INL/EXT-20-57280

Nuclear Energy Enabling Technologies (NEET)

January 2020

Advanced Sensors and Instrumentation (ASI) Program Plan

Craig A. Primer
Idaho National Laboratory

Pattrick Calderoni
Idaho National Laboratory

Vivek Agarwal
Idaho National Laboratory

Pradeep Ramahaulli
Oak Ridge National Laboratory

Rick Vilim
Argonne National Laboratory

Changing the World's Energy Future

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/EXT-20-57280

Nuclear Energy Enabling Technologies (NEET)

Advanced Sensors and Instrumentation (ASI) Program Plan

Craig A. Primer, Pattrick Calderoni, and Vivek Agarwal
Idaho National Laboratory

Pradeep Ramuhalli
Oak Ridge National Laboratory

Rick Vilim
Argonne National Laboratory

January 2020

Idaho National Laboratory
Originating Organization
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

AI	artificial intelligence
ART	Advanced Reactor Technology
ASI	Advanced Sensors and Instrumentation
CINR	Consolidated Innovative Nuclear Research
CTD	Crosscutting technology development
DOE	Department of Energy
EERE	Office of Energy Efficiency & Renewable Energy
FOA	Funding Opportunity Announcement
GAIN	Gateway for Accelerated Innovation in Nuclear
HPC	high performance computing
I&C	Instrumentation and control
INL	Idaho National Laboratory
ML	machine learning
MTR	Material Test Reactors
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEET	Nuclear Energy Enabling Technologies
NTD	National Technical Director
O&M	operation and maintenance
PI	Principal investigator
R&D	Research and development
RD&D	Research, development, and demonstration
TPOC	Technical point of contact
TREAT	Transient Test Facility
TRL	Technology Readiness Level
V&V	Verification and validation

Nuclear Energy Enabling Technologies (NEET) Advanced Sensors and Instrumentation (ASI) Program Plan

1. INTRODUCTION AND BACKGROUND

In 2012, Department of Energy Office of Nuclear Energy (DOE-NE) initiated the Nuclear Energy Enabling Technology (NEET) Program to conduct research, development, and demonstration (RD&D) to support existing, new and advanced reactor designs, and fuel cycle technologies. These cross-cutting RD&D activities have and will continue to advance the state of nuclear technology, improve its competitiveness, and promote continued contribution to meet the nation's energy and environmental challenges. The NEET Program has spurred innovation in the field of sensors and instrumentation, advanced methods for manufacturing, and cybersecurity.

The NEET Advanced Sensors and Instrumentation (ASI) Program addresses critical technology gaps in nuclear industry's monitoring and control capabilities. The ASI Program research enables deployment of advanced technologies necessary for sustaining existing nuclear power plants, deploying advanced reactors, and advancing fuel cycle technologies. The ASI Program is one element of the NEET crosscutting technology development (CTD) program addressing common sensors and instrumentation and control (I&C) needs in all DOE-NE-sponsored programs. This program has spurred innovation in the measurement science field by supporting research on sensors, I&Cs, communication, and advanced analytics. The NEET ASI Program has carried out research and development (R&D) required to deploy innovative and advanced sensors, and I&C capabilities for current and future nuclear energy systems, and to enable the advanced technologies essential to NE's R&D efforts needed to realize mission goals.

1.1 Program Mission and Vision

The NEET ASI Program Mission (Figure 1) is to develop advanced sensors and I&C that address critical technology gaps for monitoring and controlling existing[1] and advanced reactors and supporting fuel cycle development.

The NEET ASI Program Vision is realized through research of those advanced sensors and I&C technologies that are ultimately qualified, validated, and ready to be adapted by the nuclear industry.

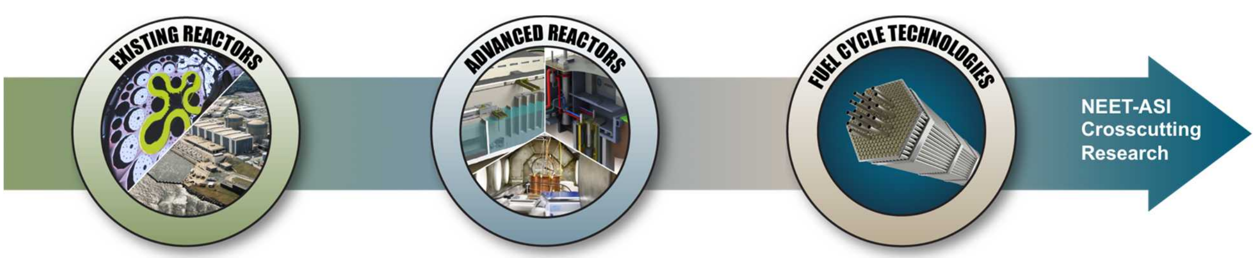

Figure 1. NEET ASI Program mission.

1.2 Connection to the NE Mission Element

The Advanced Sensors and Instrumentation (ASI) Program focuses on innovative research that directly supports and enables the sustainability of the current nuclear fleet, the development and deployment of new, next generation reactor designs, and advanced fuel cycle technologies. The ASI Program provides the crosscutting technologies research in four main areas: (1) sensors, (2) advanced

[1] Existing reactors includes both commercial fleet of light water reactors and test reactor facilities.

control systems, (3) communication, and (4) big data analytics, machine learning, and artificial intelligence. The ASI program is coordinated with NE's other R&D programs to ensure that developed technologies and capabilities are part of an integrated investment strategy aimed at improving safety, reliability, competitiveness of U.S. nuclear technologies.

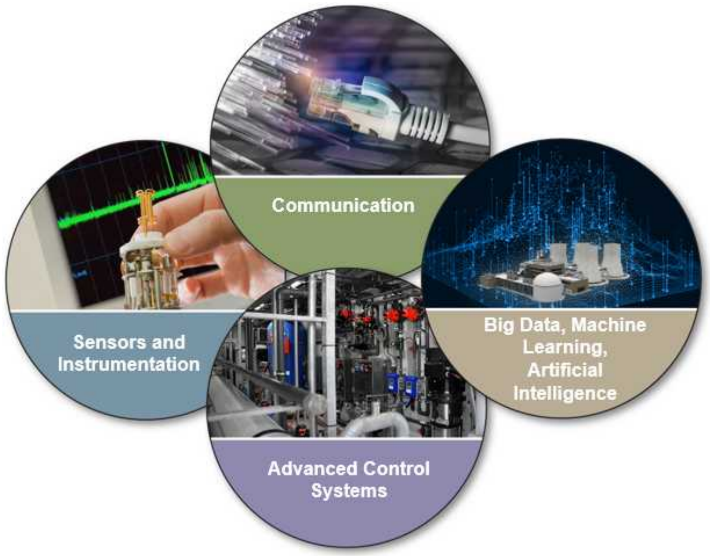

Figure 2. NEET ASI Program research areas.

1.3 Overview and Goals

I&C technologies are critical to the safe and efficient operation of nuclear power systems and are often alluded to as the "nervous system" of a plant. While I&C technologies have provided decades of safe operation for the current nuclear fleet, the I&C systems in use have not incorporated many of the advances in sensor materials, electronics, communication, controls, and data analytics that have become available over the past 40 years. In addition to the challenge associated with maintaining older systems, there is a financial challenge to stay competitive with other energy sources that are leveraging these advanced technologies. The current nuclear industry as well as the advanced reactor designers are looking to develop cost competitive technology solutions. There are challenges that need to be addressed when applying technologies in a nuclear facility due to both unique environments and regulatory commitments. These Crosscutting I&C technology challenges need to be overcome to enable revolutionary advances in nuclear energy systems across the diverse RD&D programs. These research challenges exist at:

- The foundational level, where basic but novel concepts need to be developed and demonstrated at a bench scale, before the concept can be customized to meet a specific application demand
- The applied level, where data is needed to advance a reactor or fuel cycle concept.
- More detailed goals associated with each research area are provided in Section 2. The overall NEET ASI program goals include:
- Develop key monitoring and control technologies for nuclear power systems that have the potential to address multiple DOE-NE mission needs
- Transition critical monitoring and control technologies from concept to demonstration and from research to deployment
- Enhance DOE-NE capabilities and facilities for testing and validation of monitoring and control technologies.

2. NEET ASI RESEARCH AREAS

The NEET ASI program's main research areas are discussed in this section. These research areas address the critical technology gaps in nuclear industry's monitoring and control capabilities. Each section will provide general information describing research area's goals, challenges, approach, and benefits.

Technology Readiness Level (TRL) is a key concept and needs to be generally understood. Figure 3 below shows an overview of the TRL progression and more information is provided in Section 4.

