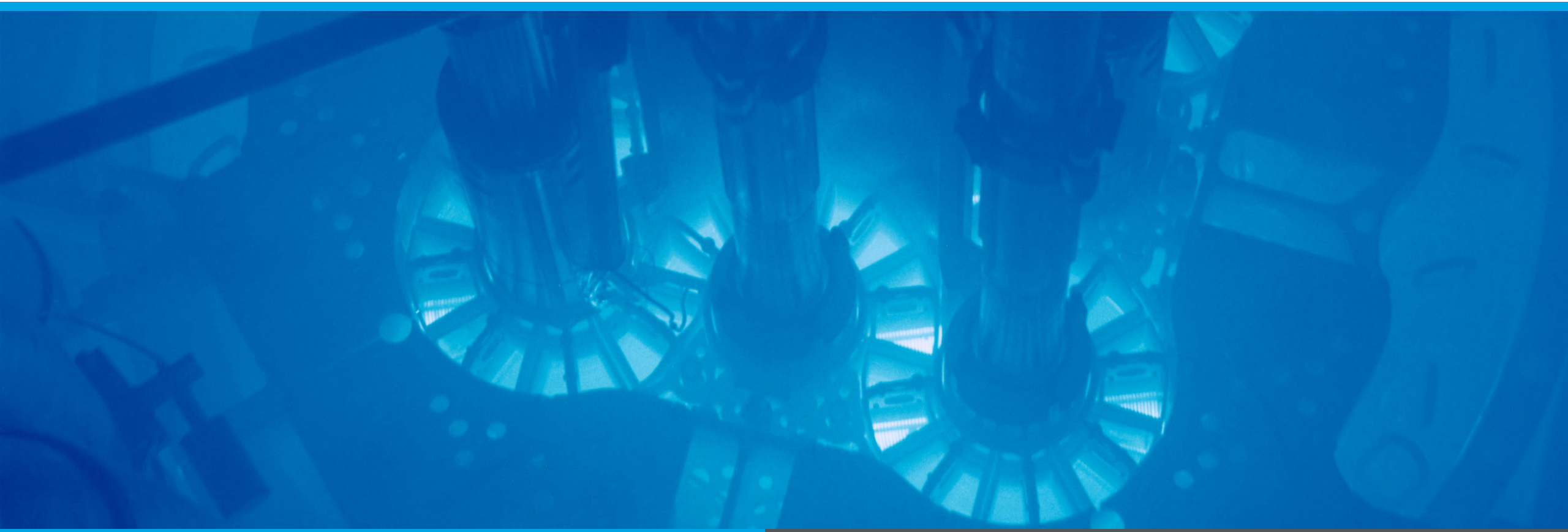
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.



Advanced Sensors and Instrumentation Research Overview

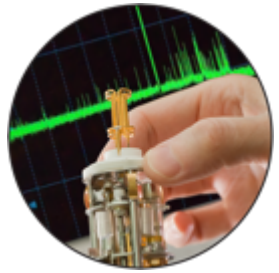
October 29, 2020

Pattrick Calderoni

National Technical Director

Idaho National Laboratory

5-years ASI Program Objectives



Sensors and Instrumentation

Develop instruments to measure plant operational parameters for advanced reactors – for example neutron flux, temperature, pressure

Develop measurement systems for real-time characterization of nuclear fuel and material properties

Develop testing systems to demonstrate instrumentation performance in relevant and operational conditions

Communication

Optimizing communication latency and access points to achieve successful deployment of a distributed autonomous control strategy

Develop electronic components to support the integration of advanced communication technologies, such as wireless and fiber optics, for nuclear applications

Develop modeling and simulation tools for communication technologies to support integration with predictive control systems

5-years ASI Program Objectives

Big Data, Machine Learning, Artificial Intelligence

Develop technologies for anomaly detection, diagnostics, prognostics, and decision making that can operate on streaming data

Develop ML methods and testing infrastructure of data sets that are spatially and temporally heterogeneous and sparse

Develop AI methods for learning/inferring decision logic for operator support, enabling semi-autonomous or fully autonomous operation

