



2026 DOE-NE Microreactor Program Winter Review Meeting

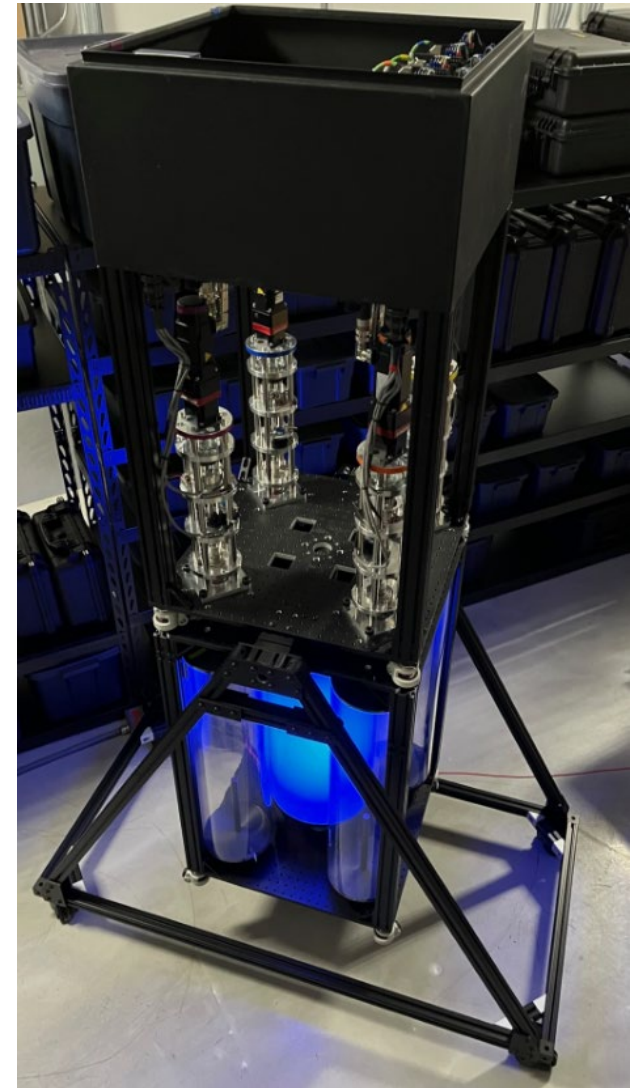
Instrumentation and Sensors - Microreactor Automatic Control System/Visual Benign Reactor as Analog for Nuclear Testing (MACS/ViBRANT) system

Principle Investigator: Anthony Louis Crawford Ph.D. P.E.

INL Collaborators: Ben Baker, Andrew Heim, Rowdie Shepherd, Casey White, Shaleena Jaison, T.J. Morton

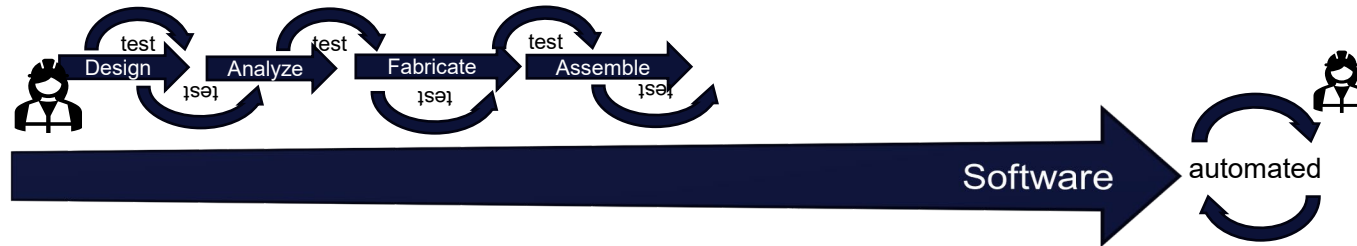
MACS/ViBRANT Objectives

- 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



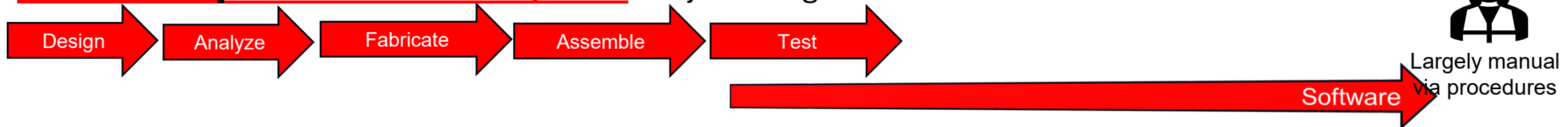
MACS/ViBRANT Development Acceleration

MACS/ViBRANT's agile development and reactor surrogate processes produce optimized results faster

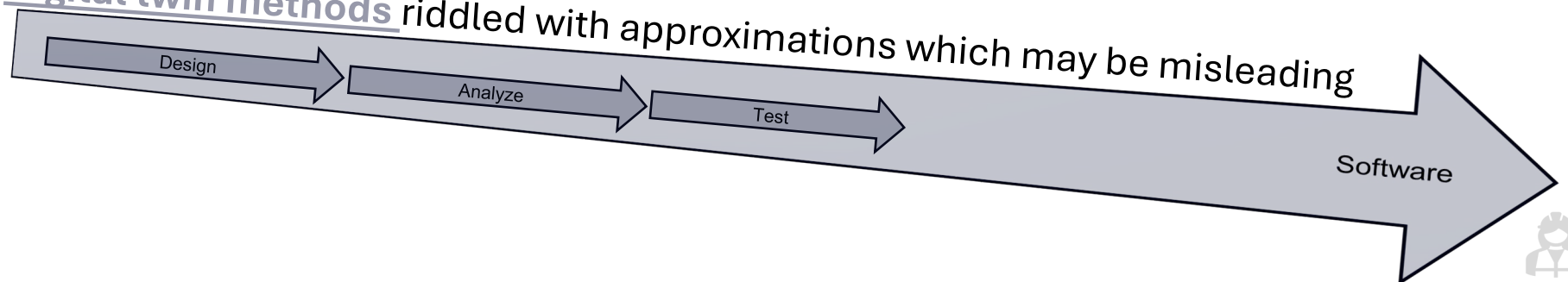


VS.

Conventional serial reactor development subject to rigid serial structure



Digital twin methods riddled with approximations which may be misleading

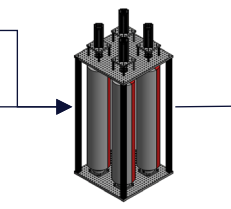


MACS/viBRANT Context

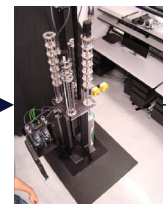
Autonomous Operation

Digital Twins

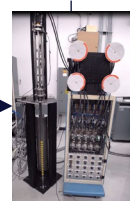
Micro-reactors



April 2020



Sept. 2021



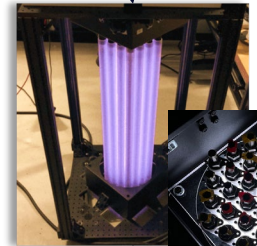
Sept. 2022



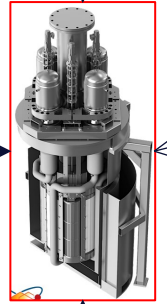
Sept. 2023



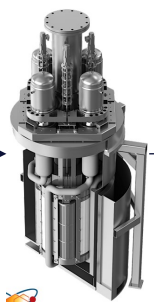
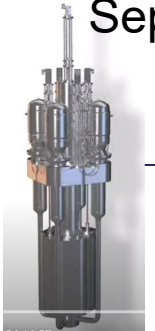
Sept. 2024