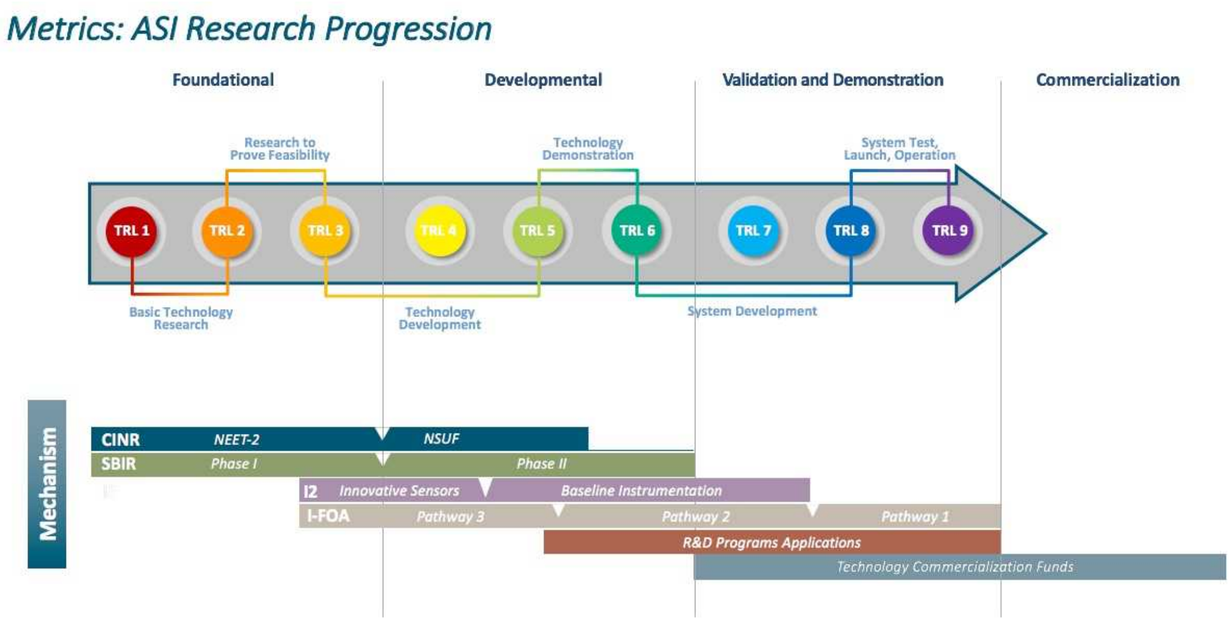

Figure 3. Technology readiness roadmap.

2.1 Advanced Instrumentation

Instruments are the foundational and enabling component of I&C systems. An instrument is the technological application of measurement science principles and methods, combining sensors (or sensing elements) and all necessary auxiliary components necessary to provide a measured parameter to the I&C system. Existing nuclear plants utilize wide range of instruments that provide data at varying temporal and spatial resolutions to support operation and maintenance (O&M). In addition, instruments are a key enabling component during demonstration tests for advanced nuclear components (for example, nuclear fuel and materials, primary loop circulation pumps, heat exchangers, etc.) and advanced reactor concepts (for example, microreactor core flow distribution).

2.1.1 Goals

The objective of the Advanced Instrumentation research area is to provide reliable, cost-effective, real-time, accurate, and high-resolution measurement of the performance of existing and advanced reactors core and plant systems. Instruments are designed, fabricated, and tested in relevant (Technology Readiness Level [TRL] 6) and operational (TRL 7) conditions to advance their technological readiness to a point in which they can be integrated in I&C systems without the significant cost and risk associated with development activities.

The development of reactor core (in-pile) instruments for material test reactors (MTR) experiment is an important component of the program objective because of the limitation of available commercial solutions and the impact that they could provide to the acceleration of nuclear systems components demonstration, such as the DOE Gateway for Accelerated Innovation in Nuclear (GAIN) initiative mission alignment. In addition, the capability of testing developmental instruments in MTRs is critical to achieve their performance demonstration in relevant and operational conditions**.** The extensive deployment of advanced instrumentation in an irradiation experiment is the most effective path towards their technological maturation and the consequent adoption by the program stakeholders. This is true not only for the adoption by other DOE-NE programs, but also for advanced reactor designers and end users for which the demonstration in relevant conditions and the accumulation of performance and reliability data is a crucial step to allow integration in the I&C system and contribution to the plant licensing case. It should be noted that the conditions of MTR irradiation experiments are widely dependent on the test facility and the experiment scope (duration, core position, etc.), thus they can be relevant to the demonstration of instruments targeting both the core and other plant systems.

2.1.2 Challenges

The behavior of fuels and materials in the high-radiation environment of a nuclear reactor is extremely complex and represents an important factor in plant safety, performance, longevity, and ultimately economic viability. Most NEET ASI program stakeholders have substantial R&D activities focusing on the in-pile behavior of nuclear fuels and materials extending from advanced fuels development, advanced modeling and simulation, and advanced reactor development. Their implementation relies primarily on irradiation test in operating MTRs. The lack of real-time instrumentation for irradiation testing has been identified as a major technological gap towards the acceleration of new power plant deployment in the energy market. Additionally, the June 2018 decision to terminate the operation of the Halden Boiling Water Reactor in Norway has created a renewed focus on the advanced instrumentation activities scope. Especially on the establishment of capabilities in the U.S. that can compensate for the loss of the Halden experiments and is an integral part of the NEET ASI program objectives and implementation strategy.

The development of in-pile instrumentation for MTR experiments is expected to lead to a disruptive evolution of demonstrated technological solutions for the measurement of core operational parameters in advanced reactors (neutron flux, temperature, pressure, vibration, etc.). Those will be combined to instruments deployed in other plant structures, systems and controls (SSCs) to support reliable and safe operation of nuclear energy systems. While the maturity of ex-core sensor is much higher due to their extensive use in the current fleet of nuclear plants, one of the lessons learned from existing plant operators is that significant modernization effort is required to accommodate advanced sensor technologies within the current plant system design requirements and in certain cases a design modification is expected or recommended. In addition, the installation of advanced sensors is expected to meet requirements on radiation tolerance, seismic qualification, power consumption to support long-term battery life, and cybersecurity. Therefore, one of the objectives of advanced instrumentation activities is to address such concerns during the demonstration phase to minimize risks and delays associated with their integration in nuclear plant operating I&C systems.

2.1.3 Approach

Research activities for advanced instrumentation development strive to use all funding mechanism available through NEET ASI in a complementary manner and implement efficient coordination with other DOE-NE programs to avoid as much as possible, duplication of effort. In this context it is useful to refer to the TRL scale presented in Figure 3 to describe the program approach in general terms:

- Competitive allocated projects target technologies not yet validated in laboratory environment (TRL 1–3)

- Direct-funded projects target the demonstration in relevant (TRL 6) and operational (TRL 7) conditions of the most promising technologies that emerge from (TRL 4) demonstration
- Other DOE-NE funding mechanism, such as those promoting technology commercialization or collaboration with the nuclear industry, are used to accelerate (TRL 7) demonstration when possible.

The approach also emphasizes the identification and timely execution of a development lifecycle for each technology based on TRL progression. Advanced solutions to the stakeholder needs are proposed mainly in response to competitive-funding opportunity announcements. Feasibility is demonstrated in laboratory testing with project awards with a typical duration of 3 years. The most promising technologies that best align with the program mission are then demonstrated in relevant conditions through direct-funded projects focused on irradiation testing. Demonstration is implemented by a staged approach that utilizes different test facilities with increasing complexity and relevance to nuclear plant conditions. Access to test facilities may be complemented by projects awarded by the Nuclear Science User Facilities program and through competitive-funding opportunity announcements. In a first-phase ion beam irradiation, focused particle sources and low-power research reactors may be considered. When relevant to the targeted application, the instrument is then tested to assess its response to transient events. The Transient Test Facility (TREAT) at Idaho National Laboratory (INL) is primarily used for such experiments. Also, irradiation in TREAT can be considered for screening test of instruments response to radiation effects at low-integrated fluence because of convenient access and flexibility in accommodating complex or otherwise intrusive measurement systems.

For similar reasons, the research reactor at the Massachusetts Institute of Technology can provide an intermediate demonstration step with neutron flux relevant to pressurized water reactor operating conditions, but without the accumulated fluence necessary to demonstrate long-term performance and reliability. The INL Advanced Test Reactor and Oak Ridge National Laboratory High Flux Isotope Reactor are the designed test facilities to demonstrate performance in relevant and operational conditions. The end user application for the technology must be identified during the demonstration phase because the test plan (radiation levels, environmental conditions, etc.) depends on the targeted application. In addition, priority for direct funds consideration is largely based on the interest of one or more stakeholders in adopting it. Therefore, in most cases the hand off from NEET ASI projects is a seamless process that utilizes existing funding or contractual mechanism within the DOE-NE portfolio, for example, Technology Commercialization Funds for hand off to a commercial instrumentation supplier or industry Funding Opportunity Announcement (iFOA) for hand off to the nuclear industry.

Based on previous experience and projections from ongoing projects, a 5-year life cycle within the NEET ASI program is estimated as a general case for innovative technologies that still requires feasibility demonstration for nuclear applications. This period is used in the development of the program timeline. Ongoing direct-funded projects prioritize technologies for which feasibility has already been demonstrated, either because are commonly used for non-nuclear applications or because they have been developed as part of other programs. Therefore, in many cases the hand off to external stakeholders is expected in parallel with the development of innovative technologies. In addition, it should be noted that support activities must be considered during and after the hand off to stakeholders, for example to implement integration in I&C systems or experiments design or to perform instruments fabrication and calibration. Therefore, it is foreseen that the service component of the NEET ASI program will grow in time as technologies have been matured and are utilized by stakeholders.

