MICROREACTOR AUTOMATED CONTROL SYSTEMS (MACS) - ORNL

March 4, 2025

Pradeep Ramuhalli, Jono McConnell, Wesley C. Williams

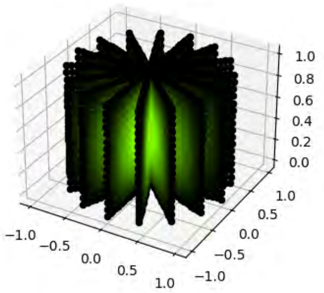
Oak Ridge National Laboratory

Outline

- Objective/scope
- Background
- Approach
- Results to Date
- Milestones for FY25
- Summary and Ongoing Research

Microreactor Automatic Control System (MACS) Objective and Scope

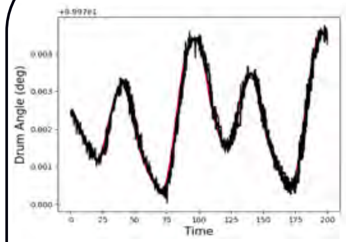
- Objective:
  - Create a robust, high fidelity and adaptable microreactor automated control system (MACS) that integrates digital twin models with hardware and enables graded automation
- Scope:
  - Integrate microreactor plant-level model with hardware-in-the-loop (HIL) to create a digital twin, leveraging data from representative surrogate hardware systems
  - Deliver control algorithms that demonstrate automation at different levels to enable
    - Autonomous operation
    - Remote operation
    - Increased reliability
    - Safety and security of operations



