DOE-NE Microreactor Program Winter Review Meeting

Instrumentation and Sensors - Microreactor Automatic Control System (MACS/ViBRANT) system

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MACS/ViBRANT Objectives

- Creates a robust, adaptable, interchangeable, hardware-in-the-loop control platform to **accelerate development**.

- Mature microreactor control technologies toward **autonomous operation** to improve:
  - Performance
  - Operational efficiency
  - Cost competitiveness

- **Advance instrumentation technology** by optimizing:
  - Parameter/sensor selection/placement
  - Communication architectures and
  - Surrogate reactor methods/applications

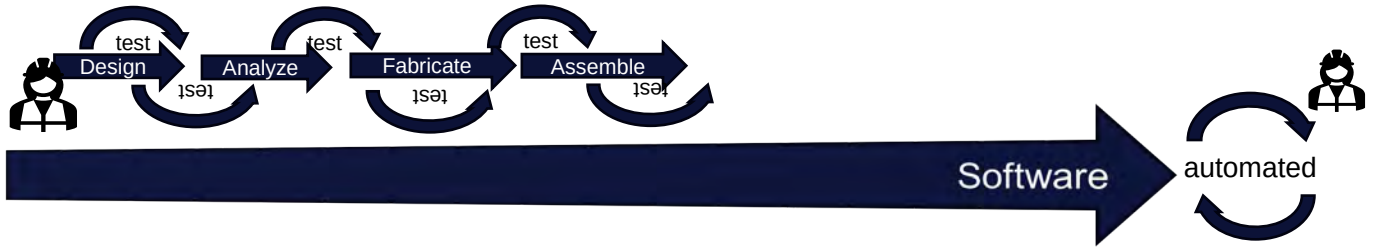
INL Idaho National Laboratory

OAK RIDGE National Laboratory

MRP Microreactor Program

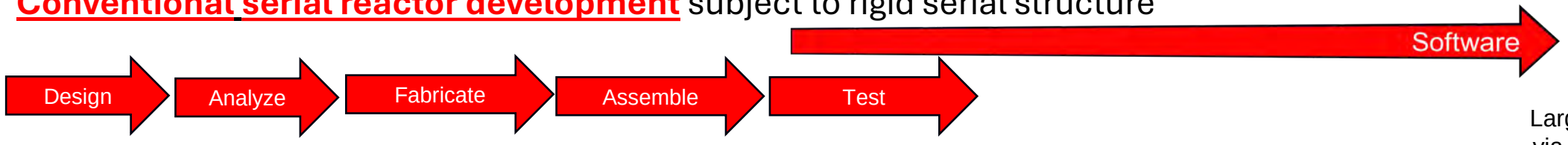
MACS/ViBRANT Development Acceleration

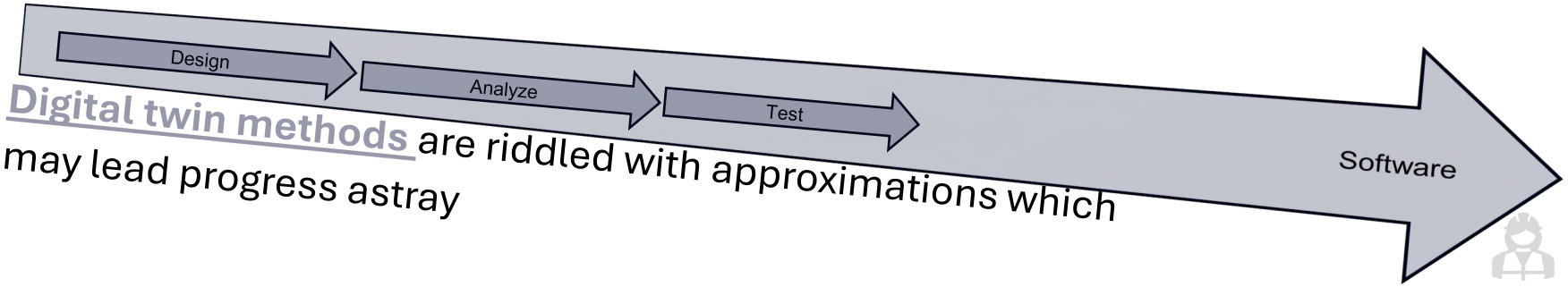
MACS/ViBRANT's agile development and reactor surrogate processes produce high quality project faster



VS.

Conventional serial reactor development subject to rigid serial structure





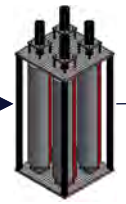
Digital twin methods are riddled with approximations which may lead progress astray

MACS/ViBRANT Context

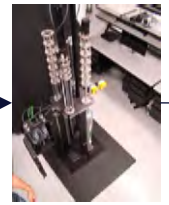
Autonomous Operation

Digital Twins

Micro-reactors



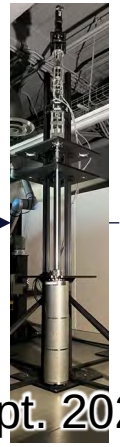
April 2020



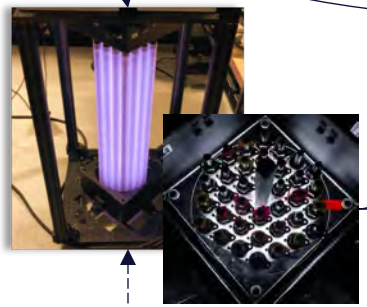
Sept. 2021

Sept. 2022

Sept. 2023

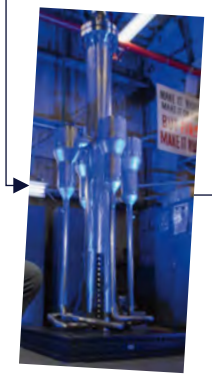


Sept. 2024



March 2025

MARVEL kicks off March 2020



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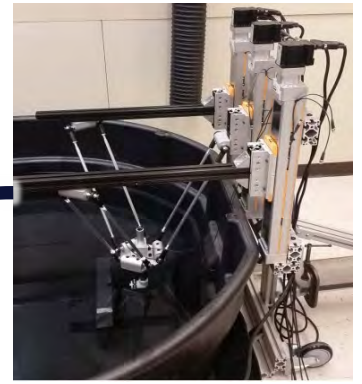
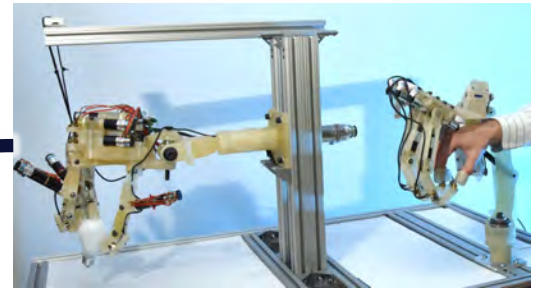
MACS/ViBRANT Contributing Techniques