March 2025

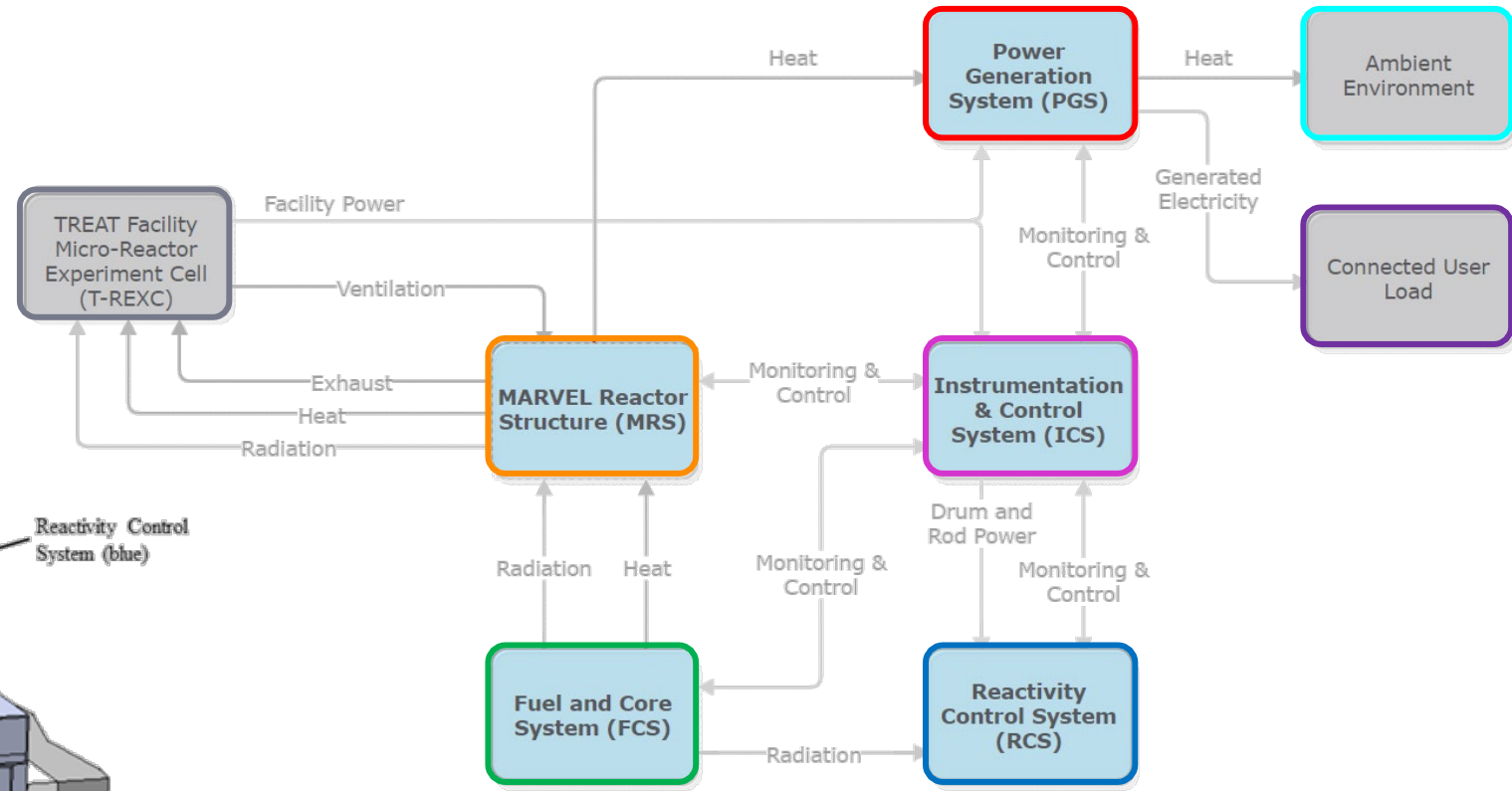
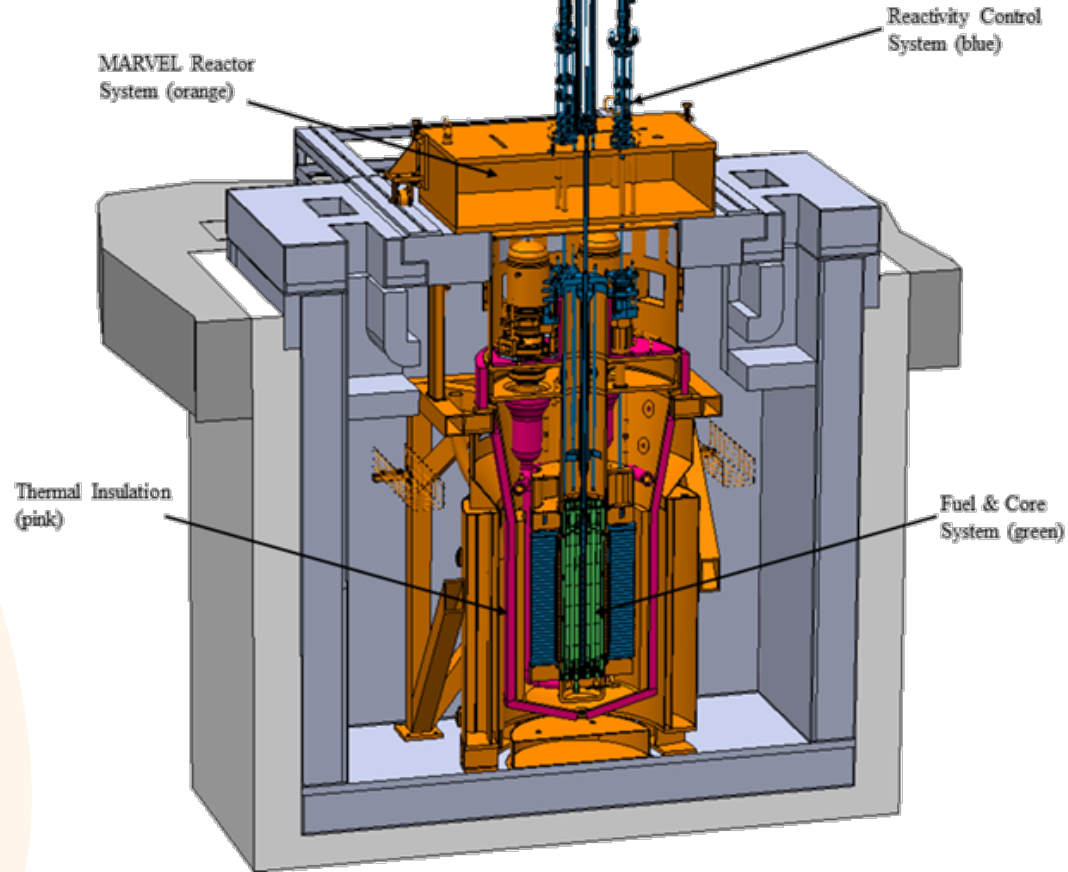


MARVEL
kicks off
March 2020

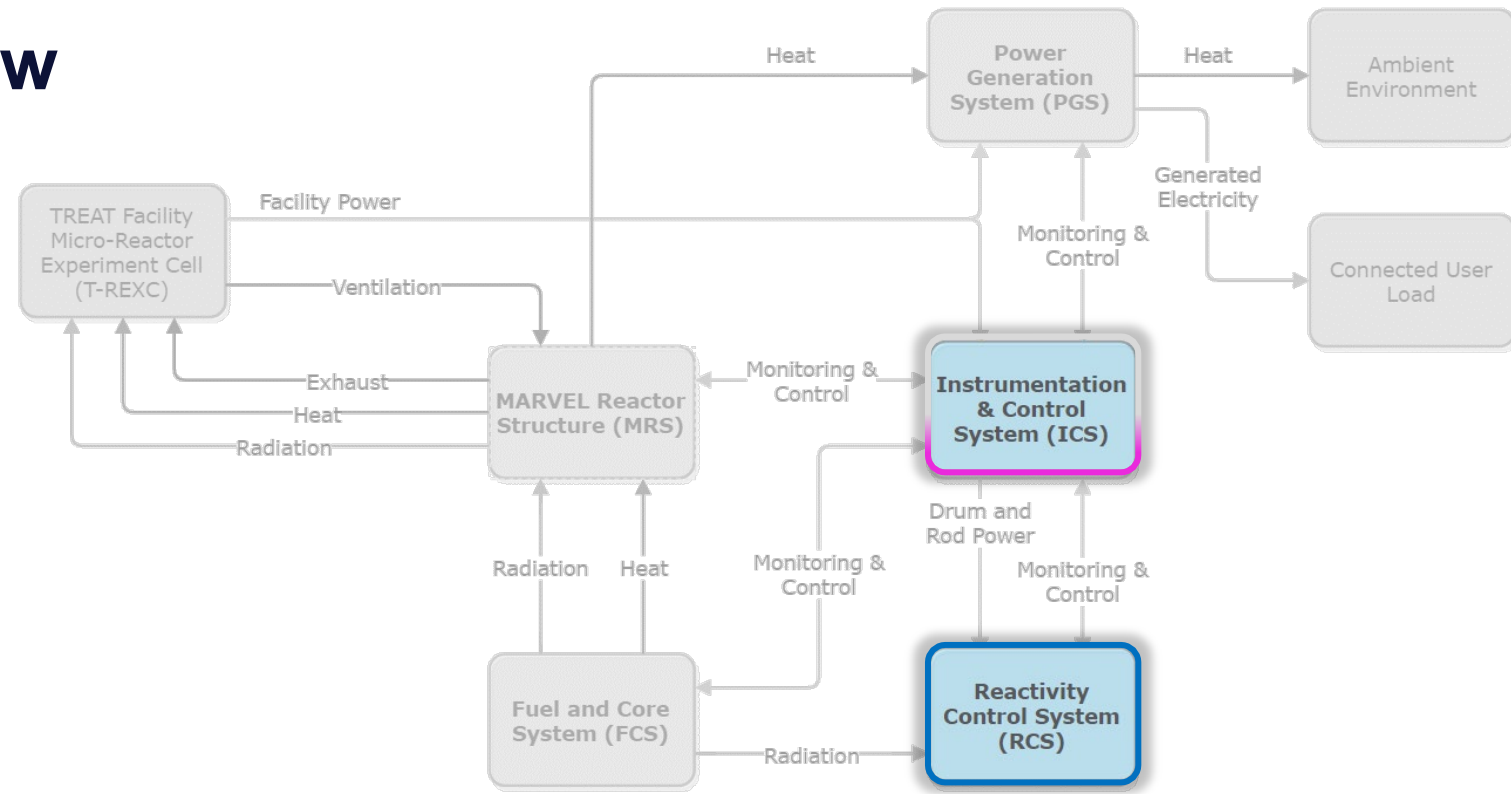


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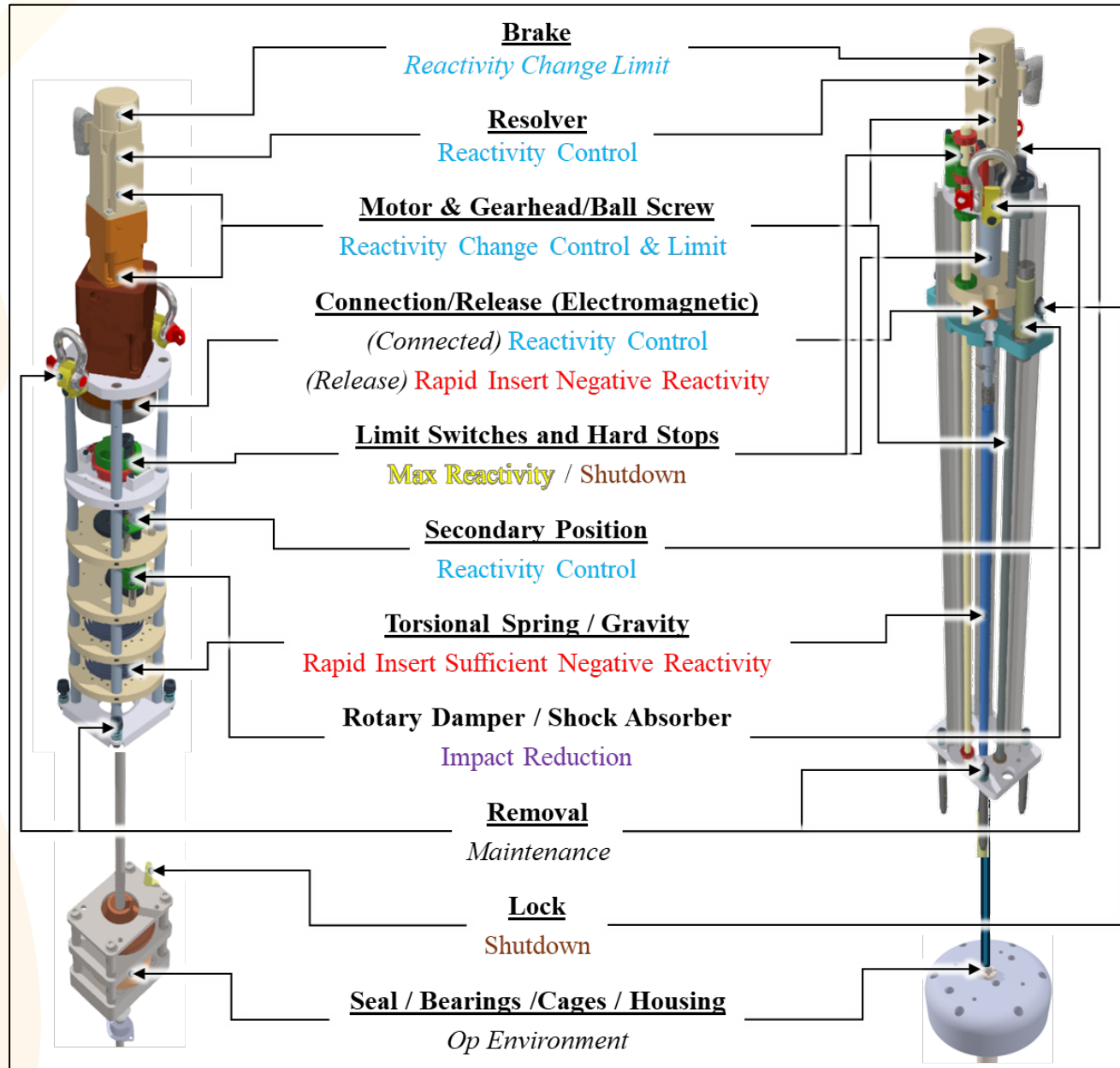
MARVEL Overview



