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Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply

Advanced Sensors and Instrumentation Annual Webinar

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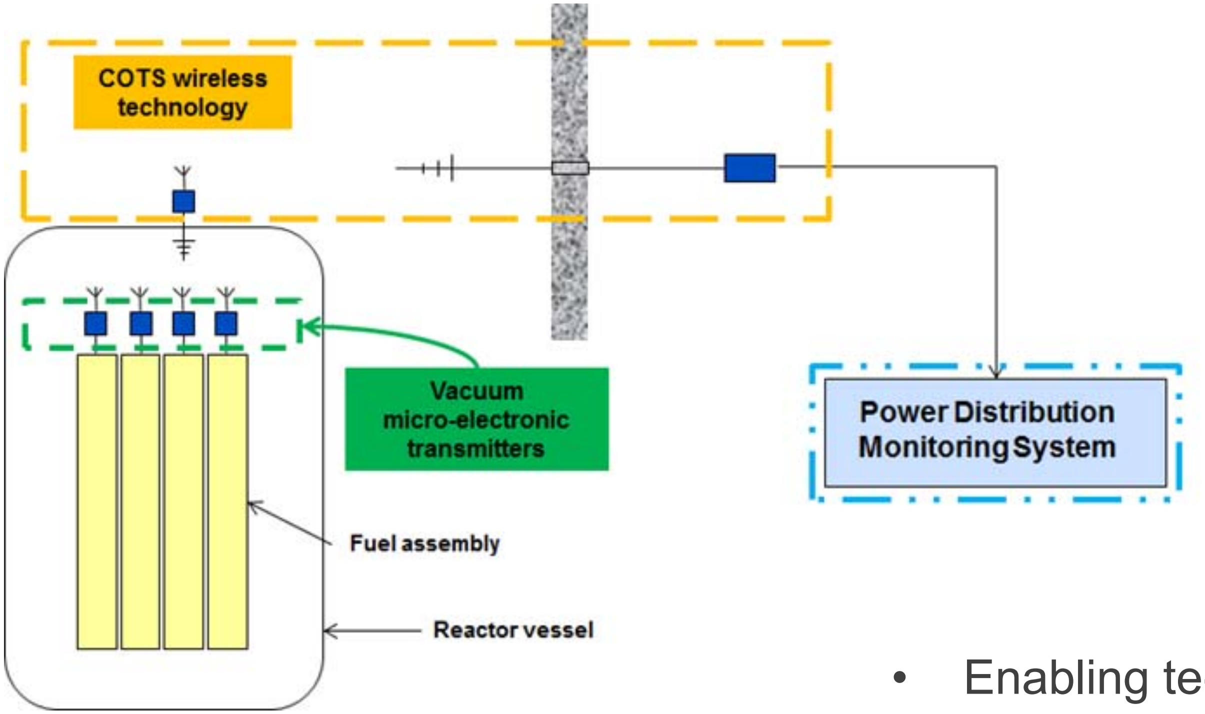
Project Overview

- Goal and Objective
  - Develop the technology necessary for a wireless reactor power distribution measurement system. This system utilizes highly radiation- and temperature-resistant vacuum micro-electronics (VME) technology that continuously broadcasts Self-Powered Detector (SPD) signals and reactor coolant temperature sensor signal measurements to a receiving antenna. Other potential applications of the technology within a LWR containment environment will also be investigated.
- Team
  - Westinghouse Electric Co: Jorge Carvajal (PI), Michael Heibel (Co-PI), Shawn Stafford, Paul Sirianni, Nick Arlia.
  - Pennsylvania State University: Dr. Kenan Unlu (Co-PI), Gokhan Corak.
- Period of Performance
  - October 1, 2016 – July 31, 2020.

Project Overview

- Increase in reactor operating margin due to measurement density increase
- Improved reactor power distribution measurement accuracy will provide the capability to produce more electricity from the same amount of nuclear fuel, or produce the same amount of electricity from less nuclear fuel



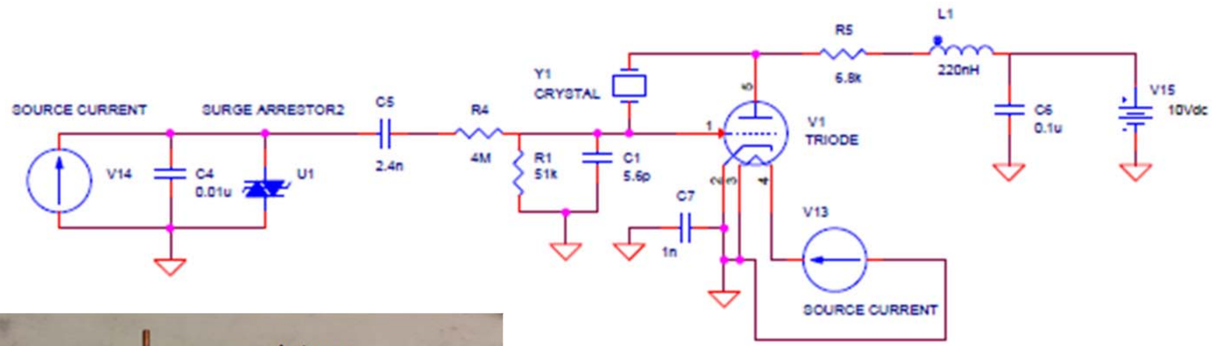
- Enabling technology for other applications such as In-pile sensors and in-containment applications

