(Microreactor Applications Research, Validation & EvaLuation),
March 9th 2023

Microreactor Applications

DOE Microreactor Program (Sponsored by NE-5)

Yasir Arafat

Technical Area Lead, DOE Microreactor Program

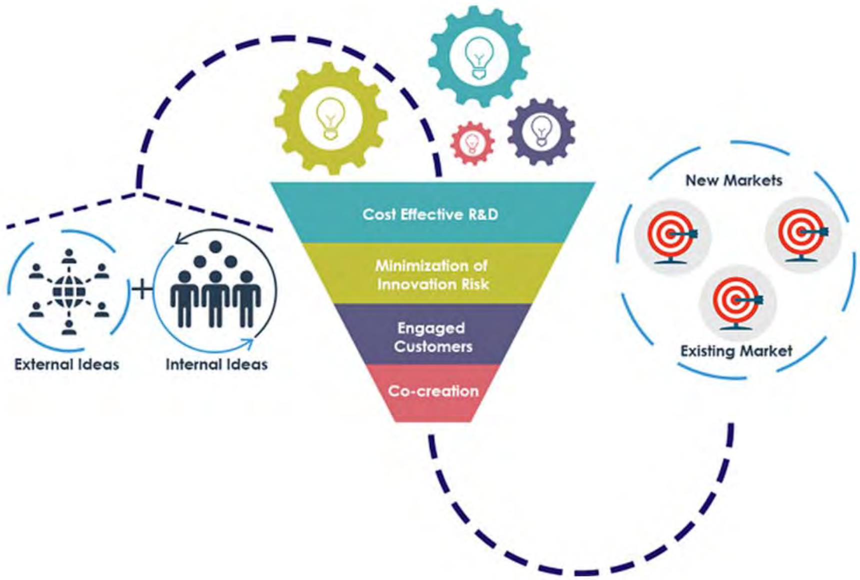
Chief Designer and Project Lead, MARVEL Project

Idaho National Laboratory

INL Idaho National Laboratory | Oak Ridge National Laboratory | MRP Microreactor Program | Los Alamos National Laboratory | Argonne National Laboratory

Microreactor Applications

“Applied Innovation” branch of the DOE Microreactor Program



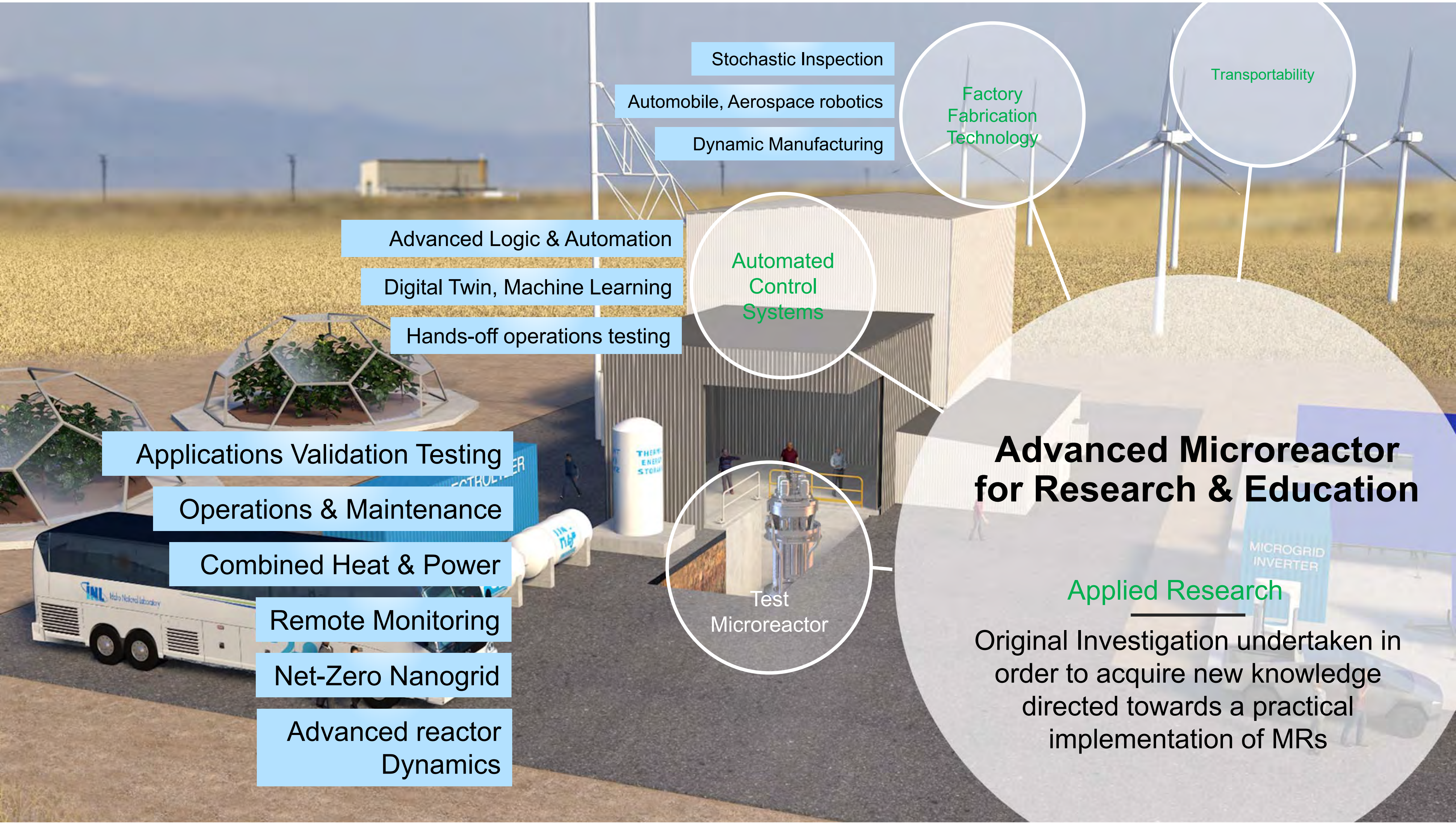
Applied Innovation Platform for the Microreactor Community?

