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

Advanced Sensors and Instrumentation

Advanced Controls for Advanced Reactors

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

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Acknowledgements

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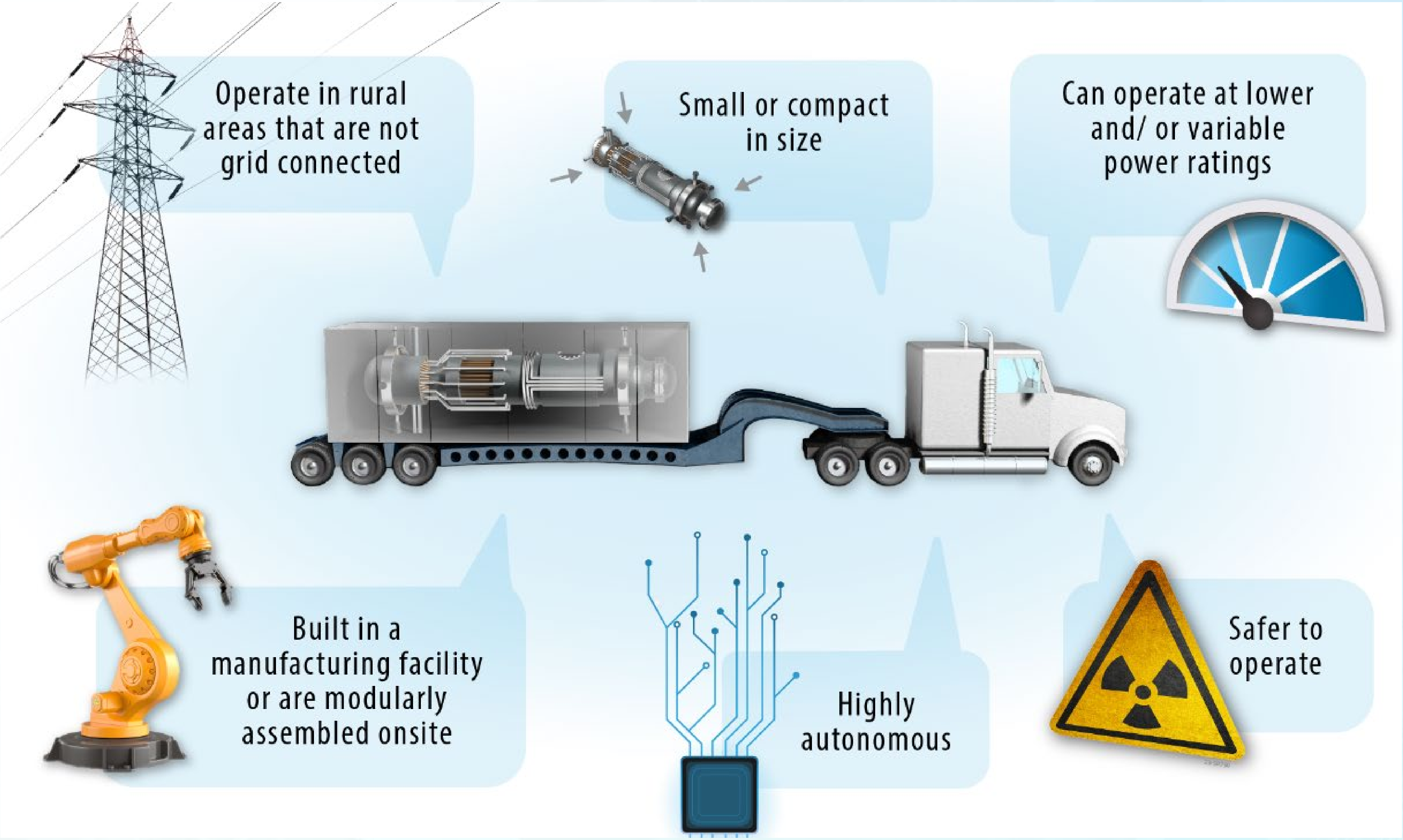
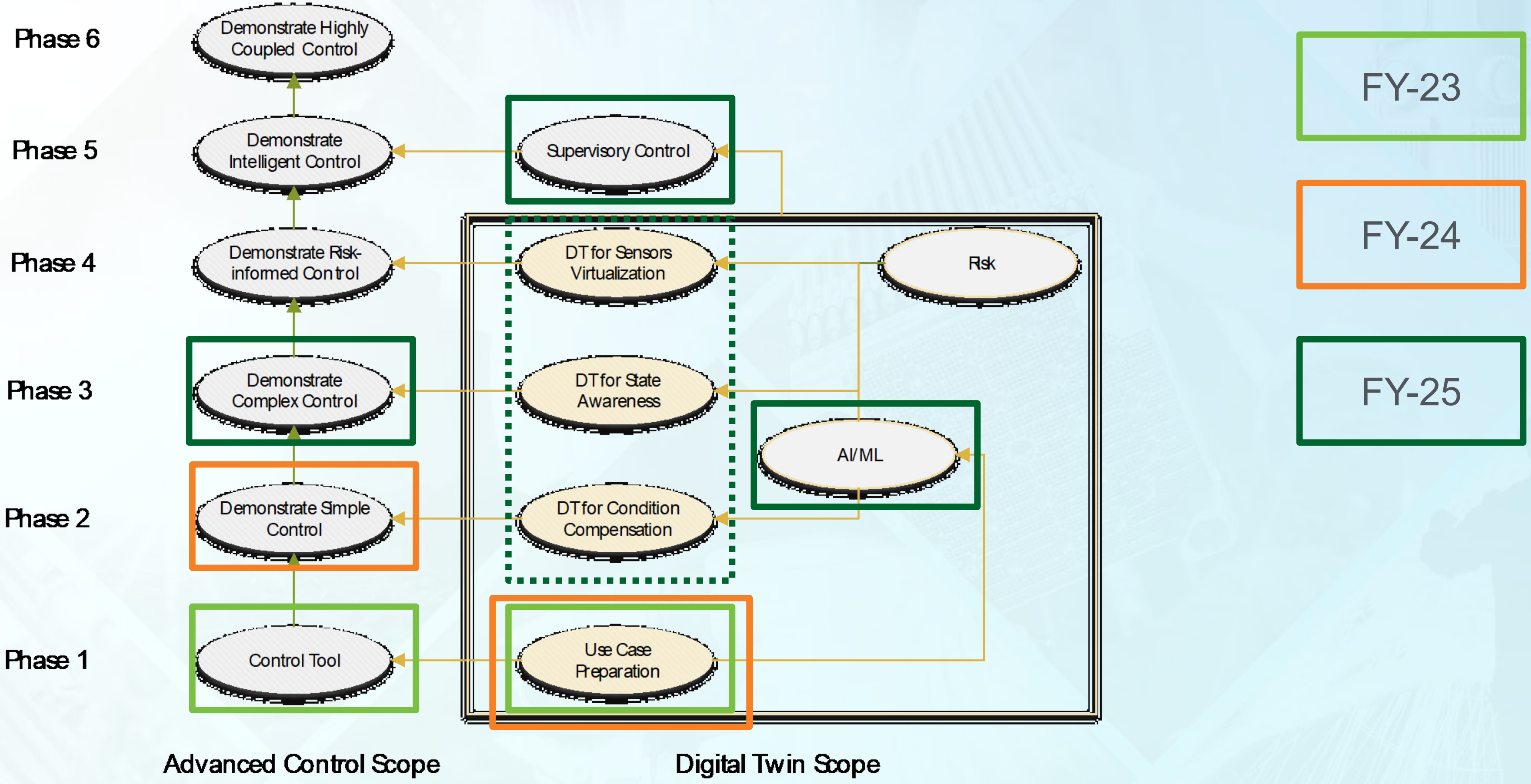
Example Microreactor Characteristics



Gap Analysis

Unique Aspect	Challenge	Control Requirement
Regulatory Requirements	Artificial Intelligence/Machine Learning (AI/ML) control may not meet regulatory requirements, such as deterministic and explainable behavior	Include an interface control layer between the plant and any AI/ML decision making
Operating Environment	Instrumentation and Control (I&C) equipment will endure harsh environments for extended periods, increasing probabilities of failures	Identify and compensate for sensor, communication, and electronics failures
High Consequence	Manual investigation to reduce uncertainty and avoid shutdown may not be feasible	Incorporate risk elements to prevent unnecessary loss of power generation
Highly Coupled	More compact and simple designs will produce strongly coupled systems, making “isolated” control less feasible	Integrate highly coupled control loops and state-awareness methods
Evolving Knowledge	Novel concepts of physics and operation will be used that may not be fully understood or validated	Incorporate robustness into the control loop design
Operating History	There will be limited operating history with which to make operational decisions	Use software models that dentify and adapt to unanticipated physical phenomena Define the human role and allowable human interventions

