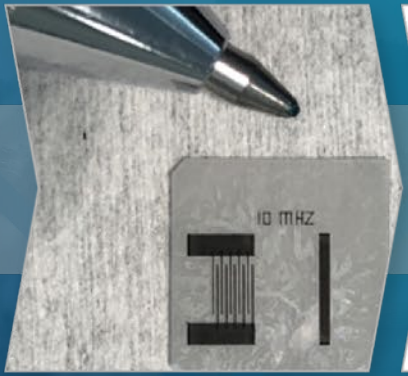
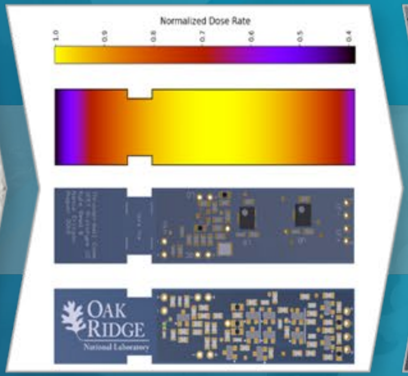
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Advanced Sensor & Instrumentation Program Roadmap





OVERVIEW: PROGRAM HISTORY

Since 1958, the United States of America has provided safe, clean, and reliable energy using nuclear reactors, with a total operating experience, as of 2020, of approximately 4,600 years [1]. Currently, the U.S. operates 93 reactors with a combined electrical output of 95,523 MW_e, supplying about 23.2% of domestic electricity generated in 2020 [2]. The development of advanced instrumentation and control (I&C) technologies is a key component of maintaining safe, efficient and reliable nuclear power.

In 2011, the Department of Energy's Office of Nuclear Energy (DOE-NE) initiated the Nuclear Energy Enabling Technologies (NEET) program to conduct research, development, and demonstration (RD&D) to support existing and next generation advanced reactor designs, and fuel-cycle technologies. Crosscutting Technology Development (CTD) is a subprogram of NEET, comprising four programs: Advanced Sensors and Instrumentation (ASI), Advanced Materials and Manufacturing Technologies (AMMT), Cybersecurity, and Integrated Energy Systems (IES). The CTD subprogram is intended to support crosscutting RD&D activities to advance the state of nuclear technology, improve its competitiveness, and promote continued contribution to meet the Nation's energy and environmental challenges.

[1] IAEA's *Power Reactor Information System* (PRIS), International Atomic Energy Agency, www.iaea.org/pris, November 2021.

[2] LLNL's *Energy Flow Charts,* Lawrence Livermore National Laboratory, flowcharts.llnl.gov/commodities/energy, March 2021.

MISSION / VISION

Department of Energy (DOE) Mission:

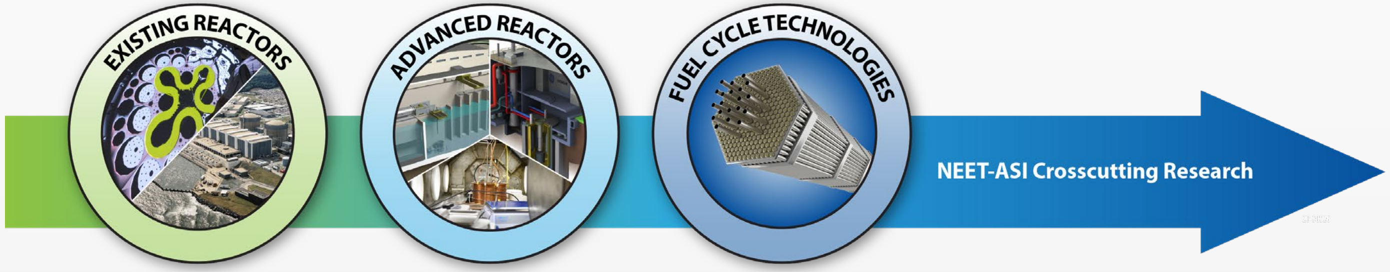
“Ensure America’s security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.”

Office of Nuclear Energy (DOE-NE) Mission:

“Advance nuclear energy science and technology to meet U.S. energy, environmental, and economic needs.”

Five goals DOE-NE has identified to address challenges in the nuclear energy sector, help realize the potential of advanced technology, and leverage the unique role of the government in spurring innovation:

- Enable continued operation of existing U.S. nuclear reactors
- Enable deployment of advanced nuclear reactors
- Develop advanced nuclear fuel cycles
- Maintain U.S. leadership in nuclear energy technology
- Enable a high-performing organization



Advanced Sensors and Instrumentation (ASI) Program Mission:

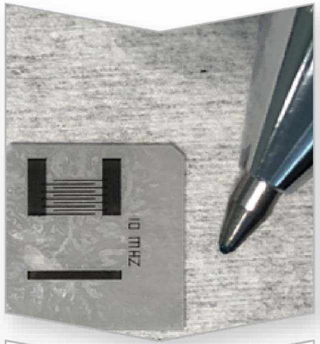
“Develop advanced sensors and instrumentation and controls (I&C) that address critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development.”

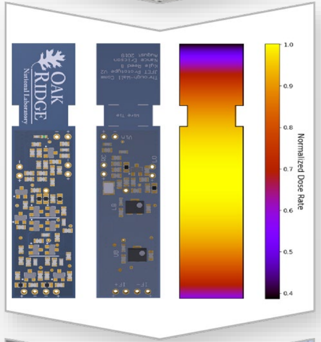
Advanced Sensors and Instrumentation (ASI) Program Vision:

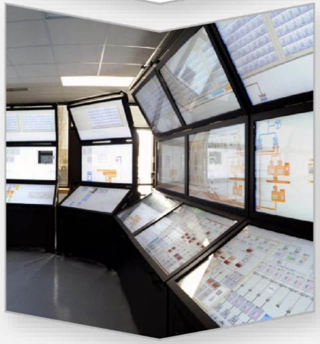
“Program research will result in advanced sensors and I&C technologies that are ultimately qualified, validated, and ready to be adapted by the nuclear industry.”

The ASI program focuses on innovative research that directly supports and enables the sustainability of the current nuclear fleet, the development and deployment of next generation reactor designs, and advanced fuel-cycle technologies.

I&C DEFINITION







The ASI program focuses on the development of *advanced sensors, instrumentation and controls*, and it is necessary to define what each term means and how they interact.

- **Sensor** – a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, radiation, or motion) and transmits a resulting impulse that can be translated into a measurement for recording or acting upon once integrated in a measuring device.
- **Instrument** – a measuring device for determining the present value of a quantity under observation. It integrates a sensor with a suitable monitoring system (analog or digital) and hardware components (for example connector, feedthrough, protective packaging) necessary to reliably fulfill its function. Instruments connect to Data Acquisition Systems (DAS) for data recording and control systems for the operation of actuators.
- **Controls** – the science and engineering of methods and tools that initiate actions to actuators through measurements captured by analog and digital instruments.

STAKEHOLDER ENGAGEMENT

As a Crosscutting Technology Development (CTD) program, the Advanced Sensors and Instrumentation (ASI) program stakeholders encompass the broad range of Department of Energy (DOE), Office of Nuclear Energy's interests: the existing fleet, developers of advanced reactors and fuel developers.

- The adoption of advanced I&C technologies in the existing fleet is constrained by economic and regulatory aspects and addressed primarily by the Light Water Reactor Sustainability (LWRS) program in terms of Plant Modernization
- An important component of ASI mission is instrumenting irradiation experiment for fuels and materials qualification, such as Accident Tolerant Fuels, to accelerate the development process – stakeholders engagement in this space is already active through other NE programs, such as the Advanced Fuel Campaign

The focus of ASI engagement is directed primarily to **developers of advanced reactors**

- As follow up to the GAIN/EPRI/NEI Sensor Technologies for Advanced Reactors Virtual Workshop (October 2020), ASI held a first round of one-to-one meetings to inform the program on stakeholders' priorities for I&C development (FY21 gap assessment). The following companies participated in this first assessment: Oklo, Terrapower, Westinghouse, Framatome, Flibe Energy, Radiant, NuScale, BWXT.
- Continued engagement with periodic updates has proven beneficial, adding Kairos, Terrestrial Energy and Copenhagen Atomics to the list of expanding contacts with active communication exchanges. Creating a formal Industry Advisory Board is being considered.

ASI actively engages with research and government organizations with interest in I&C technologies for advanced reactors

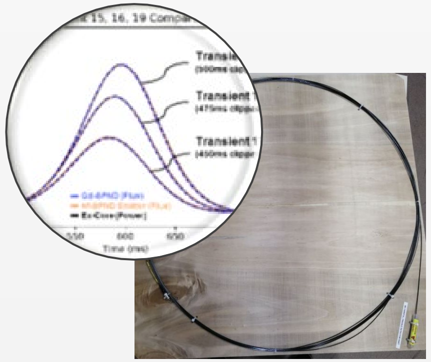
- EPRI and NRC are primary contacts, other organizations include NIST and University-based initiatives
- Engagement with international research organizations is established as part of existing collaborative agreements (CEA France, IFE Norway, SCK Belgium, JAEA Japan, KAIST/KAERI South Korea)

LEGACY ACHIEVEMENTS

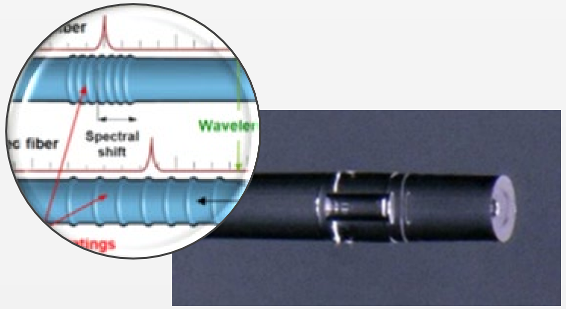
Over the course of the last 11 years, the ASI program has fostered the development and commercialization of a wide range of technologies spanning the inception of novel sensing methods and the enhancement of instrumentation with a long history of commercial utilization. The program has funded over $58 million in RD&D which supports the US Department of Energy and the US DOE Office of Nuclear Energy missions. Sensors developed under the ASI program have been used to support other DOE-NE programs and have been commercialized for nuclear industry adoption.

