 |
| 4 | 0.89 | 0.90 | 0.93 | 0.94 | 0.87 | 0.63 | 0.81 | 0.84 | 0.88 | 0.01 | 0.88 | 0.84 | 0.81 | 0.63 | 0.88 | 0.95 | 0.95 | 0.93 | 0.94 |
| 5 | 0.96 | 0.99 | 1.04 | 1.07 | 1.05 | 1.01 | 1.04 | 1.06 | 1.04 | 0.01 | 1.04 | 1.07 | 1.05 | 1.02 | 1.07 | 1.09 | 1.07 | 1.02 | 1.02 |
| 6 | 1.05 | 1.08 | 1.15 | 0.90 | 1.24 | 1.26 | 1.26 | 1.24 | 1.18 | 0.02 | 1.18 | 1.24 | 1.27 | 1.27 | 1.26 | 0.91 | 1.17 | 1.11 | 1.09 |
| 7 | 1.12 | [illegible] | 1.24 | 1.33 | 1.39 | 1.42 | 1.41 | 1.37 | 1.27 | 0.02 | 1.28 | 1.38 | 1.42 | 1.43 | 1.41 | 1.35 | 1.27 | 1.19 | 1.16 |
| 8 | 1.18 | 1.23 | 0.98 | 1.42 | 1.49 | [illegible] | 1.51 | 1.45 | 1.33 | 0.02 | 1.33 | 1.46 | 1.52 | 1.14 | 1.51 | 1.44 | 1.00 | 1.26 | 1.22 |
| 9 | 1.22 | 1.27 | 1.38 | 1.48 | 1.56 | 1.59 | 1.57 | 1.49 | [illegible] | 0.01 | 1.33 | 1.50 | 1.59 | 1.61 | 1.58 | 1.51 | 1.40 | 1.30 | 1.25 |
| 10 | 1.24 | 1.29 | 1.40 | 1.51 | 1.59 | 1.62 | 1.60 | 1.51 | 1.31 | EXP | 1.31 | 1.52 | 1.61 | 1.64 | 1.61 | 1.53 | 1.43 | 1.32 | 1.27 |
| 11 | 1.23 | 1.28 | 1.39 | 1.49 | 1.57 | 1.60 | 1.59 | 1.51 | 1.34 | 0.05 | 1.34 | 1.51 | 1.60 | 1.62 | 1.59 | 1.52 | 1.41 | 1.31 | 1.26 |
| 12 | 1.21 | 1.25 | 0.99 | 1.44 | 1.51 | 1.14 | 1.53 | 1.48 | 1.37 | 0.02 | 1.37 | 1.49 | 1.55 | 1.15 | 1.53 | 1.46 | 1.01 | 1.27 | 1.23 |
| 13 | 1.16 | [illegible] | 1.27 | 1.35 | 1.42 | 1.45 | 1.45 | 1.41 | 1.33 | 0.02 | 1.33 | 1.42 | 1.46 | 1.46 | 1.44 | 1.38 | 1.30 | 1.22 | 1.18 |
| 14 | 1.10 | 1.12 | 1.19 | 0.92 | 1.28 | [illegible] | 1.30 | 1.29 | 1.24 | 0.02 | 1.24 | 1.30 | 1.31 | 1.31 | 1.30 | 0.94 | 1.21 | 1.14 | 1.12 |
| 15 | 1.03 | 1.04 | 1.08 | 1.11 | 1.09 | 1.05 | 1.09 | 1.12 | 1.11 | 0.02 | 1.12 | 1.13 | 1.10 | 1.07 | 1.11 | 1.13 | 1.11 | 1.06 | 1.05 |
| 16 | 0.95 | 0.95 | 0.98 | 0.98 | 0.91 | [illegible] | [illegible] | 0.90 | 0.96 | 0.01 | 0.96 | 0.90 | 0.86 | 0.67 | 0.92 | 1.00 | 1.00 | 0.97 | 0.98 |
| 17 | [illegible] | 0.87 | 0.88 | 0.88 | 0.83 | 0.76 | 0.74 | 0.58 | 0.83 | 0.01 | 0.83 | 0.59 | 0.75 | 0.78 | 0.85 | 0.90 | 0.91 | 0.90 | 0.92 |
| 18 | 0.03 | 0.83 | 0.81 | 0.80 | 0.79 | 0.77 | 0.74 | 0.73 | 0.81 | 0.01 | 0.81 | 0.74 | 0.76 | 0.79 | 0.82 | 0.84 | 0.84 | 0.86 | 0.03 |
| 19 | 0.02 | 0.03 | 0.78 | 0.77 | 0.78 | 0.79 | 0.79 | 0.81 | 0.84 | 0.01 | 0.85 | 0.82 | 0.81 | 0.82 | 0.82 | 0.82 | 0.83 | 0.03 | 0.02 |

# Concluding Remarks

Summary:

- Performed testing of Rh-SPNDs at MITR for temperature ranges of 600-800ºC
  - Evaluated SPND data and identified temperature response characteristics consistent with historical work.
  - Continuing in FY23 to perform resistance measurements in temperature to predict temperature effects.

- Demonstrated performance of Photonis fission chambers, Thermocoax Rh-SPND, and CEA fission chamber at OSURR at ambient temperature and 350ºC.
  - Provided information regarding the commercial availability for neutron spectrum measurements for controlling and monitoring advanced reactor
  - Continuing in FY23 to perform higher temperature testing at OSURR (600ºC and 900ºC) with additional sensors.

- (Supplemental) Preliminary testing of Thermocoax Rh-SPND and Legacy B&W Gd-SPND at TREAT.
  - Ready for irradiation with CEA U-235, U-238 fission chambers and ion chamber.

Kevin Tsai
Idaho National Laboratory
kevin.tsai@inl.gov
W (208)-526-2828

# Thank You