The implementation of research activities is organized in three main categories:

1. The development of instruments to measure plant operational parameters (in and ex core), such as neutron flux, temperature and pressure. Instruments are designed and demonstrated in MTR irradiation experiments, but ultimately adopted by program stakeholders for integration in the I&C systems of advanced nuclear plants. The primary path to close the technologies lifecycle within the NEET ASI program is through commercialization.

2. The development of measurement systems for real-time characterization of nuclear fuel and material properties in MTR test. These activities are derived from the analysis of existing gaps performed in collaboration with DOE nuclear fuel and materials development programs. The measurement needs can be represented as the overlap of the measurement of material properties (thermal and mechanical properties, chemistry), the characterization of the material microstructure, and the prediction of the material behavior by modeling and simulation. The primary path to close the technologies lifecycle within the NEET ASI program is by adoption to other DOE-NE programs. However, the commercialization of novel instruments for components lifetime prediction (instruments for Non-Destructive Examination [NDE], early fault detection, etc.) is also expected.
3. The development of testing systems to demonstrate instrumentation performance in relevant and operational conditions, following the approach previously described. The primary focus is on experiments to be performed in the mentioned irradiation facilities. However, out-of-pile tests are also included when necessary to satisfy the requirements for deployment in MTRs. The capability to instrument irradiated fuel rods and the development of a test rig for performance demonstration of instruments in the Advanced Test Reactor and High Flux Isotope Reactor are considered key elements to implement the program mission.

2.1.4 Benefits

The benefit to DOE stakeholders of this strategy focused on near-term needs and deployment in MTR test is three-fold:

1. Accelerated completion of industry and DOE RD&D programs (GAIN objective). Real-time instrumentation that enables innovative methods of performance characterization can provide a dramatic acceleration of irradiation test programs with respect to the current approach based on post-irradiation examination and time/space-averaged analysis. The availability of higher resolution data also enables a new level of synergy between experiments and modeling, with additional acceleration of research and demonstration activities.
2. Demonstration of innovative sensor technology capabilities in relevant and operational conditions of nuclear systems toward their integration in existing and advanced reactors. Utilities and nuclear vendors are reluctant to adopt innovative technologies because of the high risk and cost associated with development. Therefore, the completion of technology demonstration (TRL 6 or 7) achieved through irradiation tests in MTR is crucial to the nuclear industry to reduce the risk of integrating novel measurement methodologies in existing and advanced nuclear plants.
3. Accumulate operational experience and qualification data towards licensing assessment. The sensors designed for MTR test may not be directly applicable to power plant operation. For instance, they may be unacceptably intrusive, have limited lifetime and reliability, and be excessively costly. However, the experience and experimental data drawn from their near-term development, fabrication, and deployment will be extremely valuable to the nuclear industry to make the case for their utilization within the plant licensing case, in addition to the inherent maturation of the technology mentioned before.
4. Support DOE-NE R&D programmatic needs, such as fuel and materials studies, integral tests.
5. Provide new capabilities for measurement, such as sensors for harsh environments, to support advanced control capabilities, semi-autonomous and fault-tolerant operation, and predictive analytics.
6. Address R&D needs for successful deployment, such as digital technology and instrumentation qualification.

2.1.5 Expected Capabilities/Outcomes

Timeline for research activities and expected outcomes are defined through the engagement of specific program stakeholders. The maturation of sensor technologies according to the research approach outlined in the previous paragraph is the underlying objective of research and development activities, which are prioritized on a yearly basis based on stakeholders needs.

The development of real time instrumentation for irradiation experiments designed to test novel forms of nuclear fuel and related materials (such as cladding) has been an important component of this research area. Related stakeholders include nuclear fuel developers for the existing fleet of reactors (such as Framatome, General Electrics and Westinghouse) and advanced reactors (such as BWXT, General Atomics and Lightbridge), utilities or representatives organizations, such as EPRI, and DOE NE programs centered around the Advanced Fuel Campaign, including the Accident Tolerant Fuel program. The following are the primary elements of the timeline for the NEET ASI program support that has been developed in response of these stakeholder needs:

1. (2018–2021) Demonstrate the performance of a small set of mature sensor technologies for integration in transient irradiation test performed at the INL TREAT facility. These include thermocouples and optical fiber pyrometry for temperature and LVDTs for fission gas pressure and fuel assembly elongation.
2. (2019–2021) Develop a prototype facility to enable the deployment of instrumentation in irradiated fuel assemblies. An aggressive schedule has been defined based on ATF program needs to allow testing of irradiated fuel (in end of life condition) in TREAT to characterize the response to accidental conditions (i.e., Reactivity Insertion Accidents and Loss of Coolant Accidents). The prototype facility will focus on mature technologies at first (thermocouples and LVDTs), but extended operation beyond 2021 will enable to assess the feasibility of including advanced sensors as they become available through maturation as part of the R&D lifecycle described earlier.
3. (2019–2022) Demonstrate the performance of a small set of sensor technologies to support ATF irradiation tests in ATR. These include SPNDs for neutron flux, thermocouples and ultrasound thermometers for temperature, LVDTs and optical fiber sensors for fission gas pressure and fuel assembly elongation and electrochemical impedance spectroscopy for material chemistry characterization. Target experiments include those planned for the ATR central loop (existing capability) as well as those foreseen in two additional positions of the ATR core (Iloops). They include instrumentation deployed in the ATF experiments as well as supporting measurements in the testing loops (such as water coolant chemistry) and surrounding elements (such as neutron flux sensors in adjacent I positions).
4. (2019–2023) Develop the capability to test developmental instrumentation in conditions prototypical to MTRs irradiation test. The phased approach include: access to coolant channels of the TREAT facility (achieved in 2019); access to MITR experiment (2018–2023, ongoing through the NSUF program and planned as part of planned collaborative activities with MIT); development of instrumented irradiation vehicles for the HFIR at ORNL (2022–2023); development of a third test rig in ATR I positions dedicated to instrumentation test (2020–2023).

As the NEET ASI program continues engagement with stakeholders (identified in Section 3) it is expected that integrated timelines similar to the one defined above will be developed. The following are additional outcomes stemming from ongoing or preliminary integrated planning activities:

- Support to the Nuclear Science User Facility program to provide passive sensors to measure integrated neutron fluence and peak irradiation temperature for irradiation experiments in ATR without instrumentation leads (2018–2020). A process to integrate NEET ASI instrumentation in more complex irradiation experiments is being defined based on the ongoing contribution to the DISECT experiment in the BR2 test reactor at SCK, Belgium.

- Support the development of instrumented Verification and Validation experiments for simulation tools developed by DOE NE programs (i.e., NEAMS) or other stakeholders. The successful application of laser-based Resonant Ultrasound Spectroscopy (RUSL) to in-pile test in TREAT in 2019 demonstrated the impact of the novel measurement approaches considered as part of NEET ASI. The definition of an integrated timeline is a priority of the program activities in FY 2020.
- Further definition of the engagement with the Versatile Test Reactor project and the Joint Use Modular Plant program are expected in FY 2020.

2.2 Advanced Control Systems

Instrumentation and control systems (I&C) are the nervous system of nuclear power plants and nuclear facilities. They monitor all aspects of a plant's behavior and communicate information to plant operators for a timely response to many foreseeable conditions. They also serve a vital role in materials test reactors to measure environmental conditions of irradiation-based experiments, and to monitor aspects of fuel and materials behavior used to develop and qualify new fuels and materials for future nuclear energy systems.

2.2.1 Goals

The focus of this NEET-ASI technical thrust is to develop and enable real-time control of plant or experimentation process variables to enhance plant thermal performance and to reduce operation and maintenance (O&M) costs through advanced risk-informed approaches to monitoring and control.

Control systems of past, present, and future can be broadly categorized as analog, mix of analog and digital, and digital, respectively. It is understood that advanced digital control system implementation is expected in current and future nuclear energy systems to address human factors concerns by supporting new concepts of operations to reduce operating costs by enhancing plant thermal performance, address regulatory considerations, and focus on advancing R&D-related digital control systems. Many aspects of digital control technologies are challenging in their implementation and adoption. These include common cause failures—both hardware and software, inclusion of digital control system with embedded intelligence, cybersecurity, and development of instruments and actuators that can handle harsh reactor conditions (e.g., high dose, high temperature, high flow).

Specific objectives of research activities under this technical thrust area include the development of advanced control system technology to enable:

1. Semi-autonomous operation that will enable a meaningful reduction in overall costs, especially for small modular reactors and microreactors where O&M as currently practiced do not scale favorably with reactor size.
2. Fault-tolerant control system operation, particularly for the case of digital implementation and where inherent feedback mechanisms are part of the safety case.
3. Performance-based control algorithms that make use of operating history data to improve plant economics through increased availability and energy output.
4. Optimal control for dispatch and unit commitment of nuclear systems with multiple products (e.g., electricity and process heat) and/or for load following and energy storage.
5. Control and safety systems that are cybersecurity-enabled through hardware and software design.

2.2.2 Challenges

There are challenges that must be addressed if these objectives are to be met. Research is needed in the following areas.