Ultrasound thermometer commercialization

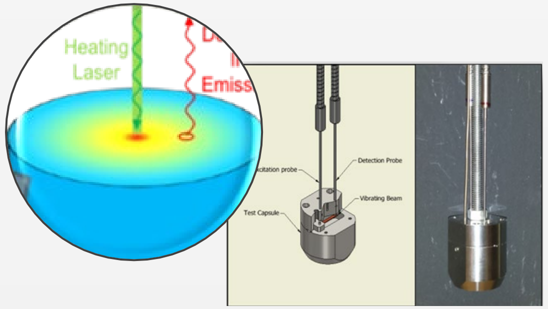
High Temperature Irradiation Resistant (HTIR) thermocouples



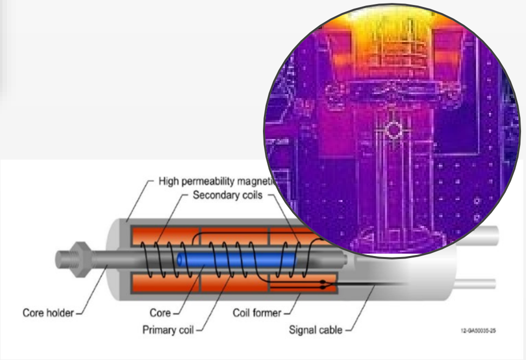
Self Powered Detectors and miniaturized Fission Chambers for local neutron flux measurement



Fiber optic sensors for nuclear applications



Real time measurement of fuel material properties in-core

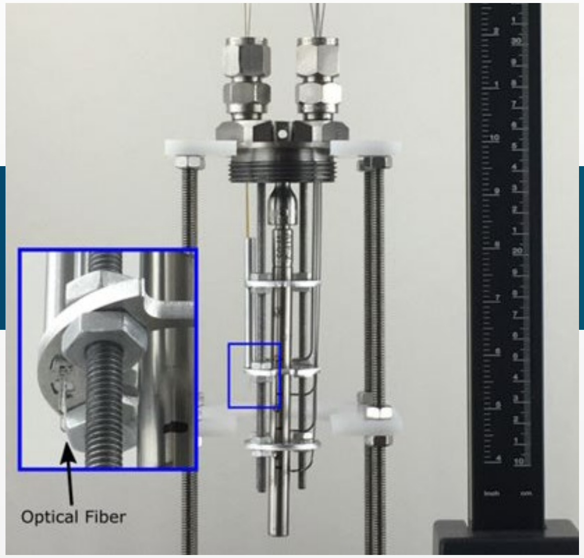


Linear Variable Differential Transformer (LVDT) for fission gas pressure measurement

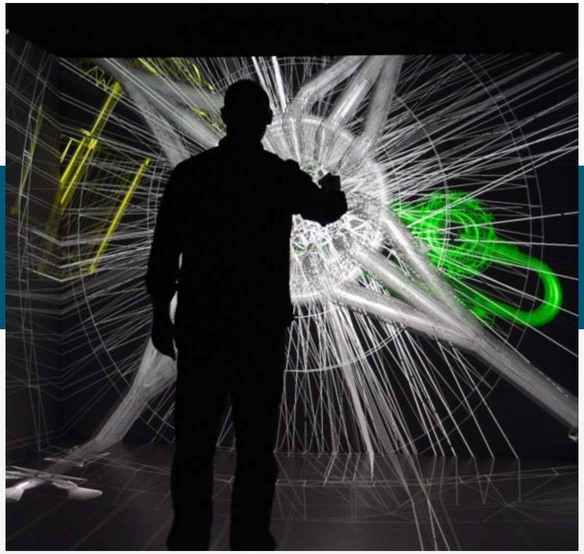
APPLICATIONS: IDENTIFICATION OF TECHNOLOGY GAPS

The ASI program activities have been structured based on three types of applications:

Sensors for Advanced Reactors

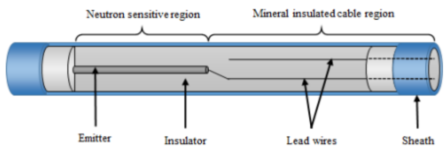


Sensors for Irradiation Experiments

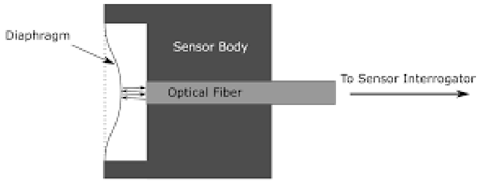


Sensors Integration

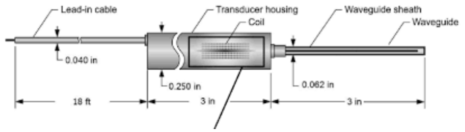
SENSORS FOR ADVANCED REACTORS



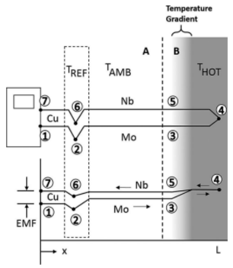
FLUX SENSORS



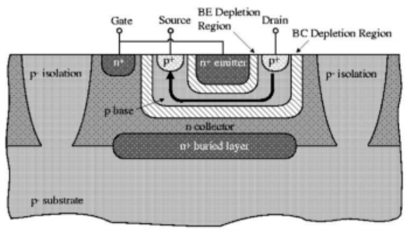
OPTICAL FIBERS



ACOUSTIC SENSORS



THERMOCOUPLES



RAD-HARD ELECTRONICS

Sensors and instrumentation for advanced reactors focuses the research, development, deployment and commercialization activities to mature specialized sensors and instrumentation that address critical technology gaps for monitoring and controlling advanced reactors. Demonstration facilities are leveraged to evaluate readiness levels and enable stakeholders to adopt technology with minimal risk. Areas of interest are grouped based on the crosscutting resources unique in each category. These categories are flux sensors, optical fiber-based sensors, acoustic based sensors, thermocouples and radiation hardened electronics.

The following sections introduces the technological attributes of interest to the advanced reactor community including a summary of recognized technology gaps. These sections link to proposed R&D activities that will address these gaps and provide a roadmap to their implementation so that availability and impact may be clearly communicated to stakeholders.

SENSORS FOR ADVANCED REACTORS: FLUX SENSORS

MEASUREMENTS	ATTRIBUTES	TECHNOLOGY GAPS
Thermal Neutron Flux (in-core)	• Response time: Delayed/Prompt • Sizes (diameter): 0.062" to +3"	• Higher temperature compatibility • Long-duration testing • Multipoint measurements
Fast Neutron Flux (in-core)	• Neutron Energy Range: 1- 20 MeV • Response time: Delayed/Prompt • Sizes (diameter): 0.062” to +3"	• Higher temperature compatibility • Long-duration testing • Multipoint measurements
Gamma Flux (in-core)	• Gamma sensitive • Sizes (diameter): 0.062" to +3"	• Multipoint measurements • Demonstration in conditions relevant to advanced reactors
Radiation detectors (power monitors)	• Response: Source range to Full Power • Ex-core only • Sizes (diameter): +3" • Scalable to reactor power	• Miniature size • Customizability for first of a kind advanced reactor startup and qualification

SENSORS FOR ADVANCED REACTORS: OPTICAL FIBERS

OPTICAL FIBER BASED MEASUREMENTS	ATTRIBUTES	TECHNOLOGY GAPS
Temperature	• Temperature Range: Application dependent, but generally <1000°C • High sensitivity, rapid response • Immune to electro-magnetic interference • Small diameter, < 1 mm • Multipoint/distributed measurement capability • Potential for embedment in structures • Multi-parameter sensing	• Reliable, low-drift sensor performance under high temperature and radiation conditions • Challenges with rugged packaging compatible with harsh in-core environments • Long-duration validations of active compensation models • Benchmarking of commercially available sensor performance for nuclear applications
Pressure		• High temperature/radiation survivability • Long-duration performance
Strain		• High temperature/radiation survivability • Attachment procedures compatible with harsh environment • Long-duration performance
Imaging (in-core)		• High temperature/radiation survivability • In-core applicability of advanced imaging techniques • Miniaturization of compatible lens system

SENSORS FOR ADVANCED REACTORS: ACOUSTIC SENSORS

MEASUREMENTS	ATTRIBUTES	TECHNOLOGY GAPS
Temperature	• Temperature Range: 0-3000°C • Sizes (diameter): 0.01" to 0.062" • High radiation tolerance • Non-intrusive/non-destructive • Materials selectable for environment	• Calibration methodology • Deployment in prototypic conditions • Commercialization/availability
Pressure	• Temperature Range: 0-500°C • Non-intrusive/non-destructive	• Incorporation of radiation resistant transducer materials • Calibration/temperature compensation strategy
Flow	• Temperature Range: 0-500°C • Non-intrusive/non-destructive	• Incorporation of radiation resistant transducer materials • Calibration/temperature compensation strategy
Level	• Temperature Range: 0-700°C • Level Range: 10's of meters • Many methods/technologies available	• Demonstration in prototypic conditions • Calibration methodology for new advanced reactor structures • Nuclearization of commercial technologies
Acoustic Emission/Vibration	• Temperature Range: 0-500°C • Non-intrusive • Passive measurement	• Demonstration in prototypic conditions • Calibration methodology for advanced reactor structures • Nuclearization of commercial technologies
Fluid Properties (Density, Viscosity, etc.)	• Temperature Range: 0-500°C	• Demonstration in prototypic conditions • Calibration methodology for new advanced reactor materials • Nuclearization of commercial technologies

SENSORS FOR ADVANCED REACTORS: THERMOCOUPLES

MEASUREMENTS	ATTRIBUTES	TECHNOLOGY GAPS
Temperature	• Temperature Range: 0-1200°C • Sizes (diameter): 0.0625" to 0.125" • Relatively low absorption cross section (low drift) • Fast response	• High temperature/high radiation predictive drift model • On-line calibration methodology • High accuracy general use calibration
Surface temperature	• Temperature Range: 0-1600°C • Sizes (diameter): 0.010" to 0.040" • Fast response	• Standardized attachment procedures • Accuracy of transient response • Performance validation
Internal temperature (e.g., fuel pellet)	• Temperature Range: 0-1600°C • Sizes (diameter): 0.040" to 0.125“ • Relatively low absorption cross section (low drift)	• Standardized installation procedures • Performance validation

SENSORS FOR ADVANCED REACTORS: RAD-HARD ELECTRONICS

ELECTRONICS	ATTRIBUTES	TECHNOLOGY GAPS
Passive Devices	• Capacitance-based technique • Cables and interconnects • Inductors and printed circuit boards	• High temperature/radiation survivability • Long-duration testing in prototypic conditions
Discrete Active Devices	• Diodes, LEDs, Photodiodes • Transistors (BJT, MOSFET, JFET) • Wide bandgap devices • Vacuum Devices	• High temperature/radiation survivability • Long-duration testing in prototypic conditions
Integrated Circuits (IC)	• Voltage regulators and power devices • Operational amplifiers • Analog and digital converters • Digital and mixed signals IC • Data-links and communication interfaces	• High temperature/radiation survivability • Long-duration testing in prototypic conditions
Systems	• Imaging Systems (cameras, spectrometers) • Power conversion and power harvesting systems • Communications and controls • Robots and remote operations	• High temperature/radiation survivability • Systems evaluations for deployment in advanced reactors systems