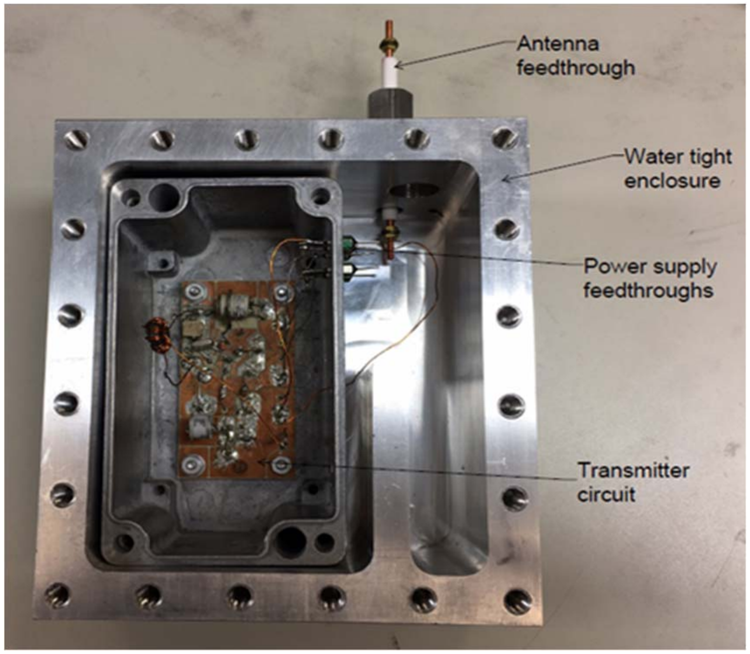
FY20 Milestones, Deliverables, Outcomes

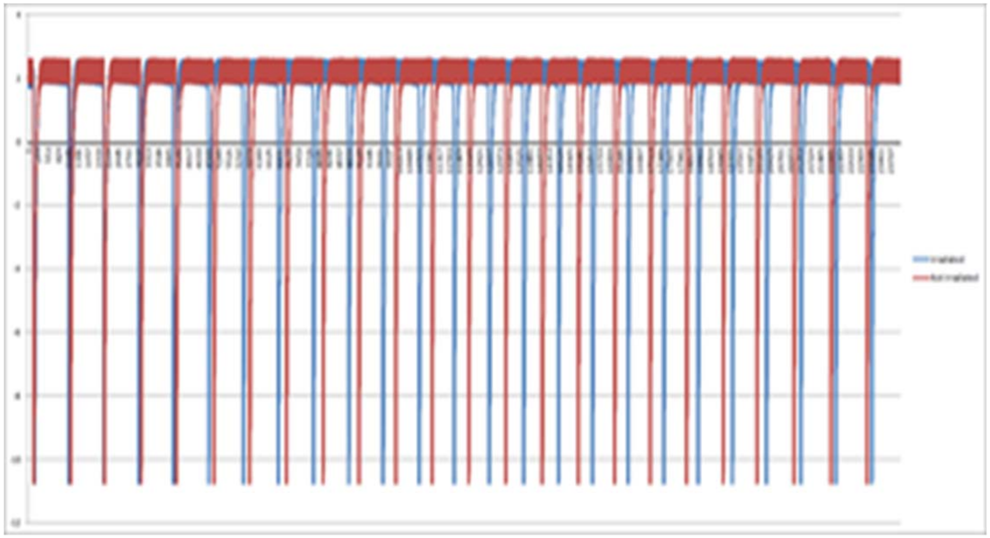
- Milestone #7: Address any VME transmitter, VME transmitter power supply, or receiving antenna system performance issues identified during Year 2 testing
  - Subtasks 7a: Passive sensor investigation
  - Subtasks 7b: Passive Sensor Signal Processing
- Milestone #8: High level system functional design for potential use in a commercial reactor pilot program

Summary of VME-based Transmitter Development

- Incorporated the VME device into an amplitude modulated transmitter circuit

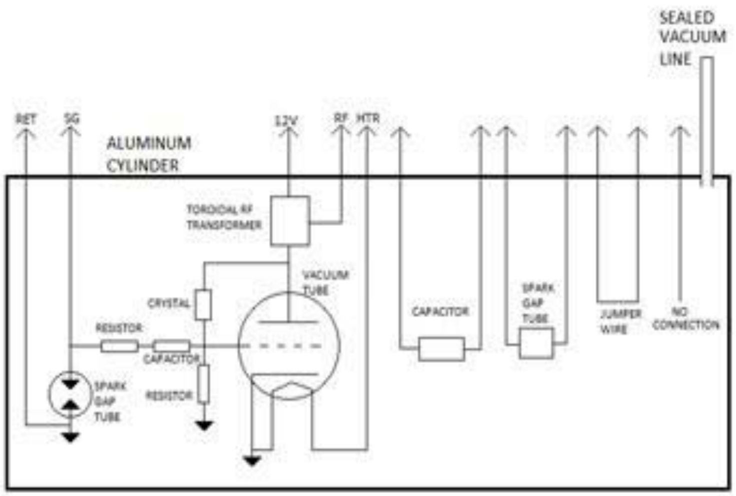


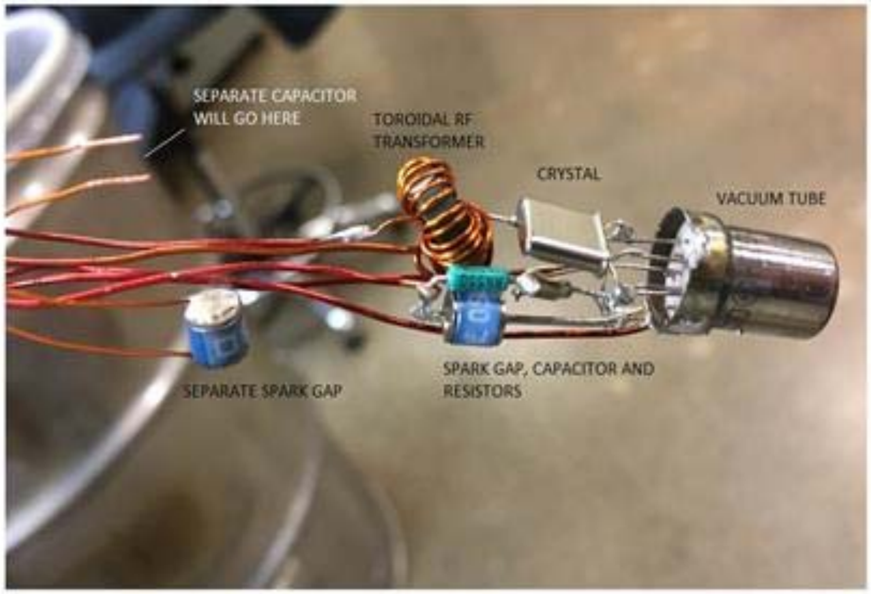




Summary of VME-based Transmitter Development

- Integrated an alternate VME device into an improved transmitter circuit
- New circuit is more compact and has improved operational stability

