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

ASI Advanced Sensors and Instrumentation

Reactor Power Monitoring - INL

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 4, 6-7, 2024

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Idaho National Laboratory – INL/MIS-24-82400

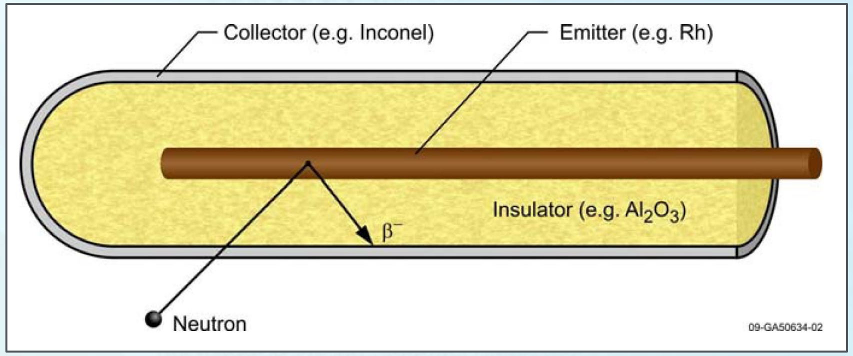
Project Overview (Summary)

The goal of the INL reactor power monitoring work package is to evaluate and develop in-core neutron flux sensors in support of upcoming advanced reactor demonstrations.

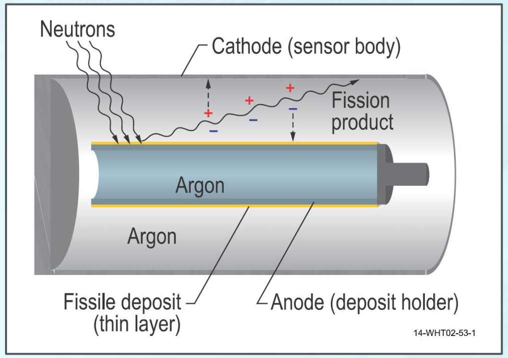
- High-temperatures
- Spectral sensitivity
- Low-flux

Technology of focus:

- Self-powered neutron detectors (SPND)
  - Passively generate electric current in a radiation field
  - Only operates in current mode
- Fission chambers (FC)
  - Detection of fission events via ionization of fill gas
  - Operates in pulse mode, Campbelling mode, and current mode



SPND overview sketch



FC overview sketch

Project Overview (Schedule)

FY 24 activities:

- M3CT-24IN0702011 – (Carryover) Performance benchmark of commercial fission chambers in elevated temperatures
  - Completed milestone report 11/30/2023
- M3CT-24IN0702012 – (Carryover) Demonstration of temperature compensation techniques for SPNDs operating in high temperature environments
  - Completed (late) milestone report 6/30/2024
- M2CT-24IN0702013 – Development of neutron energy spectrum unfolding methods using SPNDs.
  - Completed milestone report 9/30/2024
- M4CT-24IN0702014 – Assessment of neutron flux sensors for monitoring advanced reactor concepts operating with low neutron fluence rate and extended uninterrupted lifespans.
  - Completed milestone report 7/31/2024
- (Ongoing) M4CT-24IN0702015 – Conceptual design of an experiment for demonstration of neutron spectrum unfolding and reactor power controls.
  - Due 11/30/2024 on schedule.

Project Overview (Participants)

I would like to acknowledge and thank all members that contributed to this work:

OSU-NRL:

Andrew Kauffman, Susan White, Kevin Herminghuysen, and Matthew Van Zile

CEA:

Loïc Barbot and Grégoire de Izarra

ORNL:

Callie Goetz and Tony Birri

INL:

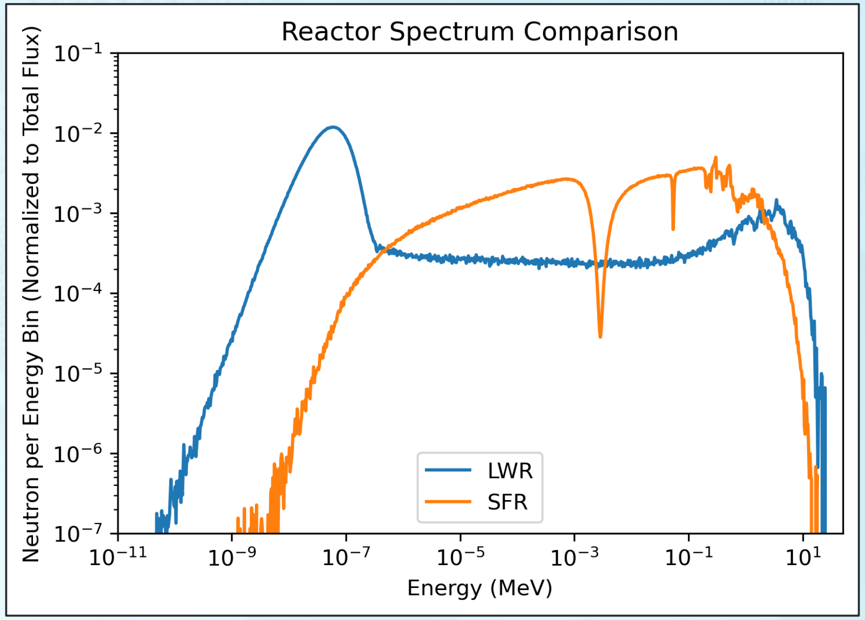
Tommy Holschuh, Teancum Quist, Michael Reichenberger, and Geran Call

Technology Impact

Success under this work package will lead to methods for monitoring and control for advanced reactors designs – specifically focusing on high-temperature fast reactors and small modular/microreactors.

Examples listed by under Advanced Reactor Demonstration Program:

- Natrium Reactor (TerraPower) – 350˚C
- Xe-100 (X-Energy) – 750˚C
- KP-FHR (Kairos Power) – 650˚C
- eVinci (Westinghouse Nuclear) – 650˚C
- BANR (BWX Technologies) – target 1000 – 1400˚C
- MCFR/MCRE (SC/TP) – 600˚C
- SMR-300 (Holtec International)



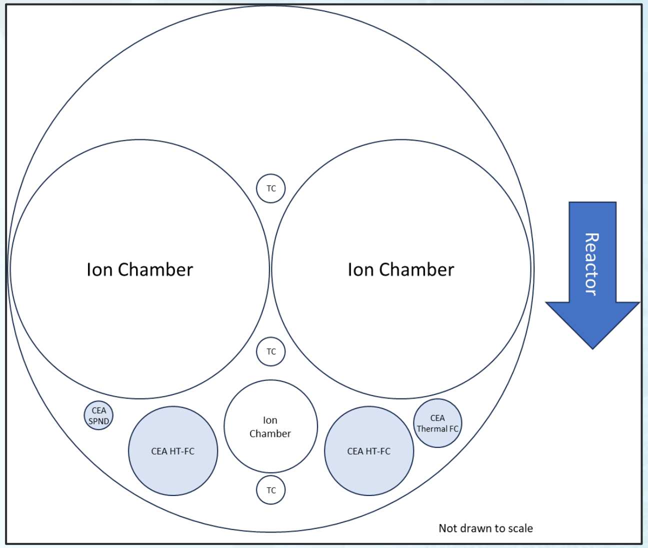
Example of neutron energy spectrum for LWR and SFR

https://www.energy.gov/ne/articles/infographic-advanced-reactor-development
https://www.energy.gov/sites/default/files/2020/05/f74/Advanced-Reactor-Types_Fact-Sheet_Draft_Hi-Res_R1.pdf

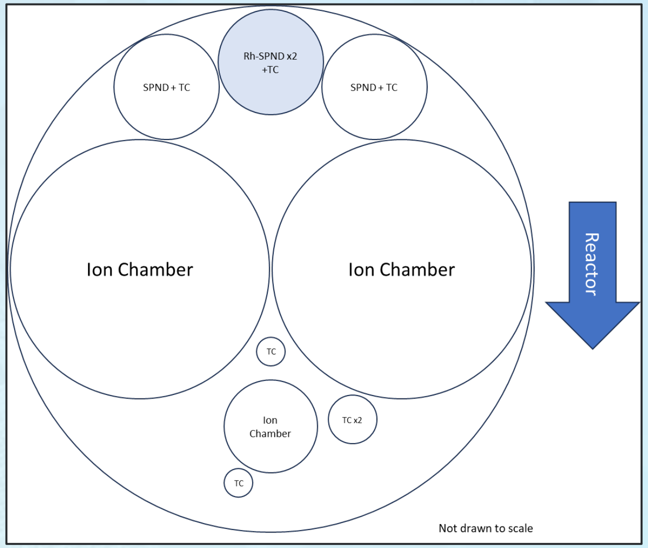
Results and Accomplishments

OSURR Heated Irradiation

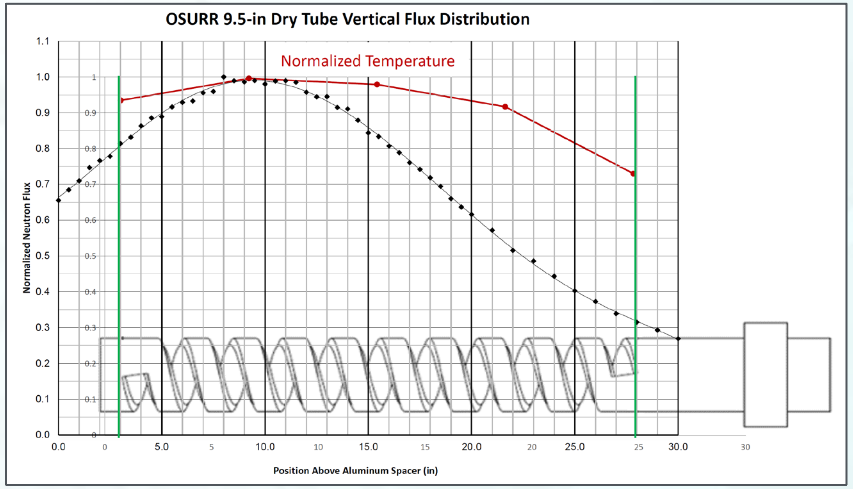
- 9.5 in. inner diameter dry-tube
- 24 in. L × 2 in. inner diameter furnace
- 2 Irradiation performed for fission chambers and SPNDs



September irradiation sensor setup



December irradiation sensor setup



24" Furnace temperature and flux profile

24" Furnace at OSU

9.5" Dry-tube experiment

Results and Accomplishments

September Fission Chamber Irradiation Plan

- 3 days of irradiation
  - Days 1 and 2 are for testing sensor operability at relevant temperatures
  - Day 3 is to test sensor limits and identify failure points

Day 1 Experiment

Power	Duration	Temperature
100 W	1 hr	Ambient
100 W 1 kW 10 kW 100 kW 200 kW	15 min each (+5 min per power change)	Ambient
1 kW	1 hr	Heat to 350°C
1 kW 10 kW 100 kW 200 kW	15 min each (+5 min per power change)	350°C
1 kW	1 hr	Heat to 600°C
1 kW 10 kW 100 kW 200 kW	15 min each (+5 min per power change)	600°C

Day 2 Experiment

Power	Duration	Temperature
100 W	1 hr	Ambient
100 W 1 kW 10 kW 100 kW 200 kW	15 min each (+5 min per power change)	Ambient
1 kW	1 hr	Heat to 650°C
1 kW 10 kW 100 kW 200 kW	15 min each (+5 min per power change)	650°C
1 kW	1 hr	Heat to 700°C
1 kW 10 kW 100 kW 200 kW	15 min each (+5 min per power change)	700°C