LED = Light-Emitting Diode

BJT = Bipolar Junction Transistor

MOSFET = Metal-Oxide-Semiconductor Field-effect Transistor

JFET = Junction-Gate Field-effect Transistor

SENSORS FOR IRRADIATION EXPERIMENTS

Sensors are required for irradiation experiments to collect data for scientific, engineering and controls purposes. The performance of these sensors often determines the success or failure of the experiment. A wide variety of sensors and sensor technologies are used in irradiation experiments, spanning the entire range of the technology readiness level (TRL) scale. Irradiation tests are also used as a platform to mature sensor technology, hence there is some overlap in the type of instruments used for the two application areas. In this document **sensors for irradiation experiments refers solely to those specifically intended for irradiation experiments**, with minimal or no potential use for reactor deployment. Irradiation experiments can be generally classified into 3 categories with different stakeholders:

- **Nuclear Fuel and Materials Qualification:** irradiation experiments designed to test the limits of nuclear fuel and cladding performance under design and off-design conditions. Most of these experiments are working toward the qualification of new fuel designs for the operating fleet (such as Accident Tolerant Fuel) and advanced reactors (such as TRISO). Primary stakeholders include advanced reactor companies, Advanced Fuel Campaign (AFC);

- **Nuclear Materials Properties and Behavior testing:** testing material properties and behavior under neutron irradiation, including advanced fuel materials and structural materials. The inclusion of instrumentation capable of providing real time measurement during irradiation can significantly accelerate the development process and reduce R&D costs. This area has significant scope synergy with material science research (ie, the Office of Basics Energy Sciences Center for Thermal Energy Transport under Irradiation) and modeling and simulation efforts(ie, NEAMS program);

- **Nuclear Component or Subsystem Testing:** The performance and reliability of nuclear components and subsystems are commonly evaluated in test reactors. These include subsets of reactor core components, heat removal systems, and loops. Stakeholders include advanced reactor companies, the Advanced Reactor Technology program and NASA nuclear programs such as Nuclear Thermal Propulsion and Fission Surface Power.

SENSORS FOR IRRADIATION EXPERIMENTS: LINEAR VARIABLE DIFFERENTIAL TRANSFORMERS (LVDT)

Linear Variable Differential Transformers (LVDT) are commonly used in many industrial applications for accurate measurements of displacement. In irradiation experiments LVDTs are utilized to measure several different properties by converting the measurand to displacement. Examples include measuring pressure through displacement of a bellows, or temperature through displacement of a component with well characterized thermal expansion. The Institute for Energy Technology (IFE) in Halden, Norway has been a reliable supplier of high temperature, radiation resistant LVDTs for irradiation experiments. However, the shutdown of the Institute material test reactor in 2019 threatens the availability of these component moving forward and an alternative supply chain should be established for Department of Energy activities. As a result, the ASI program is investigating domestically produced LVDTs to reinforce the supply chain.

ACTIVITIES	ATRIBUTES	TECHNOLOGY GAPS
Pressure Sensing (plenum pressure, thermohydraulic conditions, cladding burst)	• Customizable pressure range • Fast response time • Small footprint (<10mm) • No feed-through required	• Custom engineering required for each application • Supply chain uncertainty
Displacement (cladding elongation, fuel swelling, thermal expansion)	• High temperature • High accuracy	• Measurement uncertainty is introduced by the radiation damage and thermal effects on the fixturing/support structure • Supply chain uncertainty
Temperature (via thermal expansion)	• Sensitivity is customized by the material thermally expanding	• Lacking a standardized design for reliable implementation • Supply chain uncertainty

SENSORS FOR IRRADIATION EXPERIMENTS: PASSIVE MONITORS

Passive Monitors are ideal for irradiation experiments which do not require real-time data. The output of these sensors is determined during post irradiation examination (PIE). They can significantly reduce the cost of an experiment by eliminating the need for a data acquisition system and the design considerations required to get instrumentation leads out of the experiment and reactor vessel.

MEASUREMENT TECHNOLOGY	ATTRIBUTES	TECHNOLOGY GAP
Melt Wires	• Leadless • Small footprint • Measure irradiation temperature • Read out in PIE	• Traditional design is prohibitively large for many applications • Melt-wire materials are difficult to determine if melting has occurred leading to increased measurement uncertainties
Silicon Carbide Monitors	• Leadless • Small footprint • Measures irradiation temperature • Read out in PIE	• Readout techniques lack standardization, leading to uncertainty
Dosimetry	• Leadless • Small footprint • Measures neutron fluence • Read out in PIE	• Miniaturization and neutron energy characterization in integrated packages

SENSORS FOR IRRADIATION EXPERIMENTS: MATERIAL PROPERTIES CHARACTERIZATION

MEASUREMENT	ATTRIBUTES	TECHNOLOGY GAP
Creep Characterization (Predominately for structural or cladding materials)	• In-pile creep of nuclear materials • Capable of making accurate measurements in prototypic conditions	• Lacking in-pile qualification of system under prototypic conditions
Thermal Property Characterization	• Determination of thermal conductivity and diffusivity • Contact & non-contact techniques • Capability for solid fuel forms (oxide, metallic, TRISO, UN, UC, etc) • Capability for liquids, in particular fuel bearing salts	• Lack of demonstrated in-pile qualified techniques • High temperature and radiation environment can degrade measurement systems and increase uncertainty. • Currently lack the ability to perform high temperature in-pile thermal property measurements of liquids.
Strain Gauges	• Widely used in non-nuclear applications • Standard technique for measuring mechanical strain • Many secondary applications	• High temperature behavior is limiting • Radiation resistant attachments to nuclear relevant materials • Long term qualification under prototypic conditions is missing
Crack Growth Characterization	• Real-time measurement of crack propagation	• Previous work has demonstrated feasibility and promising results, but lack a fully qualified in-pile measurement system

TRISO = Tristructural Isotropic particle fuel

UN = Uranium Nitride

UC = Uranium Carbide

SENSORS INTEGRATION: INTEGRATING SENSORS IN ADVANCED INSTRUMENTATION AND CONTROL SYSTEMS

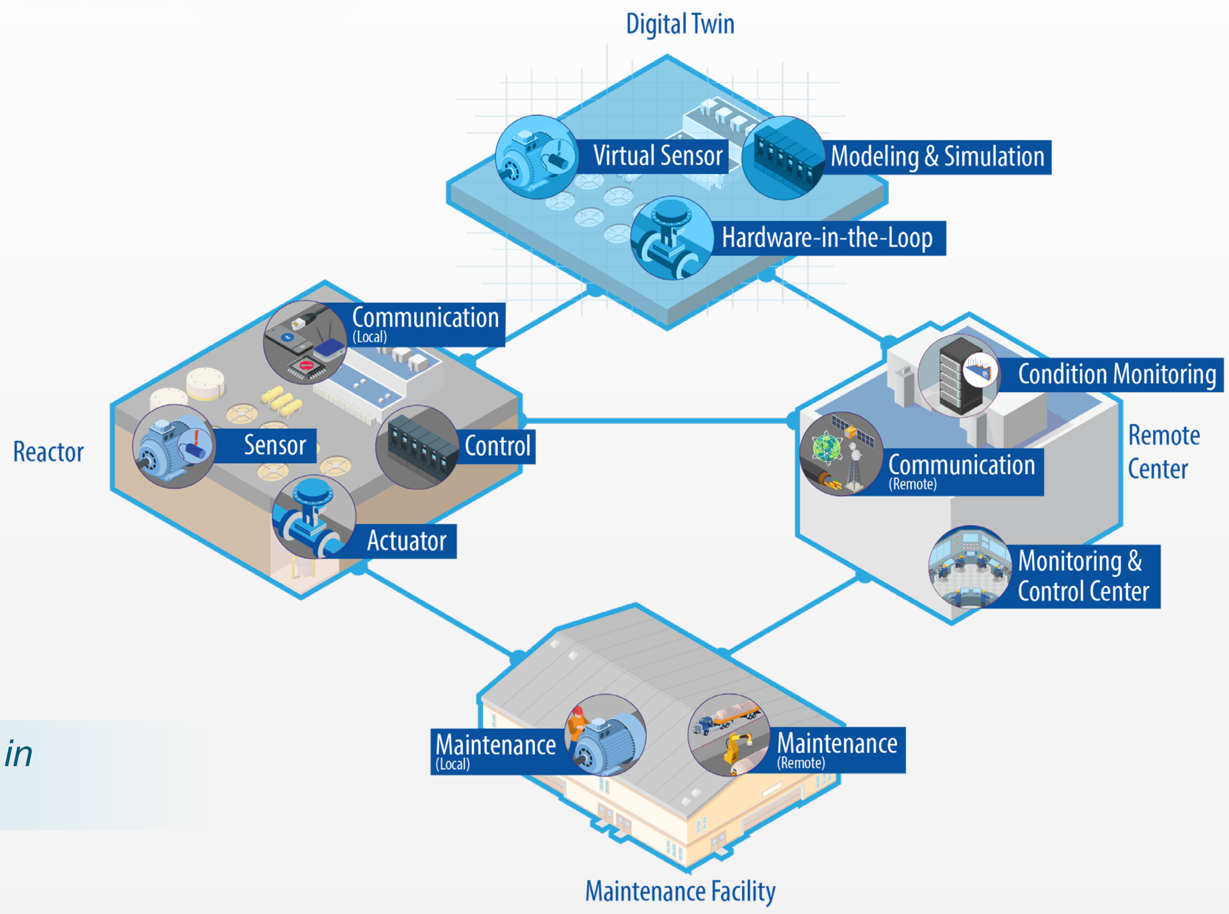
Digital Twins introduce significant opportunities in:

- Enhanced anomaly detection
- System state quantification and predictions
- Improved AI/ML assisted control systems performance

Communications enable seamless integration of new technologies, network architectures and security options

Advanced Controls support introduction of:

- Performance-based control algorithms
- Fault-tolerant controls for semi-autonomous plant operation
- Artificial Intelligence and Machine Learning assisted solutions that improve plant performance utilizing operating history and physics-based models