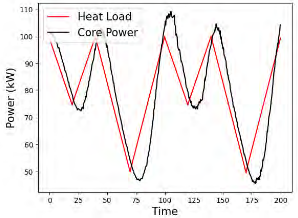
Power Density Distribution Data

ViBRANT

Hardware-in-the-Loop

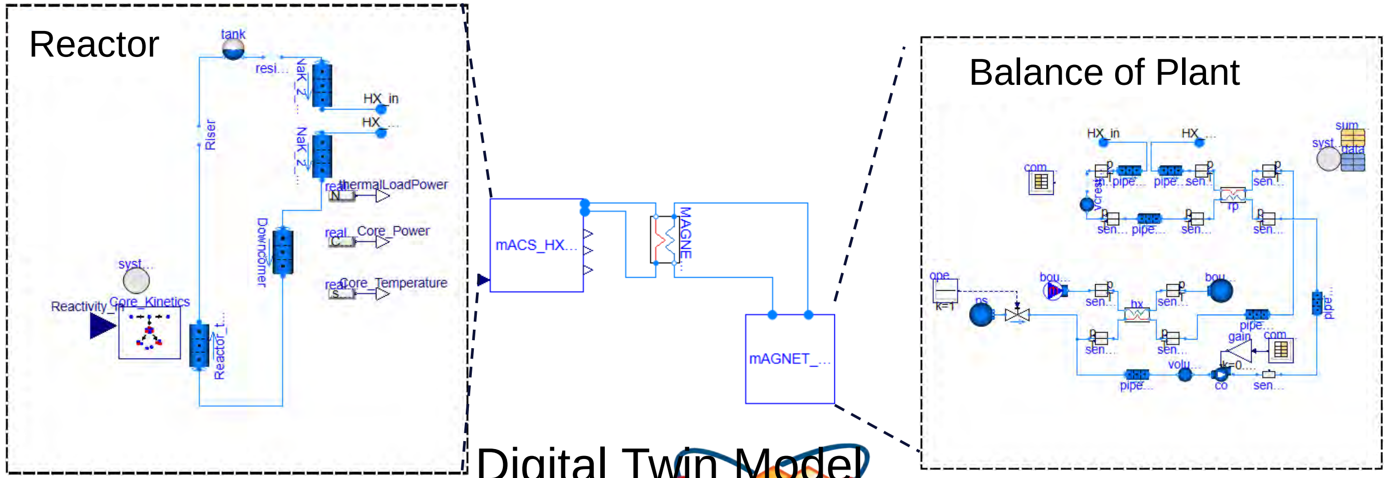


Drum Control



Measurements/Digital Twin Simulations

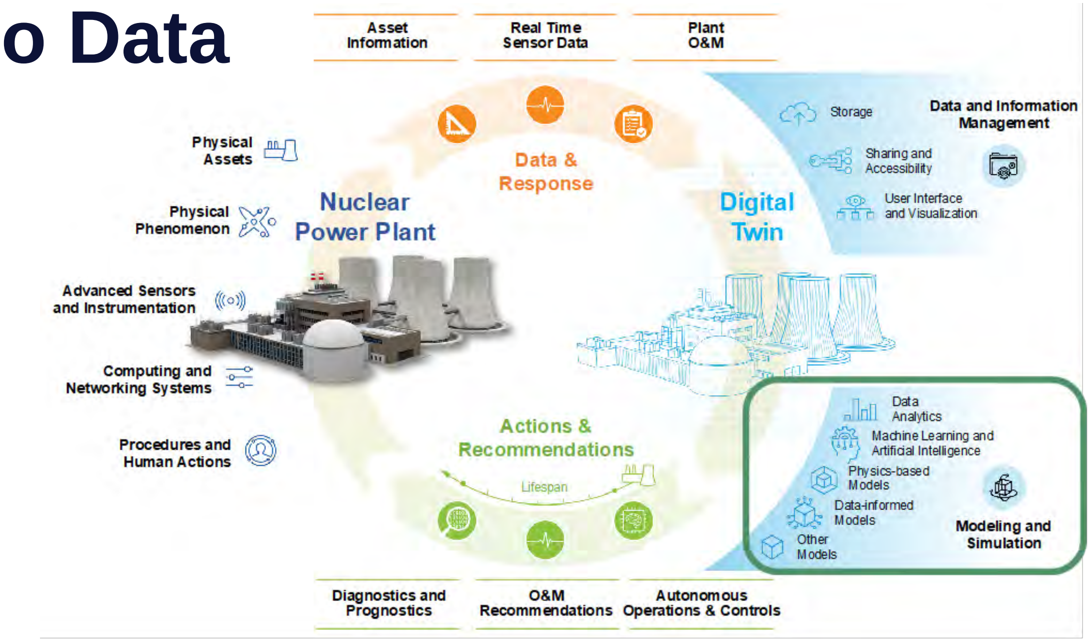
Hardware-in-Loop Control



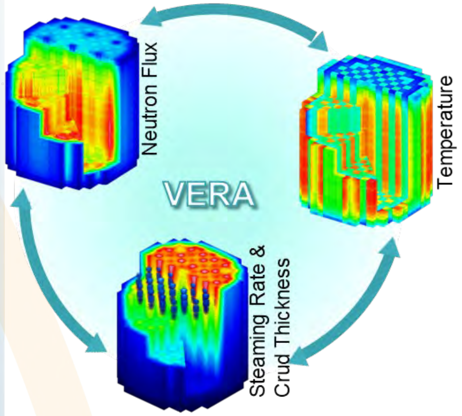
Digital Twin Model

Digital Twins: Software Models Tied to Data from Physical System

- Hybrid models (data-driven, with domain information) can serve as digital twins to support emerging needs
    - Potential for modeling system behavior at different levels of fidelity and for different uses, and spanning the range from fully data-driven to physics-based



(Image from NRC)



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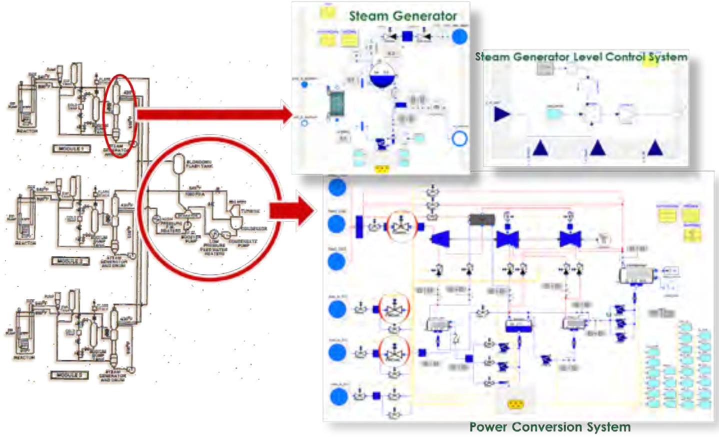
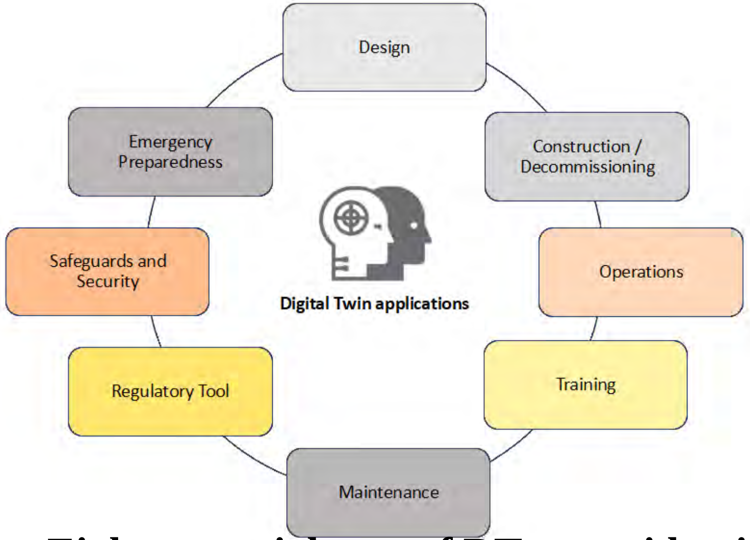


Liquid Metal Reactor Power Block

Examples of Models That May be Useful in Digital Twins



Eight potential uses of DTs were identified

MRP Microreactor Program

Expected Impact

- MACS supports
  - Automation of microreactor operations with a longer term objective of demonstrating safe autonomous microreactor operations
  - Remote operation of microreactors

- MACS leverages
  - Prior research on operational decision making
  - Prior and ongoing research on AI algorithms for controls

- MACS helps advance microreactor controls technology by enabling
  - Automating recovery from component failures
  - Identifying component health issues and recovery options (if necessary)
  - Automation for operational efficiency and cost-competitiveness

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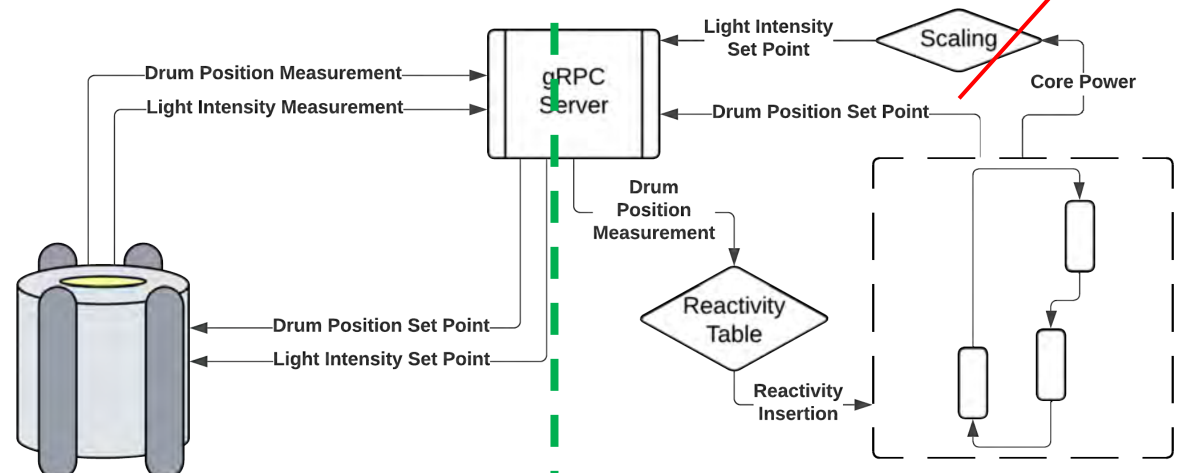
MACS Integrates Hardware, Models, and Control Algorithms