- *Many common problems/solutions across multiple concepts*
- *Risk reduction through external contributions/collaborations*
- *Early end customers while the industry develops their tech*

“Applied Innovation- The process of learning innovation through the direct application of innovation tools, techniques and methods to solve real world problems in controlled, semi-controlled or uncontrolled environments”

What technologies need to be demonstrated with a nuclear microreactor system?

MRP Microreactor Program


Stochastic Inspection
Automobile, Aerospace robotics
Dynamic Manufacturing
Factory Fabrication Technology
Transportability
Advanced Logic & Automation
Digital Twin, Machine Learning
Hands-off operations testing
Automated Control Systems
Applications Validation Testing
Operations & Maintenance
Combined Heat & Power
Remote Monitoring
Net-Zero Nanogrid
Advanced reactor Dynamics
Test Microreactor
Advanced Microreactor for Research & Education
Applied Research
Original Investigation undertaken in order to acquire new knowledge directed towards a practical implementation of MRs
MICROGRID INVERTER

Agenda: Microreactor Applications

1:00 **Microreactor Application Overview .... Yasir Arafat**

1:10 – 1:30 MARVEL Final Design .... **Yasir Arafat**

1:30 – 1:45 MARVEL PCAT .... **Derek Sommer, Scott Reed**

1:45 – 2:00 MARVEL Fuel Fabrication .... **MW Patterson**

2:00 – 2:15 MARVEL Construction Assembly Plan……………..……..**Tarrin Funderberg**

2:15 – 2:30 MARVEL ASME Calculations……………………..**Kyle Francis, Cody Hale**

2:30 – 2:45 Microreactor Factory Fabrication………………………**Abdalla Abu- Jaode**

2:45 – 3:00 (NEUP Project 19-16802) Evaluation of Semi-Autonomous Passive Control Systems for HTGR Type Special Purpose Reactors............ **Brendan Kochunas**

3:00 – 3:15 (NEUP Project 19-17185) Demonstrating Reactor Autonomous Control Framework Using Graphite Exponential Pile .... **Bren Phillips**

3:15 – 3:30 (NEUP Project 22-26910) Demonstrating Autonomous Control, Remote Operation, and Human Factors for Microreactors........................ **Stylianos Chatzidakis**