1. Understanding the altered role of the human in the control loop given a transition from automatic operation to autonomous or semi-autonomous operation. This includes human factors understanding of the altered man-machine interface to ensure workload is properly allocated and situational awareness is maintained.
2. Understanding the role and potential limitations of artificial intelligence methods for achieving semi-autonomous operation.
3. Verifying and validating software used for digital control to address regulatory issues. Solutions are needed that either provide alternate means to validate code logic or make exhaustive testing of code logic manageable.
4. Vetting from a safety perspective the impact transitioning actions from operators to automation or automata. This will include probabilistic studies to understand the risks and the success paths for recovering from upset conditions. For advanced reactors that rely on inherent feedbacks for increased safety, it must be shown that the plant control system cannot act to override this design feature.
5. Develop advanced controls that improve plant performance by comparing operating history and physic-based models. These solutions must provide adequate control during normal and off-normal operation to ensure expected operational and safety limits are maintained.
6. Develop economic optimization controls or decision systems needed by nuclear plants to safely delivers multiple products to the electricity and commodity markets.
7. Adapting to continually evolving cyber threats is a challenge for a plant control and safety system that is traditionally designed to protect against static threats.

2.2.3 Approach

The advent of powerful modeling and simulation tools and almost unlimited computational power have opened new frontiers in O&M that challenge current practices and have great potential to lower costs and improve safety and reliability. The notion of the "digital twin" lies at the heart of the many possibilities that are potentially transformational for how technical staff and the supply chain are managed for improved economics and safety. The digital twin concept can facilitate O&M procedures that are risk-informed and aimed at maintenance optimization and asset management with the goal of reduced cost through improving the supply chain lifecycle.

Semi-autonomous operation enabled through the digital twin concept presents opportunities for a significant reduction in costs to operate and maintain a nuclear power plant. Semi-autonomous operation transfers decisions that involve judgement currently performed by humans to the machine. It may include risk-informed approaches to control, incorporate passively safe responses to upsets, and provide for fail-safe modes of active control. A provision for semi-autonomous operation should begin at the plant design stage where the control strategy is developed, and the plant sensor set is assigned.

The following list identifies concepts and approaches that are tied to the objectives within this research area:

- Integrate risk-informed methods and uncertainty analyses to better manage response during upset events to minimize challenges to the protection system. This could entail probabilistic studies to understand the risks and the success paths for recovering from upset conditions.

- Progress from automatic to semi-autonomous operation through a series of individually proven steps. Automate plant surveillance, potentially using AI techniques, such that the human role is elevated to one of maintaining high-level situational awareness.
- Increase use of modeling and simulation tools for exploring scenarios.
- Approach the control system design task as a supervisory task that employs sophisticated model-based control algorithms to realize greater control capability compared to the use of single-input single-output feedback loops that exist in current plants.

Contributions and advances coming from other DOE programs include:

- Sensors and communications in NEET ASI
- Diagnostics with uncertainty treatment in NEET ASI
- Improved modeling and simulation tools across time scales from Nuclear Energy Advanced Modeling and Simulation (NEAMS)
- Machine learning integration with physics-based models from NEAMS
- Cyber security in NEET Cyber.

2.2.4 Benefits

Benefits to DOE-NE stakeholders from the R&D in this thrust area include:

- Improved staffing economics for microreactors under Advanced Reactor Technology (ART)
- More reliable operation using digital control under LWRS
- Development of control technology for IES
- Transfer of advanced I&C technology innovation to advanced reactor vendors.

2.2.5 Expected Capabilities/Outcomes

The planned R&D activities within this research area are expected to address current challenges in advanced control. This will proceed first through technology development (competitive) to be followed by technology demonstration (programmatic). The tools and concepts described above will drive research activities supporting the following accomplishments:

1. Development of a simulation platform, or adoption of an existing one, to support development, testing, and demonstration of advanced control technologies for application to a use case. Use case to be defined for an advanced reactor concept under development in an existing DOE-NE program (2–3 years).
2. Demonstration on the simulation platform of the following supporting technologies for the use case (3–4 years):
    a. Advanced sensing, communication, and machine learning and artificial intelligence (ML/AI) technologies providing a richer awareness of plant state for improved detection and diagnosis.
    b. Advanced control technologies providing greater operational flexibility and upset response.
3. Demonstration of semi-autonomous operation concepts on the simulator platform for the use case that address future operational needs that include (4–5 years):
    a. Upset management enabled through the four steps of detection, diagnosis, control, and recovery.
    b. Flexible operation in an integrated energy system enabled through advanced control algorithms.
    c. Human factors principles that enable situational awareness in semi-autonomous operating environments.

4. Risk-informed strategies for semi-autonomous operation that address regulatory hurdles (1–5 years).
5. Design methods that circumvent the need for, or simplify to the point where manageable, an exhaustive verification and validation (V&V) of digital software for safety systems (1–5 years).
6. 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 (1–5 years).
7. Supervisory and artificial intelligence control architectures that support reactors with multiple product streams and energy storage systems for load leveling (1–5 years).
8. Human factors framework for understanding the role of the human in plants using semi-autonomous operation to reduce staffing and/or reallocate staffing to a remote operations center (1–5 years).

2.3 Communications

Advanced instrumentation in Section 2.1 will collect salient measurements at different temporal and spatial resolutions (along with unique material characteristics or reactor process information) to support operations and control strategies of nuclear power plants. These salient measurements collected at different resolutions used to achieve remote, autonomous or semi-autonomous operation of advanced reactors, enable low operation and maintenance costs along with flexible operation, and expanded applications and market for nuclear energy system. To achieve these advancements, RD&D in the area of communication is required, to achieve reliable transmission and availability of the right information, in the right format, at the right time, and to the right person.

2.3.1 Goals

The goal of the communication area is to develop a resilient, secure, and real-time transmission of sufficient data for online monitoring, advanced control, and big data analytics. The R&D activities in this area are categorized in wireless, wired, and passive communications. Advancements in wireless communication technologies are starting to gain momentum in nuclear energy systems to enable remote, autonomous or semi-autonomous operation, online monitoring, inspection, security, and flexible operation to enhance plants operational efficiency and economics, without compromising on its safety and reliability. To achieve automation, plants are beginning to leverage the advancements in wireless communication technologies as the cost to deploy wired sensors is prohibitive. Wireless communication is an attractive option outside the reactor vessel but not for near-vessel and in-pile communication of information.

Specific objectives supporting successful accomplishment of goals in this thrust area include:

- Understanding the communication requirements of advanced reactors based on its design and operating conditions
- Optimal placement of access points to ensure data is available at required quality of service
- Electronic system supporting different communication technology has capability to adapt to different operation conditions
- Simulation tools that can emulate behavior of different communication technologies under different operating conditions is necessary.

2.3.2 Challenges

The challenges that needs attention in communication research area are:

- As nuclear energy system adapts wireless communication, it has become apparently clear that the "one size fit all" rule is not valid because wireless technologies are varied, and their utilization are application specific. In a nuclear plant site, different functional aspects are supported by different modes of wireless communication that operate at different frequencies and utilize different protocols. For example, frequency requirements for long-term evolution cellular signal support are 700 MHz to 1800 MHz, for LoRAWAN are 900 MHz; for Wi-Fi communication are 2.4 GHz to 5 GHz, for radio frequency identification are 300 MHz to 3000 MHz, and for millimeter Wave are 30 GHz to 300 GHz. These communication technologies support different communication range and bandwidth requirements that, in turn, translates to different power requirements.

- The electronic system to support wireless communication that are commercially available or under development are not designed nor tested to withstand the harsh environment in which they will be deployed.
- The size of the electronic system (i.e., transceiver) needs to be miniaturized to meet the design requirements of advanced reactors, including small modular reactors and microreactors.
- The design of the electronic system needs to be optimized with respect to power requirements so they can operate reliably at extremely low power.
- The design of communication system needs to address inferences and cyber concerns to ensure resilient and reliable transmission of information.
- For in-pile applications, wireless communication relying on radio frequency to transmit the information from inside of the reactor to the outside is not an option. Wired, passive, or induction-based communication system needs to be developed to enable in-pile wireless communication.
- Irrespective of data communication technology adapted by a nuclear facility, research is required to ensure data security.

2.3.3 Approach

To address the challenges of this thrust area, the following set of approaches are recommended by taking advantage of modeling and simulation tools.

- R&D in multiband wireless communication technologies and necessary infrastructure to co-host them is required. The multiband wireless communication technologies ranging from low power to high power, low-frequency range to high-frequency range, and short-range to long-range communication is encouraged in existing and future nuclear energy systems. It is envisioned that R&D multiband wireless communication technologies are expected to 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.
- R&D to support passive communication that supports transmission of information through plant structures and components. It is an effective non-intrusive mean of data communication from inside of the reactor to the outside of reactor.
- Fiber optics is one of the attractive blocks in the telecommunication infrastructure. Its high-bandwidth capabilities and low-attenuation characteristics make it ideal for gigabit transmission and beyond. The application of fiber optics in nuclear environment is gaining momentum, especially to address the needs of future reactor designs. R&D activities are required to evaluate and minimize radiation-induced aging to optical fibers, develop new fiber materials that have stable structural property when exposed to high radiation and high temperature, and develop methodologies to support deployment and demonstration of fiber-optic-based communication for safety-related functions within nuclear facilities.
- Testbed to validate and verify communication in a representative nuclear environment. This will also provide a platform to validate and verify modeling and simulation assumptions and update the communication models.
- R&D is required to develop, validate, and demonstrate metrices that ensure secure transmission of data and its availability at remote site for decision-making. The metrices must be simple and demonstrable to achieve regulatory approval.