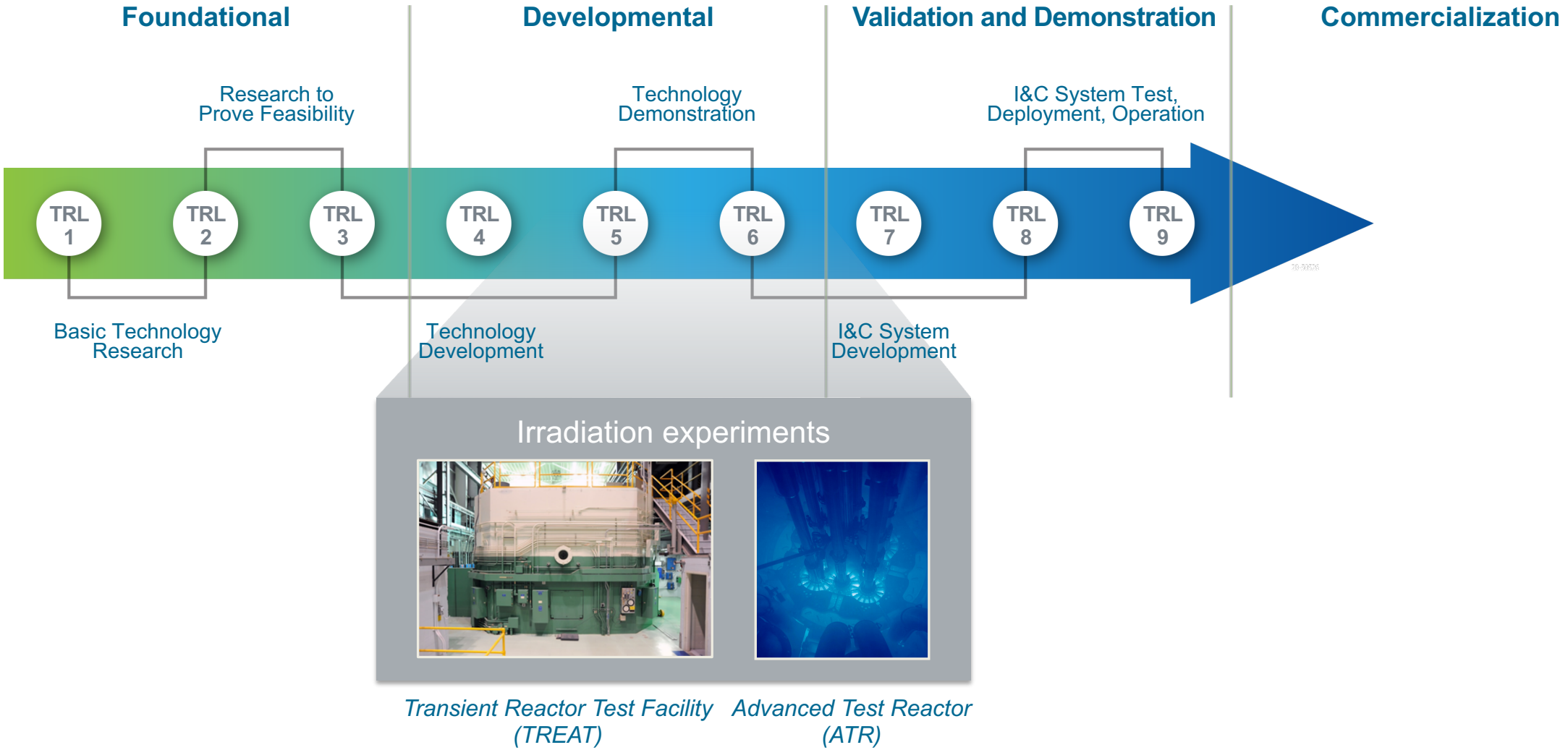
Advanced Control Systems

Enable semi-autonomous operation by developing performance-based control algorithms to improve plant economics

