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An Overview on Autonomous COntrol for Reactor TechNologies (ACORN)

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Project Team

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Laboratory Directed Research and Development

Office of Technology Commercialization

ACORN Main Features

- High fidelity physics model
- Data-driven model
- Hybrid model

Model

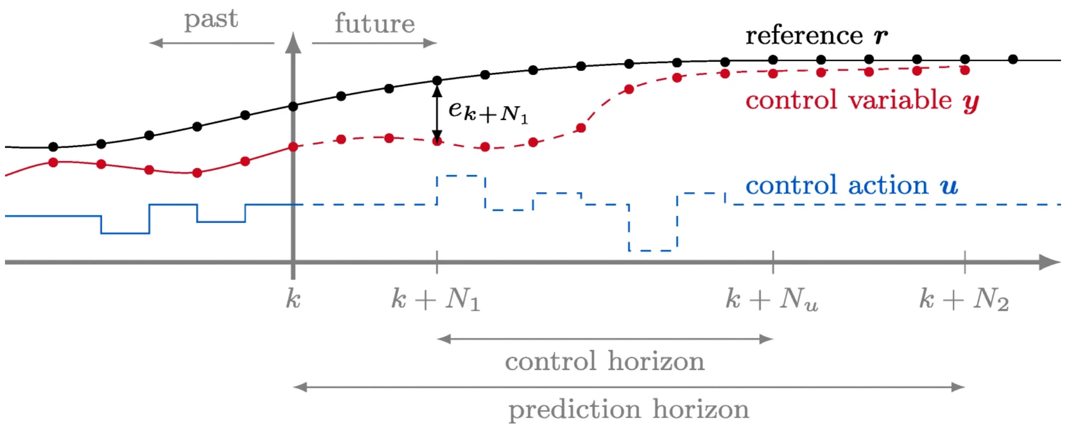
- Faster than real-time
- Artificial intelligence

Prediction

- Optimal control recommendations
- Scenario-based optimization

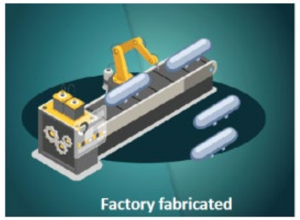
Optimization

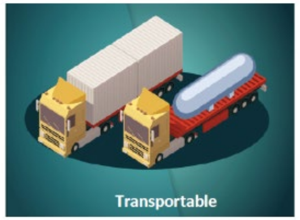
Model-Predictive Control

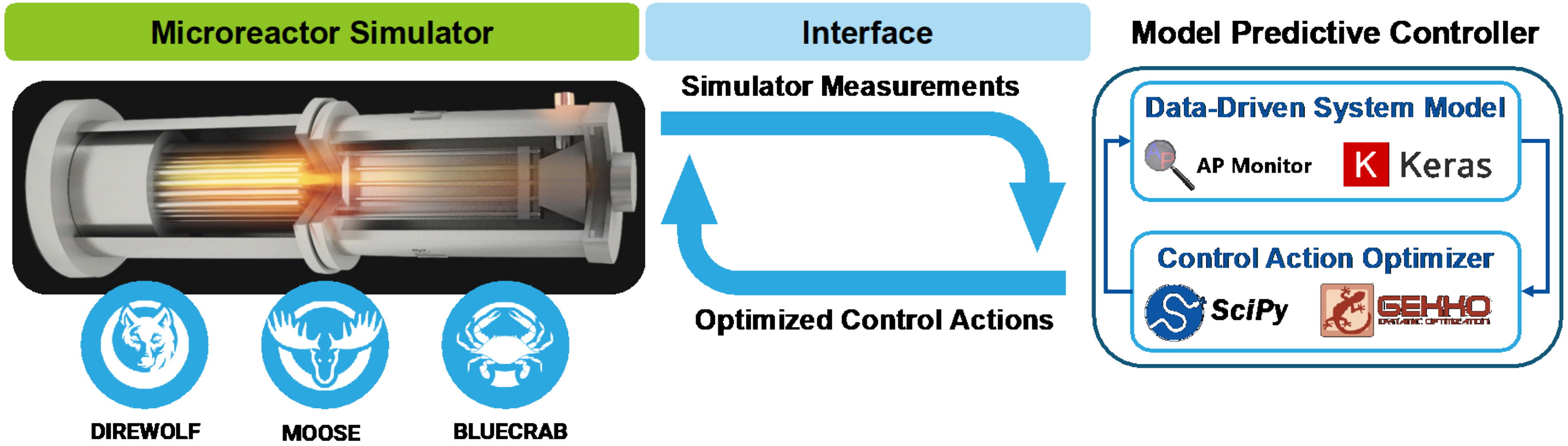


Simulation Architecture of ACORN

Leverages and expands INL's modeling and simulation capabilities like DireWolf and BlueCRAB for capturing microreactor thermal and neutronic performance