Identifying and leveraging the use of high-fidelity digital twins is crucial in developing new advanced controls

SENSORS INTEGRATION: DIGITAL TWIN

AREAS OF INTEREST	ATTRIBUTES	TECHNOLOGY / RESEARCH GAPS
Integrating models with algorithm	• Data sets and testbeds that are well-documented, integrated, and comparable • Scalable Artificial Intelligence (AI) and Machine Learning (ML) methods applied to data sets that are spatially and temporally heterogeneous and unstructured	• Develop the approach to integrate advanced control algorithms in nuclear digital twins • Development of infrastructure, including common information models, reference data sets with annotation, and testbeds, that may be used for validating and qualifying data analytic methods.
Scalable algorithms for anomaly detection	• Artificial Intelligence (AI) and Machine Learning (ML) technologies for anomaly detection, that operate on streaming data and are explainable	• Fundamental anomaly detection R&D for explainable algorithm development in scalable, assured AI/ML, including physics-informed ML.
System state quantification and prediction	• ML/AI technologies for prediction and decision making that quantify their uncertainty, are verified and validated, and identify the bounds of their expertise	• Methods to quantify the uncertainty associated with the algorithm output as well as methods for identifying meaningful latent variables that may be used to explain the results from the ML/AI algorithms • Develop risk-informed methods and uncertainty analyses to manage automation responses to plant conditions
Technologies for human-machine interaction	• Advanced human-machine interfaces to ensure transition from manual operation to autonomous operation workload is properly allocated and situational awareness is maintained	• Human factors studies are needed to understand the altered man-machine interface and to ensure workload is properly allocated • Evaluate altered role of the human responsible for operation of the advanced automation approach

SENSORS INTEGRATION: COMMUNICATION

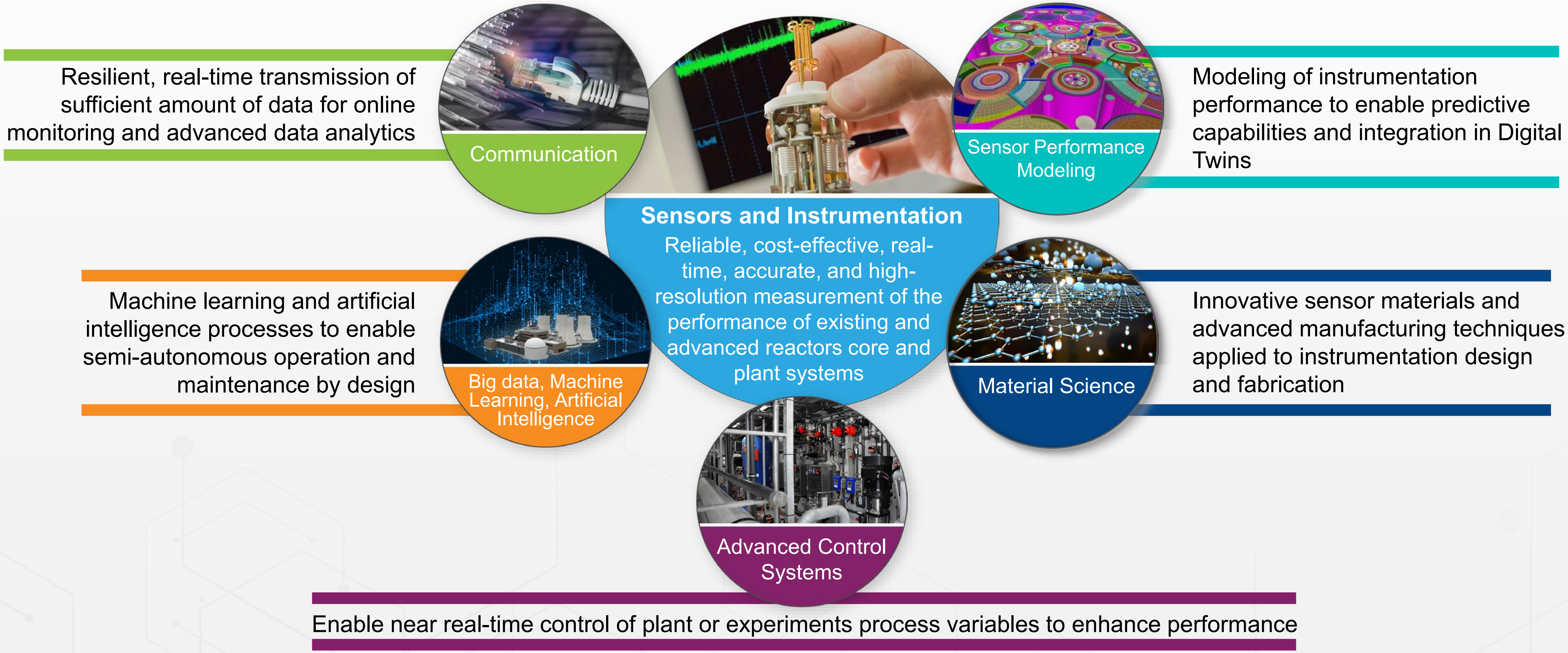
AREAS OF INTEREST	ATTRIBUTES	TECHNOLOGY GAPS
Wireless	• Develop multiband wireless communication technologies that support easy deployment and modification to meet growing needs of plant site, scalable to accommodate new technologies to enable seamless integration and co-existence, and customize network architecture and security options	• Communication requirements for advanced reactors based on design and operating conditions • Communication framework supporting multi-band frequency network architecture • Testbed to qualify and validate multiband network architecture
Wired	• Supports deployment of fiber optic-based communication for safety and non-safety related functions within nuclear facilities.	• Approach to minimize radiation-induced aging of optical fibers, • Fiber materials that have stable structural properties when exposed to high radiation and high temperature • Validation of fiber-optic-based communication for safety-related functions within nuclear facilities.
Passive	• Supports effective non-intrusive means of data communication from inside of the reactor to the outside of reactor	• Qualification of passive communication techniques that support the transmission of information through plant structures and components

SENSORS INTEGRATION: ADVANCED CONTROLS

AREAS OF INTEREST	ATTRIBUTES	TECHNOLOGY GAPS
High Performance Controls	• Performance-based control algorithms	• Safety analysis supporting the transition of actions from operators to automation • Validated high-performance control systems employing sophisticated model-based control algorithms
Artificial Intelligence (AI) / Machine Learning (ML) Assisted Controls	• Integrates advanced control algorithms and nuclear digital twins • Optimal control for dispatch and unit commitment	• Artificial intelligence methods for achieving semi-autonomous and autonomous operations • Economic optimization controls systems • AI/ML assisted solutions that improve plant performance utilizing operating history and physics-based models

RESEARCH AND DEVELOPMENT NEEDS: PLANNED ACTIVITIES

Planned R&D activities address the technology gaps identified for each section of the program focus areas and draw from a broad range of disciplines to support the development of Instrumentation and Control solutions:



FLUX SENSORS

TECHNOLOGY	NEEDED R&D
Self-Powered Detectors (SPDs)	• Benchmark commercial sensors for high temperature compatibility up to 800°C including active temperature compensation technique • Design and fabricate SPDs sensitive to higher energy neutron flux and gamma flux • Perform prototypic testing in conditions to demonstrate use for advanced reactor power control
Fission Chambers	• Benchmark commercial sensors for high temperature compatibility up to 400°C including calibration procedures • Provide compact fission chamber capability of operating above 400°C and demonstrate performance in prototypic conditions
Micro Pocket Fission Detectors (MPFDs)	• Provide long-duration performance testing to develop calibration procedures, measure signal drift and demonstrate high temperature compatibility
Gamma Thermometers	• Benchmark commercial sensors for high temperature compatibility up to 800°C including calibration procedures • Testing in prototypic conditions for advanced reactor power monitoring
Ion Chamber	• Testing in prototypic conditions for advanced reactor power monitoring

OPTICAL FIBERS

TECHNOLOGY	NEEDED R&D
Temperature Sensing	• Development of active compensation techniques for sensor drift of intrinsic fiber optic sensor • Demonstration in prototypic conditions for advanced reactors • Demonstration of sensor reliability at high temperature and high radiation • Benchmark commercial based sensors and define limitations for their use in high temperature and radiation environments based on an acceptable measurement uncertainty
Pressure Sensing	• Long term demonstration of performance at elevated temperatures • Optimize Fabry-Perot based sensor for high dose applications • Testing under prototypic cases for deployment in advanced reactors to determine compatibility with targeted applications (sodium, molten salt, radiation & temperature)
Strain Sensing	• Demonstration of sensor in prototypic conditions • Development of use-cases for deployment in advanced reactors
In-core Imaging	• In-core demonstration of imaging system • Demonstration of the in-pile system use for high temperature thermography and related applications (crack detection/defect formation, structural health monitoring) in a gas environment • Development of a system • Collect high quality out-of-pile images with system used in-pile to determine feasibility of digital image correlation and particle image velocimetry with fiber bundle system.

ACOUSTIC SENSORS

TECHNOLOGY	NEEDED R&D
Ultrasonic Thermometer	• Develop specialized electronics and data acquisition to provide real-time temperature readout for simplified adoption into experiments/commercialization • Optimize fabrication techniques for commercialization • Characterize performance of updated system and demonstrate performance under relevant conditions
Ultrasonic Pressure Sensor	• Identify and characterize performance of high temperature radiation tolerant transducer materials and characterize material compatibility for anticipated deployment environments • Assess adoption and modification of commercial ultrasonic pressure sensors • Develop temperature compensation strategy and perform in-lab testing and design refinement under prototypic conditions
Ultrasonic Flow Sensor	• Assess adoption and modification of commercial ultrasonic flow sensors • Develop temperature compensation strategy and perform in-lab testing and design refinement under prototypic conditions
Ultrasonic Level Sensor	• Assess adoption and modification of commercial ultrasonic level sensors • Perform in-lab testing and design refinement under prototypic conditions
Acoustic Emission/Vibration Sensor	• Assess adoption and modification of commercial acoustic sensors • Develop calibration methodology and demonstrate in prototypic conditions

THERMOCOUPLES

TECHNOLOGY	NEEDED R&D
High Temperature Irradiation Resistant Thermocouples (HTIR-TC)	• Develop, test and implement real-time drift models for advanced reactor conditions
Intrinsic Junction Thermocouples	• Installation on relevant materials for advanced reactor components • Assess real-time performance and related material interactions
Conventional/multi-point/coaxial Thermocouples	• Develop, test and implement real-time drift models for advanced reactor conditions • Uncertainty quantification of multi-point measurement