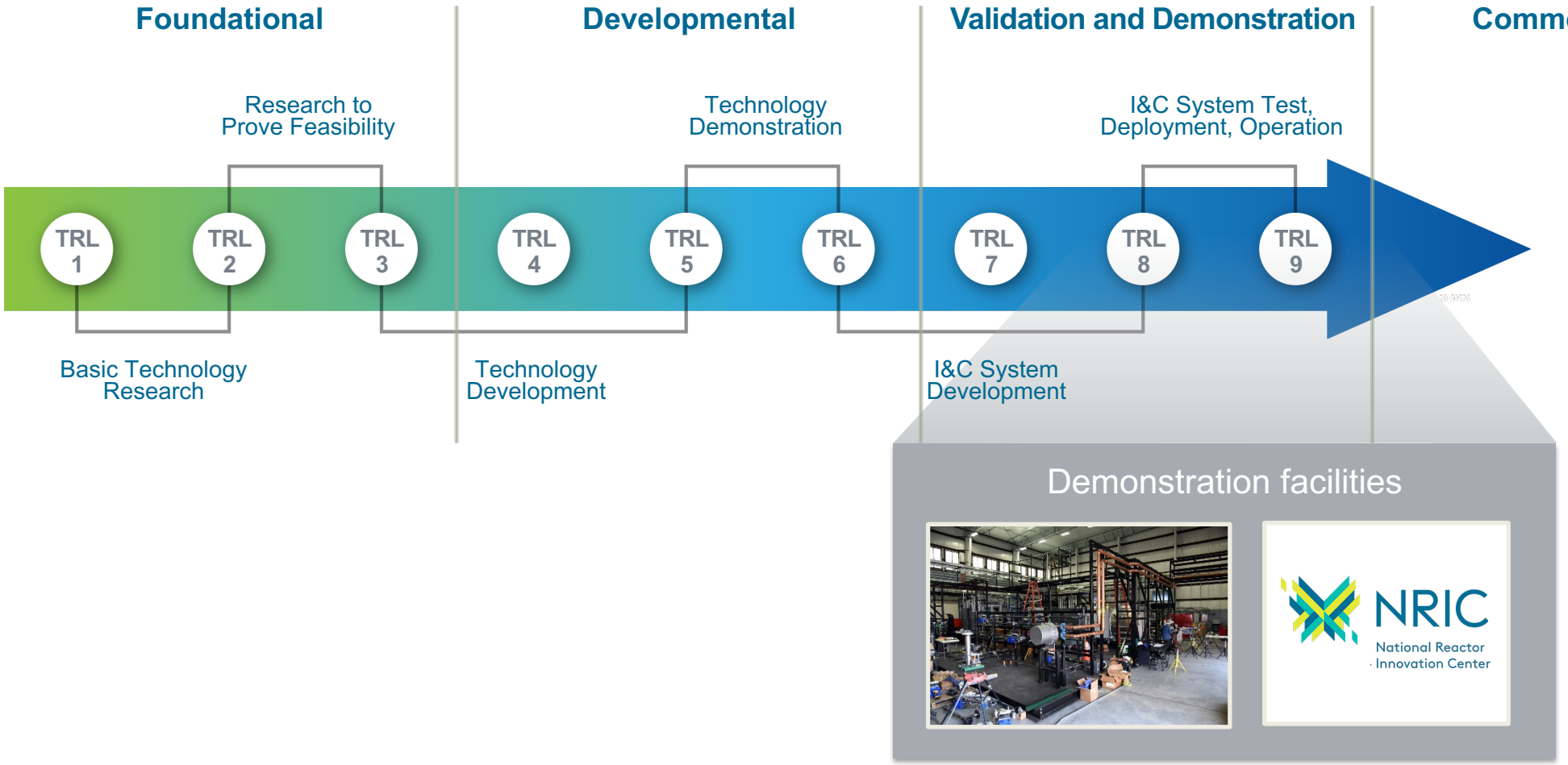
Fault-tolerant control system operation for the case of digital implementation

Optimal control for dispatch and unit commitment of nuclear systems with multiple products, load following and energy storage

Irradiation Experiments for Sensors Technology Demonstration



Demonstration Facilities for I&C System Validation



Microreactor Agile Non-Nuclear Testbed (MAGNET)

Stakeholders

Participating National Laboratories

- Idaho National Laboratory (Lead Laboratory)
- Argonne National Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

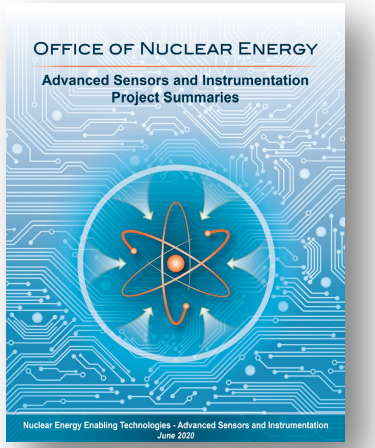
THE OHIO STATE UNIVERSITY
BOISE STATE UNIVERSITY
University of Pittsburgh
UNIVERSITY OF MICHIGAN