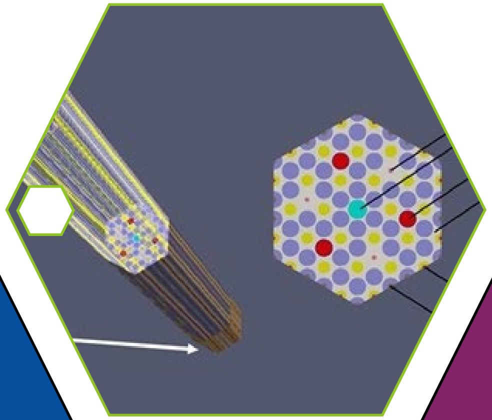






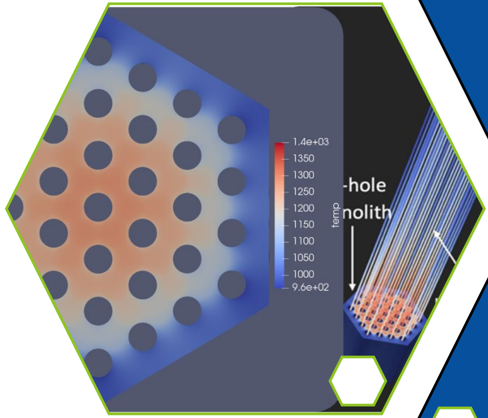
ACORN advances the level of automation to address the self-regulating attribute of microreactors. This advancement also accounts for economics of operation of microreactors.

Applications of ACORN

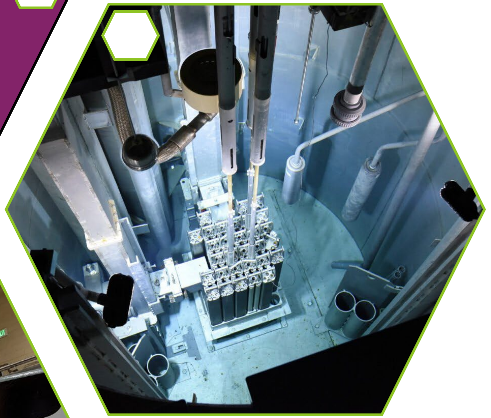


Gas Cooled Microreactor

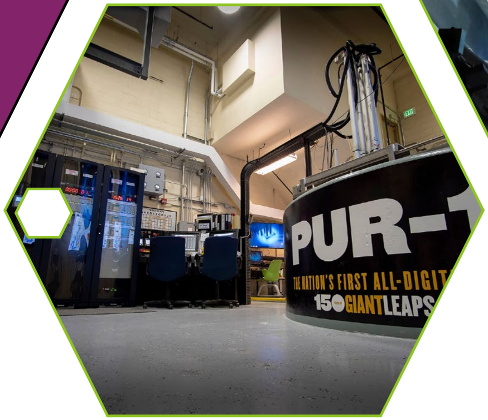
Neutron Radiography Reactor



Purdue University Reactor One (PUR-1)