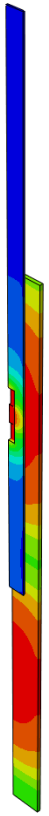
Environment Simulation

Motion Control



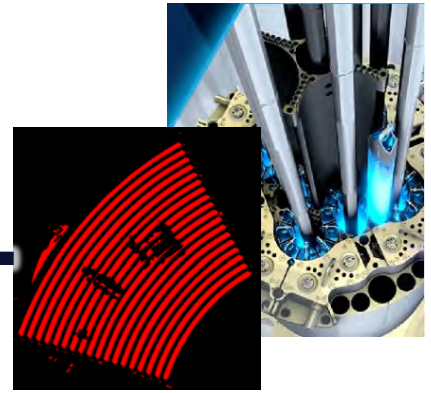
3D Volume interaction





Discrete Mapping

Reactor Light Detection/ Processing

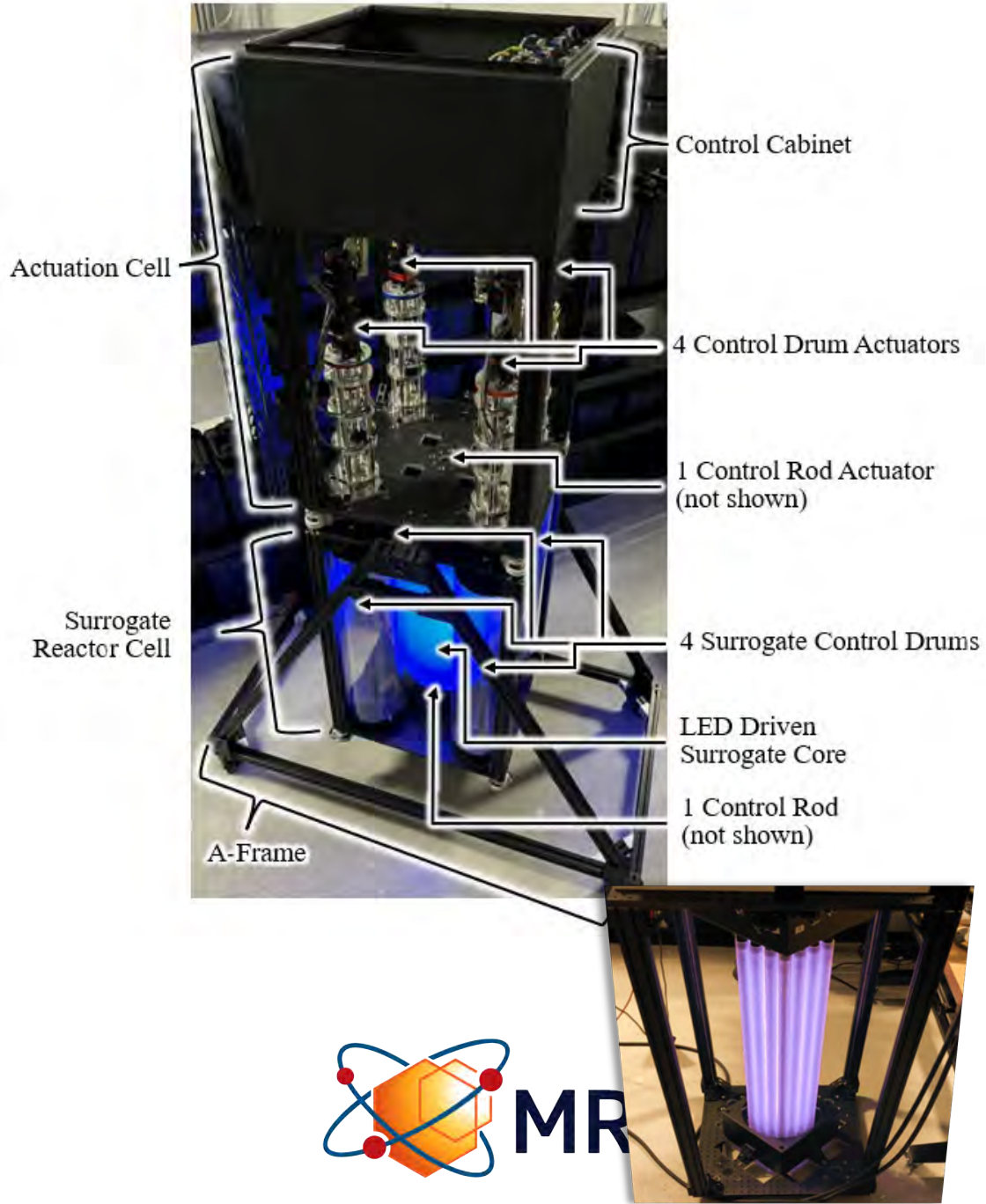


Idaho National Laboratory

MRP Microreactor Program

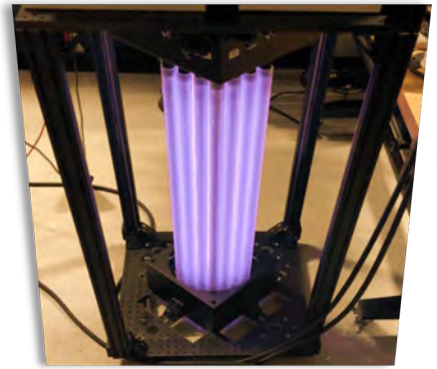
MACS/ViBRANT Key Features

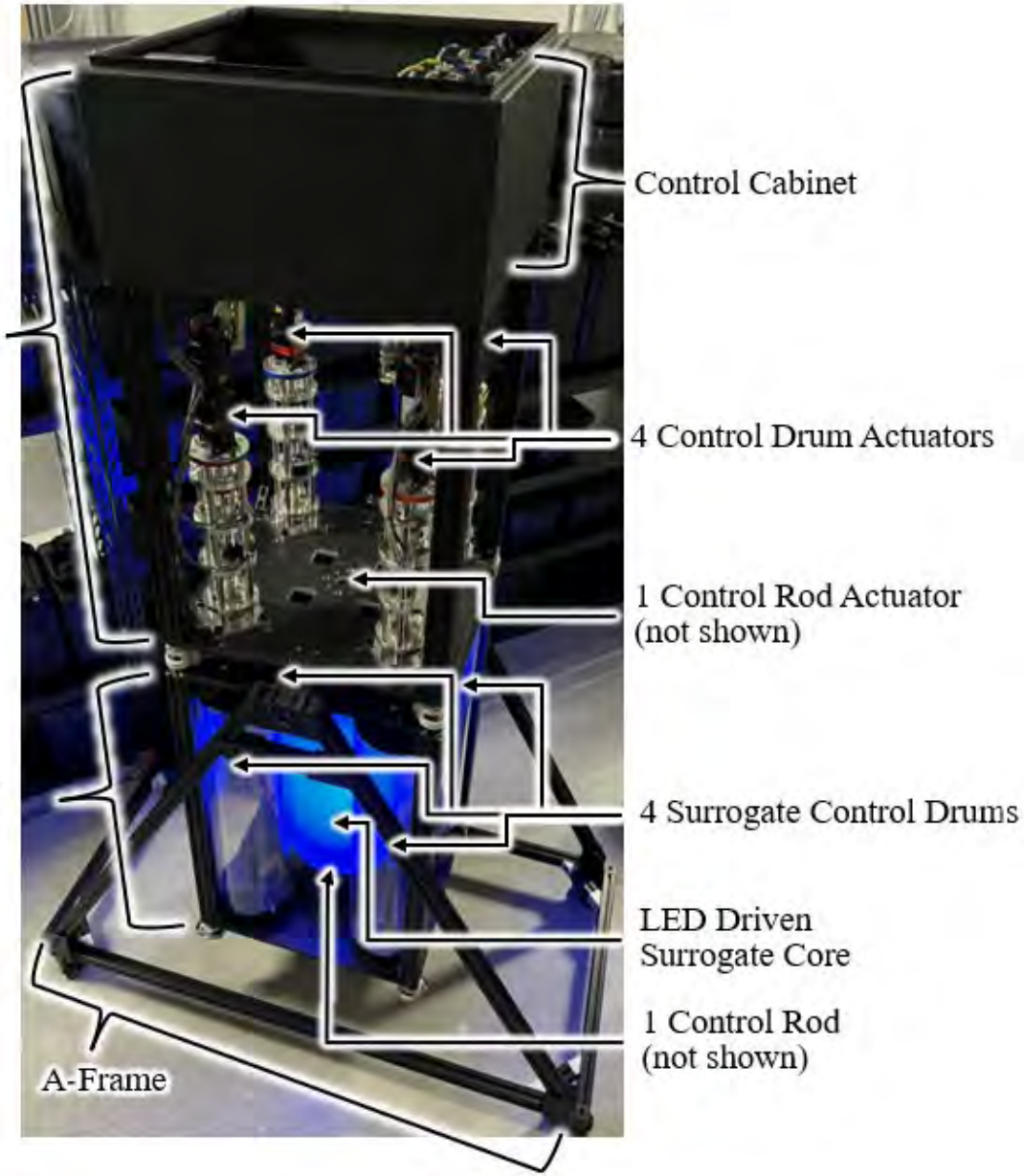
- General microreactor capabilities with accessible interfaces
  - Digital system models
  - Sensors
  - Control Schemes
  - Safety systems (hardware or simulated)
    - Interlocks
    - Reactor protection system, etc.)
- Framework
  - Enables separate effects integration
    - Actuation
    - Reactor (high-fidelity surrogate core)
      - Flux
      - Thermal
    - Etc.



MACS/ViBRANT Cells

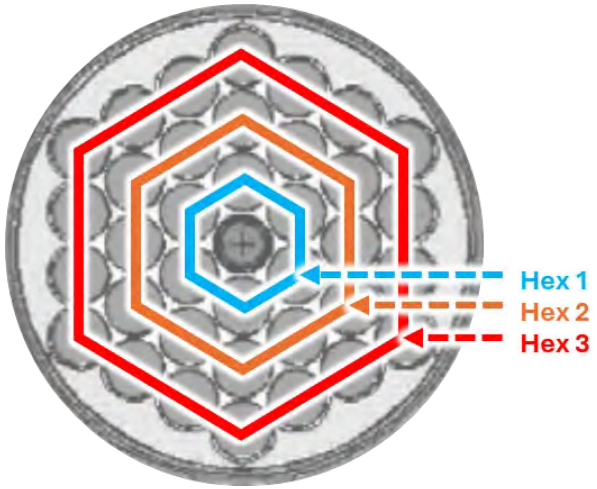
- General Microreactor Systems
  - Reactor
  - Coolant
  - Power Extraction
  - Actuation
  - Control