Outreach

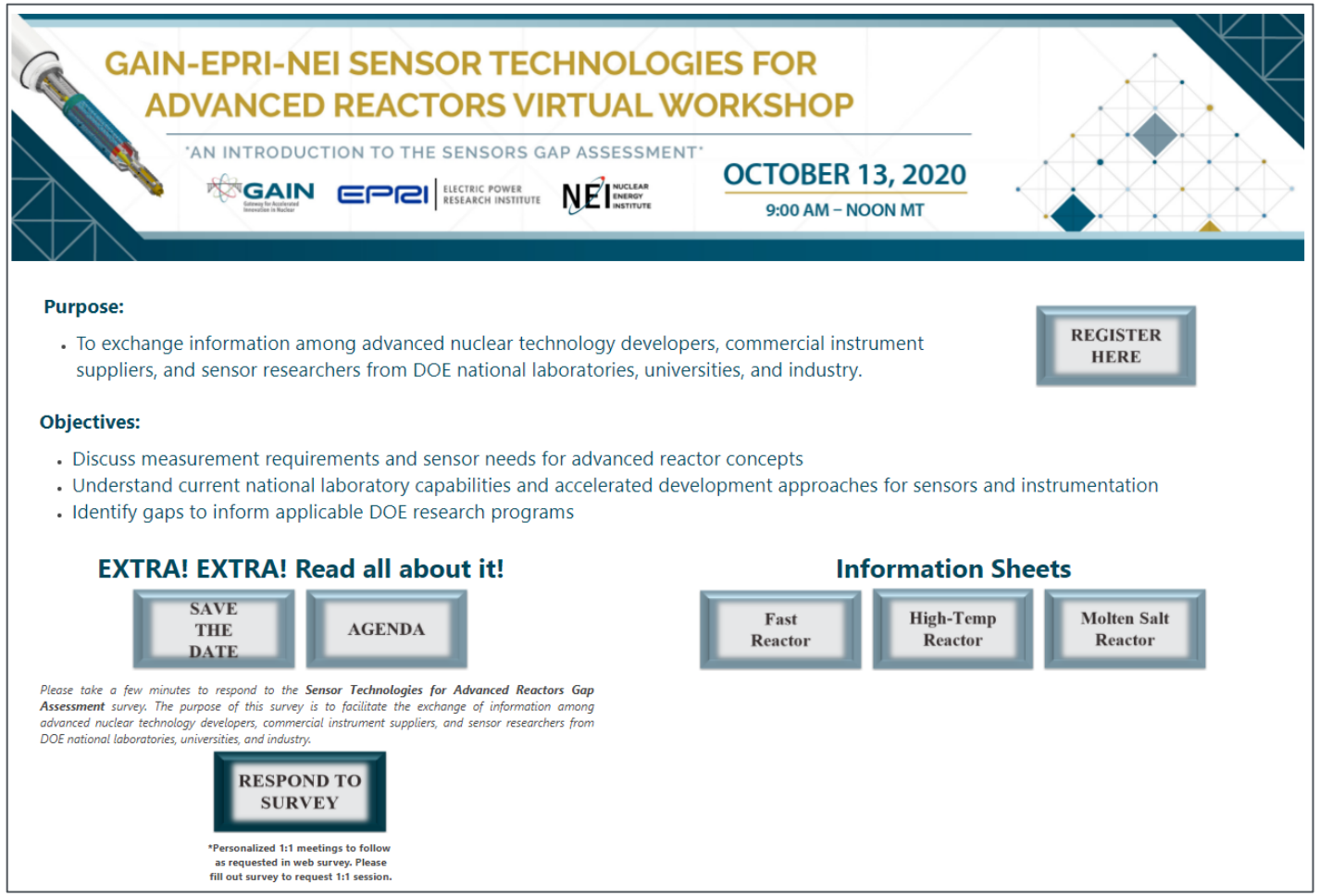
Resources:

- **ASI newsletter – twice a year:**
  - Reporting status, completed projects with focus on people and broader communication
  - Issue 12-13 (March, September 2020)

- **Yearly summaries of research projects:**
  - Comprehensive list of scope and planned activities
  - FY20 edition (June 2020)

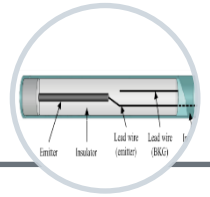


GAIN-EPRI-NEI virtual workshop and gap assessment



https://inlhrfedramp.gov1.qualtrics.com/jfe/form/SV_2aTJi2SHJFC8UKN

Directed Research 1/3

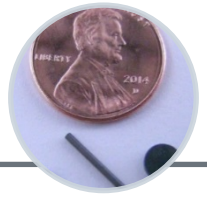


- Neutron and gamma detection
- Fast (Hf, Gd) and slow (Rd, Vd) response
- Established design and fabrication process at INL
- Performance demonstration in TREAT, AGR5/6/7 and ATRC

Self Power Detectors

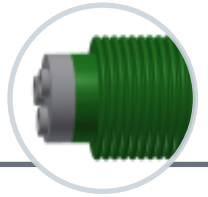
- Mo-Nb junction for high temperature applications (1600 C) and low drift under neutron irradiation
- Performance demonstration in AGR5/6/7 – highest temperature ever recorded in pile without drift (1482 C)
- Design optimization: corrosive environments, multi-point detection
- Commercialization: TCF with Idaho Labs Corp, ASTM standard and industrial qualification at AMS