Heat Pipe Microreactor

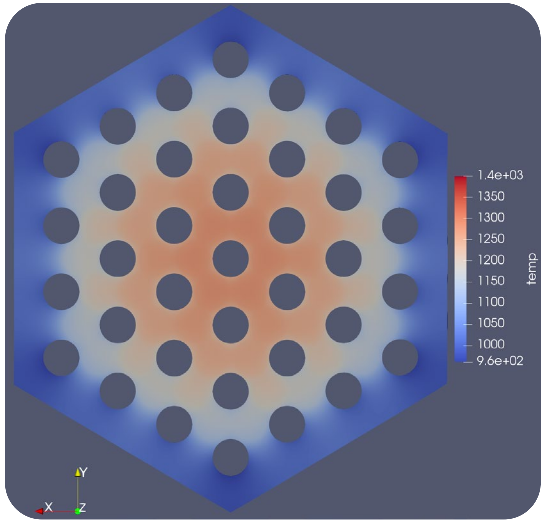


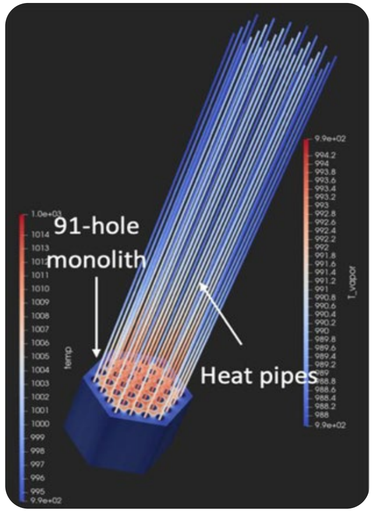
Simulated Demonstration

Hardware Demonstration (In Progress)

Simulated Scenarios for Heat Pipe Microreactor Operation

- ACORN controller provides optimal control actions for microreactor under different scenarios and external uncertainties
  - Steady state and transient operations
  - Flexible operation (load following)
  - Failure or degraded operation