3:30 – 3:50 Next Steps & Wrap Up.. **Yasir Arafat**

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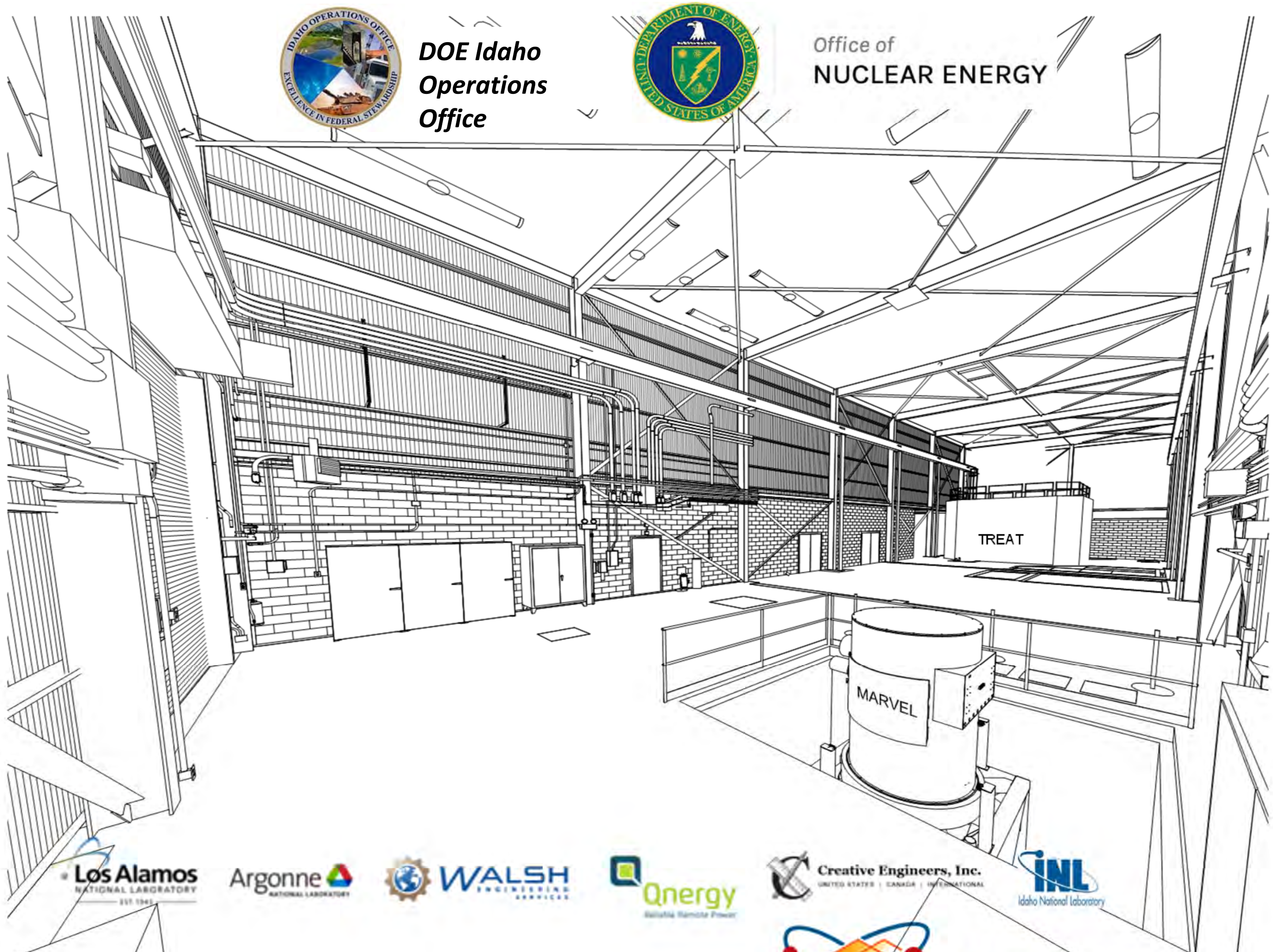
Project Status

- Final Design Review- Sept 2022
  - 4-week review
  - 2-day presentation
  - 400+ comments
- Reconciliation Engineering
- Per DOE-STD-1189,
  - Summer 2023 target
- PCAT is ready to ship to PA in ~3 weeks
- Fuel Contracts
  - HALEU shipment
  - TNBGC-1 relicensing
  - Fuel fabrication
- Long Lead Procurements
  - Purchased materials
  - DOE authorization will trigger the fabrication

DOE Idaho Operations Office

Office of NUCLEAR ENERGY



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MARVEL Goal: Establish a small-scale, test microreactor ASAP

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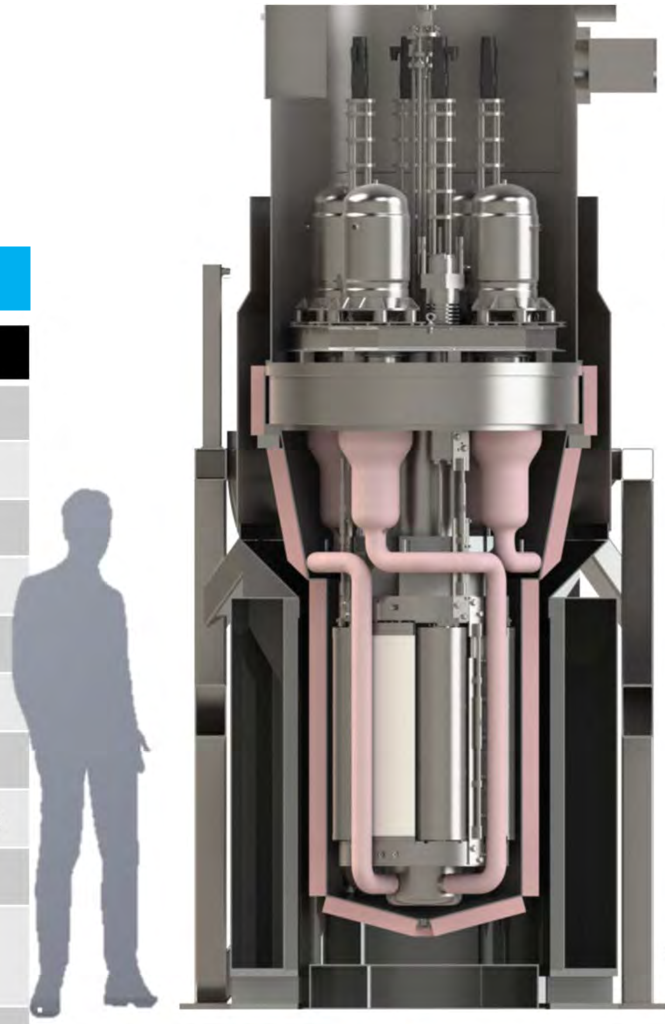
MARVEL - Test Microreactor

