INL/RPT-22-69821-Revision-0

Utilization of MARVEL: Advanced Sensors and Controls Deployment

October 2022

Changing the World's Energy Future

Troy Unruh

Idaho National Laboratory

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Troy Unruh

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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MARVEL Technology Review:

Utilization of MARVEL: Advanced Sensors and Controls Deployment

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Troy Unruh – INL Measurement Science Department / Advanced Sensors and Instrumentation

DOE Advanced Sensors and Instrumentation (ASI) program Mission, Vision, Goals, and Strategic R&D

Mission:

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

Vision:

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

Program Goals:

- Identify technology gaps for sensors and instrumentation
- Increase technology maturity to expand applicability
- Demonstrate technologies in relevant conditions
- Support modeling simulation code validation
- Support fuels and materials qualification

Strategy to achieve goal:

- Regular communication with stakeholders via conferences, surveys, and workshops
- Engage with University, National Laboratories, and Industry through Funding Opportunity Announcements
- Partner with University and National Laboratory reactors to facilitate prototypic deployment
- Compile and distribute collected experimental data for benchmarking code cases and studies
- Coordinate with congruent DOE-NE programs to supply instruments necessary for materials testing

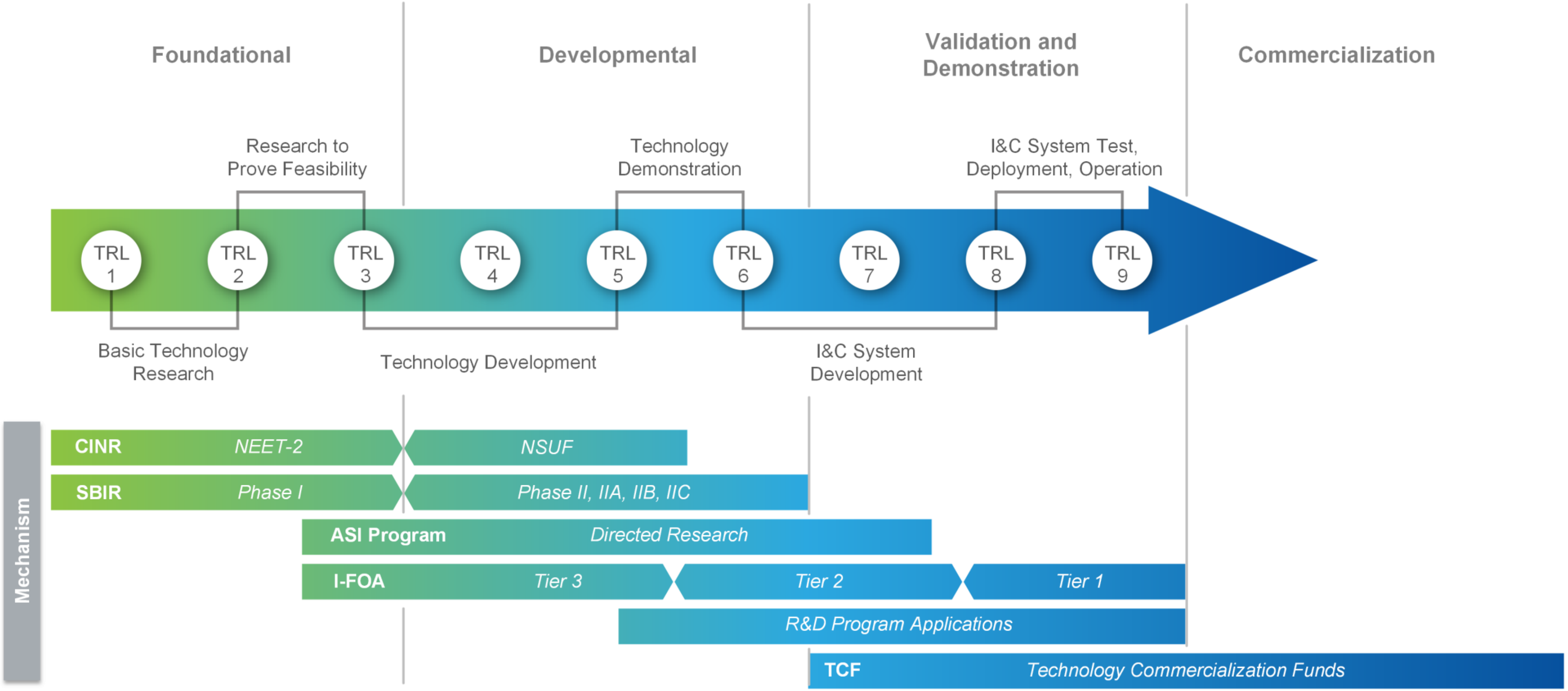
The ASI program focuses on innovative research that directly supports and enables the sustainability of the current nuclear fleet, the development and deployment of next generation reactor designs, and advanced fuel-cycle technologies