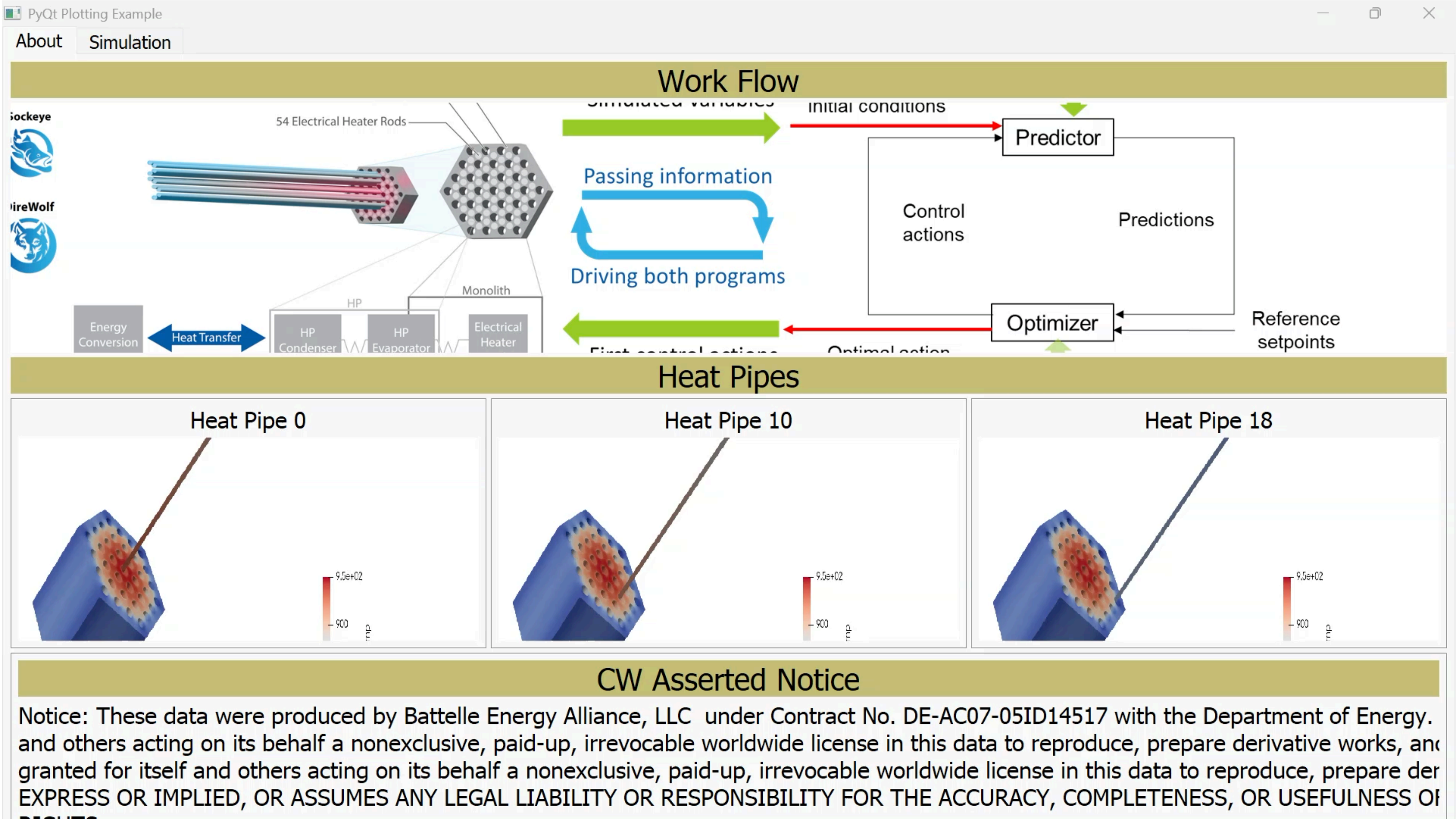




- ACORN utilizes MOOSE-based tools to create a high-fidelity simulator for a heat pipe system consists of a hexagonal stainless-steel monolith containing 37 HPs and 54 heater rods.
  - MOOSE—Multi-Apps Simulation
  - BISON—Monolith heat transfer
  - SOCKEYE—Heat Pipes

- Predictive and adaptive (i.e., online updating and transfer learning) capabilities of ACORN by utilizing artificial intelligent models to compensate for any potential failure or degraded operation

Demonstration on a Heat Pipe Microreactor



Oncken, J., L. Lin, and V. Agarwal. 2024. "Adaptive Model Predictive Control for Heat-Pipe-Cooled Microreactors under Normal and Heat-Pipe Failure Conditions." Nuclear Technology, published online 10 June 2024. https://doi.org/10.1080/00295450.2024.2342206.

Commercialization Focus

- Advance adoption readiness level and technology readiness level of ACORN

Stakeholder Engagement	Hardware-in-the-loop Demonstration	Human-in-the-loop Demonstration / Training

• Develop functional requirements.
  • Perform survey