2.3.4 Benefits

- Enable network architecture would support seamless transmission of information to support development of autonomous controls and big data analytics
- Provide a computation tool that is scalability to support incorporation of new protocols
- Provide efficient communication to enable development of data lake comprising of temporally and spatially distributed data
- Enable availability of information on demand to support just-in-time decision making
- Reduce O&M costs
- Reduce human in the loop responsible for data collection, transmission, storage, and processing.

2.3.5 Expected Capabilities/Outcomes

Expected major capabilities and outcomes from this work are categorized into technical advances and infrastructure advances:

1. Understand technical challenges and needs of wireless communication for advanced reactor technologies (1–2 years)
2. For identified technical challenges and needs, development of communication framework supporting multi-band frequency network architecture (2–3 years)
3. Develop metrics to evaluate resilience, reliability (data availability), latency, coverage, connectivity, and throughput of a network prototype under different operating condition (2–3 years)
4. Produce computational model to design inductive coupling communication and to better understand its merits and demerits to support in-pile or near vessel communication (2–3 years)
5. Model electronics system to support their design, development, and printing. To evaluate the performance under different operating conditions (3–5 years).
6. Develop a testbed to validate multiband network architecture to demonstrate and qualify multi-frequency communication (2–3 years)
7. Provide guidance/best practices for installation of wireless infrastructure at a plant site (1–2 years)
8. Establish testbed to support non radio frequency communication that includes fiber optics and induction-based transmission (2–4 years)
9. Evaluate resilience, performance, and cyber metrics (3–5 years).

2.4 Big Data Analytics, Machine Learning, and Artificial Intelligence

Data analytics technologies, including machine learning and artificial intelligence (ML/AI) techniques, are an enabling technology for advanced nuclear power systems. These technologies support the extraction and presentation of relevant information from a diverse set of existing and new sensors and enable the application of this information for decision making in O&M for advanced nuclear energy systems.

The focus of this NEET-ASI technical thrust is to develop advanced data analytics methods, to include ML and AI techniques, to enable emerging applications in nuclear energy. Examples of emerging applications in nuclear energy include but are not limited to, semi-autonomous control systems and operations, predictive maintenance, advanced reactor design optimization, and physical and cyber-physical security.

2.4.1 Goals

The goal of research activities under this technical thrust area is to enable reliable autonomous explainable decision making. To this end, this thrust area addresses current and emerging needs in algorithms and infrastructure and leverages technical developments in other applications. As with all NEET-ASI research, the results from this thrust area are cross-cutting and, with some customization, applicable to multiple reactor and fuel-cycle R&D programs within DOE-NE's portfolio.

Data from nuclear facilities tend to be heterogeneous and unstructured, distributed spatio-temporally, and recorded with varying levels of fidelity (including through non-uniform sampling). The diversity in sensor types and modalities, locations, data formats, and sample rates, challenges the ability to perform timely analysis on these data streams to extract actionable information. Of particular interest is the ability to use the information extracted from these data streams to quantify the state of the nuclear system (including diagnosing any degradation in component or system health), forecast its future state including the probability of failure and uncertainty associated with the prediction, and identify options for operational actions based on the current and future states of the system. In general, this decision support should be capable of addressing a diverse set of conditions that the nuclear system may encounter, while ensuring that operational safety, security, and safeguards are not negatively impacted. At the same time, a goal is to improve the economics of operation in a quantifiable manner.

To achieve these goals, the objectives of this technical thrust address specific gaps that are barriers to wider adoption of advanced data analytics and ML/AI technologies in nuclear energy systems:

1. Assured ML/AI technologies for anomaly detection, diagnostics, prognostics, and decision making that can operate on streaming data, quantify their uncertainty, are verified and validated (models and the data used to train), identify the bounds of their expertise, and are explainable (meaningful latent variables can be identified in a dimension reduction process).
2. Scalable ML/AI methods that may be applied to data sets that are spatially and temporally heterogeneous and unstructured.
3. Continuously learning ML/AI models that continue to improve with experience in a quantifiable, explainable manner. Such algorithms are expected to be useful in cases in nuclear systems where the amount of labelled data for all conditions/cases is not large enough for typical deep learning or other algorithms that rely on numerous examples of each type.
4. Deployable ML/AI technologies that secure and resilient.
5. AI for learning/inferring decision logic for operator support, enabling semi-autonomous or fully autonomous operation. Developing such methods will be particularly important for decision-making under uncertain or unexpected system conditions.
6. 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.
7. Best practices guidance, along with consensus standards where applicable, for verification and validation, qualification, and deployment of ML/AI solutions in for the nuclear fuel cycle (defined here as encompassing the fuel fabrication, use, and spent fuel dispositioning, and include design, fabrication, and operation/maintenance of reactor and fuel cycle facilities).

2.4.2 Challenges

Challenges that will need to be addressed to achieve these goals include:

1. Systems and data sets that are heterogeneous, and not easily accessible by the research community. Also, data from current systems may be obtained, there is a lack of data from advanced reactors making it difficult to develop, test, and qualify approaches for these reactors.

2. Available data sets and testbeds are often not well-documented, integrated, or comparable. Access to annotated data sets also can be challenging.
3. The amount of data available from a nuclear system can vary, depending on the facility and subsystem under consideration. In most instances, necessary sensors may not be optimally located. Algorithms that are capable of scaling with the amount of available data are important, as are approaches that can learn incrementally to continuously improve their performance.
4. ML/AI technologies for system monitoring and operational decision making will require insights into the decision logic used by the algorithms. Critical to this will be 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.
5. ML/AI technologies for system monitoring and operational decision making will require algorithms and approaches that can use available information (including system operational models) to generalize beyond the training data set to conditions not encountered in the training data. An example of this would be operator support tools that can provide actionable information for plant conditions that may not have been included in the algorithm training set.
6. Methods for V&V of the algorithms and the software for diagnostics, prognostics, and decision making, including digital twins and other related technologies, will be necessary to quantify their performance, generalizability, and scalability, and for regulatory purposes. Objective metrics are necessary for this purpose. V&V is also important prior to deployment to ensure that the algorithms are capable of achieving necessary performance goals.
7. The development of ML/AI technologies for system operation, especially semi-autonomous operation, will change the role of the human in the control loop and the implications of this need to be understood. Human factors studies are needed to understand the altered man-machine interface and to ensure workload is properly allocated.
8. Data-related policies, including storage methods (compression, reconstruction, etc.), sustainability of repositories over the long term (>10 years for the purpose of this plan), and anonymization approaches for facilitating access to the research community, etc. Some of these issues are also driven by the need to maintain reasonable records over the lifetime of nuclear facilities.

2.4.3 Approach

As discussed in other thrust areas in this document, the notion of the digital twin lies at the heart of many possibilities for autonomous O&M. However, technical advances in integrating the physics of nuclear systems with ML algorithms; scalable algorithms for anomaly detection, system state quantification and prediction; technologies for human-machine interaction; AI algorithms that can not only describe how a decision or conclusion was reached but also quantify the limits of their knowledge; and algorithms that continuously learn from data and models are needed to make the vision of autonomous nuclear systems a reality. These enabling technologies, when integrated with complex modeling and simulation and high-performance computing (HPC) will facilitate the development of digital twin technologies as well as AI for complex decision making, which enables semi-autonomous operation and predictive maintenance.

Specific approaches to addressing the technical objectives and challenges identified above include:

- Fundamental R&D (through the Consolidated Innovative Nuclear Research [CINR] Funding Opportunity Announcement [FOA]) for algorithm development in scalable, assured ML/AI, including physics-informed ML.

- Participation in national and international conferences and workshops to disseminate findings from his program as well as to baseline the R&D results from the program against advances from other programs/agencies.
- Expert elicitation (through focused workshops) to evaluate emerging needs for ML/AI in nuclear energy and to elevate previously unidentified challenges.
- Infrastructure development to enable development and testing of ML/AI technologies
  - Development of benchmark or reference data sets and testbeds for use in algorithm development and performance quantification. Data sets would need to include anomaly detection and predictive maintenance applications, as well as semi-autonomous operations. Testbeds to demonstrate and deploy semi-autonomous operation and the human-algorithm interaction are also necessary, along with testbeds to demonstrate economics of predictive maintenance. Testbeds may be physical or virtual, with virtual testbeds (consisting of modeling and simulation environments) useful for demonstrating technologies for advanced reactor or fuel-cycle systems. Reference problems (such as automatic control or semi-autonomous operation/control for advanced reactors) may be included as part of the testbed.
  - Development of software modules/libraries for ML/AI that can be executed on HPC systems. Such libraries may be made available to researchers for developing scalable ML/AI and may provide a path to deployment of ML/AI tools that learn from fleet-wide experience and apply the insights to benefit a specific facility.
  - Metrics to quantify performance of ML/AI algorithms that can be used in objective evaluations of performance, or for qualification purposes, and regulatory review and acceptance of the technology.
- Transition of selected ML/AI technologies from fundamental research to applied problems, with formal V&V. The development of a mechanism for this transition will allow for rapid movement of technology from basic R&D to prototypes that are available to industry for adoption.
- Work with other programs/offices within DOE (such as Artificial Intelligence and Technology Office, Fossil Energy, Advanced Research Projects Agency-Energy, and Office of Energy Efficiency & Renewable Energy) to leverage advances from other applications and identify cross-sector opportunities to deploy technologies developed by this program.