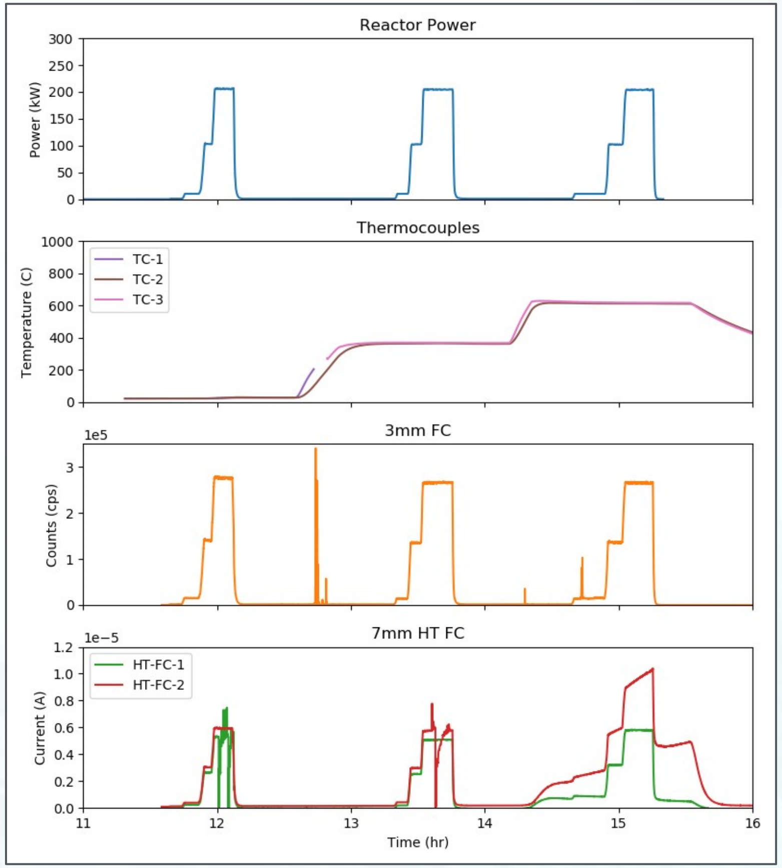
Day 3 Experiment

Power	Duration	Temperature
100 W	5 min each (+5 min per temperature change)	Ambient 600°C 650°C 700°C 750°C
100 W 1 kW 10 kW 100 kW 200 kW 450 kW	15 min each (+5 min per power change)	750°C
1 kW	1 hr	Heat to 850°C
1 kW 10 kW 100 kW	15 min each (+5 min per power change)	850°C
1 kW	1 hr	Heater off

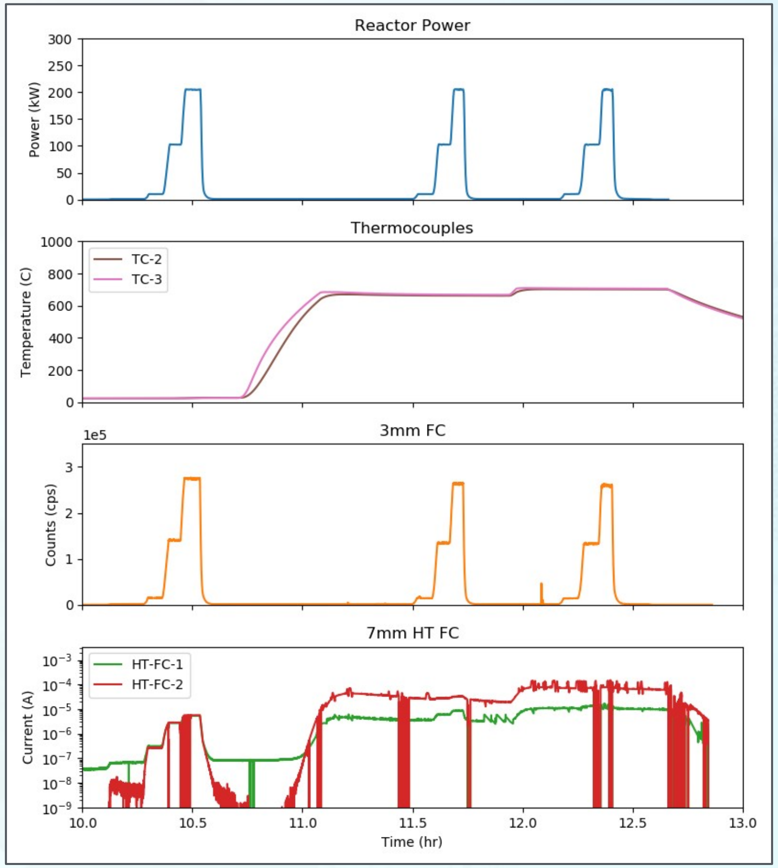
Results and Accomplishments

Fission Chamber Results

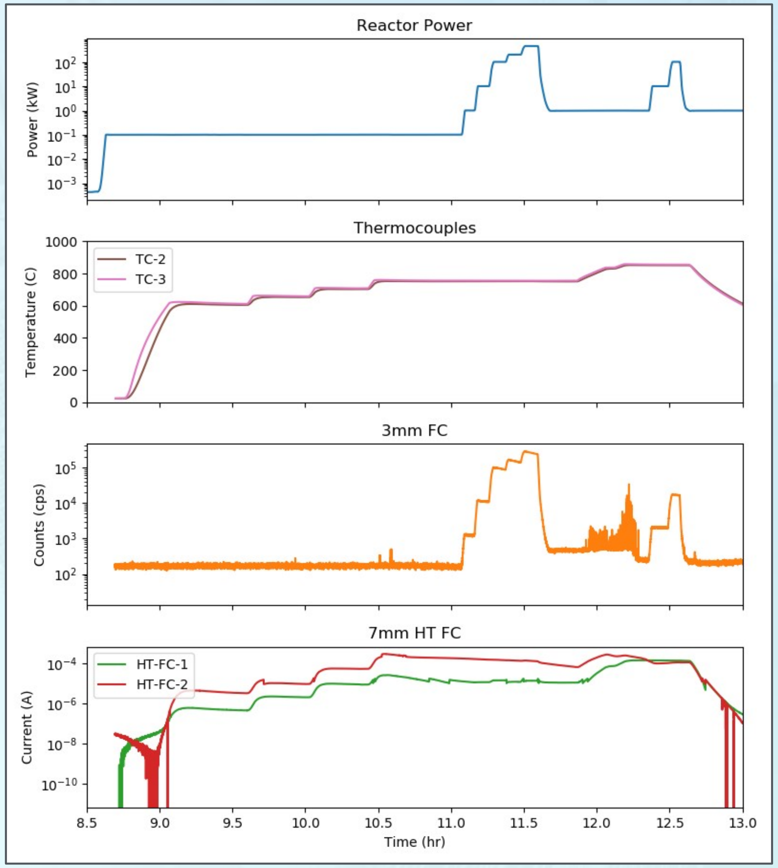
- Detector response overview



Day 1 Experiment
Max temp 600°C



Day 2 Experiment
Max temp 700°C

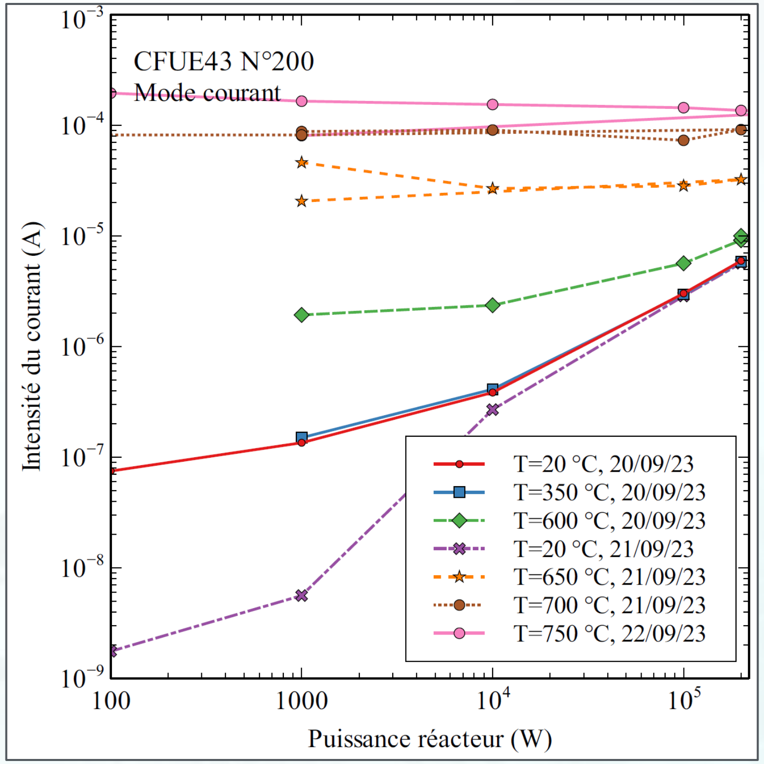


Day 3 Experiment
Max temp 850°C

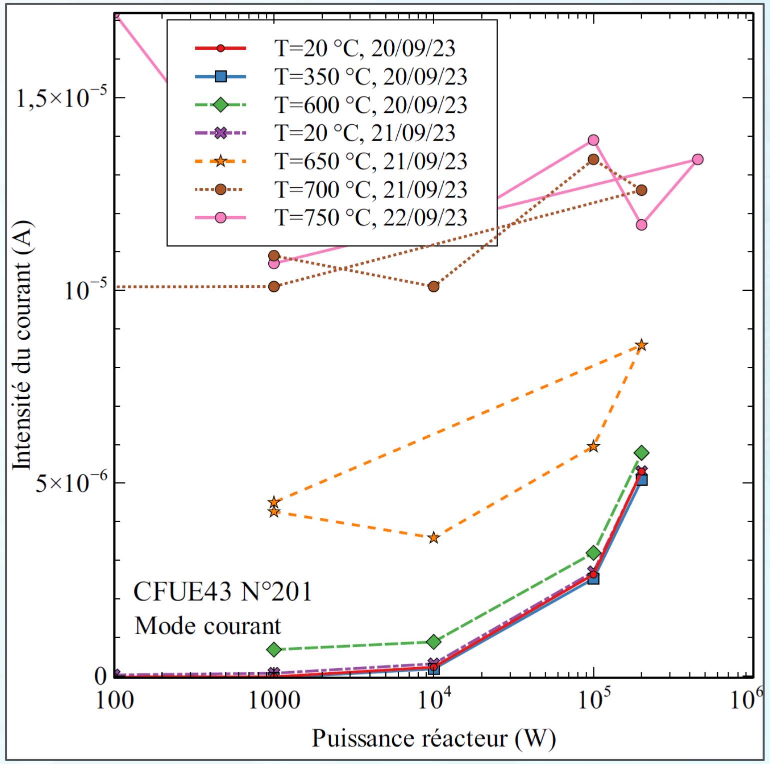
Results and Accomplishments

Fission Chamber Results

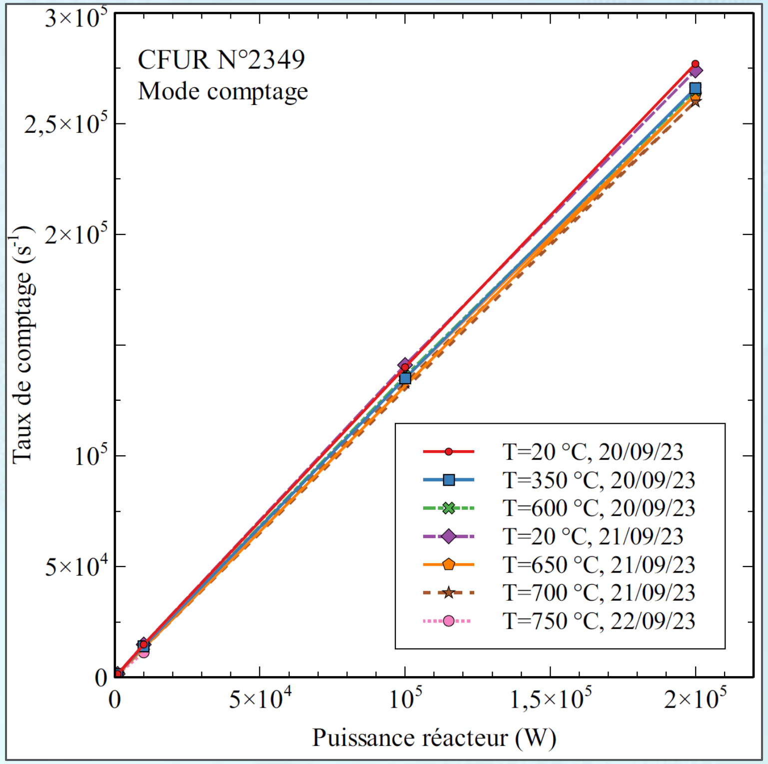
- Detector sensitivity as a function of temperature