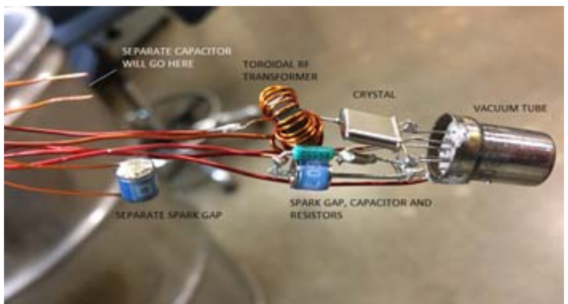


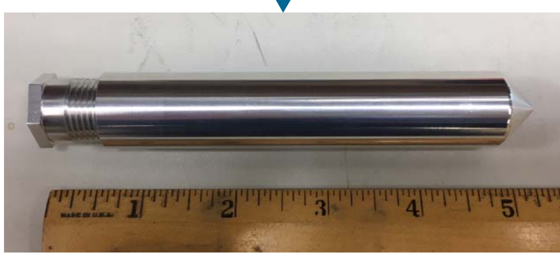


Summary of VME-based Transmitter Development

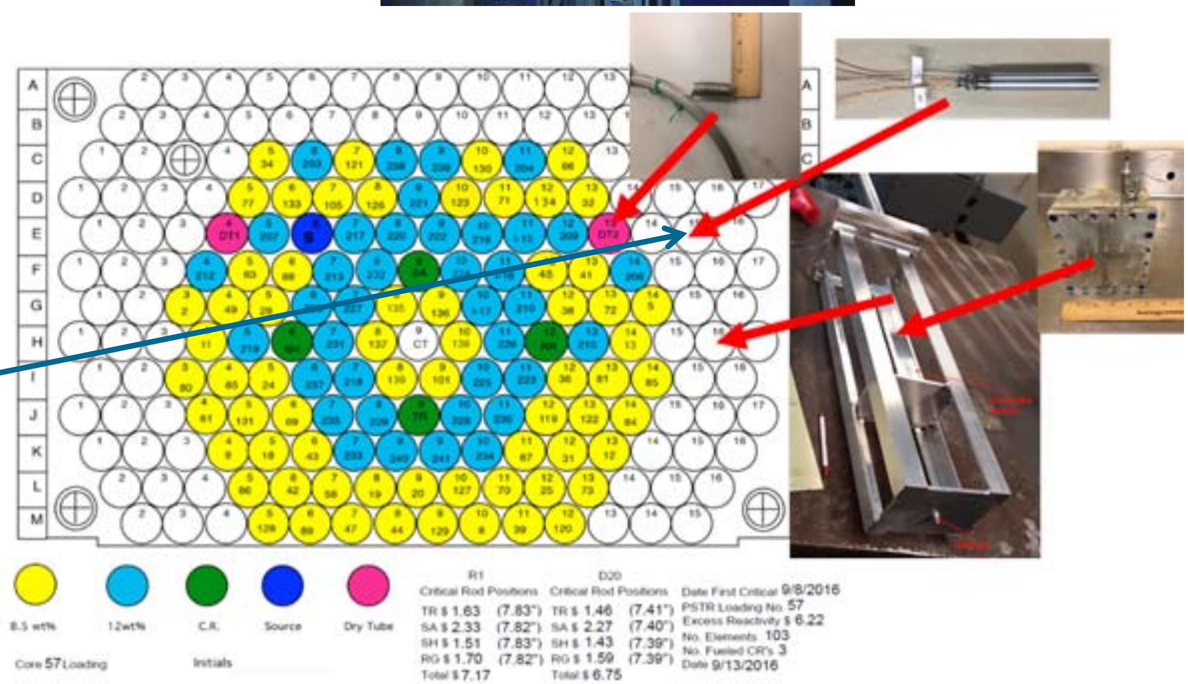
Penn State Breazeale Reactor Irradiation Test Results

- Total Neutron Fluence (n/cm^2)
  - DT2 position (Rh detectors): 6.6E+18
  - E15 position (Capacitors): 2.6E+18
  - H16 position (Transmitters): 2.6E+18