High Temperature Irradiation Resistant (HTIR) thermocouple



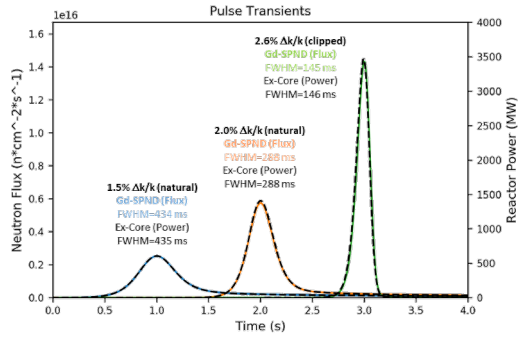
- Passive monitors are needed when real-time sensors are not practical or economical to install
- Specialized peak temperature and neutron fluence monitors and related analysis techniques for Post Irradiation Examination (PIE)
- Development focus on reliability and compatibility with standard material samples sizes (ie, 3 mm disc)

Passive temperature and flux monitors

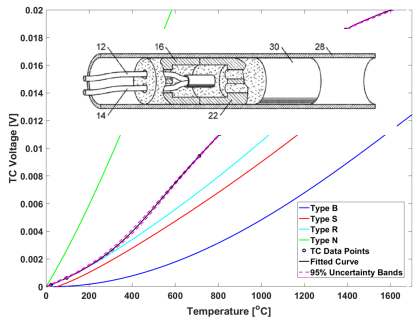


- Demonstrated performance under irradiation to measure pressure and elongation
- Contract in place with IFE (Halden) for the supply of multiple LVDT types
- Calibration and design integration for deployment in stakeholders' projects
- Development and modeling activities to establish manufacturing capability

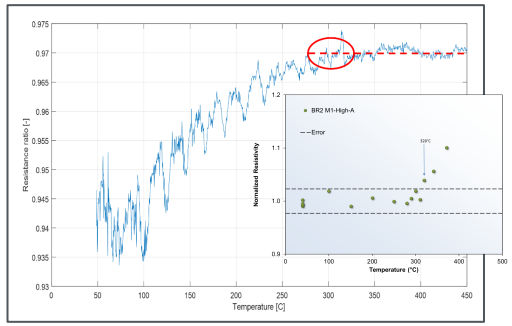
Linear Variable Differential Transformer (LVDT)



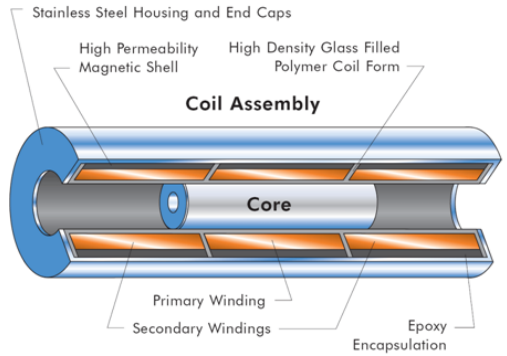
TREAT pulse transient with Gd- and Hf-SPNDs compared to an ex-core detector.



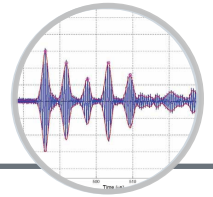
HTIR response compared with standard types



Continuous reading of SiC monitors in PIE after BR2 irradiation

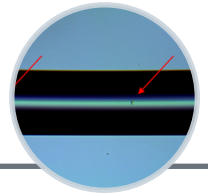


Directed Research 2/3



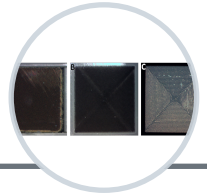
- Ultrasound based sensors enable distributed temperature measurements up to 2200ºC
- INL had demonstrated the reliability of magnetostrictive material transducers under irradiation
- Current research focuses on waveguide design optimization and unfolding signal response of distributed measurements

Ultrasonic Thermometers



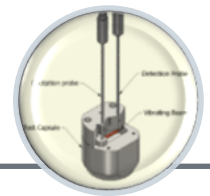
- Advanced sensor configuration and interrogation techniques to measure:
  - Distributed temperature, strain and vibration
  - Fission gas pressure and composition
- Engineering solutions for sensor packaging, pressure feeds
- Active compensation techniques for OF sensors operating in radiation environments

Optical Fibers



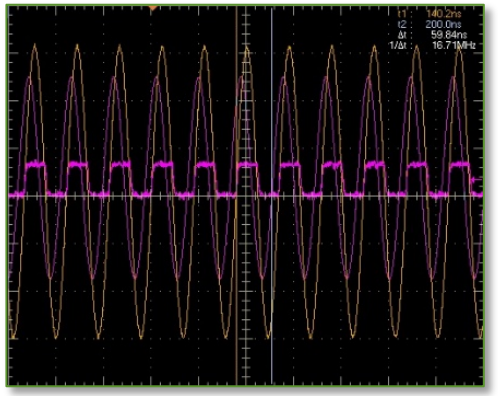
- Additive-manufacturing techniques (aerosol-jet printing, ink-jet printing and micro-dispense printing) for the fabrication of miniature sensors (ink development, process control)
- Cost-efficient, mechanically robust and with reliable performance
- Sensor types: melt wire arrays, dosimeters and strain gauges