Reactor Type: Liquid Metal Thermal Reactor

Key Design Features	
Thermal Power	100 kW (85kW nominal)
Electrical Power	~20 kWe (QB80 Stirling Engines)
Primary Coolant	Sodium-Potassium eutectic, (33 psig)
Intermediate Coolant	Lead
Coolant Driver	Natural Convection, single phase
Fuel	HALE(UZrH), 304SS clad, end caps
Moderator	Hydrogen
Core Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary Metal	SS316H
Weight	~7.5 metric ton



Factory Fabricated

transportable

Self-regulating

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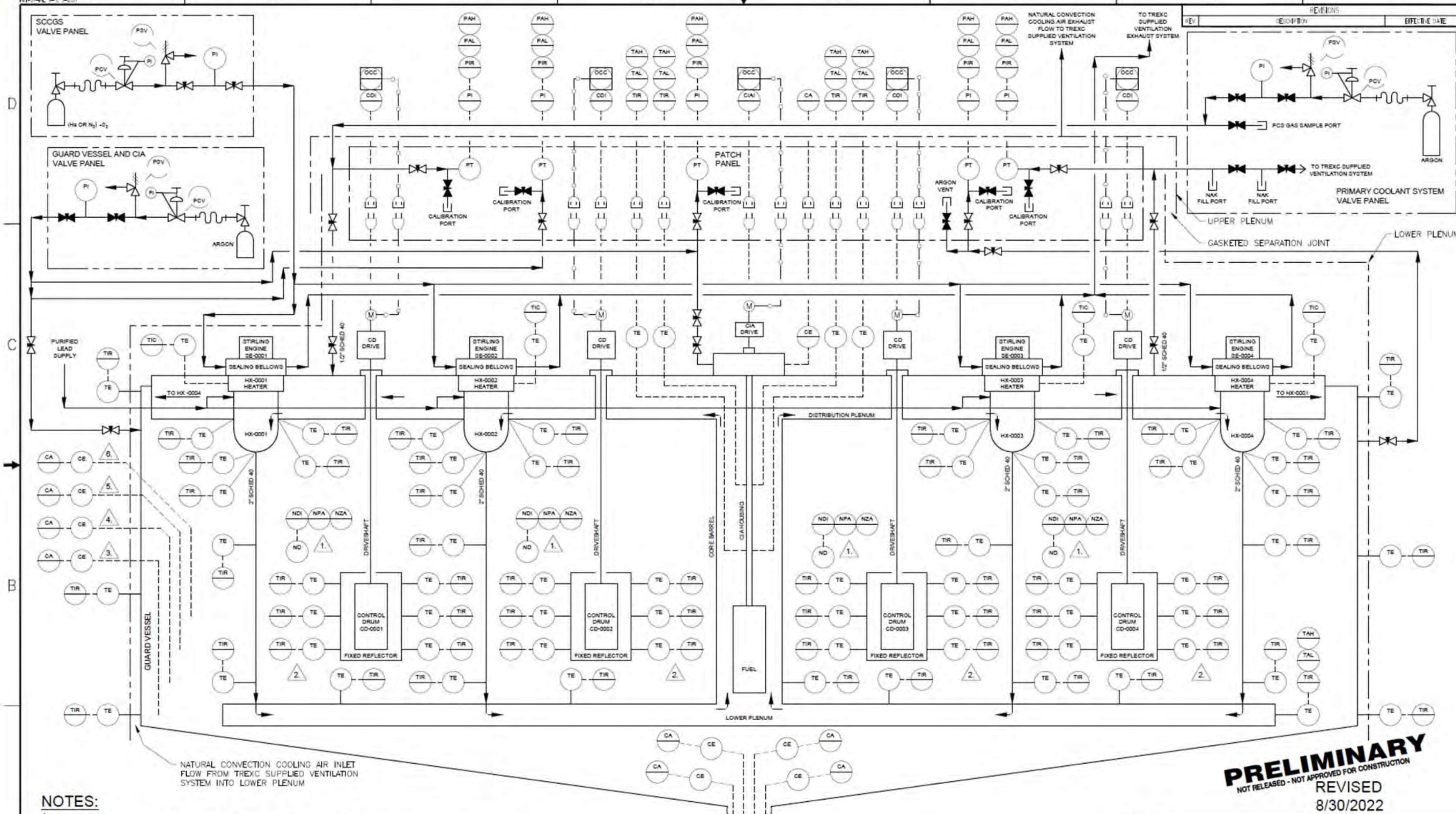