  • Engage with advanced reactor stakeholders
  • Solicit regulatory inputs
	• HITL validation
	  • Integration of ACORN with PUR-1
	  • Scenario-based evaluation
	  • Cyber security considerations
		• User-centric visualization
		  • Situational awareness
		  • Human automation interaction
		• Training Program at Purdue University

Completed	In Progress	Yet to Start

Industry Engagement and Major Outcomes

47 Responses

- Surveyed advanced reactor developers, I&C vendors, universities, space reactor developers, and international organizations.

17 AR Developers

- Coverage spanned molten-salt, gas-cooled, heat-pipe, liquid metal, water, and thorium reactors

4 AR Pilot Selectees

- Emphasizing relevance to long-term microreactor deployment

Outcome #1

Lead with Cost Reduction & Efficiency as the Core Value Proposition

Outcome #2

Prioritize Regulatory Pathway & Cybersecurity

Outcome #3

Only 21% view AI as necessary for autonomy

Outcome #4

AI should be offered as a transparent, explainable option.

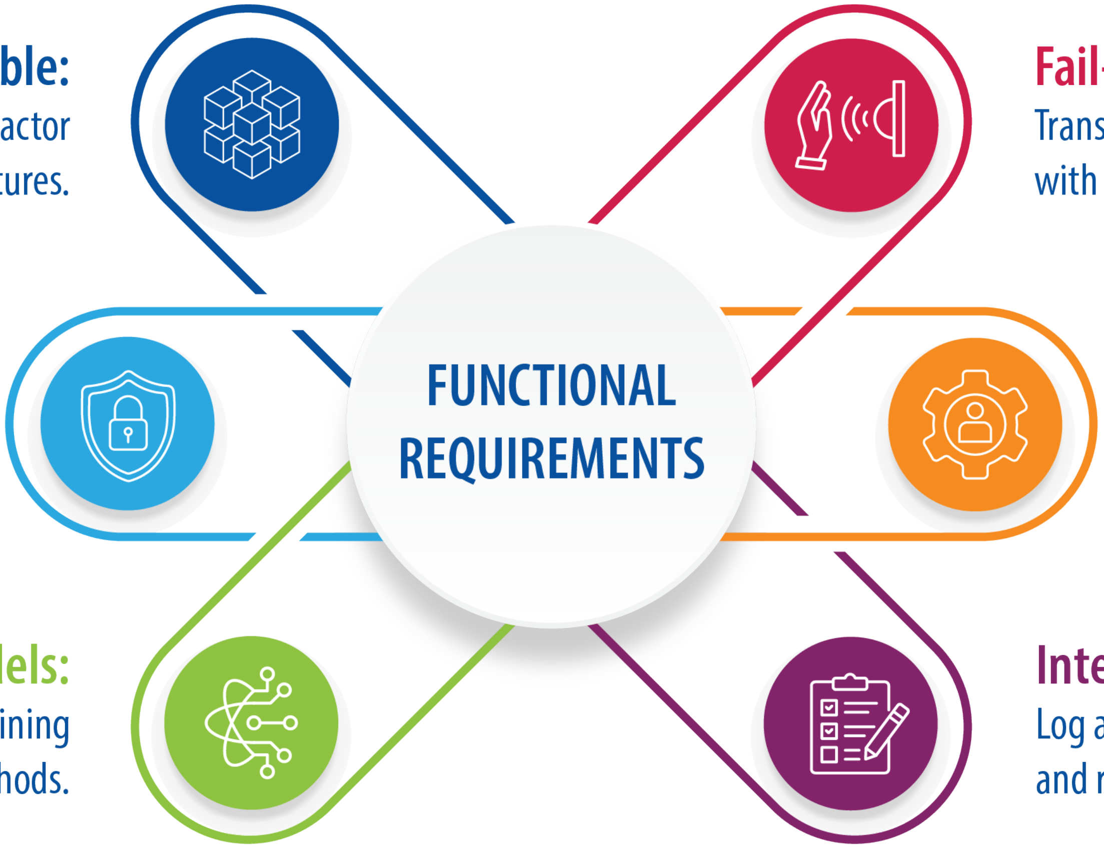
Functional Requirements (a representative set)