ASI Advanced Sensors and Instrumentation

Pattrick Calderoni, *ASI National Technical Director*

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

ASI technology maturation mechanisms



ASI Advanced Sensors and Instrumentation

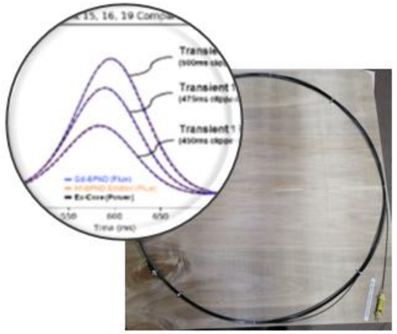
MRP Microreactor Program

Various ASI program achievements on sensors and sensor systems for irradiation experiments

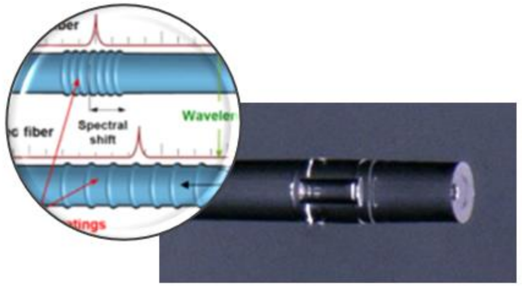
Ultrasound thermometer commercialization

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

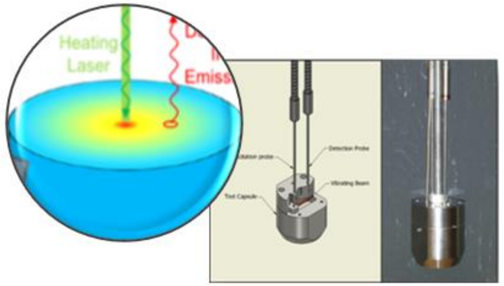
High Temperature Irradiation Resistant (HTIR) thermocouples



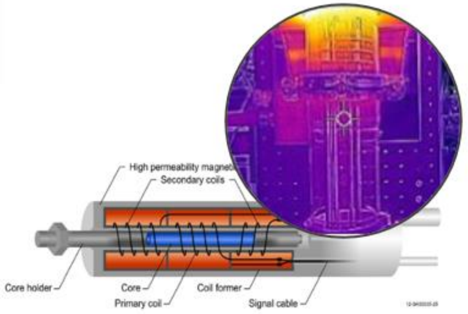
Self Powered Detectors and miniaturized Fission Chambers for local neutron flux measurement