HT-FC-1 response to temperature



HT-FC-2 response to temperature

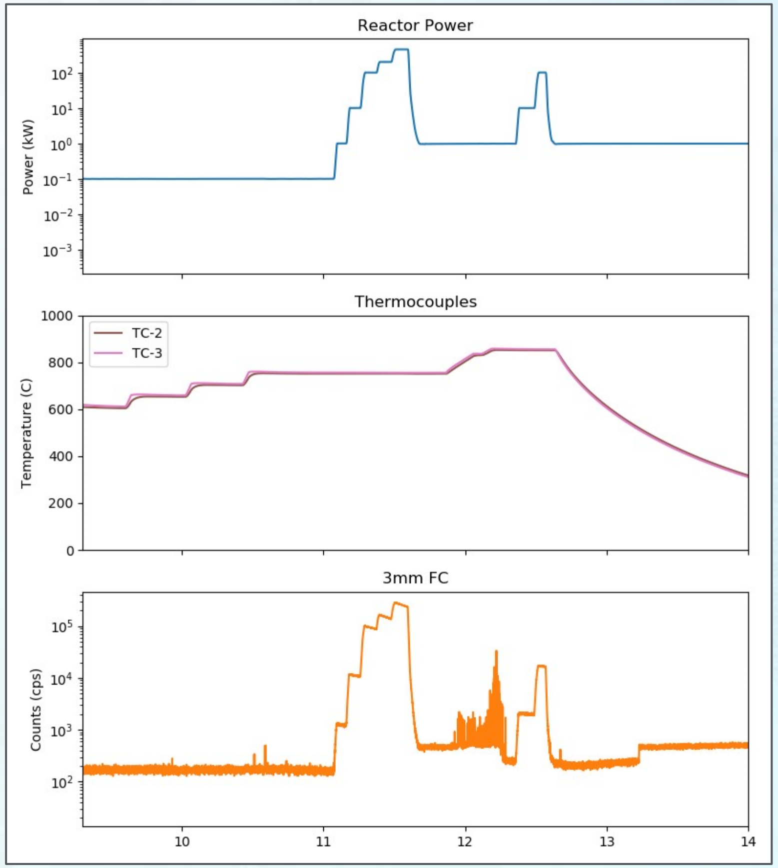


3mm FC response to temperature

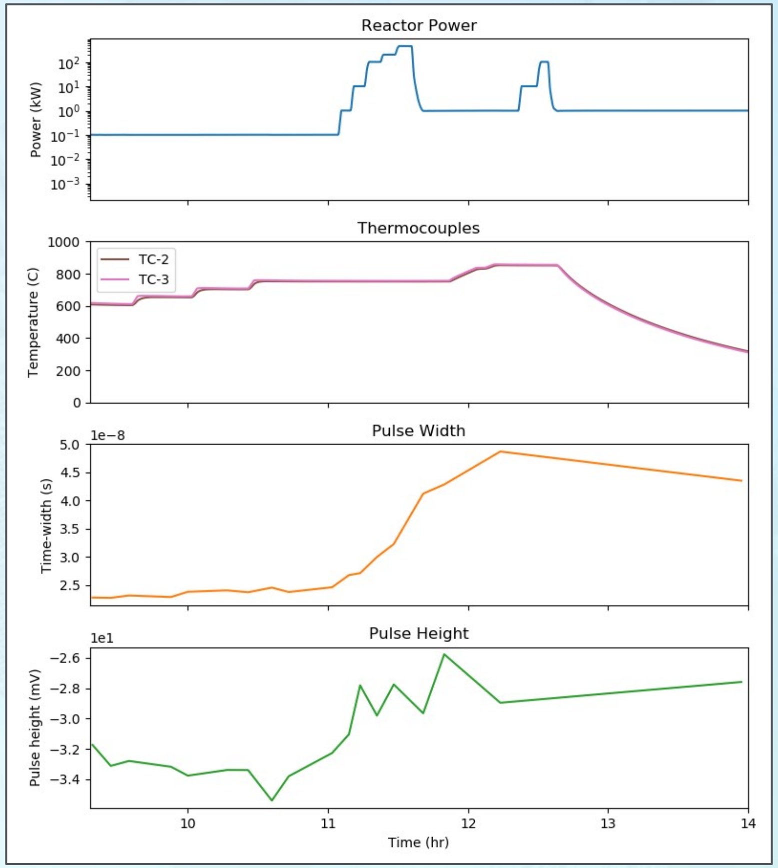
Results and Accomplishments

Fission Chamber Results

- 3mm Fission Chamber Failure Mode
- Failure of the gas-chamber seal
  - Occurs at 750℃ near power increase
  - Loss of fill-gas pressure
  - Decrease in count rate over time
  - Increase in average pulse width
  - Decrease in average pulse amplitude
- High voltage decrease from 250V to 150V



3mm fission chamber failure observed



Pulse width and pulse height progression

Concluding Remarks

Overview of Fission Chamber Activity

Performed heated irradiation of commercial fission chambers at OSURR for temperature ranges of 600 – 850˚C.

- Demonstrated the advantages of pulse mode operation – informed potential fabrication improvements
- Identified drawback of current mode operation at temperature – over saturation of signal from leakage currents
- M3CT-24IN0702011 – Performance benchmark of commercial fission chambers in elevated temperatures
  - Completed milestone report 11/30/2023

Results and Accomplishments

December SPND Irradiation Plan

- 3 days of irradiation
  - Days 1 is to test temperature effects at low power
  - Day 2 and 3 is to test sensor limits and identify failure points

Day 1 Experiment

Power	Duration	Temperature
10-30W	15-30 min each (+5min per temperature change)	Ambient 550 °C 575 °C 600 °C 625 °C 650 °C 675 °C 700 °C

Day 2 Experiment

Power	Duration	Temperature
100 W	1 hr	Ambient
100 W 1 kW 10 kW 100 kW	15 min each (+5 min per power change)	Ambient
1 kW	1 hr	Heat to 350 °C
1 kW 10 kW 100 kW	15 min each (+5 min per power change)	350 C
1 kW	1 hr	Heat to 600 °C
1 kW 10 kW 100 kW	15 min each (+5 min per power change)	600 °C
1kW	30 min for gamma stable initial 15-30min ea (+5 min per temperature)	625 °C 650 °C

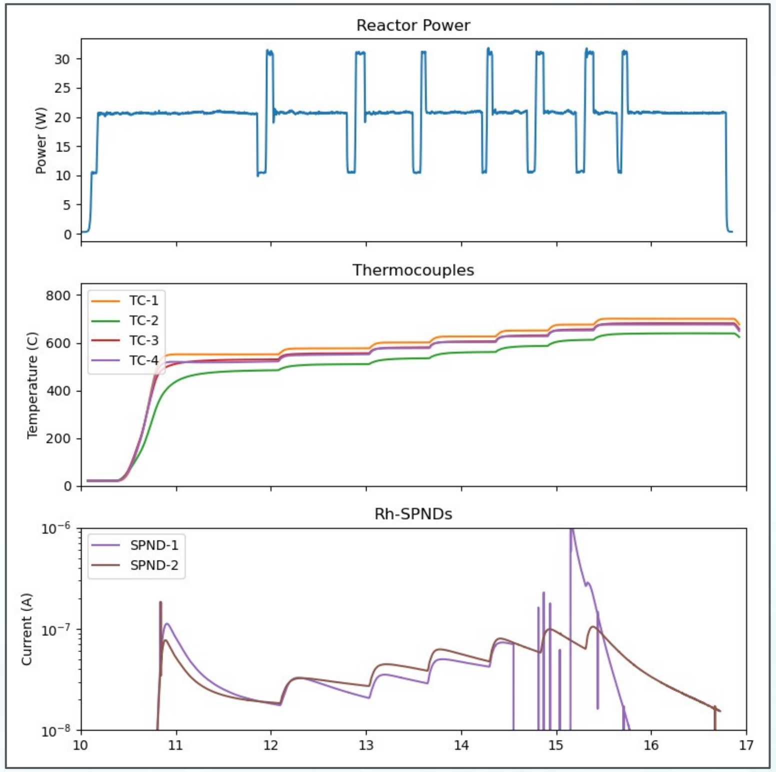
Day 3 Experiment

Power	Duration	Temperature
100 W	1 hr	Ambient
100 W 1 kW 10 kW 100 kW	15 min each (+5 min per power change)	Ambient
1 kW	1 hr	Heat to 700 °C
1 kW 10 kW 100 kW	15 min each (+5 min per power change)	700 °C
1 kW	1 hr	Heat to 850 °C
1 kW 10 kW 100 kW	15 min each (+5 min per power change)	850 °C