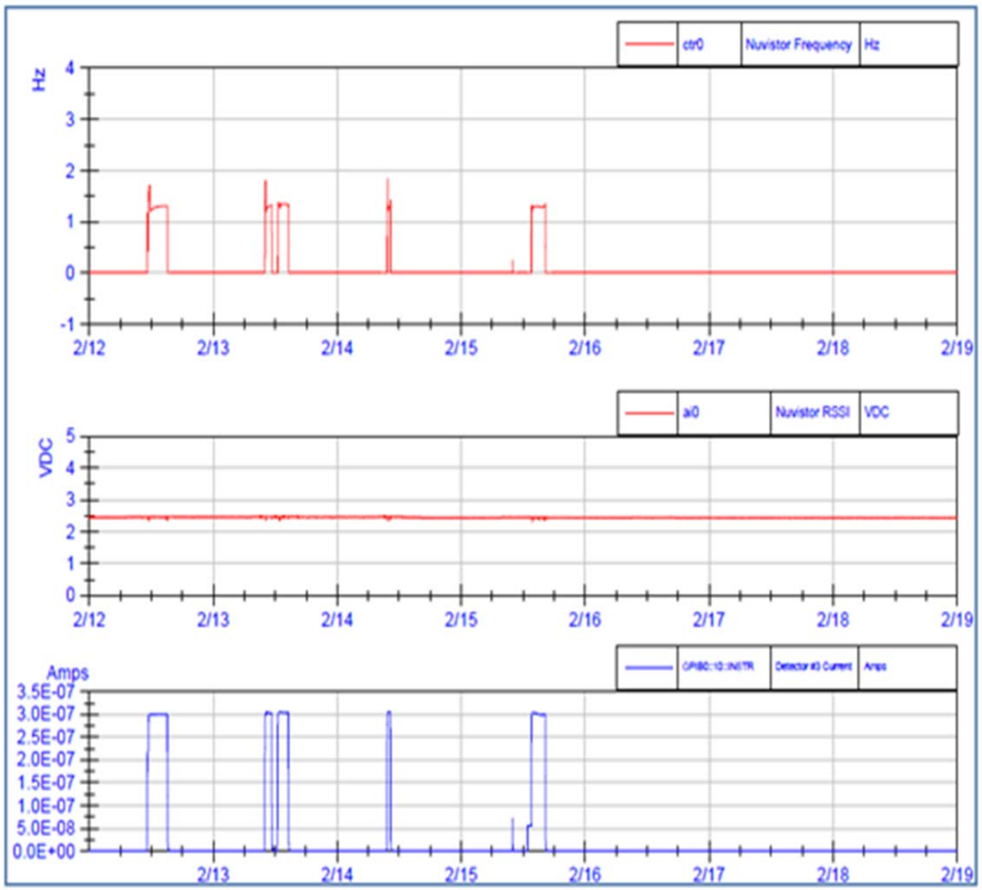


New AM transmitter with vacuum pulled inside enclosure



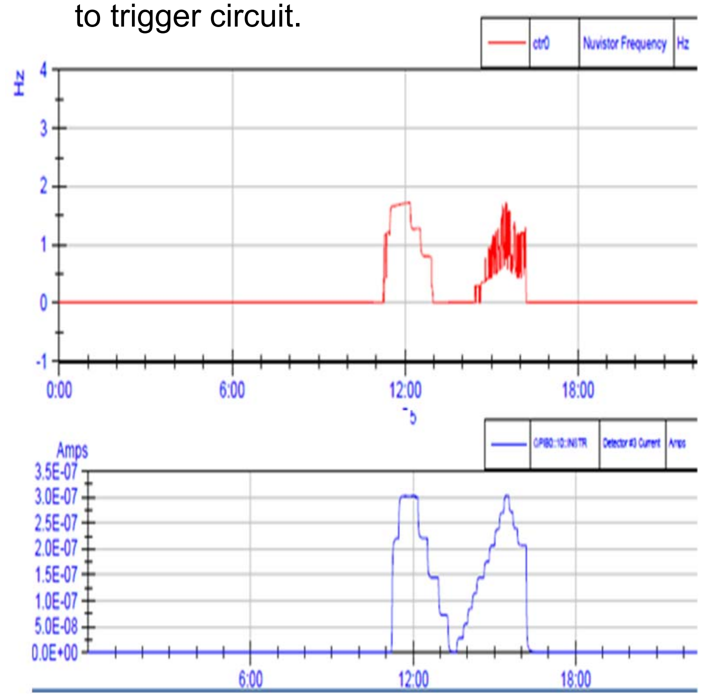
Summary of VME-based Transmitter Development

- Improvements in the setup produced reliable data



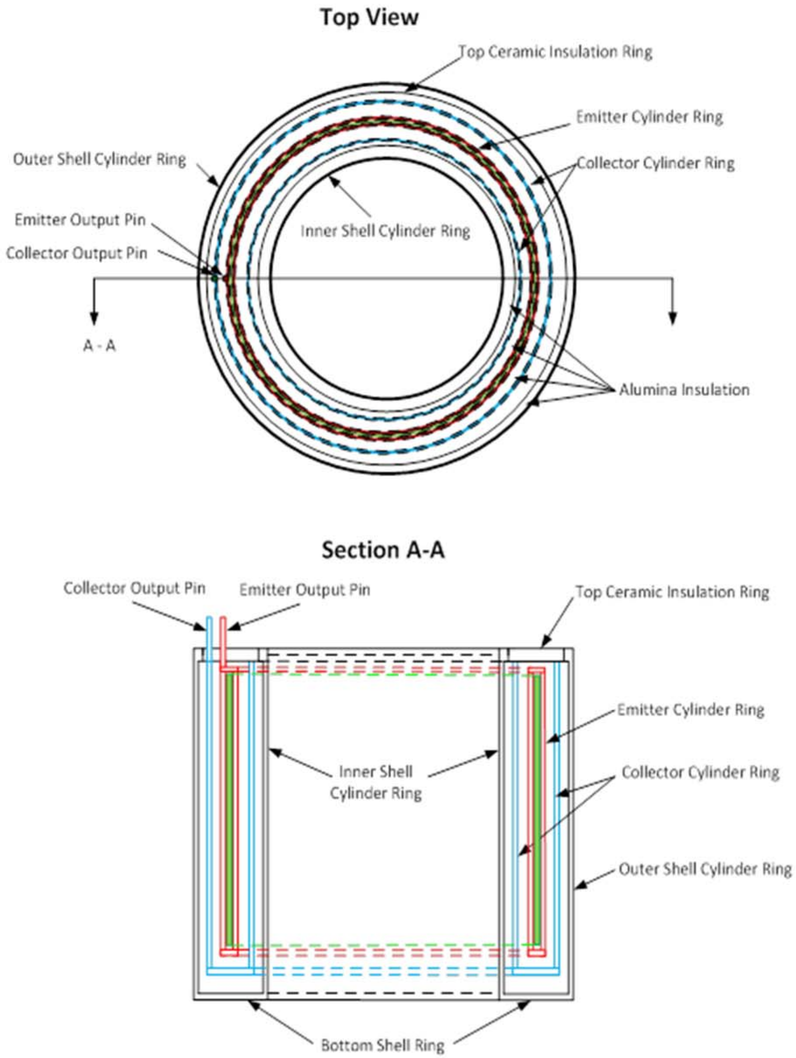
- Pulse responses (left-top) proportional to Rh SPD (left-bottom)
- Signal amplitude (left-middle) stable as Rx power varies
- 2 Rh SPD feeding the transmitter.
- 1 Rh SPD used as the detector