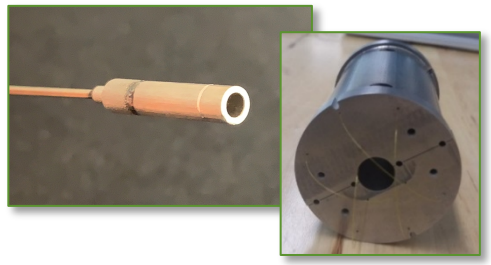
Advanced Manufactured Sensors



- Real time monitoring of microstructure during irradiation enables study of material behavior that can't be captured in PIE
- RUSL (Resonant Ultrasound Spectroscopy – Laser) uses an optical fiber based technique to measure elastic properties
- Thermal conductivity probes, Photo-Thermal Radiometry

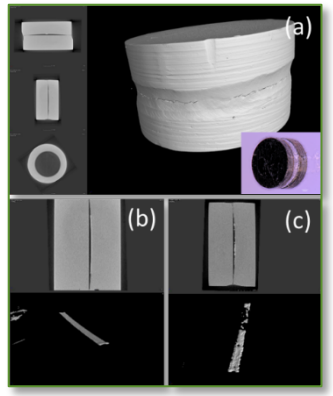
Materials and Fuels Codes V&V

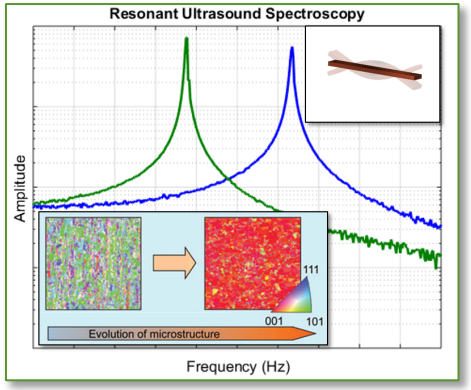




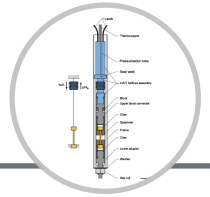
Prototype optical fiber pressure sensor based on Fabry-Perot interferometry

OFDR technology for temperature mapping of TREAT heat sink





Directed Research 3/3



- Develop instruments to (1) measure mechanical properties of nuclear fuels and materials and (2) characterize the mechanical response of nuclear plant components in operation.
- Creep test rigs based on LVDT technology have been fabricated and tested out of pile in static autoclaves.
- Measurement systems for the characterization of Irradiation Induced Degradation (ie, crack growth)

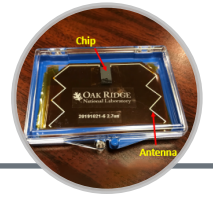
Structural materials characterization

- The capability of instrumenting irradiated fuel rods is the key factor to enable real time measurement during irradiation test in high flux MTRs
- The ASI program has developed specifications and procured a set or prototype equipment modules designed to “refabricate” previously irradiated commercial nuclear fuel into shorter lengths with integral instrumentation embedded

Fuel Re-instrumentation Facility

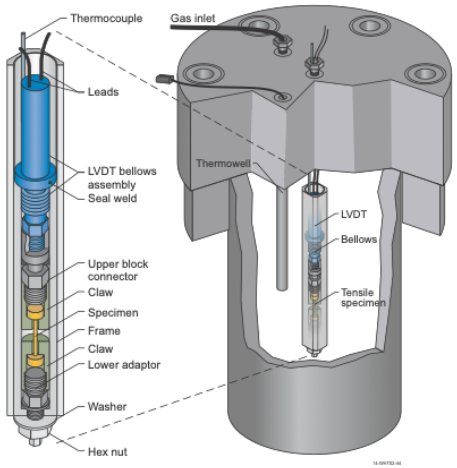
- Completed technology assessment and research plan for the development of a passive monitoring and wireless communication architecture for nuclear systems inside the containment structure
- Sensing is based on power harvesting RFID technology
- Ongoing research on acoustic transmission should be leveraged for communication

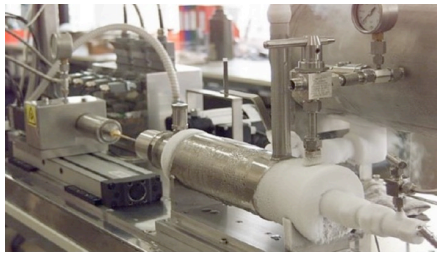
Wireless Sensing and Communication Capabilities



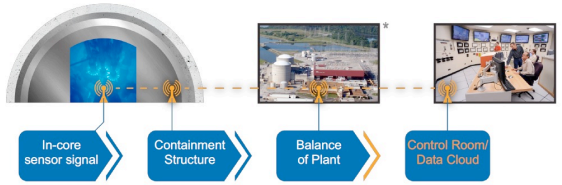
Passive wireless sensor technology (PWST) deploys a network of comprised of digitally printed radio frequency (RF) surface acoustic wave (SAW) devices that act as a platform for a multitude of sensing modalities. Sensor types include temperature, hydrogen gas, voltage, and current. The RF/SAW sensor platform is fabricated by state-of-the-art additive manufacturing (AM) technologies.