Control Logic



Drum Position Measurement

Light Intensity Measurement

gRPC Server

Light Intensity Set Point

Scaling

Core Power

Drum Position Set Point

Drum Position Measurement

Reactivity Table

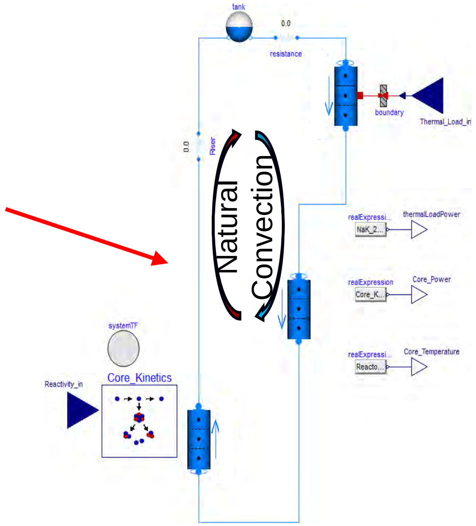
Reactivity Insertion

Drum Position Set Point

Light Intensity Set Point

Test Bed Hardware

Modelica FMU

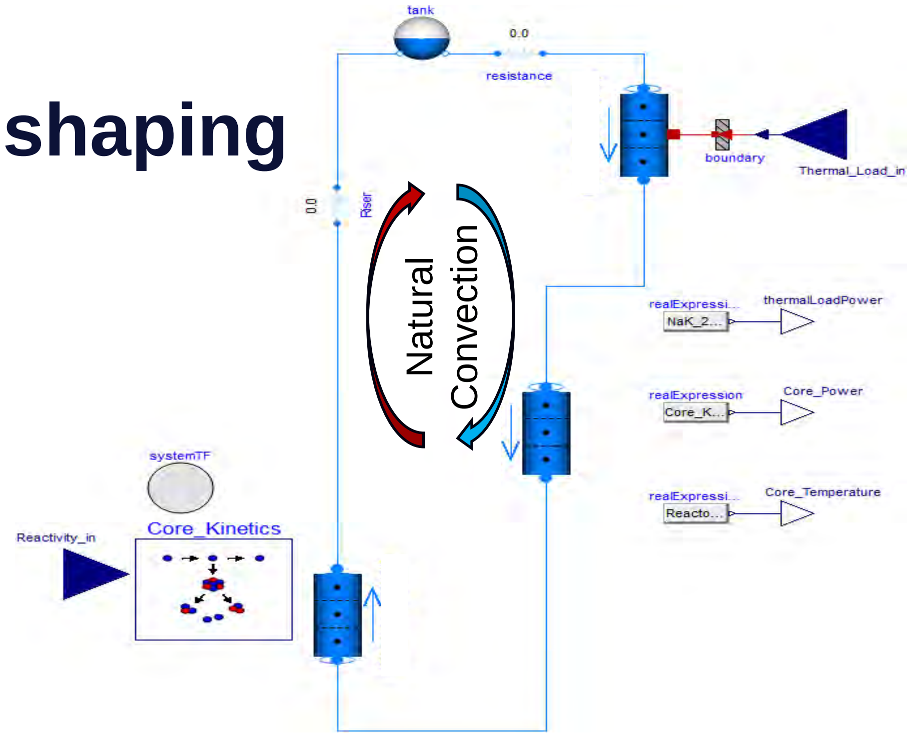


Hardware and Controllers

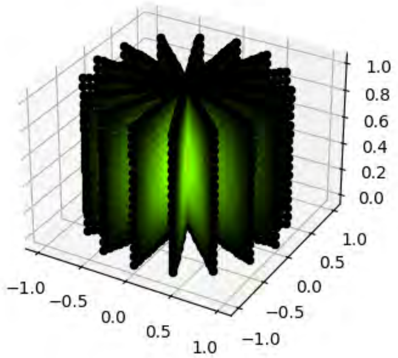
Models and Reactor/Plant Control Algorithms

MACS Uses a Modelica Model Based on MARVEL, with externally applied power shaping

- Point kinetics core
  - Provides heat to riser and informs total power level
  - Receives thermal feedback from local region of NaK primary coolant loop
- Natural convection drives heat removal
  - Prescribed heat removal applied on downcomer leg
- Reactivity insertion calculated externally and taken as input
- Power density function applied externally to inform power distribution
  - Corresponds to light intensity distribution on ViBRANT