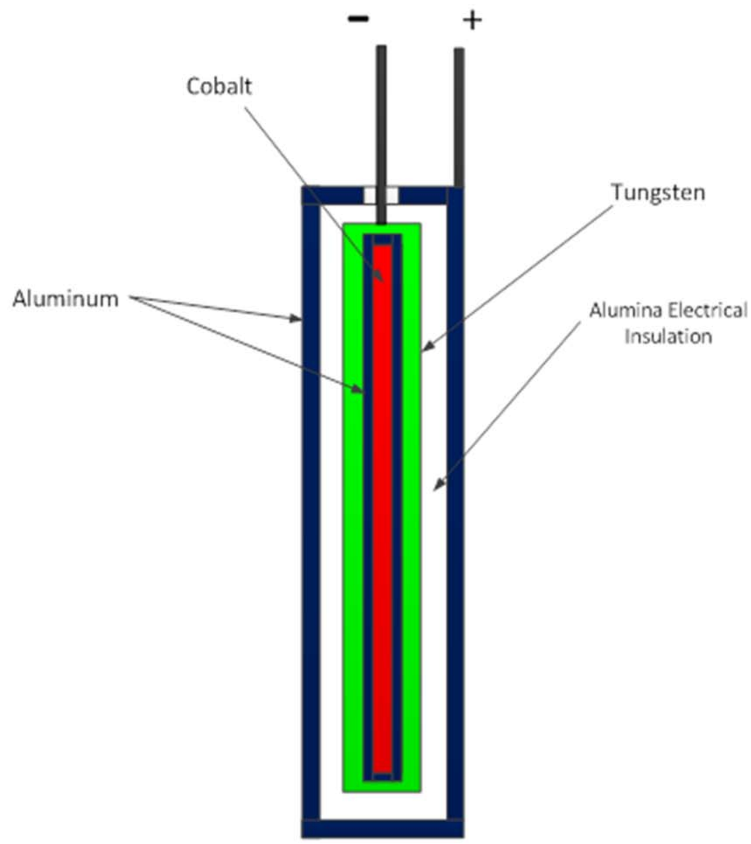
- Modulation rate matches reactor power (below) but detector current below approximately 25% Rx power is not sufficient to trigger circuit.



Summary of VME-based Transmitter Power Supply Development

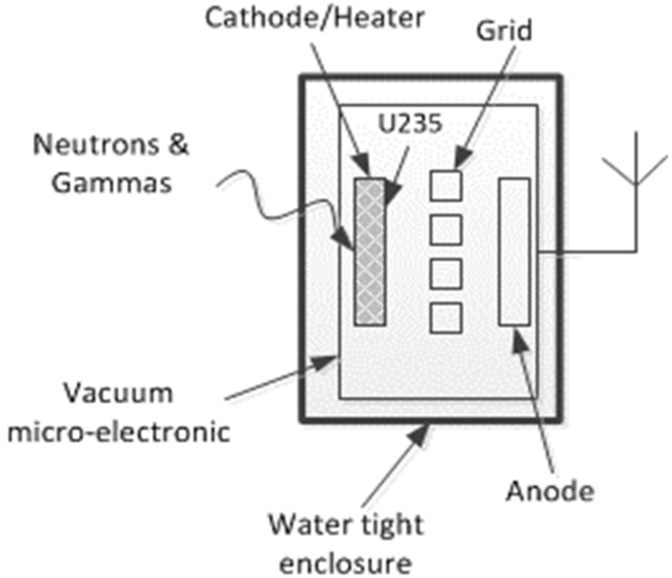
- Gamma Harvesting Power Supply Design

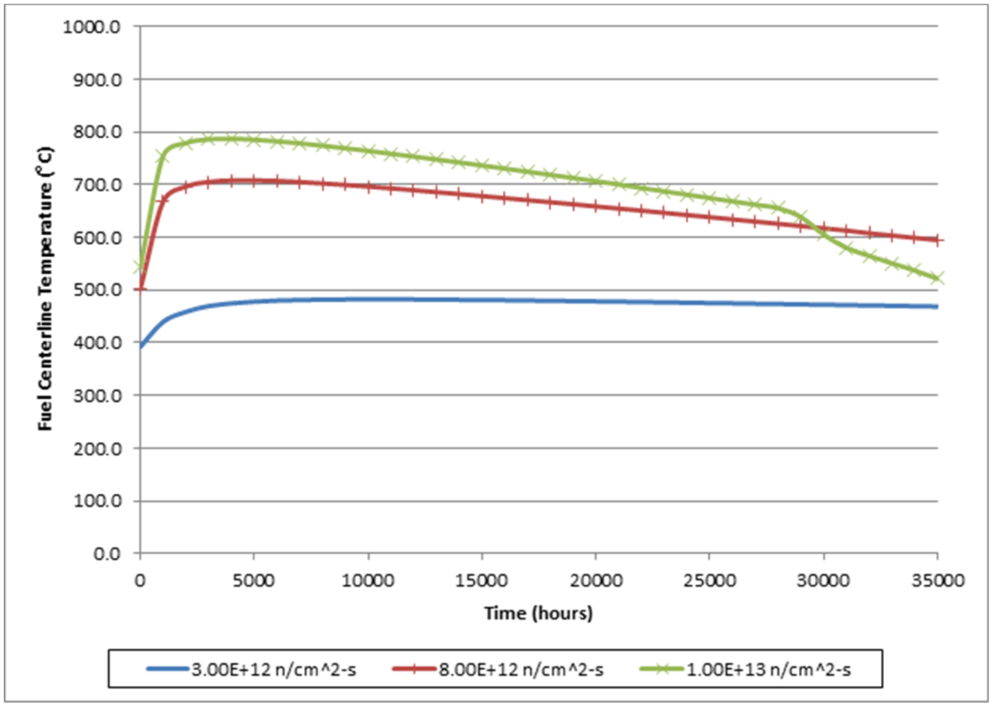




Summary of VME-based Transmitter Power Supply Development

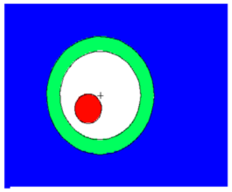
- Alternative gamma harvesting power supply
- Miniature – suitable for integration into VME
- Modelling using MCNP

