The US DOE Advanced Sensors and Instrumentation Program
Mission

Develop **advanced sensors and I&C** that address **critical technology gaps** for monitoring and controlling existing and advanced **reactors** and supporting **fuel cycle** development.

Vision

NEET ASI Research results in advanced sensors and I&C technologies that are **qualified, validated, and ready to be adopted** by the nuclear industry.
ASI R&D Components

- Machine learning and artificial intelligence processes to enable semi-autonomous operation and maintenance by design
- Resilient, real-time transmission of sufficient amount of data for online monitoring and advanced data analytics
- Modeling of instrumentation performance to enable predictive capabilities and integration in Digital Twins
- Innovative sensor materials and advanced manufacturing techniques applied to instrumentation design and fabrication
- Reliable, cost-effective, real-time, accurate, and high-resolution measurement of the performance of existing and advanced reactors core and plant systems
- Enable near real-time control of plant or experiments process variables to enhance performance
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

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

**DEVELOPMENT**
- OSUR
  - University Reactor
- PULSTAR
  - University Reactor
- MITR
  - University Reactor

**TREAT (INL)**

**NRAD (INL)**

**MARVEL**

**PROTOTYPIC DEPLOYMENT**
- ATR/HFIR (INL/ORNL)
FY23 Program Directed Research Activities

**Sensors for Advanced Reactors**
- Reactor power monitoring
- Thermometry
- Fiber optic sensing
- Structural health monitoring
- Rad-hard electronics

**Sensors for Irradiation Experiments**
- LVDT
- Passive monitors
- Material properties characterization
- Sensor qualification test

**Sensors I&C integration**
- Advanced controls
- Communication

4 guide tubes inserted into the air gap between the guard vessel and the reactor shielding house BF₃ and B-10 neutron detectors for MARVEL power control.

The ASI program has interest in demonstrating neutron sensors in MARVEL for the following objectives:

1. Benchmarking commercial neutron sensors for low fluence rate environments.
2. Developing an advanced control algorithm using a neutron sensor array.

Minor design mod to accommodate 8 more guide tubes is under consideration.
Proper mechanical compliance between sensors and components is an essential aspect of SHM and a major challenge for nuclear applications.

Embedding sensors through advanced manufacturing techniques is a key enabling technology for SHM. ASI is assessing two pathways complementing the work implemented at ORNL under MRP (ultrasound assisted sintering):

- Electric Field Assisted Sintering (INL)
- Hot confined rolling (PNNL)

A workshop (Aug 27-29, PNNL) will bring together ASI, AMMT and MRP experts to prioritize coordinated DOE efforts in this area (Chris Petrie for MRP).
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**Sensors I&C integration**
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- Communication
Example Program Effort: Advanced Controls for Advanced Reactors
# Acknowledgements

## Project Team
- Jacob Farber
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## Collaboration Team
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## Coordination Team
- Richard Vilim
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- Roberto Ponciroli
Example Microreactor Characteristics

- Operate in rural areas that are not grid connected
- Small or compact in size
- Can operate at lower and/or variable power ratings
- Built in a manufacturing facility or are modularly assembled onsite
- Highly autonomous
- Safer to operate
## Gap Analysis