Potential contributions and advances coming from other DOE programs include:

- Other technical thrusts in NEET ASI (advanced sensors, controls, and communications)
- Improved modeling and simulation tools across time scales from NEAMS/CASL/Mod-Sim-X
- Machine-learning integration with physics-based models from NEAMS/CASL/ModSim-X
- Machine-learning tools and technologies across LWRS, ART, and Integrated Energy programs
- Testbeds from ART and Microreactors
- Cybersecurity research in NEET Cyber
- AI/ML R&D across other DOE offices and from other agencies.

2.4.4 Benefits

Benefits to DOE-NE stakeholders from the R&D in this thrust area include:

1. Accelerated completion of industry and DOE-NE RD&D programs. ML and AI algorithms for real-time analysis and decision making enable rapid performance characterization for measurements from advanced sensors in irradiation test programs. Algorithms that incorporate explainability (explainable

AI) provide insights into complex system behavior and help accelerate RD&D activities for advanced reactors and enable improved synergy between experiments and modeling.

2. Demonstration of innovative ML/AI technology capabilities for applications relevant to robust control and autonomous nuclear systems operation towards their integration in existing and advanced reactors. Utilities and nuclear vendors are reluctant to adopt innovative technologies because of the high risk and cost associated with development. In particular, the completion of technology demonstration (TRL 6) requires testing for prototypical conditions before integration in the intended system (TRL 7–9). In the case of ML/AI, the need is for technology development and demonstration of generalizability of algorithms and results to help build confidence in the use of ML/AI in the nuclear industry. For nuclear application this means developing and testing algorithms with data collected under typical plant operating conditions (neutron and gamma flux, temperature, pressure, flow, and materials).
3. Accumulation of reference data bases for use in ML/AI algorithm development, performance quantification, and qualification is expected to be a supplementary benefit. Such data sets might be from testbeds (either established within this program or from other DOE-NE R&D programs). Results from this program may also provide requirements for data, for use in the design phase of testbeds being established through other DOE-NE R&D programs.
4. Methods for sensor selection and optimizing location of measurements to enhance the ability for applying ML/AI and data fusion algorithms. Such insights may benefit advanced reactor designs with the sensor and instrumentation design and placement incorporated into the design phase rather than being a post-design decision.

2.4.5 Expected Capabilities/Outcomes

Expected major capabilities and outcomes from this work are categorized into technical advances and infrastructure advances, which include:

1. Development of prototypic algorithms for anomaly detection, diagnostics and prognostics, and autonomous decision making, demonstrated through application to a simplified nuclear system or process (1–2 years)
2. Demonstration of ML/AI-enabled reduction in O&M costs for a pilot nuclear system or process (2–3 years)
3. Demonstration of methods for assured ML/AI (3–4 years)
4. Hardware-in-the-loop demonstration of robust autonomous control of a reference nuclear system (4–5 years).
5. Data sustainability policies and best practices (1–2 years)
6. An annotated initial set of benchmark data sets from a subset of nuclear facilities published online (2–3 years)
7. Set of ML/AI tools with standardized interfaces, capable of leveraging DOE HPC facilities (2–3 years)
8. Guidance/best practices for national testbeds for demonstrating and qualifying ML/AI-enabled digital twins and semi-autonomous operations (3–4 years)
9. 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, nuclear materials manufacturing, and nuclear fuel cycle processes (5+ years).

3. STAKEHOLDER ENGAGEMENT

Previously, this program has adopted a systematic engagement strategy with existing and future nuclear energy system owner/operators, industry support organizations, and other DOE-NE programs. These engagements have been essential and instrumental to ensure that the R&D activities of this program are relevant and of the maximum impact for existing and future nuclear energy systems. The goal of this engagement strategy is to develop a shared vision between different stakeholders and DOE-NE programs. To support this strategy, this program is involved in specific engagement opportunities. These include:

- Annual Advanced Sensors and Instrumentation Webinar is held the first quarter of each fiscal year and serves as the annual review of the ASI projects, and seeks to identify new areas of technical collaboration that supports DOE-NE R&D programs and promote greater coordination among the various programs on topics of sensors, instrumentation, controls, and related technologies. https://www.energy.gov/ne/downloads/2019-advanced-sensors-and-instrumentation-webinar

- Quarterly Advanced Sensors and Instrumentation Newsletters provides information on Instrumentation and Controls, sensors, and related technology research being funded by DOE-NE and will provide readers with updates on NE's research, development and demonstration activities. https://www.energy.gov/sites/prod/files/2019/10/f67/ne-asi-newsletter-sept-2019.pdf

- Presentation of research results at the American Nuclear Society Topical Meeting on Nuclear Plant Instrumentation and Controls and Human-Machine Interface Technologies Conference, and the annual American Nuclear Society Utility Working Group Conference
- Other international conferences venues, such as the International conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA)
- One-on-one meetings with stakeholders, major industry support organizations, namely, Electric Power Research Institute, the Nuclear Energy Institute, the Institute of Nuclear Power Operations, and the Nuclear Information Technology Strategic Leadership, and regulatory agency
- DOE-NE sponsored workshops have been held to exchange of information among advanced nuclear technology developers, commercial instrument suppliers, and sensor researchers from DOE national laboratories, universities and industry. The goal for future workshops is to obtain nuclear industry input related to measurement requirements and needs for advanced reactor concepts.

The purpose of this engagement strategy is oriented to:

1. Identify issues and challenges in the research areas (Section 2) to support operation of existing fleet of light water reactors and enable advancements of future reactor technologies
2. Prioritize the research gaps and potentially address them through suitable federal funding
3. Enable other DOE-NE programs to leverage the research outcomes in enacting their respective mission and vision
4. Identify potential and right path for commercialization and deployment of the research to benefit the nuclear industry
5. Highlight and share major milestones and research outcomes with stakeholders and different DOE-NE programs
6. Review awarded project progress and provide technical inputs.

3.1 Collaboration and Stakeholders

The NEET ASI program have established collaboration and partnerships with several national and international research institutes, industry stakeholders, domestic universities, nuclear science user facilities, and national laboratories working on similar and awarded research projects to maximize its impact. These include the following:

National Research Organizations

- National Institute of Standards and Technology
- Southwest Research Institute
- Electric Power Research Institute

International Research Organizations

- International Atomic Energy Agency (IAEA)
- National Energy Agency (NEA)
- Korea Atomic Energy Research Institute (KAERI)
- Halden Reactor Project
- SCK-CEN
- CEA

Industrial Stakeholders

- Westinghouse Electric Company
- Flibe Energy
- Terrestrial Energy USA
- Kairos Power
- Terra Power
- Framatome
- GE Hitachi
- NuScale
- L3 Communications
- GSE Systems

U.S. Nuclear Plant Owners

- Exelon Generation
- Southern Company
- Xcel Energy
- Duke Energy
- Dominion Energy

Nuclear Science User Facilities

The program focuses support for programs within DOE-NE and program offices within DOE to ensure effective coordination and collaboration while achieving the stated program mission and vision. The program also focuses engagement with non-nuclear industries to understand the progress achieved by each industry in the research areas presented in Section 2. These include the following:

U.S Department of Energy Office of Nuclear Energy

- Light Water Reactor Sustainability Program
- Nuclear Technology Research and Development Program
- Accident Tolerant Fuels
- Advanced Fuel Cycle Program
- Advanced Reactor Technologies
- Nuclear Energy Advanced Modeling and Simulation Program
- Joint User Modular Plant – Part of the Integrated Energy System Program under the NEET CTD

U.S Department of Energy Program Offices

- Office of Science
- Office of Energy Efficiency and Renewable Energy
- Office of Fossil Energy
- Advanced Research Projects Agency-Energy
- National Nuclear Security Administration

Non-Nuclear Industries

- Aviation and Aerospace
- Oil and Gas
- Automotive
- Chemical

4. RESEARCH IMPLEMENTATION

The selected R&D within the NEET ASI program receive support opportunities: (1) competitive-funding opportunity and (2) direct-funding opportunity based on technology readiness and NEET program priorities.

The concept of technology readiness assessment is helpful for the classification of instrumentation technology as part of the program strategy. A technology readiness assessment evaluates technology maturity using the Technology Readiness Level (TRL) scale and was pioneered by the National Aeronautics and Space Administration in the 1980s for space technology (see Figure 4). It has recently been adopted to advance fuels and materials. The NEET ASI program objective is to mature (1) sensors, (2) advanced control systems, (3) communication, and (4) big data analytics, machine learning, and artificial intelligence technology to TRL 6, which is "demonstration of the technology in relevant environment." The program identifies gaps and technology challenges by engaging program stakeholders. While there may be instances in which a different strategy is justified, the aim of the program is to respond to DOE program and stakeholder needs for nuclear technologies then hand off the technology after demonstration for integration in a more complex system, for example an irradiation test, experimental loop or a plant component such as the core, primary system or heat exchanger. As research progresses NEET ASI will collaborate with the appropriate stakeholders during and after the adoption to develop the appropriate research paths within DOE to complement NEET ASI activities and extend the maturity beyond TRL 6, for example through GAIN, technology commercialization funding, and small-business programs, and integration with direct-funded program stakeholder demonstrations.