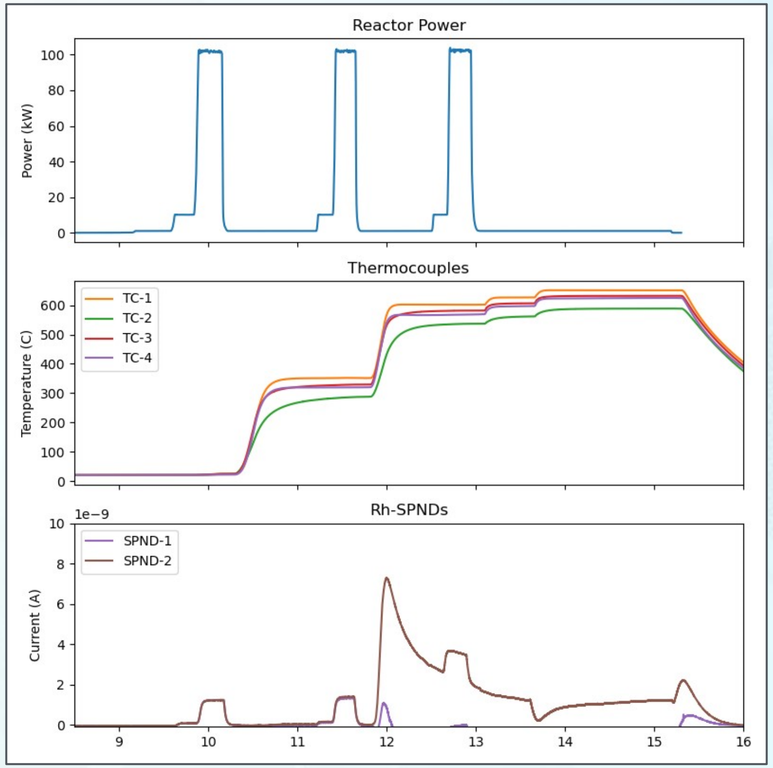
Results and Accomplishments

Self-Powered Neutron Detector Results

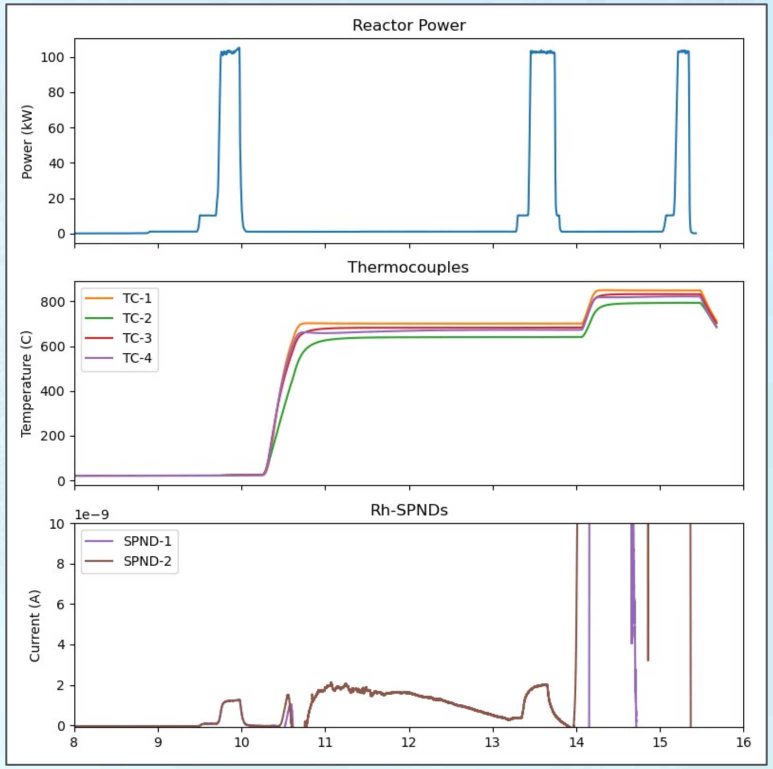
- Detector response overview



Day 1 Experiment
Max temp 700°C



Day 2 Experiment
Max temp 650°C

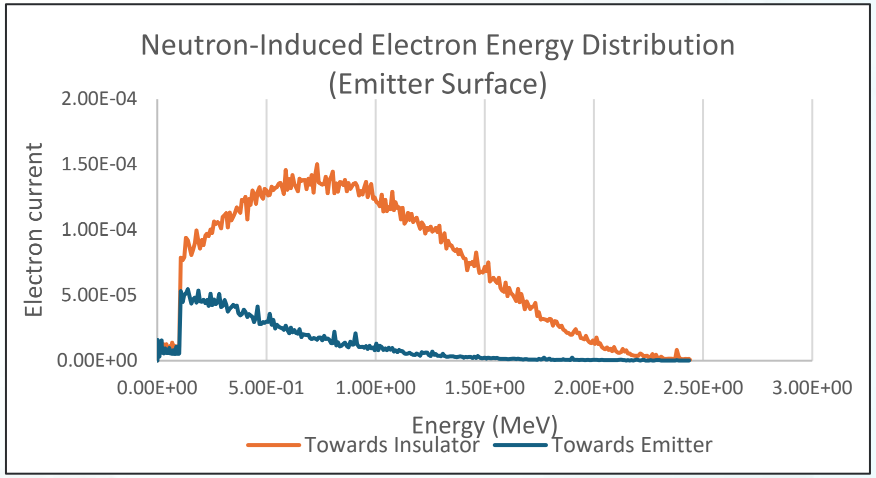


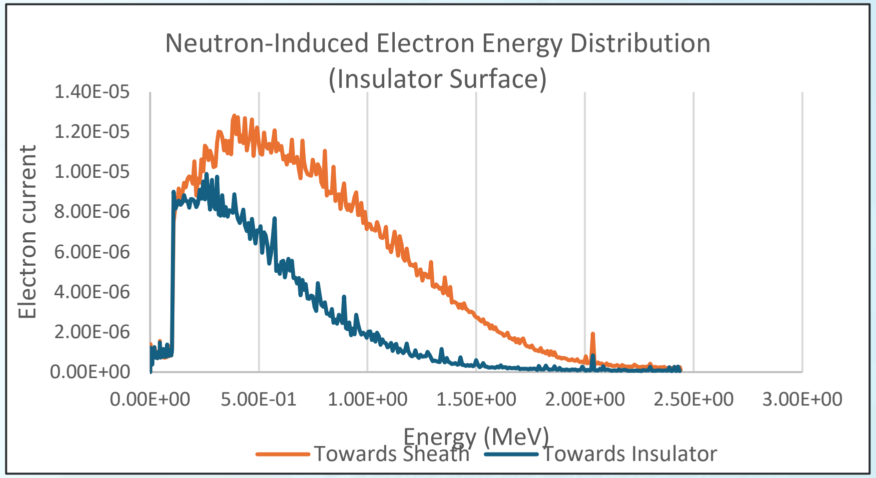
Day 3 Experiment
Max temp 850°C

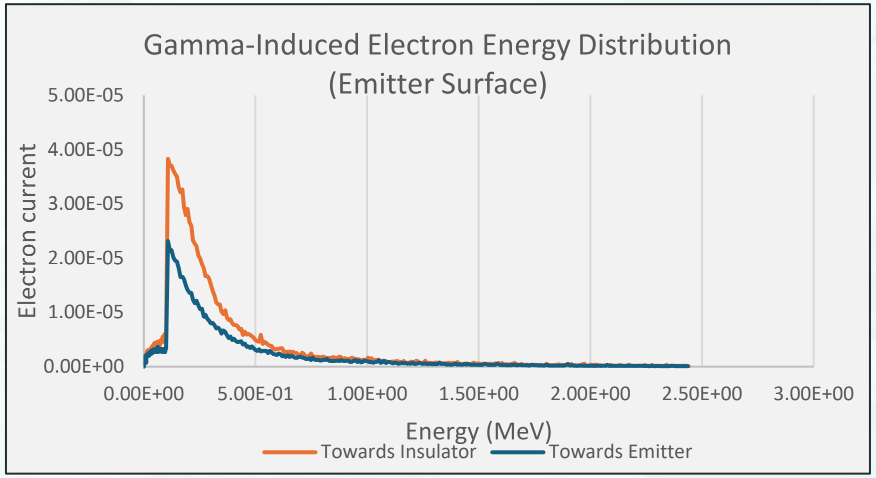
Results and Accomplishments

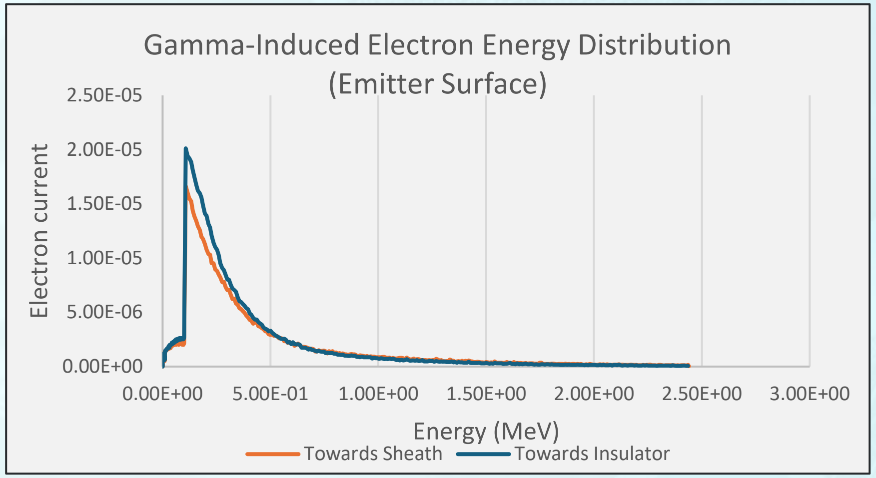
Self-Powered Neutron Detector Results

- Detector modeling for temperature effects





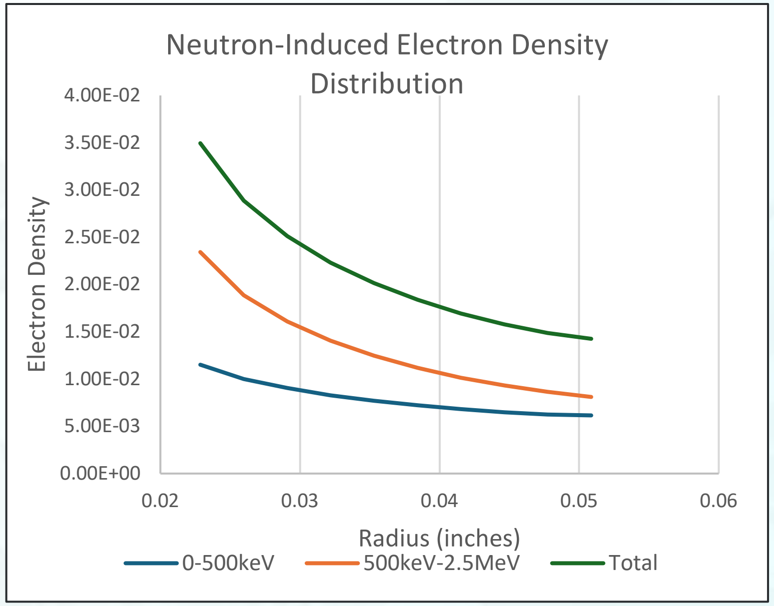


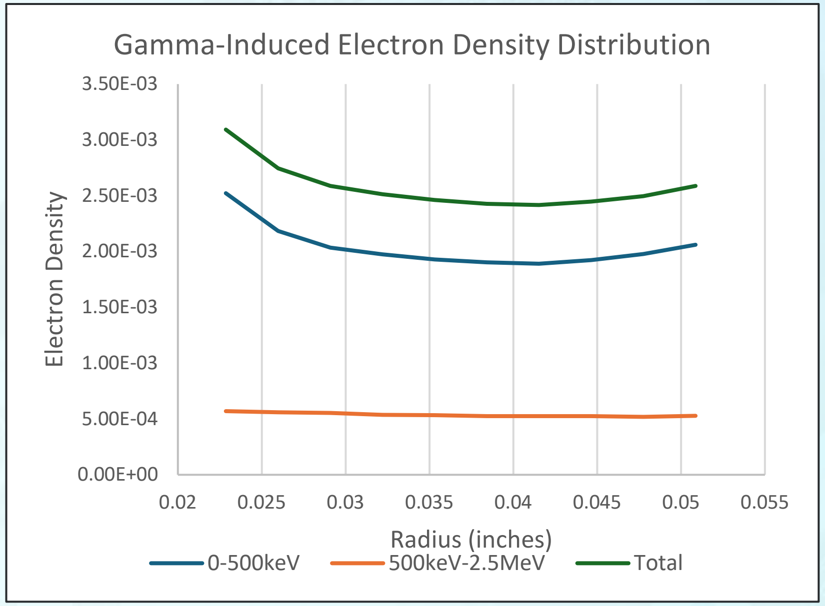


Results and Accomplishments

Self-Powered Neutron Detector Results

- Modeling electron distribution from neutron and gamma contribution
- 500 keV threshold determined from Warren' model[1] for qualitative view of "trapped electron"
- Gamma-induced electron density has higher fraction in the 0-500 keV energy range
  - Expected to be the root cause of temperature effects
- Neutron-induced effects are super-imposed, as observed.