Full Demonstration of an Autonomous Reactor



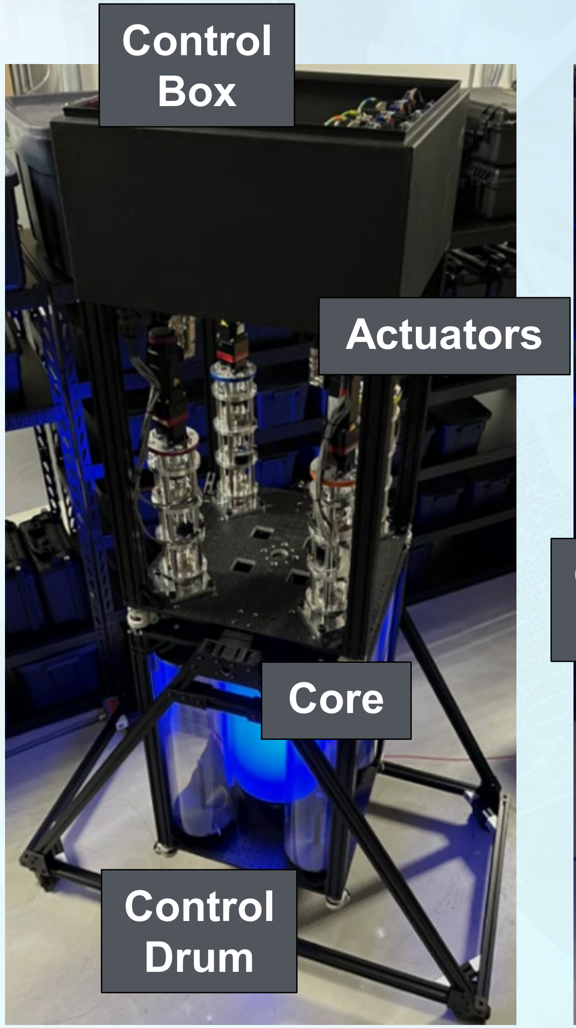
Motivations and Objectives

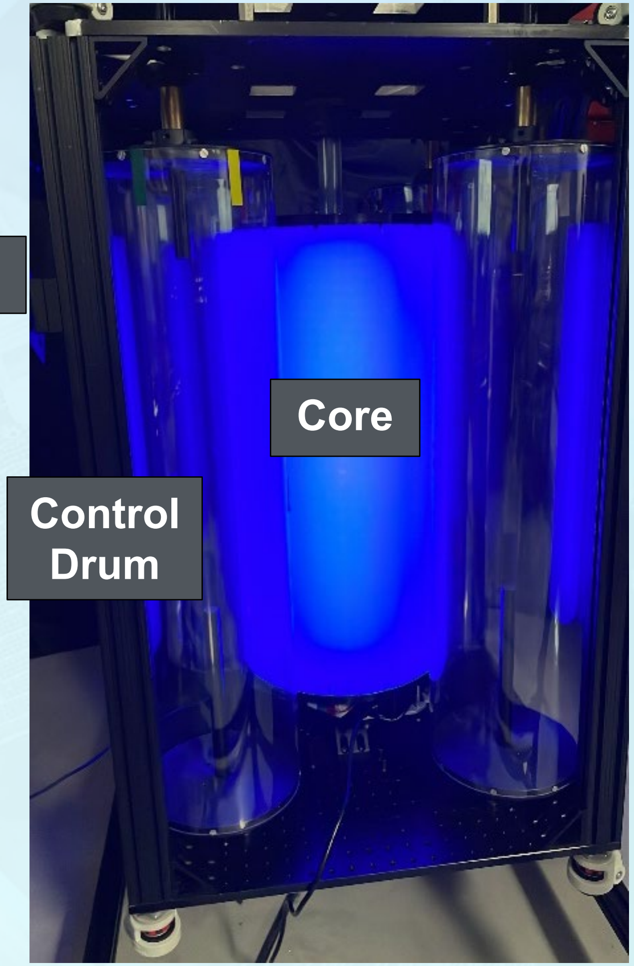
- M1: For advanced reactors, there is critical need for flexible, expandable software/hardware infrastructure to validate and integrate new control methods and technologies.
- M2: Control strategies developed solely in simulation can face significant performance limitations when applied to real systems.
- O1: Enable Microreactor Automated Control System (MACS) hardware testbed to serve as physical twin of Microreactor Applications Research Validation and Evaluation (MARVEL) for control method evaluation.
- O2: Demonstrate control scenarios using MACS with goal of comparing simulation and hardware.

Objective 1: Enable Microreactor Automated Control System (MACS) hardware testbed to serve as physical twin of Microreactor Applications Research Validation and Evaluation (MARVEL) for control methods evaluation.

MACS

- Developed by DOE Microreactor program
- Hardware testbed used for microreactor R&D
- Advance development, refinement, and maturation of microreactor control
- Developed in concert with MARVEL
  - 4 drum actuators
  - Core emulated by lights
- Measurements
  - Control drum positions
  - Control light intensity; measured with light sensors

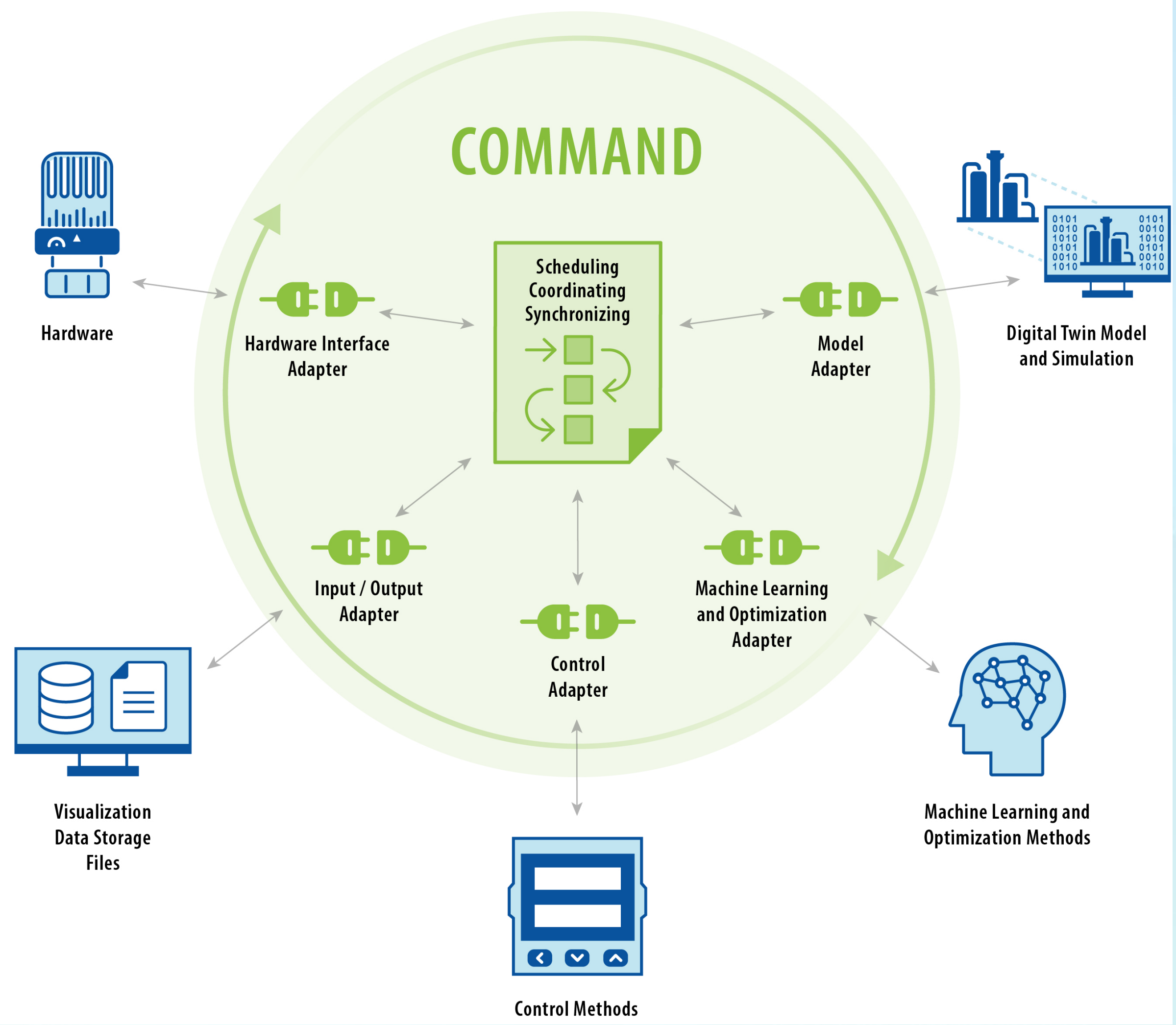




COMMAND (Control and Optimization Modular Modeling Application for Nuclear Deployment)

COMMAND is a flexible simulation platform designed to be:

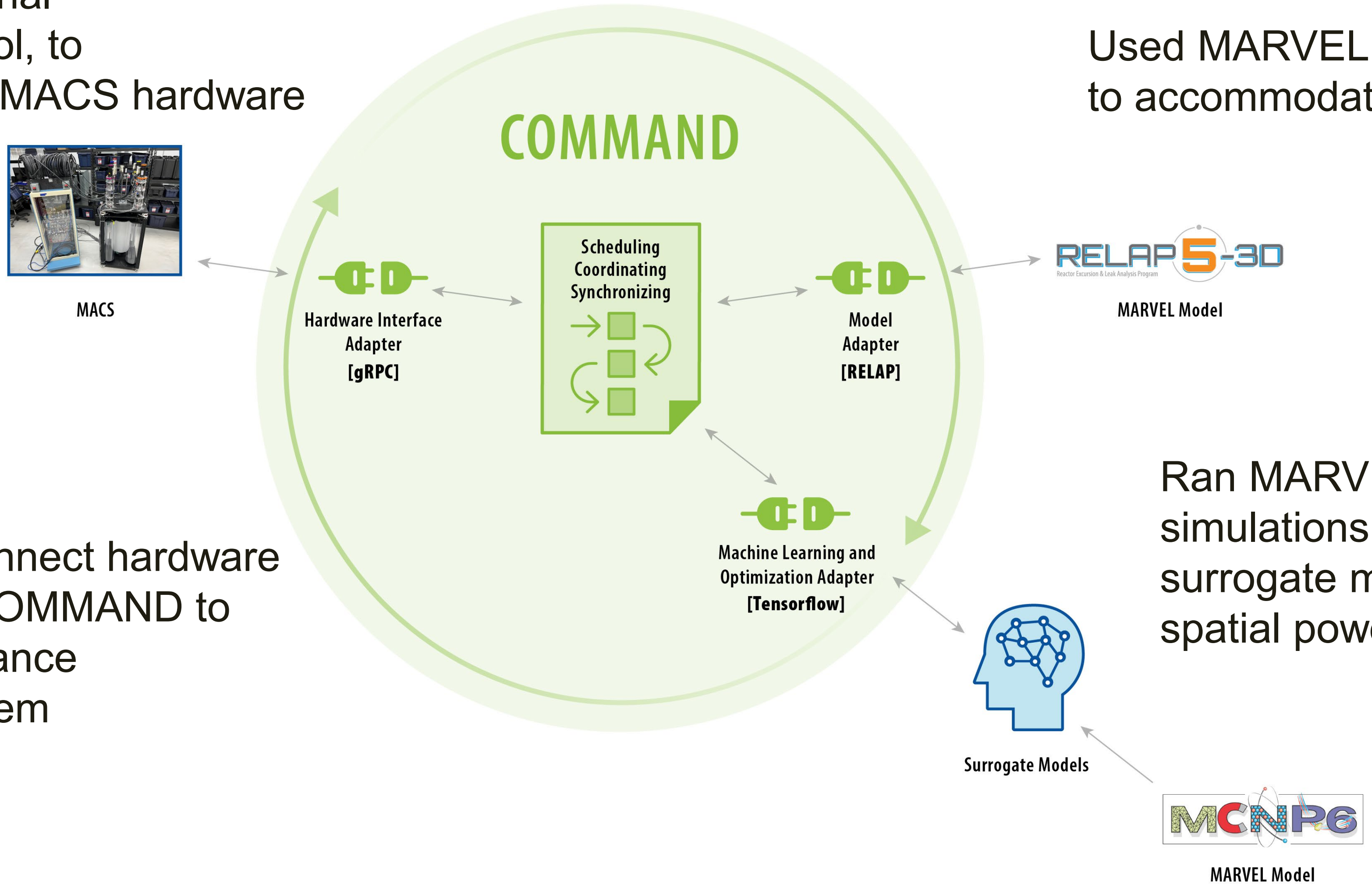
- **Accessible**: Open-source and publicly available
- **Modular**: Software “pieces” inherit from generic building blocks and can be combined/connected to create complicated simulations
- **High performing**: Designed for parallel processing, enabling simulations to take advantage of multi-core computers, servers, and nodes



Demonstration Platform: MACS + COMMAND

Used gRPC, an industrial communication protocol, to communicate with the MACS hardware

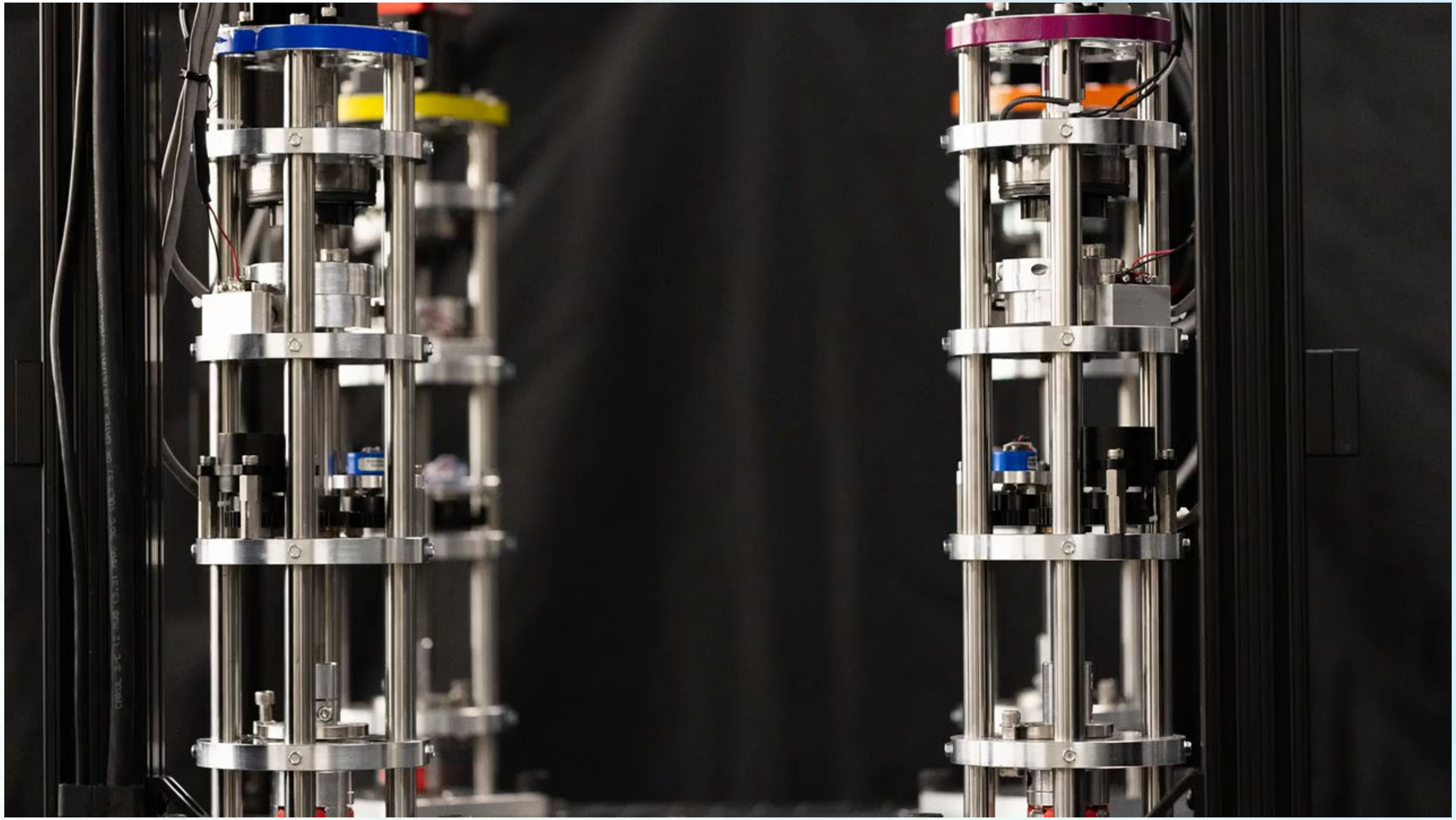
Used MARVEL RELAP model to accommodate MCNP inputs



Used pipeline to connect hardware running locally to COMMAND to INL's High Performance Computing ecosystem

Ran MARVEL MCNP simulations and developed surrogate models to capture spatial power distribution

Demonstration Platform: MACS + COMMAND

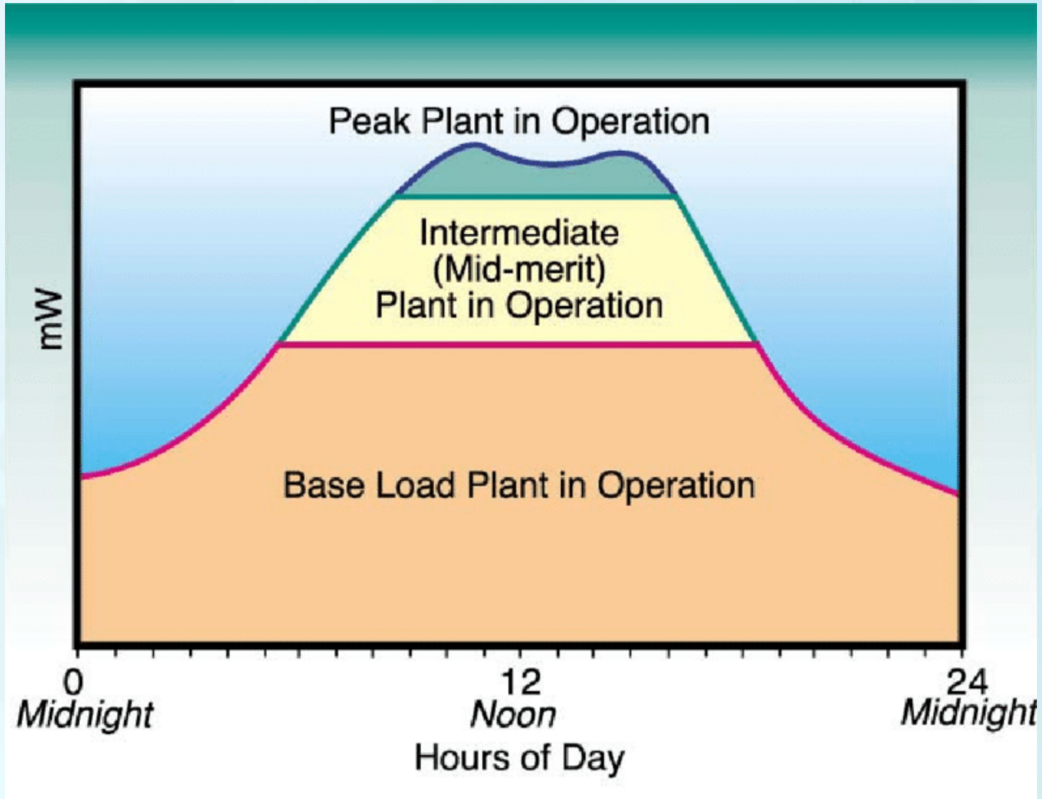


In collaboration with the DOE Microreactor Program

Objective 2: Demonstrate control scenarios using MACS with goal of comparing simulation and hardware.