Technological Advancements

Scalable:
Modular design supports various reactor types with plug-and-play features.

Secure:
Evaluate cybersecurity concerns in software, hardware, and their integration.

Hybrid Models:
Reliable hybrid predictors combining physics- and data-driven methods.



Adoption Advancements

Fail-Safe:
Transition the reactor to a low-risk state with potential for human intervention.

Human Factors:
Incorporated human factors engineering principles to comply with regulatory and user requirements.

Interpretable and Traceable:
Log actions to build trust with operators and regulators.

Demonstration of ACORN on PUR-1 Operational Data

ACORN

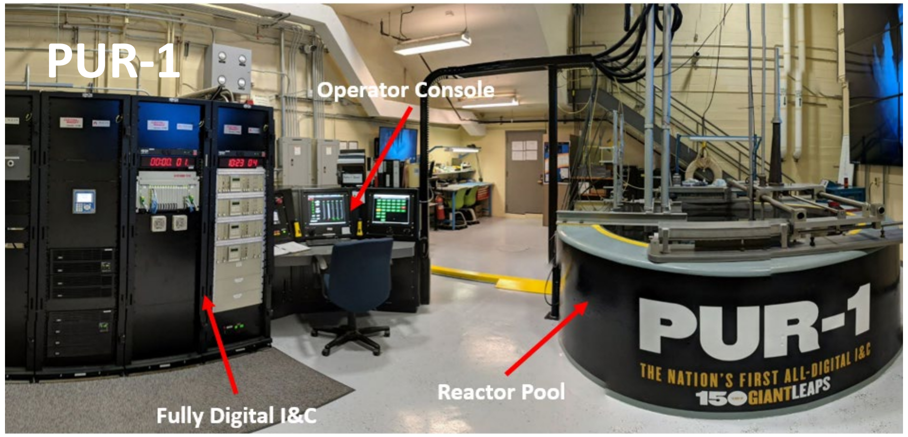
Proposed Testing Scenarios

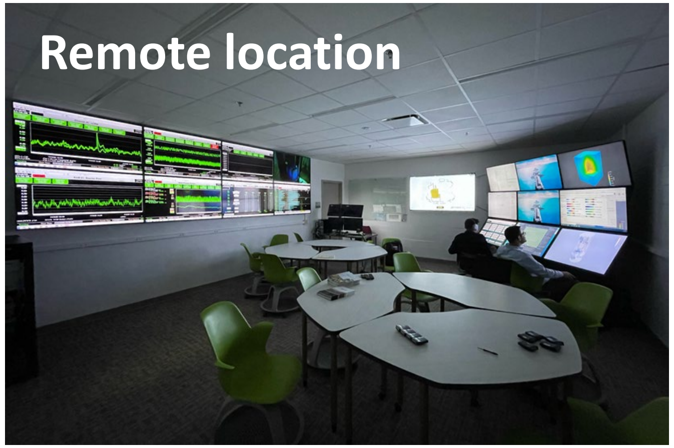
Scenario	Description	Functional Requirement
Steady State Performance	Maintain steady state at different power levels (e.g., 1%, 10%, 100%, etc.)	Hybrid
Transient Performance	Evaluate performance while moving between power setpoints. Evaluate metrics such as rise time, steady state error, overshoot, etc.	Hybrid
Reject Sensor Noise	Maintain steady state but with added sensor drift or heavy noise in one of the sensors to emulate a sensor anomaly.	Hybrid
Reject Process Noise	Maintain steady state but with added AMDR position drift/noise to emulate actuator anomaly.	Hybrid
False Data Injection	Maintain steady state but with False Data Injection in one of the sensors to emulate a cyber event.	Secure Hybrid
Denial of Service	Maintain steady state but with Denial of Service (increased latency to full DoS) in the remote HMI to emulate a cyber event.	Secure Hybrid
Combination Cyber	Maintain steady state but with False Data Injection AND Denial of Service to emulate a worst case cyber event.	Secure Hybrid
Unanticipated Transient	Detect and unanticipated transient, such as a gradual or sudden positive/negative reactivity insertion and bring reactor back to a nominal state.	Fail-Safe