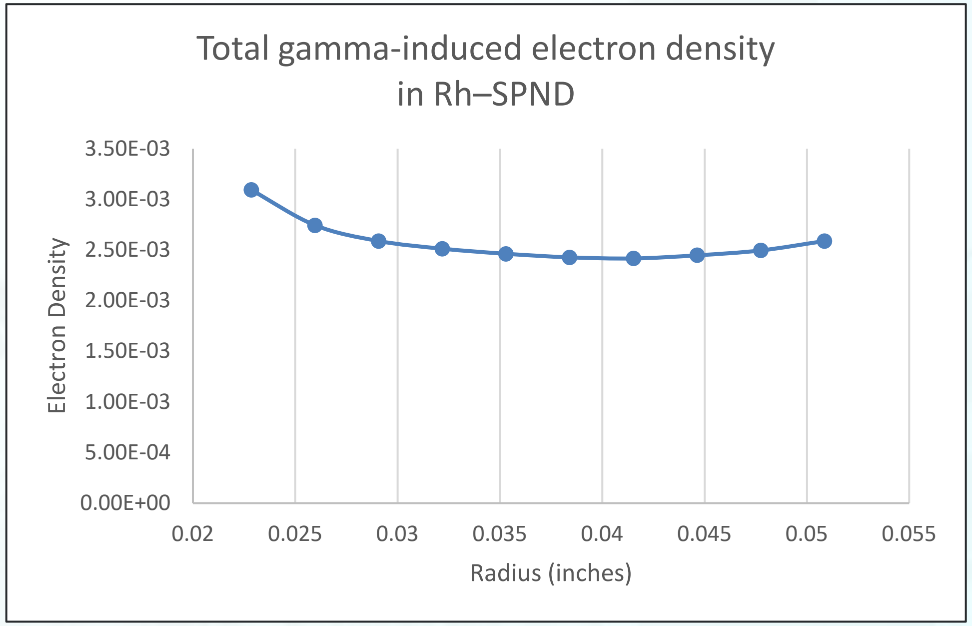


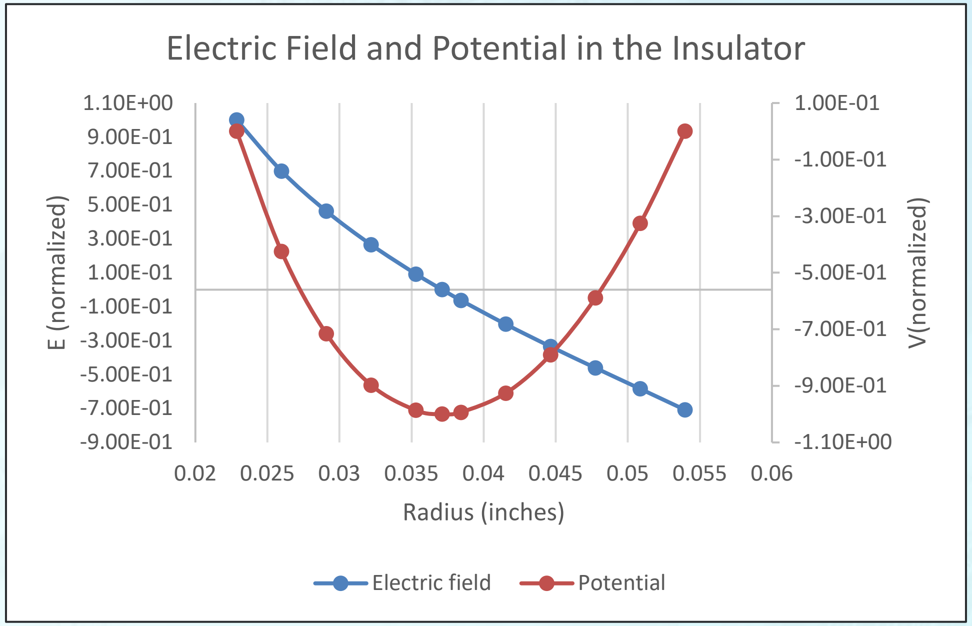
[1] H. D. Warren, "Calculational Model for Self-Powered Neutron Detector," *Nuclear Science and Engineering, vol. 48, no. 3, pp. 331-342, 2017, doi: 10.13182/nse72-a22491.*

Results and Accomplishments

Self-Powered Neutron Detector Results

- From the total gamma-induced distribution, an electric field and potential in the insulator can be calculated along with a critical radius, r_c
- Ratio of charge in radius $R < r_c$ over $R > r_c$ is 60%
  - Expect an increase in signal with heating to release "trapped" electron

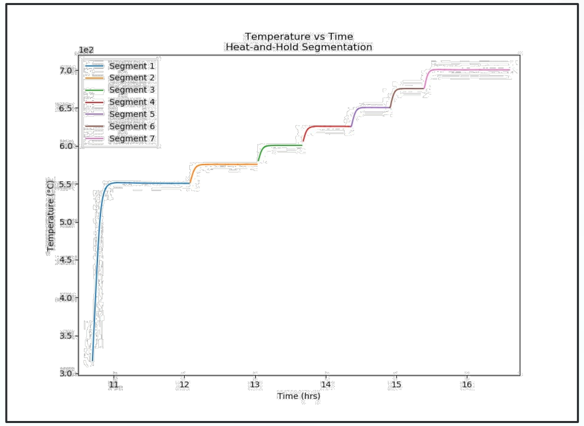


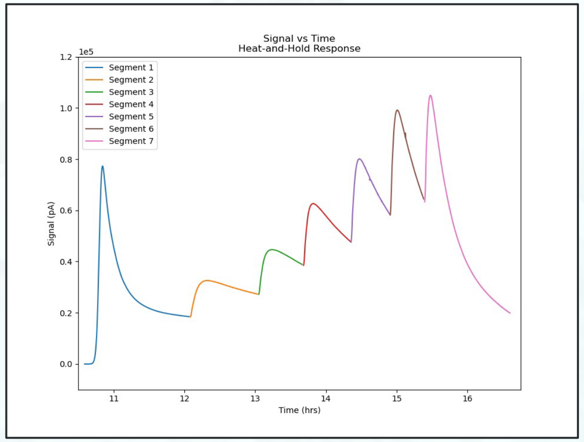


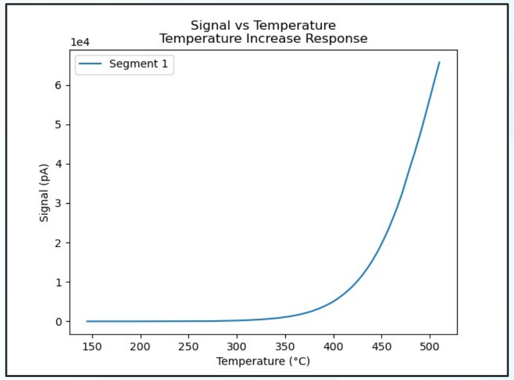
Results and Accomplishments

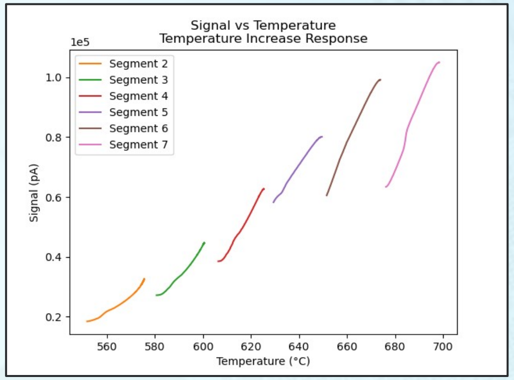
Self-Powered Neutron Detector Results

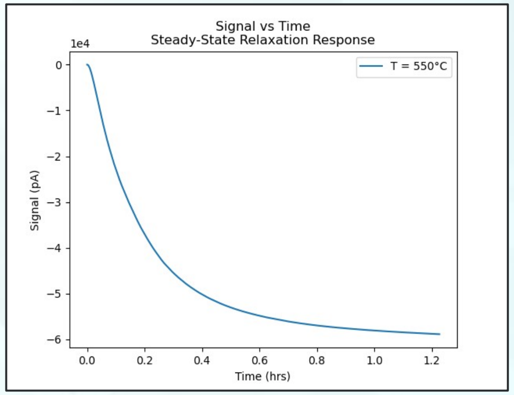
- Curve-fitting of the released electron under temperature ramps for compensation algorithm

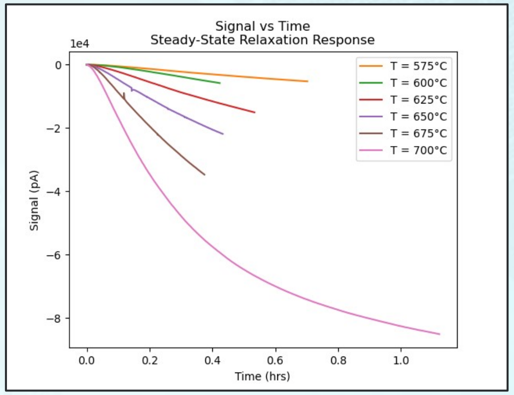


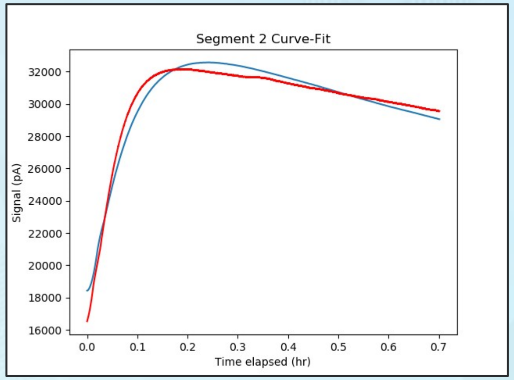


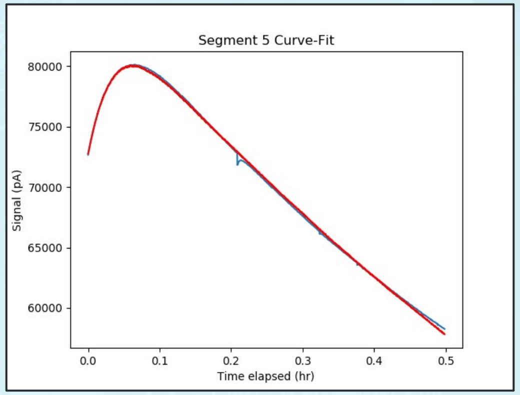












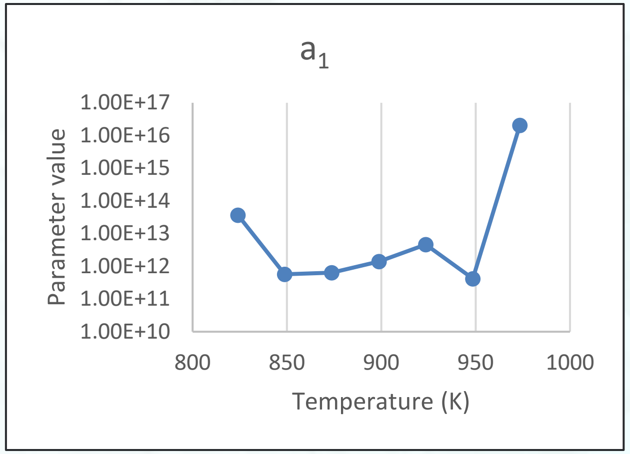
Results and Accomplishments

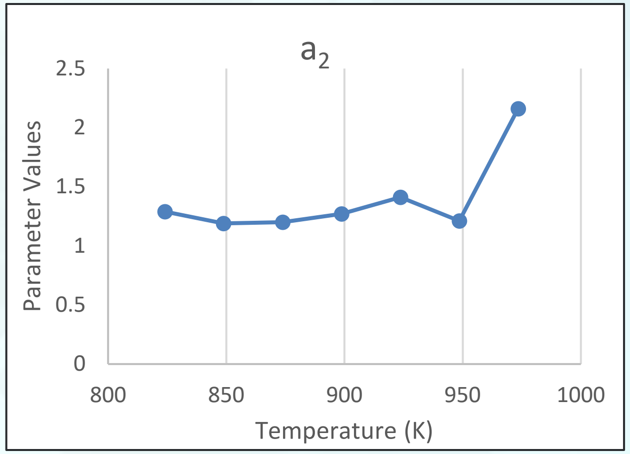
Self-Powered Neutron Detector Results

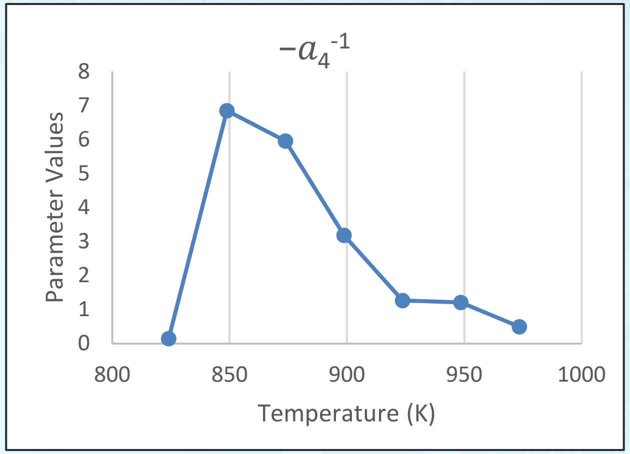
- Fitting results and comparison to underlying models for photoconduction and ionic conduction.

$$i_T(T,t) = a_1 e^{-a_2/kT} e^{a_4(T)(t-t_0)} + a_5$$

  - a_1 is the proportional value related to the field strength
  - a_2 is the energy necessary to free the electron from the imperfection and impurity sites to the conduction band
  - a_4 is related to the relaxation time constant. This is expected to increase in magnitude (decreasing decay time-constant) with increasing temperature with a proportionality of $-a_4^{-1} \propto R$ (insulator resistance)
  - a_5 is the expected relaxed steady-state signal at temperature – a dark current. It is related to leakage current as well as low-energy electron emission, however, its behavior in irradiation environments is not well understood.
  - Transition points are at 850K and 950K photoconduction to ionic to electronic conduction







