Micro-Pocket Fission Detectors for In-Core Neutron Flux Monitoring

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Presentation Agenda

- Research Motivation
- Traditional Fission Chamber-MPFD Comparison
- MPFD Design and Fabrication
  - Multi-Cathode Model
  - Common Cathode Model
- Experiments & Results
  - 5-Node Common Cathode Array in the KSU TRIGA Mk II Nuclear Reactor
  - 4-Node Multi-Cathode Array in the KSU TRIGA Mk II Nuclear Reactor
  - 2-Node Multi-Cathode Array in the CEA MINERVE Nuclear Reactor
- Recommendations & Ongoing Deployments

Research Motivation

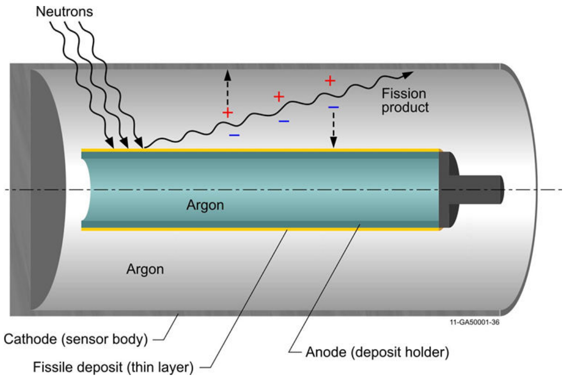
- Advanced fuel and material development requires measurements of material behavior at smaller length and time scales during irradiation
- NE has taken an approach that combines advance post-irradiation examination with multiscale and multi-physics fuel performance modeling
    - Reactor physics models can capture highly resolved neutron flux and temperature distributions
    - Traditional experiments and sensors are unable to provide neutron flux mapping with similar level of detail
- Advanced in-core instrumentation is needed to complete the connection between measurement and predictive modelling
    - MPFDs can provide multi-axial neutron flux measurements and a thermocouple measurement in a single device and can be made small enough to fit in a flux wire port

**Slide content based from "New Instrumentation Strategy: R&D to Revolutionize In-Reactor Measurement Capabilities" presented at the Idaho National Laboratory by Dr. Carl Stoots in May 2016

Traditional Fission Chamber–MPFD Comparison

Traditional fission chamber design

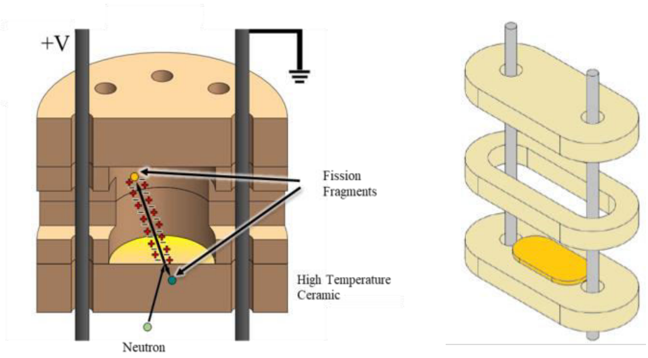
- Concentric electrodes geometry
- Rigid assembly
- Single point neutron flux measurement



Cut-away view of traditional fission chamber geometry[1]

MPFD design

- Parallel electrodes geometry
- Loose assembly
- Multiple point neutron flux measurements
- Can add single thermocouple measurement

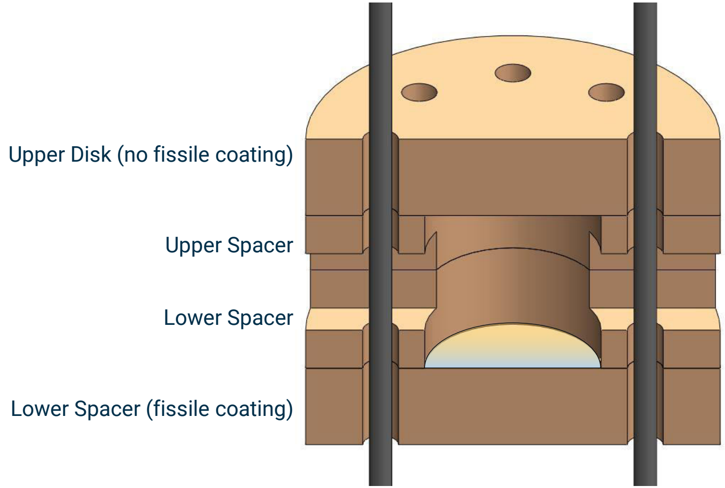


Cut-away view of multi-cathode (left) [2] and common cathode (right)[3] MPFD geometries