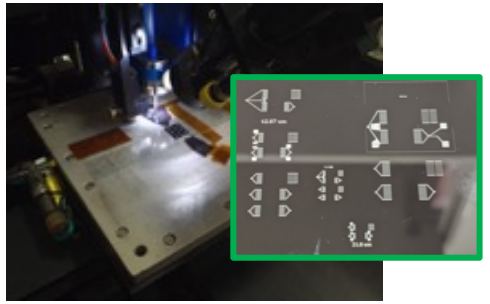
Direct Digital Printing of Passive Wireless Sensors





An irradiated fuel rod is drilled in preparation for installation of a thermocouple. The fuel is frozen cryogenically to stabilize it during the drilling process.





Printed SAWs developed and fabricated at ORNL

NEET ASI awards

3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures

This project develops an automated technology coupled with advanced data analytics for assessing the health of pipes in nuclear power plants as the pipe material degrades due to corrosion that grows from the inside out. The interdisciplinary technology combines innovations in materials for sensing both chemical and mechanical degradation with statistical algorithms based on Bayesian modeling.

D. Adams, K. Jennings, S. Mahadevan, Vanderbilt University
Y. Zhang, University of Notre Dame
V. Agarwal, Idaho National Laboratory

Material removal on inside of elbow in yellow

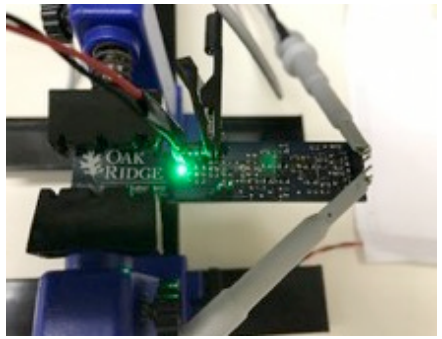
Thermocouples installed on outside diameter of a pipe elbow

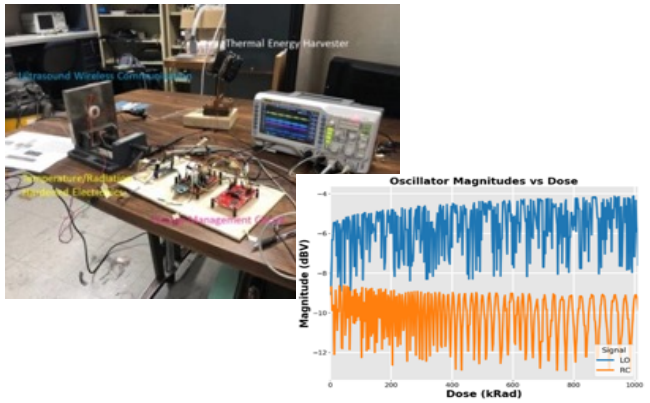
Pipe elbow with thermocouples installed on pipe diameter and locations for thermocouples along the length in red

Self-Powered Wireless Through-wall Data Communication for Nuclear Environments

The objective of this project is to develop novel energy harvesting and wireless through-wall data communications technology for in-situ monitoring of interior conditions in enclosed metal vessels or thick concrete walls as found in dry storage canisters and nuclear reactor vessels. This objective is achieved through three innovations: direct harvesting of electrical energy from gamma irradiation heating using thermoelectric devices; transmission of data through metal wall using ultrasound; creative design and packing of high-temperature electronics circuits with radiation hardening and/or shielding.