Concluding Remarks

Overview of Self-Powered Neutron Detector Activity

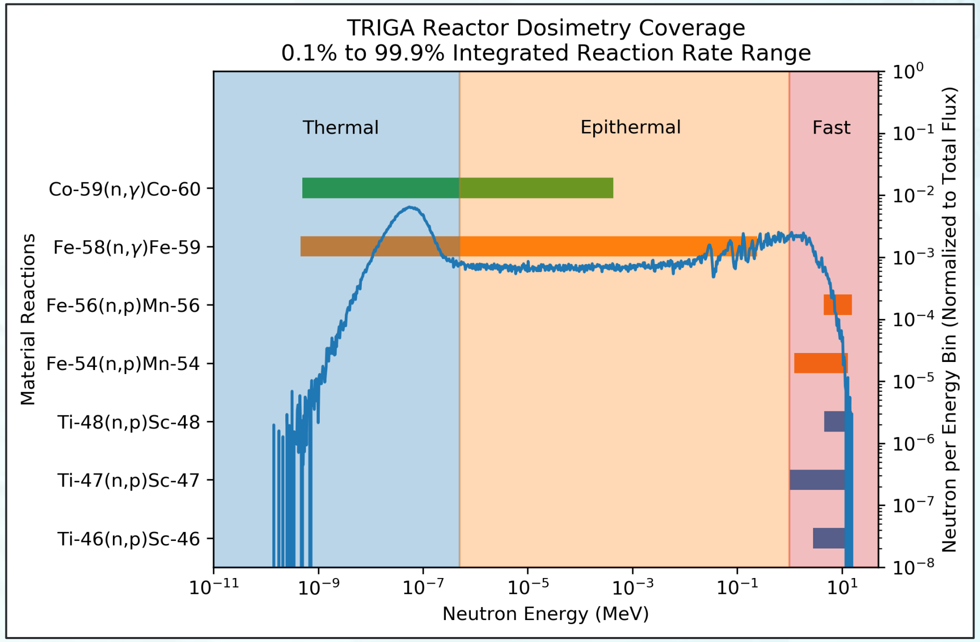
Performed heated irradiation of self-powered neutron detectors at OSURR for temperature ranges of 550 – 700˚C for characterizing temperature effect

- Failed to demonstrate algorithm for removing the temperature effect due to lack of data.
- Future work to better characterize the insulator properties for an SPND is needed.
  - Consideration for a heated gamma irradiation as (γ, e) effects are the primary cause of temperature effects.
- M3CT-24IN0702012 – Demonstration of temperature compensation techniques for SPNDs operating in high temperature environments
  - Completed (late) milestone report 6/30/2024

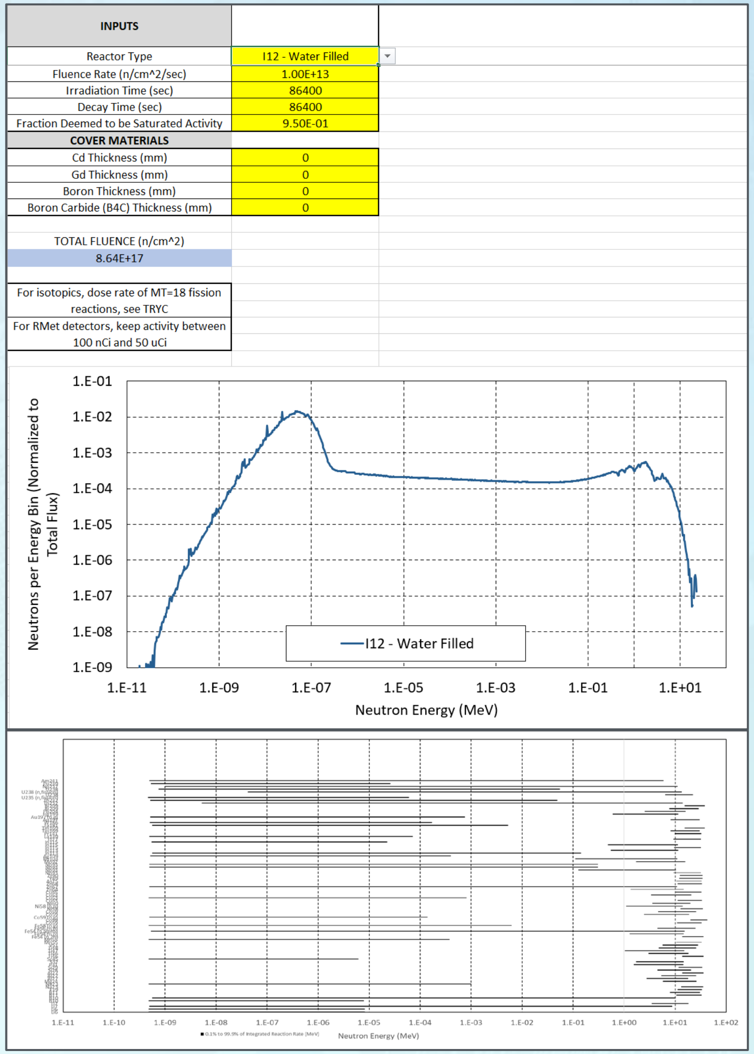
Results and Accomplishments

Spectral Unfolding Self-Powered Neutron Detectors - Introduction

- Based on method of dosimetry and spectrum adjustment algorithm
- Dosimeter packages are “custom” designed based on operational requirements:
  - Total reaction rate
  - Reaction rate range
  - Half-lives



Example of a spectrum coverage with titanium, iron, and cobalt wires.

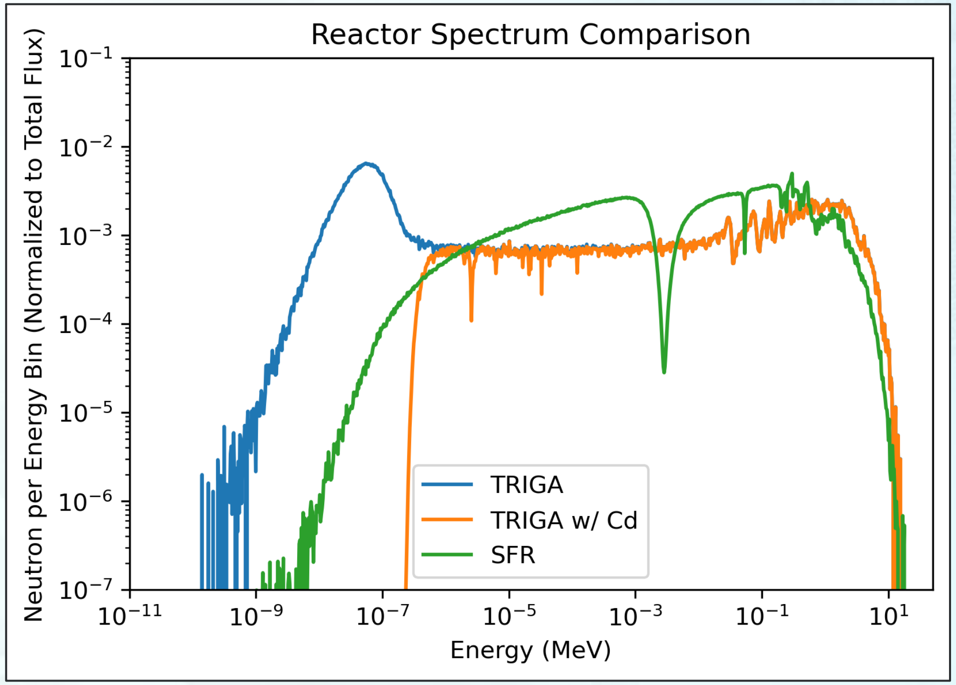


INL Dosimetry design spreadsheet

Results and Accomplishments

Spectral Unfolding Self-Powered Neutron Detectors - Introduction

- This work contains three parts:
  - Design and verification of a dosimetry package as a reference – ATRC
  - Evaluation of SPND emitters that are suitable for spectral unfolding – TRIGA w/ Cd cover
  - Development of a live visual spectral unfolding algorithm

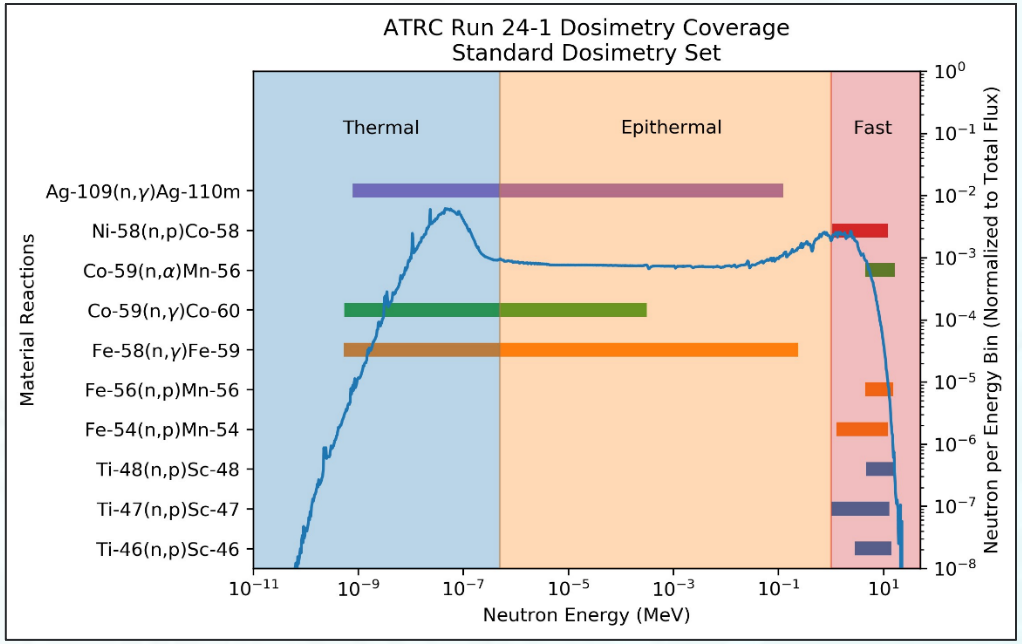


Example of a spectrum coverage with titanium, iron, and cobalt wires.

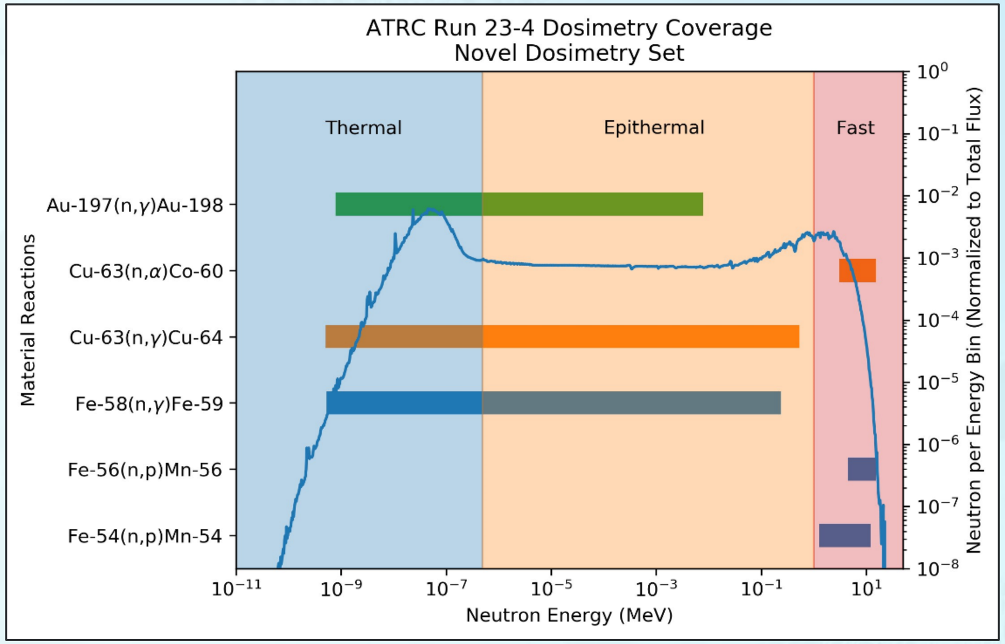
Results and Accomplishments

Spectral Unfolding Self-Powered Neutron Detectors - Dosimetry

- Dosimetry activation verification is performed at the ATRC.
  - ATRC provides a low flux to identify lower limits for threshold reactions (fast spectrum detection)
  - Fast turnaround to demonstrate additional “novel” dosimetry methods to be considered for calibrating SPNDs



Standard ATRC dosimeter set containing titanium, iron, cobalt, nickel, and silver wires.