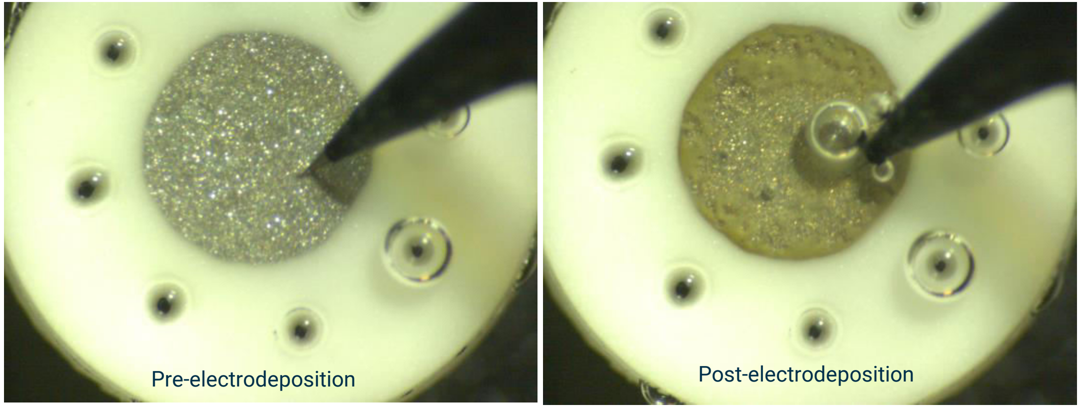
[1]Image reproduced from T. Unruh, M. Reichenberger, S. Stevenson, D. McGregor, K. Tsai, J.F. Villard, "Enhanced Micro-Pocket Fission Detector for High Temperature Reactors," Advanced Sensors and Instrumentation Newsletter, 7 (2017) pp. 1-3.
[2]Image reproduced from D. Nichols, M. Reichenberger, S. Stevenson, T. Swope, . Hilger, J. Roberts, N. Edwards, and D. McGregor, "Characterization of Argon, P-10, and Neon Ionization Gases for Use in Modular Micro-Pocket Fission Detector Arrays," ANIMMA Conference, 2017
[3]Image reproduced from M. Reichenberger, T. George, R. Fronk, P. Ugorowski, J. Geuther, J. Roberts, T. Ito, H. Vo-Le, S. Stevenson, D. Nichols and D. McGregor, "Advances in the Development and testing of Micro-Pocket Fission Detectors," IAEA Conference on Research Reactors, November, 2015

MPFD Design & Fabrication: Multi-Cathode Model

- Each sensor region consists of 4 pieces of alumina threaded onto electrode wires
    - Fissile material is electro-deposited between the anode and cathode before threading



Cut-away view of MPFD sensor region[1]

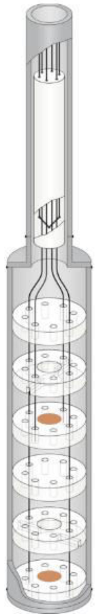


MPFD alumina substrate with a Ti-Pt electrode before and after electrodeposition of natural uranium[1]

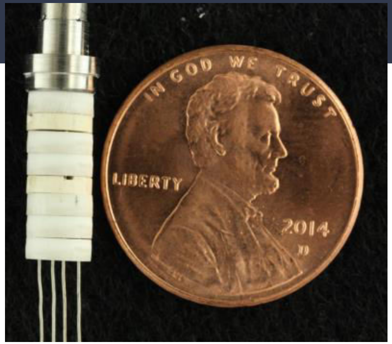
[1]Image reproduced from D. Nichols, M. Reichenberger, S. Stevenson, T. Swope, . Hilger, J. Roberts, N. Edwards, and D. McGregor, "Characterization of Argon, P-10, and Neon Ionization Gases for Use in Modular Micro-Pocket Fission Detector Arrays," ANIMMA Conference, 2017

MPFD Design & Fabrication: Multi-Cathode Model

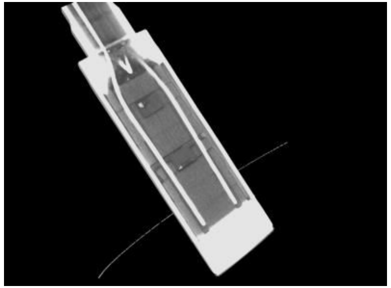
- Up to 4 sensor regions, each separated by insulated wire
- Additional insulated wire extends the full length of the array
- Array is inserted into a stainless steel tube with a welded cap, normally 5/16 in x 0.020 in diameter
- Electronic feedthroughs and A gas purge/fill system is installed at the top



(Right) Cut-away view of MPFD sensor assembly with thermocouple[1]



MPFD sensor assembly before encapsulation



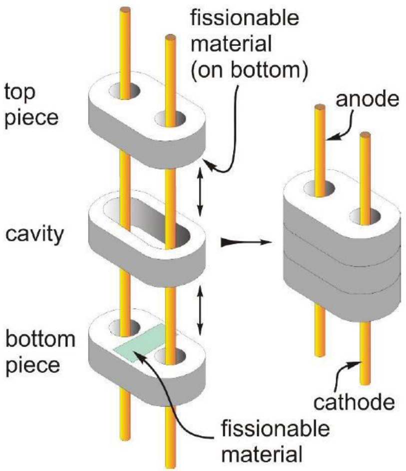
3D CT scan of MPFD sensor assembly after encapsulation[2]

Full MPFD array with gas purge/fill assembly at top[2]

[1]Image reproduced from T. Unruh, M. Reichenberger, S. Stevenson, D. McGregor, K. Tsai, J.F. Villard, "Enhanced Micro-Pocket Fission Detector for High Temperature Reactors," Advanced Sensors and Instrumentation Newsletter, 7 (2017) pp. 1-3.
[2] Image reproduced from M. Reichenberger, "Micro-pocket fission detectors: development of advanced, real-time, in-core, neutron-flux sensors" (Doctoral Dissertation), 2017.