NOTES:

1. NEUTRON DETECTORS (ND) ARE LOCATED OUTSIDE OF GUARD VESSEL AND MID-WAY BETWEEN CONTROL DRUMS.
2. THESE TEMPERATURE ELEMENTS (TE) ARE INSIDE THE FIXED REFLECTOR, WHICH IS LOCATED OUTSIDE THE GUARD VESSEL BEYOND THE CONTROL DRUMS.
3. PCS DRAINED TO BOTTOM OF DISTRIBUTION PLENUM.
4. PCS DRAINED TO BOTTOM OF CORE.
5. PCS DRAINED TO MIDDLE OF CORE.
6. PCS DRAINED TO TOP OF CORE.

ALL INSTRUMENTS, VALVES, AND EQUIPMENT ON THIS DRAWING WILL HAVE EQUIOMENT NUMBERS ASSIGNED AFTER FINAL DESIGN REVIEW TO ENSURE SIMILAR COMPONENTS HAVE CONSISTENT NUMBERS TO AID IN OPERATION AND MAINTENANCE OF THESE SYSTEMS. MARVEL HAS BEEN ASSIGNED SYSTEM NUMBER A01 THROUGH A06. THE EQUIPMENT NUMBERING WILL FOLLOW TREAT REQUIREMENTS AND STRUCTURE AS FOLLOWS: BUILDING NUMBER - SYSTEM NUMBER - EQUIPMENT TYPE - UNIQUE EQUIPMENT IDENTIFIER (e.g. 720-A01-M-XXX.)

LEGEND

CA = CONDUCTIVITY ALARM
CE = CONDUCTIVITY ELEMENT
CDI = CONTROL DRUM INDICATOR
CIA = CENTRAL INSURANCE ABSORBER
CIAI = CIA INDICATOR
IHX = INTERMEDIATE HEAT EXCHANGER

ND = NEUTRON DETECTOR
NDI = NEUTRON DETECTOR INDICATOR
NPA = NEUTRON POWER ALARM
NPZ = NEUTRON PERIOD ALARM
OCC = OPERATOR COMPUTER CONTROLLED

PRELIMINARY
NOT RELEASED - NOT APPROVED FOR CONSTRUCTION
REVISED 8/30/2022

REQUESTER:	
RESP ENGR:	B. BAKER
DESIGN:	B. BAKER
DRAWN:	C. OLSEN
PROJECT NO.	
SPCL CODE	
FOR REVIEW/APPROVAL SIGNATURES SEE DOR NO.	
EFFECTIVE DATE:	

Idaho National Laboratory

MARVEL

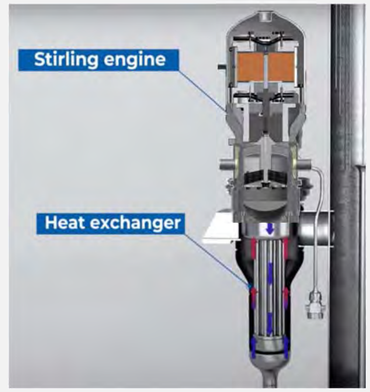
INITIAL LAYOUT

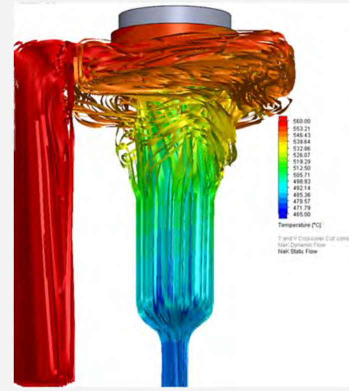
PROCESS AND INSTRUMENTATION DIAGRAM

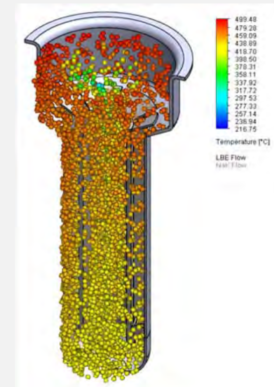
SIZE	CAGE CODE	AREA	TYPE	DL	DRI	DWG NO.	REV
D	01MF3	273		24	920		