Modelica Model of Reactor



Cosine Power Density Function

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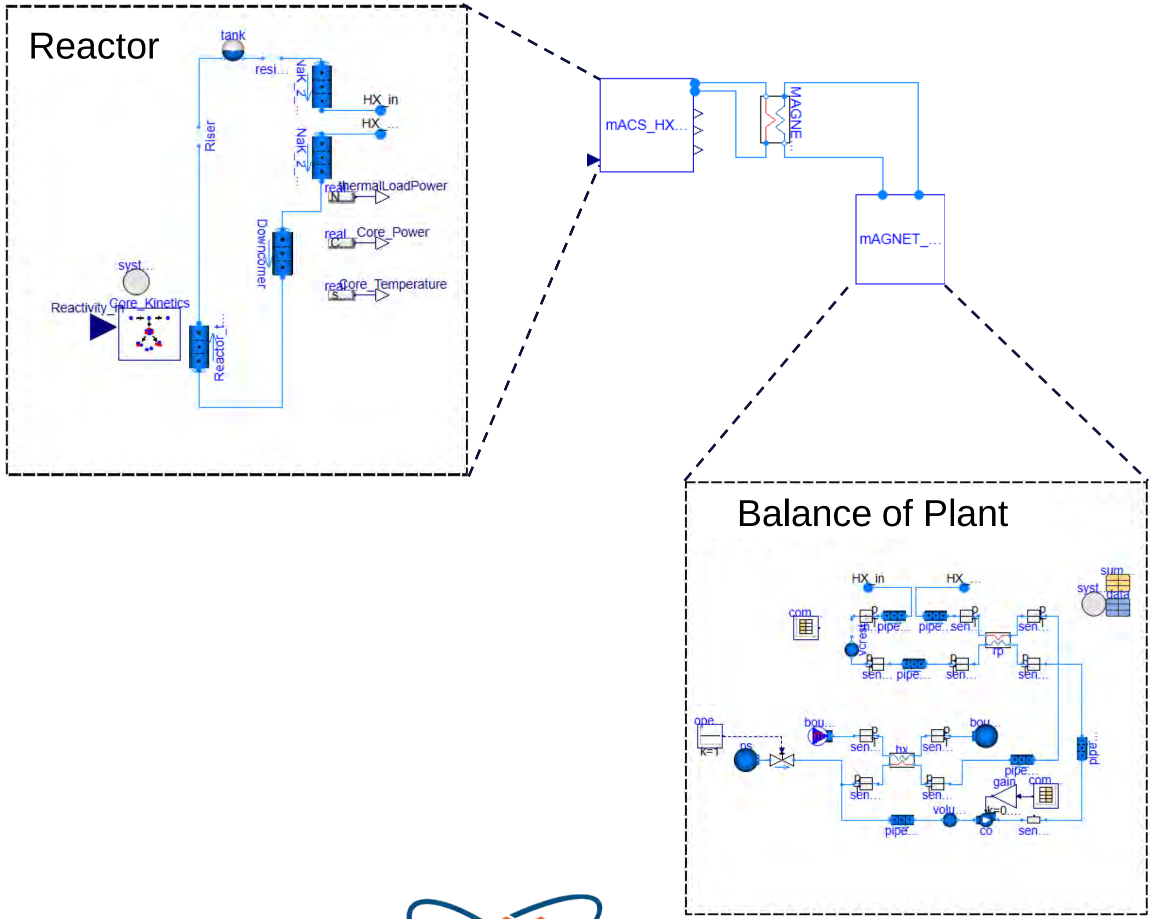
Balance of Plant Model Integration

- Heat exchanger couples primary coolant to HYBRID MAGNET Model (representative downstream thermodynamic system)
- Coupled balance of plant (BOP) model provides a more complex simulated environment with multiple control inputs
  - Drum rotation
  - Valve opening
- BOP integrated model is being evaluated in Modelica/TRANSFORM



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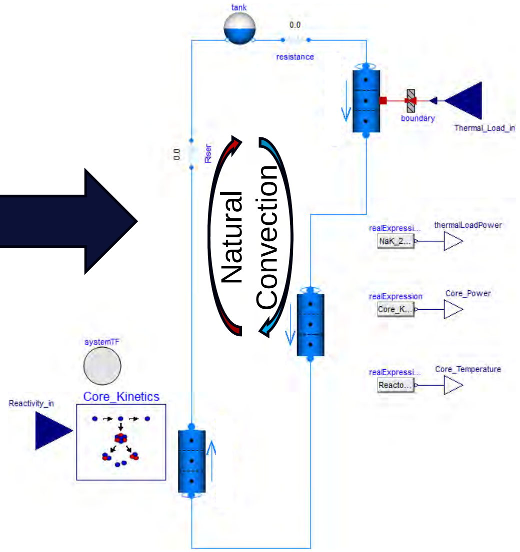
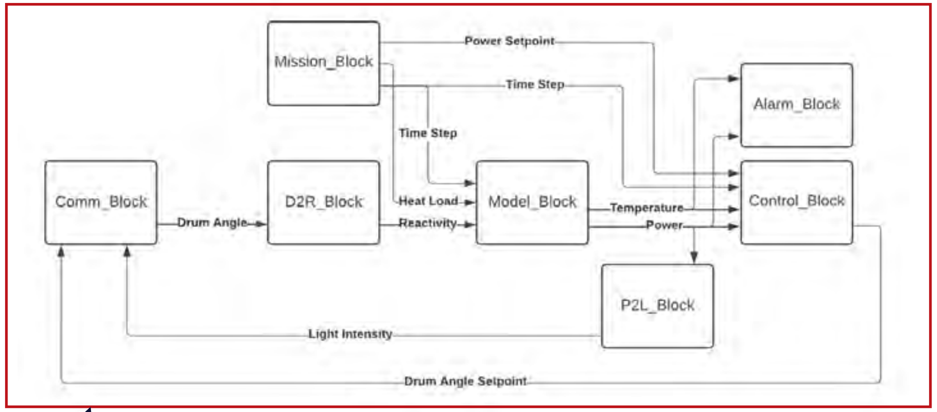
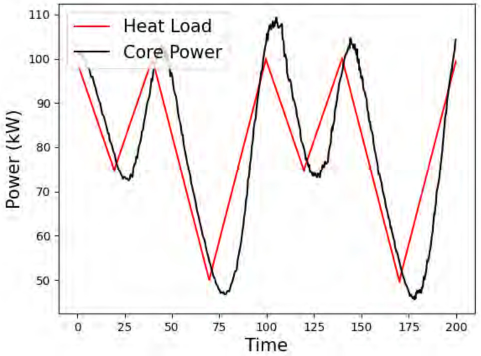
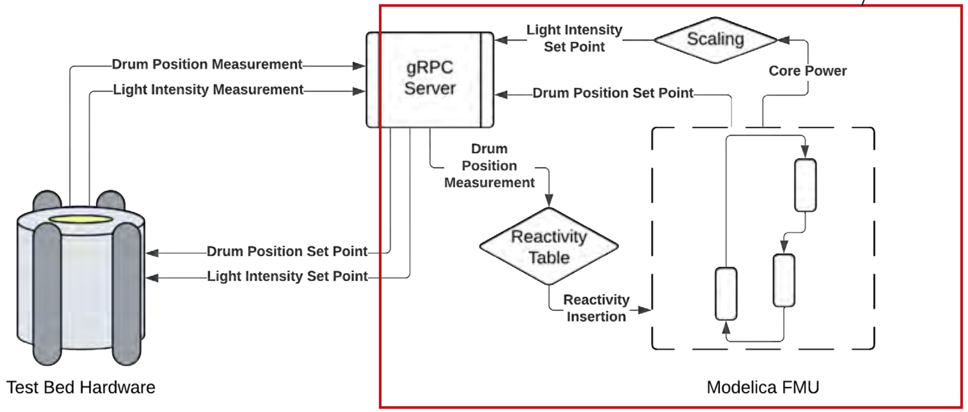
MACS/ViBRANT Hardware-in-the-Loop