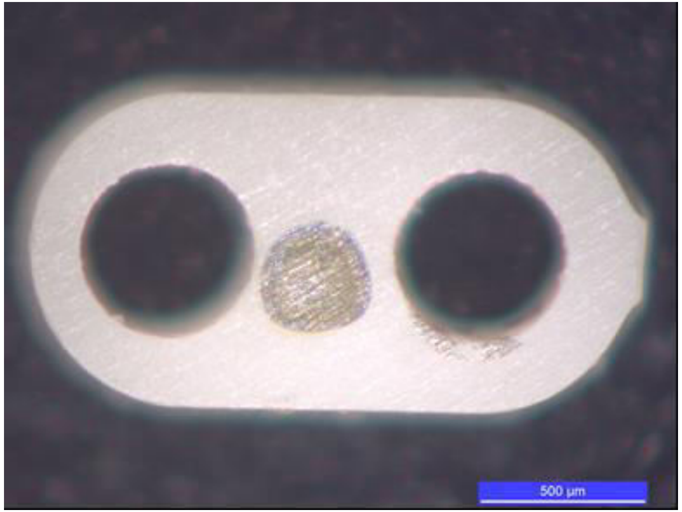
MPFD Design & Fabrication: Common Cathode Model

- Each sensor region consists of 3 pieces of alumina threaded onto electrode wires
  - Fissile material is electro-deposited between the anode and cathode before threading



Exploded view of MPFD sensor assembly[1]

The small size of the MPFD sensor allows for insertion into a flux wire port[1]

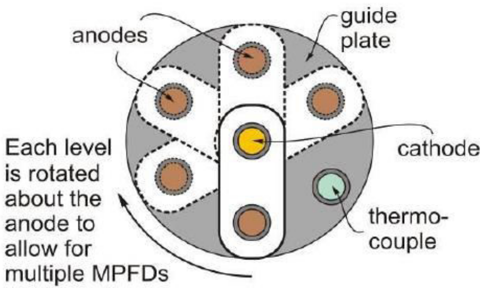


Natural uranium electrodeposited onto the MPFD substrate[1]

[1]Image reproduced from M. Reichenberger, "Micro-pocket fission detectors: development of advanced, real-time, in-core, neutron-flux sensors" (Doctoral Dissertation), 2017.

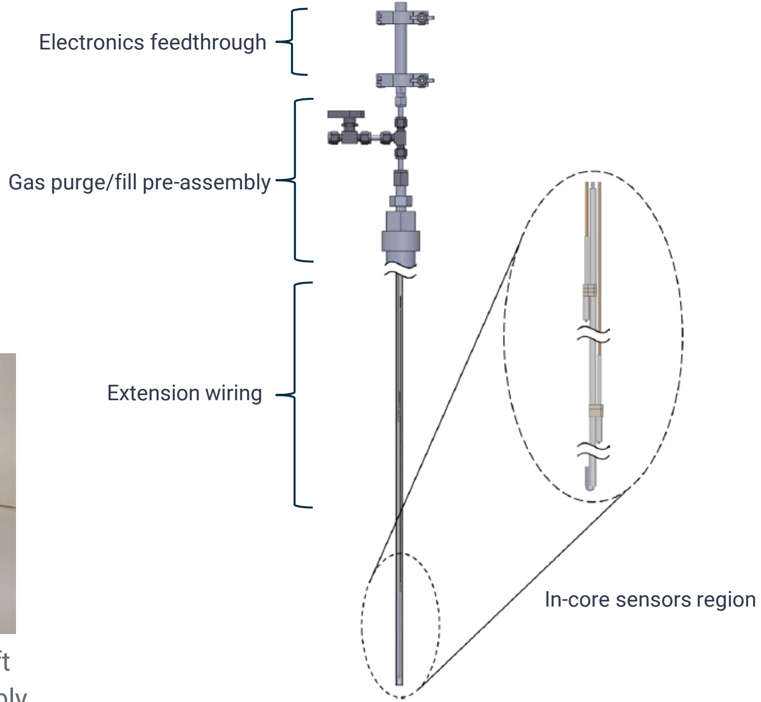
MPFD Design & Fabrication: Common Cathode Model

- Up to 5 sensor regions, each separated by insulated wire
- Additional insulated wire extends to the top and regions without nodes are braided
- Assembly is inserted directly into a flux wire port
- A 3-way valve is installed at the top of the flux wire port and is used to purge/fill the port with gas



Top-down view of common cathode geometry[1]

5-node common cathode MPFD with 10 ft extension wiring, gas purge/fill pre-assembly and electronics feedthrough[1]

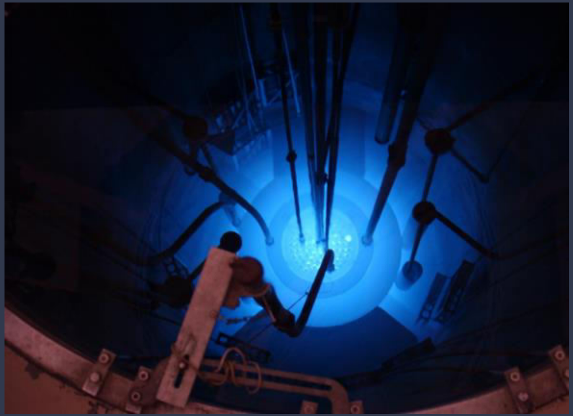


Common cathode MPFD array schematic[1]

[1]Image reproduced from M. Reichenberger, "Micro-pocket fission detectors: development of advanced, real-time, in-core, neutron-flux sensors" (Doctoral Dissertation), 2017.