Fiber optic sensors for nuclear applications

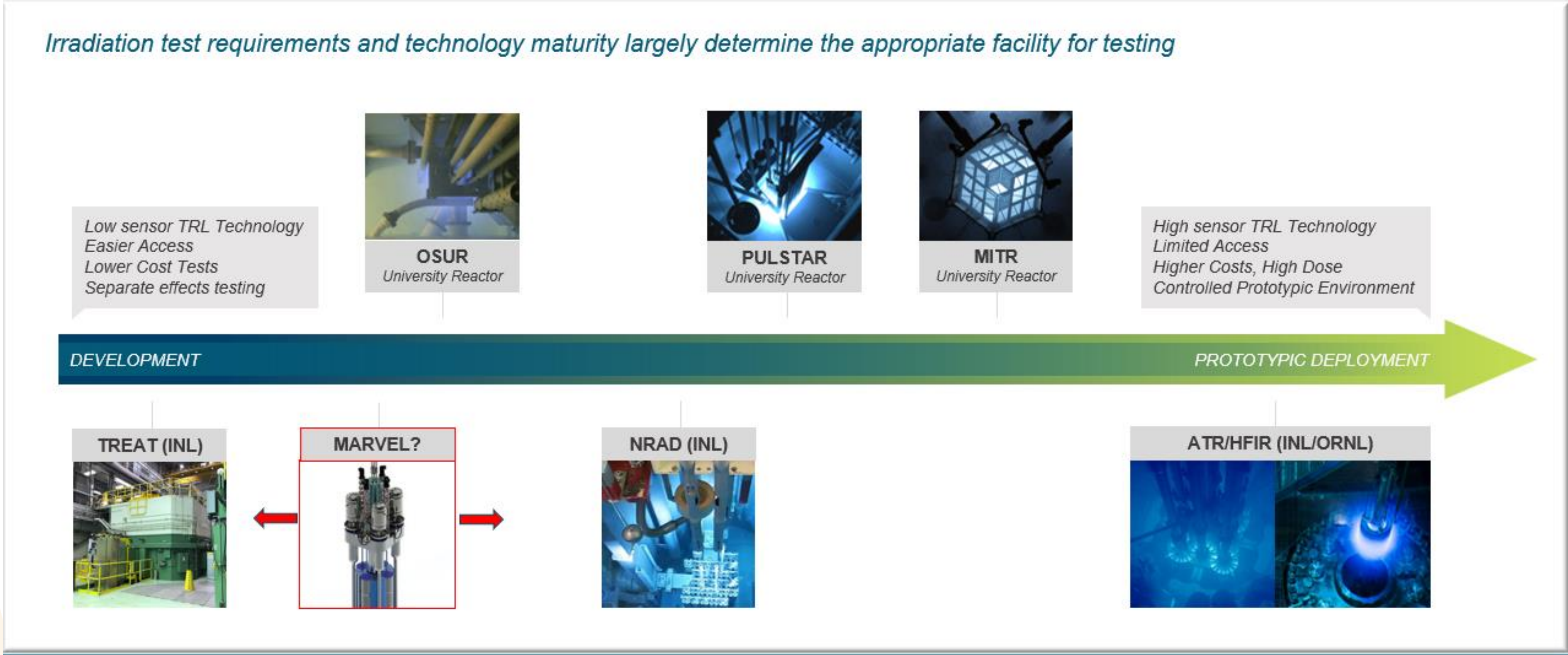


Real time measurement of fuel material properties in-core

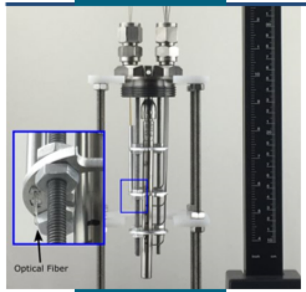


Linear Variable Differential Transformer (LVDT) for fission gas pressure measurement

Sensor maturation using DOE testing infrastructure & MARVEL?

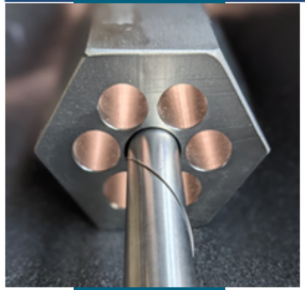


ASI Focus Activities and Near-Term Outcomes & MARVEL?



Sensors for Irradiation Experiments

LVDT	Evaluate domestic supply chain for temperature tolerance *by 2023* and radiation resistance *by 2024*
Passive Monitors	Benchmark SiC readout capabilities *by 2024*, incorporate advanced readout functionality for printed melt wires *by 2025*
Material Properties	Finish development of thermal conductivity probe *by 2023*, perform test on U10Zr fuel specimen *by 2025*



Sensors for Advanced Reactors

Self Powered Detectors (SPD)	Develop temp compensation *by 2024*, establish neutron spectrum unfolding tool *by 2026*