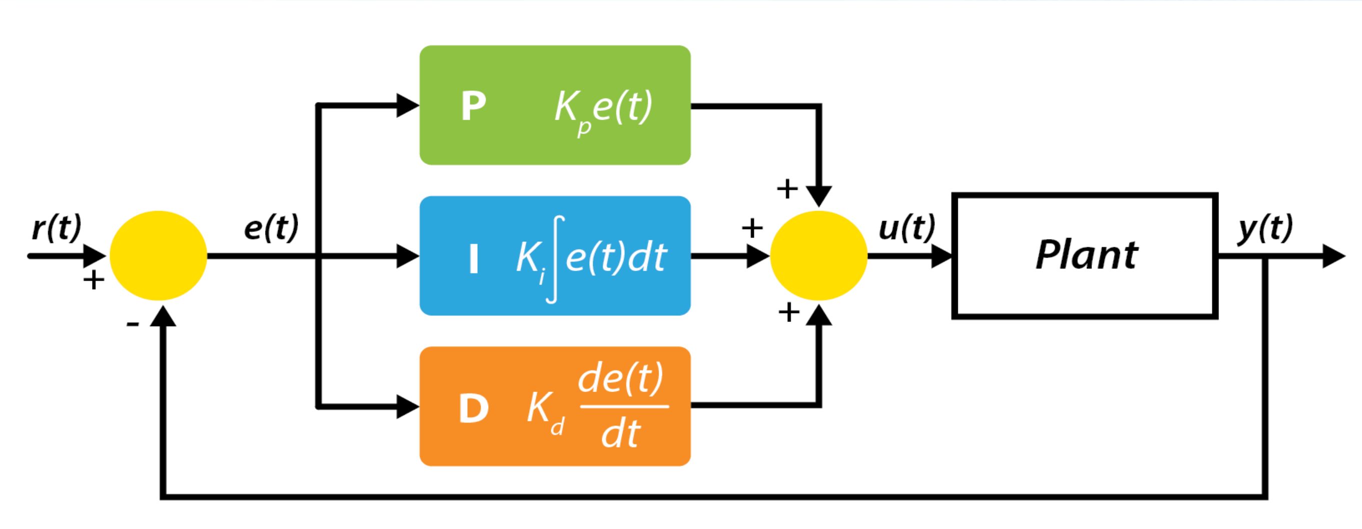
Test Scenario

- Both simulation and experimental tests evaluated performance of control strategy in **power load-following** scenarios.
- Load-following: electricity output is adjusted in response to changes in power demand.
- Two load-following scenarios were considered:
  - “Small step” (10 kW) power change
  - “Large step” (60 kW) power change
- **Only one** drum was actuated while rest were stationary at 127.5 deg.



Controller Design

- Utilized proportional integral derivative (PID) controllers tuned with Ziegler-Nichols method.
- Determined stability limit of simplified controller and then adjusted control gains based on limit.
- Gains were tuned using the large-step control scenario.



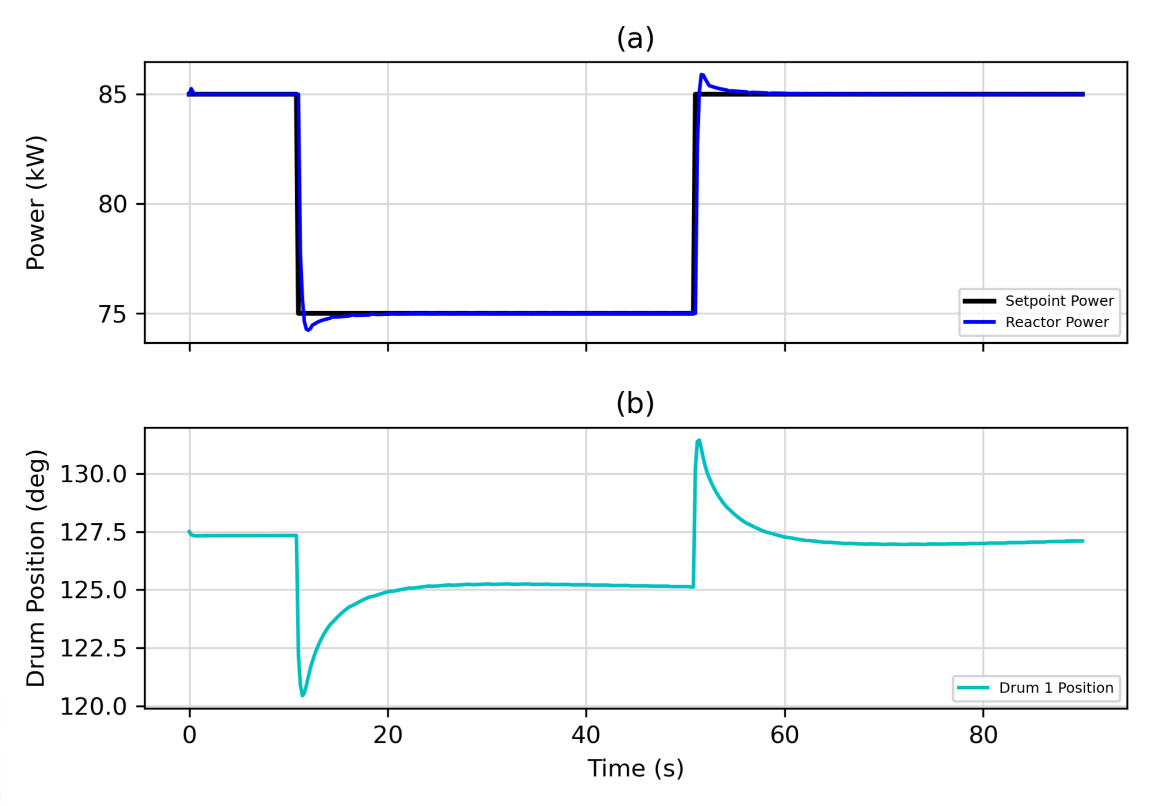
Controller Design

- Starting from baseline scenario, we incrementally added **complexity** to system until reaching final simulated scenario.
  - **Actuator saturation:** 0 ≤ drum angle ≤ 128 deg; drum speed ≤ 2 deg/sec
  - **Light sensor noise:** White and Gaussian

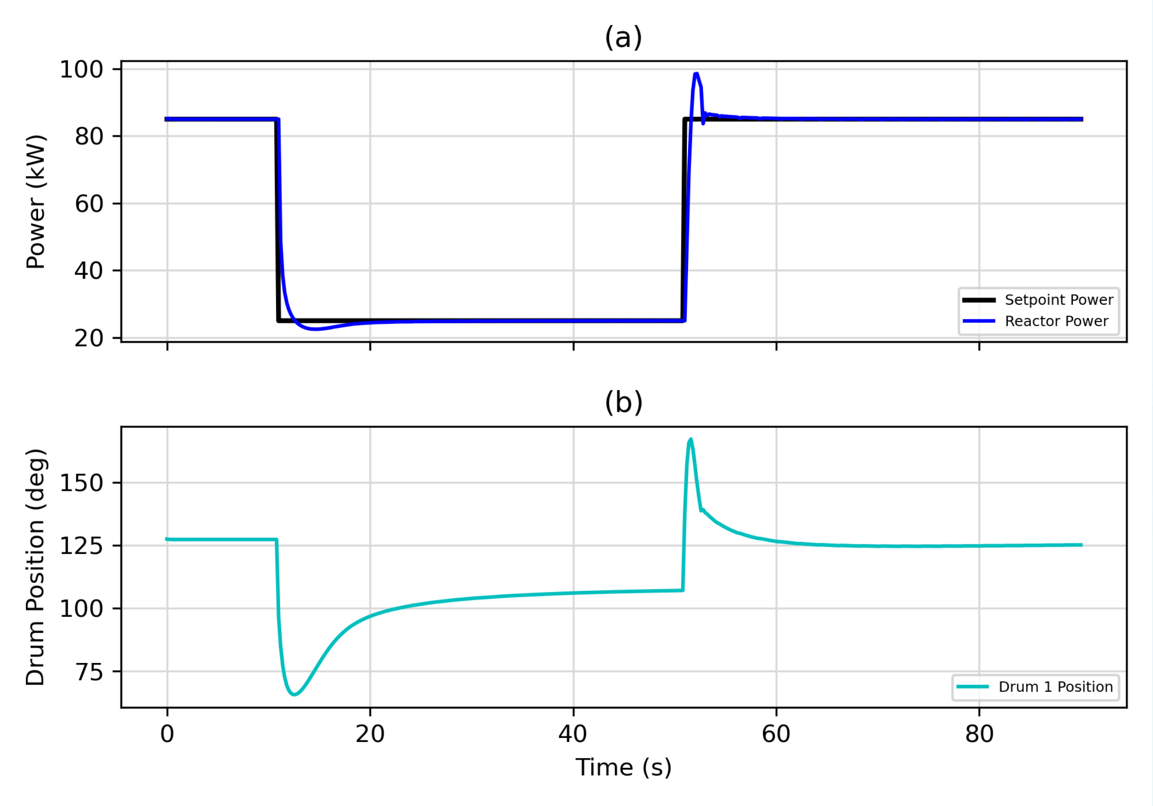
- Control performance in simulation and hardware were compared in terms of **overshoot** and **steady-state error**.