Overview of Highlighted Experiments

- 5-node common cathode array in KSU TRIGA Mk II nuclear Reactor
  - M. Reichenberger, D. Nichols, S. Stevenson, T. Swope, C. Hilger, R. Fronk, J. Geuther, D. McGregor, “Fabrication and Testing of a 5-node Micro-Pocket Fission Detector Array for Real-Time, Spatial, Iron-Wire Port Neutron-Flux Monitoring.” Ann. Nucl. Energy, 110 (2017) pp. 995-1001.
- 4-node multi-cathode array in KSU TRIGA Mk II Nuclear Reactor
  - M. Reichenberger, D. Nichols, S. Stevenson, T. Swope, C. Hilger, T. Unruh, D. McGregor, J. Roberts, “Fabrication and Testing of a 4-node Micro-Pocket Fission Detector Array for the Kansas State University TRIGA Mk.II Research Nuclear Reactor.” Nucl. Instrum. Meth., A862 (2017) pp. 8-17.
- 2-node multi-cathode array in CEA MINERVE Zero-Power Reactor
  - S. Stevenson, T. Unruh, J-F Villard, B. Geslot, G. de Izarra, S. Breaud, M. Reichenberger, D. Nichols, A. Pepino, and D. McGregor, “In-Pile Fission Chamber R&D: A Collaborative Internship with the French Alternative Energies and Atomic Energy Commission (CEA).” American Nuclear Society Winter Meeting, 2017.



KSU TRIGA Mk II nuclear reactor

CEA MINERVE nuclear reactor

5-Node Common Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Goals of the experiment:

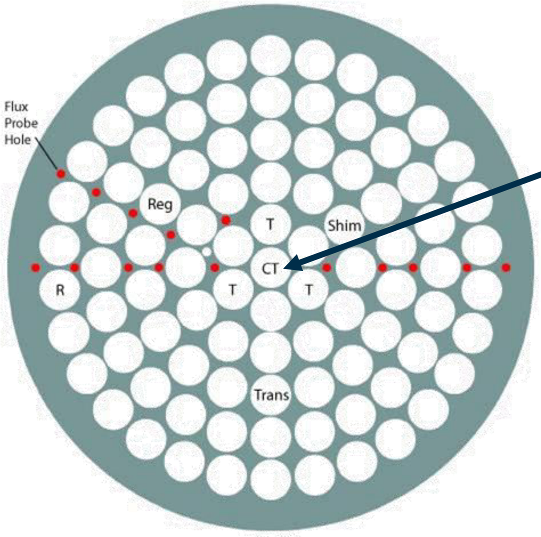
- Demonstrate the common cathode MPFD multiplexing ability
- Evaluate the common cathode MPFD pulse-mode signal response over a range of steady state powers and during power transients

Experimental setup:

- Inserted a 5-node MPFD array in the central thimble flux well
  - The central thimble terminates at the fuel centerline
  - Neutron flux @ 250 kWth: ~1E13 (thermal) ~1E13 (fast)
  - Gamma flux @ 250 kWth: ~2.5E4 (rad/s)
- Tests conducted from 0 - 100 kWth

KSU TRIGA core schematic

CT → Central thimble
T → instrumented fuel
R → Rabbit
Reg → Regulating rod
Shim → Shim rod
Trans → Transient rod