RAD-HARD ELECTRONICS

TECHNOLOGY	NEEDED R&D
Gallium Nitride (GaN) Integrated Circuits (ICs)	• Fabrication of radiation hard, high temperature ICs • Demonstration of reliability at high temperature and high radiation
Joint Field Effect Transistor (JFET) technology applied to Front end digitizer (FREND) for optical fiber data transmission	• Fabrication and demonstration of prototype acquisition system • Implementation of rad-hard circuits • Demonstration of radiation hardness in irradiation experiment

LVDT

TECHNOLOGY	NEEDED R&D
Pressure Sensing	• Engineer a set of standardized configurations coupled with a bellows for key applications (determining operating pressure and temperature range) • Quantify the high temperature and irradiation resistance of potential alternatives to Halden supplied LVDTs. • Qualify commercially available LVDT/bellows systems for pressure measurements
Displacement	• Establish an optimized fixturing/support methodology to minimize measurement uncertainty introduced by nuclear and thermal effects • Quantify the high temperature and irradiation resistance of potential alternatives to Halden supplied LVDTs.
Temperature	• Establish an standardized design for implementing a thermal expansion based temperature measurement using LVDTs • Qualify this design through laboratory and in-pile testing

PASSIVE MONITORS

TECHNOLOGY	NEEDED R&D
Silicon Carbide	• Conduct round robin study on readout methodologies from a common set of silicon carbide samples • Establish standardized readout methodology documented by ASTM • Evaluate advanced readout capability technologies and quantify associated uncertainties
Melt Wires	• Miniaturize packaging of melt wires by utilizing additive manufacturing • Standardize readout method for specific melt wire materials • Develop advanced readout capability to reduce ambiguity of measurement and performer subjectivity. Potential advanced readout methods include Enhanced visual readout, X-ray CT, and electrical interrogation
Dosimetry	• Establish additive manufactured dosimetry capability enabling directional & spectrum unfolding capability

ASTM = American Society for Testing and Materials

CT = Computed Tomography

MATERIAL PROPERTIES CHARACTERIZATION

TECHNOLOGY	NEEDED R&D
Creep Testing	• In-pile demonstrate the system under prototypic conditions
Thermal Property Characterization	• In pile demonstration of techniques under prototypic condition coupled • Further development of both contact and non-contact techniques for advanced thermal property characterization • Develop methodology and infrastructure for thermal property measurements of liquids
Strain gauges	• Benchmarking long term performance under prototypic conditions • Develop advanced manufactured strain gauges for improved performance • Benchmark advanced manufactured strain gauges to traditional high temperature strain gauges
Crack Growth	• Complete the qualification of a standardized design for in-pile measurement of crack growth propagation

DIGITAL TWIN

TECHNOLOGY	NEEDED R&D
Models	• Develop prototypic plant models of simplified nuclear systems
Algorithms	• Develop algorithms to demonstrate system state quantification • Develop prototypic algorithms for anomaly detection • Develop algorithms that incorporate explainability (explainable AI) • Develop and demonstrate generalizability of algorithms • Demonstration of methods for assured ML/AI
Data, Tools & Test Beds	• Data sustainability policies and best practices • An annotated initial set of benchmark data sets from a subset of nuclear facilities published online • Set of ML/AI tools with standardized interfaces, capable of leveraging DOE HPC facilities • Guidance/best practices for testbeds for demonstrating and qualifying ML/AI-enabled digital twins and semi-autonomous operations • Sustainable access to benchmark data sets, testbeds, and tool suites for existing and new application domains in nuclear energy, along with consensus standards and best practice documents for the application of ML/AI to address needs in nuclear system O&M, and nuclear fuel cycle processes

HPC = High Performance Computing

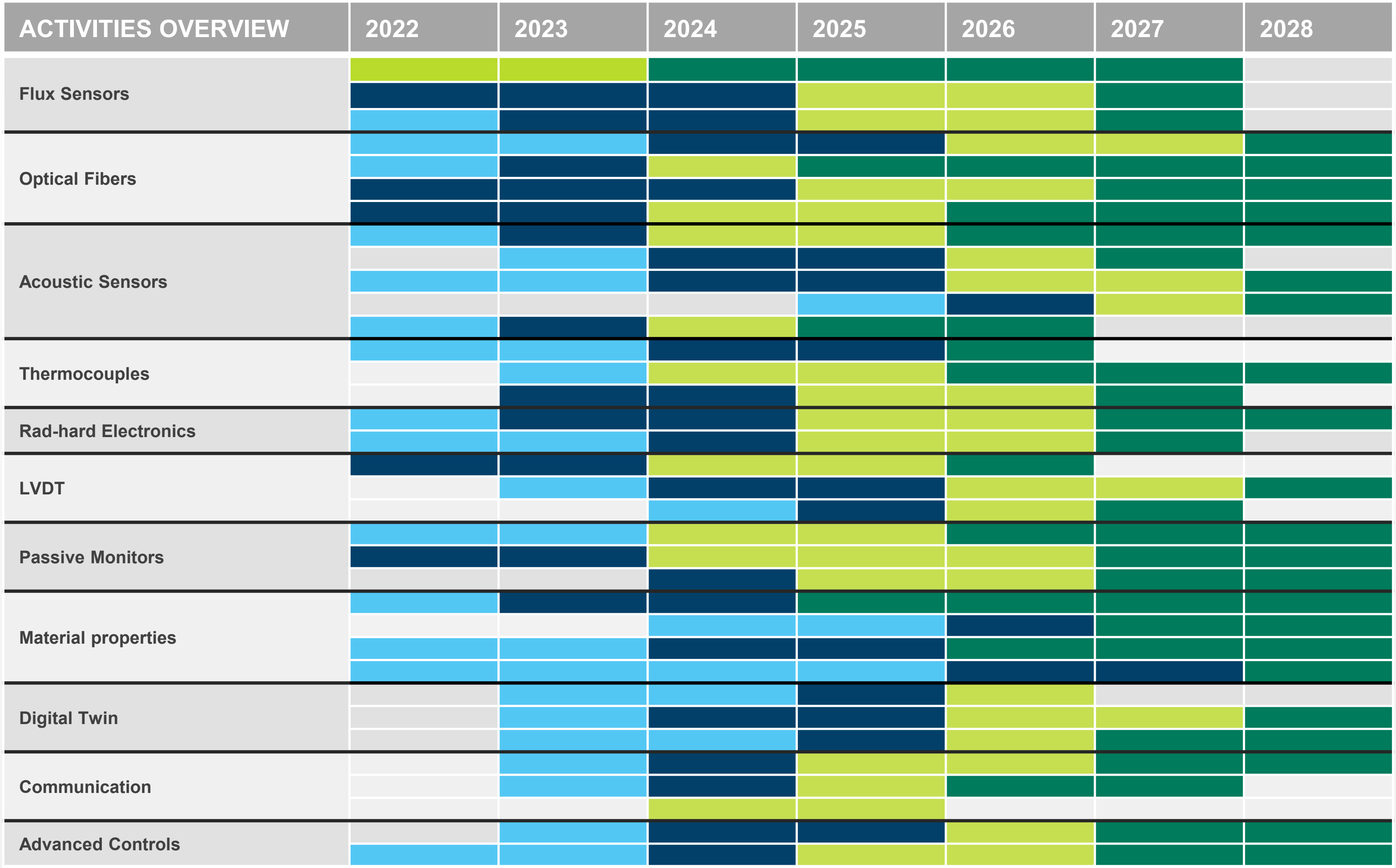
O&M = Operations and Maintenance

COMMUNICATION

TECHNOLOGY	NEEDED R&D
Wireless Communications	• Develop multi-band frequency network architecture • Model electronics system to support their design, to evaluate the performance under different operating conditions • Develop metrics to evaluate resilience, reliability (data availability), latency, coverage, connectivity, and throughput of a network prototype under different operating condition • Develop a testbed to validate multiband network architecture to demonstrate and qualify multi-frequency communication • Provide guidance/best practices for installation of wireless infrastructure at a plant site
Passive Communication	• Produce computational model to design inductive coupling communication and to better understand its merits and demerits to support in-pile or near vessel communication
Wired Communication	• Establish testbed to support non radio frequency communication that includes fiber optics and induction-based transmission

ADVANCED CONTROLS

TECHNOLOGY	NEEDED R&D
High Performance	• Develop and demonstrate a High Performance Control System simulation platform • Human factors framework for understanding the role of the human in plants using High Performance Control Systems
AI/ML Assisted	• Human factors principles that enable situational awareness in AI/ML assisted controls operating environments • Control strategies that improve performance by making use of methodologies that combine operating-data-based machine-learning models and physics-based models to improve knowledge of plant condition • Hardware-in-the-loop demonstration of robust autonomous control of a reference nuclear system. • Supervisory and artificial intelligence control architectures that support reactors with multiple product streams and energy storage systems for load leveling



Development

Identification and research of needs, applications, functional requirements and complete feasibility demonstration

Testing

Performance assessment and design optimization under relevant conditions

Qualification

Demonstration through benchmarking using relevant methods and/or facilities

Deployment

Transition to end-user applications and/or commercialization partners

ROADMAP: FLUX SENSORS

R&D Activity	2022	2023	2024	2025	2026	2027	2028
Self Powered Neutron Detectors (SPND)	Develop temperature compensation tools		Deploy in advanced reactors demonstration facilities				
			Develop neutron spectral unfolding tools		Qualify SPNDs for fast reactors		
Fission Chambers	Cross calibration of in-core fission chambers, Micro-Pocket Fission Detectors (MPFDs) with SPDs in heated irradiation tests			Qualification of miniature in-core fission chambers for advanced reactors power measurement and control		Establish commercial supply chain	
Gamma detectors	Develop optical fiber-based gamma thermometer (OFBGT)	Test gamma thermometers and miniature ion chambers at high temperature		Qualify gamma thermometers and miniature ion chambers against external detectors for reactor power measurement and control		Establish commercial supply chain	

Development | **Testing** | **Qualification** | **Deployment**

ROADMAP: OPTICAL FIBERS

R&D Activity	2022	2023	2024	2025	2026	2027	2028
Active Compensation	Test sensor under gamma irradiation	Test sensor with mixed neutron gamma irradiation				Establish commercial supply chain	
			Test active compensation sensor with other intrinsic sensors		In-pile demonstration of active compensation coupled with intrinsic measurement capability		
Pressure Sensor	Complete testing in low dose irradiation environments						
		Extend high temperature range operation		Deploy in advanced reactors demonstration facilities			
			Long term testing in radiation environment				
In-pile Imaging	Test design in gas environment			In-pile demonstration of advanced imaging techniques		Deploy in advanced reactors demonstration facilities	
		Test in water-based environment		Evaluate the use of fiber bundles for PIV and DIC application			
Intrinsic temperature sensing	Distributed sensing in high temperature, low dose environments		Benchmarking of commercially available sensor to determine operating limitations		Deploy in advanced reactors demonstration facilities		

