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

ASI | Advanced Sensors and Instrumentation

Reactor Power Synthesis with Simulated SPND Responses & SPND Analysis of WIRE-21

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 30 – November 2, 2023

Oak Ridge National Laboratory

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Reactor Power Synthesis with Simulated SPND Responses

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Anthony Birri, K. C. Goetz,
Daniel C. Sweeney, Tyler Gates, N. Dianne Bull Ezell
Oak Ridge National Laboratory

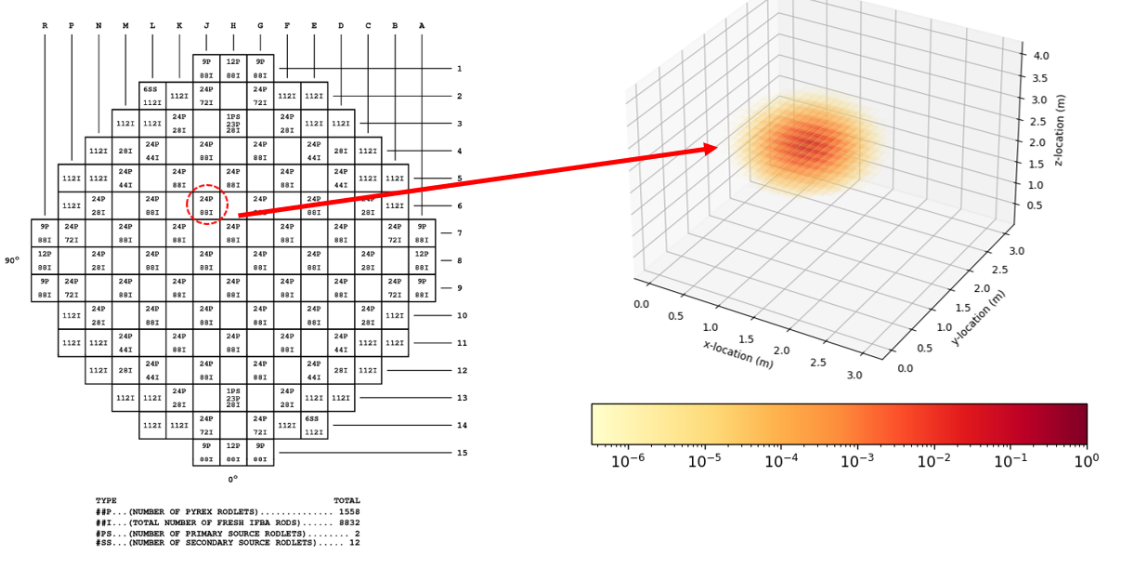
Project Overview

- The goal of this project is to utilize a weighting function based method to synthesize core power based on simulated sensor responses
  - Reactor models come from MCNP, sensor physics can come from Geant4
- Looking at multiple reactors in order to assess
  - Impact of sensor uncertainty
  - What types of perturbations can be accurately detected
  - Sensor arrangement optimization
- In FY23, there were to main focuses:
  1. **Assess impact of sensor uncertainty in AP1000 and NuScale SMR**
  2. **Develop a highly realistic model and demonstrate perturbation detection w/ TAMU TRIGA**
- Participants

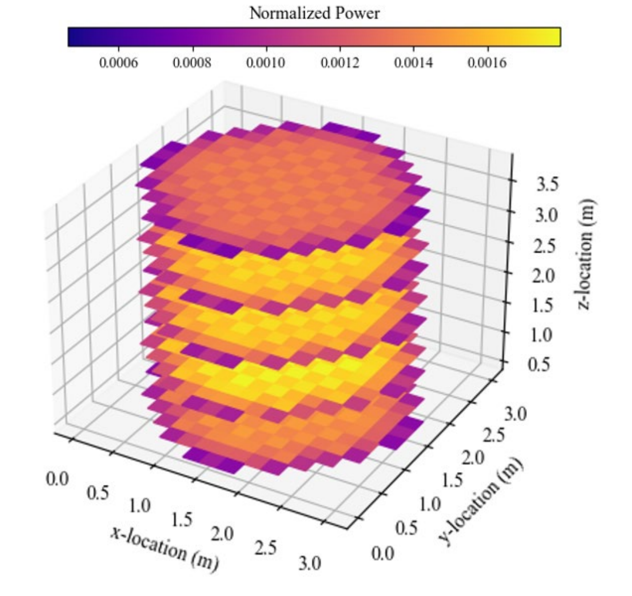
  ORNL: Anthony Birri (PI), Callie Goetz (Geant4 modeling), Daniel Sweeney (python expertise), N. Dianne Bull Ezell (supervision)

  TAMU: Tyler Gates (TAMU, MCNP modeling)

Simulate Sensor Responses



Infer Power Distribution



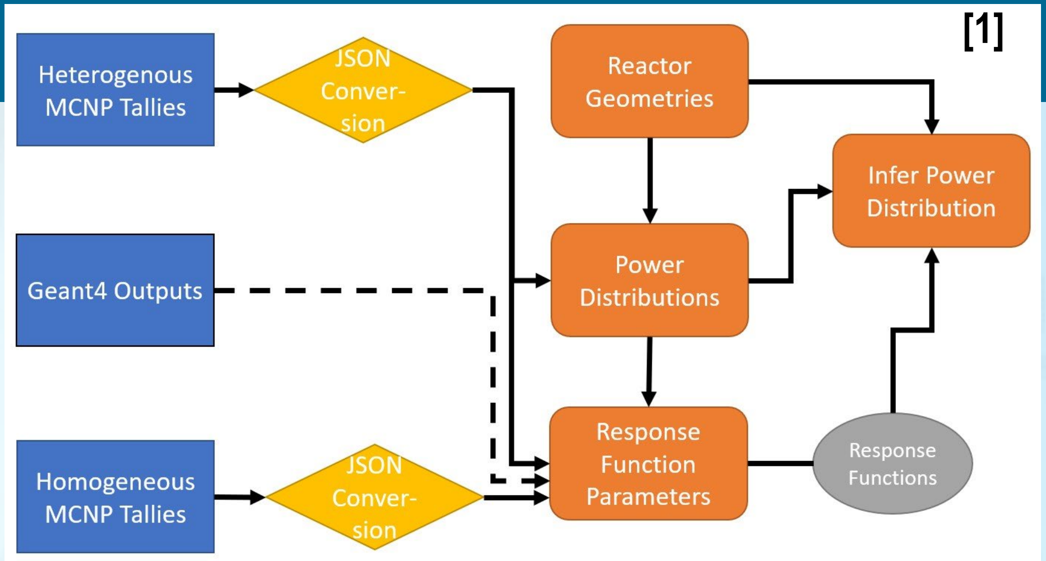
Overview of Methodology

- The method we have developed is coined the "Point Based Iterative" (PBI) method
  - It is fundamentally a weighting function based method
- The idea is that each sensor can provide an estimate of the power in each 'chunk' of fuel via a response function
  - MCNP informed flux data
- Through a weighted average, each chunk power is determined based on all the sensor estimates
  - This is an iterative process

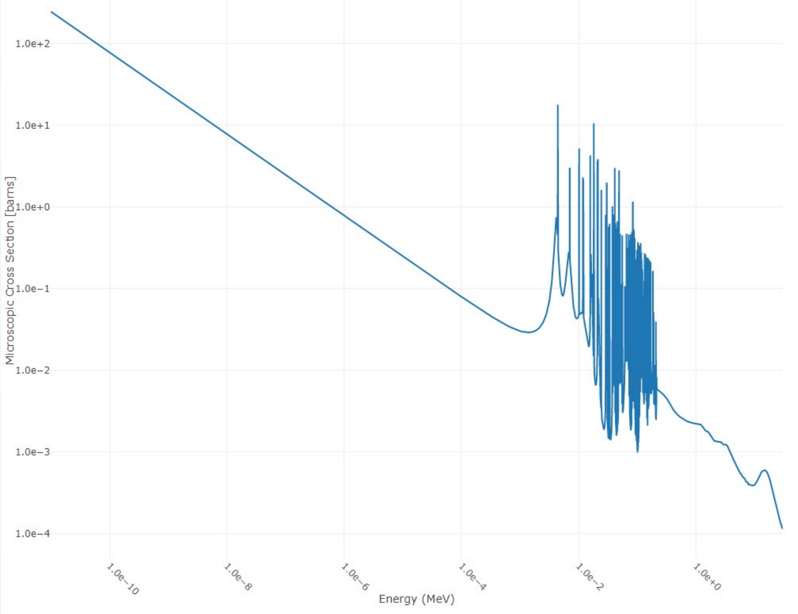
[1] DOI: 10.2172/1996662

[2] DOI: 10.1016/j.pnucene.2022.104437

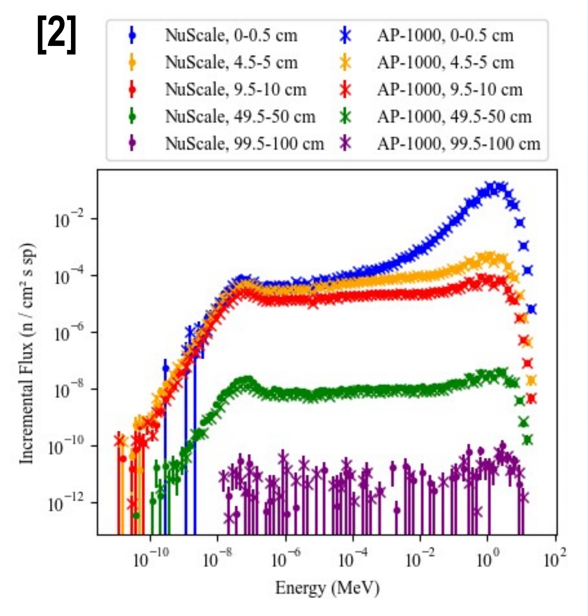
Software Flowchart



V-51 neutron absorption cross section



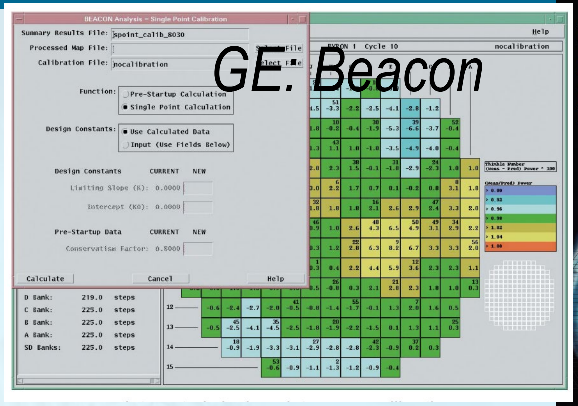
Flux Characterization

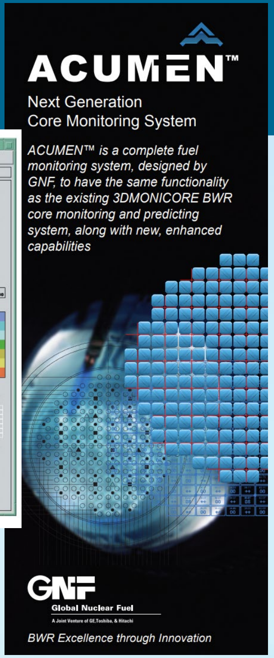


Technology Impact

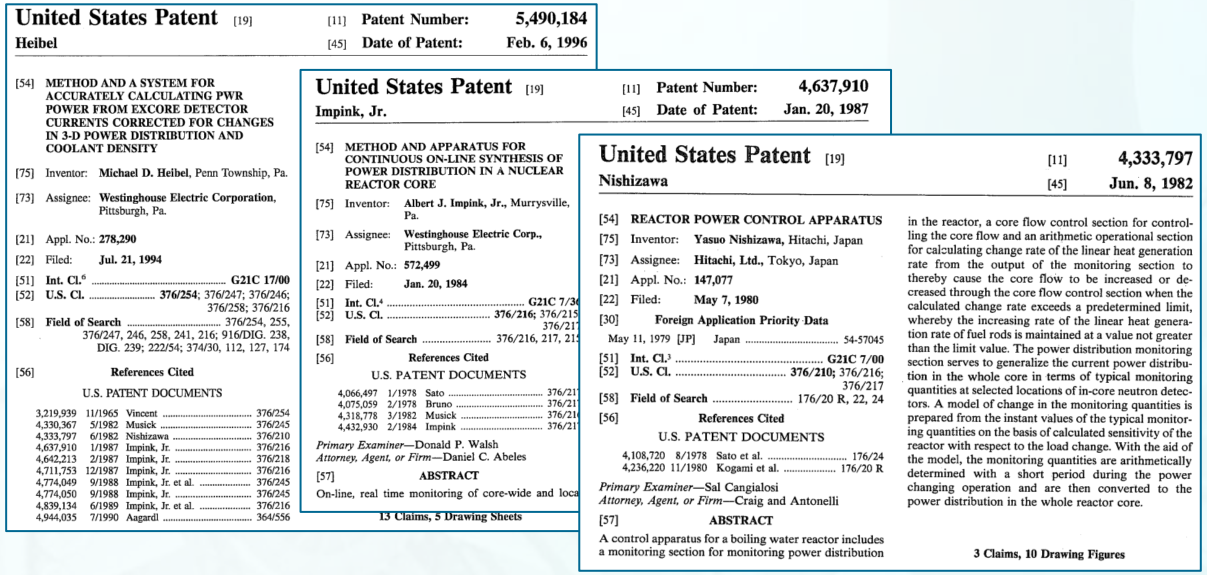
- It is clear that core power shape synthesis is utilized by industry
- However, efficacy of implemented methods in software is unclear
- A small body of research literature exists, but there are still many questions which remain, regarding optimization, uncertainty, etc.