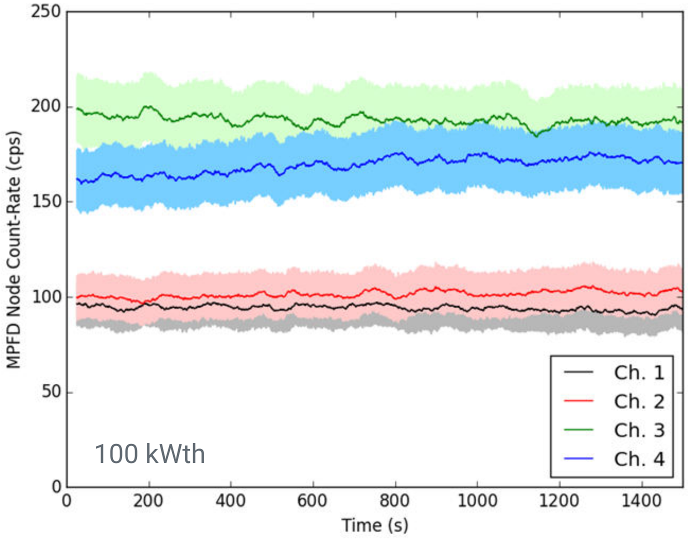


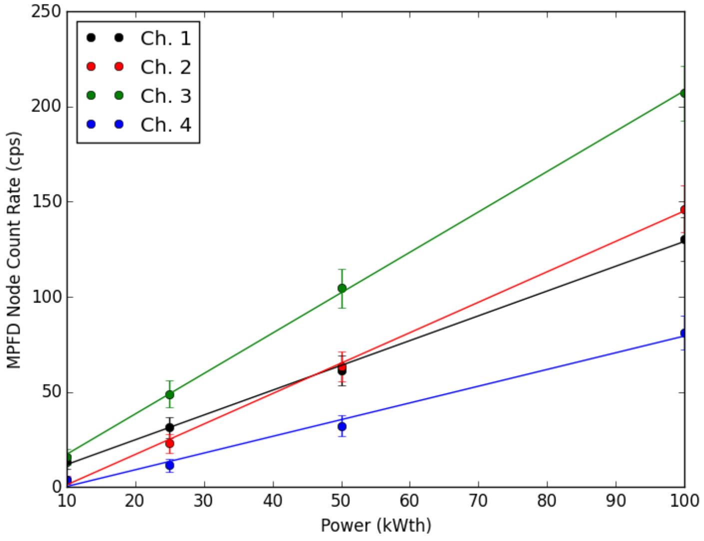
Node #	Nat. Uranium Mass (µg)	Location (inches above core center)
1 (bottom of array)	0.09 ± 0.006	1.5
2	0.05 ± 0.005	2.5
3	0.07 ± 0.006	3.5
4	0.12 ± 0.007	4.5
5 (top of array)	0.09 ± 0.006	5.5

5-Node Common Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Results:

- **Steady response over long (~30 min) durations from 10 – 100 kWth**
- **Four of the five MPFD nodes exhibited linear response rates with reactor power**
- Power transients were observed at increasing reactor powers of 10, 25, 50, and 100 kWth

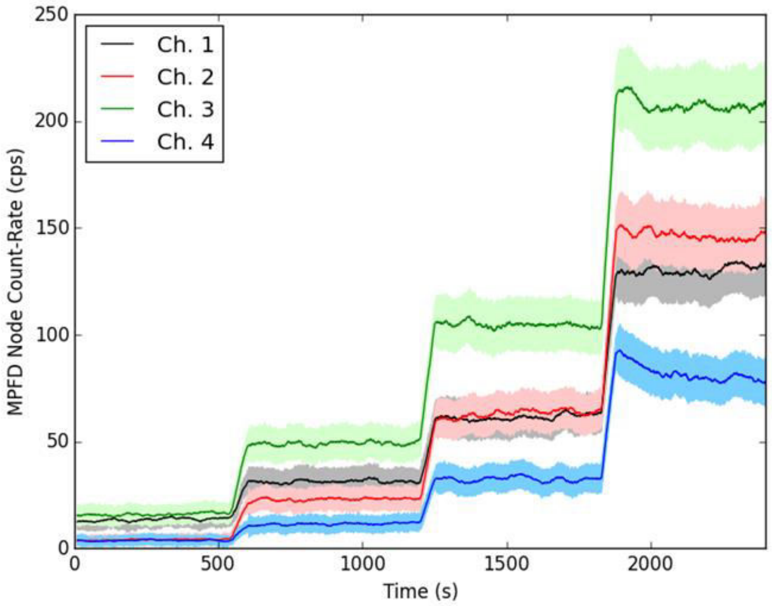




5-Node Common Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Results:

- Four of the five MPFD node exhibited linear response rates with reactor power
- **Power transients were observed at increasing reactor powers of 10, 25, 50, and 100 kWth**



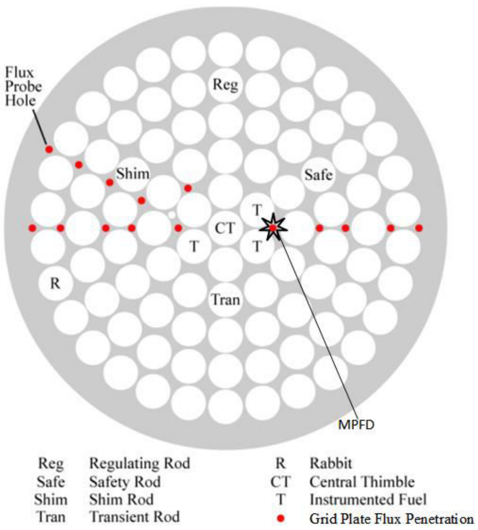
4-Node Multi-Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Goals of the experiment:

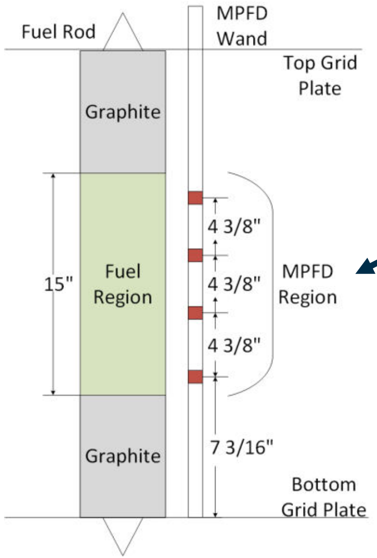
- Demonstrate the multi-cathode MPFD multiplexing ability
- Evaluate the multi-cathode MPFD pulse-mode signal response at a range of steady state powers and during power transients

Experimental setup:

- Inserted a 4 node MPFD array in a grid plate flux penetration
  - The 4 nodes were equally spaced over 15" long fuel region
  - Neutron flux @ 250 kWth: ~1E13 (thermal) ~1E13 (fast)
  - Gamma flux @ 250 kWth: ~2.5E4 (rad/s)
- Tests conducted from 0 - 700 kWth