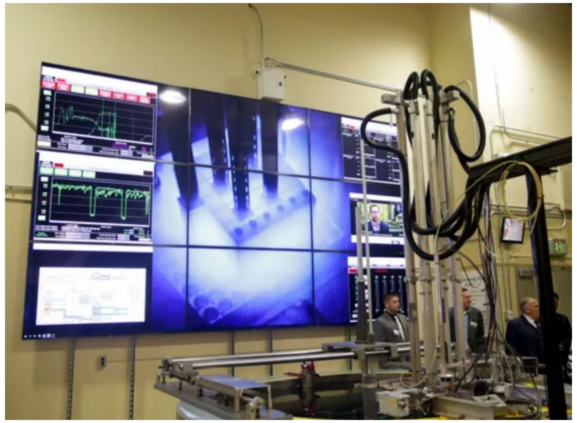
PUR-1 Setup and Demonstration

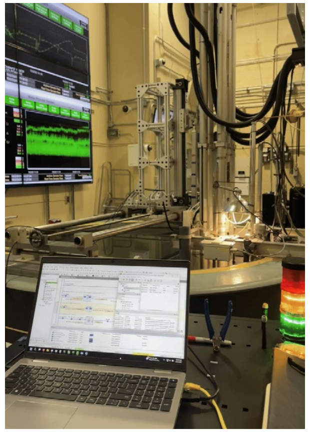
Completed: Remote movements of AMDR

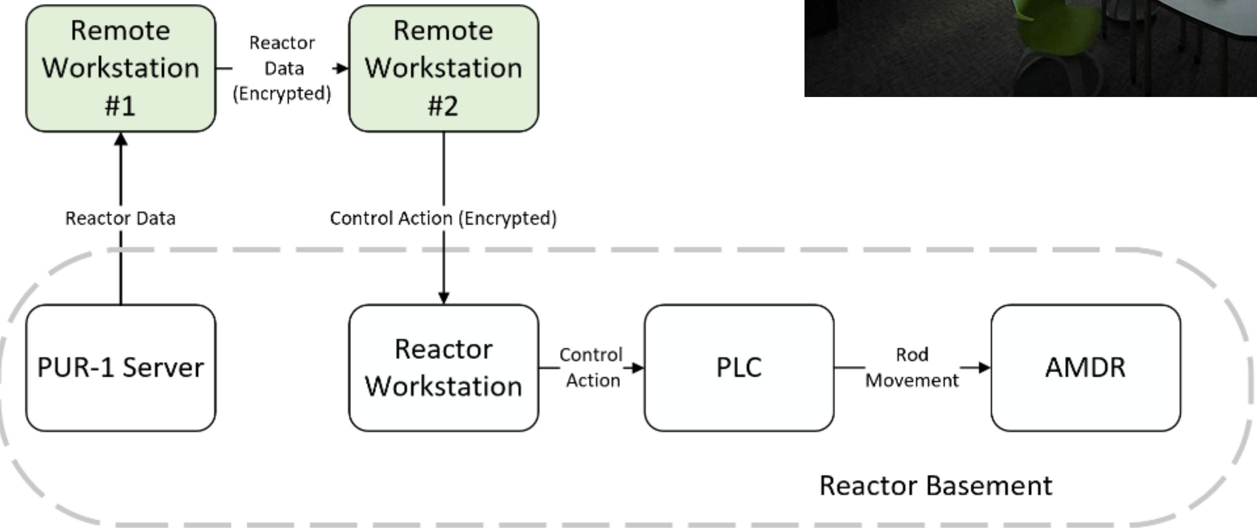
Completed: Two-way Communication





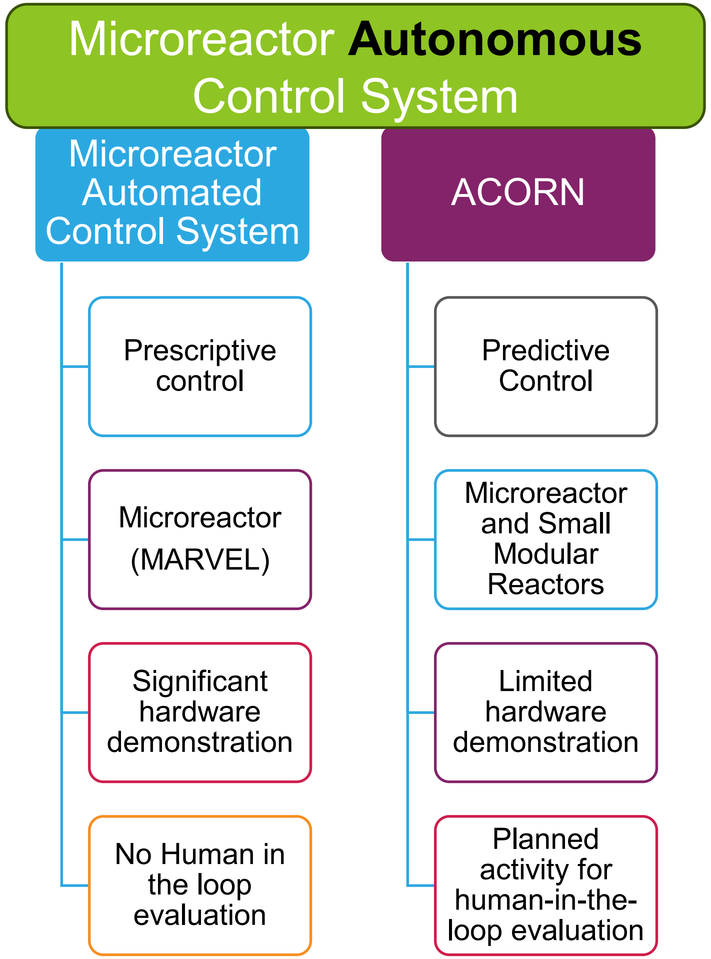






Summary and Path Forward

- ACORN technology is moving from a concept to commercialization.
- Modular architecture enables simulated, hardware-in-the-loop, and human-in-the-loop evaluation for different reactor technologies.
- Artificial intelligence can be implemented as modular solution that provides predictive capability enabling proactive control.
- Synergy with MARVEL selected end users
  - Amazon Web Services (AWS) Inc. coupling with modular data center
  - GE Vernova to demonstrate remote and autonomous reactor operations.



Publications

Oncken, J., L. Lin, and V. Agarwal. 2024. “Adaptive Model Predictive Control for Heat-Pipe-Cooled Microreactors under Normal and Heat-Pipe Failure Conditions.” Nuclear Technology, 210(12), 2274–2289. https://doi.org/10.1080/00295450.2024.2342206

Lin, L., J. Oncken, and V. Agarwal. 2024. “Anticipatory Control for Heat-Pipe Microreactor using Data-Driven Model Predictive Control.” Annals of Nuclear Energy, 200, 110399. https://doi.org/10.1016/j.anucene.2024.110399

Lin, L., J. Oncken, V. Agarwal, C. Permann, A. V. Gribok, T. McJunkin, S. Eggers, and R. L. Boring. 2023. “Development and Assessment of a Model Predictive Controller Enabling Anticipatory Control Strategies for a Heat-Pipe System.” Progress in Nuclear Energy, 156, 104527. https://doi.org/10.1016/j.pnucene.2022.104527

Poudel, B., L. Lin, T. Phillips, S. Eggers, V. Agarwal, and T. McJunkin. 2022. “Operational Resilience of Nuclear-Renewable Integrated-Energy Microgrids.” Energies, 15(3), 789. https://doi.org/10.3390/en15030789

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