MARVEL RCS Overview



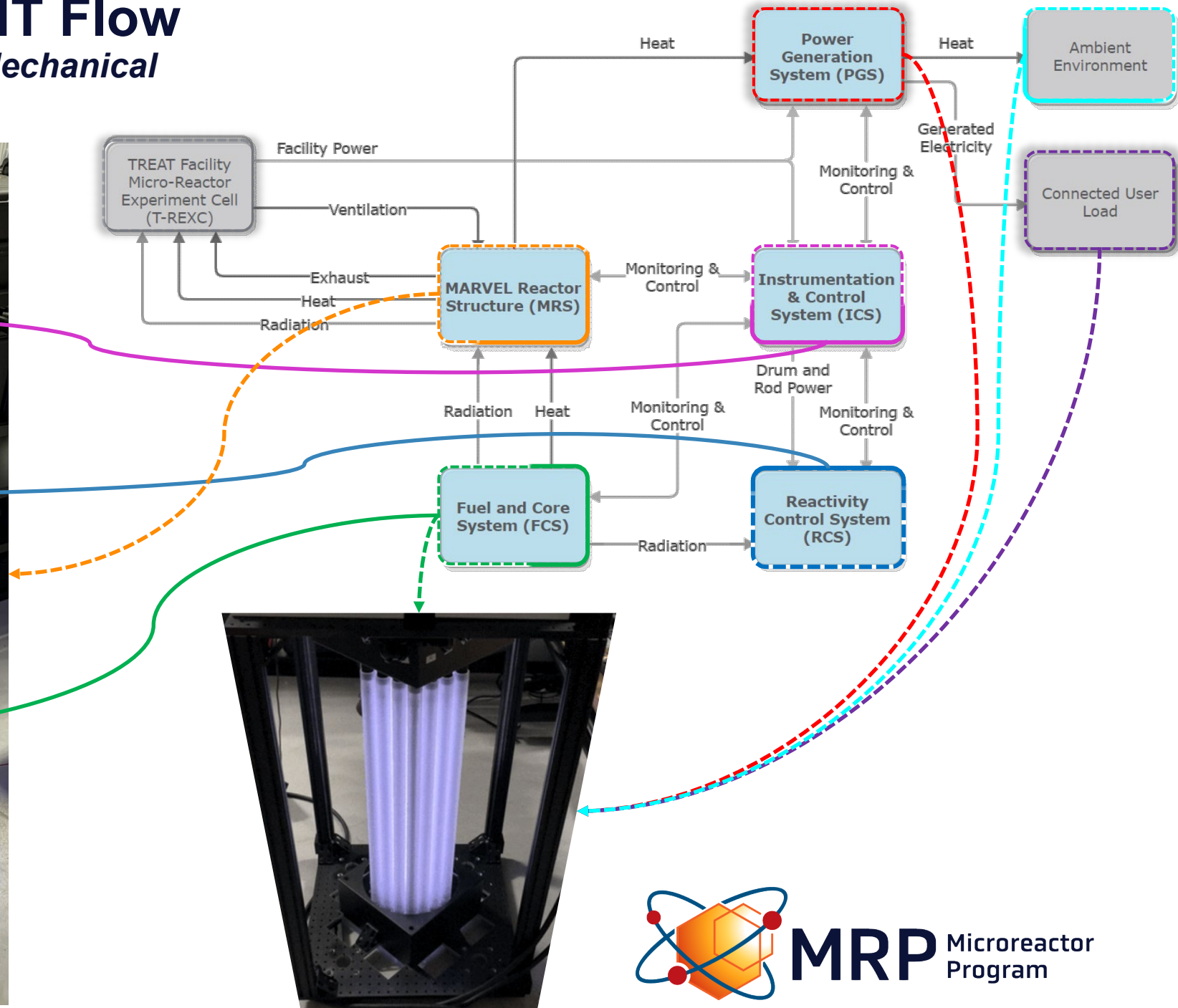
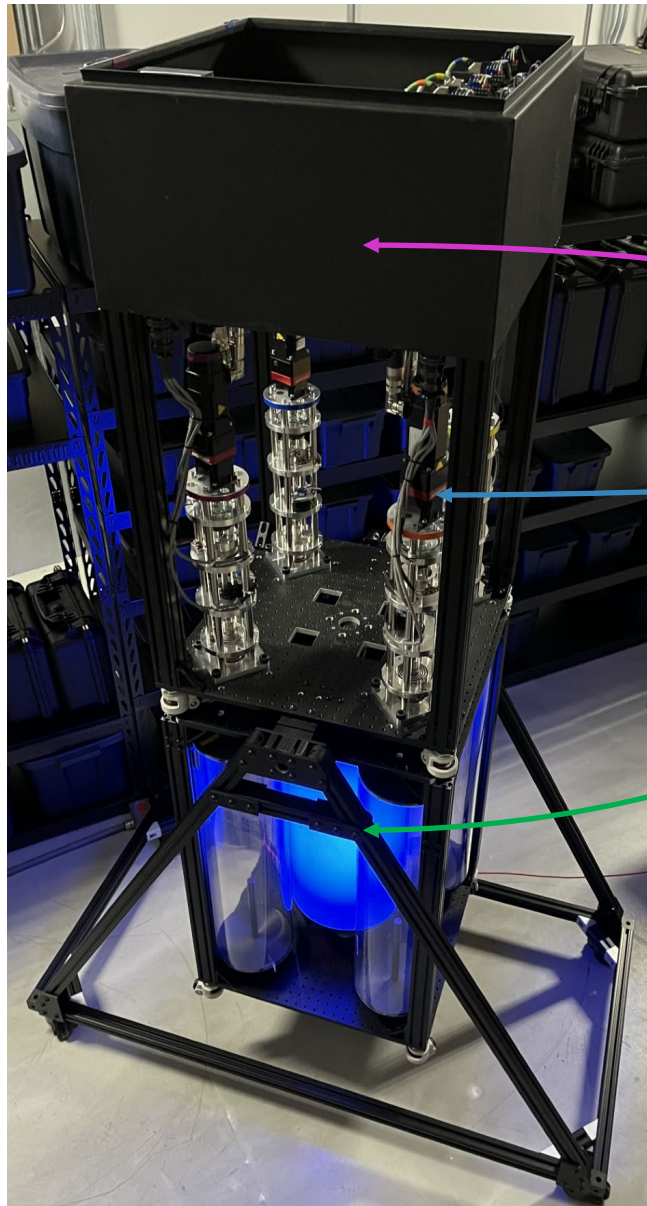
Requirement/Component Relationships



Component	MARVEL vs. ViBRANT
CD Servo Motor (Model)	1:1
CD Planetary Gearhead (Ratio)	200:1
CD Electromagnetic Clutch (Torque)	3:1
CD Limit Switches (Model)	1:1
CD Potentiometer (Range)	1:2
CD Rotary Damper (Torque/Speed)	4:1
CD Spiral Spring (Stiffness/Range)	1.9:1, 3:2
Drum (Inertia)	22:1

MACS and ViBRANT Flow

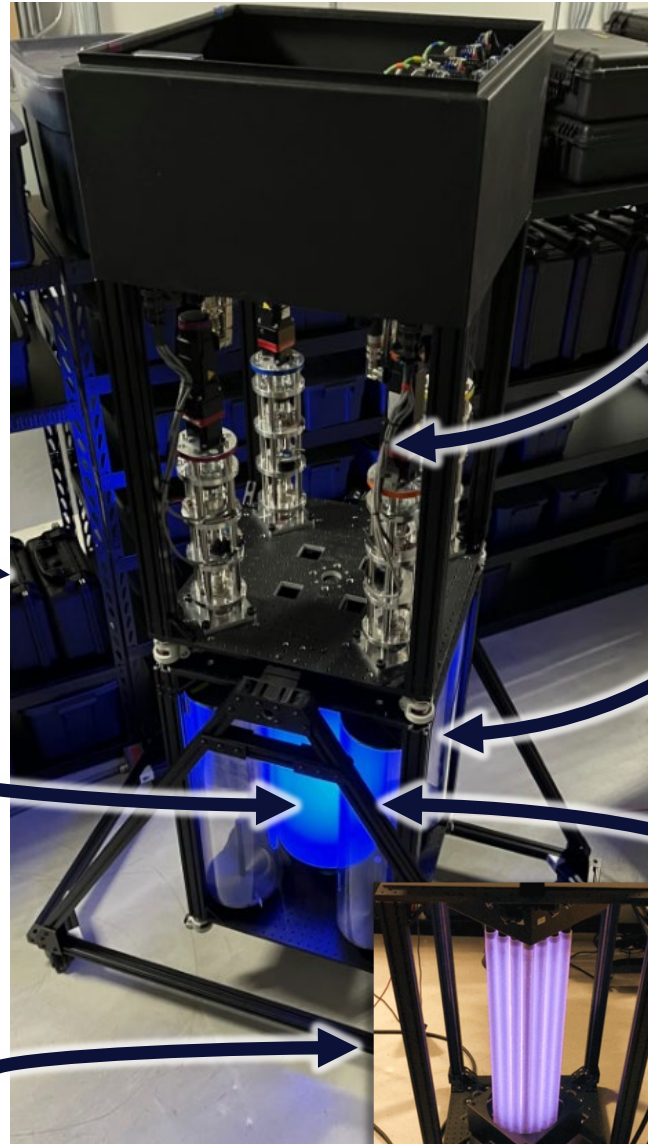
Primarily I&C With Flexible Mechanical Support