KSU TRIGA core schematic



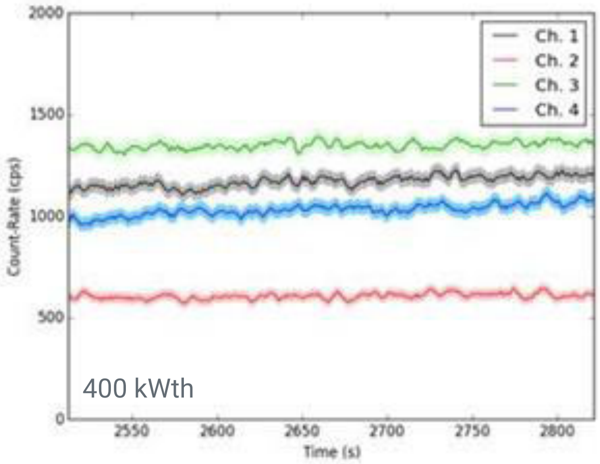
MPFD node alignment with fuel region

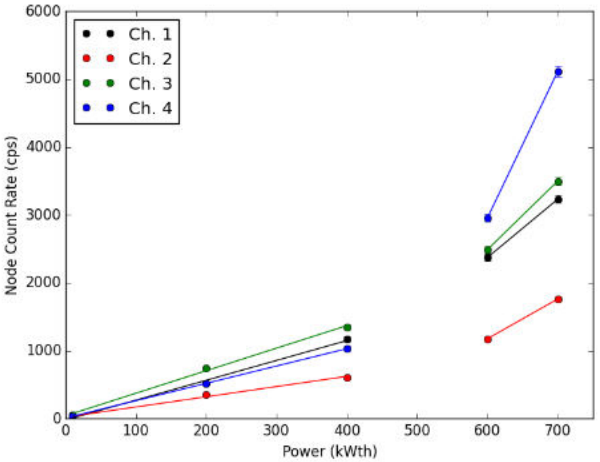
Node #	Nat. Uranium Mass (μg)
1 (top of array)	0.533 ± 0.023
2	0.630 ± 0.026
3	0.548 ± 0.025
4 (bottom of array)	0.619 ± 0.014

4-Node Multi-Cathode Array in KSU TRIGA Mk II Nuclear Reactor

<u>Results:</u>

- **Steady response over long (~1hr) durations from 10 – 700 kWth**
- **All four MPFD nodes exhibited a linear response to reactor power until 400 kWth**
- Power transients were observed at increasing reactor powers
- Positive reactivity insertions with power periods of 30, 15, and 5 sec were tracked using a 1 sec counting interval
- Increasing and decreasing power transients were tracked using a 100 ms counting interval

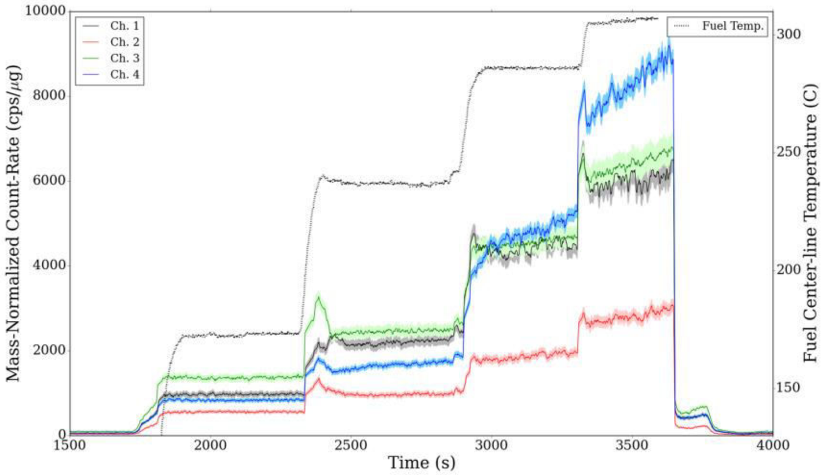




4-Node Multi-Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Results:

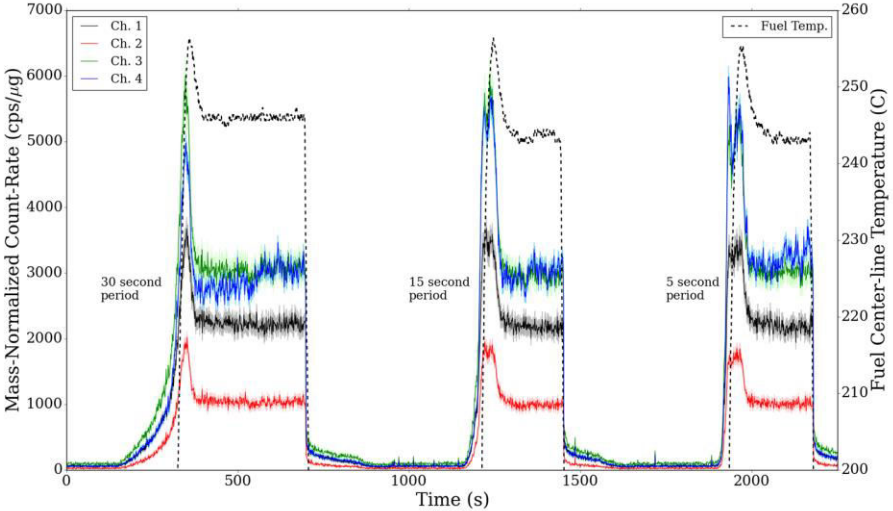
- Steady response over long (~1hr) durations from 10 – 700 kWth
- All four MPFD nodes exhibited a linear response to reactor power until 400 kWth
- **Power transients were observed at increasing reactor powers**
- Positive reactivity insertions with power periods of 30, 15, and 5 sec were tracked using a 1 sec counting interval
- Increasing and decreasing power transients were tracked using a 100 ms counting interval