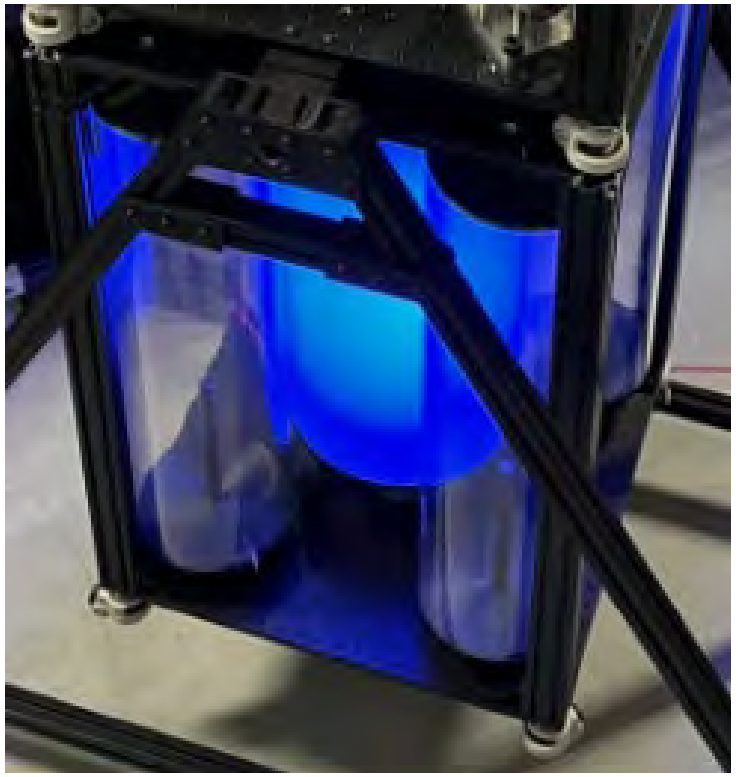




ViBRANT

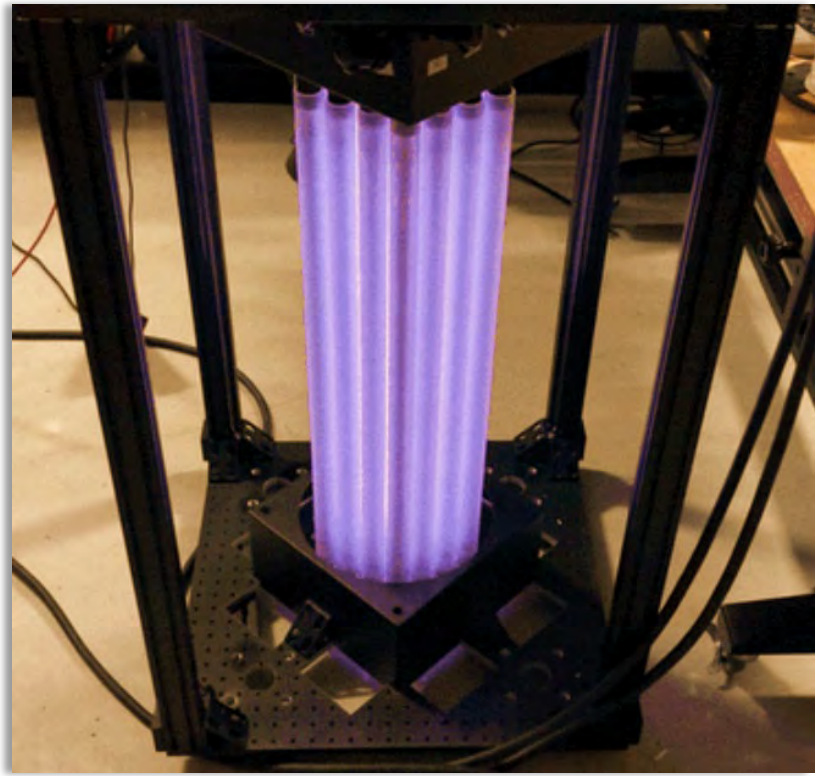
- Surrogate Reactor that uses light physics to represent reactor physics in an accessible way.





ViBRANT: Barrel

- 1,500 LEDS on outer surface of 3-layer hexagon pattern
- 16 photodiodes



ViBRANT: Hexagon

- 60,000 LEDS in 36 pin 3-layer hexagon pattern
- 16 photodiodes
- 5 TCs

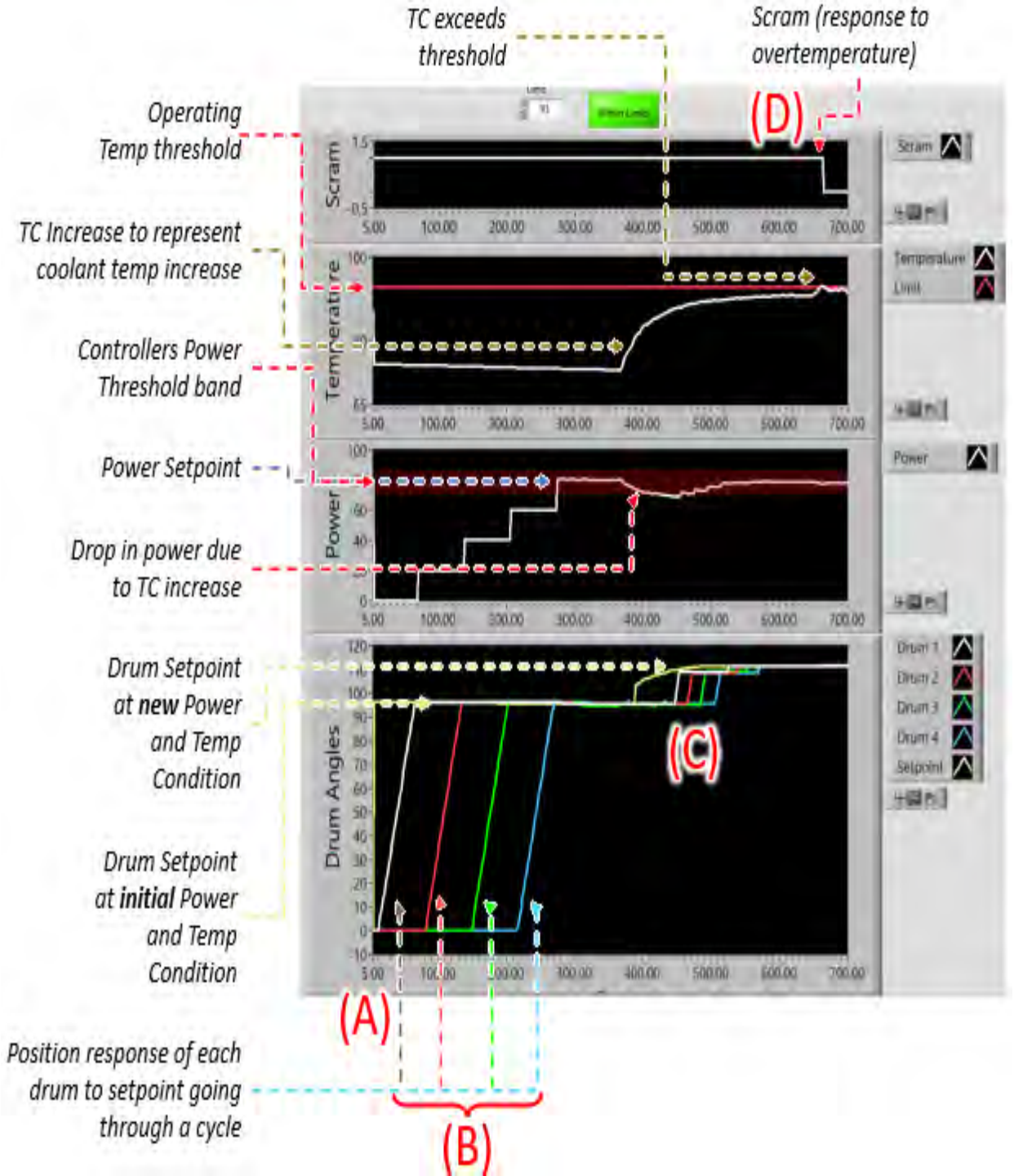
Key Demonstration Milestones

- Autonomous Control (M2AT-23IN0804054)
- Flexible/Optimized Software Architecture (M3AT-24IN0804031)
- Surrogate Flux and Temperature Integration (M3AT-24IN0804033)
- Validation of Analog Surrogate Absorber Influence (M3AT-25IN0804055)
- Brayton main parameters (M4AT-25IN0804056)
- Bilateral communications (M3AT-25IN0804053)
- Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)

MRP Microreactor Program

Autonomous Control *(M2AT-23IN0804054)*

A. Individual Setpoint Achievement
B. Four Drum Iteration
C. Power Setpoint Threshold Control
D. Overtemperature Scram



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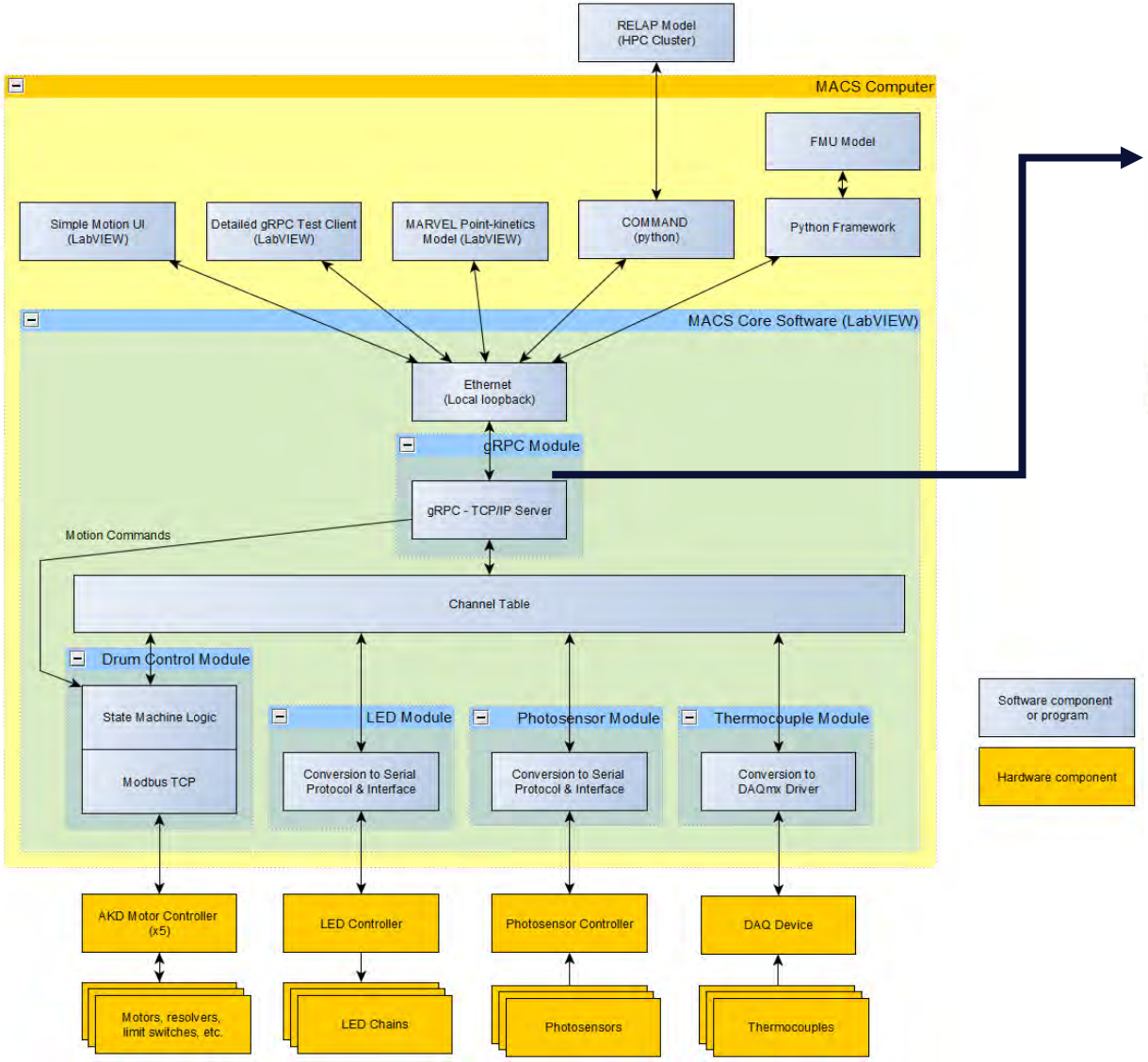
Flexible/Optimized Software Architecture *(M3AT-24IN0804031)*