MACS/ViBRANT Contributing Techniques



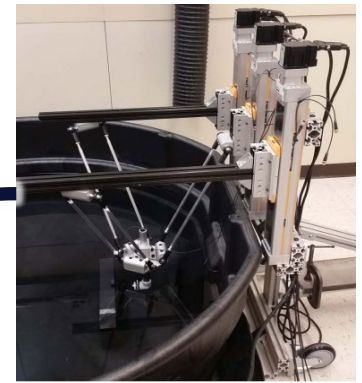
Environment Simulation



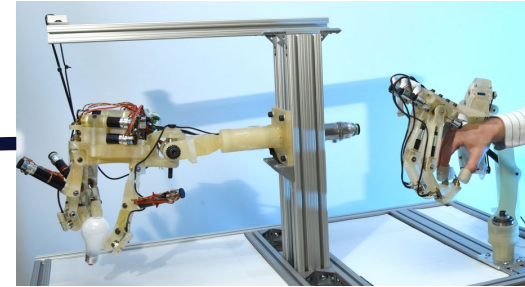
Discrete Mapping



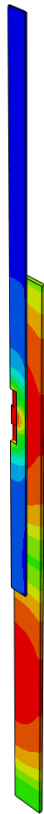
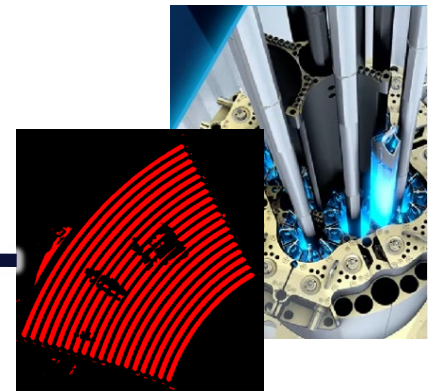
Motion Control



3D Volume interaction



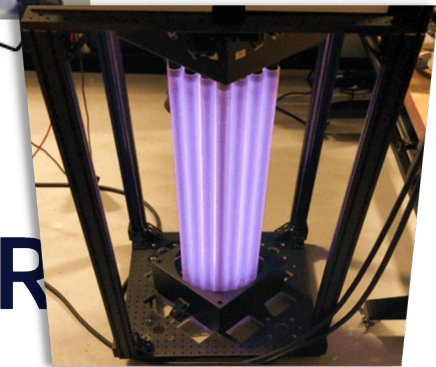
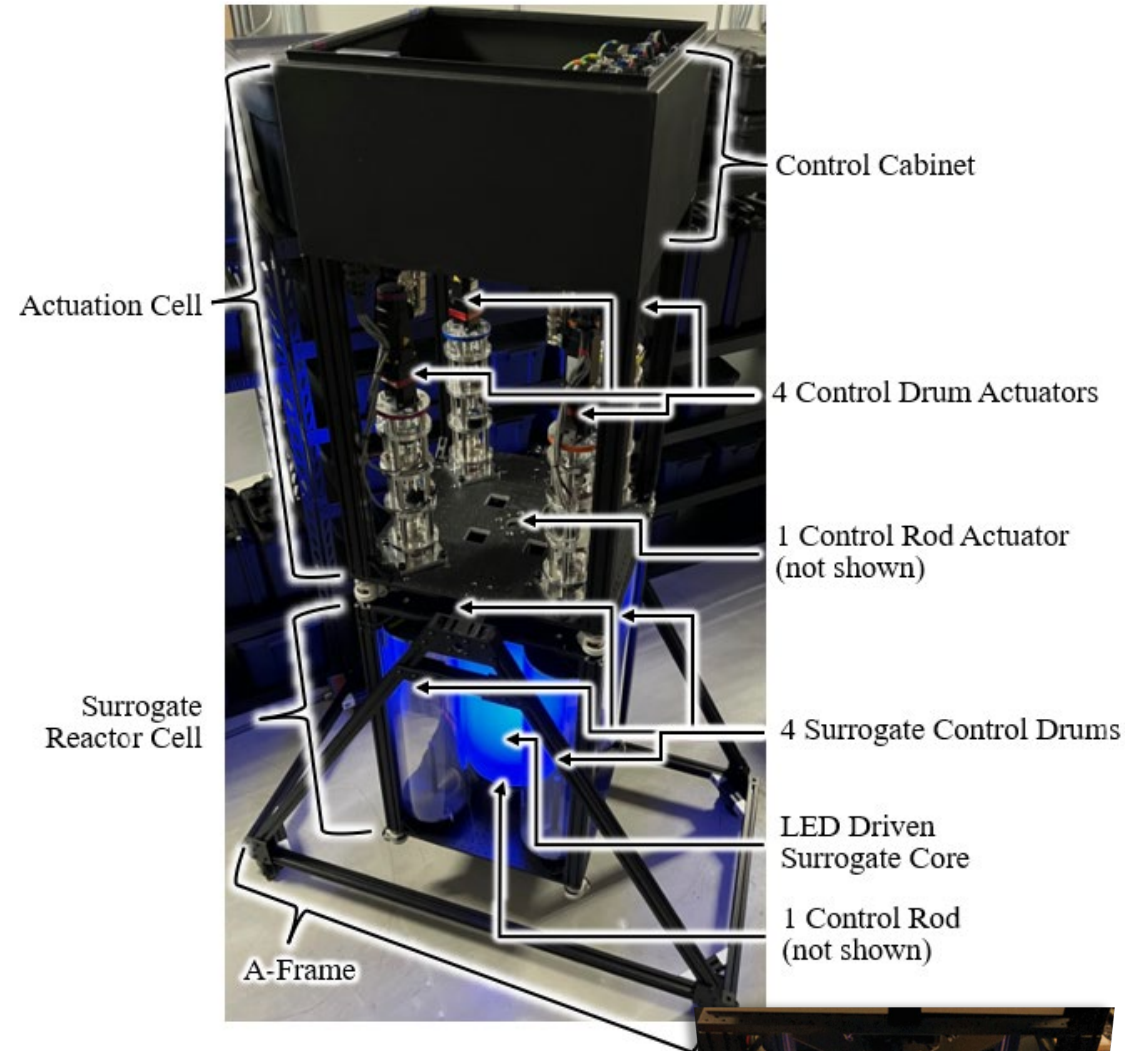
Reactor Light Detection/Processing



MRP Microreactor Program

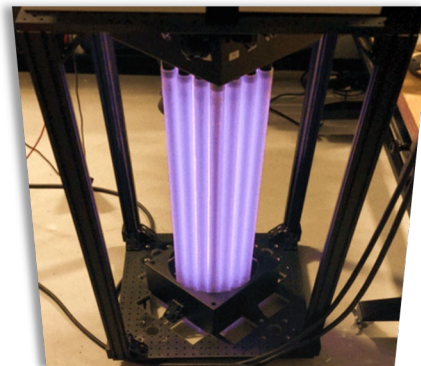
MACS/ViBRANT Key Features

- 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

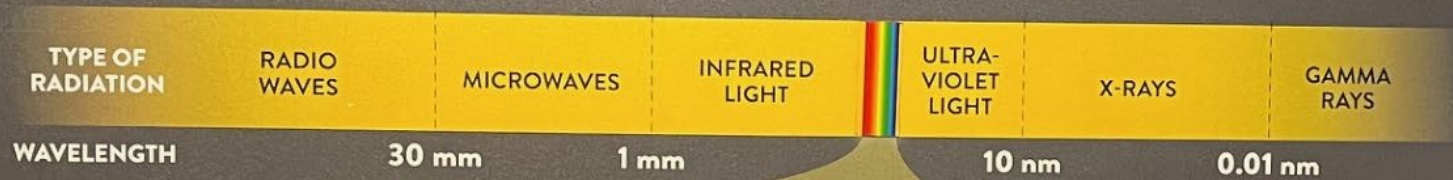
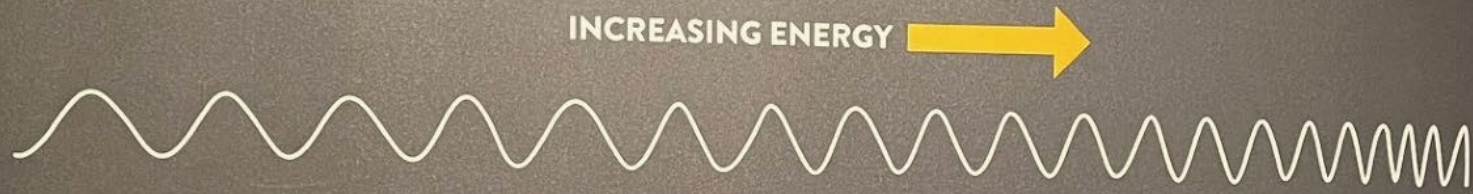
- General Microreactor Systems
 - Reactor
 - Coolant
 - Power Extraction
 - Actuation
 - Control



Surrogate
Reactor Cell



What is Light?



What makes light bright?
The number of photons—tiny packets of light—hitting your eye per second makes things appear brighter or dimmer.

Down Here vs. Out There:
Visible light, radio waves, and many infrared rays can be observed from Earth. But our atmosphere absorbs most x-ray, gamma, microwave, and UV radiation—so astronomers study them using spacecraft.

Astronomy is closely tied to light—light from space provides information on our celestial surroundings, while light here on Earth can interfere with astronomers' observations.

So what is this phenomenon that both helps and hinders?
Light is electromagnetic energy radiating through space.