Development | **Testing** | **Qualification** | **Deployment**

ROADMAP: ACOUSTIC SENSORS

<table>
<tr><th>R&D Activity</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th></tr>
<tr><td rowspan="2">Ultrasonic thermometer</td><td>Improve fabrication methods</td><td>Characterize updated design</td><td colspan="2" rowspan="2">Benchmark performance</td><td colspan="3" rowspan="2">Deploy in advanced reactors demonstration facilities</td></tr>
<tr><td colspan="2">Develop custom electronics and data acquisition system</td></tr>
<tr><td rowspan="2">Ultrasonic pressure sensor</td><td rowspan="2"></td><td>Assess adoption and modification of commercial sensors</td><td colspan="2">Perform benchtop testing and design optimization</td><td rowspan="2">Benchmark performance of developmental and commercial sensors</td><td rowspan="2">Establish commercial supply chain</td><td rowspan="2"></td></tr>
<tr><td>Explore high temperature radiation tolerant transducer materials</td><td>Develop methods for temperature compensation</td><td>Characterize material compatibility</td></tr>
<tr><td rowspan="2">Ultrasonic flow sensor</td><td colspan="2" rowspan="2">Assess adoption and modification of commercial sensors to advance reactors and develop low intrusiveness technologies for local measurements</td><td colspan="2">Perform benchtop testing and design optimization</td><td colspan="2" rowspan="2">Demonstrate under relevant conditions</td><td rowspan="2">Deploy in advanced reactors demonstration facilities</td></tr>
<tr><td colspan="2">Develop methods for temperature compensation</td></tr>
<tr><td>Ultrasonic level sensor</td><td></td><td></td><td></td><td>Assess adoption and modification of commercial sensors</td><td>Perform benchtop testing and design optimization</td><td>Demonstration in prototypic conditions</td><td>Establish commercial supply chain</td></tr>
<tr><td rowspan="2">Acoustic Emission/ Vibration sensor</td><td rowspan="2">Assess adoption and modification of commercial sensors to advance reactors</td><td>Perform benchtop testing and design optimization</td><td rowspan="2">Demonstration in prototypic conditions</td><td colspan="2" rowspan="2">Deploy in advanced reactors demonstration facilities</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Develop calibration methodology</td></tr>
</table>

Development | Testing | Qualification | Deployment

ROADMAP: THERMOCOUPLES (TCs)

R&D Activity	2022	2023	2024	2025	2026	2027	2028
High Temperature Irradiation Resistant Thermocouples (HTIR-TCs)	Development of real-time drift compensation methods for advanced reactors		Demonstration of drift model in prototypical conditions		Establish commercial supply chain		
	Heat treatment optimization						
Intrinsic junction thermocouples		Develop fabrication methods for advanced nuclear fuel and materials					
			Assess real-time performance		Deploy in advanced reactors demonstration facilities		
Conventional, multi-point and coaxial thermocouples		Uncertainty quantification of multi-point measurement		Benchmarking and reliability assessment		Establish commercial supply chain	

Development | Testing | Qualification | Deployment

ROADMAP: RAD-HARD ELECTRONICS

R&D Activity	2022	2023	2024	2025	2026	2027	2028
Gallium Nitride (GaN) integrated circuits (ICs)	Design and fabrication				Establish commercial supply chain		
		Test in prototypical conditions		Demonstration of reliability			
Fiber optic front end digitizer (FREND)	Fabrication of prototype acquisition system		Implementation of rad-hard ICs	Benchmarking of operation in irradiation experiment		Establish commercial supply chain	

Development | **Testing** | **Qualification** | **Deployment**

ROADMAP: LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)

<table>
<tr><th>R&D Activity</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th></tr>
<tr><td>LVDT supply chain assessment</td><td colspan="2">Furnace based testing</td><td colspan="2">Test in prototypical conditions</td><td>Establish commercial supply chain</td><td></td><td></td></tr>
<tr><td>LVDT-based Pressure sensor</td><td></td><td>Design and fabricate standardized configuration</td><td colspan="2">Furnace and initial irradiation-based testing of design</td><td colspan="2">In-pile Qualification testing of LVDT-based pressure sensor</td><td>Deploy for advanced reactors fuels and materials demonstration</td></tr>
<tr><td>High Temperature Measurement</td><td></td><td></td><td>Design of sensor feasibility testing</td><td>Laboratory Furnace Testing</td><td>In-Pile Qualification</td><td>Deploy for advanced reactors fuels and materials demonstration</td><td></td></tr>
</table>

Development	Testing	Qualification	Deployment

ROADMAP: PASSIVE MONITORS

R&D Activity	2022	2023	2024	2025	2026	2027	2028
Melt Wires	Miniaturization through printing	Miniaturization through printing					
		Develop advanced readout capability	Develop advanced readout capability				
			Establish a standard for readout of melt wire materials	Establish a standard for readout of melt wire materials	Deploy for advanced reactors fuels and materials demonstration	Deploy for advanced reactors fuels and materials demonstration	Deploy for advanced reactors fuels and materials demonstration
Silicon Carbide	Benchmarking existing readout capabilities	Benchmarking existing readout capabilities	Establish ASTM standard for SiC temperature monitors	Establish ASTM standard for SiC temperature monitors	Establish ASTM standard for SiC temperature monitors	Deploy for advanced reactors fuels and materials demonstration	Deploy for advanced reactors fuels and materials demonstration
Advanced Dosimetry			Advanced Manufacturing of dosimetry coupons	Benchmark to traditional Dosimetry	Benchmark to traditional Dosimetry	Deploy for advanced reactors fuels and materials demonstration	Deploy for advanced reactors fuels and materials demonstration

Development | Testing | Qualification | Deployment

ROADMAP: MATERIAL PROPERTIES CHARACTERIZATION

<table>
<tr><th>R&D Activity</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th></tr>
<tr><td rowspan="2">Thermal conductivity for solid nuclear fuel and materials</td><td>Line source method development</td><td colspan="2">Line Source In-pile (ATR) demonstration on U10Zr fuel specimens</td><td colspan="2" rowspan="2">Deploy for advanced reactors fuels and materials demonstration</td><td></td><td></td></tr>
<tr><td>Photothermal radiometry development</td><td colspan="2">Photothermal Radiometry In-pile (MITR) demonstration on a variety of materials</td><td></td><td></td></tr>
<tr><td>Thermal conductivity of liquids (fueled molten salt and high temperature coolants)</td><td></td><td></td><td colspan="2">Measurement technique development</td><td>Benchtop testing</td><td colspan="2">Deploy for advanced reactors fuels and materials demonstration</td></tr>
<tr><td rowspan="2">Strain Gauges</td><td colspan="2">Benchtop benchmarking of traditional and additively manufactured strain gauges for high temperature applications</td><td colspan="2">Testing of high temperature strain gauges in prototypical conditions</td><td colspan="2" rowspan="2">Qualification of strain gauges for Application of strain gauges to Structural Health Monitoring of advanced nuclear reactor components</td><td rowspan="2">Deploy in advanced reactors demonstration facilities</td></tr>
<tr><td></td><td colspan="3">Application of strain gauges to Structural Health Monitoring of advanced nuclear reactors components</td></tr>
<tr><td rowspan="2">Methods for in-core measurement of creep and crack growth</td><td colspan="2">LVDT-based creep test rig development</td><td colspan="2">In-core testing of LVDT-based creep measurement methods</td><td colspan="3">Deploy for advanced reactors fuels and materials demonstration</td></tr>
<tr><td></td><td></td><td colspan="2">LVDT-based crack growth test rig development</td><td colspan="2">In-core testing of LVDT-based crack growth measurement methods</td><td>Deploy for advanced reactors fuels and materials demonstration</td></tr>
</table>

Development | **Testing** | **Qualification** | **Deployment**

ROADMAP: DIGITAL TWIN

<table>
<tr><th>R&D Activity</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th></tr>
<tr><td rowspan="2">Models</td><td></td><td>Develop plant models of a simplified nuclear system</td><td>Test plant models of simplified nuclear for use in adv controls</td><td>Qualify simplified plant models</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Develop plant models of advanced nuclear system</td><td>Test plant models of nuclear for use in adv controls</td><td>Qualify advanced plant models</td><td></td><td></td></tr>
<tr><td rowspan="2">Algorithms</td><td></td><td>Develop algorithms that incorporate explainability</td><td colspan="2">Test generalizability of algorithms</td><td colspan="2" rowspan="2">Qualify methods for assured ML/AI</td><td rowspan="2">Deploy explainable ML/AI for anomaly detection in advanced reactors demonstration facilities</td></tr>
<tr><td></td><td>Develop prototypic algorithms for anomaly detection</td><td>Test anomaly detection algorithms</td><td>Qualify anomaly detection algorithms</td></tr>
<tr><td rowspan="2">Data, Tools & Test Beds</td><td></td><td>Annotated initial set of benchmark data sets from a subset of nuclear facilities published online</td><td>Develop ML/AI tools with standardized interfaces</td><td rowspan="2">Test ML/AI-enabled digital twins for semi-autonomous operations</td><td rowspan="2">Qualify digital twin test beds supporting adv controls testing</td><td colspan="2" rowspan="2">Deploy digital twin test bed in advanced reactors demonstration facilities</td></tr>
<tr><td></td><td>Data sustainability policies and best practices</td><td>Develop Guidance and best practices for test beds</td></tr>
</table>

Development | **Testing** | **Qualification** | **Deployment**

ROADMAP: COMMUNICATION

<table>
<tr><th>R&D Activity</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th></tr>
<tr><td rowspan="2">Wireless</td><td></td><td>Develop multi-band frequency network architecture</td><td>Test multi-band frequency network architecture</td><td></td><td>Develop guidance and best practices for installation of wireless infrastructure at a plant</td><td colspan="2" rowspan="2">Deploy multi-band network architecture in advanced reactors demonstration facilities</td></tr>
<tr><td></td><td></td><td>Develop metrics to evaluate network prototypes</td><td colspan="2">Qualify multi-band network architecture</td></tr>
<tr><td>Passive</td><td></td><td>Develop computational model to design inductive coupling communication</td><td>Test inductive coupling communication</td><td>Qualify inductive coupling communication</td><td colspan="2">Deploy inductive coupling communication in advanced reactors demonstration facilities</td><td></td></tr>
<tr><td>Wired</td><td></td><td></td><td colspan="2">Qualify non-radio frequency communication that includes fiber optics and induction-based transmission</td><td></td><td></td><td></td></tr>
</table>