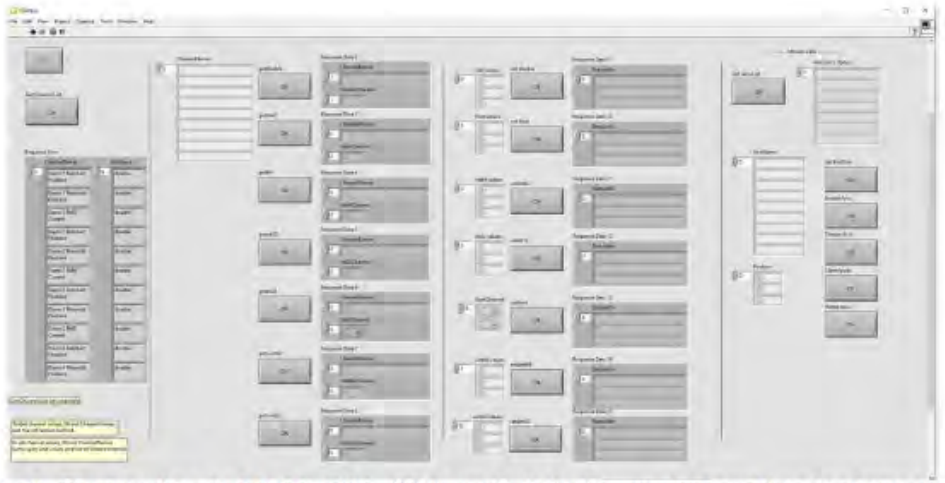
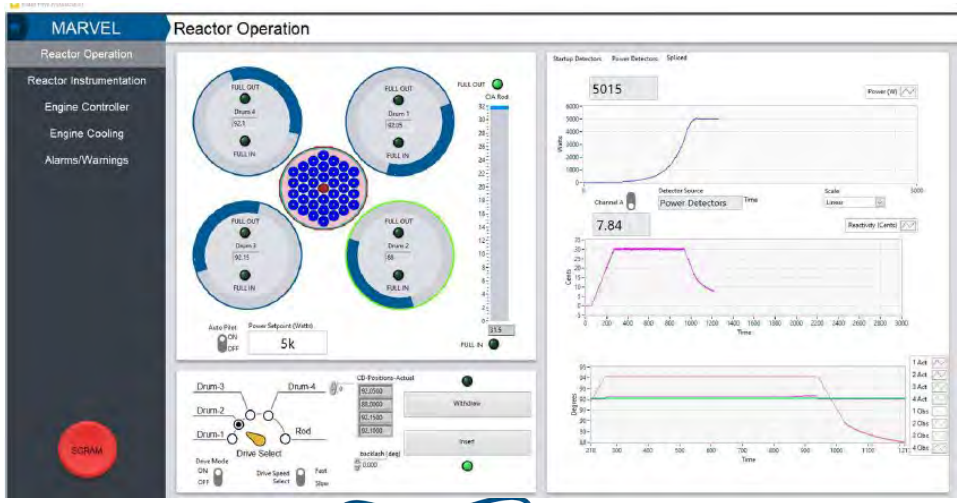


Figure 5 - Test interface for MACS gRPC. While not built for beauty, this panel lets developers test every read and write in the MACS gRPC interface to validate its function.



MRP Microreactor Program

Surrogate Flux and Temperature Integration *(M3AT-24IN0804033)*

Software/Actuation Architecture

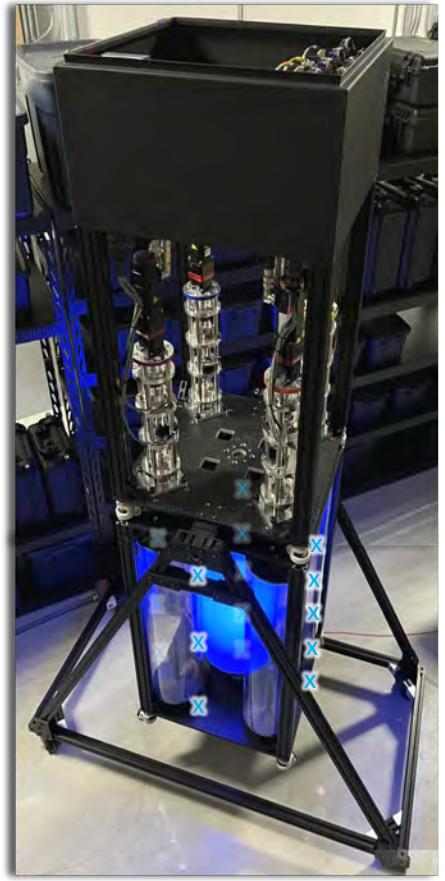
- *Closed-Loop Feedback*
- *AND Autonomous Control*