4-node Multi-Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Results:

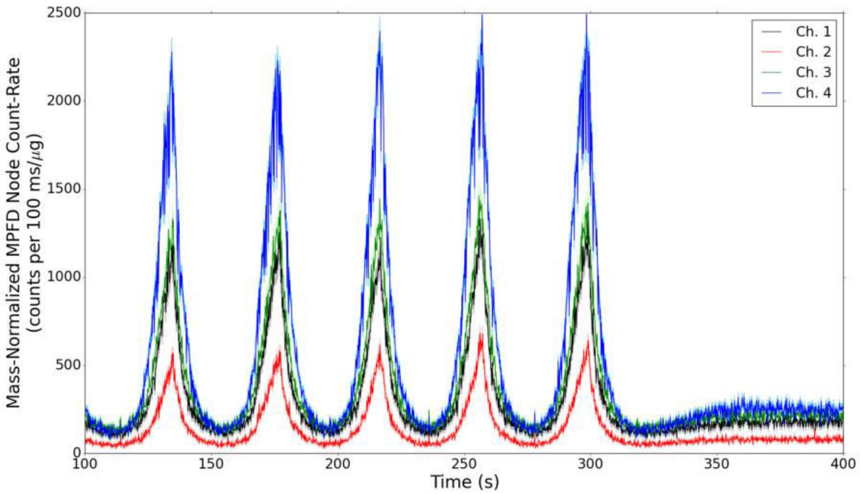
- Steady response over long (~1hr) durations from 10 – 700 kWth
- All four MPFD nodes exhibited a linear response to reactor power until 400 kWth
- Power transients were observed at increasing reactor powers
- **Positive reactivity insertions with power periods of 30, 15, and 5 sec were tracked using a 1 sec counting interval**
- Increasing and decreasing power transients were tracked using a 100 ms counting interval



4-node Multi-Cathode Array in KSU TRIGA Mk II Nuclear Reactor

Results:

- Steady response over long (~1hr) durations from 10 – 700 kWth
- All four MPFD nodes exhibited a linear response to reactor power until 400 kWth
- Power transients were observed at increasing reactor powers
- Positive reactivity insertions with power periods of 30, 15, and 5 sec were tracked using a 1 sec counting interval
- **Increasing and decreasing power transients were tracked using a 100 ms counting interval**



2-Node Multi-Cathode Array in CEA MINERVE Reactor

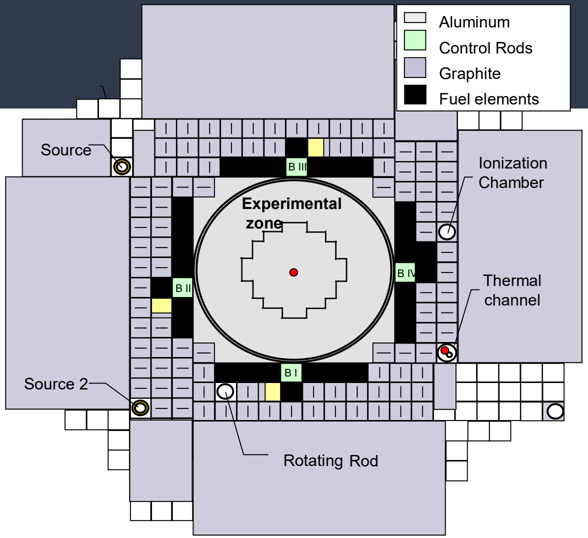
Goals of the experiment:

- Validate MPFD in a characterized neutron flux
- Compare the MPFD signal with the CEA's calibrated fission chamber signal

Experimental setup:

- MINERVE is a pool-type reactor with a maximum power of 80 W
- Inserted a 2-node MPFD array in the thermal channel with a CEA fission chamber
  - The sensors were positioned at the fuel mid-plane
  - Expected U-235 fission rate of 252 s^{-1}/μg at full power
- Inserted another 2-node MPFD array in the central port with another CEA fission chamber
  - The sensors were positioned at the fuel midplane
  - Expected U-235 fission rate of 283 s^{-1}/μg at full power
- Tests conducted from 0 – 80 W

Schematic of CEA MINERVE reactor[1]

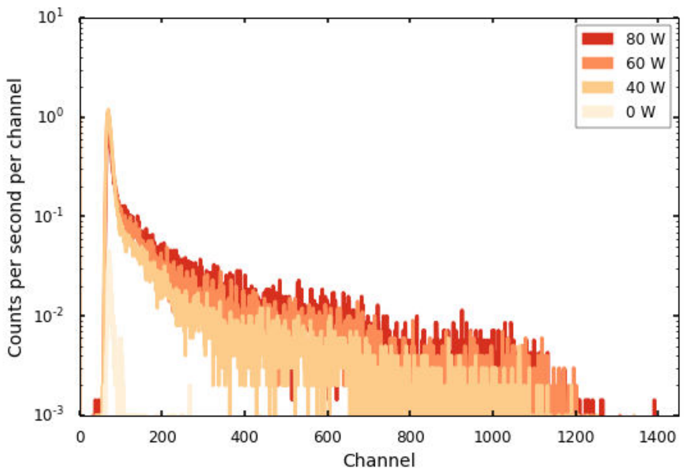


Detector	Isotope mass deposited (μg)	Isotope (purity)
CEA Fission chamber 2250	5	U235 (98%)
CEA fission chamber 2238	25.7	Pu239
Thermal channel MPFD	0.4 (upper sensor) 0.61 (lower sensor)	U235 (93%)
Central port MPFD	0.5 (upper sensor) 0.5 (lower sensor)	U235 (93%)