SCALE NONE — SHEET 1 OF

Naturally Driven Coolants







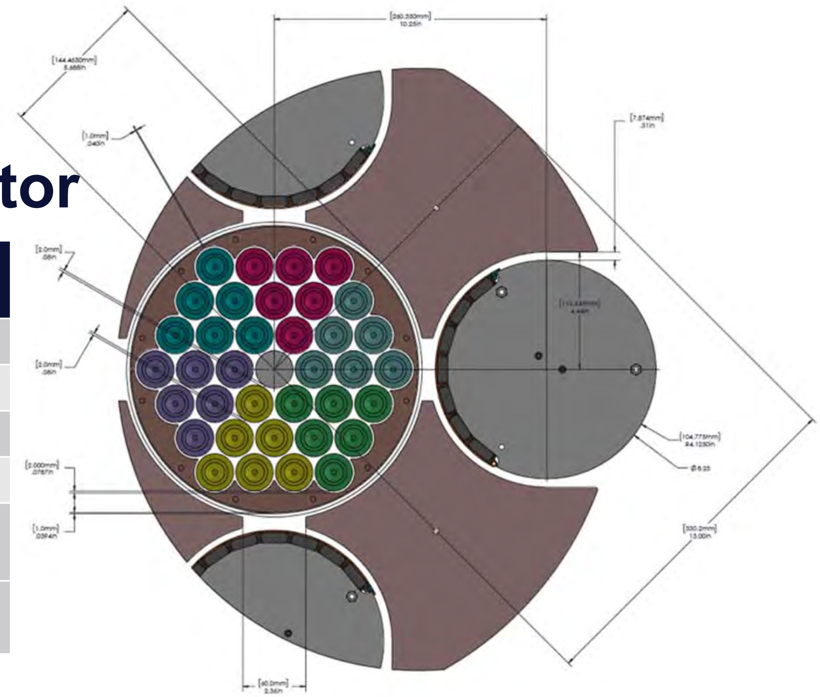
- Primary Coolant is driven by natural circulation
  - Reynold's Number < 6000
  - P/D <1.1
- Four intermediate lead loops- also natural circulation
- Vibrating Stirling engine in lead

PARAMETERS - PRIMARY & SECONDARY SIDE	SS VALUES
NaK inlet core temperature, ºC	465
NaK outlet core temperature, ºC	532
NaK core temperature rise, ºC	67
Total mass flow, kg/s	1.55
IHX Pb minimum temperature, ºC	386
IHX Pb maximum temperature, ºC	411
Pb temperature rise, ºC	25
IHX Pb mass flow, kg/s	5.2

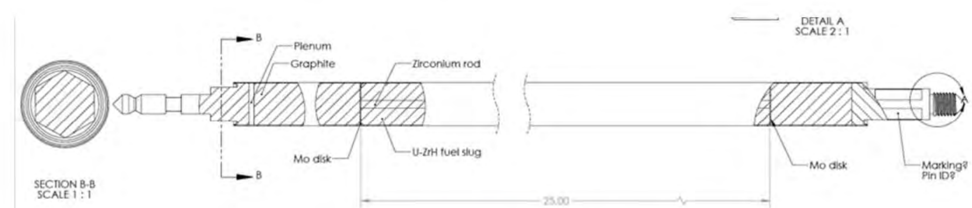
Natural circulation reduces failure modes, but limited in how much power can be produced

Highest Prompt Negative Temperature Coefficient for a High-Temperature Reactor

	Reactivity Coefficient [pcm/K]	1-sigma	Averaged over temperature range
UZrH Fuel (1e-3 s)	-5.22	0.15	293-1200 K
Beryllium oxide* (minutes)	1.26	0.09	293-1200 K
Metallic beryllium* (minutes)	0.30	0.06	293-1200 K
NaK Density (minutes)	0.16	0.08	293-1000 K
Pin Pitch Thermal Expansion (minutes)	-0.34	0.04	293-1200 K
Net	-3.84	0.42	293K-1200K



UZrH fuel gives the reactor a "prompt negative temperature coefficient of reactivity" versus a delayed coefficient



UZrH is an NRC Licensed Fuel for university research reactors, NUREG-1282

MARVEL Fuel Performance Report (INL/RPT-22-68555, Rev. 2, Nov. 2022: **Jordan Evans**, R. Sweet, & D. Kaiser)