Fission Chambers	Perform cross calibration with SPDs in heated irradiation *by mid-2025*
Optical Fibers	Incorporate active compensation technique *by 2023*, extend temperature tolerance range of pressure sensor *by 2025*
Acoustic Sensors	Benchmark new UT design *by 2025*, design optimization and benchtop testing of ultrasonic flow sensor *by 2026*
Thermocouples	Develop drift compensation model *by 2024* and perform/complete evaluation testing *by 2026*
Rad-hard electronics	Fabricate radiation tolerant digitizer *by 2024*, with reliability demonstration *by 2027*

Sensors Integration

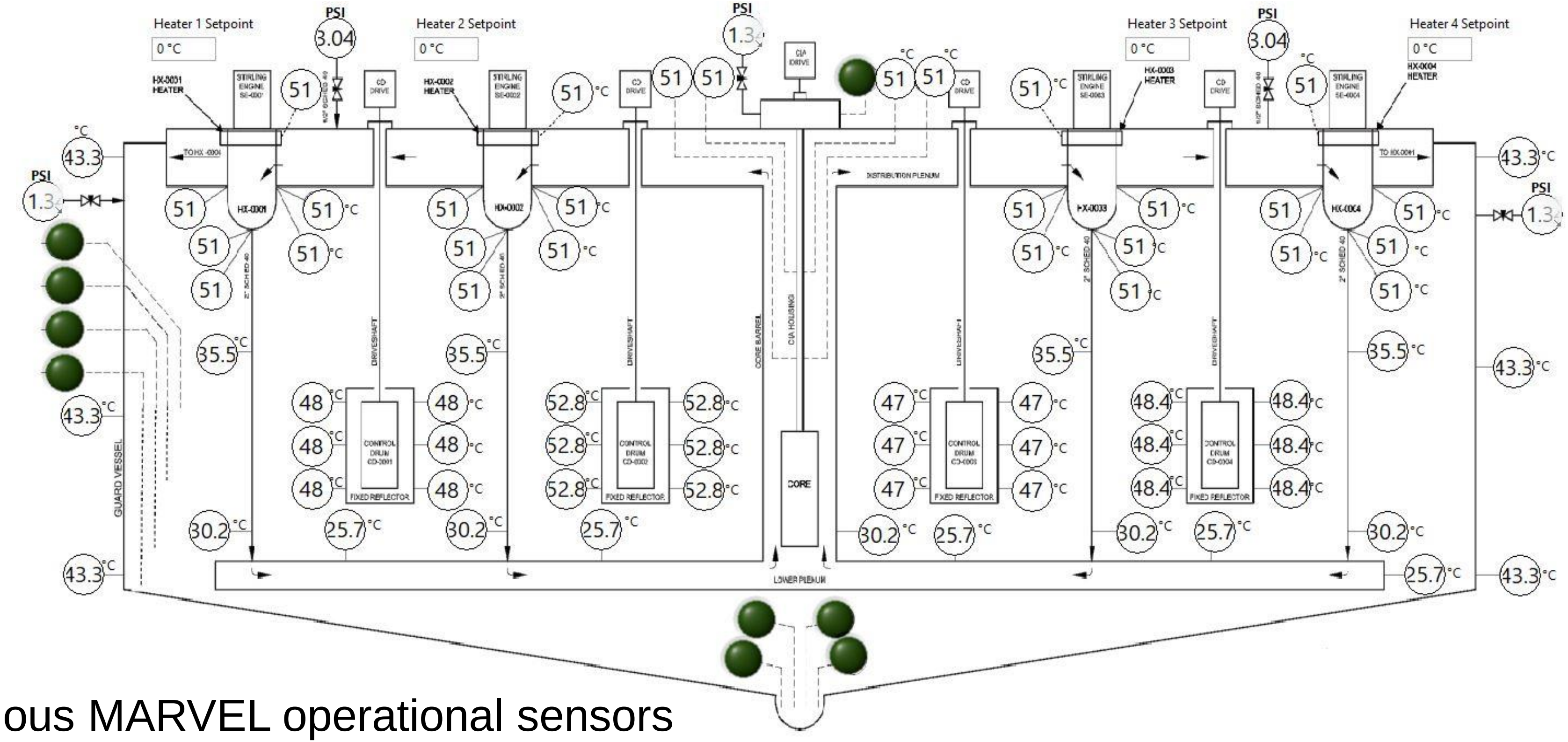
Digital Twin	Develop model of adv. nuclear system *2023-2024*, and develop AI/ML tools with standard interfaces *by 2025*
Communication	Qualify non-RF communication methods (i.e., fiber optics, induction, and acoustic) *2024-2025*
Advanced Controls	Develop simulation platform for adv. digital control technology dev. *by 2024*, and initiate testing of platform *2024-2025*