Industry Software





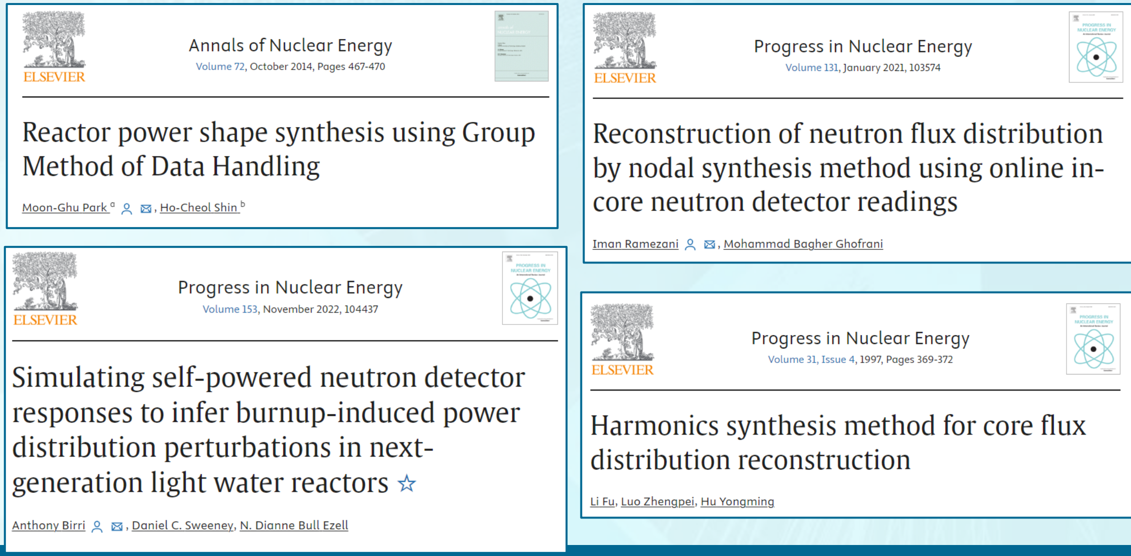
Patents


United States Patent [19] Heibel
[11] Patent Number: 5,490,184
[45] Date of Patent: Feb. 6, 1996
[54] METHOD AND A SYSTEM FOR ACCURATELY CALCULATING PWR POWER FROM EXCORE DETECTOR CURRENTS CORRECTED FOR CHANGES IN 3-D POWER DISTRIBUTION AND COOLANT DENSITY
[75] Inventor: Michael D. Heibel, Penn Township, Pa.
[73] Assignee: Westinghouse Electric Corporation, Pittsburgh, Pa.
[21] Appl. No.: 278,290
[22] Filed: Jul. 21, 1994

United States Patent [19] Impink, Jr.
[11] Patent Number: 4,637,910
[45] Date of Patent: Jan. 20, 1987
[54] METHOD AND APPARATUS FOR CONTINUOUS ON-LINE SYNTHESIS OF POWER DISTRIBUTION IN A NUCLEAR REACTOR CORE
[75] Inventor: Albert J. Impink, Jr., Murrysville, Pa.
[73] Assignee: Westinghouse Electric Corp., Pittsburgh, Pa.
[21] Appl. No.: 572,499
[22] Filed: Jan. 20, 1984

United States Patent [19] Nishizawa
[11] 4,333,797
[45] Jun. 8, 1982
[54] REACTOR POWER CONTROL APPARATUS
[75] Inventor: Yasuo Nishizawa, Hitachi, Japan
[73] Assignee: Hitachi, Ltd., Tokyo, Japan
[21] Appl. No.: 147,077
[22] Filed: May 7, 1980
[57] ABSTRACT
A control apparatus for a boiling water reactor includes a monitoring section for monitoring power distribution in the reactor, a core flow control section for controlling the core flow and an arithmetic operational section for calculating change rate of the linear heat generation rate from the output of the monitoring section to thereby cause the core flow to be increased or decreased through the core flow control section when the calculated change rate exceeds a predetermined limit, whereby the increasing rate of the linear heat generation rate of fuel rods is maintained at a value not greater than the limit value. The power distribution monitoring section serves to generalize the current power distribution in the whole core in terms of typical monitoring quantities at selected locations of in-core neutron detectors. A model of change in the monitoring quantities is prepared from the instant values of the typical monitoring quantities on the basis of calculated sensitivity of the reactor with respect to the load change. With the aid of the model, the monitoring quantities are arithmetically determined with a short period during the power changing operation and are then converted to the power distribution in the whole reactor core.
3 Claims, 10 Drawing Figures

Existing Studies


Annals of Nuclear Energy, Volume 72, October 2014, Pages 467-470
Reactor power shape synthesis using Group Method of Data Handling
Moon-Ghu Park, Ho-Cheol Shin

Progress in Nuclear Energy, Volume 131, January 2021, 103574
Reconstruction of neutron flux distribution by nodal synthesis method using online in-core neutron detector readings
Iman Ramezani, Mohammad Bagher Ghofrani

Progress in Nuclear Energy, Volume 153, November 2022, 104437
Simulating self-powered neutron detector responses to infer burnup-induced power distribution perturbations in next-generation light water reactors
Anthony Birri, Daniel C. Sweeney, N. Dianne Bull Ezell

Progress in Nuclear Energy, Volume 31, Issue 4, 1997, Pages 369-372
Harmonics synthesis method for core flux distribution reconstruction
Li Fu, Luo Zhengpei, Hu Yongming

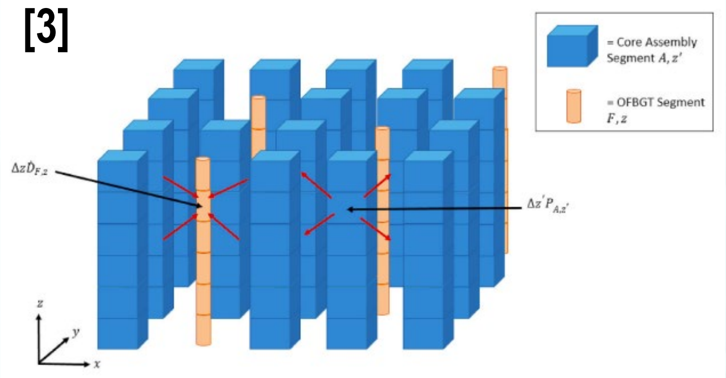
Developments to Date

- The current project stems from previous work with OFBGT development at OSU
  - A method was developed to synthesize core power based off of an OFBGT array
- This method was demonstrated experimentally in the OSURR
  - Reasonable agreement, sensor design could be improved
- The method was adapted to intake SPND data at ORNL
  - A study was conducted to assess core follow impact on a variety of sensor-core configurations
  - Studied in the context of AP1000 and NuScale SMR

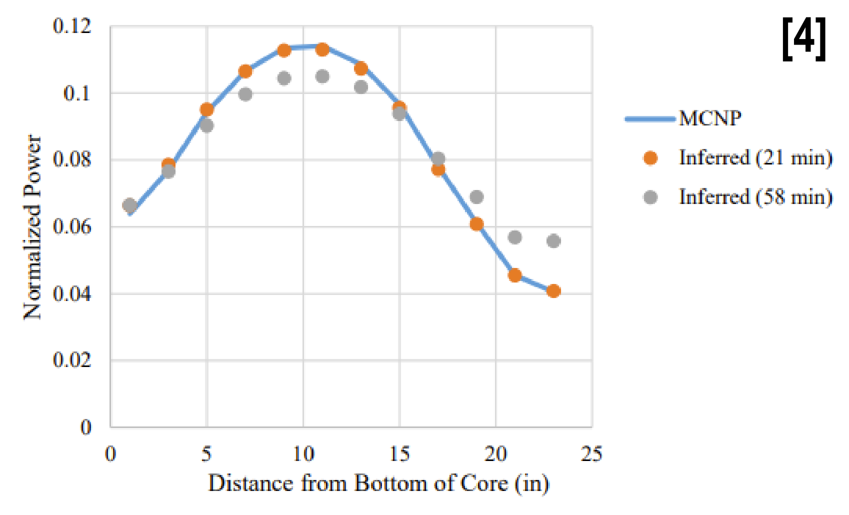
[2] DOI: 10.1016/j.pnucene.2022.104437
[3] DOI: 10.1016/j.pnucene.2020.103552
[4] Birri, Dissertation (2021)

Methodology Development (for OFBGTs, 2018-2020)

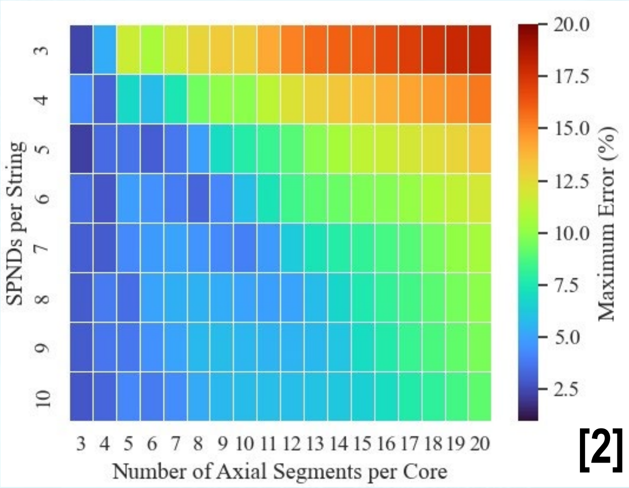
[3]



Experimental Application (with OFBGTs, 2020-2021)



Adaptation to SPNDs, and further analysis (2021-present)

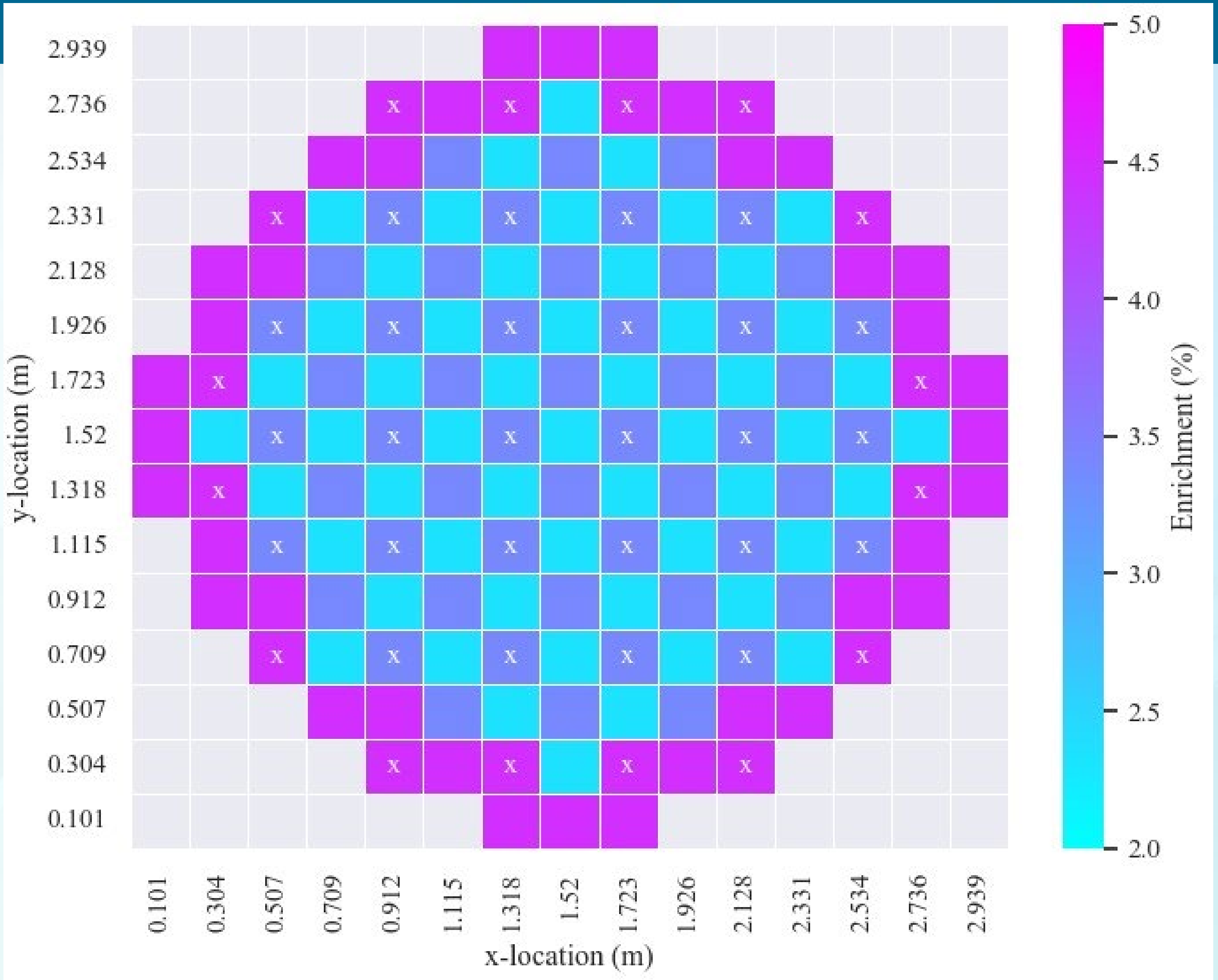


[2]