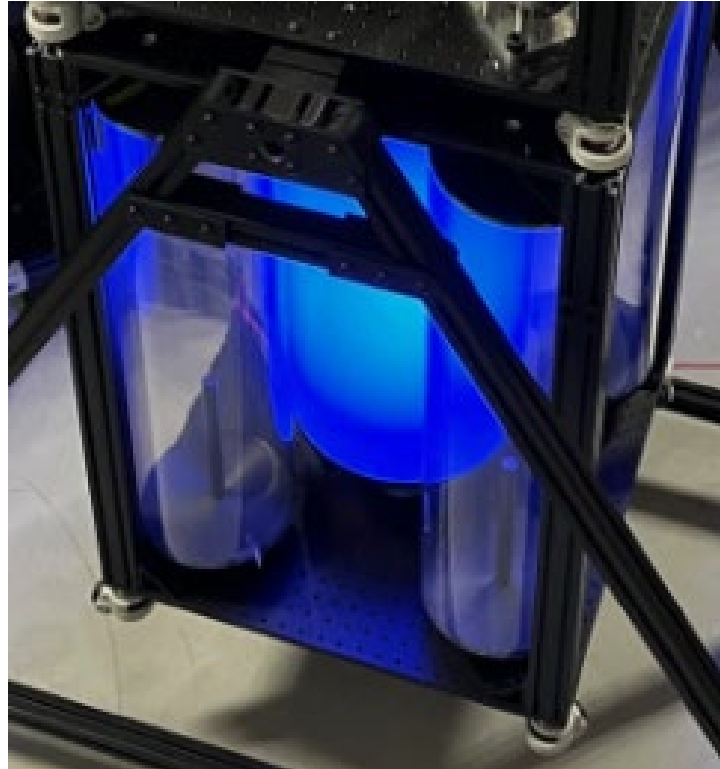
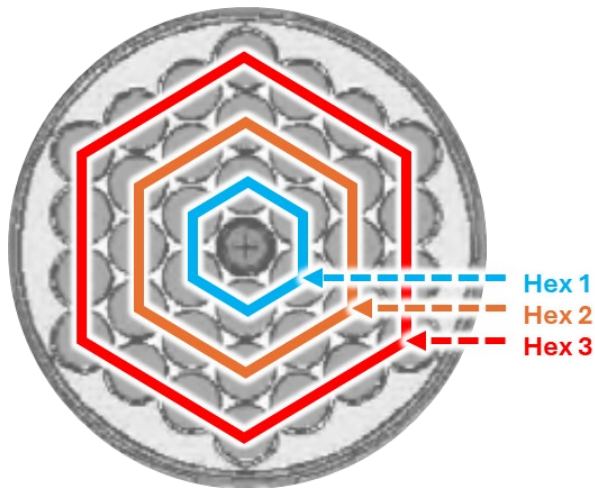
Waves, Rays, or Radiation? It's all light!
However, humans can only see a sliver of the spectrum—like only being able to hear a couple notes around middle C out of a piano's entire 88 keys.

Color Waves: Visible light's color depends on its wavelength—from long red waves to short violet ones. Combining all these wavelengths makes white light.



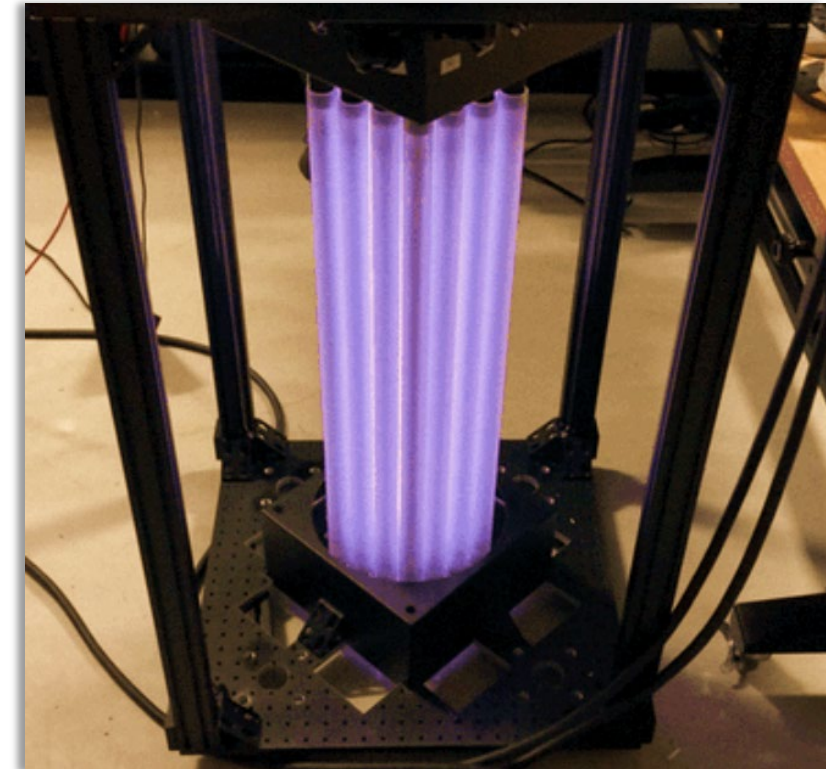
ViBRANT

- 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



MRP Microreactor Program

Key Demonstration Milestones

- Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)
- MACS/MAGNET/MIB communications (M2AT-26IN0804021)

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

Build mixed simulation reactor using MACS

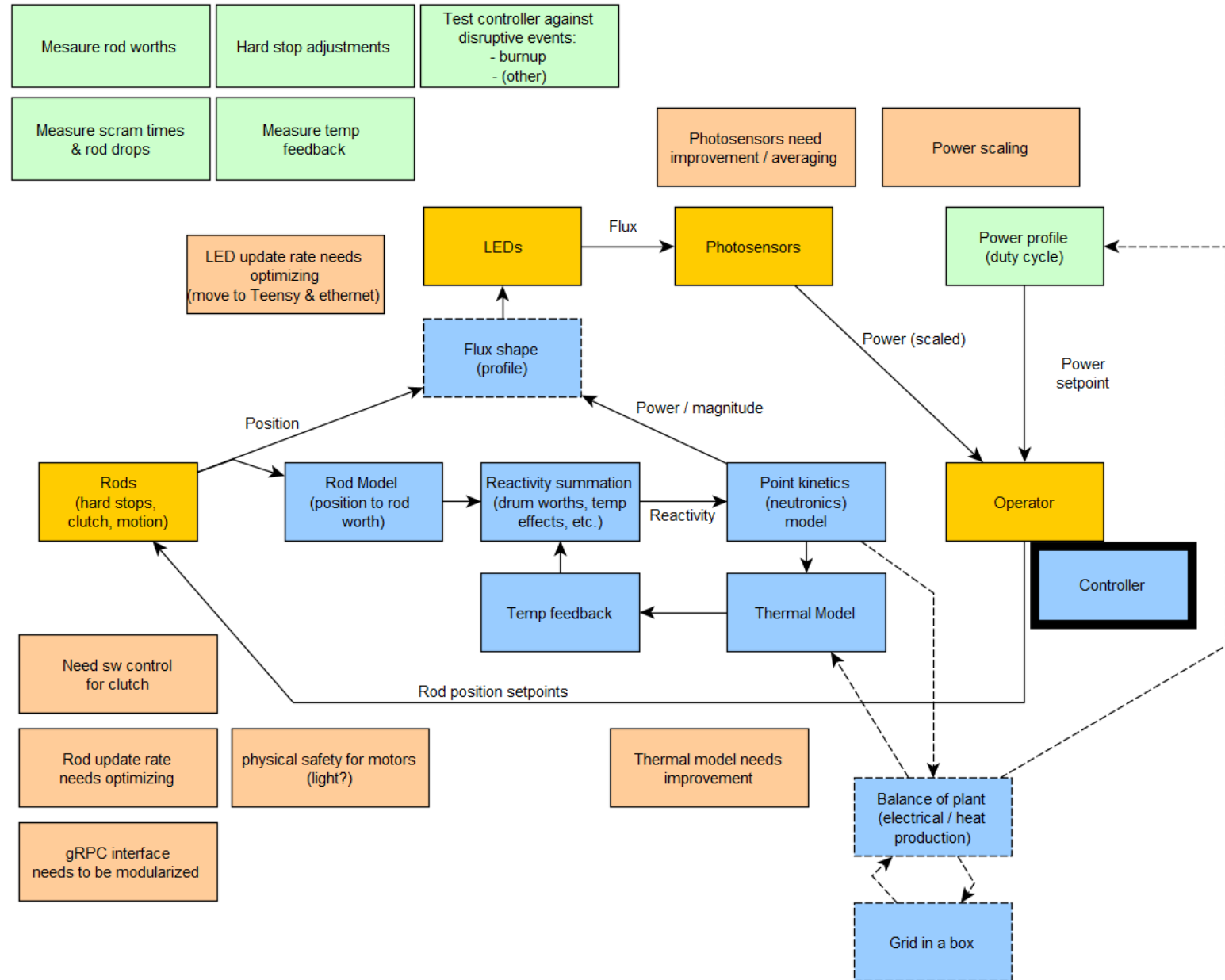
- Models shown in blue
- Hardware shown in Gold

Perform

- Startup-related tests, show in green (MRP)
- Operations with various controllers and disruptive events (ASI)

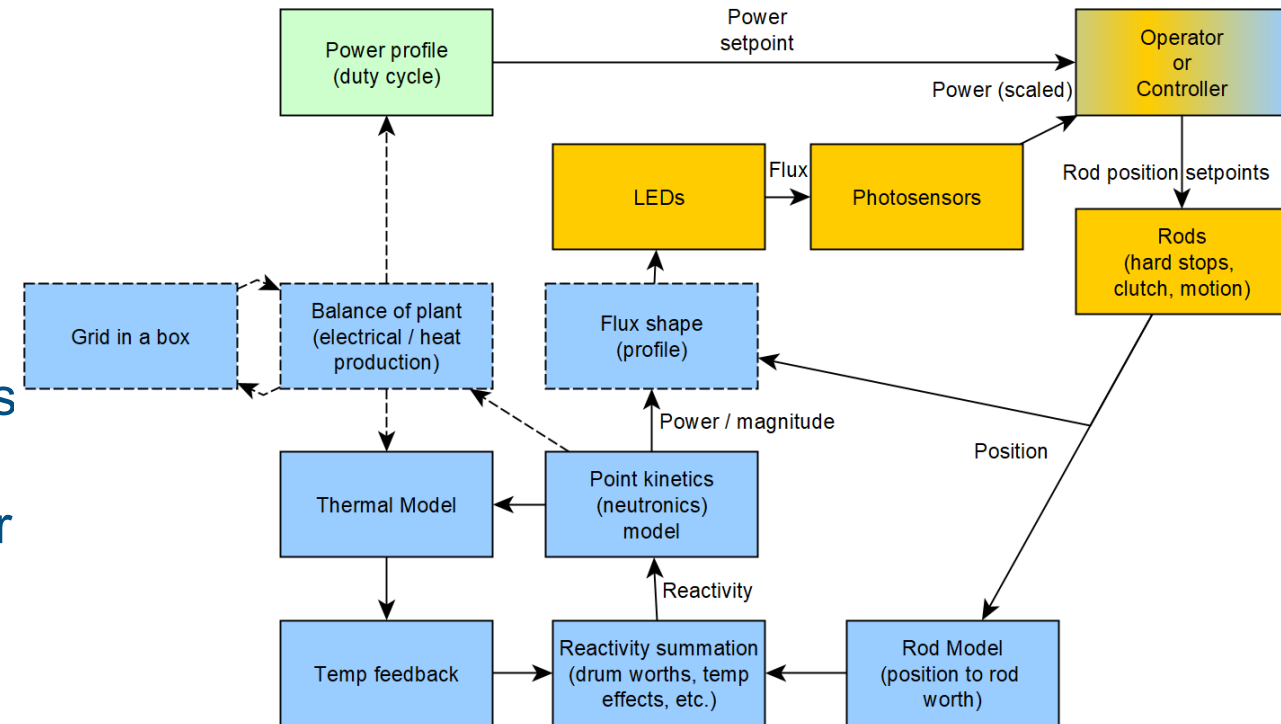
Upgrade fidelity as we go

- Various models considered: point kinetics, RELAP, COMMAND, ORNL
- Various improvements to be done shown in peach boxes