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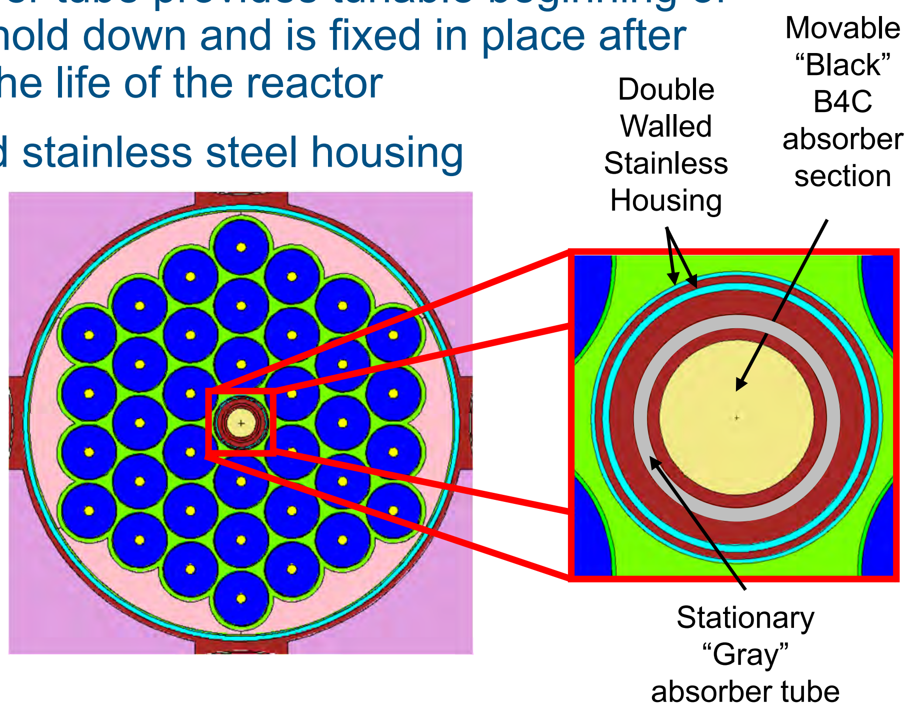
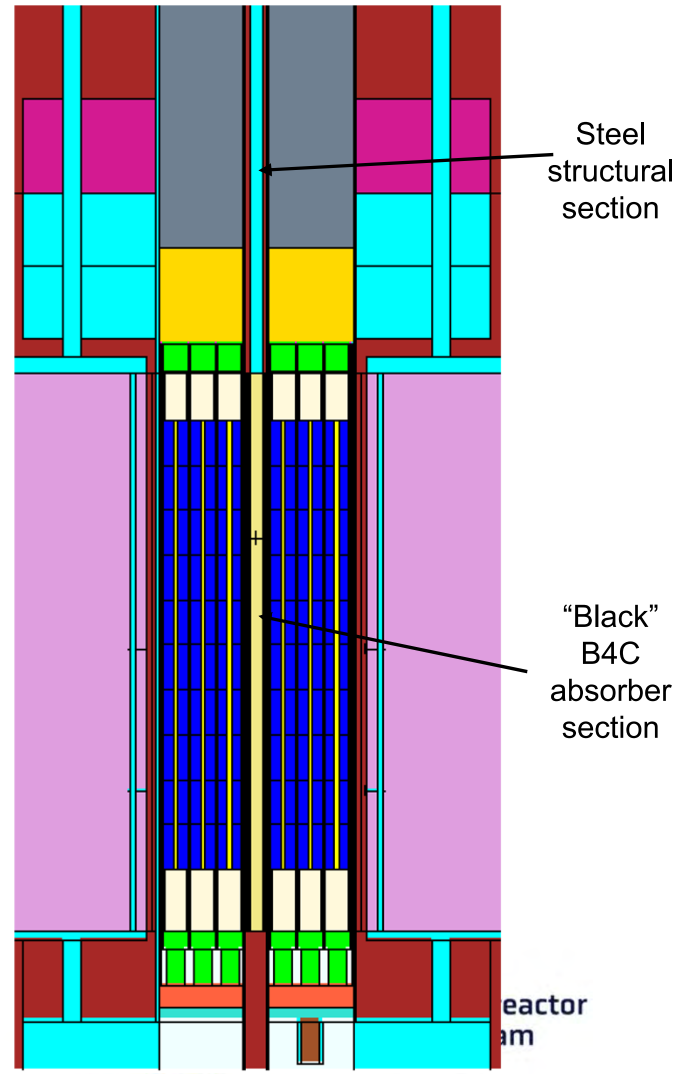
CIA Rod Design Overview

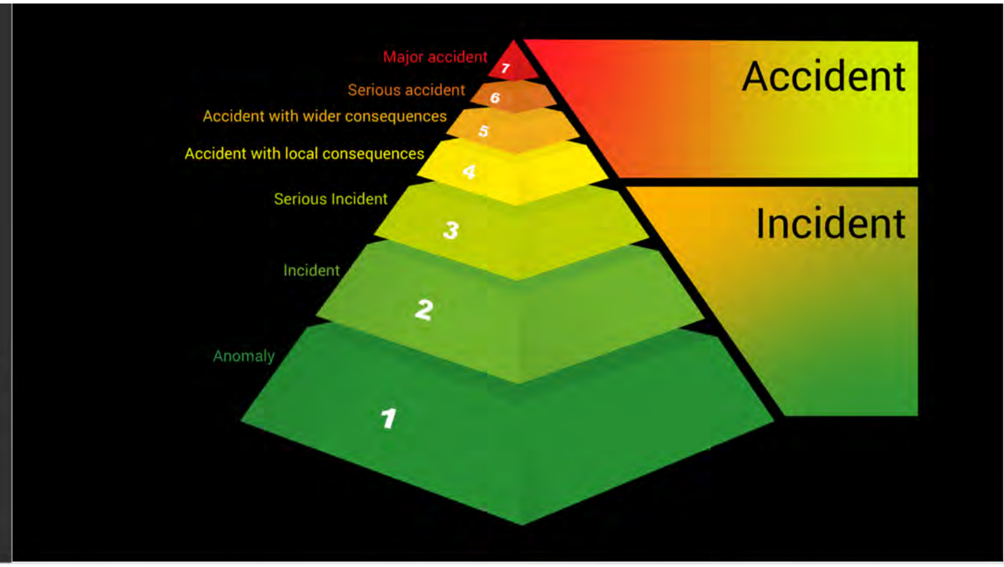
- “Black” absorber for shutdown and reactivity hold down that can be moved. Reactor only operated with CIA rod fully withdrawn from core. Not used for reactor control
- ”Gray” absorber tube provides tunable beginning of life reactivity hold down and is fixed in place after selection for the life of the reactor
- Double walled stainless steel housing