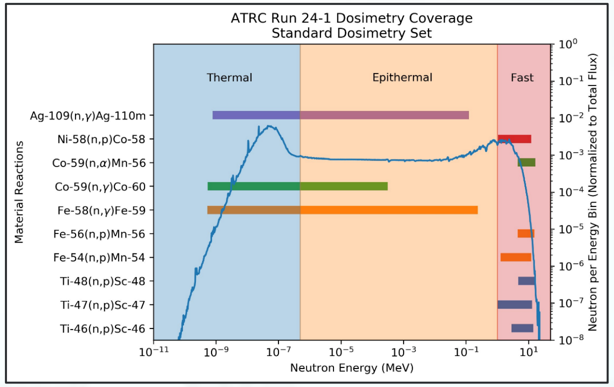


“Novel” dosimeter set containing a copper/gold alloyed wire

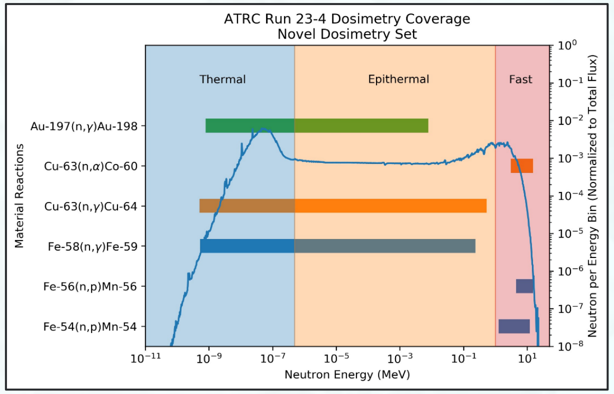
Results and Accomplishments

Spectral Unfolding Self-Powered Neutron Detectors – Dosimetry

- Acceptable reaction rate
- High uncertainty tied to counting order and priority.



Interaction	Predicted Activity (uCi/g)	SE-2 Measured Activity (uCi/g)	2σ % Total Uncert.	C/E SE-2	SE-4 Measured Activity (uCi/g)	2σ % Total Uncert.	C/E SE-4
Ti-46(n, p)Sc-46	1.74E-06	4.46E-05	17.86%	3.90E-02	2.49E-04	9.51%	6.99E-03
Ti-47(n, p)Sc-47	6.24E-05	1.34E-03	3.65%	4.66E-02	1.65E-02	3.47%	3.78E-03
Ti-48(n, p)Sc-48	1.71E-05	2.88E-04	7.26%	5.94E-02	2.08E-03	4.26%	8.22E-03
Co-59(n, γ)Co-60	6.59E-03	3.97E-02	3.06%	1.66E-01	5.39E-02	3.06%	1.22E-01
Co-59(n, α)Mn-56	5.95E-05	6.01E-01	3.17%	9.90E-05	8.08E-01	3.20%	7.36E-05
Ni-58(n, p)Co-58	1.31E-04	1.94E-03	4.46%	6.75E-02	1.26E-03	6.21%	1.04E-01
Fe-54(n, p)Mn-54	1.97E-06	3.29E-05	18.73%	5.99E-02	4.16E-05	7.35%	4.74E-02
Fe-56(n, p)Mn-56	3.78E-04	2.29E-02	4.88%	1.65E-02	1.84E-02	4.00%	2.05E-02
Fe-58(n, γ)Fe-59	2.73E-05	2.59E-04	7.78%	1.05E-01	2.36E-04	7.35%	1.16E-01
Ag-109(n, γ) Ag-110m	2.97E-03	1.07E-02	6.57%	2.78E-01	1.16E-02	6.26%	2.56E-01

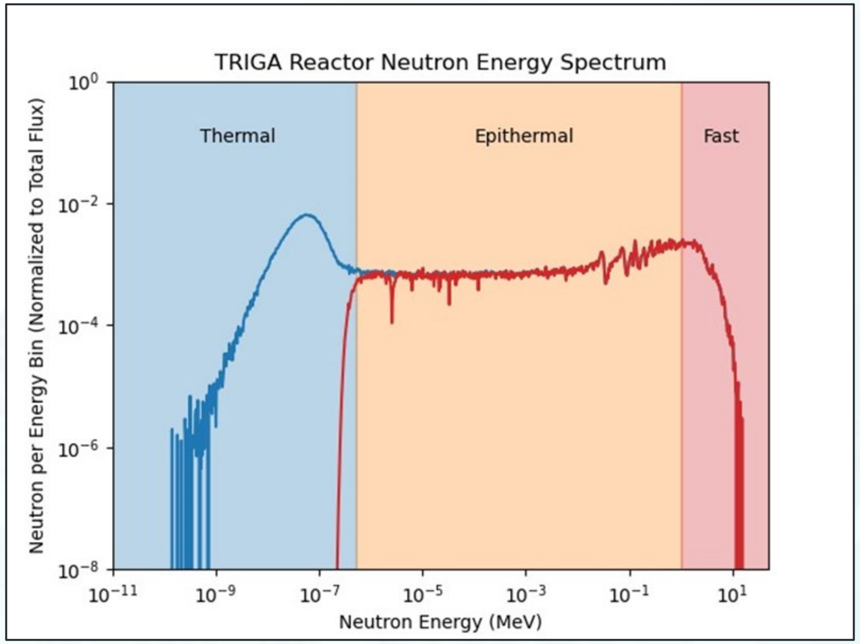


Interaction	Predicted Activity (uCi/g)	SE-2 Measured Activity (uCi/g)	2σ % Total Uncert.	C/E SE-2	SE-4 Measured Activity (uCi/g)	2σ % Total Uncert.	C/E SE-4
Fe-54(n, p)Mn-54	1.97E-06	-	-	-	5.87E-05	48.03%	3.36E-02
Fe-56(n, p)Mn-56	3.78E-04	-	-	-	1.93E-02	16.89%	1.96E-02
Fe-58(n, γ)Fe-59	2.73E-05	3.13E-04	44.19%	8.72E-02	4.65E-04	25.27%	5.87E-02
Cu-63(n, γ)Cu-64	1.30E+00	1.50E+01	4.64%	8.67E-02	1.55E+01	5.08%	8.39E-02
Cu-63(n, α)Co-60	2.29E-08	-	-	-	3.11E-04	29.06%	7.36E-05
Au-197(n, γ)Au-198	7.01E+00	1.00E+00	3.47%	7.01E+00	1.21E+00	3.81%	5.79E+00

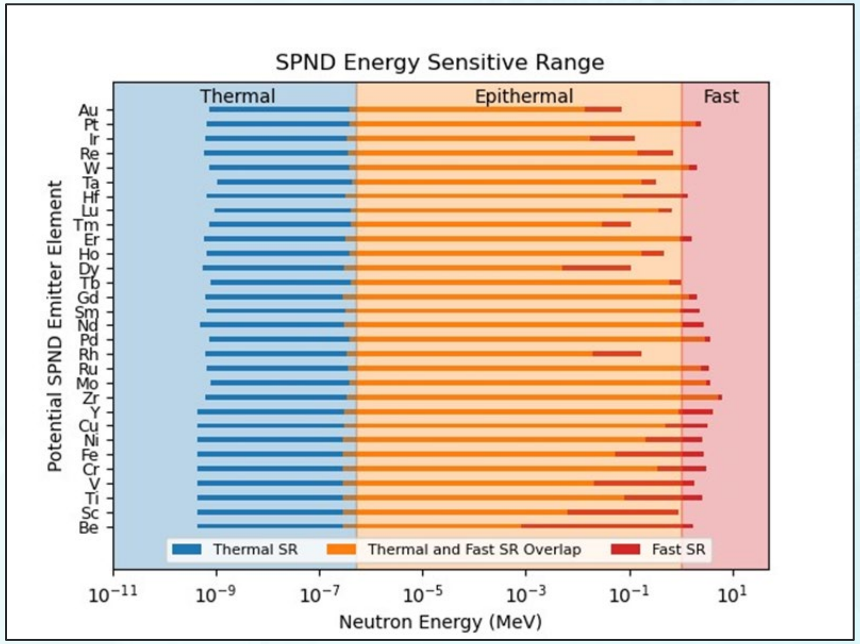
Results and Accomplishments

Spectral Unfolding Self-Powered Neutron Detectors – Emitter Search

- SPND reactions from all potential elements were added to the dosimeter search list
- The emitter sensitive ranges with and without cadmium cover were calculated



TRIGA spectrum w/ and w/o Cd cover for SPND emitter search



Potential SPND emitter sensitivity range based on reference spectra

Element	Thermal	Fast
Be	x	x
Sc	x	—
Ti	x	x
V	x	x
Cr	x	x
Fe	x	x
Ni	x	x
Cu	x	x
Y	x	x
Zr	—	x
Mo	—	x
Ru	—	x
Rh	x	—
Pd	—	x
Nd	—	x
Sm	x	x
Gd	—	x
Tb	x	x
Dy	x	—
Ho	x	—
Er	x	x
Tm	x	—
Lu	x	—
Hf	x	x
Ta	x	—
W	—	x
Re	x	—
Ir	x	—
Pt	—	x
Au	x	—

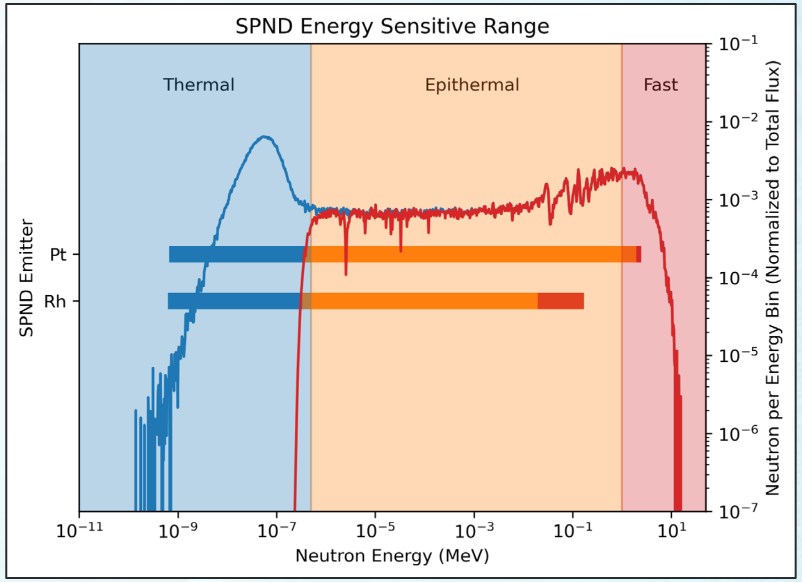
Application range of elements

Results and Accomplishments

Spectral Unfolding Self-Powered Neutron Detectors – Emitter Search

- A narrowed down list is available:

Thermal	Fast
Rh	Gd
Ir	W
Dy	Pt



- Rh is a good choice for thermal as it is a commonly used SPND
- Gd is a specific design only tested at INL/TREAT, so Pt is chosen as another common type SPND.

Concluding Remarks

Overview of Spectrum Unfolding Activity

Performed ATRC irradiation of dosimetry sets to test activation limits

- Verified acceptable limits based on ATRC flux
- Demonstrated capability for "novel" dosimetry technique

Performed evaluation for SPND emitter

- Integrated SPND reactions to dosimetry spreadsheet
- Identified emitter sensitivity range
- Selected Rh and Pt as candidates for spectral unfolding

M2CT-24IN0702013 – Development of neutron energy spectrum unfolding methods using SPNDs.