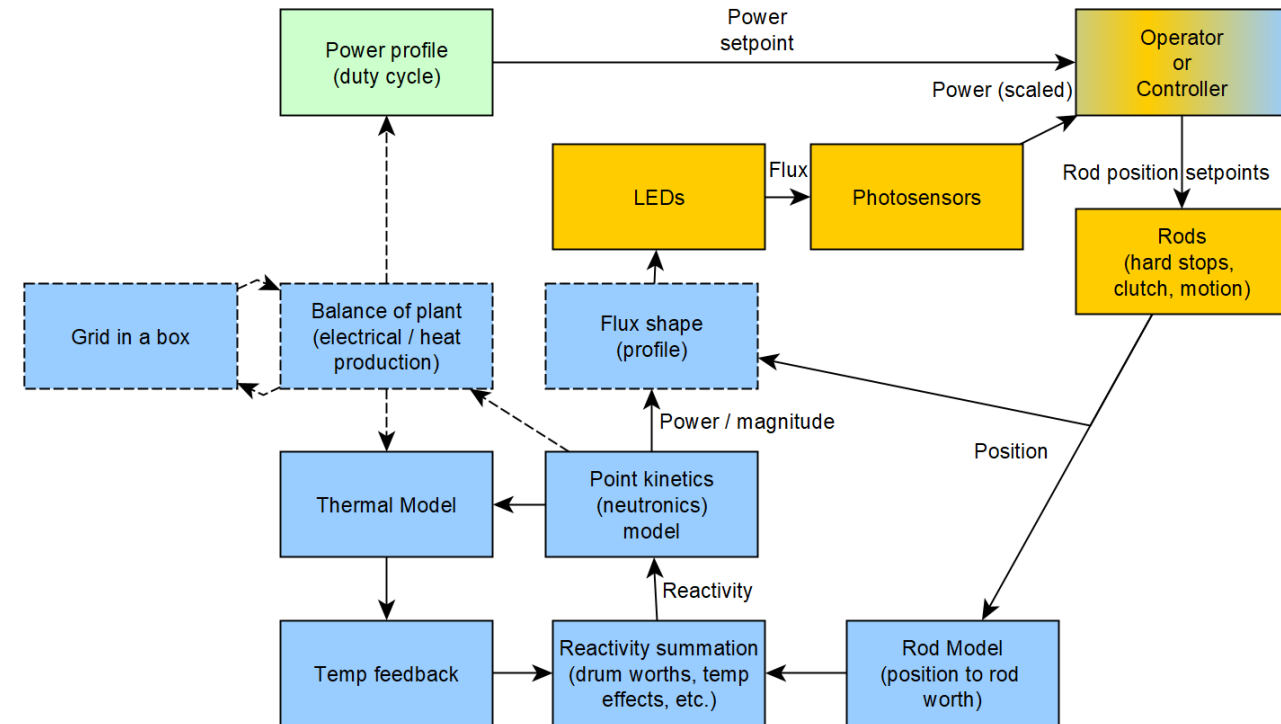
Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)

- 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



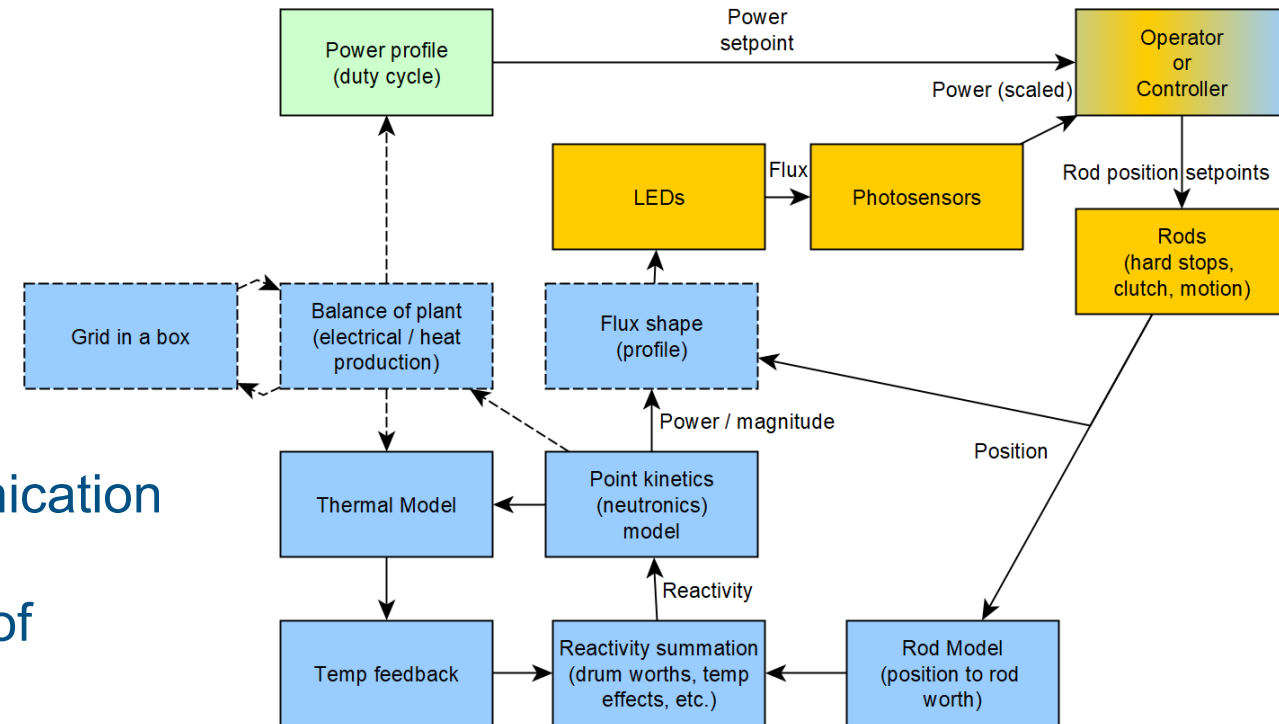
Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)

- 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



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.



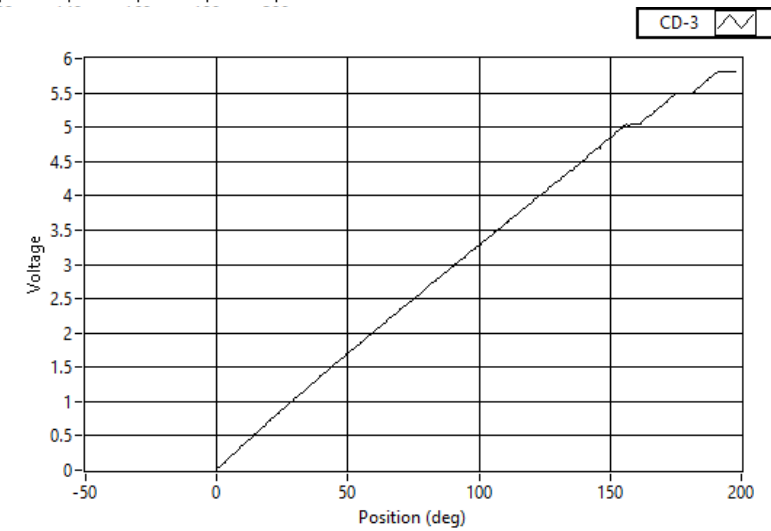
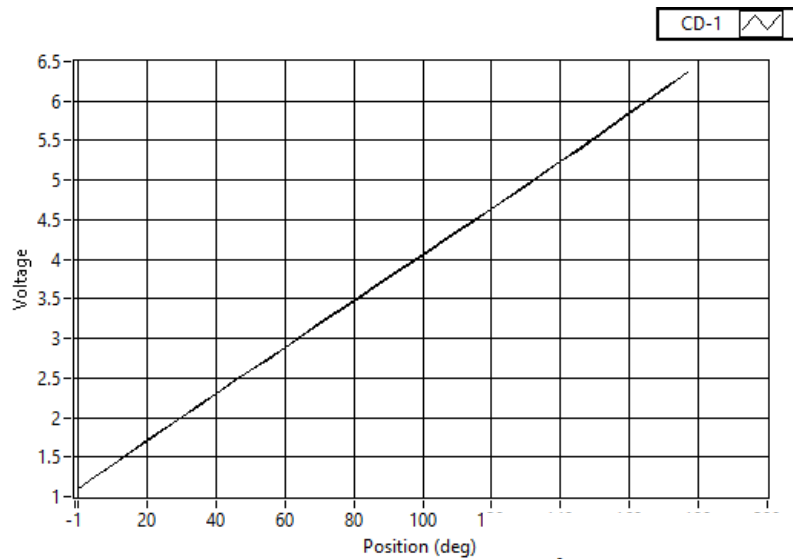
Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)

- MRP
 - Startup-related procedure methodology
 - ANS-19.13-2004, “Initial Fuel Loading and Startup Physics Tests for First-Of-A-Kind Advanced Reactors,” American Nuclear Society, (2004).