Development | Testing | Qualification | Deployment

ROADMAP: ADVANCED CONTROLS

<table>
<tr><th>R&D Activity</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th></tr>
<tr><td rowspan="2">High Performance</td><td></td><td>Develop a High-Performance Control System Simulation Platform</td><td>Test High Performance Control Systems Simulation Platform</td><td>Qualify a High-Performance Control Simulation Platform</td><td rowspan="2">Qualify High-Performance Controls using simulation platform</td><td rowspan="2" colspan="2">Deploy High-Performance Controls in advanced reactors demonstration facilities</td></tr>
<tr><td></td><td></td><td>Develop High-Performance Controls using simulation platform</td><td>Test High-Performance Controls using simulation platform</td></tr>
<tr><td rowspan="2">AI-ML Assisted</td><td>Develop the approach to integrate advanced control algorithms in nuclear digital twins</td><td>Develop control strategies that combine operating-data-based machine-learning models and physics-based models</td><td>Test Human factors principles that enable situational awareness in AI/ML assisted controls operating environments</td><td colspan="2">Qualify Hardware-in-the-loop demonstration of robust autonomous control of a reference nuclear system</td><td colspan="2">Deploy AI/ML assisted controls in advanced reactors demonstration facilities</td></tr>
<tr><td></td><td colspan="2">Develop Supervisory and AI control Architectures that support reactors with multiple product streams and energy storage systems for load leveling</td><td></td><td></td><td></td><td></td></tr>
</table>

Development | **Testing** | **Qualification** | **Deployment**

IMPLEMENTATION

There are several key components of the ASI program building the foundation of performing successful research:

ASI Program Personnel | Congruent Program Synergies | ASI Program Resources | Research Avenues and FOAs

ASI Program Personnel provides the structure to streamline coordination among the program leadership, focus area leads, principal investigators, and subject matter experts. Program personnel currently include National Laboratory experts from ANL, INL, ORNL and PNNL, subject matter experts (SMEs), and several distinguished universities.

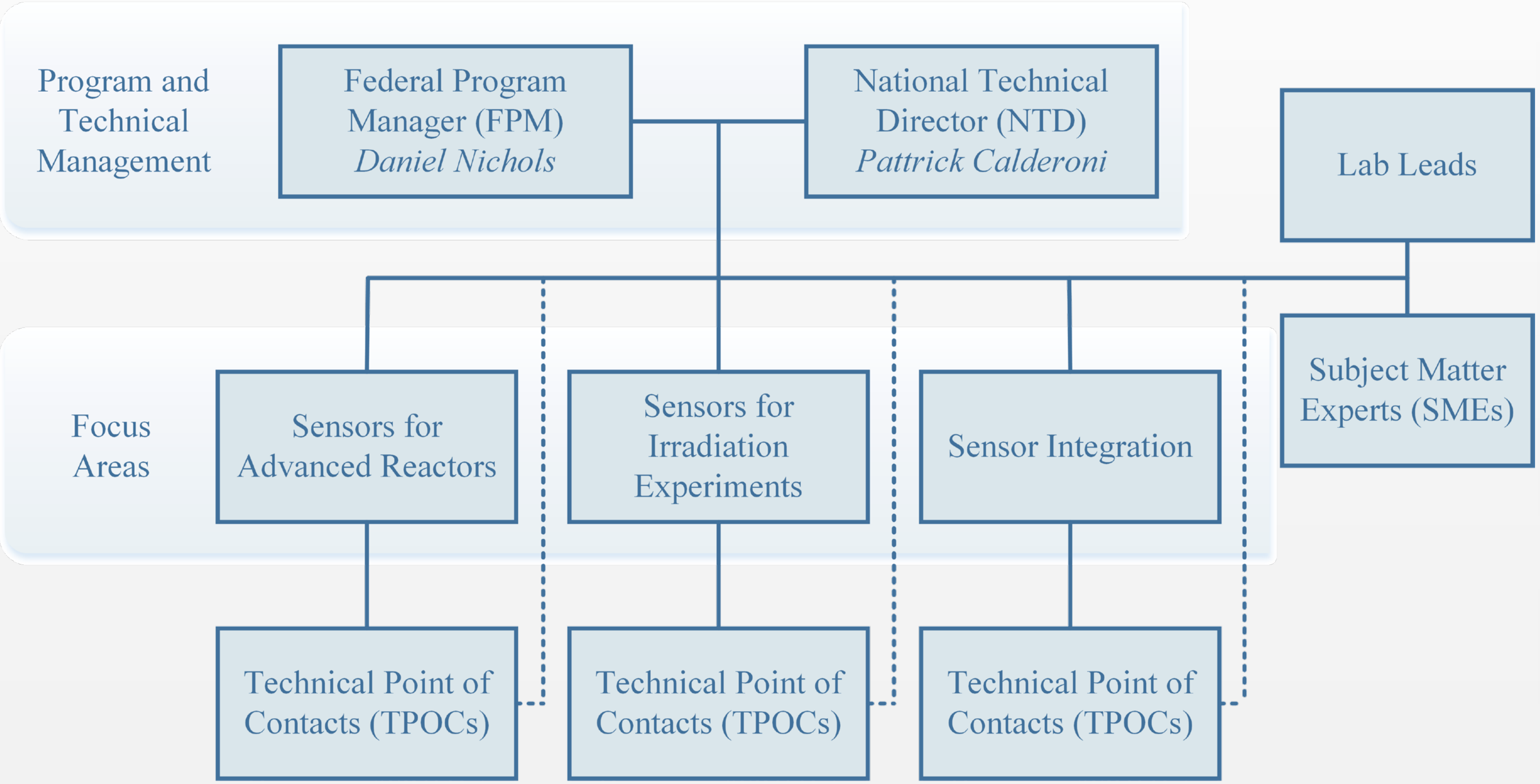
Congruent Program Synergies with other Federal agencies and DOE programs helps to strengthen technology development and improve use case deployment. Continuous and active engagement will other programs allows for coordination of scope to achieve the DOE-NE mission.

ASI Program Resources such as the irradiation test facilities, sensor qualification processes, national laboratories, universities and industry partners helps to combine technical expertise and human capital to accelerate technology development.

Research Avenues and Funding Opportunity Announcements (FOAs) provide methods to engage with the National Laboratories, universities and industry partners through both competitive and non-competitive mechanisms to pursue research and development (R&D).

PERSONNEL

The program personnel structure is designed to provide consolidated information to the program management to analyze progress and to connect project across different cross-sectional domains. Therefore, the program can be reviewed from the standpoint of down stream stakeholders (captured by focus areas), intra-laboratory projects (captured by lab leads), and by technology type (captured by SMEs).



The FPM and NTD have direct contact with every program personnel level

Lab leads provide consolidated project information for all work being conducted at their laboratory

Focus area leads are responsible for direct connect with projects in their category

SMEs provide expertise regarding technology (i.e., optical fiber sensors, thermocouples, etc.)

PROGRAM SYNERGIES: ACTIVITIES WITH DIRECT COORDINATION OF SCOPE

Nuclear Energy – *Reactor Fleet and Advanced Reactor Deployment*

- Advanced Materials and Manufacturing Technologies (AMMT)
- Nuclear Energy Advanced Modeling and Simulation (NEAMS)
- Nuclear Science User Facilities (NSUF)
- Gateway for Accelerated Innovation in Nuclear (GAIN)
- Light Water Reactor Sustainability (LWRS)
- Nuclear Cybersecurity
- Sodium-Cooled Fast Reactors (SFR)
- High-Temperature Gas-Cooled Reactors (HTGR)/TRISO Fuel
- Molten Salt Reactors (MSR)
- Microreactors
- National Reactor Innovation Center (NRIC)

Nuclear Energy – *Nuclear Fuel Cycle and Supply Chain*

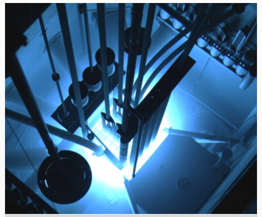
- Advanced Fuels Campaign (AFC)
- Nuclear Energy – International Nuclear Energy Policy and Cooperation
- Office of Bilateral, Multilateral and Commercial Cooperation
- Other programs or Organizations
- Nuclear Regulatory Commission (NRC)
- Electric Power Research Institute (EPRI)
- Advanced Research Projects Agency – Energy (ARPA-E)
- Navy Nuclear Laboratory (NNL)
- National Institute of Standards and Technology (NIST)

PROGRAM RESOURCES: IRRADIATION TEST

Irradiation test requirements and technology maturity largely determine the appropriate facility for testing

Low sensor TRL Technology
Easier Access
Lower Cost Tests
Separate effects testing

OSURR
University Reactor



PULSTAR
University Reactor

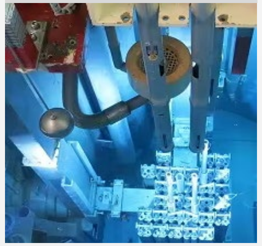
MITR
University Reactor

High sensor TRL Technology
Limited Access
Higher Costs, High Dose
Controlled Prototypic Environment

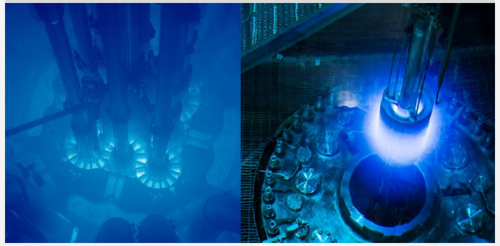
DEVELOPMENT → *PROTOTYPIC DEPLOYMENT*

TREAT (INL)

NRAD (INL)



ATR/HFIR (INL/ORNL)



PROGRAM RESOURCES: SENSOR QUALIFICATION DEVICES

Phased approach to qualification of sensors under irradiation environments:

Laboratory-based Testing

Benchtop, Furnace, Autoclave testing (non-nuclear).

Concurrent/Initial Nuclear Testing

Low cost, rapid deployment, generally uncontrolled environment instrumentation may be included in experiment funded by other programs.

Qualification Nuclear Testing

Highly controlled environment, reference measurements for measurand in addition to cross sensitivity parameters. National Institute of Standards and Technology (NIST) traceable references where appropriate.