Mission_Block
Power Setpoint
Time Step
Time Step
Alarm_Block
Comm_Block
Drum Angle
D2R_Block
Heat Load
Reactivity
Model_Block
Temperature
Power
Control_Block
P2L_Block
Light Intensity
Drum Angle Setpoint

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Test Bed Hardware
Modelica FMU

- LabVIEW-based gRPC communication protocol manages data exchange between MACS software and ViBRANT
- Modular Python client organizes real-time simulation and control for plug-and-play of simulated components
- Preliminary hardware-in-the-loop (HIL) testing with reactor model and ViBRANT shows reasonable and automated load following with PID control

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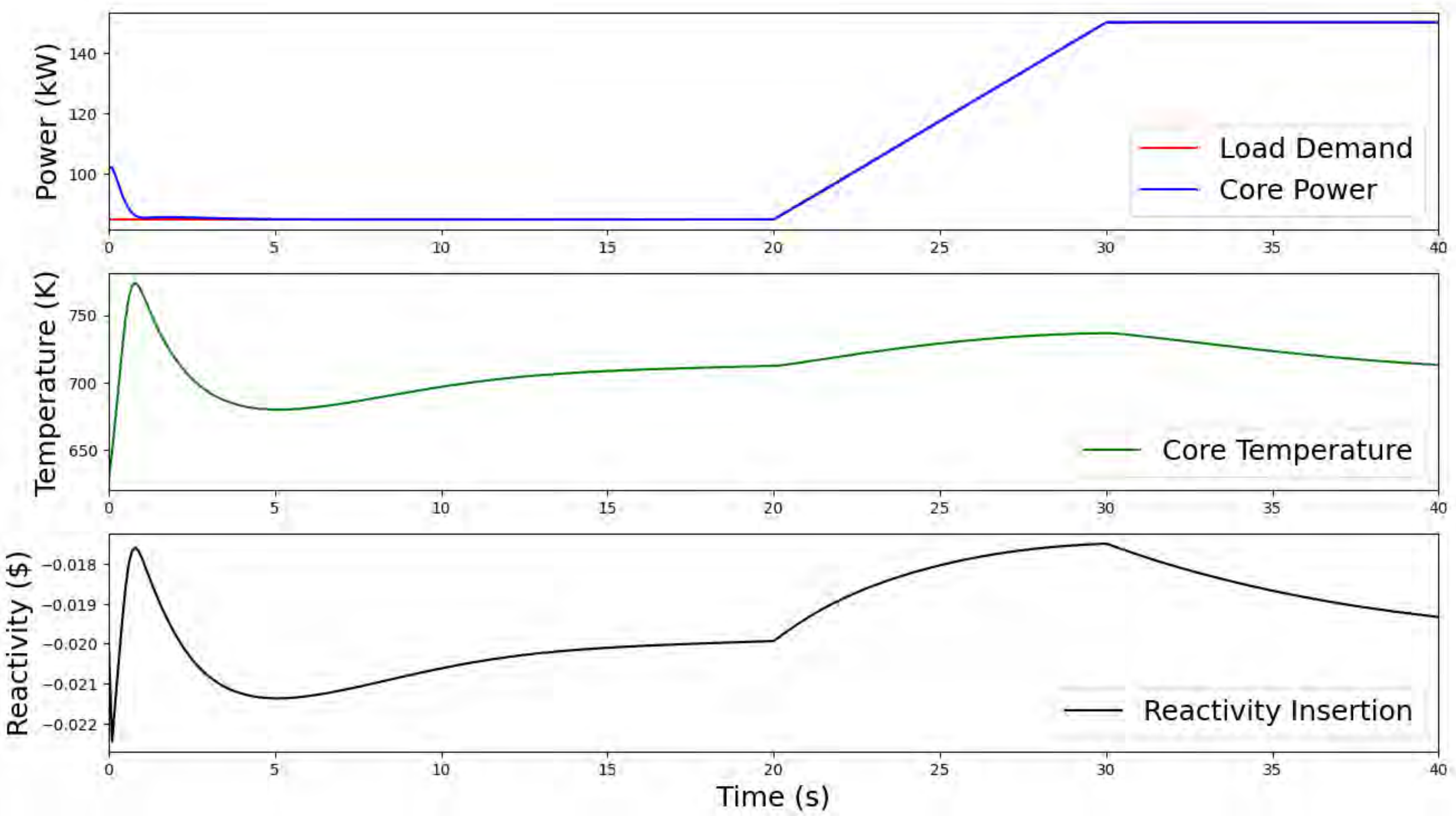
Model Testing in TRANSFORM