Baseline Simulation Results

Small Step

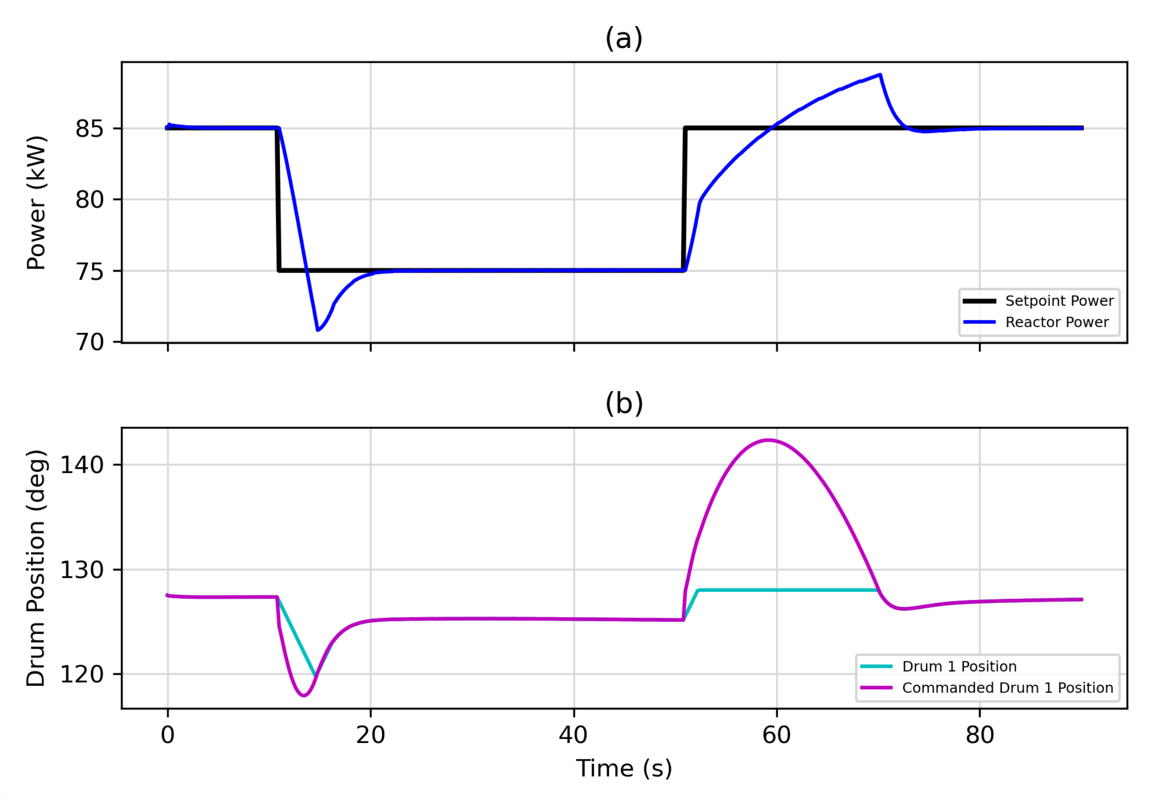


Large Step

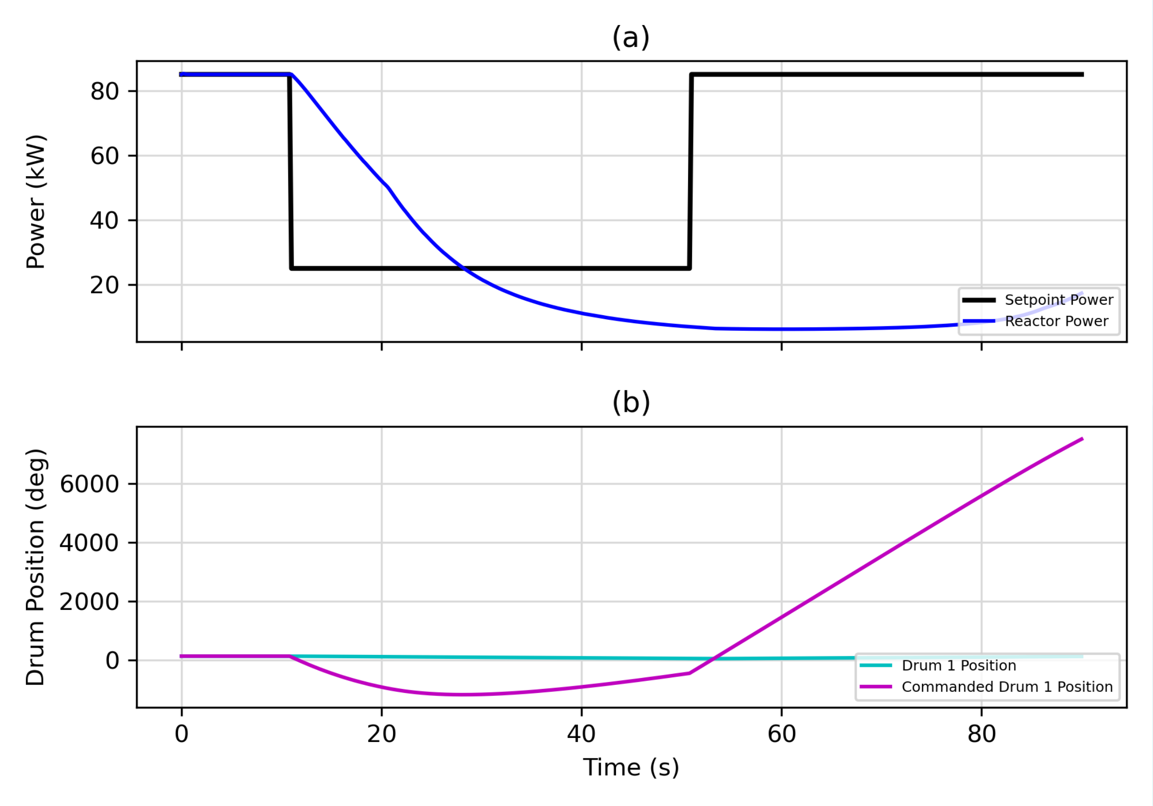


Simulation with Amplitude and Rate Saturations

Small Step

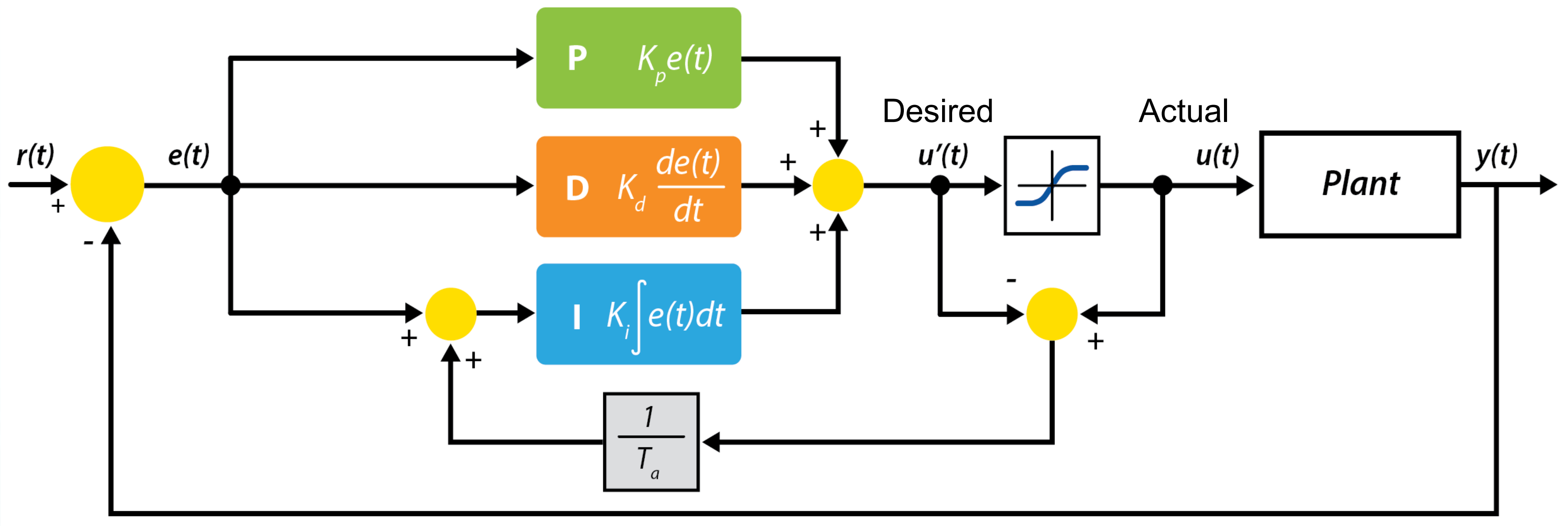


Large Step



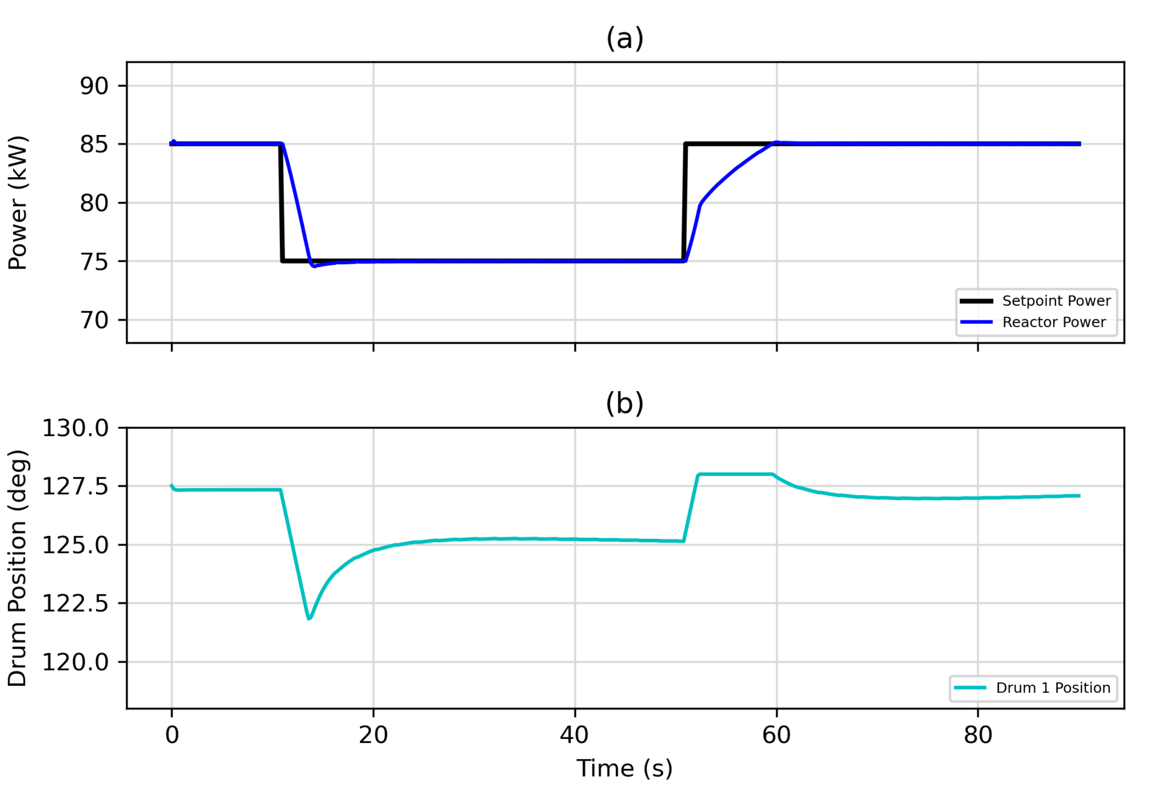
Anti-Windup Control

- In previous slide, integral term experienced **windup** (control effort required to reach setpoint exceeds actuator's capabilities).
- By implementing **anti-windup control**, we can prevent this and transform control into **constraint-aware** PID controller.