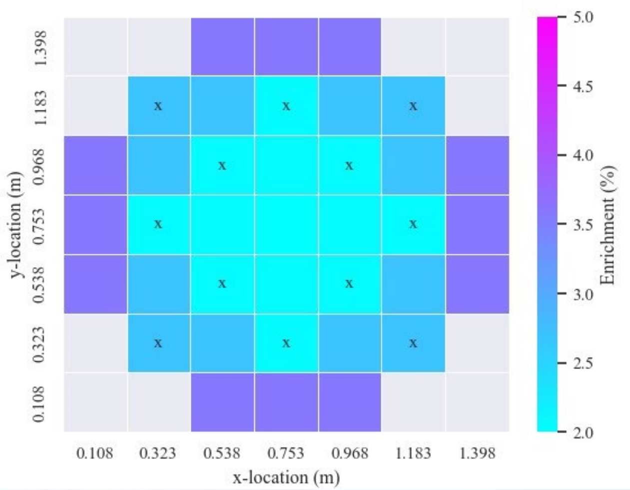
Next Gen LWR Model Details

- NuScale SMR and AP1000 are pressurized LWRs
- They both use SPNDs, assumedly Vanadium emitters
- Assumed power distributions determined heterogeneously
- Response functions determined homogenously (i.e. less realistic sensor responses)

AP1000



NuScale SMR

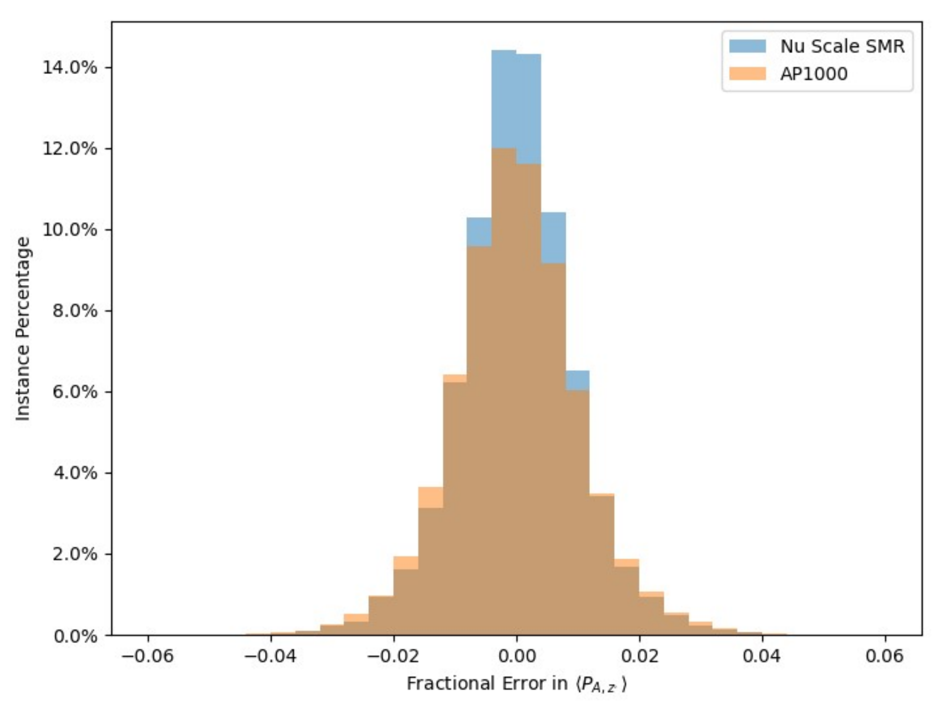


x = SPND string

Next Gen LWR Uncertainty Analysis Results

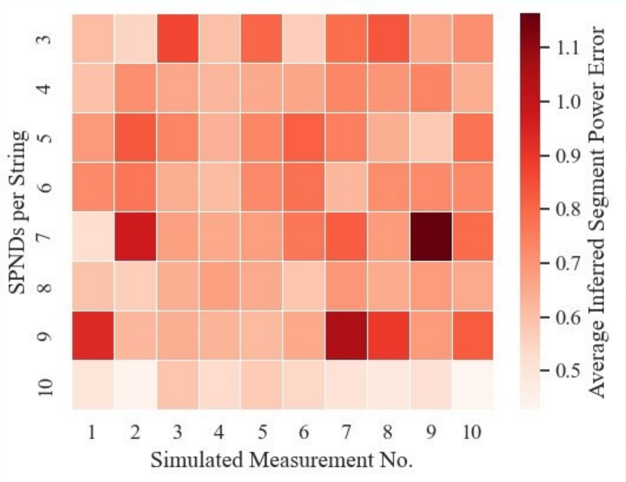
- Varied SPND uncertainty and number of SPNDs per string, assessed error in power synthesis
  - Increasing uncertainty results in increased average error (not a surprise), close to a 1:1 trend
  - Minimal benefit to increasing number of SPNDs per string from 3 to 10
- AP1000 slightly more prone to error for same SPND uncertainties

Distribution of Error: Reactor Comparison w/ 1% SPND uncertainty

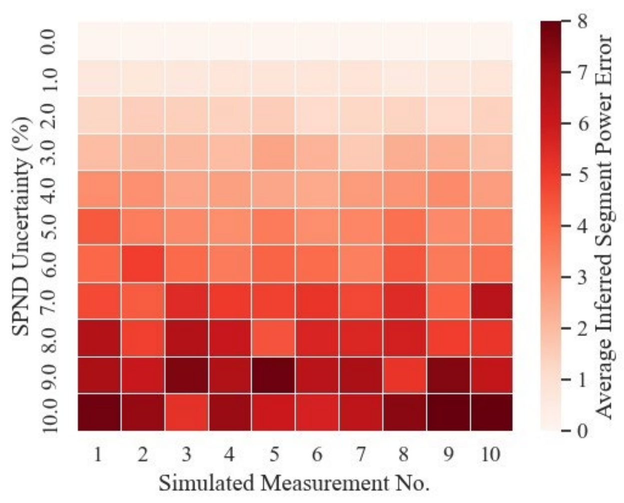


NuScale Error Results

1% SPND Uncertainty

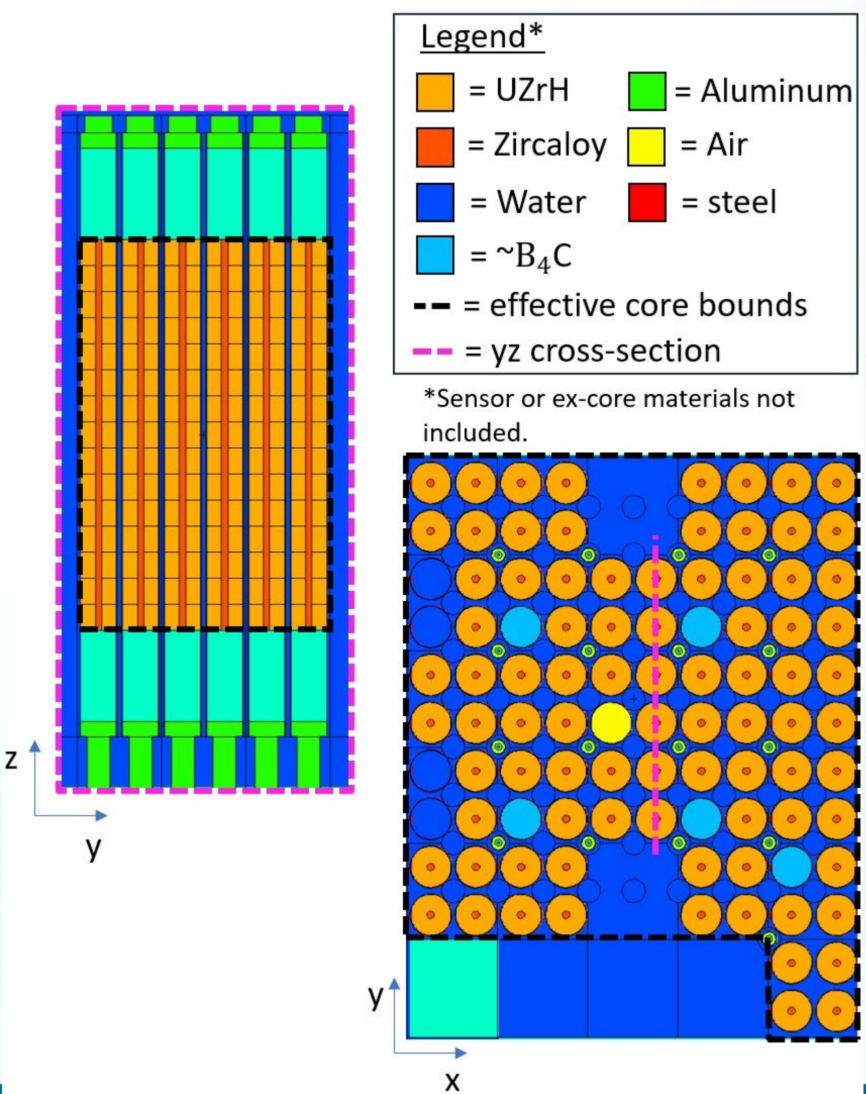


4 SPNDs per string

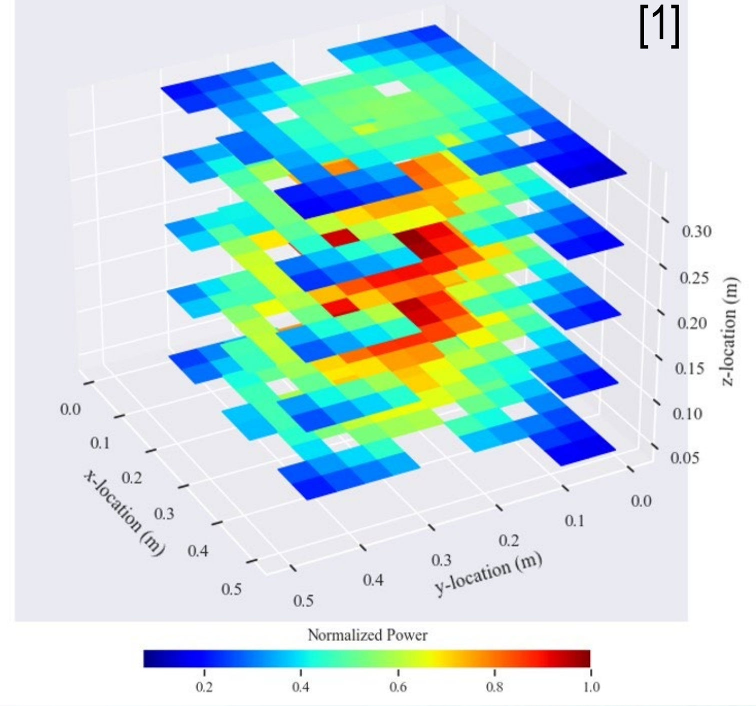


TAMU TRIGA Model Details

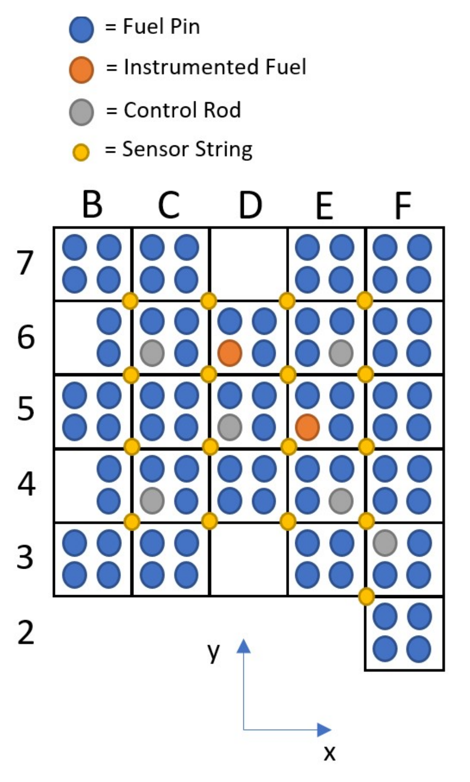
MCNP Model



Power Distribution



Simple Schematic

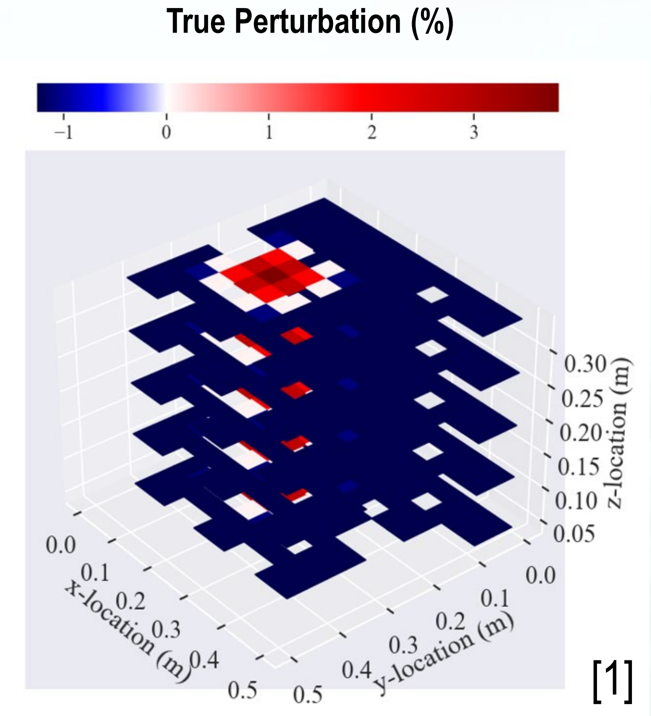


- Pool-type research reactor w/ TRIGA elements (UZrH fuel)
- 17 modeled string locations, 4 SPNDs assumed per string
- Heterogeneous power distribution and response function calculations (more realistic)