AI/ ML = Artificial Intelligence & Machine Learning
SiC = Silicon Carbide
LVDT = Linear Variable Differential Transformer
SPD = Self-Powered Detector
RF = Radio Frequency
UT = Ultrasonic Thermometer

Sensor testing

- MARVEL operational instrumentation
  - Observe trends
  - Noise analysis using independent loop comparisons
  - Analog/digital comparisons
    - Radiation hardened electronics

ORNL Front End Digitizer (FREND)

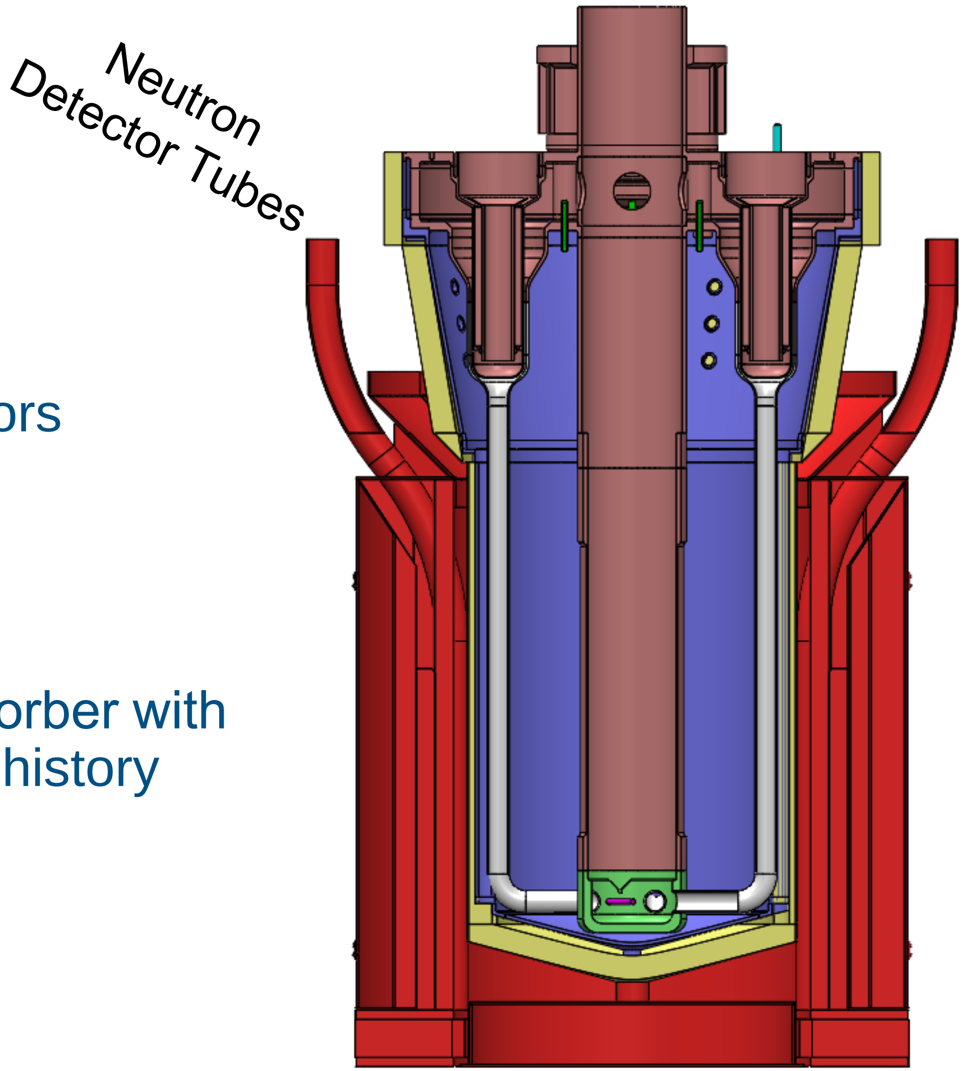


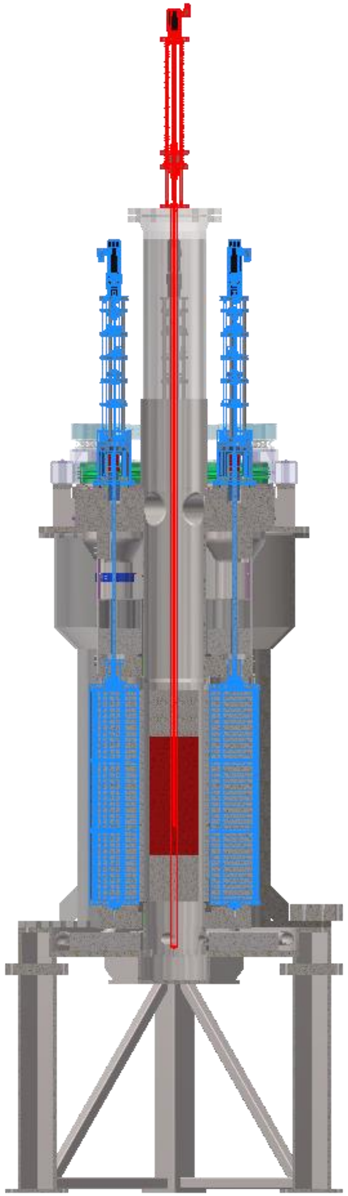
Various MARVEL operational sensors

MRP Microreactor Program

Additional sensor testing

- Neutron detector tubes accessible
  - Share space with neutron detectors
- Sealed Primary
  - Very limited inside guard vessel
  - “Replace” Central Insurance Absorber with instrumentation after operational history established