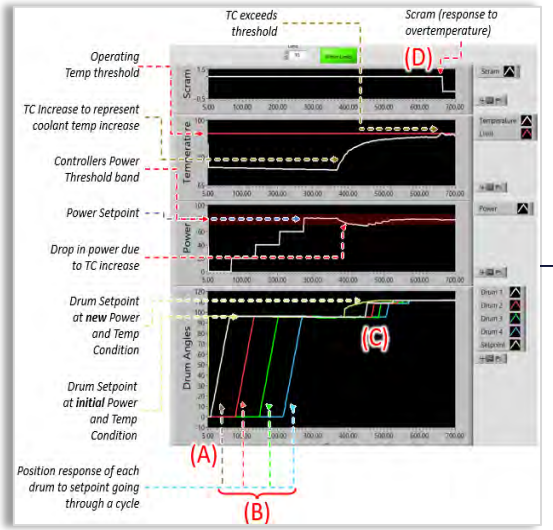
Barrell Reactor Core Surrogate

- *Represent Reactivity*
- *AND Measure Reactivity (x)*

Hexagon Reactor Core Surrogate

- *Represent Thermal*
- *AND Measure Thermal (x)*

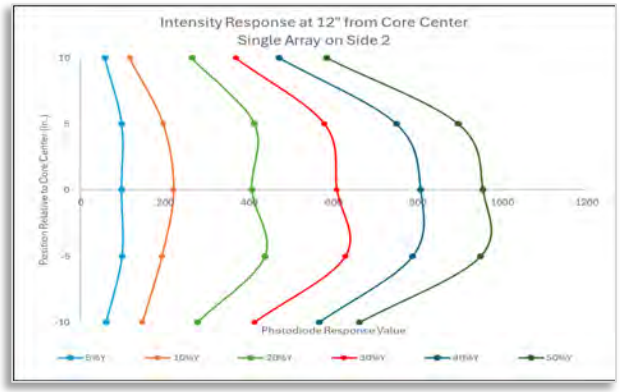


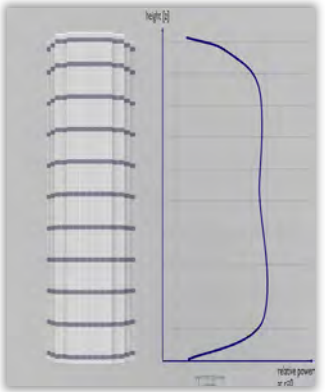


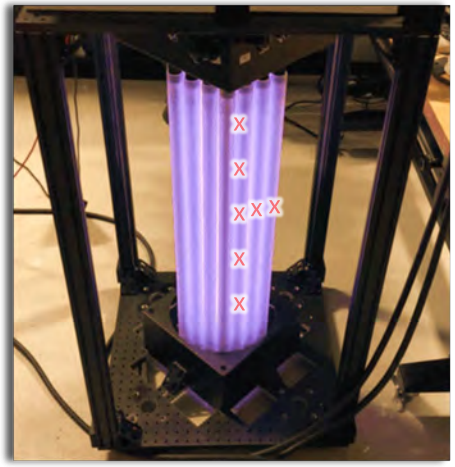
ORNL Studies

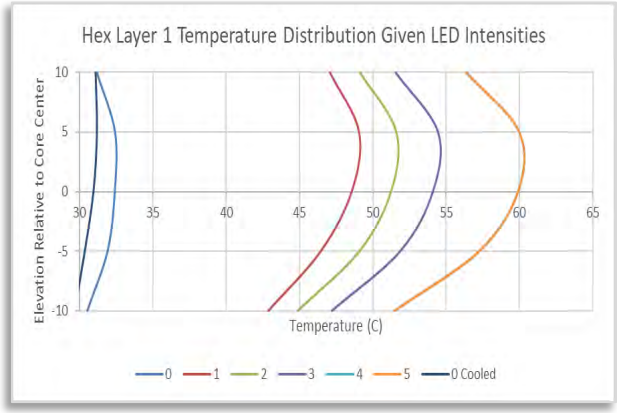
ASI Studies

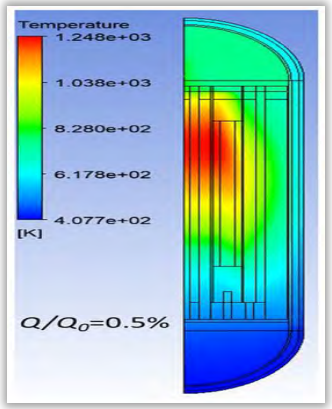
MARVEL Point Kinetics







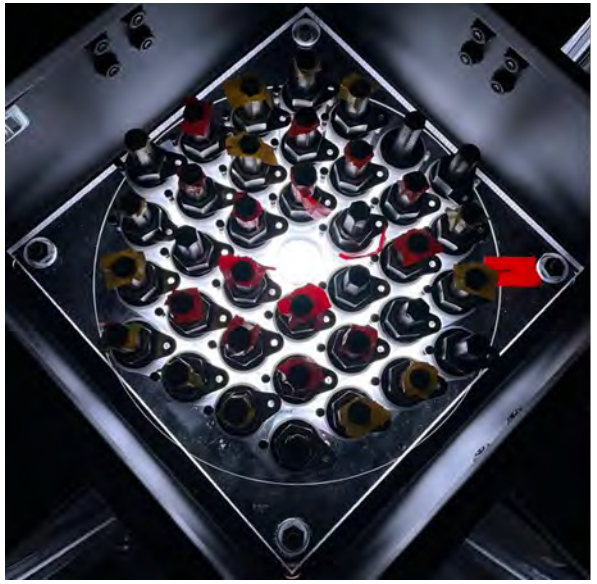




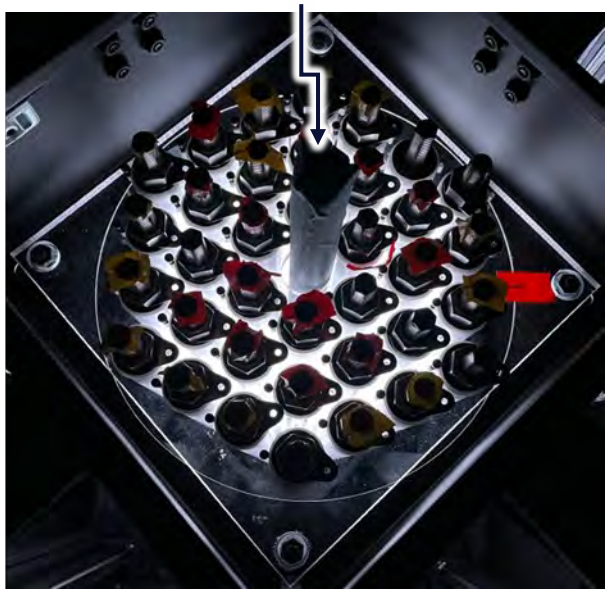
Validation of Analog Surrogate Absorber Influence *(M3AT-25IN0804055)*

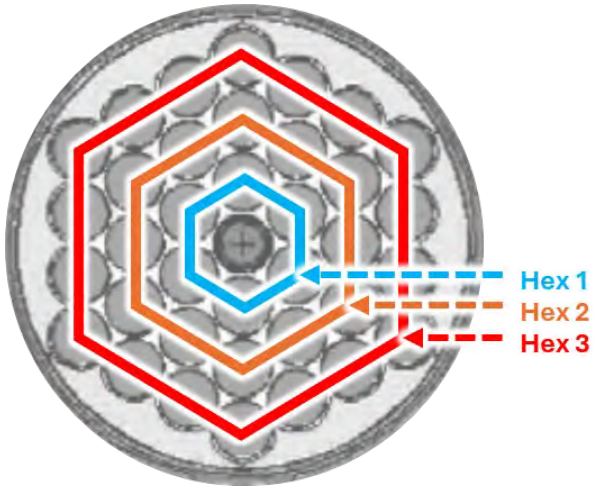
- Results
  - Whole Core @ 15% Max Intensity:
    - 2.3% reduction at photodiode
  - Partial Core (Hex layer 1) @ 15% Max Intensity
    - 22% reduction at photodiode
- Implications
  - Validates physical absorber capability useful for physical:
    - Reactivity tuning
    - Reactivity control

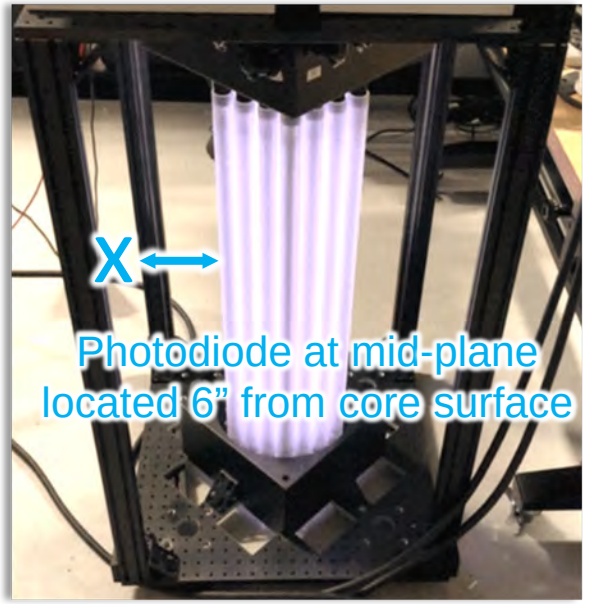
Open Core



Surrogate Absorber Rod



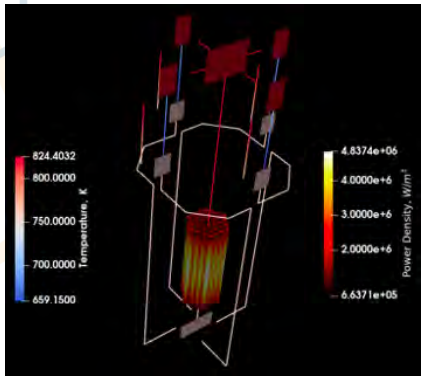




MARVEL Beyond the Reactor: Non-Nuclear Integration and Controls as a Stepping-Stone

(Slide pulled from Abdalla Abou Jaoude ANS Winter 2024 Presentation)

Virtual simulation of MARVEL core physics



Electric heat output and outlet temperatures

MAGNET
(non-nuclear heat source with test article integrated power conversion unit)

Drum position and core response

MACS Hardware
(non-nuclear surrogate for MARVEL controls)

Electricity generation and dispatch

RAPID MIB
(Microgrid in a box)