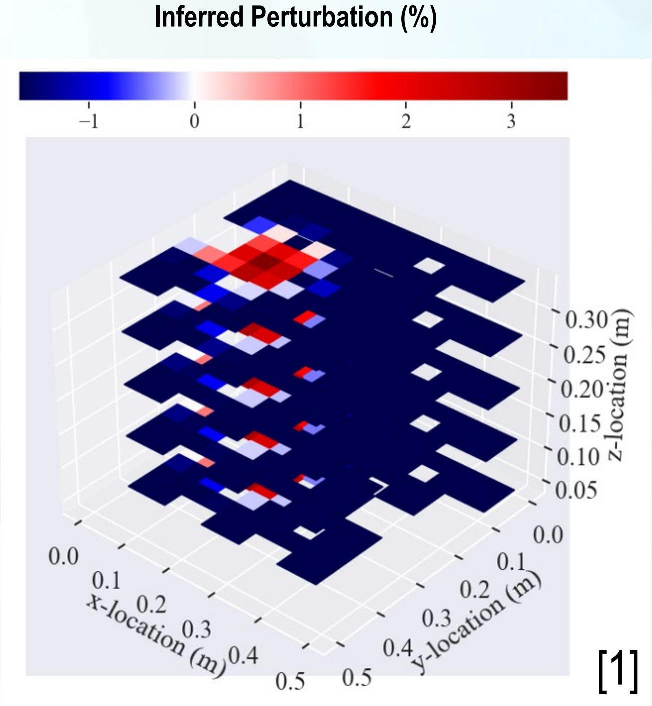
[1] DOI: 10.2172/1996662

TAMU TRIGA Perturbation Analysis Results

- Considered a Gaussian type Perturbation centered on instrumented fuel pin
  - Variance of Gaussian was 0.125 m
- Average error in synthesized distribution was 0.19%, general shape is clearly accurate
- Note: SPND responses assumed to be responding perfectly



[1]



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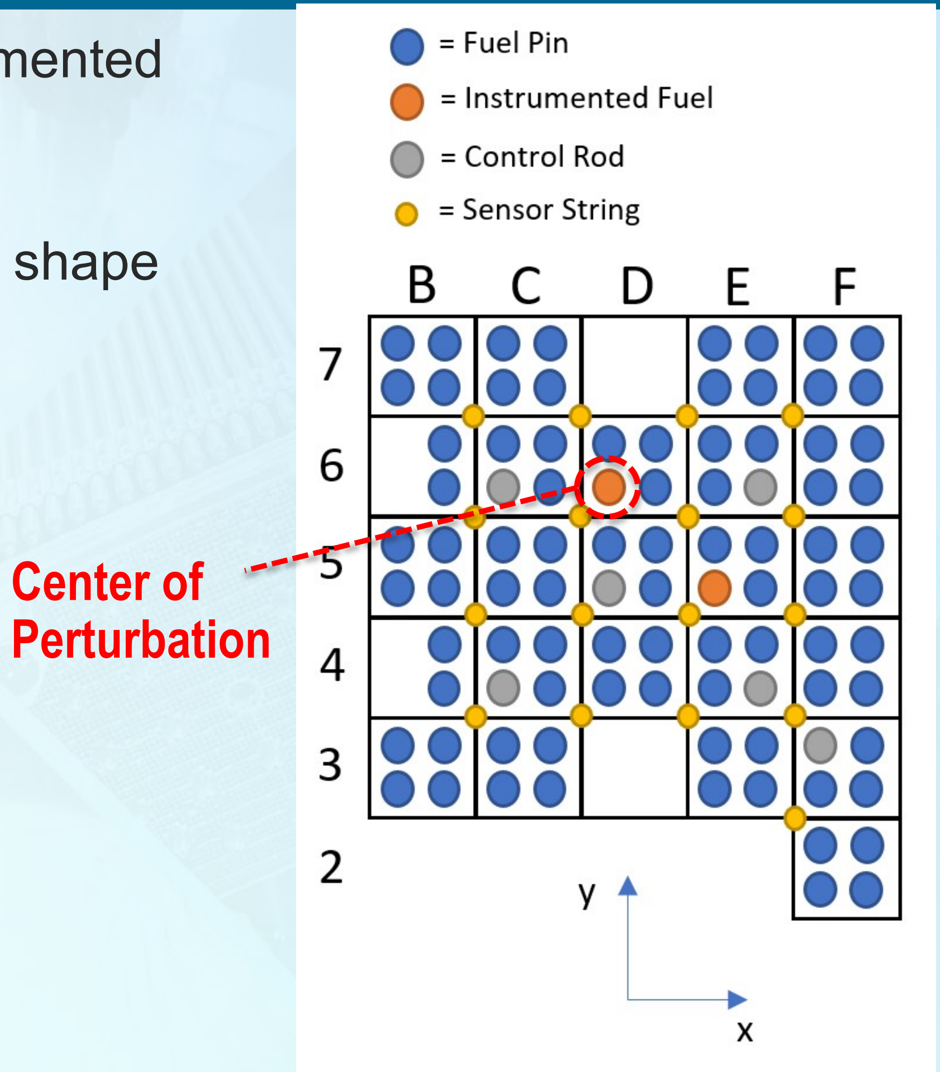
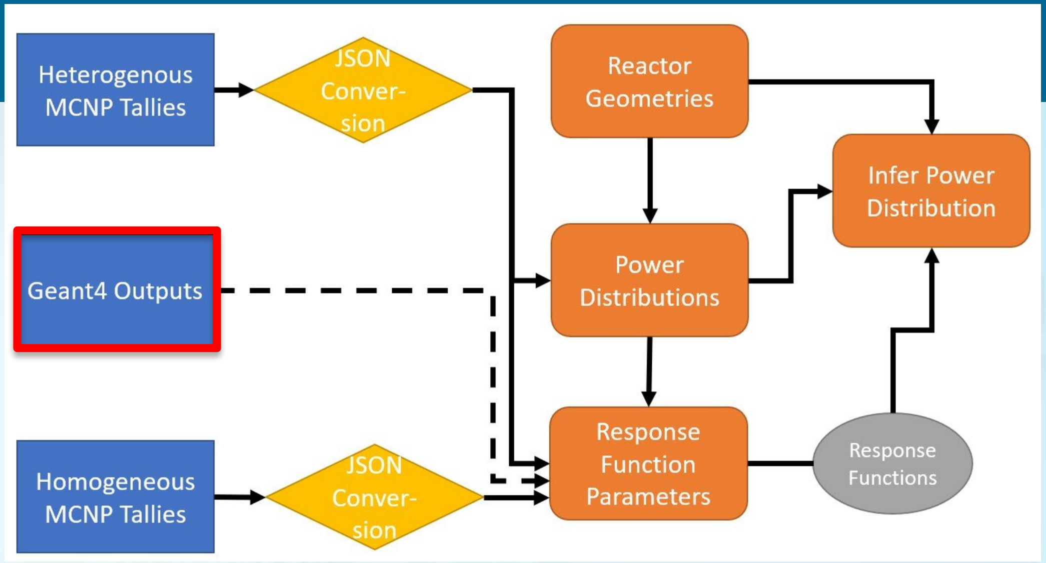
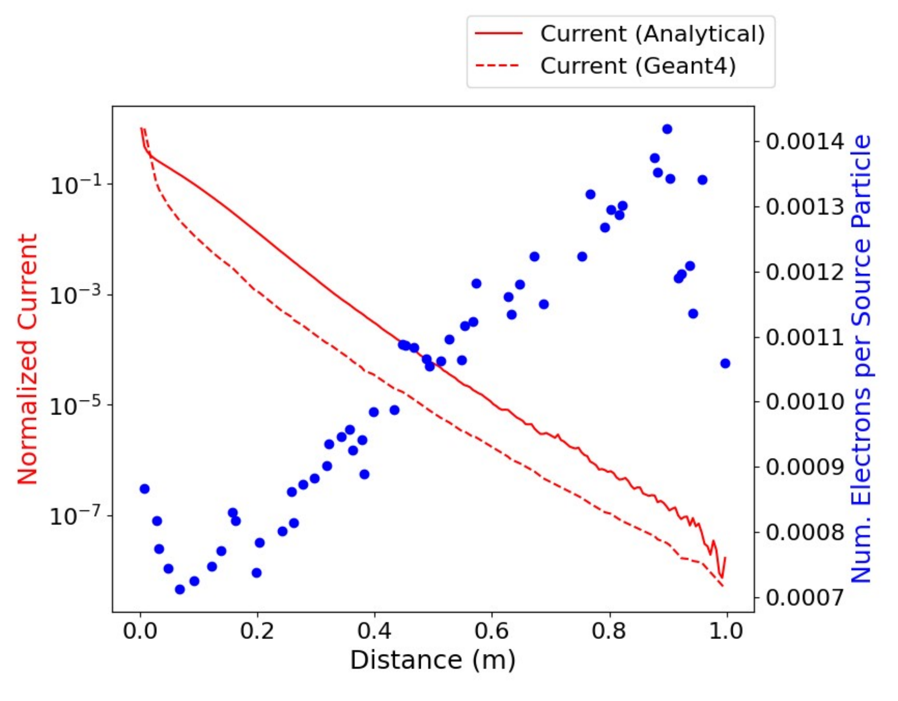


[1] DOI: 10.2172/1996662

Geant4 Integration

- Developed a Geant4 SPND model to integrate with power synthesis software
  - Monte Carlo sensor modeling package developed by CERN
- Currently, analytical models are utilized
  - Doesn't account for neutron self-shielding
  - Doesn't account for electric field effects in insulator
- Preliminary results w/ NuScale highlight impact of self-shielding on current response
- Currently working on Geant4 model E-field optimization, and software integration



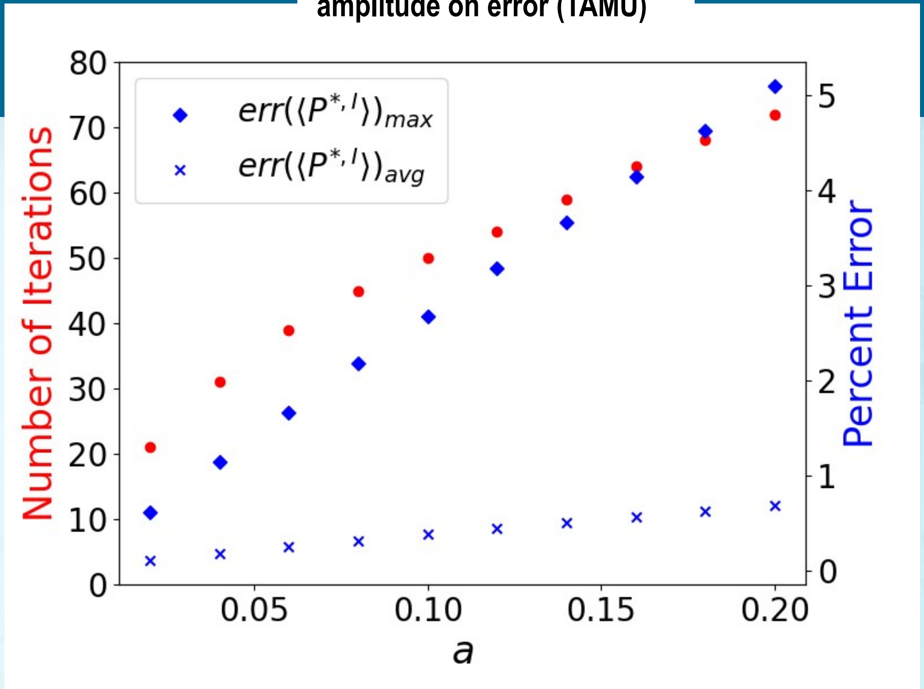


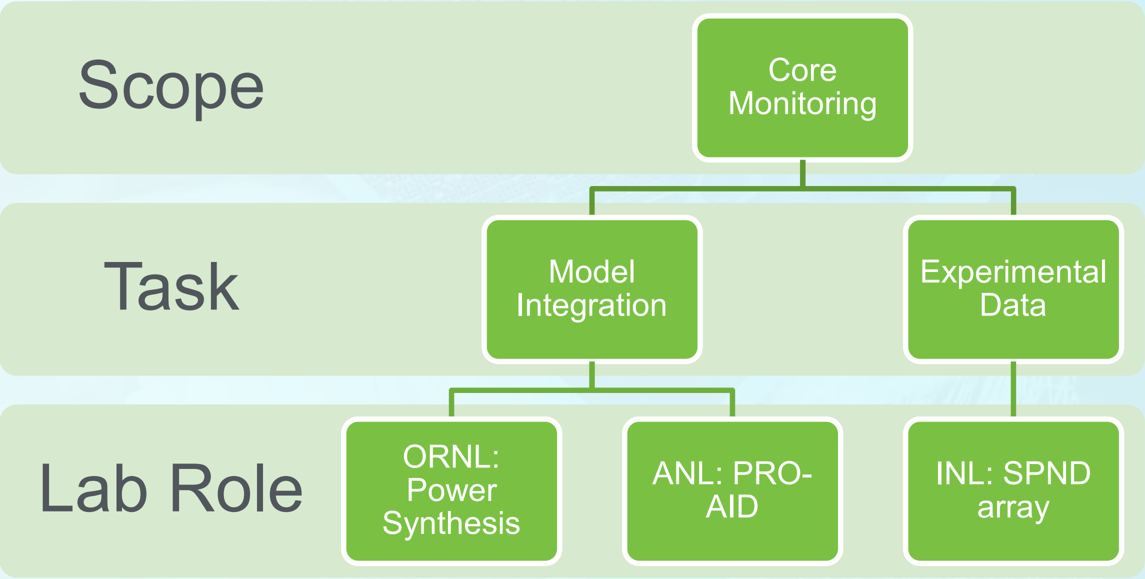
POC for Geant4: Callie Goetz

Follow-On Work

- Perform additional analyses with TAMU TRIGA to identify trends in perturbation variables on synthesis error
- After integration of Geant4, reassess uncertainty impacts in next gen LWRs
- Collaborate with INL for future experimental collaboration with SPNDs for core power monitoring
- Identify potential for connection between the power synthesis software developed at ORNL and PRO-AID developed at ANL