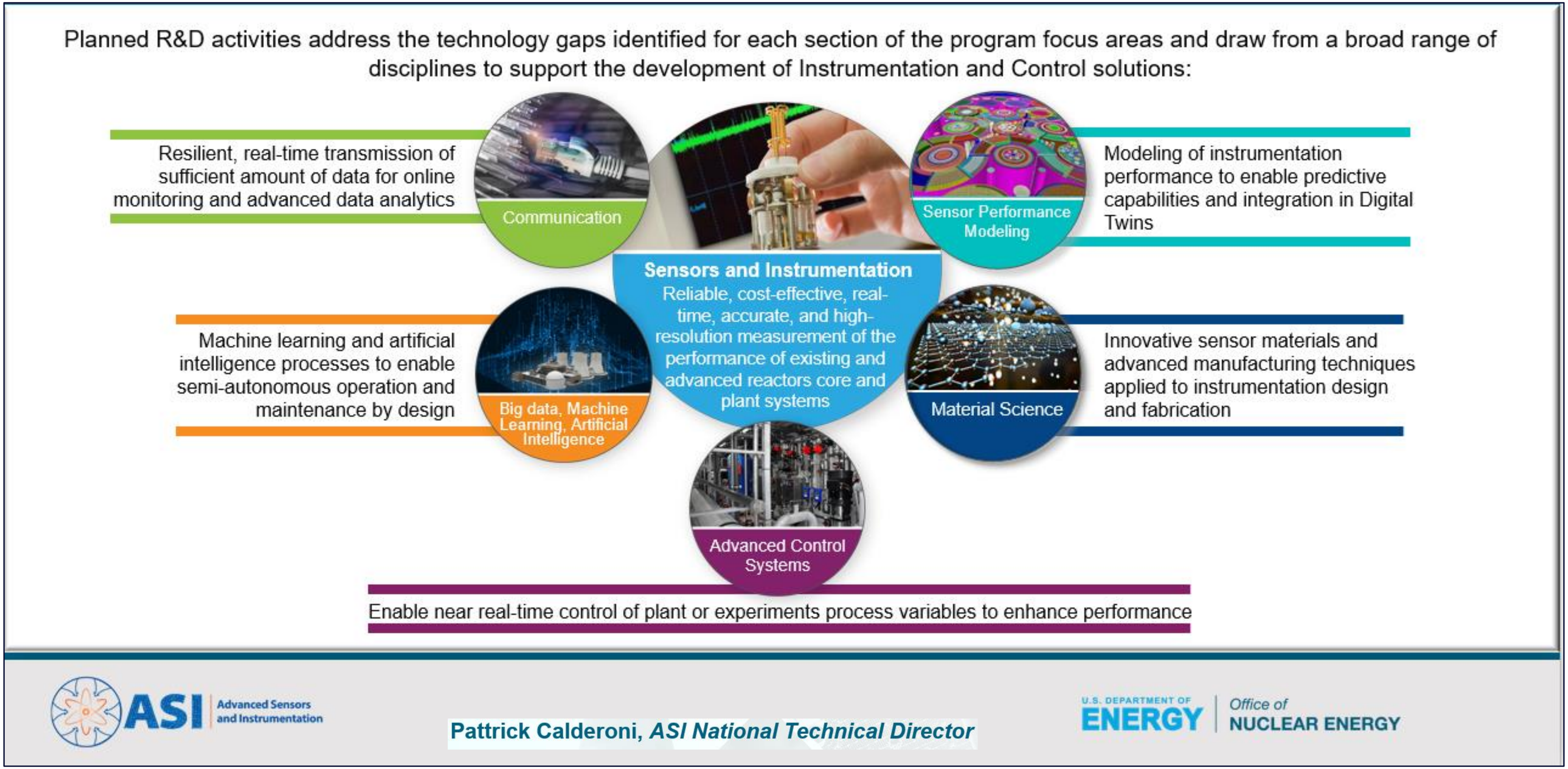




In place of CIA?

MRP Microreactor Program

Beyond sensors, ASI has several related R&D areas that can benefit from MARVEL



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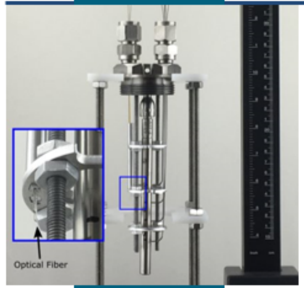

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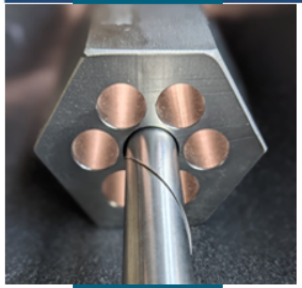

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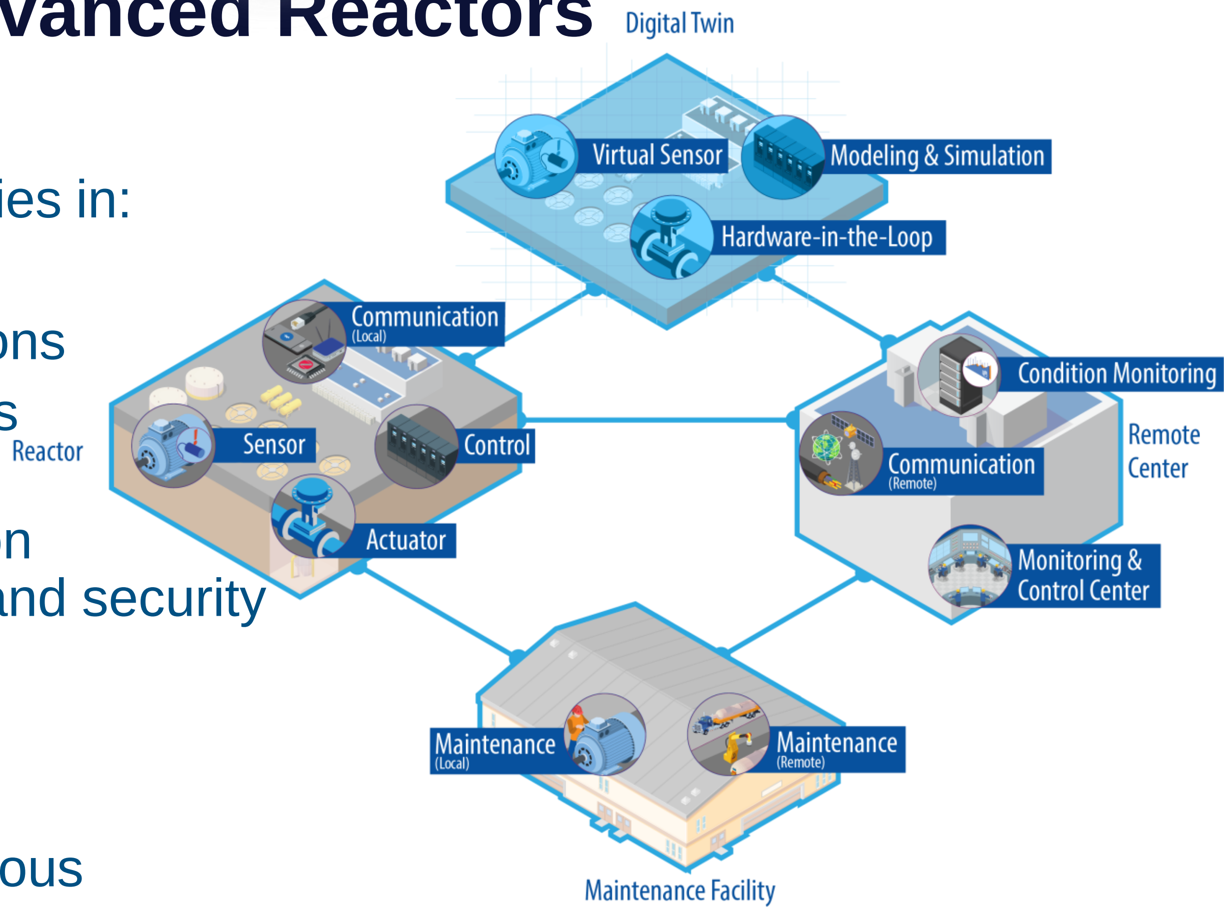
ASI - Digital Technology for Advanced Reactors