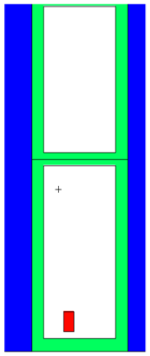


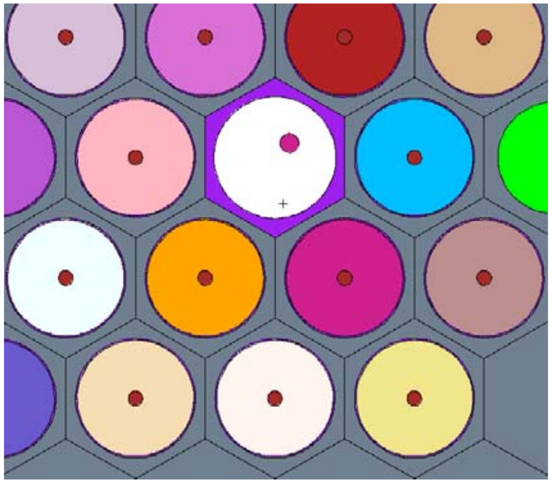


Summary of VME-based Transmitter Power Supply Development

- Results of model promising
- Tungsten rod gamma heating



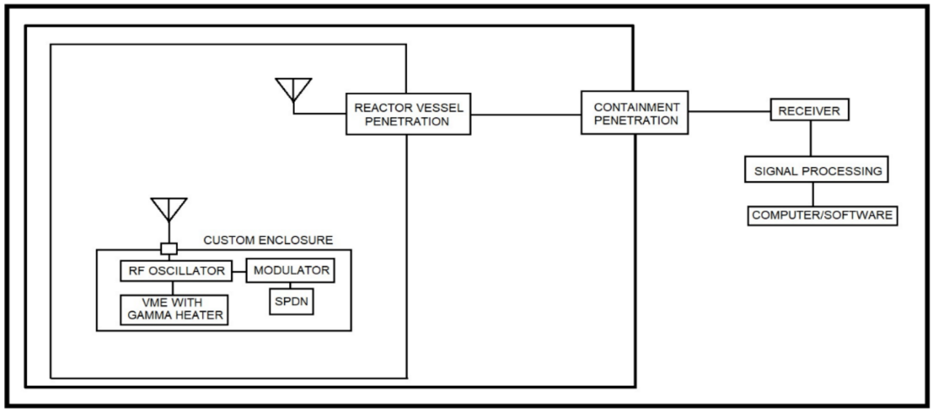




Drytube-1 location for Tungsten heater element

Row #	Radius (cm)	Height (cm)	Area (m^2)	Mass (g)	F6 Tally	Energy Deposition (W)	Temperature (°C)	Error
1	0.2921	0.254	1.00E-04	1.31	1.40E-05	0.22964279	729.71	0.05
2	0.2921	0.254	1.00E-04	1.31	2.52E-05	0.41386898	888.81	0.03
3	0.35	0.254	1.33E-04	1.89	1.34E-05	0.31589259	738.44	0.04
4	0.35	0.395	1.64E-04	2.93	2.44E-05	0.89487098	972.26	0.02
5	0.43	0.254	1.85E-04	2.85	2.44E-05	0.86798506	926.12	0.02

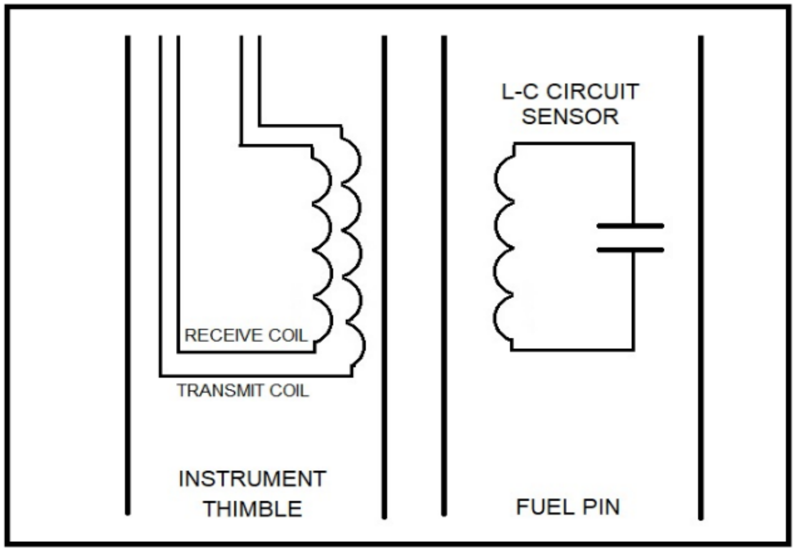
High Level System Roadmap

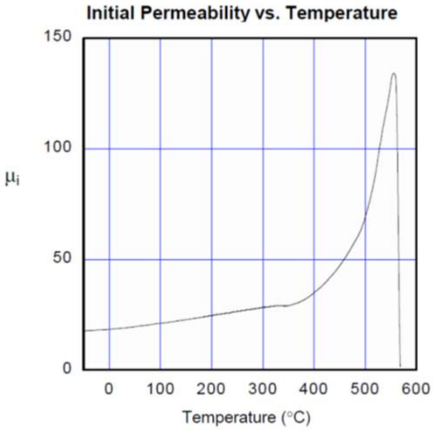


Block	Description	Options Evaluated	Status
VME	Triode device	Vacuum tube	Tested
RF Oscillator	Supporting passive components	Several ceramic/printed caps, metal film/printed resistors and ferrite inductors	Tested
Power supply	Harvest surrounding energy	Gamma harvesting, fissionable material	Simulated
Modulator	Modulated AM transmitter proportional to neutron flux	Gas discharge tube	Tested
SPND	Neutron detectors	Vanadium or Rhodium commercially available	Tested
Antennas	Transmit and receive antennas	Small dipoles	Tested
In-containment receiver and re-transmitter	Receives VME transmitter and relays data	SiC based components or others with shielding	Tested
Signal processing	Filtering, gain control and data processing	Various custom made and commercial solutions available	Tested

Passive Sensor Development

- Passive sensor implementation
- Power delivered wirelessly at close range
- Moves more complex, rad-sensitive elements of system outside reactor
- Relies on the material properties of the sensors