Impact of perturbation amplitude on error (TAMU)





Concluding Remarks

- Power synthesis is a crucial core monitoring capability which reactor operators must have for safe operations
- ORNL is addressing some of the many questions in this scope with targeted studies of uncertainty, perturbations, and sensor arrangement alterations
- AP1000 and NuScale SMR have served as model test beds for sensor uncertainty analysis
- A high fidelity, realistic TAMU TRIGA MCNP model has been used to develop a highly realistic modeling framework, which has been demonstrated with perturbation detection simulation.

Acknowledgements:

- This work was directly funded by the ASI Program under the U.S. Department of Energy Office of Nuclear Energy
- Credit goes to Thomas Blue at OSU for conceptualization of the methodology used herein

Anthony Birri
Oak Ridge National Laboratory
R&D Associate Staff Member
Nuclear and Extreme Environment Measurements Group
Cell: (614) 406-2416 | birriah@ornl.gov

Thank You

SPND Analysis of WIRE-21

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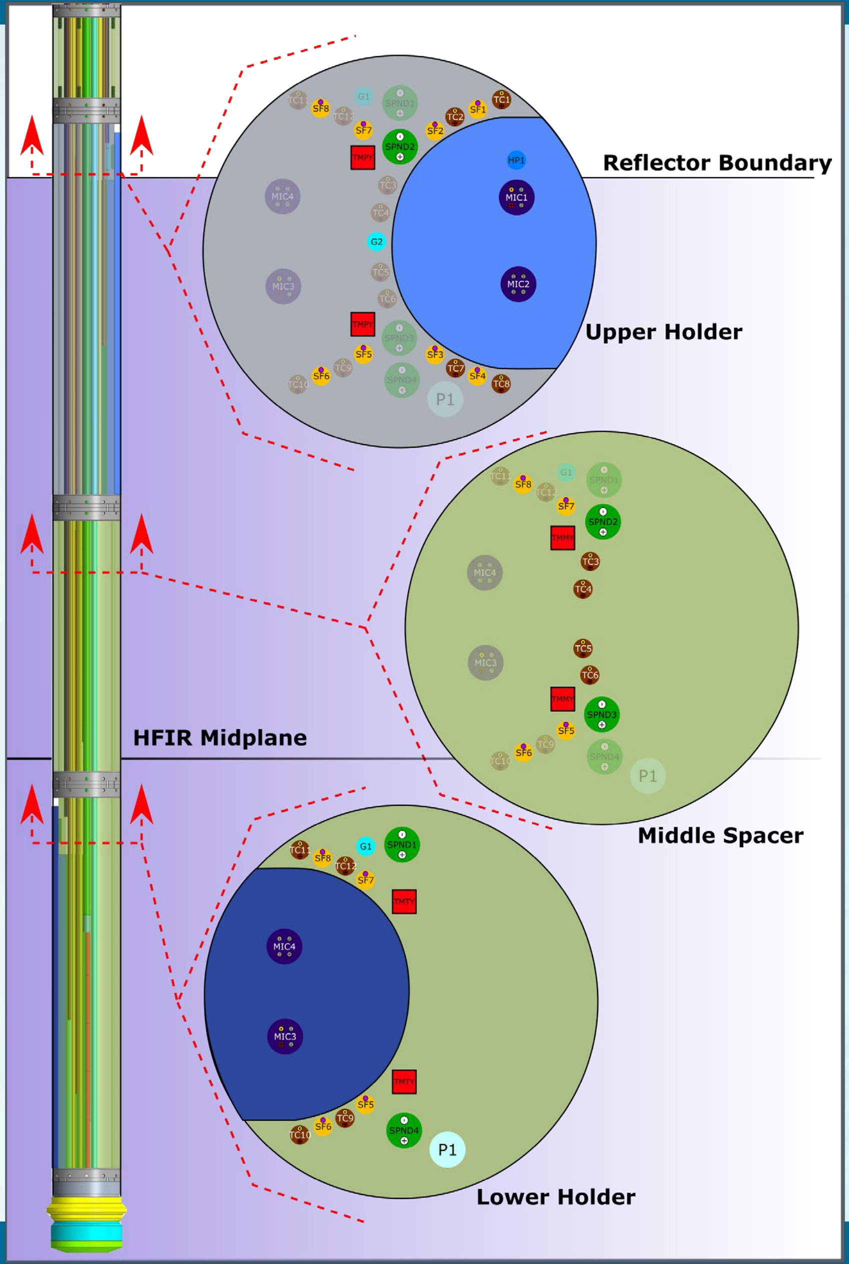
Padhraic L. Mulligan, Daniel C. Sweeney,
Kara M. Godsey, N. Dianne Bull Ezell, Christian M. Petrie
Oak Ridge National Laboratory

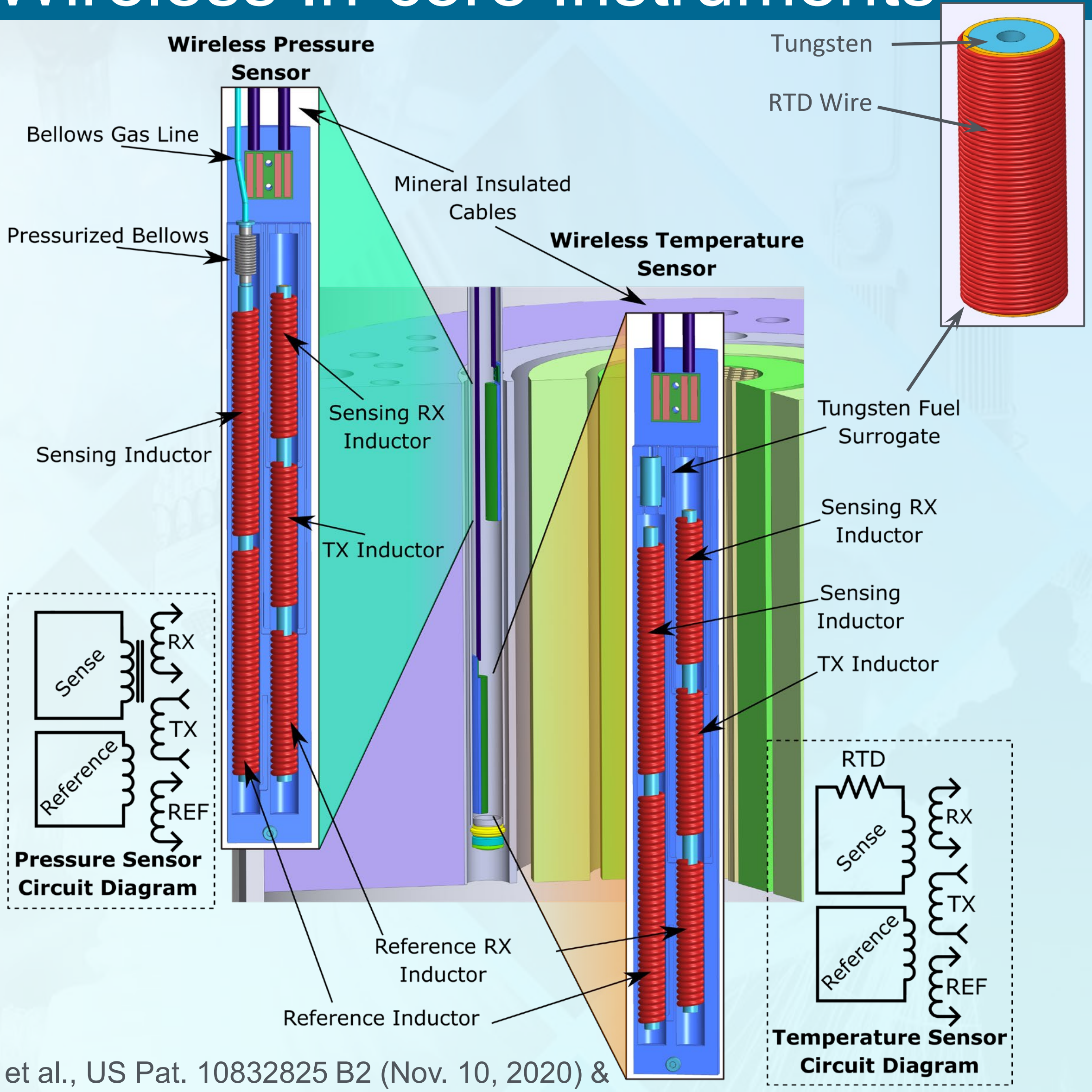
Wireless Instrumented Removable beryllium Experiment (WIRE-21)

- Most highly instrumented experiment in HFIR's 58-year history
- Designed to test several sensing technologies in real-time
  - Validate instruments for future real-time in-core testing
  - Compare against established technologies
- Three primary zones (holders) for experiment arrangement and heat transfer
  - Active temperature & pressure control
- Primary purpose to test wireless sensors developed by Westinghouse Electric Company (WEC) for 3 HFIR cycles



Westinghouse Electric Company Wireless In-core Instruments

- WEC wireless pressure sensor [1]
  - Moveable ferritic core connected to bellows
  - Inductive coupling energizes sensing and reference inductors
  - Probed using complimentary receiving inductors
- WEC wireless temperature sensor [1]
  - Tungsten cylinder acts as fuel surrogate material
  - Thermocouple attached for local temperature monitoring
  - Wire wrap operates as resistance temperature detector (RTD)



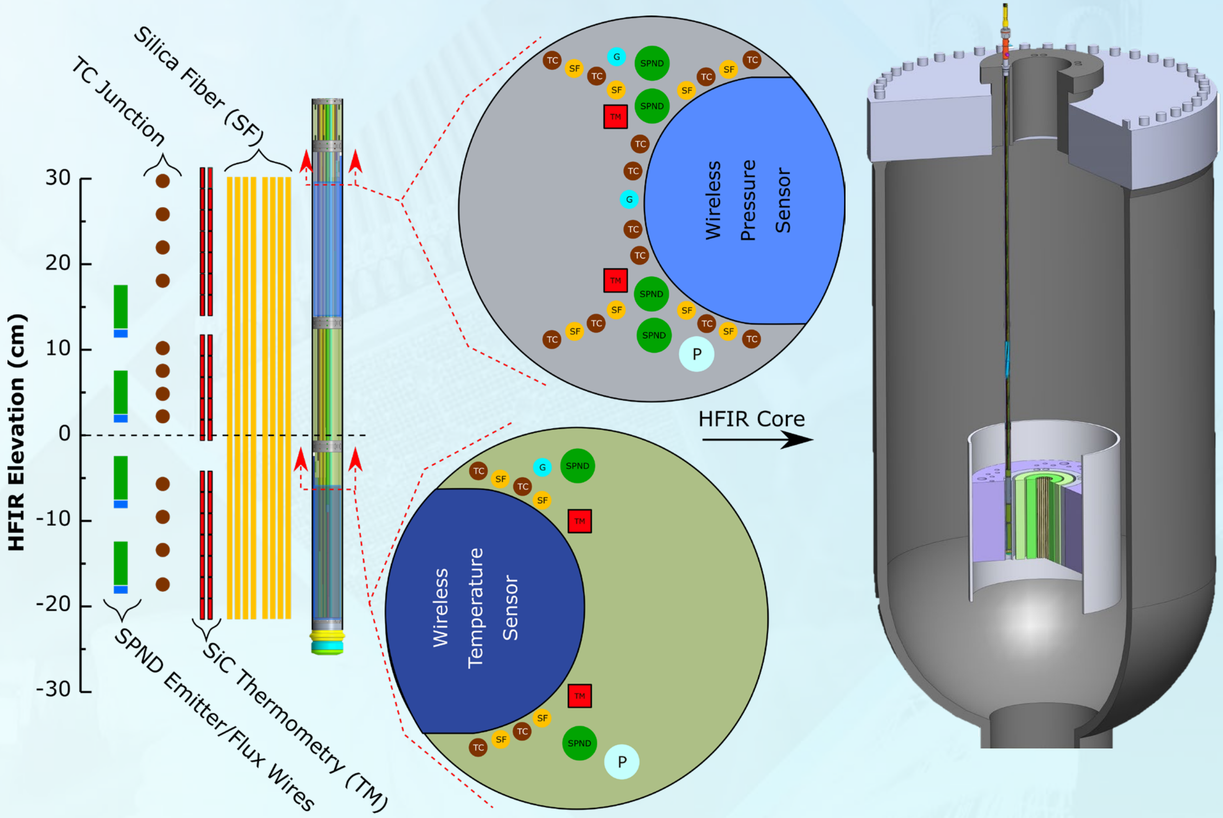
[1] J. Carvajal, et al., US Pat. 10832825 B2 (Nov. 10, 2020) & US Pat. 10811153 B2 (Oct. 20, 2020)