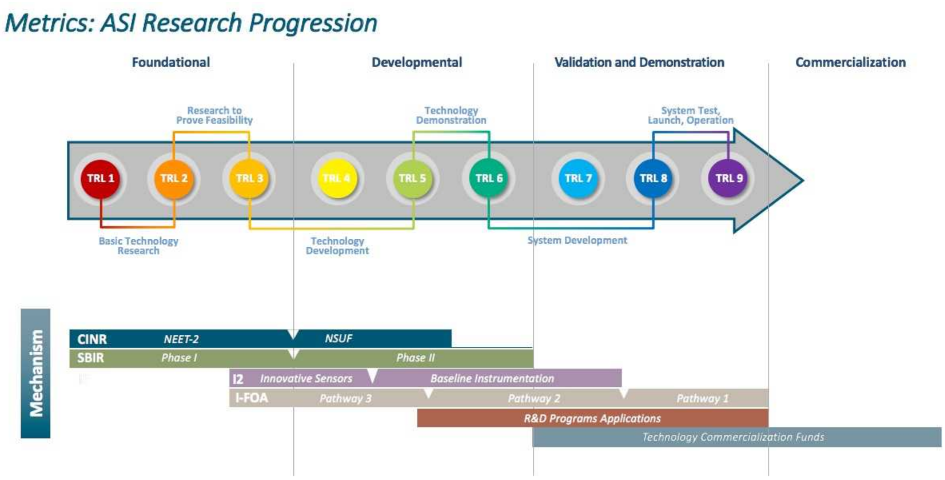

Figure 4. Technology readiness roadmap.

4.1 Competitive-Funding Opportunity

Competitive funding is provided under the DOE's Annual CINR FOA. Technical proposals in four research areas identified in Section 2 are requested to support CTD that directly support and enable the development of new and advanced reactor designs and fuel cycle technologies. U.S. universities and national laboratories are eligible to respond to the FOA as primary institution. Technical and relevancy review of the submitted proposals is performed prior to final decision making by DOE program manager.

- NEET-ASI
- Nuclear Science User Facilities 1.1 – ASI
- Small Business Innovation Research (SBIR) – ASI
- Technology Commercialization Funds Relevant to ASI.

4.2 Direct-Funding Opportunity

Each fiscal year, a list of projects or work packages to support R&D associated with baseline instrumentation capability, innovative sensors, integrated measurement systems, and infrastructures to enable development of sensors and instrumentation across different TRL is prepared and prioritized based on impact and stakeholders need. The following identified projects or work packages are consolidated as part of the integrated priority list and submitted to DOE-NE for review and approval:

- Sensors
- Advanced Control Systems
- Communication
- Big Data Analytics, Machine Learning, and Artificial Intelligence.

4.3 Budget Estimates

Since FY 2011, NEET-ASI has funded 36 projects competitively for a total of $30,006,253. These projects are successful in advancing the state of the art for measuring, controlling, and broadly managing nuclear energy systems being developed by the DOE-NE. Some of these technologies have the potential to impact systems and technologies beyond nuclear energy. They all address critical needs and gaps in current capabilities and are aimed at many of the highest priorities shared by different R&D programs. They include participation from several laboratories, universities, and industry. The eventual goal for this research is the deployment of these technologies in a manner that most benefits individual DOE-NE R&D programs, the nuclear energy industry, as well as other power generation sectors. As these research projects progress, the interest from stakeholders and industry has also increased, as have the number of individual technology deployments and partnerships.

Going forward, the program is expected to increase its annual budget to support direct-funded projects providing instrumentation capabilities for nuclear technology testing, validation and demonstration. In addition, the program is expected to select six to eight competitively funded awards over the next 3 years. To continue to refine and expand the scope of R&D activities, the program is developing an engagement strategy as described in Section 3, with other DOE-NE, program offices within DOE, and non-nuclear industries. Some of the funding will be allocated to support a workshop to expand the engagement strategy (see Figure 5).

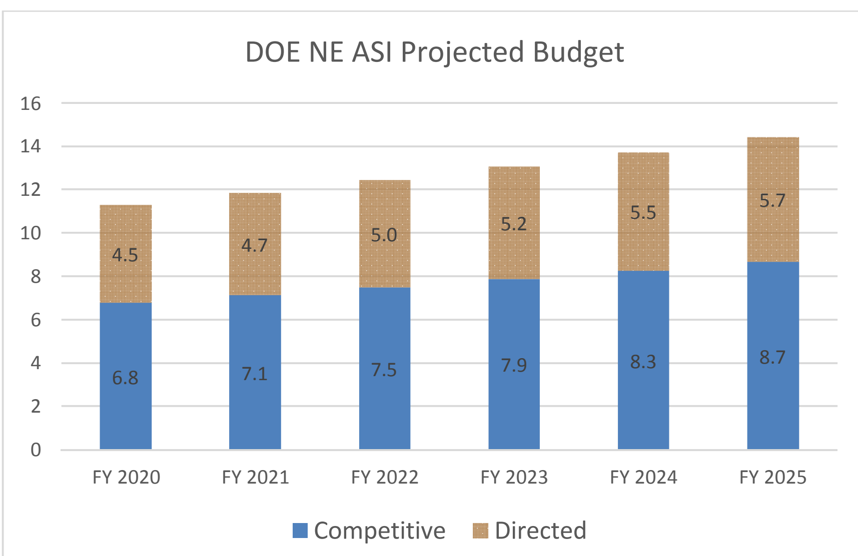

Figure 5. NEET ASI budget projection FY 2020–FY 2025.

5. RESEARCH SUCCESS METRICS

The NEET ASI program uses a number of metrics to evaluate the performance and success of a project and program. These include (1) external peer-reviewed publications, (2) internal and external recognition of the project based on its outcomes, (3) potential patent application filed and copyright submission, and (4) ability to secure other federal funding or funding from other DOE-NE programs and private industries.

5.1 Research Oversight

The projects that are selected based on the guidelines outlined in the CINR FOA are notified via a formal email notification to the principal investigator (PI) and announcement on the NEUP.GOV website. The PI of selected project develops a work package is the PICS:NE system for a period of performance of up to 36 months. Within the PICS:NE system, the PI is required to submit project activities and identify list of Level 2 and Level 3 milestones with a due dates as part of project deliverables. The PI is also responsible for submission of yearly annual report on project performance.

All the project deliverables reports associated with milestones are reviewed by DOE assigned technical point of contact (TPOC). The PI is expected to coordinate technical discussions and project progress with the assigned TPOC. At minimum, the TPOC is required to:

- Be present at the monthly review meeting to evaluate the project progress and provide feedback to enhance project outcomes
- Assist and provide recommendations to PI on any technical aspects of the project
- Review quarterly technical summary, milestone, and annual reports on the project and provide feedback to PI, National Technical Director, federal manager, and DOE-HQ program manager via PICS:NE
- Review the article to be published as part of the NEET ASI Newsletter.

The NTD interacts with TPOCs on a periodic basis to get an update on the project and address any issues or concerns related to the execution of the project. The NTD interacts with federal manager on weekly basis to provide update on the program and to discuss program-related activities.

The direct-funded projects have an assigned work package manager (also referred as principal investigator). The PI or work package manager is required to submit project activities and identify list of Level 2 and Level 3 milestones with a due date as part of project deliverables with the PICS:NE system. All the project deliverables reports associated with milestones are reviewed by the NTD to assess project progress and address any issues or concerns related to the execution of the project.

5.2 Methods and Metrics

The program achieves its goals through a combination of activities to help identify and prioritize research.

Criteria used to develop research scope include:

- Stakeholder Engagement (see Section 3)
- Diverse research funding mechanisms
- Collaborations (with other domestic and international entities, and between project teams).

Criteria used in the prioritization research include:

- Critical technical need being addressed
- Expected impact across multiple DOE-NE programs
- Ability to leverage prior research results.

5.3 Publications and Awards

The NEET ASI program encourages dissemination of research findings through peer reviewed publications, patent applications and technology transfer. The external peer-reviewed publications include conference proceedings, journal articles, and peer-reviewed presentations to stakeholders and to other DOE-NE programs. The external peer-reviewed publications include conference proceedings, journal articles, and peer-reviewed presentations to stakeholders and to other DOE-NE programs. The research projects funded by the NEET ASI program since 2014 have resulted in 98 peer-reviewed conference proceedings, 40 journal articles, 98 publications (published/posted), 9 awards/recognitions, and 6 patents (filed/awarded).

5.3.1 Awards

Some of the research projects had transformational impacts that lead to project or project team recognized nationally or internationally. The list of projects includes:

- GAIN Voucher Awards
  - Advancement of Instrumentation to Monitor IMSR® Core Temperature and Power Level (Terrestrial Energy USA, New York, New York)
  - Radiation Testing for Nuclear Inspection Systems (Vega Wave Systems, Inc. West Chicago, Illinois)
- I-FOA Award
  - Passive Radio Frequency Tags and Sensors for Process Monitoring in Advanced Reactors (Dirac Solutions Inc. Pleasanton, California).

5.4 Patent Application and Copyright

Some of the research outcomes have resulted in filing of a patent application and copyright.