Characteristics	Example measured parameters used for confirmation	Testing requirements and recommendations	
Core reactivity, including fuel loading	Critical fuel loading	Shall be determined using $1/M$ extrapolation.	
	Integral and differential control element worth	Shall be measured at zero power and appropriate higher powers.	
	Critical control element positions	Shall be measured at relevant reactor statepoints.	
	Excess reactivity	Shall be determined at zero power.	
	Reactivity deficit (HZIP to HFP)	Shall be determined at full power (if applicable).	
	Prompt and delayed neutron parameters	Shall be measured for systems with flowing fuel.	
	Neutron lifetime	Shall be measured at zero power and at higher relevant powers.	
	Control element worth interference (shadowing)	Shall be measured individually and in groups as appropriate.	
	Reactor shutdown	Shutdown margin	Shall be determined from measurements of excess reactivity and control element worth at cold and hot zero power and at higher powers, if appropriate.
	Reactivity control	Isothermal temperature coefficient	Shall be measured, if applicable to safety.
Power coefficient of reactivity		Shall be measured at power levels above the point of adding heat.	
Prompt and delayed component temperature coefficients		Should be measured when important to system performance.	
Coolant void coefficient		Should be measured if important to system performance.	
Reactor stability during transient reactivity events		Shall be demonstrated at zero power and higher relevant power levels.	
Reactivity response during pump startup and coastdown		Should be measured at several power levels, including full power, if applicable to safe operation.	
Load following		Should be measured at full and partial power, if a design requirement.	
Power, temperature, and flow distribution		Power or flux distributions	Shall be measured at zero and higher powers if applicable to safety.
		Natural circulation	Shall be measured from zero power if required for normal operation and anticipated operational occurrences. The transition to natural circulation shall be evaluated at low power with heat rejection through the secondary or power conversion system.
		Flow distribution	Shall be measured if applicable to safety.
	Temperature distribution	Should be measured when important to system performance.	

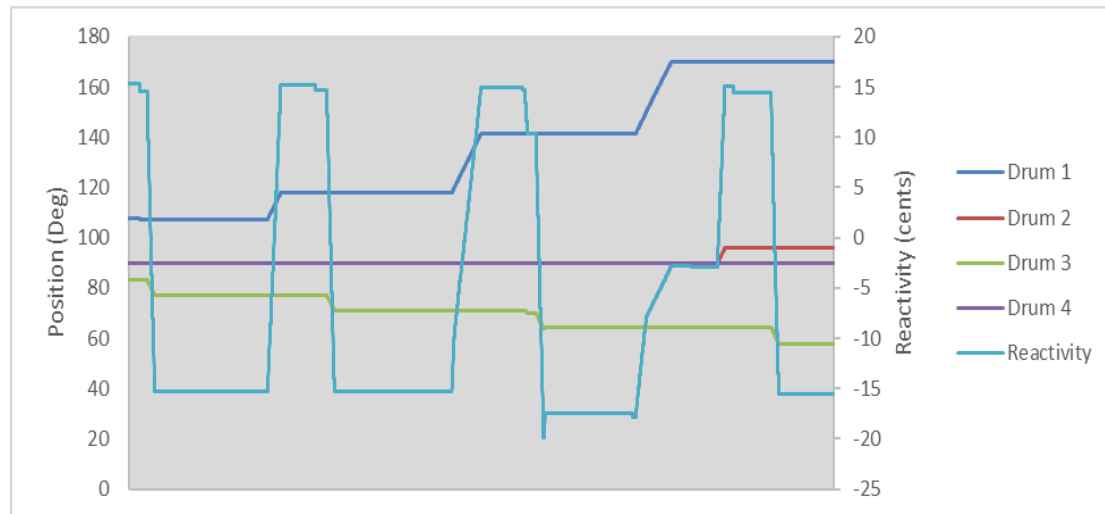
Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)

- MRP
 - Startup-related procedure methodology
 - Calibrate Potentiometers



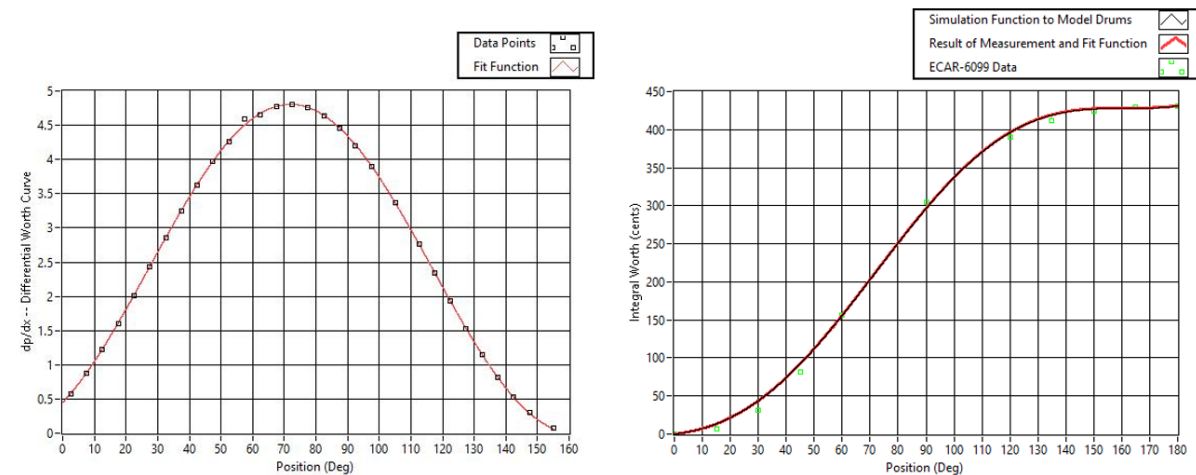
Demonstrate a Reactor Startup MRP/ASI Collaboration (M2AT-25IN0804051)

- MRP
 - Startup-related procedure methodology
 - Rod worth measurement



$$\frac{d\rho(x)}{dx} = C1 * \cos^2(2 * (x - C3))$$

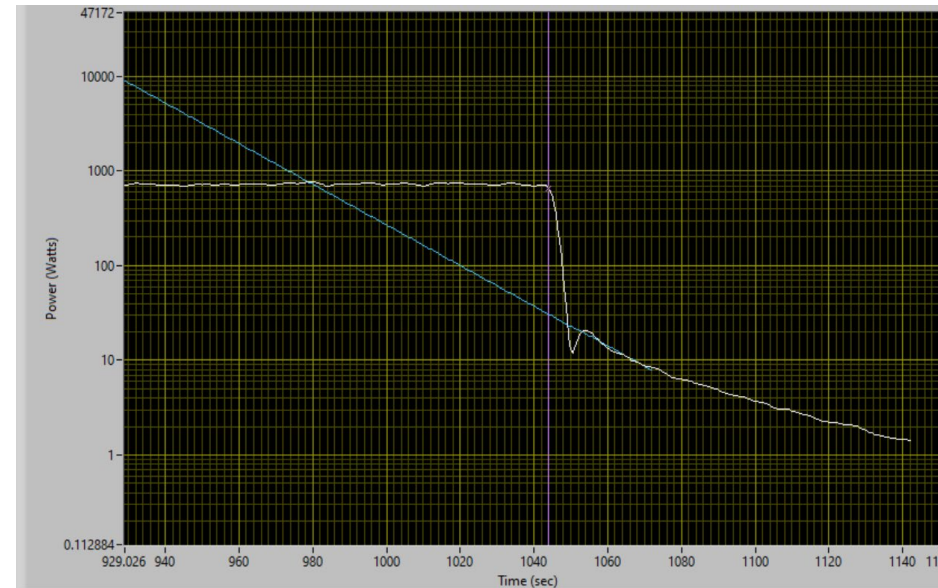
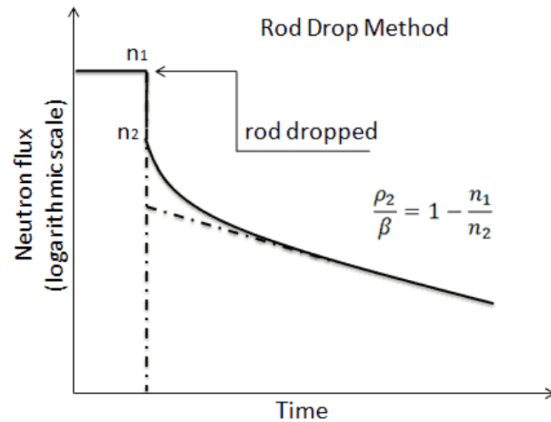
$$\rho(x) = \frac{C1}{4C2} * (\sin(2 * C2 * (x - C3)) + \sin(2 * C2 * C3) + 2 * C2 * x)$$



Differential worth measured data curve fit to identify coefficients amenable to both differential worth (left) and control drum reactivity worth (right) curves.

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

- MRP
 - Startup-related procedure methodology
 - Rod worth measurement



Rod-drop method to determine shutdown worth [power = white, time of rod drop = purple, fit to decay = cyan].

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

- MRP
 - Startup-related procedure methodology
 - Measure temperature feedback

Table 2. Input data from a temperature-feedback test.

	Drum Position (Deg)	Rho (use Drum curve)	Temperature (K)	Temperature (°C)
Start	90	297.85	293.15	20.00
Stop	170	421.76	546.32	273.17
Start	90	297.85	546.32	273.17
Stop	131.69	395.87	730.75	457.60

Table 3. Measured data results for feedback.

	Feedback		
	(cents/°C)	dk/k/°C	<u>Pcm</u> /°C
20–273	0.49	3.65E-05	3.65
273–457	0.53	3.96E-05	3.96

These measured data were compared with the data used in the simulator. The simulator used tabulated data obtained from MCNP, and the check involved looking at the nearest reactivity-feedback data at the temperatures used in the test. The simulator data is shown in Table 3.

Table 4. Feedback Data from the Simulator.

	Feedback		
	(cents/°C)	dk/k/°C	<u>Pcm</u> /°C
20–273	0.47	3.54E-05	3.54
273–457	0.54	4.01E-05	4.01

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

- MRP
 - Startup-related procedure methodology
 - Measure scram & rod drop times



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

- MRP
 - Startup-related procedure methodology
 - Measure temperature feedback

Table 6. Thermal feedback up to 270°C.

Thermal Feedback up to 270°C Approx. steady state power with no heat rejection = 1100 W	Example of Suggested Hard-Stop Limit
CD-1	90 degrees
CD-2 (used to measure)	130 degrees (critical at 270°C)
CD-3	90 degrees
CD-4	90 degrees

Table 7. Thermal feedback up to 304°C.