WIRE-21 Instrumentation

- Temperature, pressure, neutron flux measured in multiple positions along reflector
  - Total of 70 independent measurements
  - 7 measurement techniques
- Collected in real-time and through PIE
- Spatially discrete and continuous measurements
- Range of technological maturity

WIRE-21 measurement methods

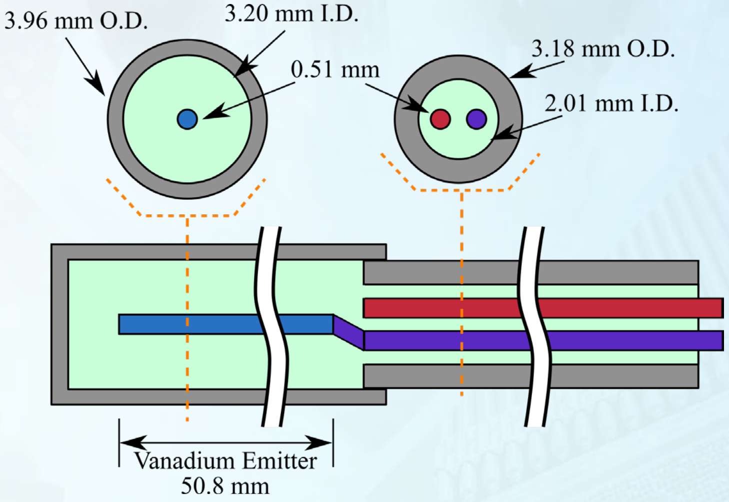
	Temperature	Pressure	Flux/Fluence
Active	• WEC Wireless • Thermocouple • Optical Fiber	• WEC Wireless • [Externally]	• Self-Powered Neutron Detector
Passive	• SiC Thermometry		• Activation Flux Wires

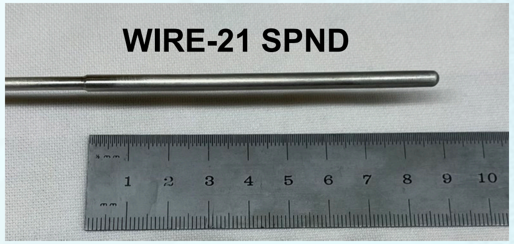


WIRE-21 instrumentation locations

SPND Devices

- Emitter: V (62.6±0.1 mg)
- Insulation: MgO
- Collector: Inc600
- Leads: Inc600
- Positioned ±5, ± 15 cm above/below HFIR midplane

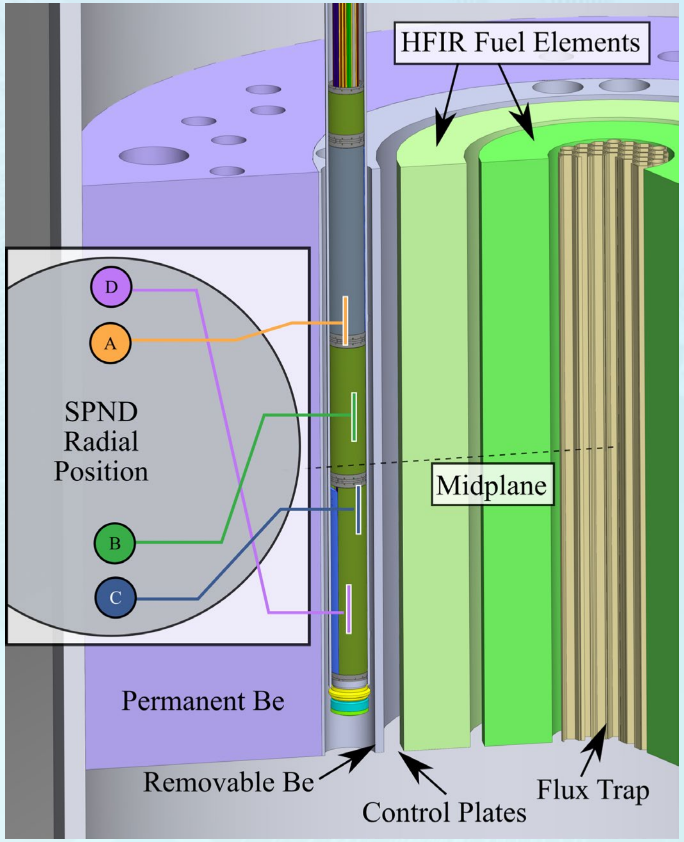




SPND Dimensional Comparison

	Radius emitter	Radius insulator	
WIRE-21	0.255	1.6	
Thermocoax	0.25	0.43	[3]
INL Small	0.24	0.575	[4]
INL Large	0.39	0.69	[4]

Flux activation wires



SPND Positions

[3] Vermeeren, et al., ANIMMA 2019, EPJ Web of Conferences **225**, 04015 (2020)
[4] Palmer, et al., Conceptual Design Report for the I2 Instrumentation Experiment in ATRC. INL/MIS-19-55710 (2019)

SPND Theory

Current (I_0) under steady state:

$$I_0 = k \times \mathrm{N} \times \sigma_c \times \Phi \times e$$

Step increase in neutron flux:

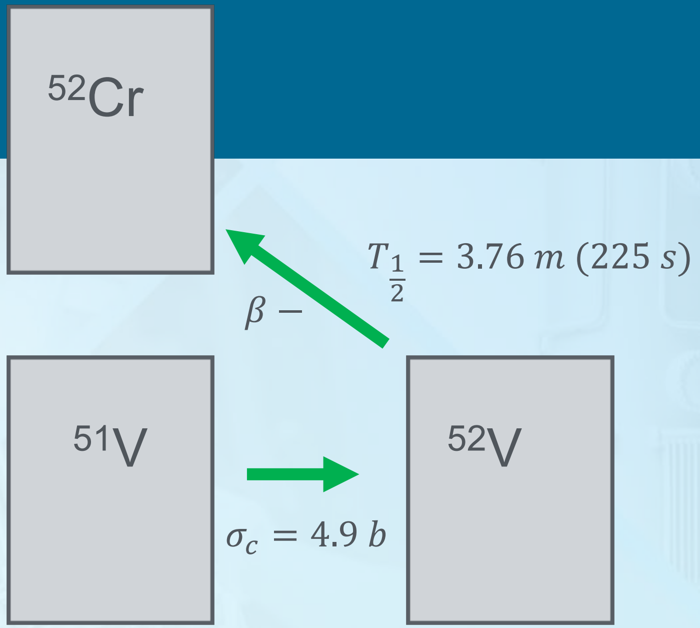
$$I(t) = I_0\left(1 - \exp\left(\frac{-\ln(2) \times t}{T_{\frac{1}{2}}}\right)\right)$$

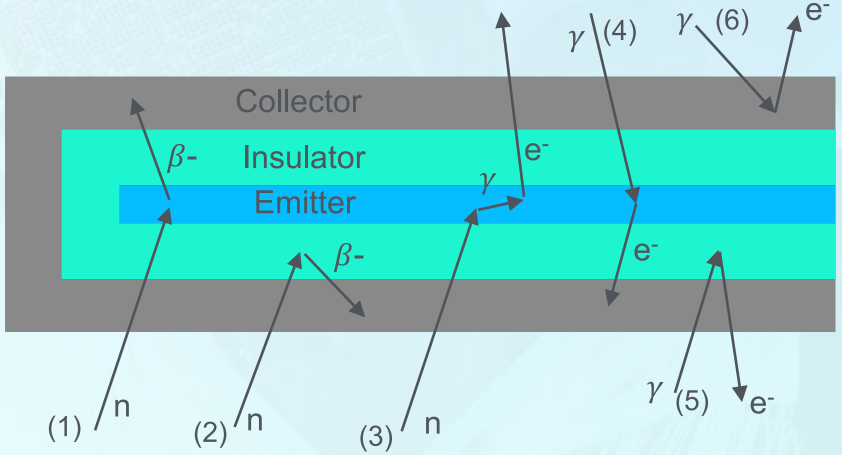
Step decrease in neutron flux:

$$I(t) = I_0 \exp\left(\frac{-\ln(2) \times t}{T_{\frac{1}{2}}}\right)$$

Where

- k = detection efficiency factor
- N = number of useful target nuclei in emitter
- σ_c = neutron capture cross section
- Φ = neutron flux
- e = elementary charge
- $T_{\frac{1}{2}}$ = emitter isotope half-life

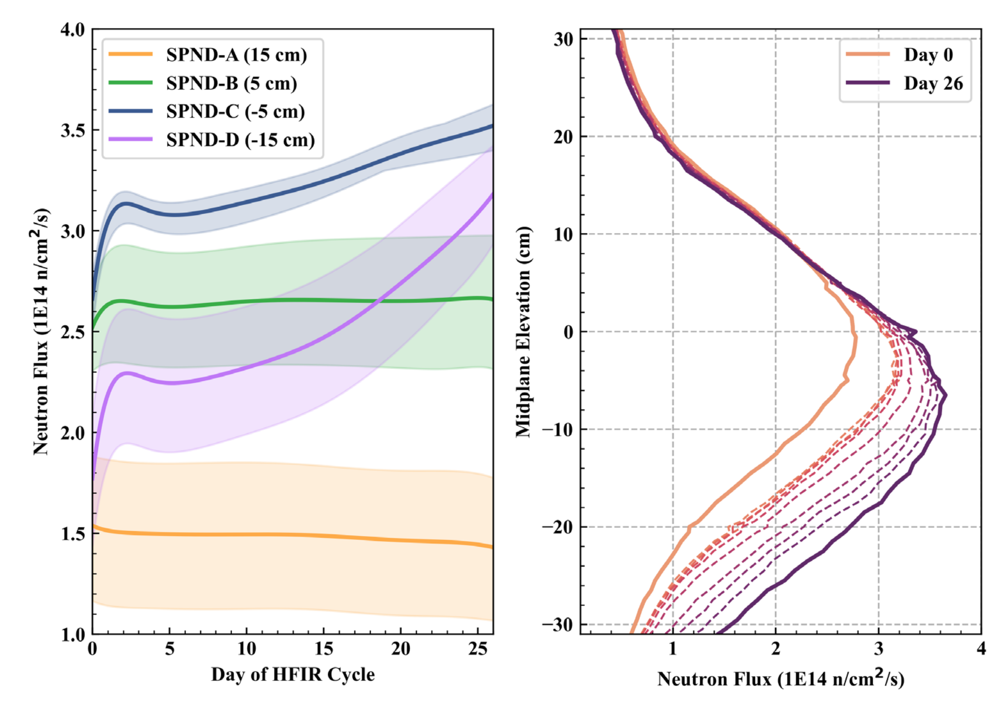




Adapted from Moreira & Lescano, Ann. Nucl. Energy 58 (2013) 90.