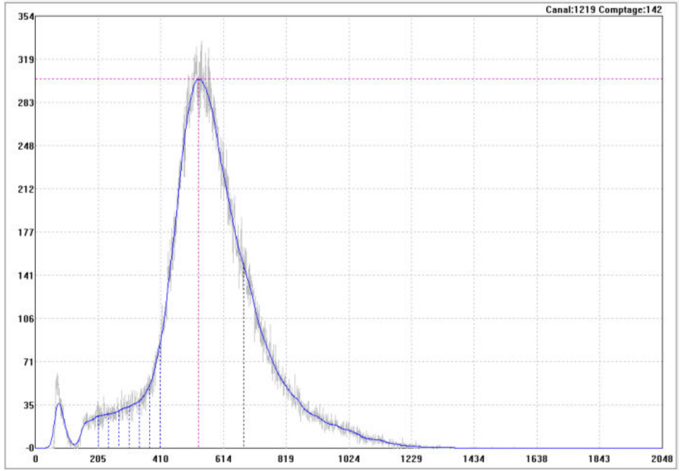
2-Node Multi-Cathode Array in CEA MINERVE Reactor

Results:

- Due to a large amount of electromagnetic noise, only the upper nodes of MPFDs were usable
- The MPFD signal was proportional to reactor power from 0 to 80 W
- The MPFD experimental count rate was 10x lower than the expected value (value based on deposited mass)
- Compared to the CEA fission chambers, no “valley” is noticeable in the MPFD pulse height amplitude spectrum



Thermal channel MPFD pulse height amplitude spectrum

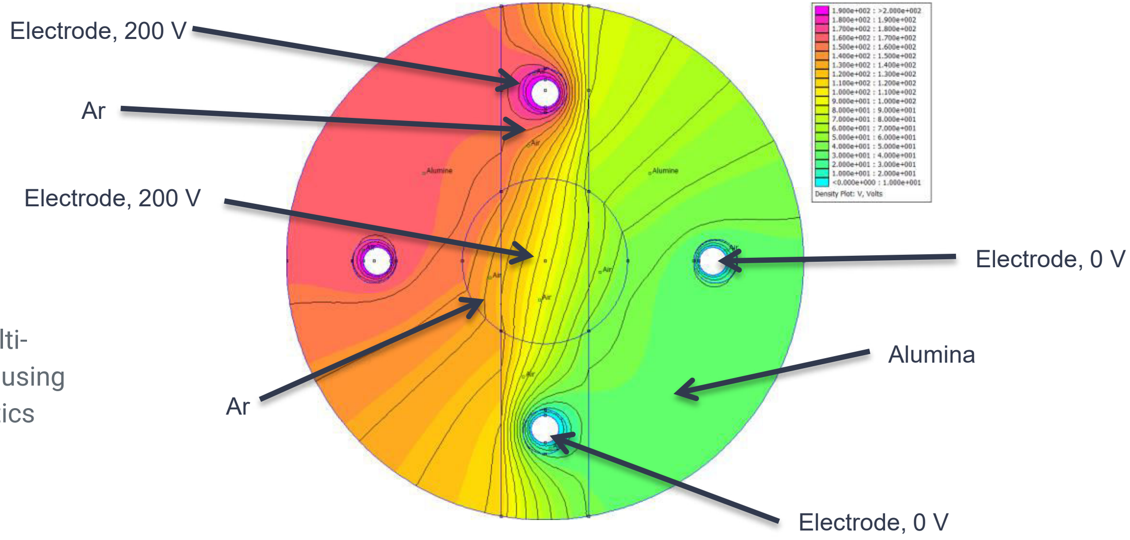


Thermal channel CF2250 pulse height amplitude spectrum

2-Node Multi-Cathode Array in CEA MINERVE Reactor

The low MPFD count rate prompted a brief investigation

- Simple electric field simulation showed a significant amount of charges may not be collected
- A new design is presently being investigated at KSU



Electric field simulation of multi-cathode MPFD design generated using Finite Element Method Magnetics

Recommendations & Ongoing Deployments

Recommendations

- Continue MPFD simulation studies and collaborate with the CEA to characterize detectors
- Reduce noise in the MPFD circuit
- For deployments in high gamma fields, include a “blank” sensor for gamma subtraction
- Optimize MPFD electrodeposition chemistry to use less material and deposit all material
- Produce neutron-flux unfolding MPFD device
  - Multiple axial sensors with various fissile deposits

Ongoing Deployments

- High-Temperature Multi-Cathode MPFDs fabricated at the Idaho National Laboratory:
  - Advanced Test Reactor Deployment as part of the AGR 5/6/7 irradiation program
  - Transient REActor Test (TREAT) facility deployment as part of the multi Static Environment Rodlet Transient Test Apparatus (multi-SERTTA) experiment
- Multi-Cathode MPFDs fabricated at KSU
  - University of Wisconsin Nuclear Reactor (UWNR) deployment for comparison to simulation results

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