Thermal Feedback up to 304°C	Example of Suggested Hard-Stop Limit
CD-1	90 degrees
CD-2 (used to measure)	180 degrees (critical at 304°C)
CD-3	90 degrees
CD-4	90 degrees

Table 8. Thermal Feedback up to 350°C

Thermal Feedback up to 350°C	Example of Suggested Hard-Stop Limit
CD-1	92 degrees
CD-2 (used to measure)	180 degrees (critical at 350°C)
CD-3	92 degrees
CD-4	92 degrees

Table 9. Thermal Feedback up to 400°C

Thermal Feedback up to 400°C	Example of Suggested Hard-Stop Limit
CD-1	94 degrees
CD-2 (used to measure)	180 degrees (critical at 400°C)
CD-3	94 degrees
CD-4	94 degrees

Table 10. Thermal Feedback up to 450°C

Thermal Feedback up to 450°C	Example of Suggested Hard-Stop Limit
CD-1	97 degrees
CD-2 (used to measure)	180 degrees (critical at 450°C)
CD-3	97 degrees
CD-4	97 degrees

Table 11. Thermal Feedback up to 500°C

Thermal Feedback up to 500°C Approx. steady state power with no heat rejection = 2400 Watts (Note: actual MARVEL heat losses are expected to be about 4000 W)	Example of Suggested Hard-Stop Limit
CD-1	99 degrees
CD-2 (used to measure)	180 degrees (critical at 500°C)
CD-3	99 degrees
CD-4	99 degrees

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

- MRP
 - Startup-related procedure methodology
 - Hard stop adjustments

2.3.6.4. Hard-Stop Adjustment Strategy

The strategy employed for adjusting the hard stops during the drum worths, temperature-feedback measurements, and ascension to full power will need to coordinate with calculations to determine the acceptable margin for each test. These margins are informed by subsequent startup-[physics](#) tests. This starts with the first approach to [critical](#) to determine how close the calculations were to the measured result. Each test will cause information to be learned and confirmed.

2.3.6.3. Rod Worth

It is advantageous to set the hard stops such that the drums can get as much movement as possible. If the rod worths are performed after sufficient data has been obtained from thermal feedback, a case can be made to allow much more than 40 cents in excess but less than needed for hot full power conditions (i.e. around \$2.30 in excess). The total worth of a drum is about \$4.31. Thus, the drums can move just past [half way](#), with such allowance. The absolute maximum placement for the [hard-stops](#) would be about 2.30 plus the 40 cents extra, or around \$2.70.

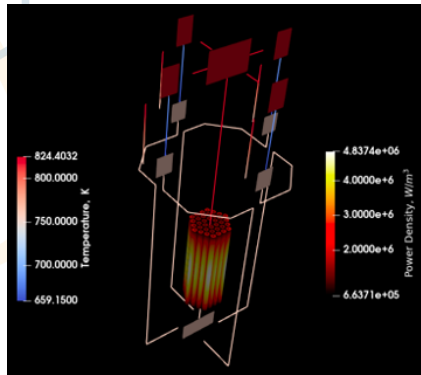
This might be achieved with a scheme such as:

- Critical, with one drum fully in and another fully out, and the remaining two drums set to 110 degrees with their hard stops set to those positions.
- The hard stop is set on the drum that starts at the shutdown position, such that it can only go to around \$2.30 worth, which is about 76 degrees. Thus, this drum would only be able to rotate from 0 to 75 degrees.
- The drum that is at the shutdown position is swapped with the drum that is in the full-out position, following the procedure outlined in the drum-worth measurement section of this report.
- The two drums may not be perfectly balanced, and the other two drums may be adjusted to provide a little extra motion. However, the limitation is the amount of excess reactivity allowed in the core by the placement of the hard stops.
- The measurements should [calibrate](#) the fully inserted drum from 0 to ~75 degrees and 180 to ~70 degrees for the drum that started fully withdrawn.
 - The [hard-stops](#) are then switched on the fully inserted and fully withdrawn drums so that the remaining positions may be measured.
 - The process is then repeated for the remaining two drums that were used to establish criticality.
 - This example requires one set of hard stops to be fabricated. However, the hard stops will be shifted to a different drum for each calibration and require a total of four adjustments.

MARVEL Beyond the Reactor: Non-Nuclear Integration and Controls as a Stepping-Stone (M2AT-26IN0804021)

(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)

Mobile Data Center



Drum position and core response



MACS Hardware (non-nuclear surrogate for MARVEL controls)

Electricity generation and dispatch



RAPID MIB (Microgrid in a box)

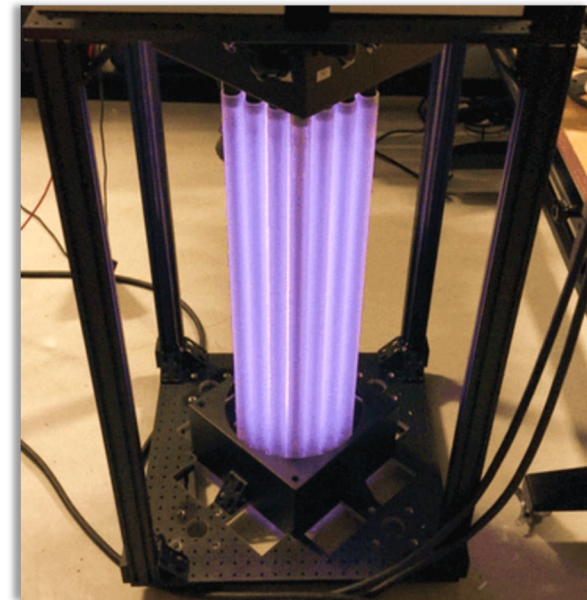
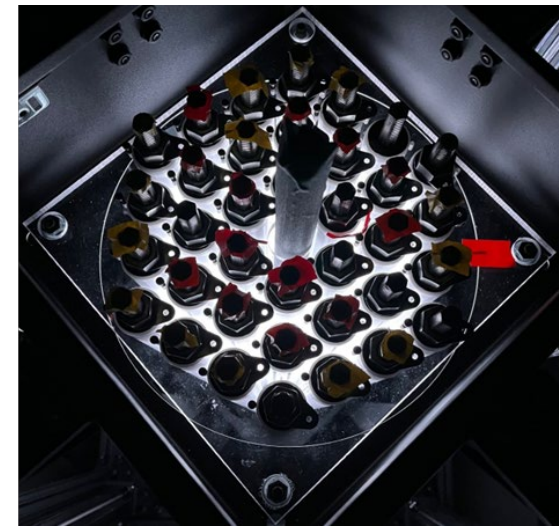
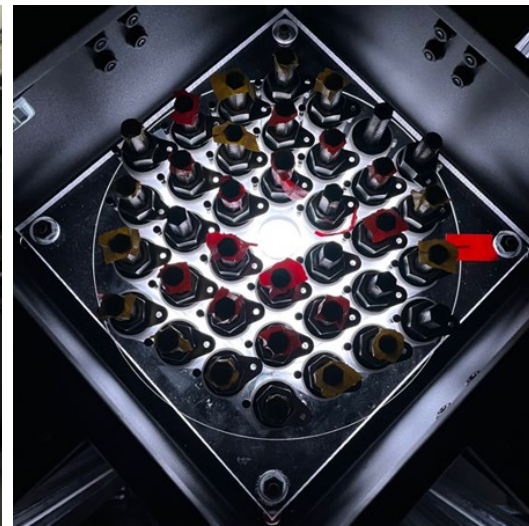
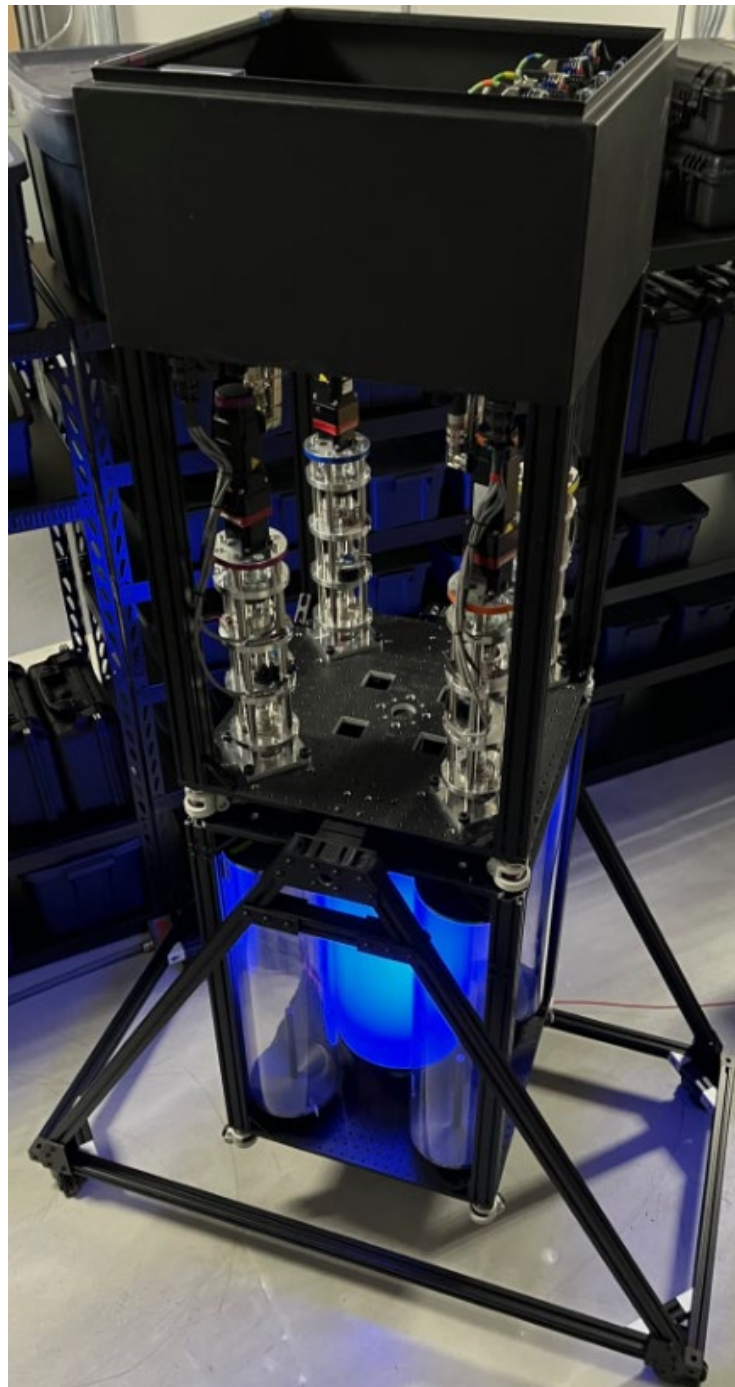
Nuclear-powered data center demonstration



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



Discussion?



References

- <https://www.youtube.com/watch?v=5I925aHloVE>
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