Integrating Digital Twins with Advanced Controls

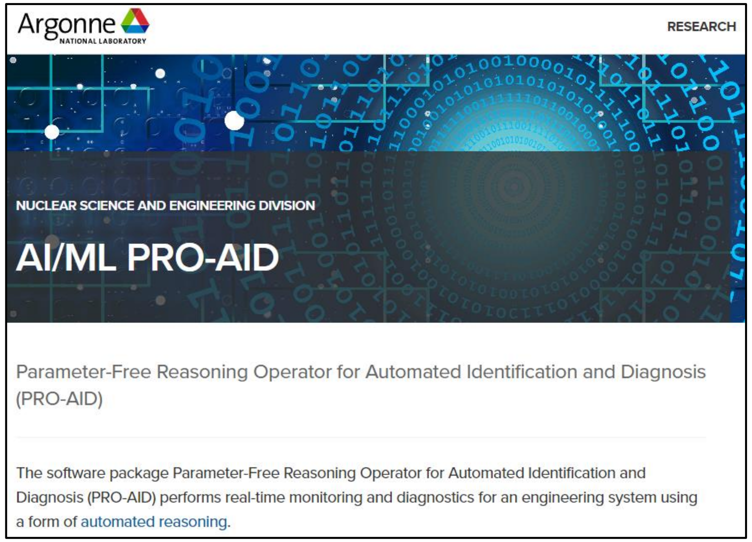
- Digital Twins introduce significant opportunities in:
  - Enhanced anomaly detection
  - System state quantification and predictions
  - Improved AI/ML assisted control systems performance
- Communications enable seamless integration of new technologies, network architectures and security options
- Advanced controls support introduction of:
  - Performance-based control algorithms
  - Fault-tolerant controls for semi-autonomous plant operation
  - Artificial Intelligence and Machine Learning assisted solutions that improve plant performance utilizing operating history and physics-based models

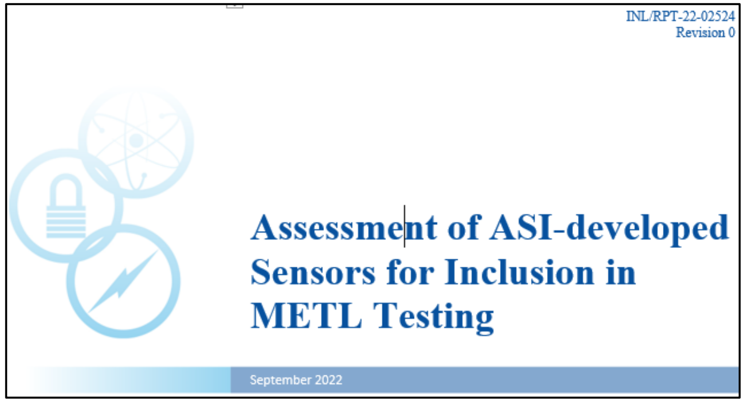


MRP Microreactor Program

ASI Digital Technology for Advanced Reactors, ANL/INL FY23

- Advanced Controls
  - Show how a Digital Twin (DT) can be used to design and inform a controller of the state of a process to switch to different operations modes and to demonstrate this use case using ANL's Parameter-Free Reasoning Operator for Automated Identification and Diagnosis (PRO-AID) at Mechanisms Engineering Test Loop (METL), a non-nuclear liquid sodium flow facility
  - Control method (high performance, digital, or AI/ML based) demonstration using existing models
    - MARVEL
    - METL
    - MAGNET
    - etc.





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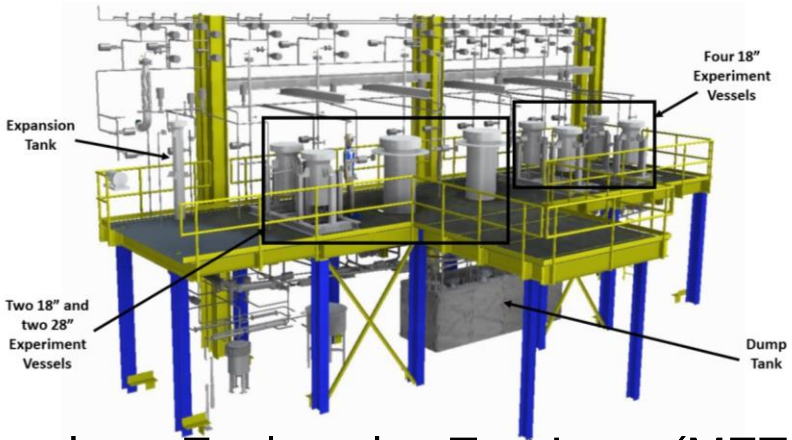
Revision 0