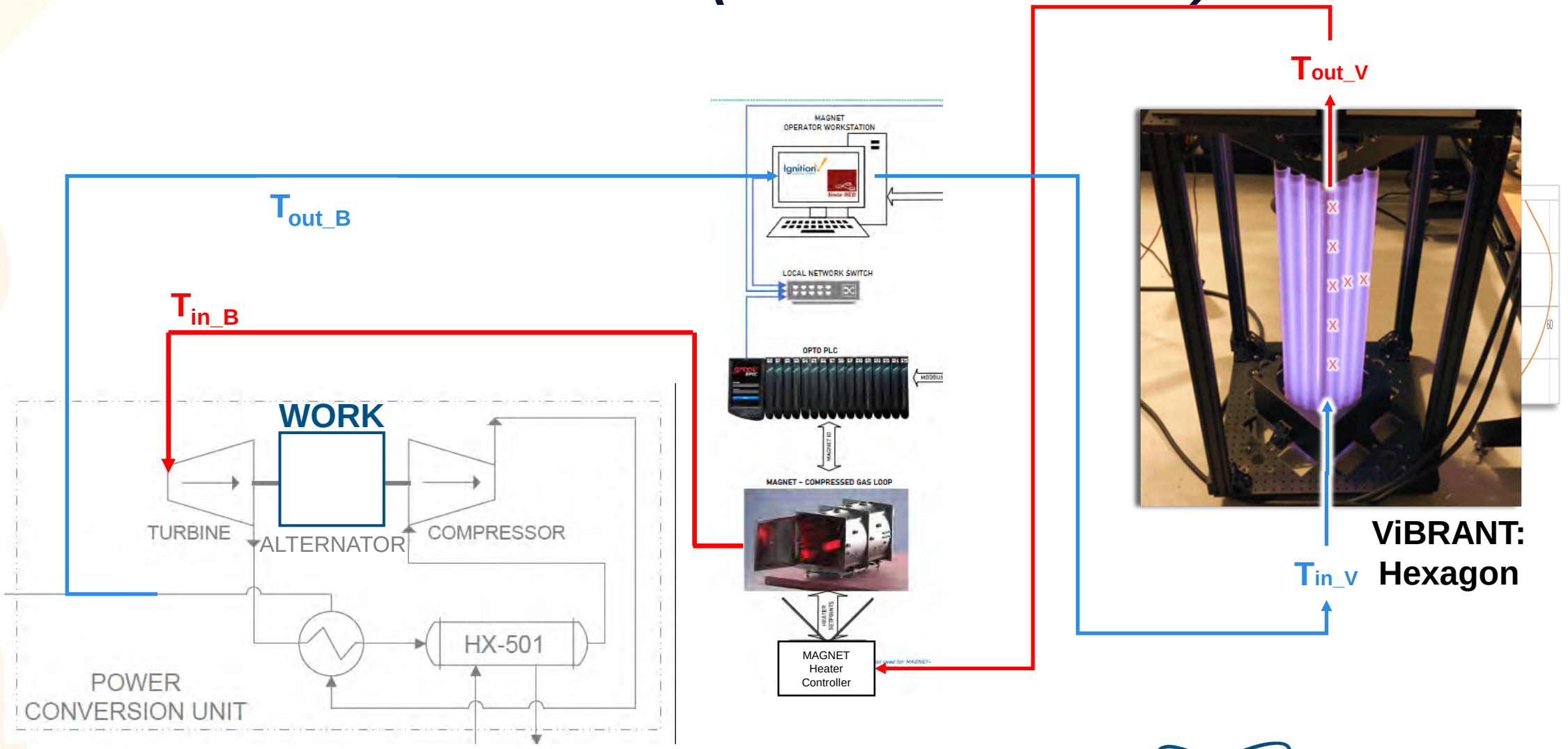
Mobile Data Center

Nuclear-powered data center demonstration

Demonstrate Autonomous & remote operation in non-nuclear system first, prior to testing in MARVEL

MRP Microreactor Program

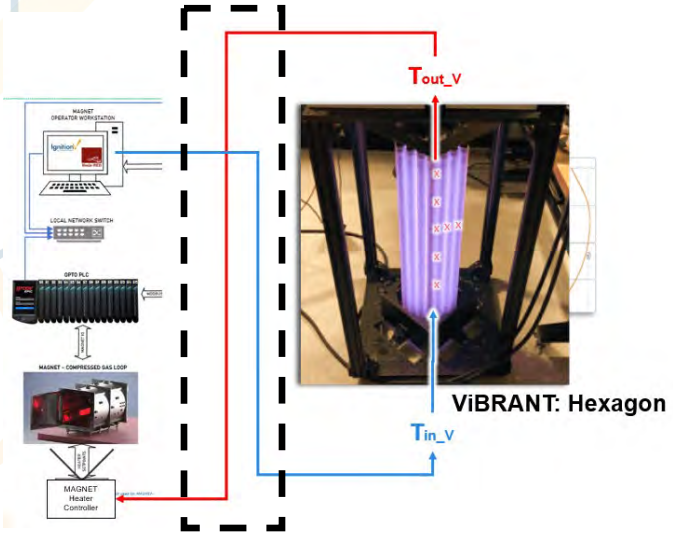
Brayton Parameters *(M4AT-25IN0804056)*
Bilateral communications *(M3AT-25IN0804053)*