- Control testing performed within Modelica environment
    - Normalized proportional control sufficient for ramp dynamics
- Test assumes instantaneous control of reactivity value with no drum dynamics
- Test applies control at internal solver time step (near continuous)



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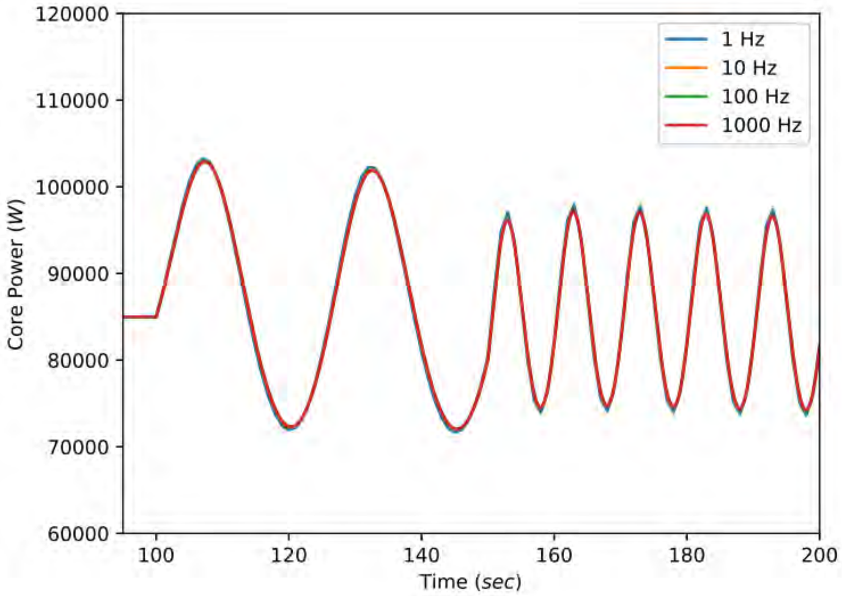
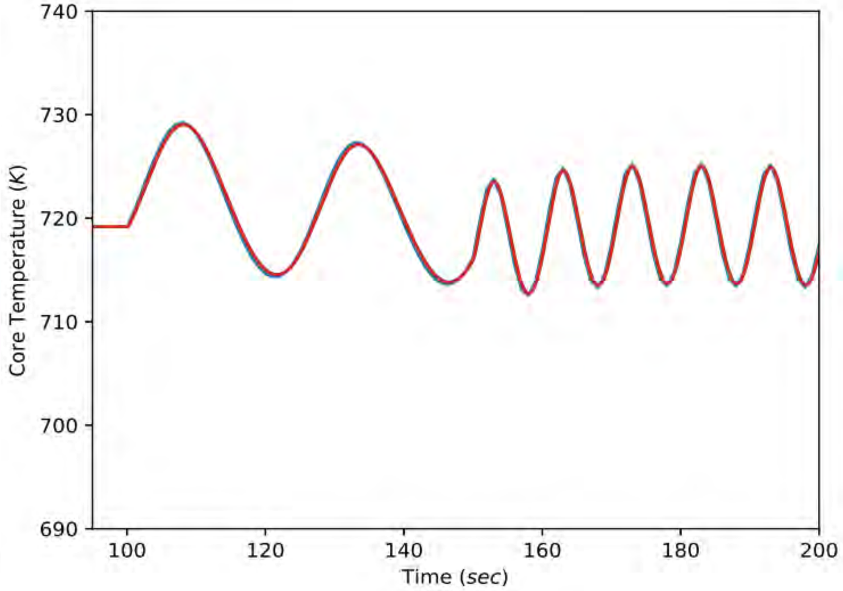
Model Testing with Python

- Modelica Functional Mockup Unit (FMU) tested at different simulation speeds in Python
  - Brought to steady state, perturbed, and allowed to respond in open loop dynamics
- Dynamics do not stray significantly with coarse simulation (1 Hz)
- Real-time is maintained up to ~10 Hz





	1 Hz		10 Hz		100 Hz	
Ramp	137.6 W	0.162%	13.79 W	0.016%	3.401 W	0.004%
Sine	531.5 W	0.625%	55.29 W	0.065%	17.15 W	0.020%

$$\%Error = 100 * \frac{\sum_{i=1}^{n} |P_i' - P_i|}{nP_{ref}}$$

	1 Hz	10 Hz	100 Hz
Ramp	10.65 sec	61.58 sec	368.1 sec
vs. Real Time	9.39×	1.62×	0.27×
Sine	13.46 sec	73.75 sec	417.5 sec
vs. Real Time	7.43×	1.36×	0.24×