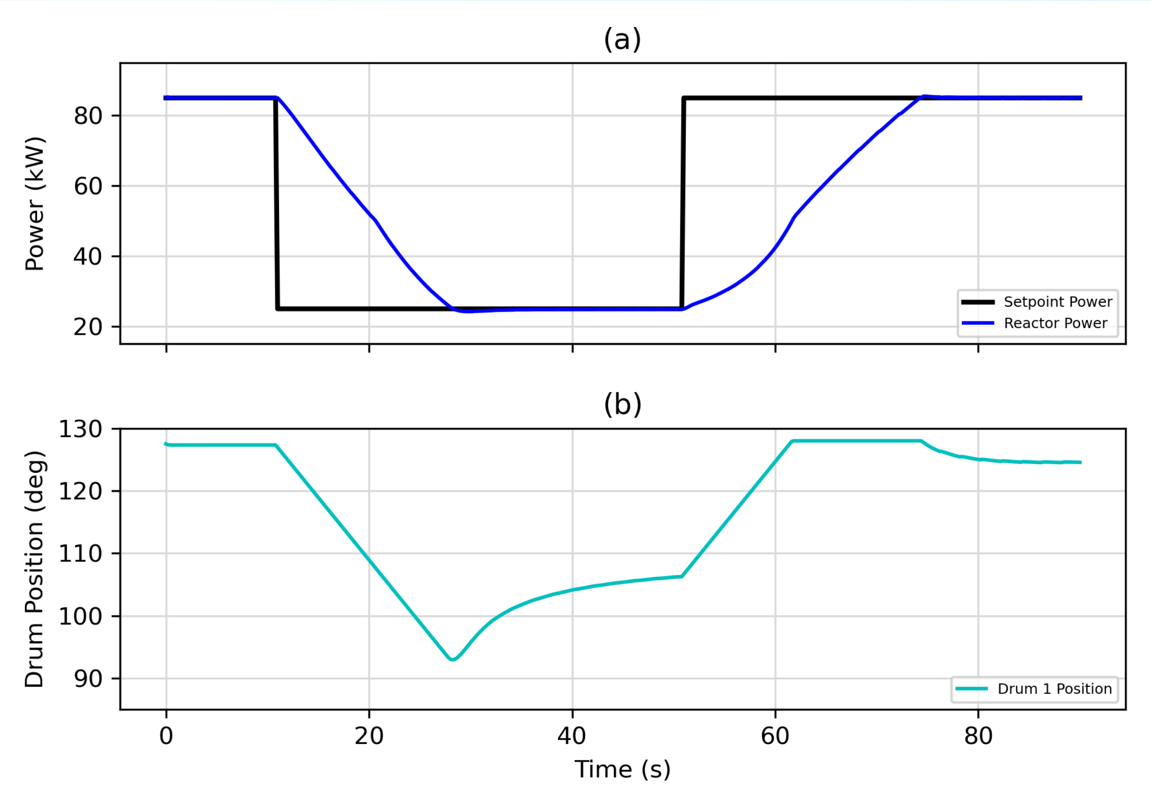


Simulation with Anti-windup Control

Small Step

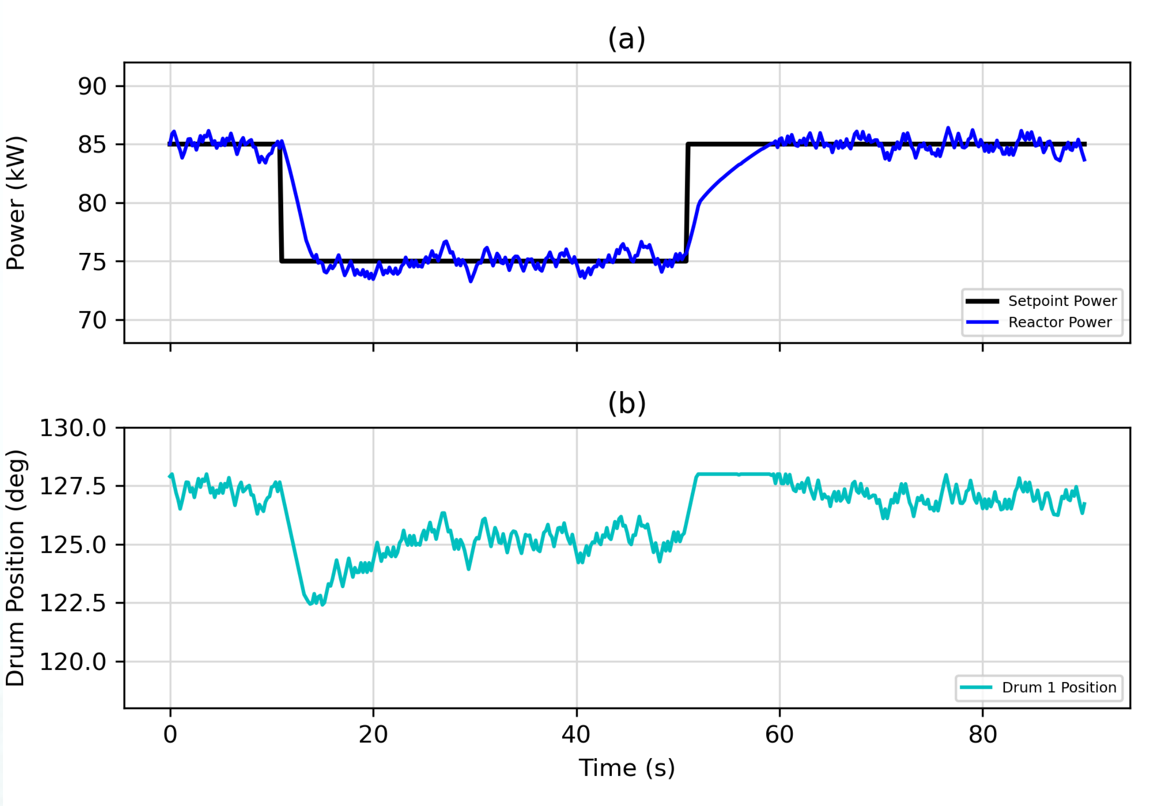


Large Step

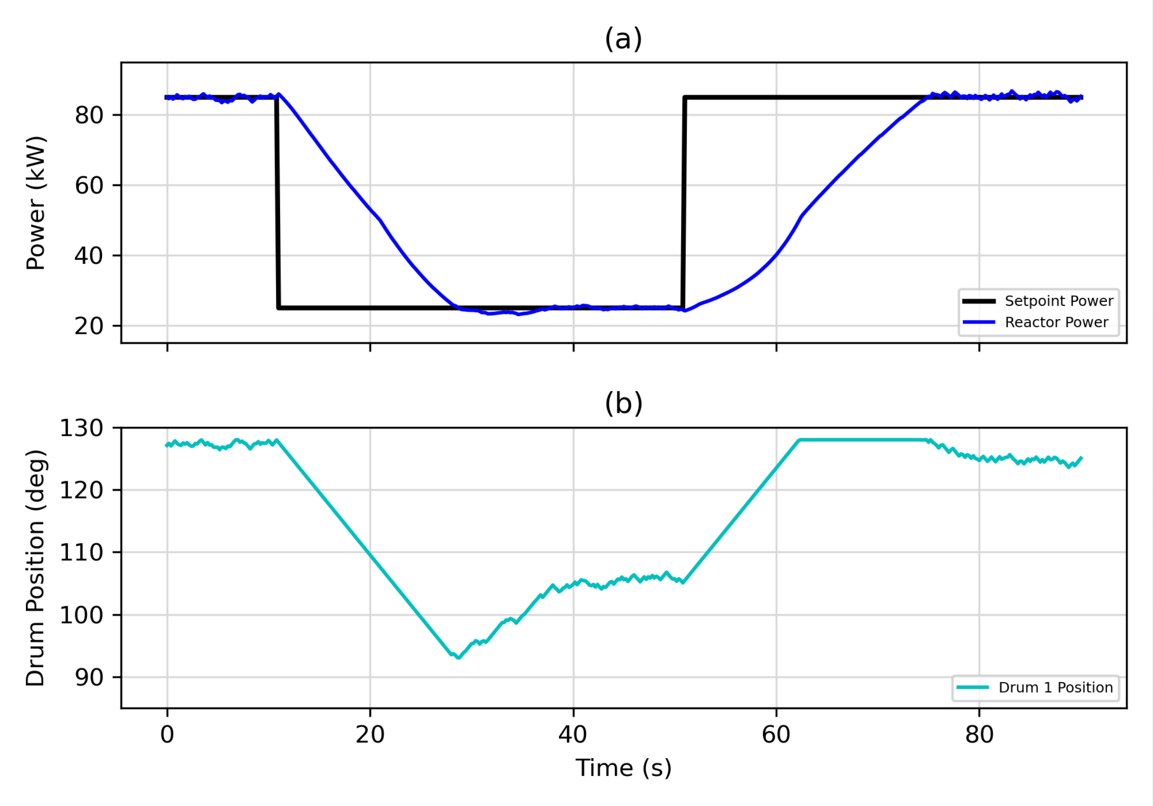


Simulation with Sensor Noise

Small Step

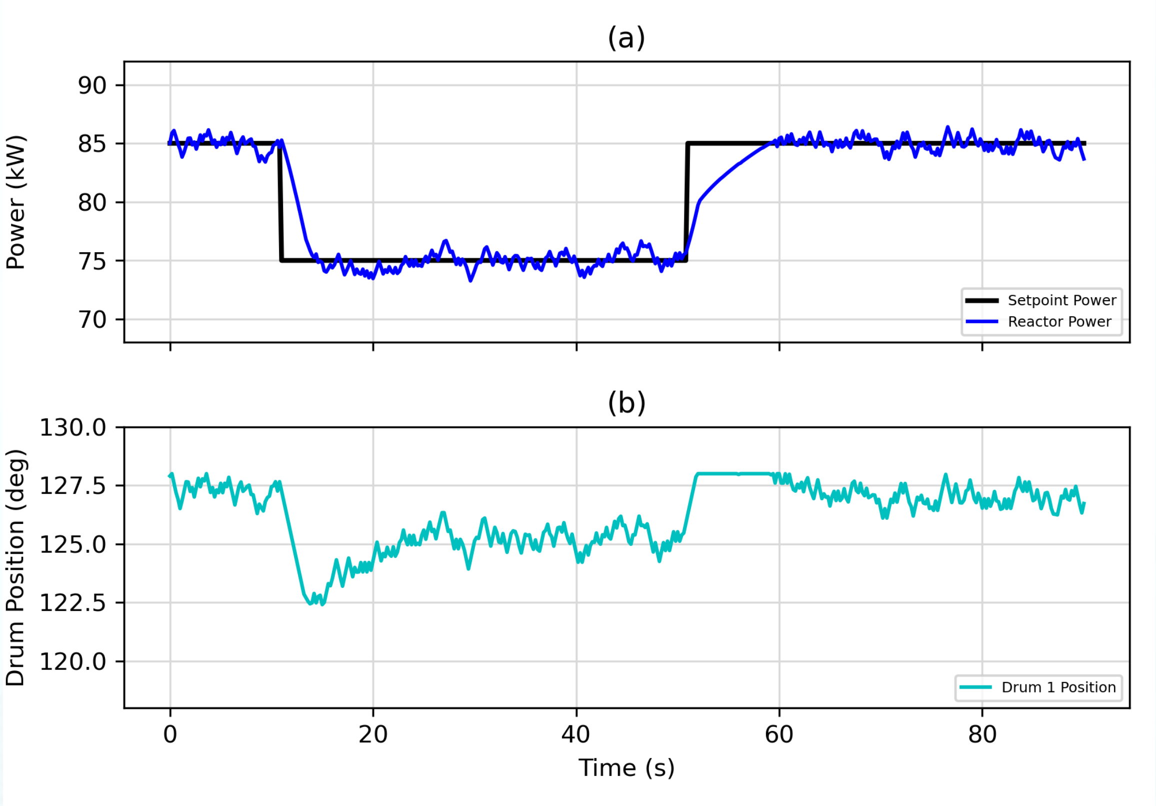


Large Step

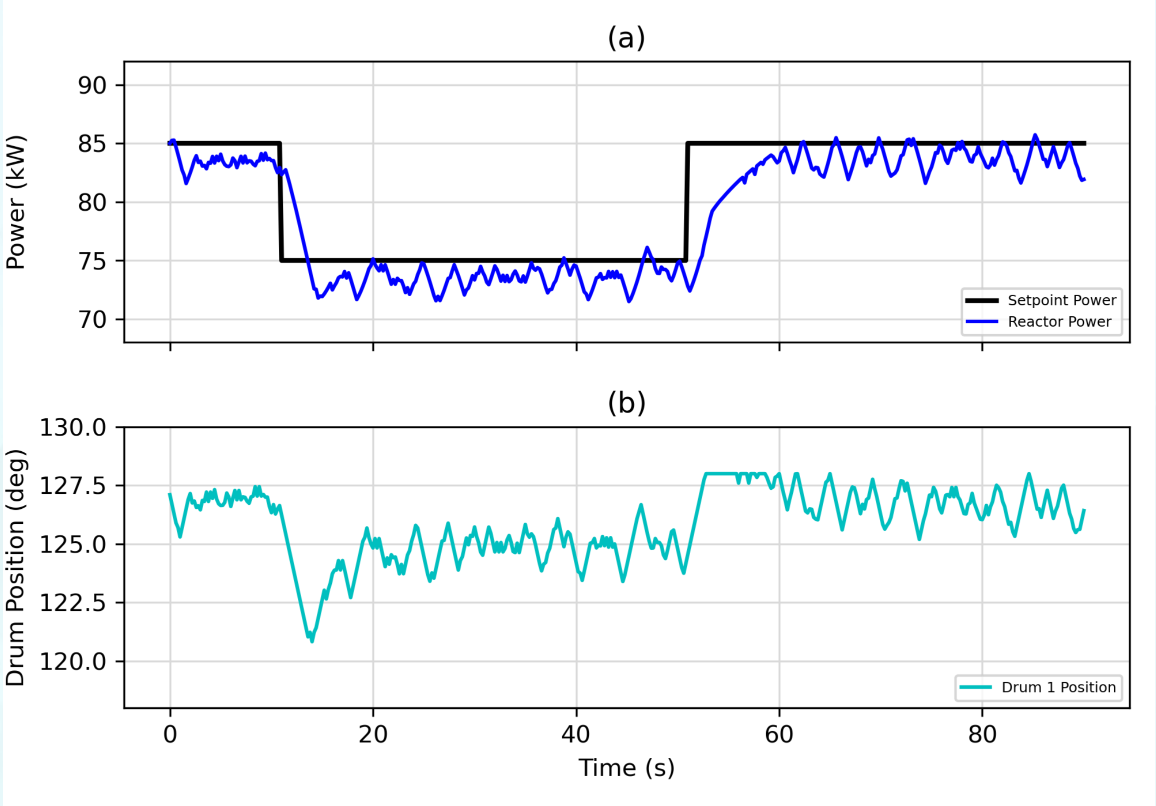


Comparing Simulation and Hardware – Small Step

Simulation

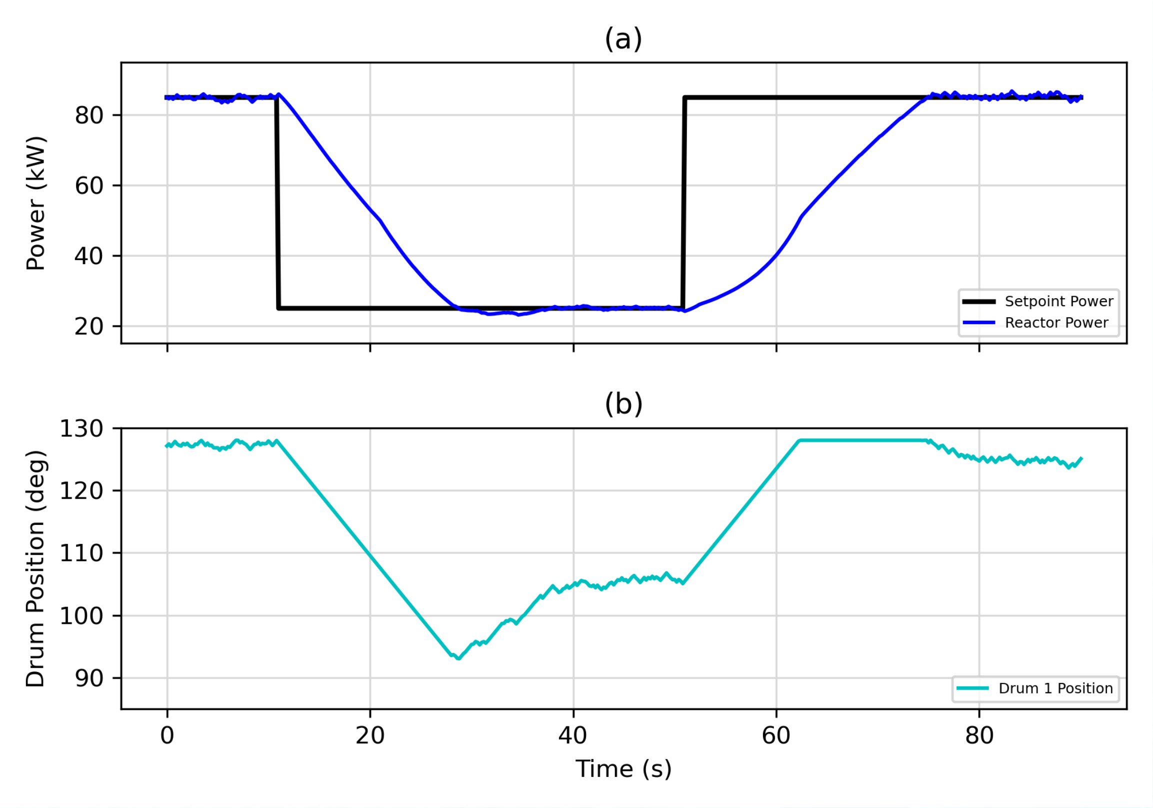


Hardware

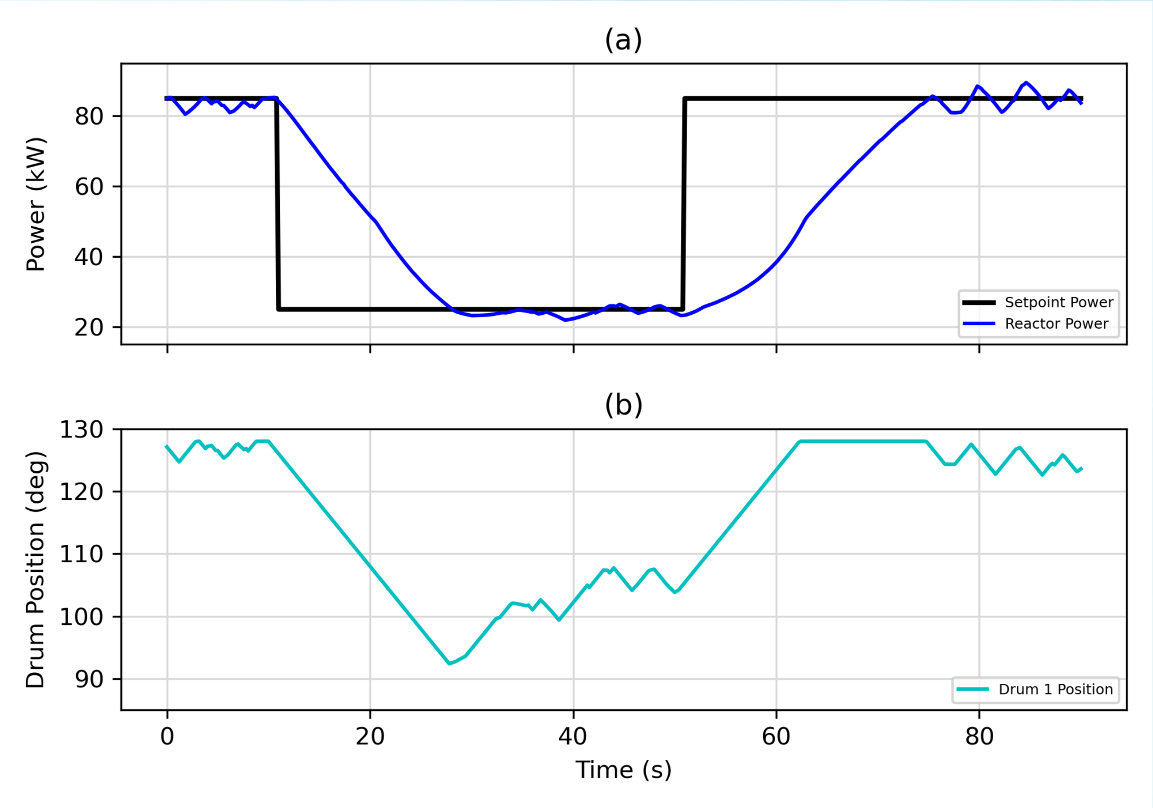


Comparing Simulation and Hardware – Large Step

Simulation



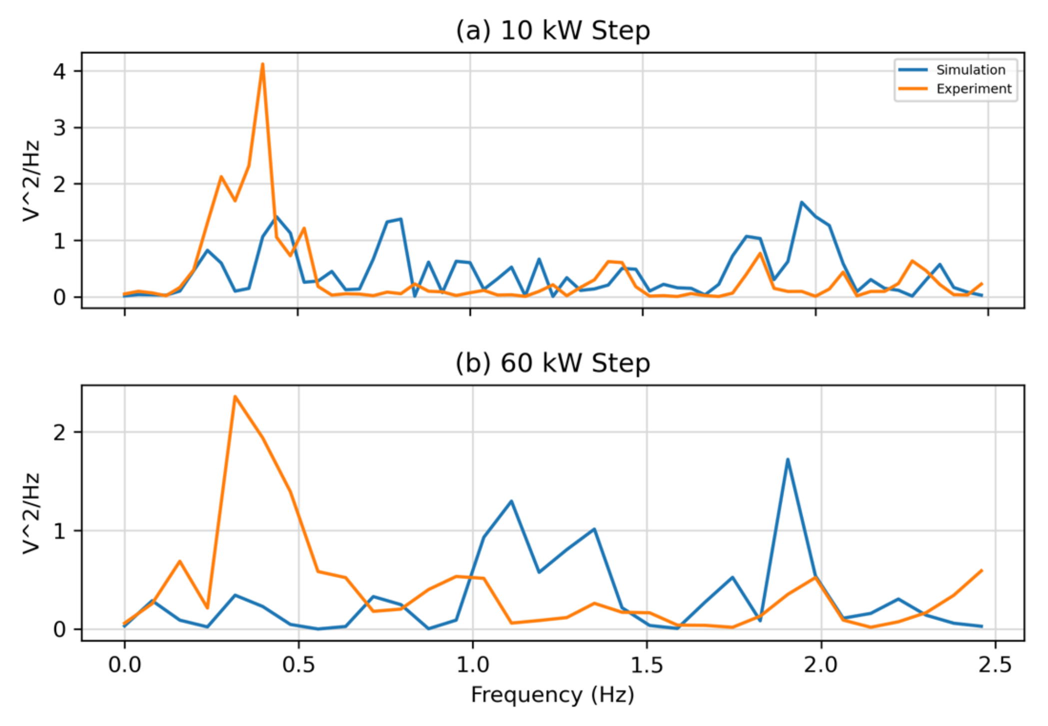
Hardware



Comparing Simulation and Hardware

Step Size	Testing Environment	Variable	Undershoot (kW)	Overshoot (kW)	Low Setpoint Error RMS (kW)	High Setpoint Error RMS (kW)