Radiation Transport Modeling

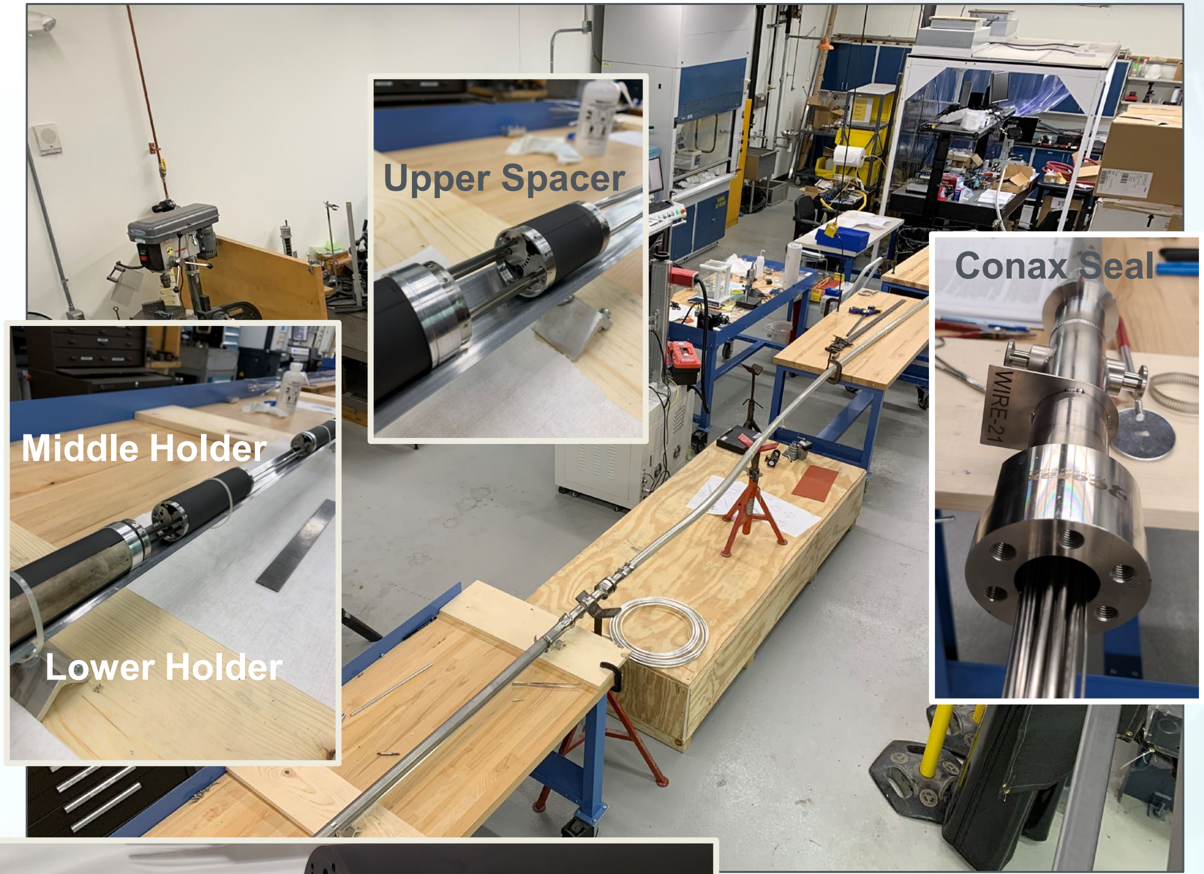
- Representative geometry and materials of WIRE-21 modeled using ORNL developed HFIRCON [5] code
  - Time-dependent, coupled radiation transport and depletion code
  - WIRE-21 geometry divided into 1 cm axial subsections
  - Modeled for 10 timesteps over one 26-day HFIR cycle
  - Cells separated into “core facing” and “reflector facing” to capture shielding effects
- HFIRCON model provides
  - 256 group neutron flux
  - Material heat generation rates
    - Prompt gamma, neutron
    - Fission product decay heat
    - Local activation/decay heat

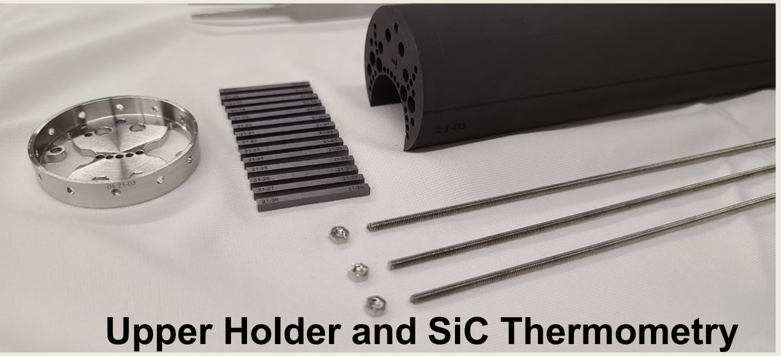


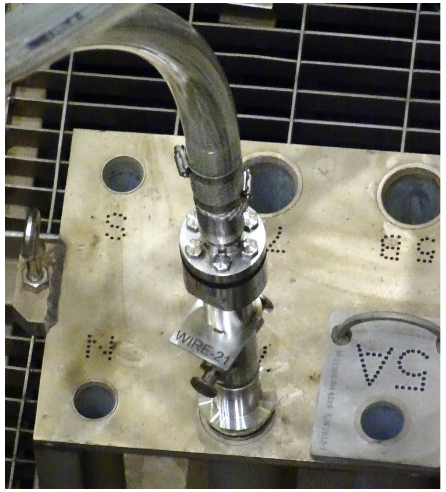
(Left) Modeled time dependent, thermal neutron flux (E_n<0.025 eV) for each SPND. (Right) Spatial- and time-dependent thermal neutron flux across reflector.

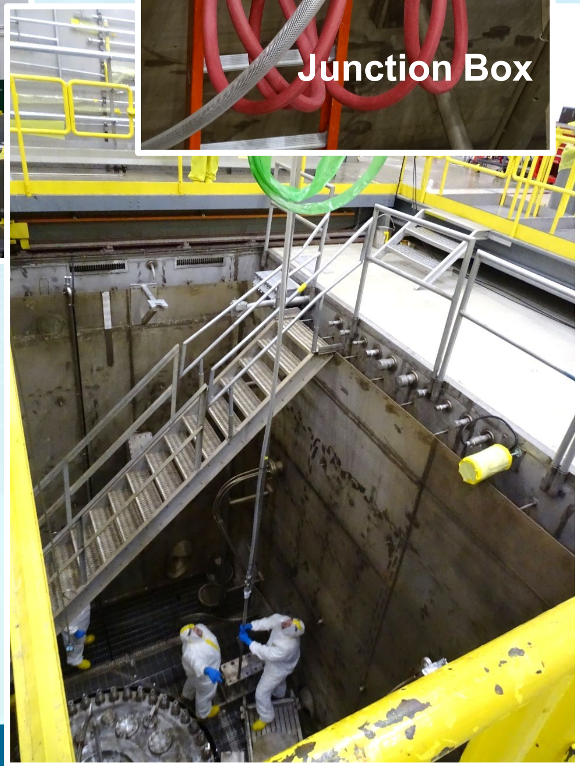
[5] C. Daily, et al., "HFIRCON Version 1.0.5 User Guide," ORNL/TM-2020/1742: Oak Ridge National Laboratory, Oak Ridge, TN (2020).

WIRE-21 Assembly and Installation



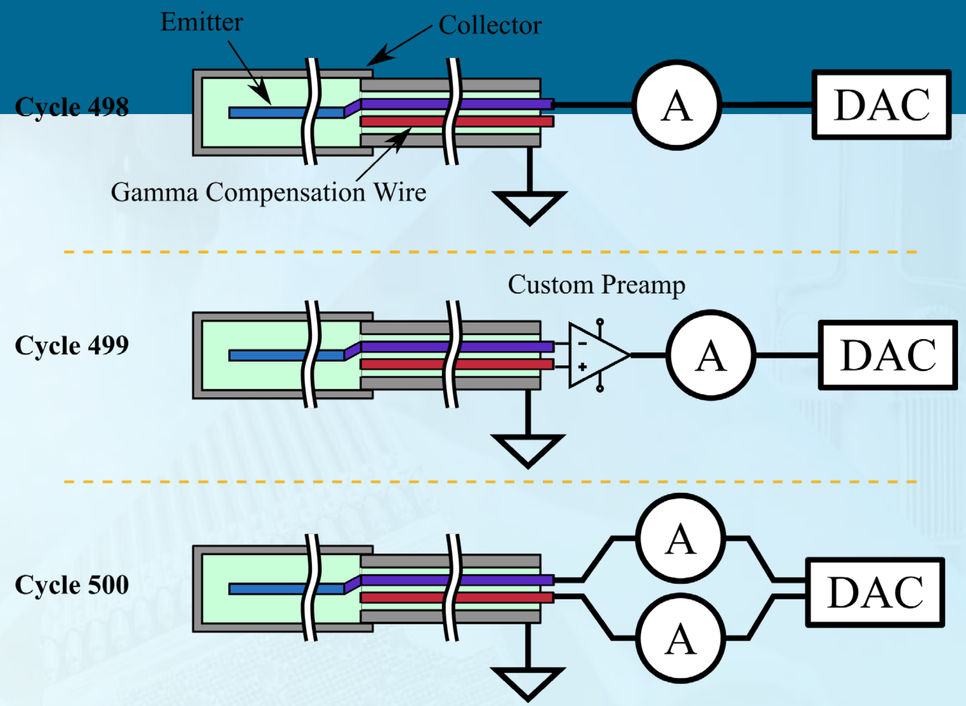




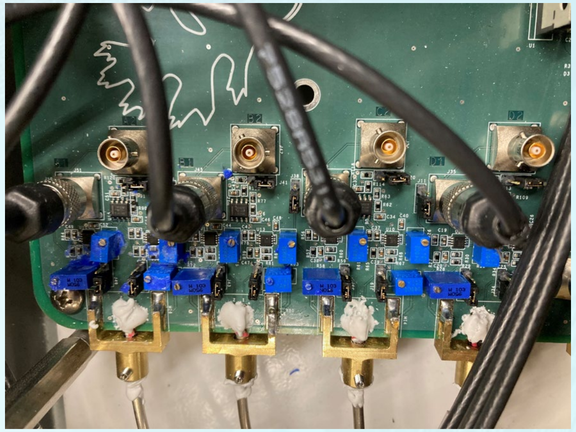


SPND Measurement Configuration

- Current measured using Keithley 6482 Dual Channel Picoammeter
- 3 different configurations for each cycle
- Cycle 498
  - x4 SPNDs, emitter wire only
- Cycle 499
  - x4 SPNDs, emitter/compensation differential signal
- Cycle 500
  - x2 SPNDs, emitter and compensation separately



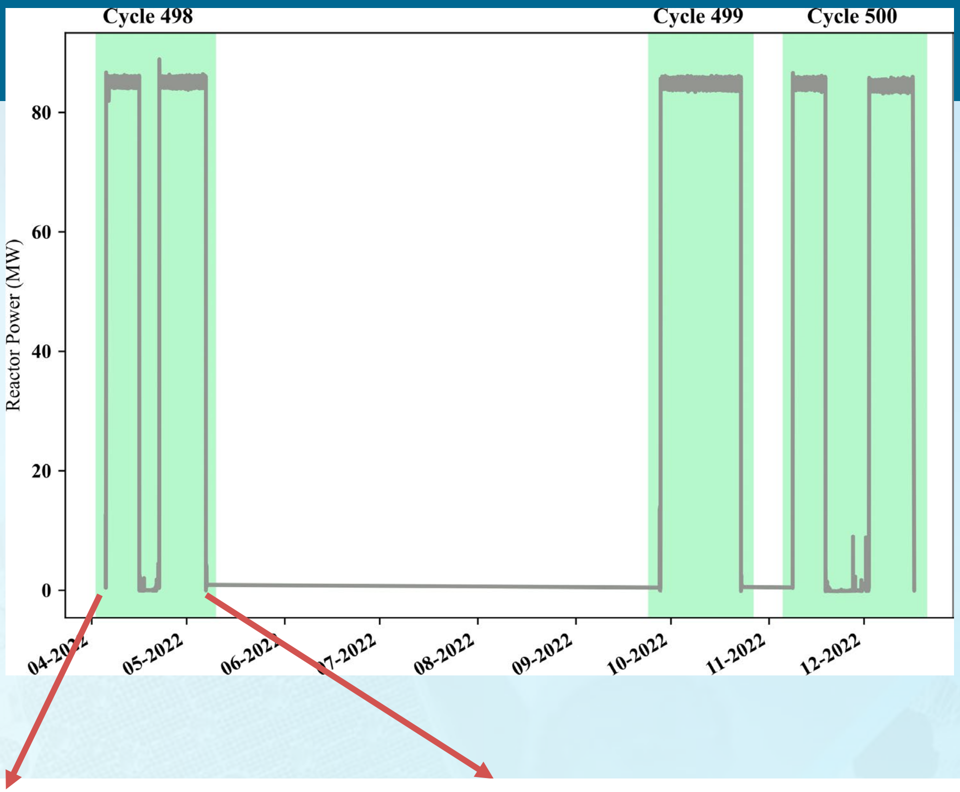
SPND signal measurement for each HFIR cycle