- Completed milestone report 9/30/2024
  - Spectrum unfolding algorithm presented in Pacific Basin Nuclear Conference 2024: Teancum Quist, "Curve Fitting Parameterization of Neutron Spectra"
  - Dosimetry results submitted for ANIMMA 2025
  - Drafting manuscript of M2 report for journal publication

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Reactor Power Monitoring – INL

Reactor Dosimetry Complement to Self-Powered Neutron Detectors

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
November 4, 6-7, 2024

Nuclear Engineer: Tommy Holschuh, Ph.D.

Idaho National Laboratory – INL/MIS-24-81823

Project Overview

The measurement of neutron energies in a reactor or reactor experiment is a crucial method for determining quantities of interest

- Material reaction rates
- Experiment's reactivity worth as a function of energy
- Reactor kinetics parameters
- Confirmation of computational model physics

Radiochemistry and Nuclear Measurements:

- Tommy Holschuh, Ph.D.
- Teancum Quist, Ph.D. (postdoctoral researcher)

Radiation Measurements:

- Michael Reichenberger, Ph.D.

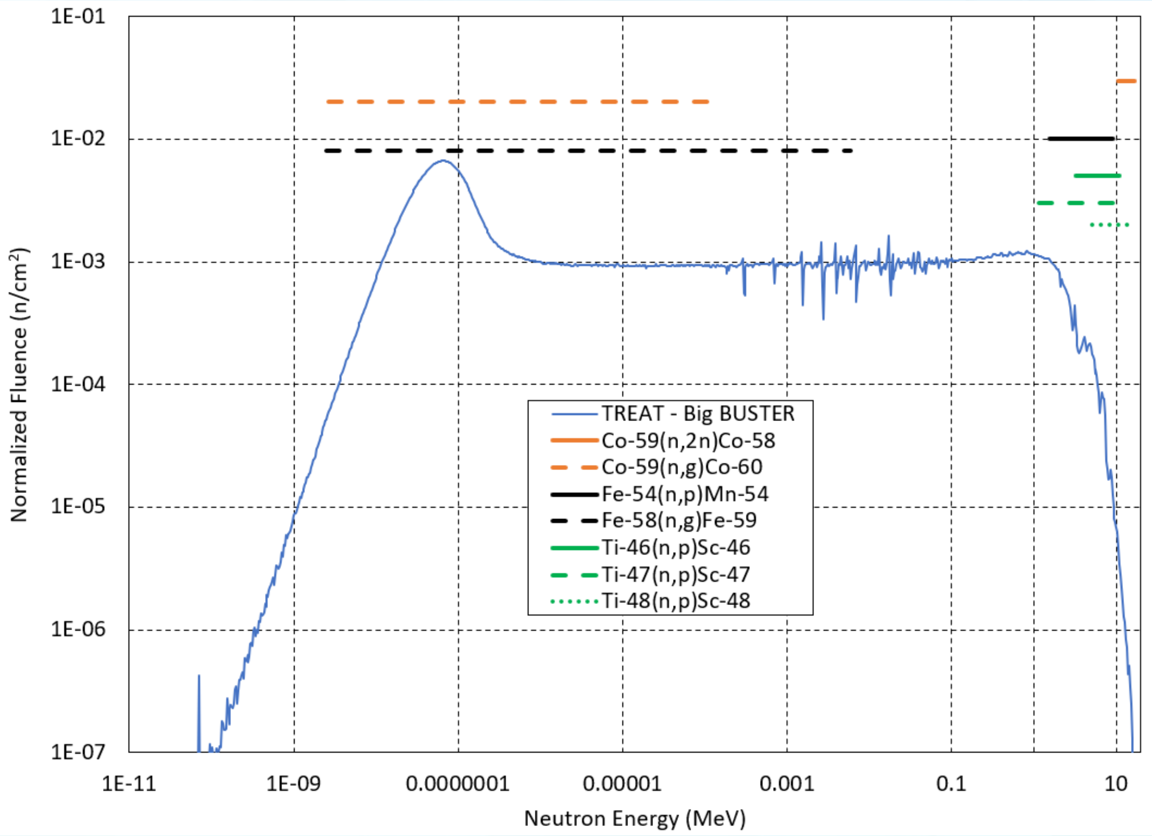
Measurement Sciences:

- Kevin Tsai

Technology Impact

Comprehensive reactor dosimetry can include up to 30 material reactions

- There are many instances where a smaller subset must be used.
  - Space, applicability of wires, etc.
- Image to right shows 3 wires (Ti, Fe, Co) that provide 7 neutron energy groups.
- Disadvantage – not real time, activation materials must be removed from reactor.
- The objective of the reactor dosimetry connected to ASI is to validate a method for performing crude neutron energy group measurements with SPNDs rather than a suite of wires.



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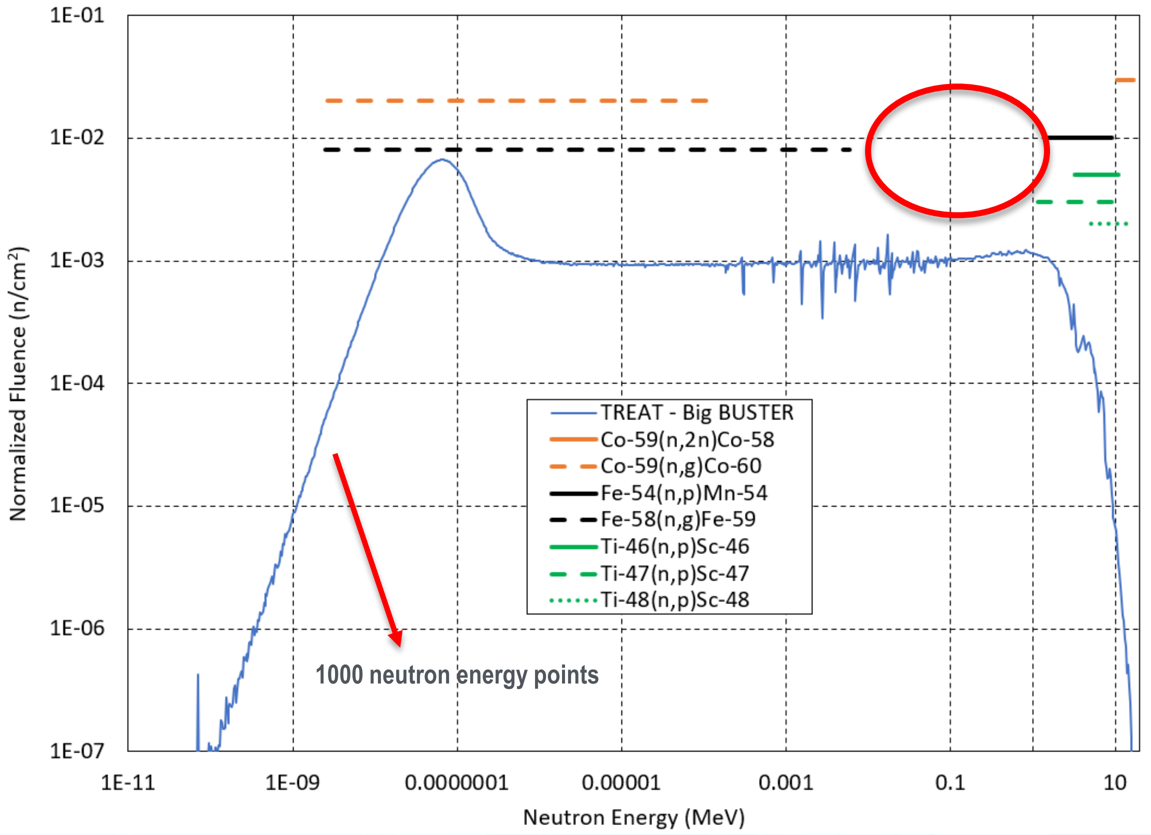
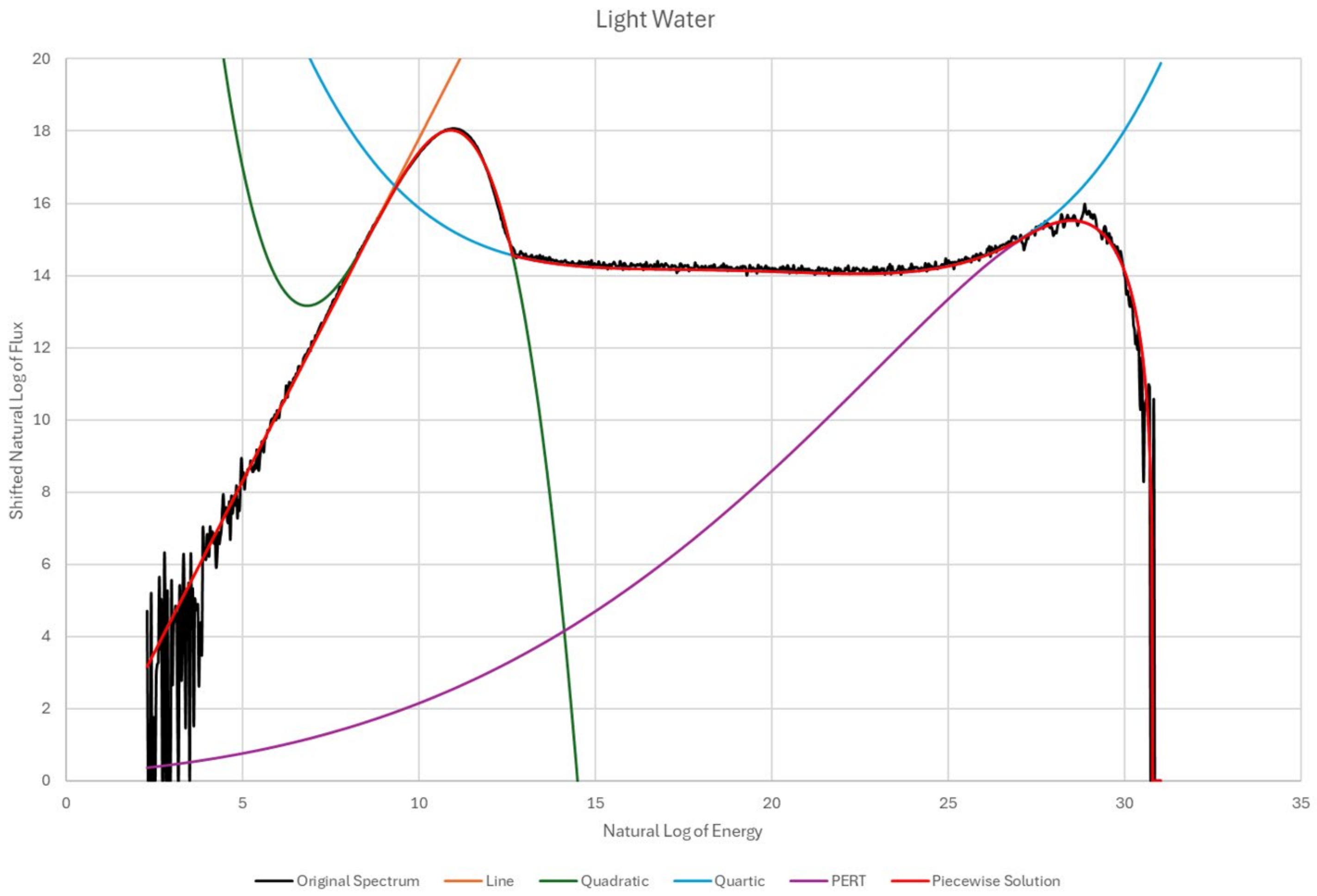


Results and Accomplishments

Presented at American Nuclear Society Pacific Basin Nuclear Conference

(October 2024)

- The neutron spectrum (typically 100's of energy groups) is fit with curve types
  - Depending on neutron physics in region
- This allows two SPNDs to manipulate four equations
  - Opposed to 3 wires, 1000 neutron energy groups
- Pt, Rh have different neutron responses, so the signals will affect each "curve" separately.



Concluding Remarks

- Proof of concept for performing reactor dosimetry with just two SPNDs has not been shown yet
  - Reactor experiments can be performed several different ways.

- In FY25, this is our goal.
- Curve fitting parameterization may need to be “tweaked.”

- Reactor experiments will have a backup of traditional dosimetry as a comparison for “fitted” parameters in the neutron energy curve.

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Thank You