Small	Simulation	Reactor Power	1.7	1.4	0.7	0.6
	Hardware	Reactor Power	3.5	0.7	0.9	1.0
Large	Simulation	Reactor Power	1.9	1.8	0.5	0.6
	Experimental	Reactor Power	1.8	1.5	0.6	1.1

- The experiment over/undershoot was higher in one case but smaller in another.
- Higher steady-state errors in hardware results; noise content is possible cause.
  - Hardware noise has lower frequency content (not white gaussian).
  - Origin of 0.3-0.4 Hz peak is unknown at this point (sensor, software integration timing, actuator dynamics?).

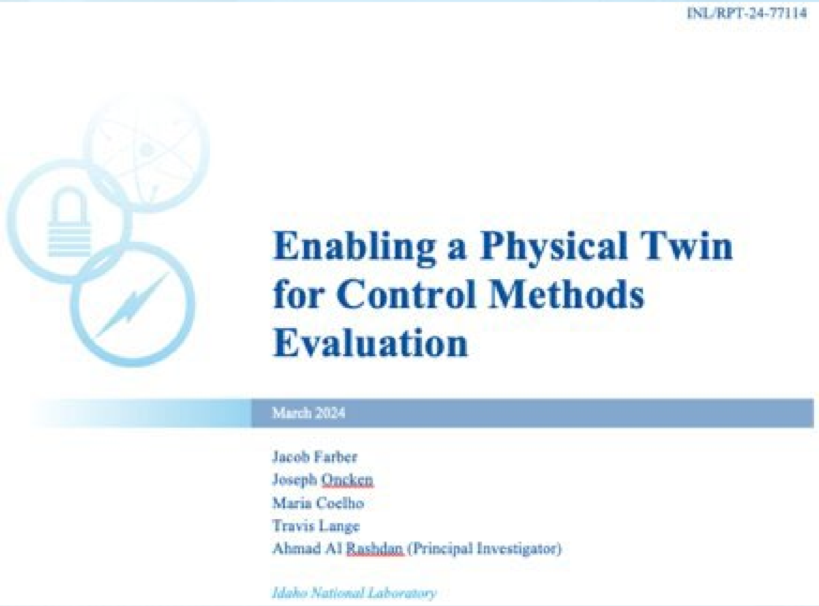


Conclusions and Future Work

- In concert with DOE Microreactors program, this effort enabled MACS hardware to serve as testbed for developing and validating reactor control strategies.

- Demonstrated differences between simulation and hardware, highlighting critical need for hardware validation in developing control strategies for advanced reactors.

- For FY25, use of AI for supervisory control, ranging from rule-based architectures to fully intelligent systems.



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Enabling a Physical Twin for Control Methods Evaluation

March 2024

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A Comparative Study of Control Performance: Simulation vs. Experiment

November 2024

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Thank You