ViBRANT: Hexagon

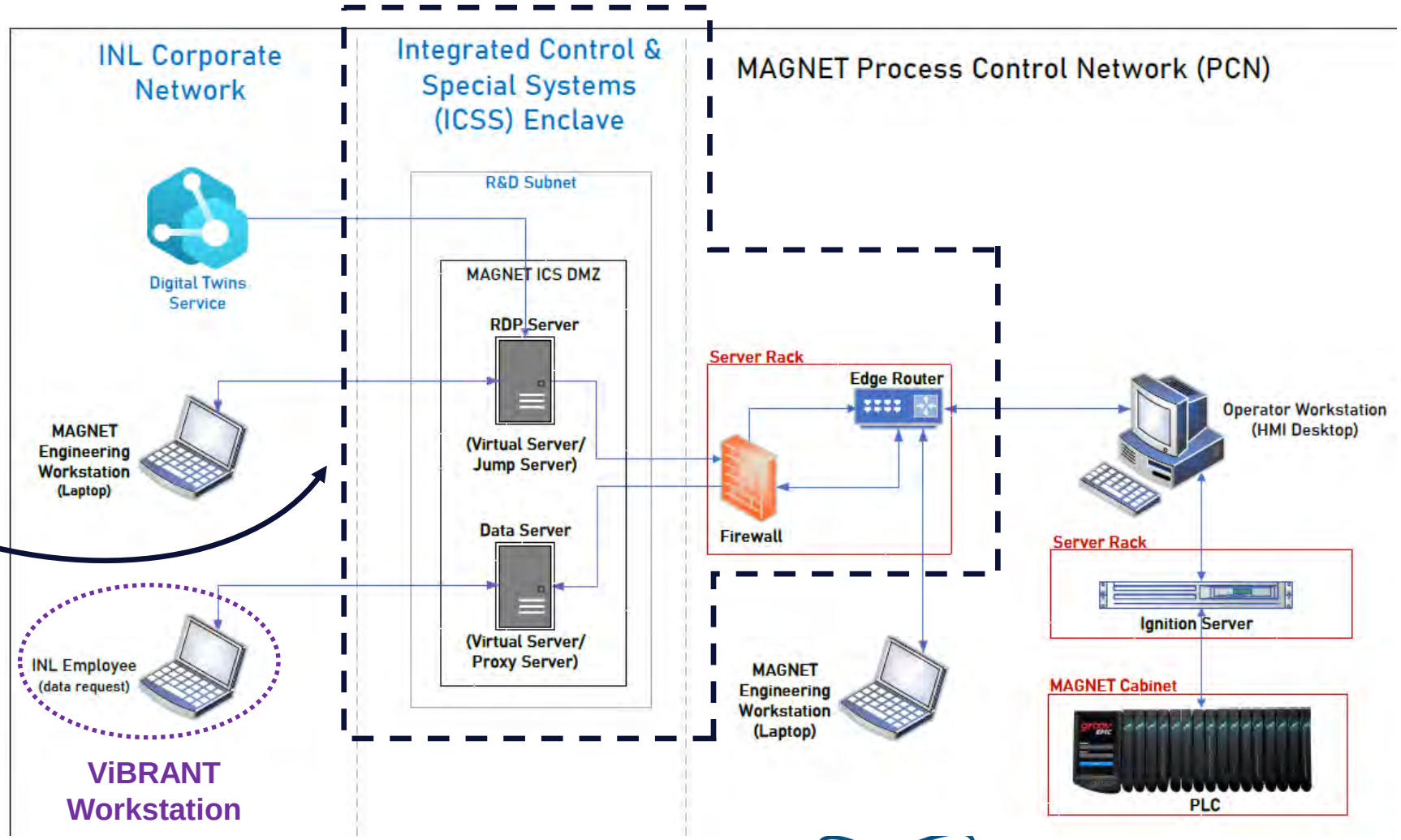
MAGNET: PCU

Bilateral communications *(M3AT-25IN0804053)*



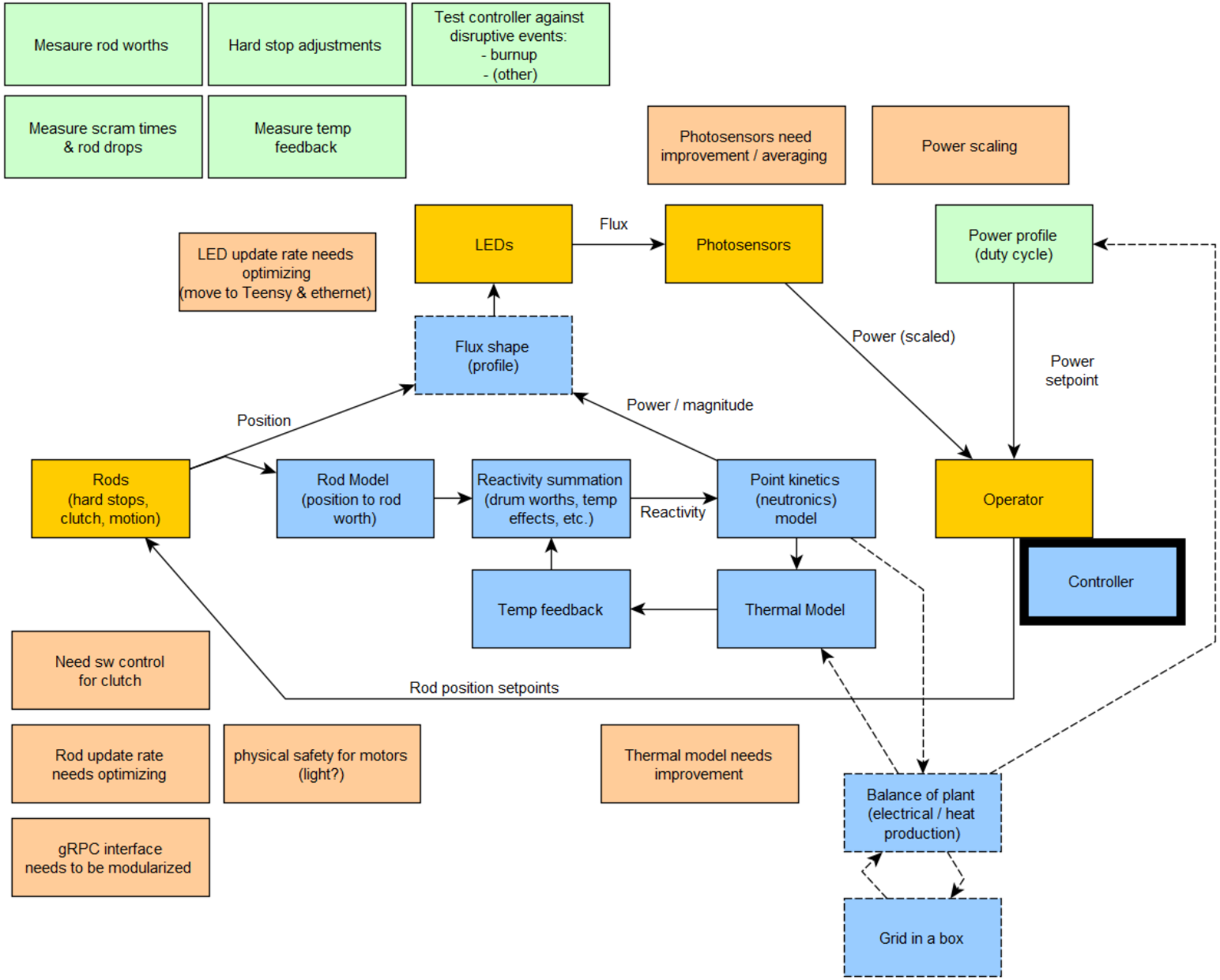
MAGNET-ViBRANT Network Interface

- Facilitated by ICSS network architecture
- Managed by IT/Cybersecurity



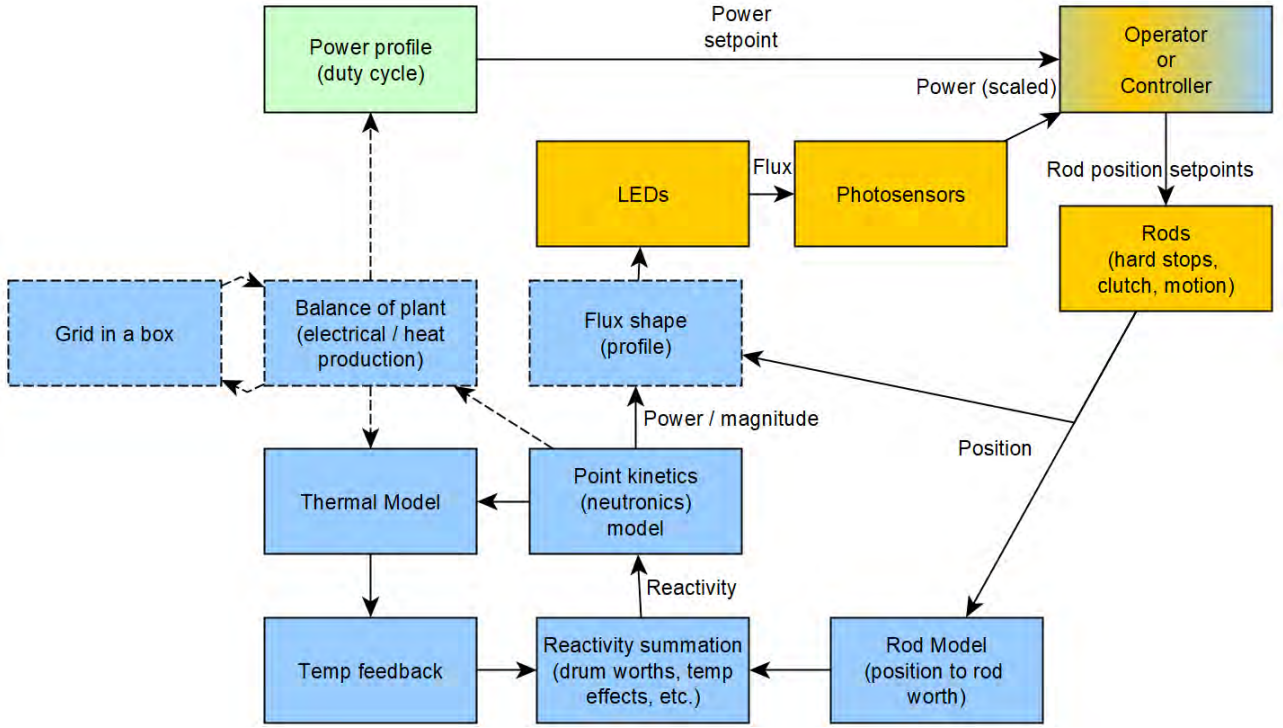
Demonstrate a Reactor Startup MRP/ASI Collaboration *(M2AT-25IN0804051)*

- Build mixed simulation reactor using MACS
  - Models shown in blue
  - Hardware shown in Gold
- Perform
  - Startup-related tests, show in green (MRP)
  - Operations with various controllers and disruptive events (ASI)
- Upgrade fidelity as we go
  - Various models considered: point kinetics, RELAP, COMMAND, ORNL
  - Various improvements to be done shown in peach boxes



Demonstrate a Reactor Startup MRP/ASI Collaboration *(M2AT-25IN0804051)*

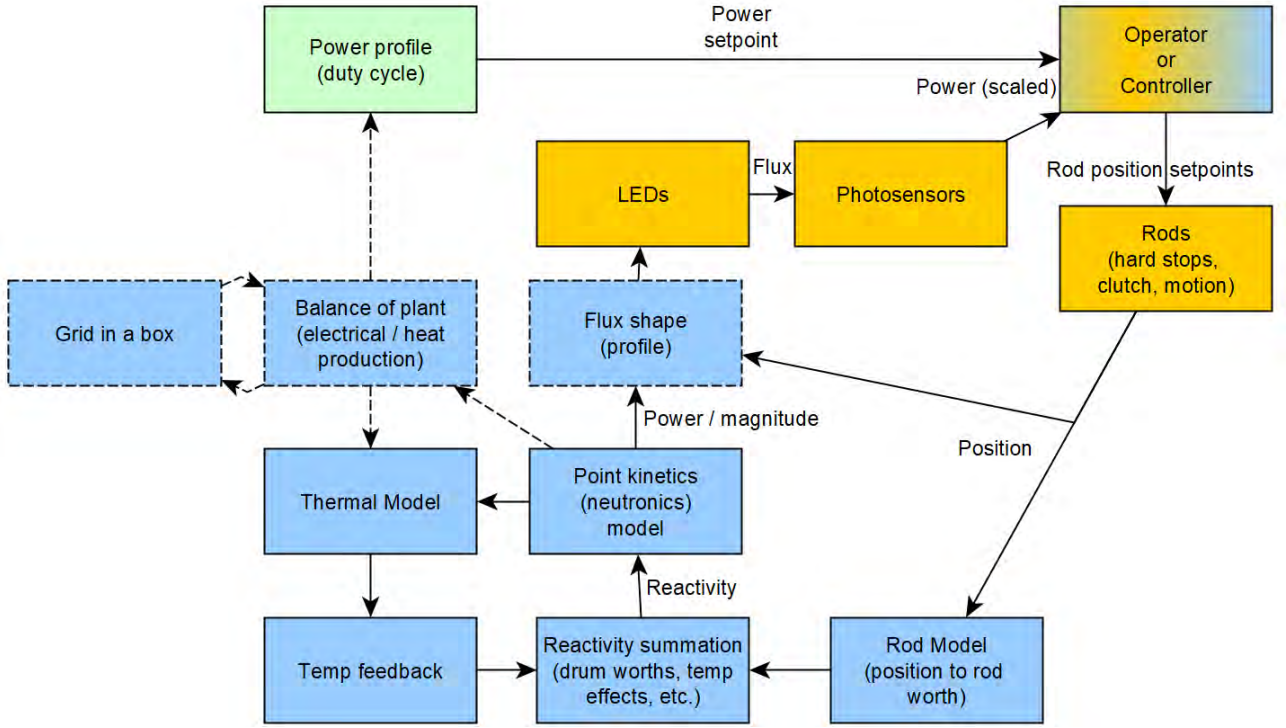
- Build mixed simulation reactor
  - Physical components include (Gold)
    - Physical rods and rod motion dynamics
    - Motion controllers, loops, and profiles
    - ViBRANT core spatially simulates flux or power with photons
    - Photosensors represent power or flux sensors
  - Software models (Blue)
    - Note: dotted lines are stretch goals