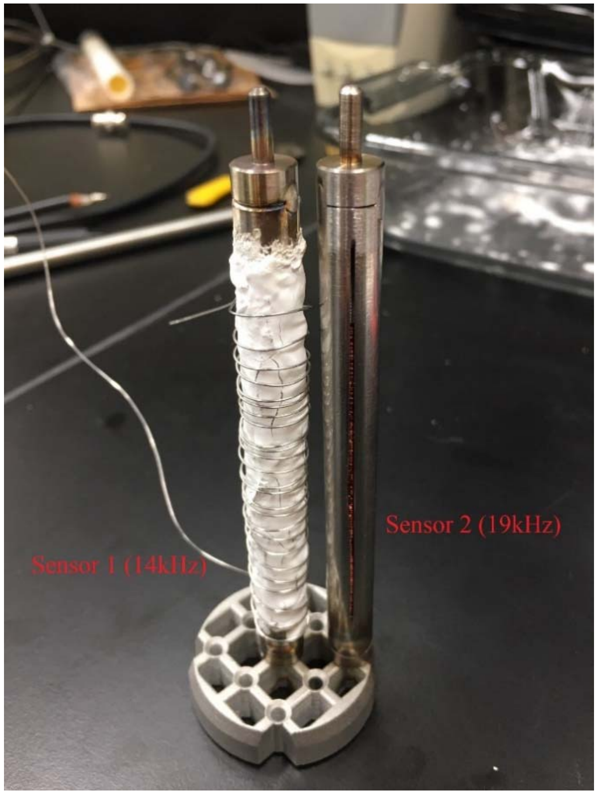


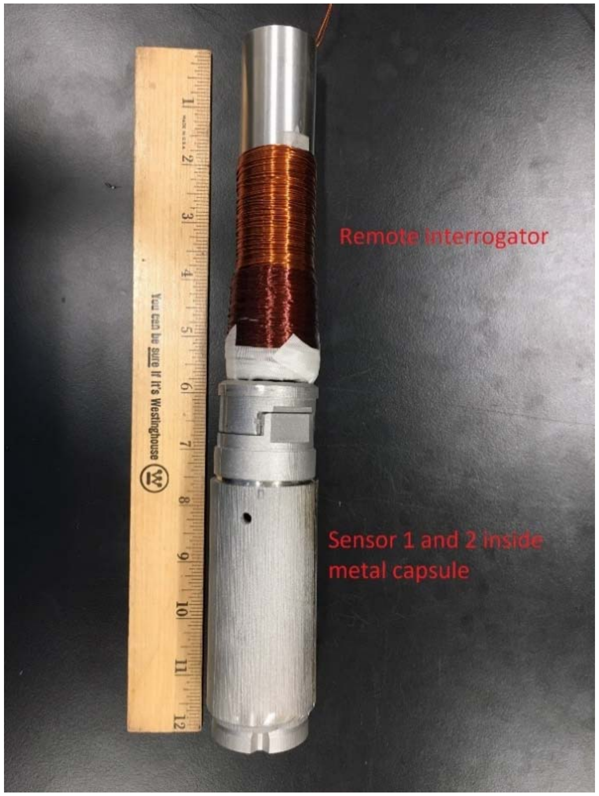


$$F = \frac{1}{2\pi\sqrt{LC}}$$

Passive Sensor Development

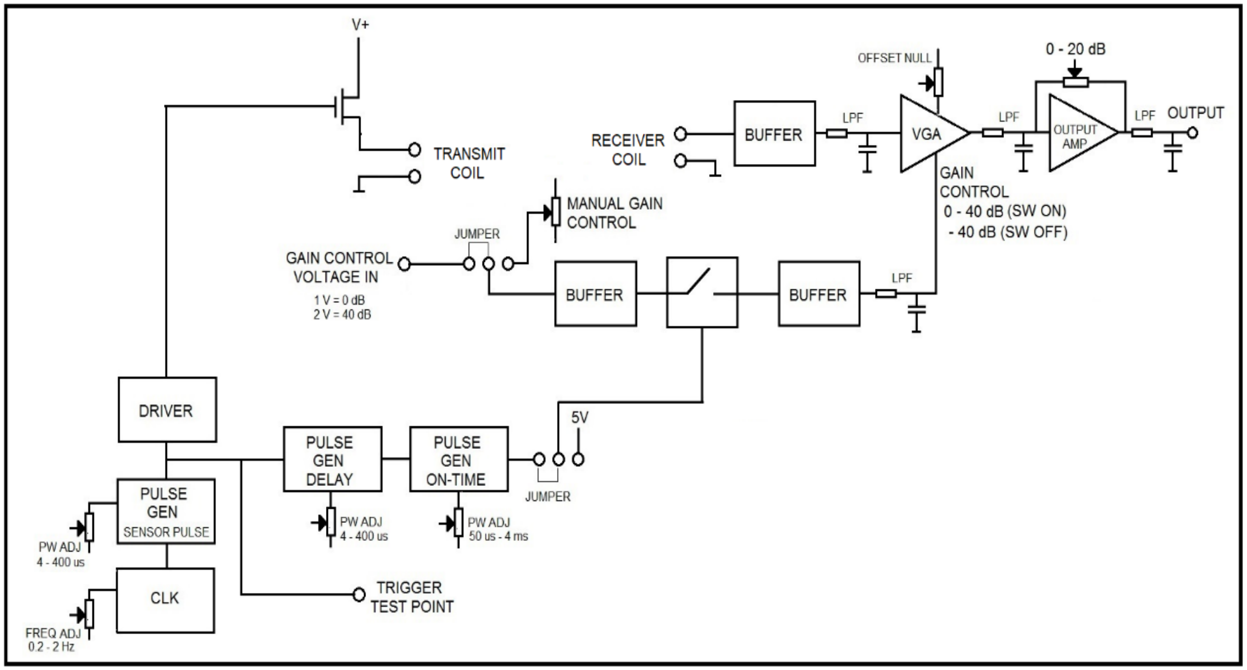
- Multiple sensor processing for spatial differentiation
- Relies on frequency domain analysis to differentiate sensors