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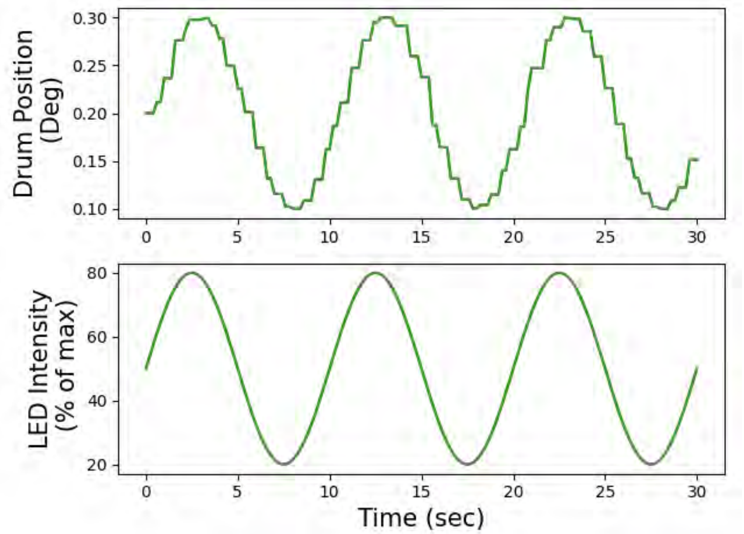
Hardware Interface Speed Testing

- Initial test of gRPC/Hardware communication with client-side control
- Waiting for confirmation of signal actualization proved too slow for real-time simulation, especially for multi-drum actuation
- Streaming commands showed promising results
  - Stair-stepping in drum dynamic data implies limitations on current hardware API to maintain 0.2 second cycle times

Test	Average	Minimum	Maximum
Drum 1 Small	0.849 sec	0.599 sec	1.899 sec
Drum 1 Med.	1.169 sec	0.799 sec	2.499 sec
Drum 1 Large	1.148 sec	0.697 sec	2.099 sec
All Drum Small	4.909* sec	0.998 sec	Time Out
All Drum Med.	3.838* sec	1.199 sec	Time Out
All Drum Large	2.858* sec	1.096 sec	Time Out
1 LED	0.118 sec	0.093 sec	0.199 sec
All LED	0.108 sec	0.098 sec	0.196 sec
1 LED & 1 Drum	1.238 sec	0.797 sec	2.099 sec

*Timeout set at 7 seconds



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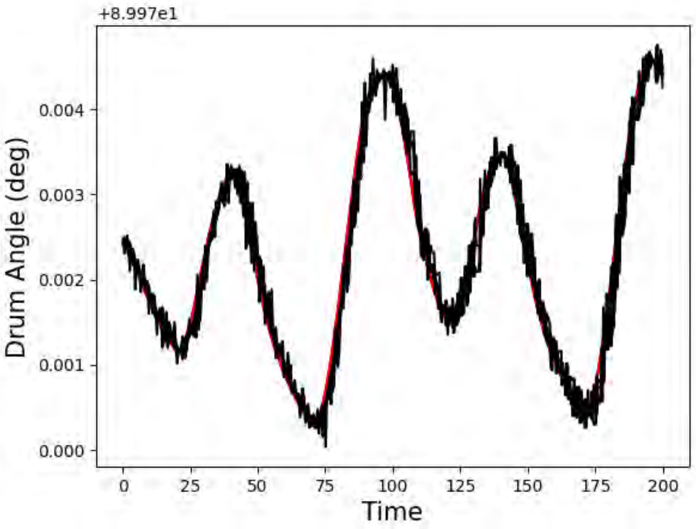
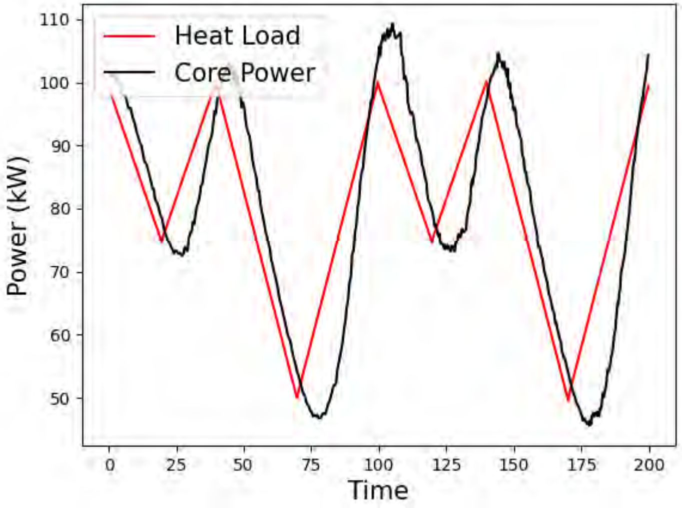
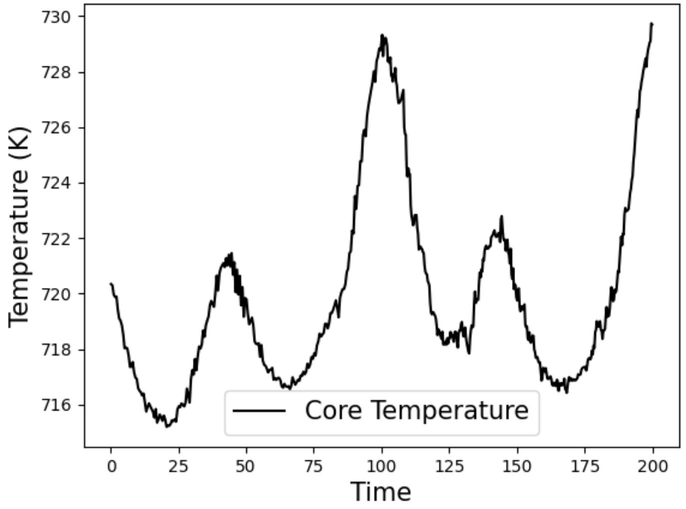
Hardware-in-the-Loop Testing – Ramp Power-Following Test