Assessment of ASI-developed Sensors for Inclusion in METL Testing

September 2022



Mechanisms Engineering Test Loop (METL)

MRP Microreactor Program

MRP - Microreactor Automated Control System (MACS)

Physical Digital Twin under construction

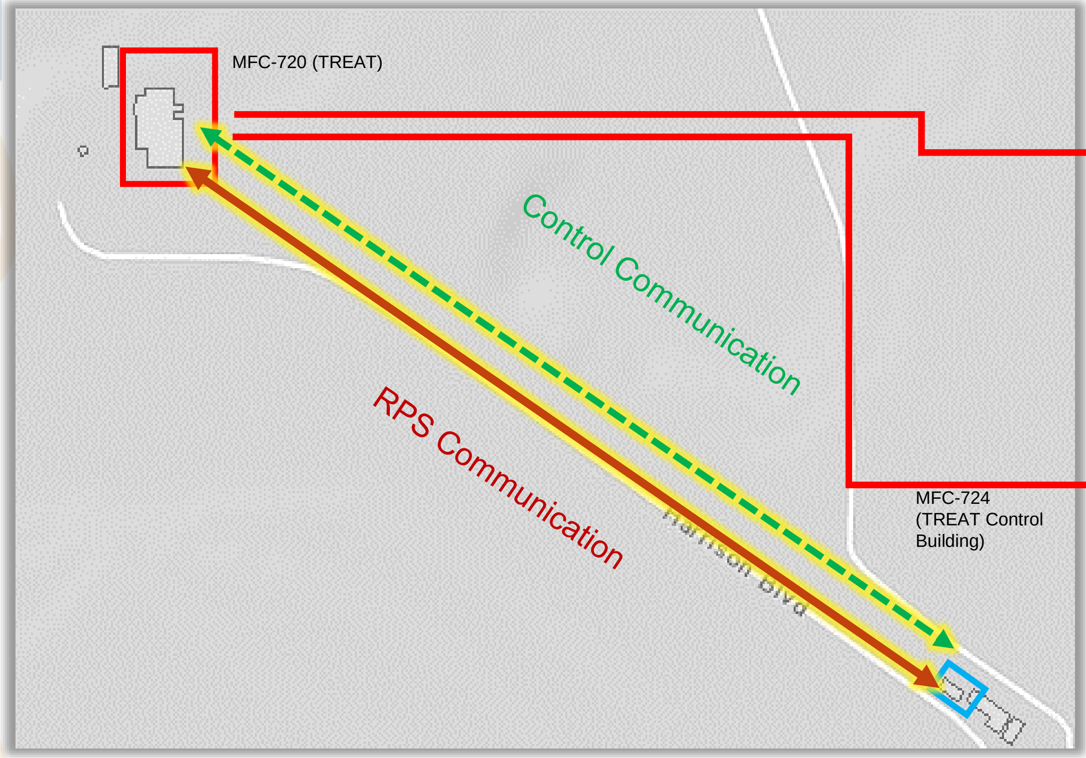
- MACS will use digital twins to automatically control microreactor hardware based on inputs from multiple sensors that could include measurements of reactor power, temperature, control element position, and heat rejection
- Development and demonstration activities will leverage existing designs for microreactors (initially MARVEL) to develop, test and demonstrate a high fidelity and robust MACS that can operate with minimal need for human-in-the-loop action
- Experimental demonstrations will focus on actuating microreactor-relevant hardware such as control element drive mechanisms, based on a simulated response from sensor inputs and the hardware in the loop simulator
- Operations training aid will allow operators to manipulate surrogate MARVEL control hardware prior to startup

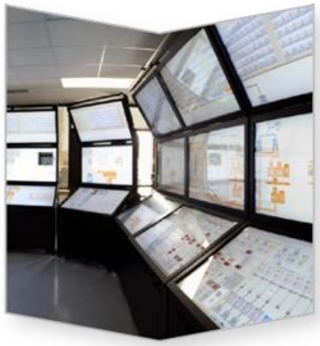
OAK RIDGE National Laboratory

INL Idaho National Laboratory

MRP Microreactor Program

Enable remote operations and/or monitoring of MACS/MARVEL





Human System Simulation Laboratory (HSSL)

ORNL campus

- Remote operation could be "bootstrapped" with in-person operator oversight and facility monitoring
- Verify secure operation and evaluate cybersecurity concerns

MRP Microreactor Program

MRP Microreactor Program

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https://asi.inl.gov/#/ www.linkedin.com/in/pcalderoni

Troy Unruh
Nuclear Instrumentation Engineer (INL)
Troy.Unruh@inl.gov
W (208)-526-6281
ORCiD: 0000-0003-2417-9060

LinkedIn