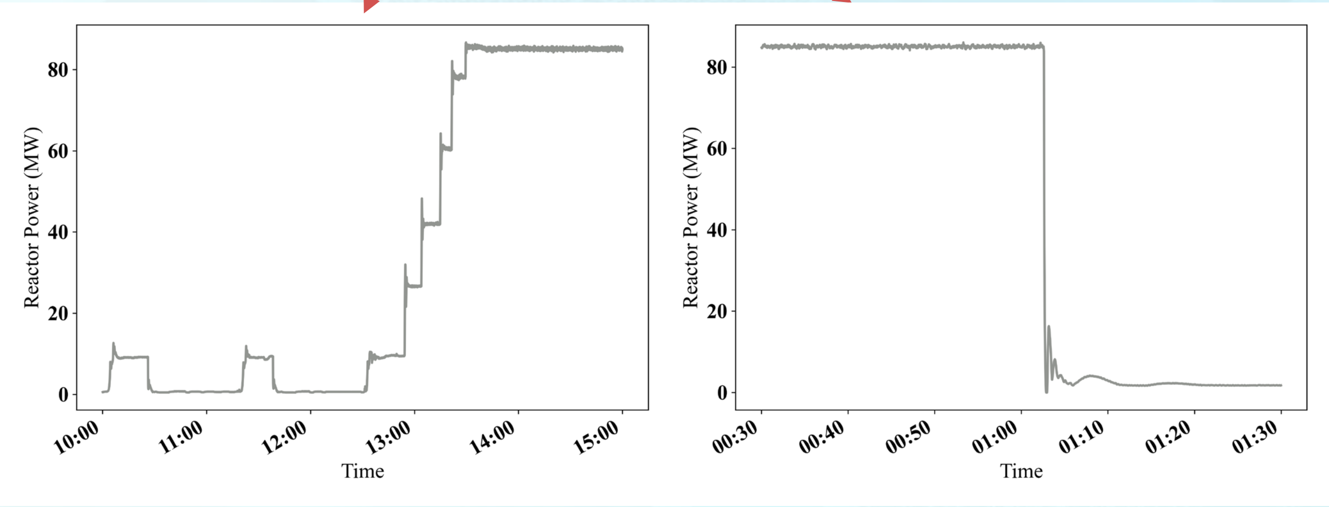


Custom PCB for passthrough or differential measurement

WIRE-21 Operational History

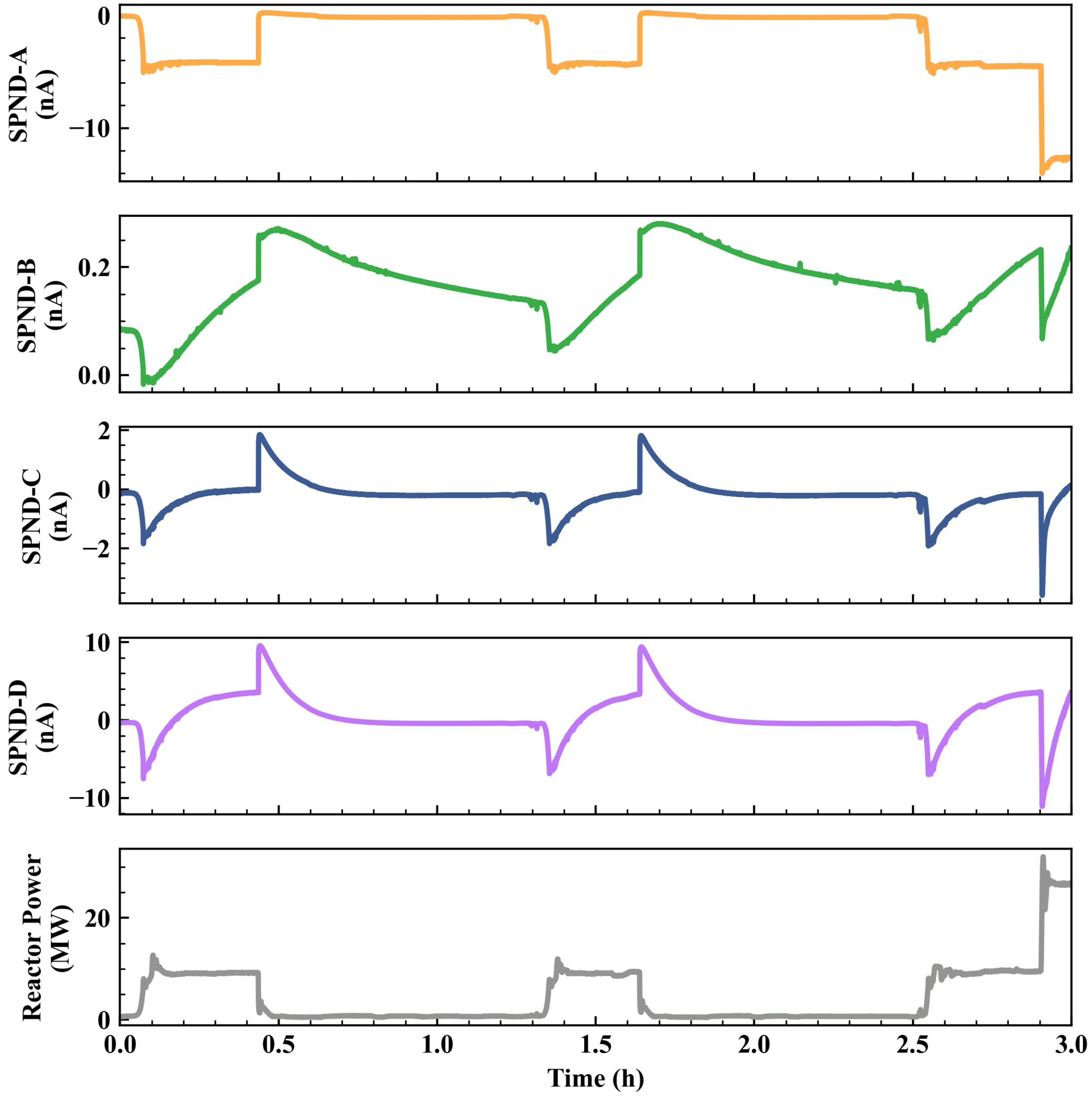
- 3 HFIR cycles
  - 75 effective full power days (EFPDs)
  - 5.8×10^{21} n/cm^2 thermal fluence
- Multiple temperature and pressure manipulations during reactor operation
- Startups and SCRAMs provided interesting transients for SPND investigation





Reactor Power Transients (498)

- Reactor power raised to 10 MW several times during startup
- SPND-A,-C,-D showed similar but unusual behavior
  - Prompt negative current
  - Exponential positive current
- SPND-B exhibited linear increase in current with steady power
  - Assumed SPND-B was either broken during installation or compensation wire was being measured

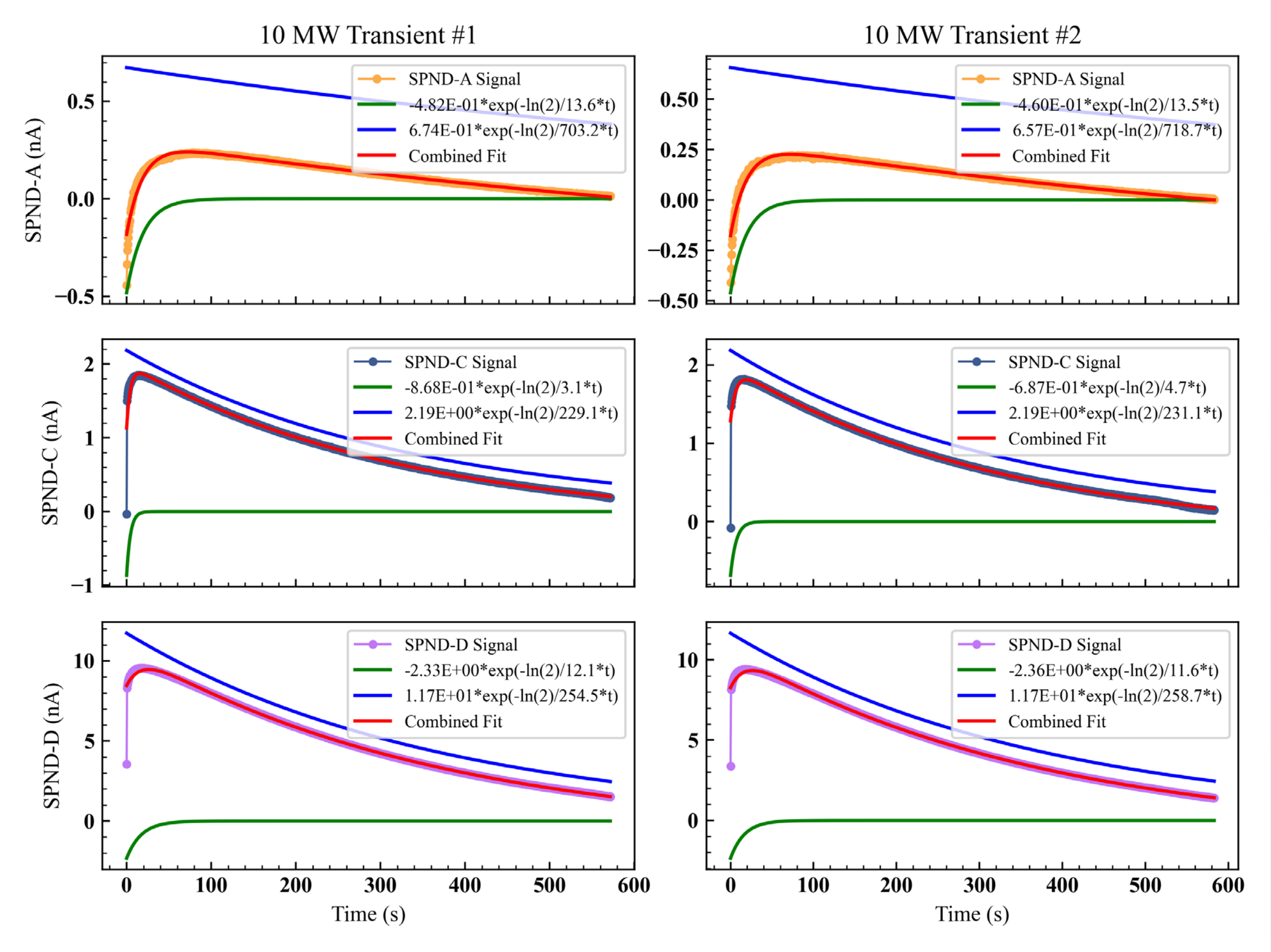


Signal Curve Fitting

- SPND signal following power decrease was fit to equation of the form:

$$I(t) = A + B * exp(p \times t) + C * exp(q \times t)$$

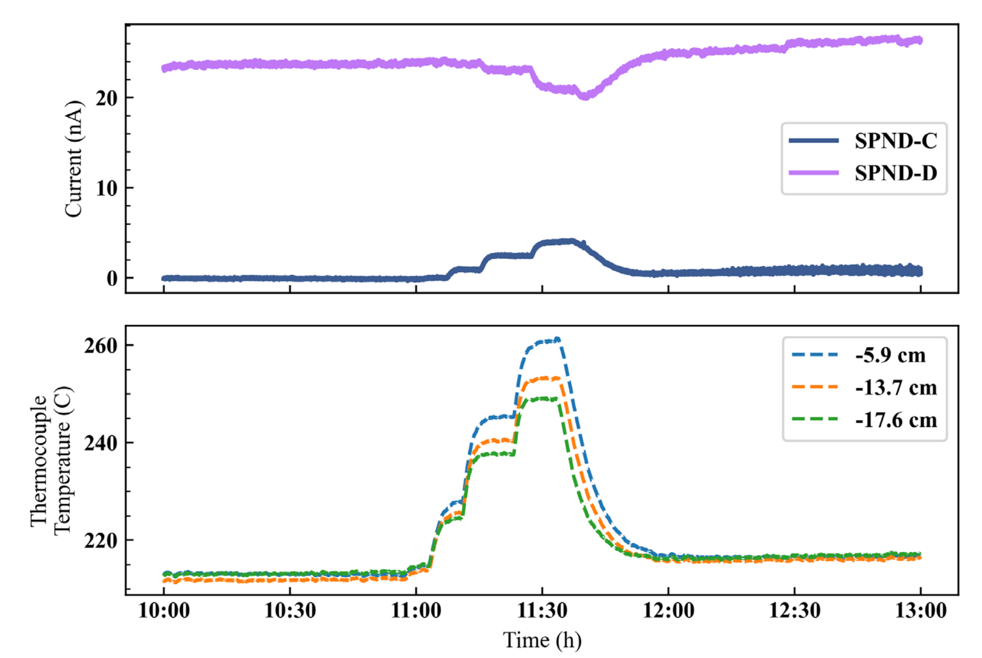
- Exponential coefficients showed good agreement with $T_{1/2}$= 225 s of ^{52}V for -C/-D
  - Validates slow response signal is neutron capture in V
- Less conclusive for -A ($T_{1/2}$=700 s)
  - Likely caused by large difference in magnitude between γ and neutron signal
- Gamma component had very short (prompt)time constant (3-13 s) and negative contribution in all 3 SPNDs

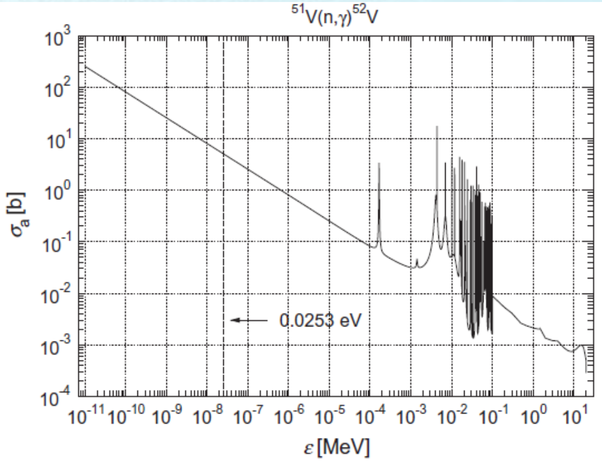


Signal curve fitting for cycle 498 startup transient (0.4 and 1.6 hrs)

SPND Temperature Response

- Experiment temperature was increased stepwise for WEC sensors during cycle 498
- SPND-C/-D signals followed temperature increase, though in different directions
- Doppler broadening should result in increased SPND signal
- Higher temperature could be perturbing neutron energy in 1/v region





Moreira & Lescano, Ann. Nucl. Energy 58 (2013) 90.

Concluding Remarks

- WIRE-21 experiment was performed in 2022 to test novel in-pile sensors
- Included the first SPND flux measurements in HFIR
- Three SPNDs demonstrated neutron induced signal
- Two SPNDs agreed with modeled flux trends
- SPNDs showed response to temperature
- Future SPNDs require optimization to mitigate gamma signal

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Padhraic Mulligan
Oak Ridge National Laboratory
R&D Staff Member
Nuclear and Extreme Environment Measurements Group
mulliganpl@ornl.gov

Thank You