- Testing HIL data flow with FMU and sensor data feedback
  - 0-100 s – 0.3 s time step
  - 100-200 s – 0.5 s time step
- Drum response fuzziness shows slight differences of the four drum responses superimposed
- PID controller yielded power following with some overshoot and lag, but overall reasonable ramp trend following
  - Drum actuation successfully followed requested control angles,
  - Lag suggests need for improvement in controller



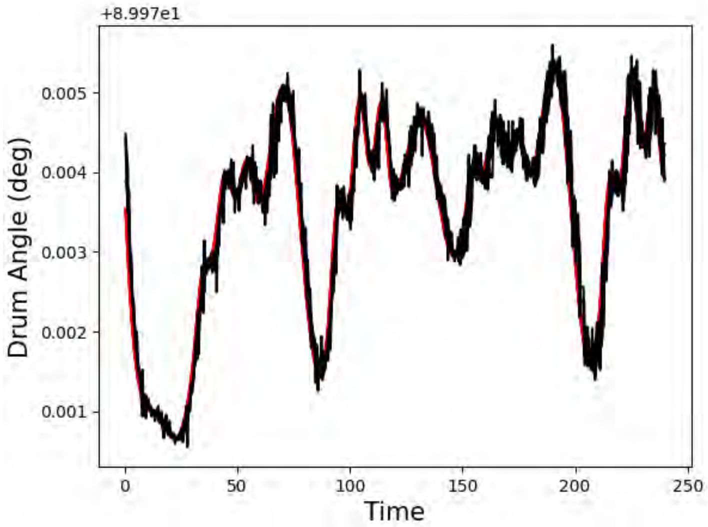


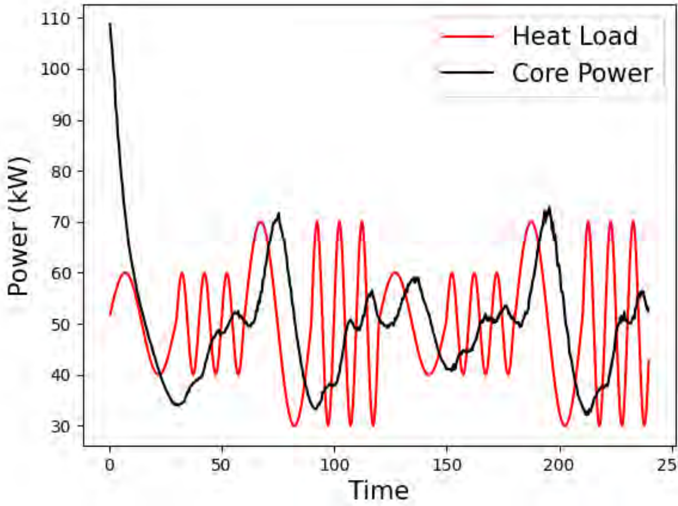


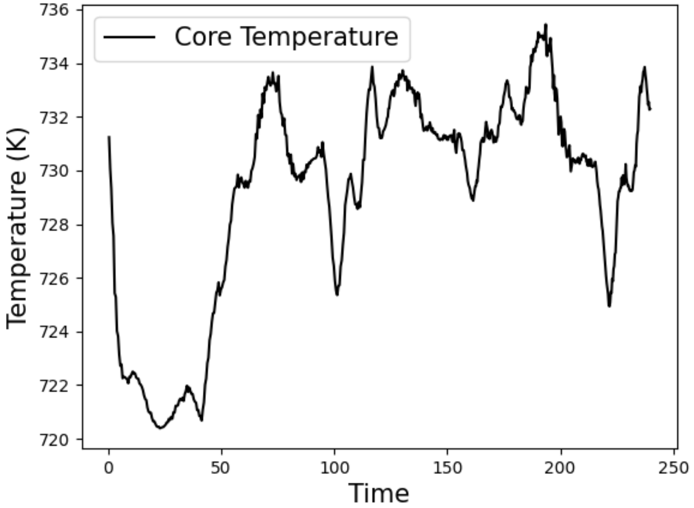
MRP Microreactor Program

Hardware-in-the-Loop Testing – Sinusoidal Power-Following Test

- Testing HIL data flow with FMU and sensor data feedback
    - 0-100 s – 0.3 s time step
    - 100-200 s – 0.5 s time step
    - Test conducted in series with ramp explains mismatch in initial conditions
- Similar lag in power load following was experienced as well as a filtering effect for higher frequency requested oscillations
    - Suggests need for improved controller design
- Temperature response remains within desired range







Deliverables and Future Planned Tasks

Title	Description	Progress/Due Date	Challenges
Complete development and integration of digital twin of balance of plant for prototypic microreactor with MACS.	Develop and integrate a digital twin that utilizes MAGNET as balance of plant for a prototypical microreactor. Perform and document basic functionality test (automated response to collected temperature data)	08/31/25	-
iIdentify data needs for balance of plant system for integration into MACS digital twin	Determine MAGNET testbed data/information needed for developing the balance of plant digital twin for MACS	02/28/25	-

Summary and Ongoing Work

- Microreactor automated control system (MACS) integrates models with hardware-in-the-loop to create a microreactor digital twin that enables graded automation

- Baseline control algorithms show promise of automation but point to the need for advanced control algorithms that demonstrate automation at different levels of autonomy
  - Ongoing work focused on advanced control algorithms (MPC, AI-driven control)
  - Risk-informed operational decision making methods being leveraged for control decision making

- Hardware-Model integration showed need for improving speed of computational models and incorporating data from newer sensors/actuators for improved fidelity of digital twins

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