Specialized devices are required to provide a *known* environment to benchmark sensors, define sensor uncertainty, and ultimately qualify for deployment.

- Measurement Parameters: Temperature, Neutrons (Flux/fluence/spectrum), Pressure, Displacement

Device for qualifying temperature and neutron sensors

- High dose, transient, gamma-only irradiation devices for each measurement parameter
- Requirements for temperature and neutron sensors are conducive to them being the same device

Device for qualifying pressure

- Device design will be based on the temperature/neutron device, but will require ex-core pressure control with NIST traceable reference sensor

Displacement

- Similarly based on the temperature/neutron device, but will require precise mechanical controls to impose a known and repeatable displacement for the sensors to measure

	Temperature/ Neutron	Pressure	Displacement
High Dose	X	X	X
Transient	X		X
Gamma Only	X	X	

PROGRAM RESOURCES: RODLET REFABRICATION

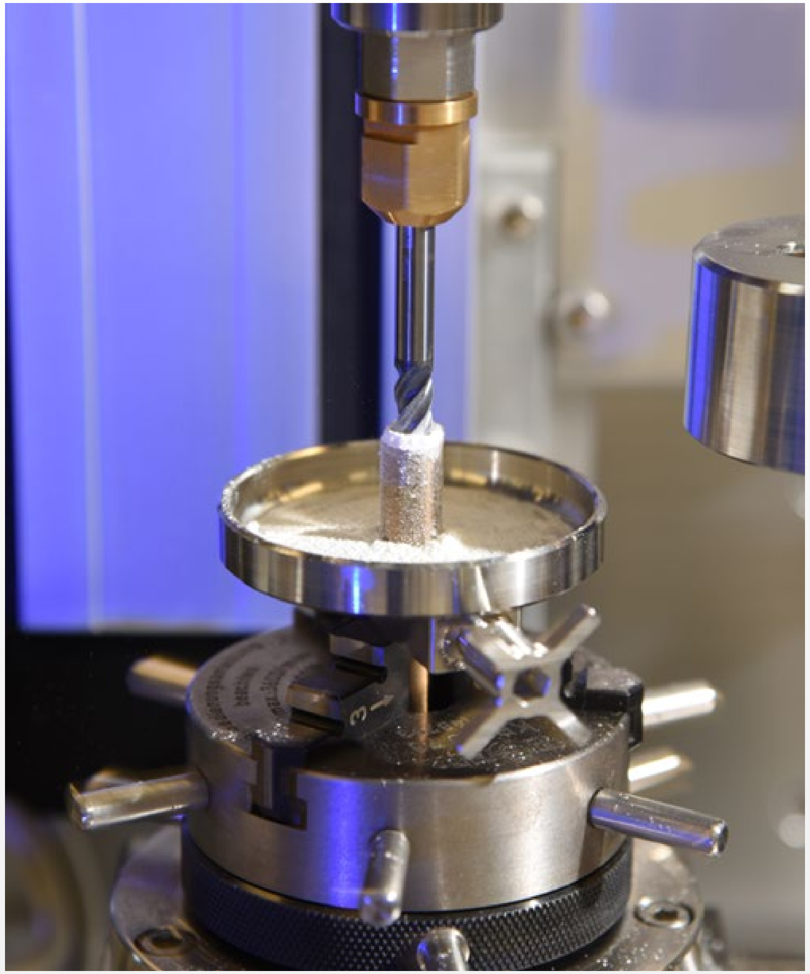
The testing and qualification of nuclear fuel systems provides significant demand for in-pile sensors and instrumentation:

Qualification of nuclear fuel systems requires accident testing at end-of-life scenarios. Few materials can survive these conditions throughout the irradiation. Rodlet Refabrication is a methodology to take irradiated fuel rods and refabricate them with new sensors.

- Rodlet refabrication was pioneered by Halden and work has begun at INL
- Refabrication usually takes the form of a new rodlet endcap which is welded to the irradiated cladding

Integrating instrumentation into advanced endcap designs compatible with rodlet refabrication is key to sensor performance. Desired endcaps include:

- Plenum pressure (LVDT-based)
- Fiber optic sensors in plenum (Temperature, fission gas, pressure, etc.)
- Ultrasonic centerline temperature
- Thermocouple (centerline & plenum)
- Potential combination of these technologies



PROGRAM RESOURCES: NATIONAL LABORATORIES

The ASI Program currently has National Laboratory partnerships which include:

INL Idaho National Laboratory

OAK RIDGE National Laboratory

Argonne NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

National Laboratory Research Reactors

- Transient Reactor Test Facility (TREAT)
- Advanced Test Reactor (ATR)
- Advanced Test Reactor Critical Facility (ATRC)
- Neutron Radiography Reactor (NRAD)
- High Flux Isotope Reactor (HFIR)

National Laboratory Facilities

- Measurement Science Laboratory (MSL)
- Digital Innovation Center of Excellence (DICE)
- Microreactor Agile Non-Nuclear Experimental Test Bed (MAGNET)
- Single Primary Heat Extraction and Removal Emulator (SPHERE)
- Microreactor Applications Research Validation and Evaluation (MARVEL)
- Low Activation Materials Development and Analysis (LAMDA) laboratory
- Mechanisms Engineering Test Loop Facility (METL)

PROGRAM RESOURCES: UNIVERSITIES COLLABORATIONS

R&D projects awarded competitively through the DOE Consolidated Innovative Nuclear Research FOA

Virginia Tech

Boise State University

Vanderbilt University

NC State University

University of Pittsburgh

Notre Dame

The Ohio State University

University of Michigan

Massachusetts Institute of Technology

Texas A&M University

2016 2017 2018 2019 2020 2021

PROGRAM RESOURCES: INDUSTRY PARTNERS

Commercialization projects

Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) connected the ASI program with instruments developers and supplier since the program start. Examples from currently active projects include:

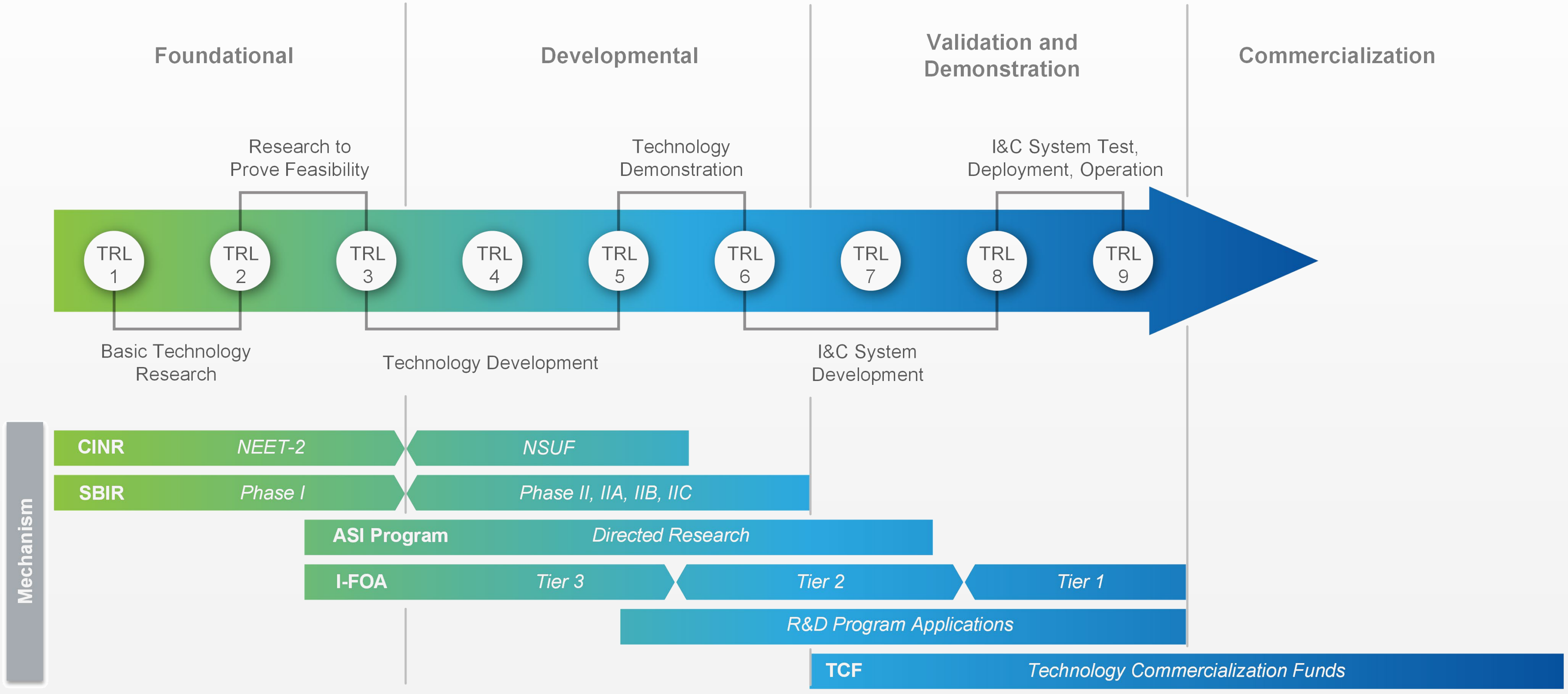
- Alphacore Inc. - Video Camera for Harsh Environments in Nuclear
- Analysis & Measurement Services Corp. - Health Monitoring of Digital I&C systems using Online Electromagnetic Measurements
- Goldfinch Sensor Technologies and Analytics LLC - Metamaterial Void Sensor for Fast Transient Testing
- Intelligent Optical Systems, Inc. Advanced Laser Ultrasonic Sensor for Fuel Rod Characterization
- Sporian Microsystems, Inc. - High Temperature Operable, Harsh Environment Tolerant Flow Sensors for Nuclear Reactor Applications
- X-Wave Innovations, Inc. - Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors

Technology Commercialization Fund (TCF) offer opportunities for technology transfer from Laboratories to industry. Examples from recent project:

- Idaho Laboratories Corporation / Idaho National Laboratory - High Temperature Irradiation Resistant Thermocouple

PROGRAM RESOURCES: AVENUES / FOAs

The concept of technology readiness assessment is to determine the maturity level of a technology toward commercialization and final usage. There are various funding opportunity announcements (FOAs) that the ASI program uses to target specific points in the technology development lifecycle. Outlined here is an overview of how the program utilizes different funding mechanisms over the course of the technology development lifecycle.



U.S. DEPARTMENT OF
ENERGY

Office of
NUCLEAR ENERGY