<table>
<thead>
<tr>
<th>Unique Aspect</th>
<th>Gap</th>
<th>Control Requirement</th>
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<tbody>
<tr>
<td>Regulatory Requirements</td>
<td>AI/ML control requires the development of a special form of model that meet regulatory requirements.</td>
<td>Introduce layered approach of control that enables AI/ML-assisted control but cannot compromise the main control role that meets regulatory requirements.</td>
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<tr>
<td>Operating Environment</td>
<td>Given the high autonomy requirement, it is necessary to deploy methods that introduce better awareness of the plant and compensate for sensors failure.</td>
<td>Couple to low and high-fidelity digital twins that create a virtual knowledge of lost plant information and indirectly feeds into the control function of the reactor.</td>
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<tr>
<td>High Consequence</td>
<td>Need to understand the broader plant condition and challenges, and make a risk-informed decision on the best action to take.</td>
<td>Incorporate risk elements into control methods to achieve optimal performance.</td>
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<tr>
<td>Highly Coupled</td>
<td>Multi-input and multi-output control need to handle high level of non-linearity and interface continuous and discrete states.</td>
<td>Interface the various means of control including AI/ML-assisted control methods that can handle multi-input multi-output high level of non-linearity and digital control for discrete states control.</td>
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<tr>
<td>Evolving Knowledge</td>
<td>Control methods performance is dependent on the accuracy associated with the estimated control model.</td>
<td>Interface the various means of control including AI/ML-assisted control methods that can empirically and gradually model the process and adjust the control method as knowledge is gained.</td>
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<tr>
<td>Lack of Operating History</td>
<td>Useful history to feed into optimization the control methods design and development does not exist.</td>
<td>Leverage hybrid systems (using digital twins and hardware in the loop) to generate synthetic operating history. This requires a provision to interface with a pool of software and physical technologies. Enable a limited provision for human intervention, especially during the initial operation of reactors.</td>
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In July 2023, the DOE NEET ASI hosted its first control-focused workshop at ANL.

Motivation: Industry has been focusing more on core reactor design problems. Control is rarely mentioned in discussions of advanced nuclear reactor design as it is assumed that when needed, the solution would be available.

Approach: Convene subject matter experts and stakeholders in control methods and technologies for a comprehensive discussion on challenges and research and development needs to focus the program research.

Participation: Three national laboratories, eight industry representatives, the Nuclear Regulatory Commission, and several universities.
The need for advanced control:

- There seemed to be a disagreement of what the control and human role would be in autonomous systems, which is potentially due to the different types of reactors being developed.
- Autonomous control in nuclear reactors has not been demonstrated for advanced nuclear reactors and there could be challenges that we are not aware of yet.

Challenges and current state (One Example):

- The changing environment: Controllers that can adapt to changing environments have not been demonstrated.
- Testing and demonstration: The research community lacks a platform to freely manipulate, disturb, and validate methods to develop control methods and digital twins, and a standard set of benchmark datasets and scenarios that can be used for validation.
Approach to Meet the Control Requirements

Introduce layered approach of control that enables AI/ML-assisted control but cannot compromise the main control role that meets regulatory requirements.

Interface the various means of control including AI/ML-assisted control methods that can empirically and gradually model the process and adjust the control method as knowledge is gained.

Enable a limited provision for human intervention, especially during the initial operation of reactors.

Couple to low and high-fidelity digital twins that create a virtual knowledge of lost plant information and indirectly feeds into the control function of the reactor.

Interface the various means of control including AI/ML-assisted control methods that can handle multi-input multi-output high level of non-linearity and digital control for discrete states control.

Leverage hybrid systems (using digital twins and hardware in the loop) to generate synthetic operating history. This requires a provision to interface with a pool of software and physical technologies.

Incorporate risk elements into control methods to achieve optimal performance.

External Requirements

Sensor Measurements

Approach to Meet the Control Requirements

Full Demonstration of an Autonomous Reactor
COMMAND is a flexible simulation platform designed to be:

- Accessible: the intent is to make it open-source and publicly available
- Modular: the software “pieces” all inherit from generic building blocks and can be combined and connected to create complicated simulations
- High performing: designed for parallel processing, enabling simulations to take advantage of multi-core computers, servers, and nodes
FY24 Accomplishments

Developed adaptor to gRPC, an industrial communication protocol

Updated MARVEL RELAP model to accommodate MCNP inputs

Developed pipeline to connect hardware running locally to COMMAND running on INL’s High Performance Computing ecosystem

Ran MARVEL MCNP simulations and developed surrogate models to capture spatial power distribution
Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.