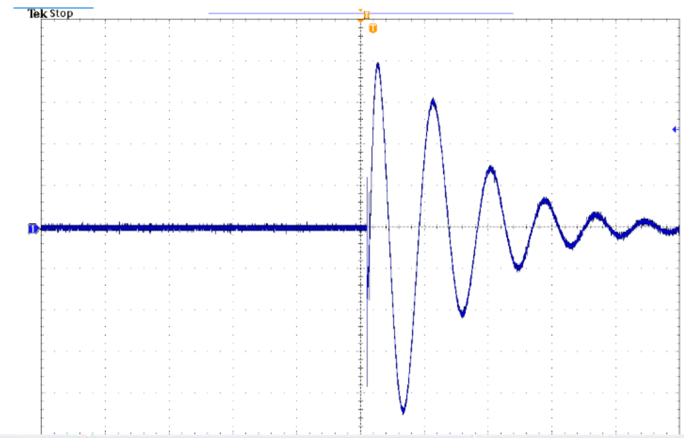
Passive Sensor Development

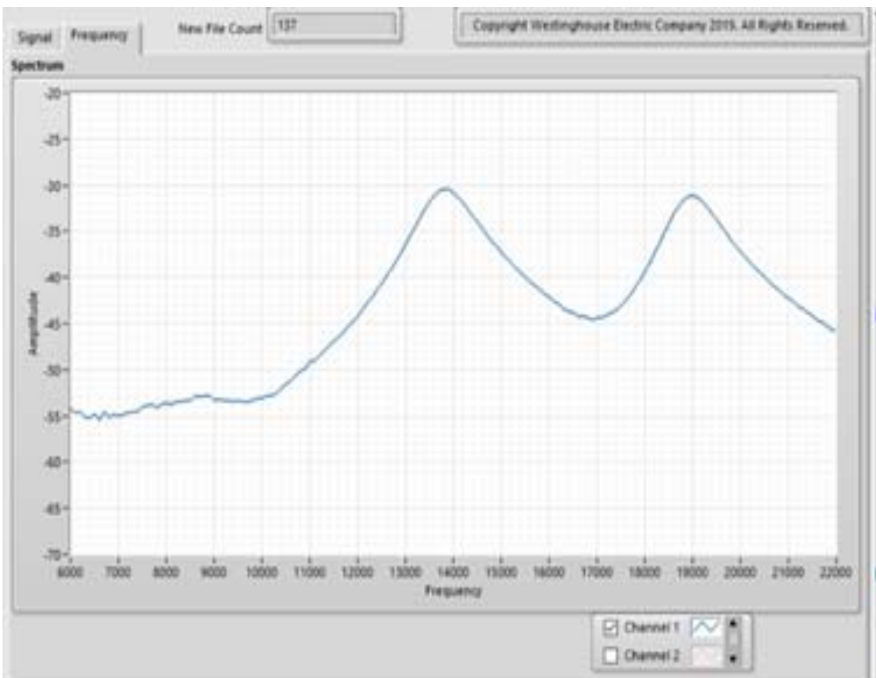
- Signal attenuation: Eddy current losses dependent on operating frequency
- Signal processing: Gating circuitry needed to minimize cross coupling



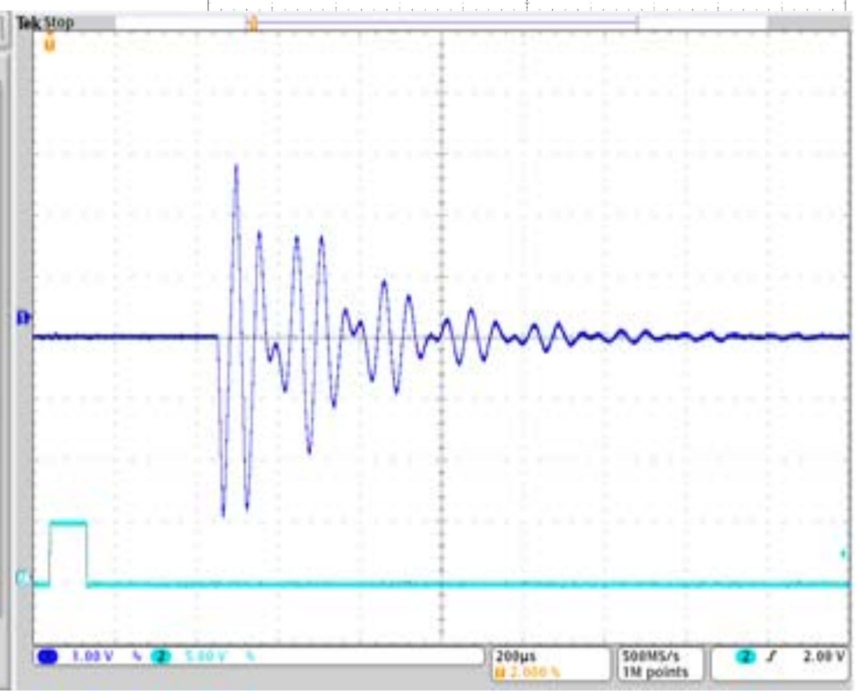
Passive Sensor Development

- Transient nature of signals widens bandwidth
- Peak frequencies from multiple sensors can be discerned





Two sensor signals resolved in frequency domain



Two sensor signals mixed in the time domain

Technology Impact

- *Miniature VME based sensors offer rad hard active complex electronics within the reactor environment*
- *VME devices, passive sensors offer wireless solutions*
- *Industry could adopt technology for industry-wide inclusion in fuel rod manufacture*
- *Relative simplicity makes VME, passive sensors inherently immune to cyber-security threats*
- *Improves operating costs, increases profits*

Publications

Item	Method	Event/journal title (if applicable)	Product title (if applicable)	Author(s)	Date
1	Journal	Annals of Nuclear Energy	Toward the Implementation of Self-Powered, Wireless, Real-Time Reactor Power Sensing	J. Turso, J. Carvajal, S. Stafford, M. Heibel, P. Sirianni, M. Heagy, G. Corak, R. Flammang, N. Arlia, K. Unlu	December 2019
2	Paper	NPIC & HMIT 2019 Conference	Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Radiation-Harvesting Power Supply	J. Carvajal, M. Heibel, S. Stafford, M. Heagy, P. Sirianni, R. Flammang, N. Arlia, J. Turso, K. Unlu	February 2019
3	Article	Department of Energy NEET	Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Radiation-Harvesting Power Supply	J. Carvajal, M. Heibel, S. Stafford, P. Sirianni, J. Turso, K. Unlu	September 2018

Conclusions

- *VME based circuitry operates within reactor environments while providing wireless sensor information*
- *Less power intensive methods with wireless passive sensors can provide critical reactor information*
- *Overall our research shows in-pile wireless VME based devices and passive sensors are viable and provide new opportunities for further sensor technology development.*