MRP Microreactor Program

Demonstrate a Reactor Startup MRP/ASI Collaboration *(M2AT-25IN0804051)*

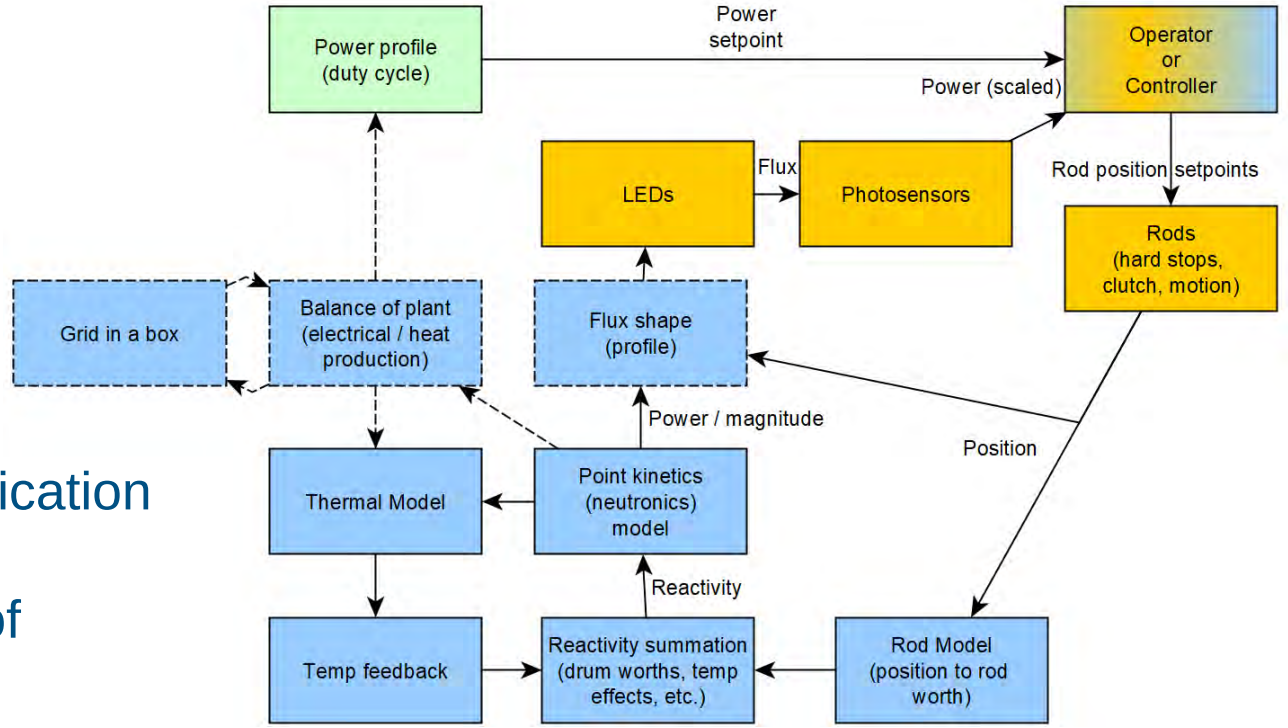
- MRP
  - Startup-related procedure methodology
    - Rod worth measurement
    - Hard stop adjustments
    - Measure scram & rod drop times
    - Measure temperature feedback
- ASI
  - Operate with various advanced controller algorithms
  - Demonstrate disruptive events, e.g.:
    - High fuel burnup
    - Backlash in control drum shaft



MRP Microreactor Program

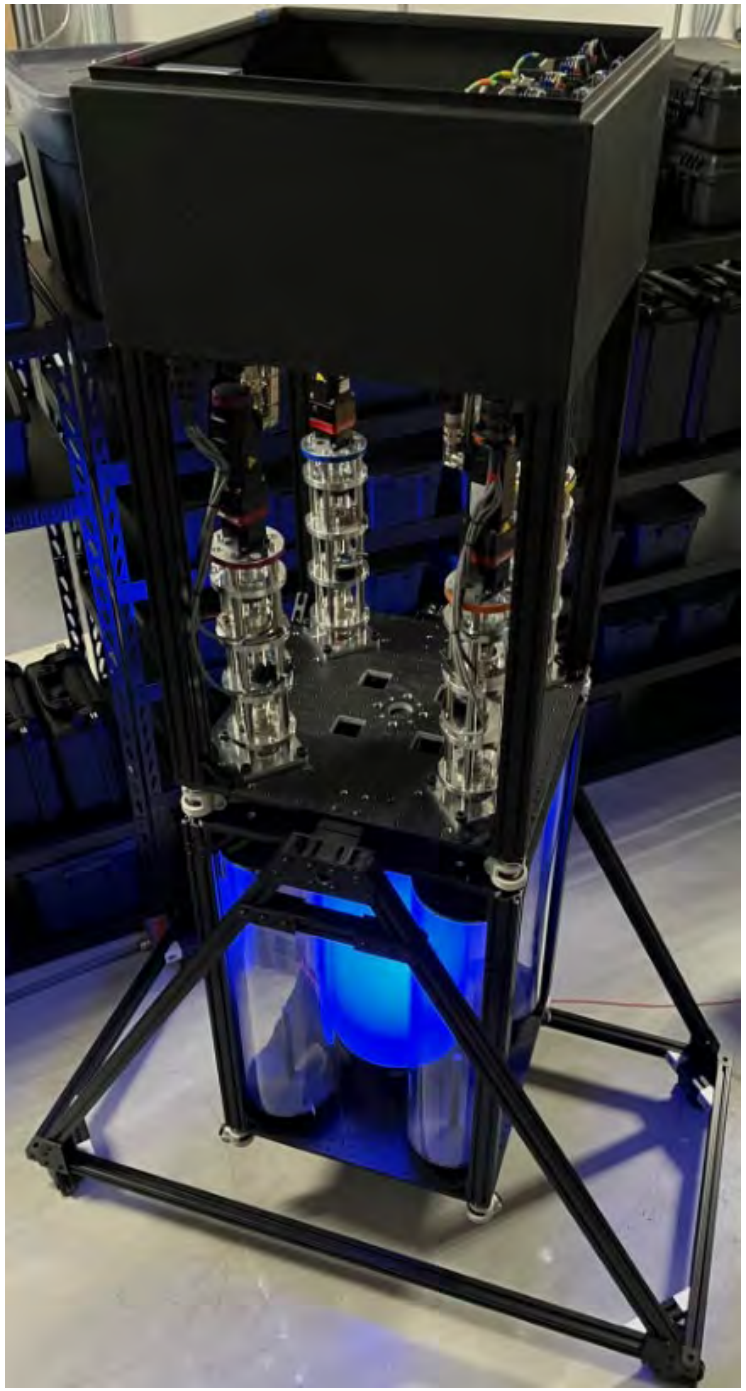
Demonstrate a Reactor Startup MRP/ASI Collaboration *(M2AT-25IN0804051)*

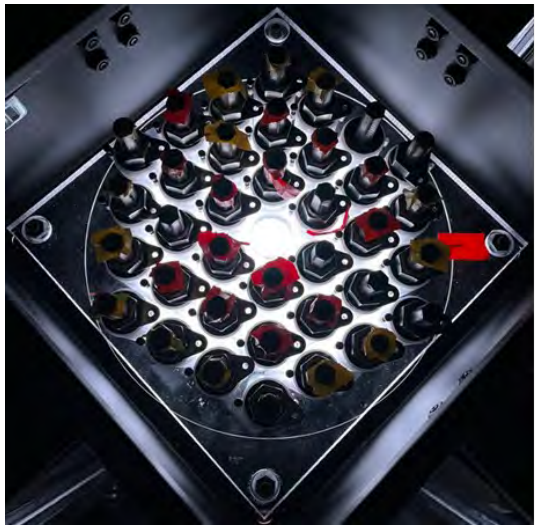
- Upgrade fidelity as we go
  - Various models to be used
    - Point Kinetics
    - RELAP & COMMAND
    - ORNL Modelica Models
  - Various upgrades planned
    - Increase ViBRANT core communication bandwidth & update rate
    - Improve performance & stability of motion controllers
    - Reduce noise in Photosensors
    - Etc.

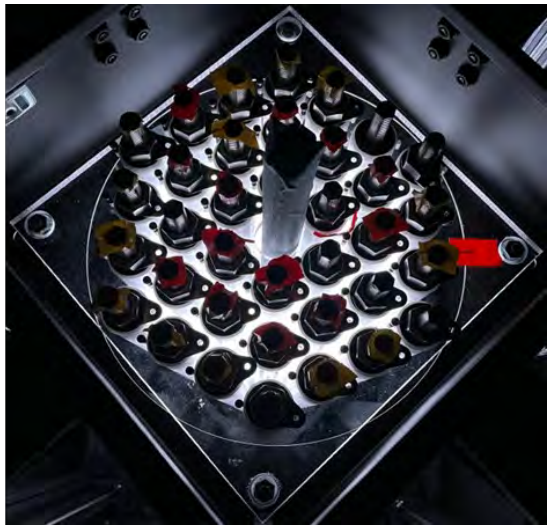


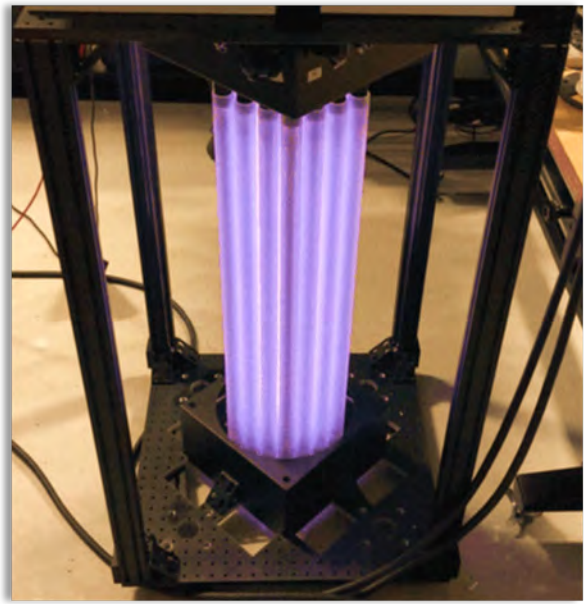
MRP Microreactor Program

Discussion?









MRP Microreactor Program

References

- https://www.youtube.com/watch?v=5I925aHIoVE
- https://gain.inl.gov/SiteAssets/MicroreactorProgram/2023MicroreactorProgramWinterReview/TechnologyMaturation-2023.pdf
- https://www.ans.org/news/article-3951/profile-published-on-head-of-marvel-project-at-idaho-national-laboratory/
- https://gain.inl.gov/2022MARVELTechRevPresentations/1.07-Crawford_ReactivityControlSystem_2022MARVELTechReview_19Oct22.pdf
- https://gain.inl.gov/SiteAssets/MicroreactorProgram/2022MicroreactorProgramWinterReview/MA_WinterReviewPresentation_2022.03.04.pdf
- https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_38634.pdf
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MRP Microreactor Program