- L. T. Clark, J. Adams, K. E. Holbert, "Secure True Random Number Generation Using 1.5-T Transistor Flash Memory," U.S. Patent 10,078,494, Sept. 18, 2018.
- Filed: D. McGregor, R. Fronk, M. Reichenberger, Micro cavity fission chamber radiation detection system, filed 2016.
- Invention Disclosure: T2019-073 – "A Model Based Assessment Approach and an Automation Environment for Qualification of Embedded Digital Devices," Inventors: Smidts, Carol | Diao, Xiaoxu | Li, Boyuan
- A. Heifetz, R. Vilim, and S. Bakhtiari "Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities," filed U.S. Patent and Trademark Office, Application No. 15947303, June 4, 2018.
- R. B. Vilim and A. M. Heifetz, "Transient Multivariable Sensor Estimation," Patent No. 9,574,903, U.S. Patent and Trademark Office, issued February 21, 2017.
- Intellectual Property Disclosures
  - Hileman, Zachary, Jiaji He, Daniel Homa, Anbo Wang, and Gary Pickrell. "Fused Silica Horns."
  - Hileman, Zachary, Jiaji He, Daniel Homa, Anbo Wang, and Gary Pickrell. "Acoustic Mode Control in Unique Fused Silica Geometries for Passive Non-Destructive Structural Monitoring."
  - Hileman, Zachary, Jiaji He, Daniel Homa, Anbo Wang, and Gary Pickrell.

5.5 Funding from other DOE-NE Programs and Technology Transition

One of the key focus areas for the NEET ASI program is to assist research projects lay out the overall research funding approach to develop a transition plan leveraging other federal agencies and other DOE-NE programs. The ultimate goal is to support the continuation of the next phase of the R&D, thereby advancing TRL of the project. The list of NEET ASI program projects is funded under CINR and SBIR and is provided in Appendix A. Direct-funded projects provided in Appendix B.

6. REFERENCES

1. Calderoni, P., *In-Pile Instrumentation Strategic Plan*, Idaho National Laboratory, INL/EXT-18-51432, October 2018.
2. Primer, C. A., *Digital Environment for Advanced Reactor Workshop Report*, Idaho National Laboratory, INL/EXT-18-46051, June 2018.
3. DOE-NE, *Advanced Sensors and Instrumentation Award Summaries*, Department of Energy Office of Nuclear Energy, June 2019.
4. Colby Jensen, et al, *Fuel program post-Halden gap report,* INL/EXT-18-46101 R1, December 2018

Appendix A

NEET ASI Projects

Page intentionally left blank

Appendix A

NEET ASI Projects

Table A-1. List of completed NEET ASI projects funded as part of CINR FOA.

FY	Project Title	Principal Investigator, Institute
2014	Irradiation Testing of Ultrasonic Transducers	Joshua Daw, Idaho National Laboratory
2014	High Temperature Fission Chamber	Zane Bell, Oak Ridge National Laboratory
2014	Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation	Pradeep Ramuhalli, Pacific Northwest National Laboratory
2014	Enhanced Micro Pocket Fission Detector for High Temperature Reactors	Troy Unruh, Idaho National Laboratory
2014	High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle Systems	Kevin Chen, University of Pittsburgh
2014	Operator Support Technologies for Fault Tolerance and Resilience	Rick Vilim, Argonne National Laboratory
2014	Embedded Instrumentation and Controls for Extreme Environments	Roger Kisner, Oak Ridge National Laboratory
2014	Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-Powered Sensor Networks	Jacques Brian, Boise State University
2015	Digital Technology Qualification at ORNL	Richard Wood, Oak Ridge National Laboratory
2015	Nuclear Qualification Demonstration of a Cost-Effective Common Cause Failure Mitigation in Embedded Digital Devices	Matt Gibson, Electric Power Research Institute
2015	Development and Demonstration of a Model Based Assessment Process for Qualification of Embedded Digital Devices in Nuclear Power Applications	Richard Wood, University of Tennessee, Knoxville

Table A-2. List of current NEET ASI projects funded as part of CINR FOA.

FY	Project Title	Principal Investigator, Institute
2016	Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities	Richard Vilim, Argonne National Laboratory
2016	Wireless Reactor Power Distribution Measurement System Utilizing an In-core Radiation and Temperature Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply	Jorge Carvajal, Westinghouse Electric Company
2016	Self-powered Wireless Through-wall Data Communication for Nuclear Environments	Lei Zuo, Virginia Tech
2017	Integrated Silicon/Chalcogenide Glass Hybrid Plasmonic Sensor for Monitoring of Temperature in Nuclear Facilities	Maria Mitkovia, Boise State University
2017	High-Temperature Embedded/Integrated Sensor (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems	Xiaoning Jiang, North Carolina State University
2017	3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics, and Prognostics of Corrosion Process in Nuclear Power Plants Secondary Piping Structures	Douglas Adams, Vanderbilt University
2017	Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring	Gary Pickrell, Virginia Polytechnic Institute and State University
2018	Process-Constrained Data Analytics for Sensor Assignment and Calibration	Richard Vilim, Argonne National Laboratory
2018	Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants	Vivek Agarwal, Idaho National Laboratory
2018	Development of Optical Fiber Based Gamma Thermometer and its Demonstration in a University Research Reactor using Statistical Data Analytic Methods to Infer Power Distribution from Gamma Thermometer Response	Thomas Blue, The Ohio State University
2019	Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control	Michael Larche, Pacific Northwest National Laboratory
2019	Design of risk informed autonomous operation for advanced reactor	Michael Golay, Massachusetts Institute of Technology
2019	Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostic	David Grabaskas, Argonne National Laboratory
2019	Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, Maintenance	Daniel Cole, University of Pittsburgh
2019	Context-aware Safety Information Display for Nuclear Field Workers	George Gibson, Arizona State University

Table A-3. List of current NEET ASI projects funded as part of SBIR.

FY	Project Title	Principal Investigator, Institute
	Phase II	
2016	High Temperature Operable, Harsh Environment Tolerant Flow Sensors for Nuclear Reactor Applications	Jon Lubbers, Sporian Microsystems, Inc.
2017	A robust wireless communication system for harsh environment including nuclear facilities	Richard Twogood, Dirac Solutions Inc.
2018	Distributed Antenna System for Wireless Data Communication in Nuclear Power Plants	Chad Kiger, Analysis & Measurement Serv Corp
2018	Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure	Derek Rountree, Luna Innovations Inc.
2019	Metamaterial Void Sensor for Fast Transient Testing	Mark Roberson, Goldfinch Sensor Technologies and Analytics LLC
2019	Health Monitoring of Digital I&C Systems using Online Electromagnetic Measurements	Chad Kiger, Analysis & Measurement Serv Corp
2019	Fault Detection of Digital Instrumentation and Control Systems using Integrated Electromagnetic Compatibility and Automated Functional Testing	Greg Morton, Analysis & Measurement Serv Corp
	Phase I	
2019	Sapphire Single Mode Fiber Development Towards High Temperature Radiation Resilient Sensors	Derek Rountree, Luna Innovations Inc.
2019	Noncontact Flow Rate Sensor Using Laser Ultrasonics	Marvin Klein, Intelligent Optical Systems Inc.
2019	Radiation Hardened Vision System for Nuclear Energy, Visual Inspection, and Accountability	Alan Sugg, Vega Wave Systems
2019	Video Camera for Harsh Environments in Nuclear	Esen Salcin, Alphacore Inc.
2019	Development of Radiation Endurance Ultrasonic Transducer for Nuclear Reactors	Uday Singh, X-wave Innovations Inc.
2019	A Radiation and Temperature-Tolerant Plasma Contact Microphone for Sensing Ultrasonic Acoustic Emissions in Fatiguing Metal Structures	John Carlsson, RadiaSoft, LLC

Page intentionally left blank

Appendix B

Current NEET ASI Direct-Funded Projects

Page intentionally left blank

Appendix B

Current NEET ASI Direct-Funded Projects

Table B-1. List of current NEET ASI direct-funded projects.

FY	Project Title	Principal Investigator, Institute
20	Direct Digital Printing Sensors for Nuclear Energy Applications	Timothy McIntyre, Oak Ridge National Laboratory
20	Sensor Database for Nuclear Energy	Tim Downing, Pacific Northwest National Laboratory
20	Develop Methods and Tools using NSUF Data to support Risk-Informed Predictive Analytics	Vivek Agarwal, Idaho National Laboratory
20	Nuclear Instrumentation • Activities within project: - Thermocouples - Neutron Flux Sensors - Passive Monitors - Acoustic Sensors - Optical Fibers - Wireless Communication	Kort Bowman, Idaho National Laboratory
20	Instrumentation Deployment • Activities within project: - Autoclave Test - Mock-up Fuel Re-Instrumentation Facility - Irradiation Test	Kort Bowman, Idaho National Laboratory
20	Sensor Fabrication by Advanced Manufacturing • Activities within project - Process control and sensor fabrication - Feedstock Development - Implement combinatorial material science for sensor development	Kort Bowman, Idaho National Laboratory
20	Measurement Systems for Nuclear Materials Properties Characterization • Activities within project: - Mechanical Properties - Photo-Thermal Radiometry - Probe (line source) Method - Resonant Ultrasound Spectroscopy - Electromechanical Measurements	Kort Bowman, Idaho National Laboratory