L. Zuo, Virginia Tech
H. Zhang, University of North Texas
N. Ericson, Oak Ridge National Laboratory



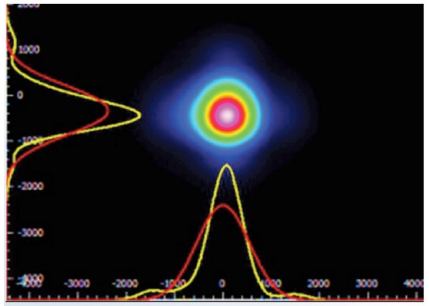


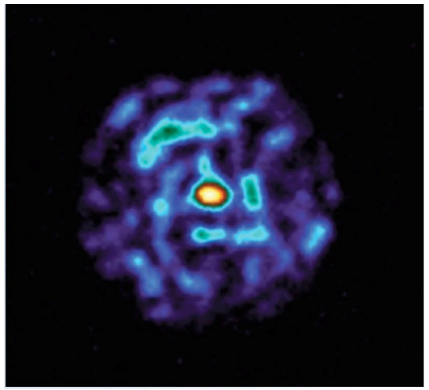
Small Business Innovation Research and Technology Commercialization Funds

Sapphire Single-Mode Fiber Development Towards High-temperature Radiation Resilient Sensors

Phase 1 results: characterized the SMSF index profile and modal structure and demonstrated independently fs-laser inscribed fiber Bragg grating (FBG) distributed sensor performance to 1300°C and to 5E17 n/cm2 fluence at the OSU Research Reactor

Luna Innovations, Inc.



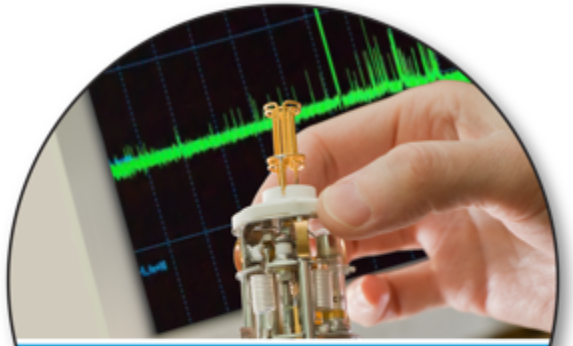


High Temperature Operable, Harsh Environment Tolerant Flow Sensors for Nuclear Reactor Applications

Phase 2 demonstrated high temperature (500 – 800 C), high pressure (2000 psi) capability in PWR environment of thermal anemometry sensor with integrated electronics - digital communications, internal compensation (temperature), internal calibration and sensor self-identification.

Sporian Microsystems, Inc.

Strategic ASI R&D Areas



Sensors and Instrumentation

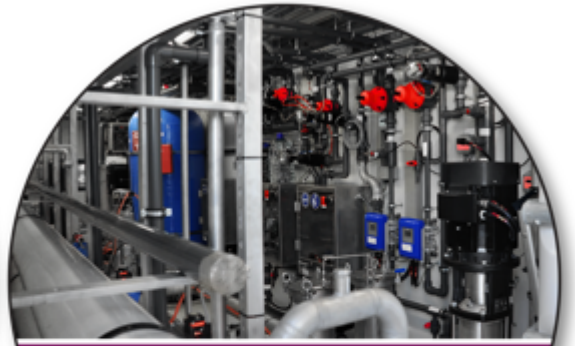
Reliable, cost-effective, real-time, accurate, and high-resolution measurement of the performance of existing and advanced reactors core and plant systems

Communication

Resilient, real-time transmission of sufficient amount of data for online monitoring and advanced data analytics

Big Data, Machine Learning, Artificial Intelligence

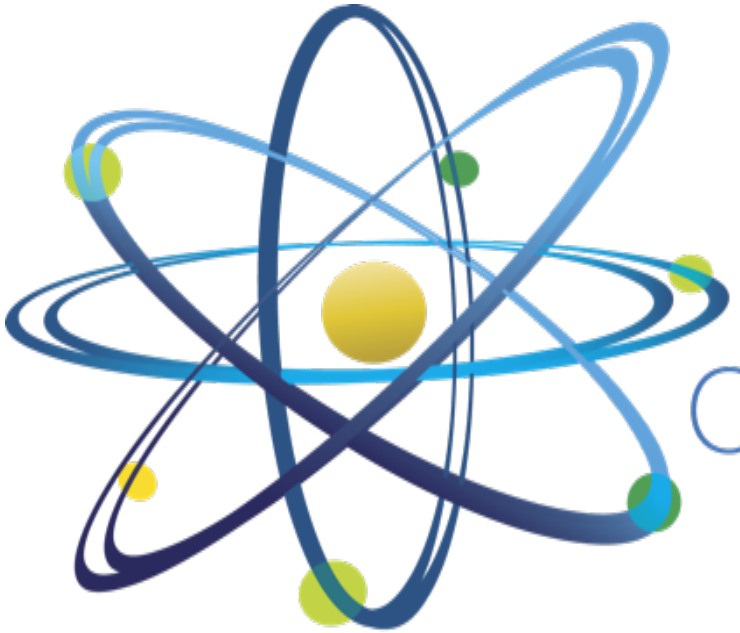
Machine learning and artificial intelligence processes to enable semi-autonomous operation and maintenance by design



Advanced Control Systems

Enable near real-time control of plant or experiments process variables to enhance performance

Thank You!



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