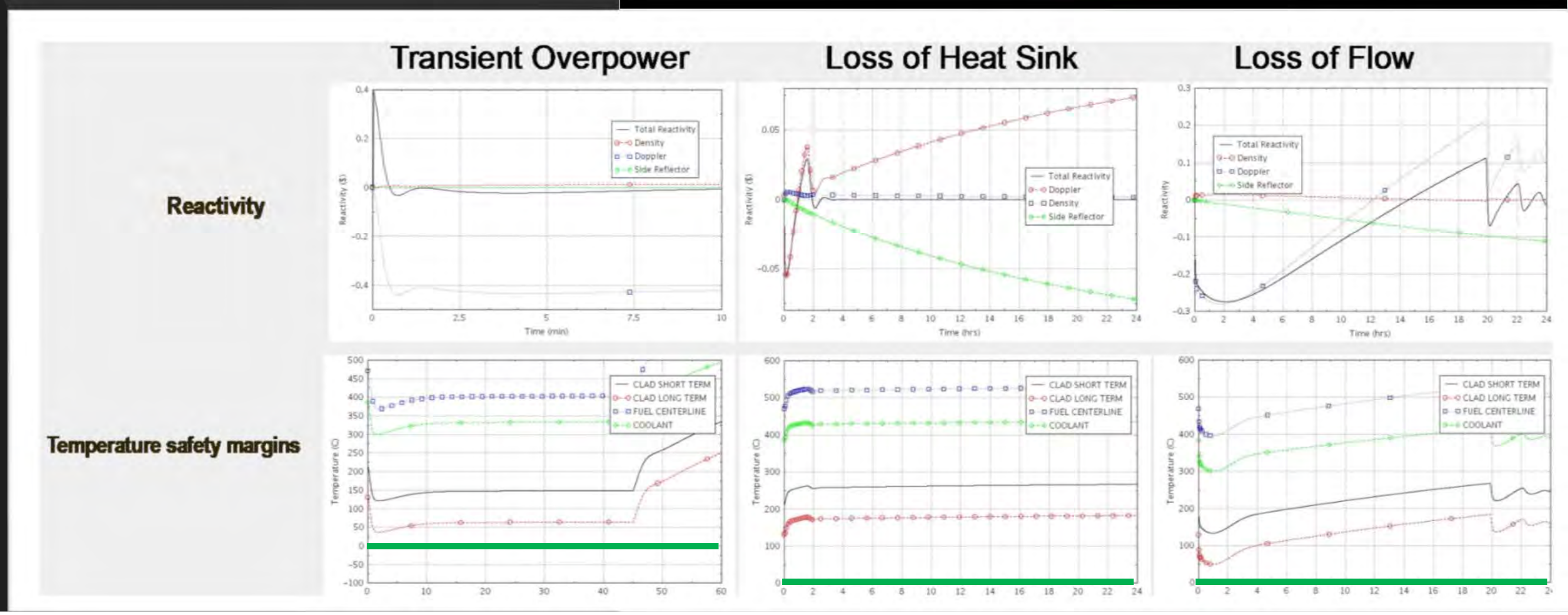




High Safety Pedigree

- **No safety concerns: no breach of FP barriers**
- **Even in the worst case, extremely unlikely cases**
- *ECAR-6332 "RELAP5-3D THERMAL-HYDRAULIC ANALYSIS OF MARVEL MICROREACTOR - FINAL DESIGN"*





Multiple Separate Effects Tests for Rapid Learning

1. Stirling Engine Operation and Control
2. Fuel Pin Fabrication and Assembly
3. Control Drum Actuator functionality- V1
4. Intermediate Heat Exchanger Test using PbBi
5. Reactivity Control Cabinet Prototype-
6. Control Drum Actuator functionality- V2
7. Reactivity Control system Qualification Test Rig
8. Central Insurance Absorber actuator
9. Neutron Detector circuit test at TREAT
10. MARVEL HMI and Simulator
11. Mixed Reality Control Room MVP
12. Alkali Metal Flow Meter Calibration

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MARVEL Control Drum Qualification Test Validated Performance Calculations

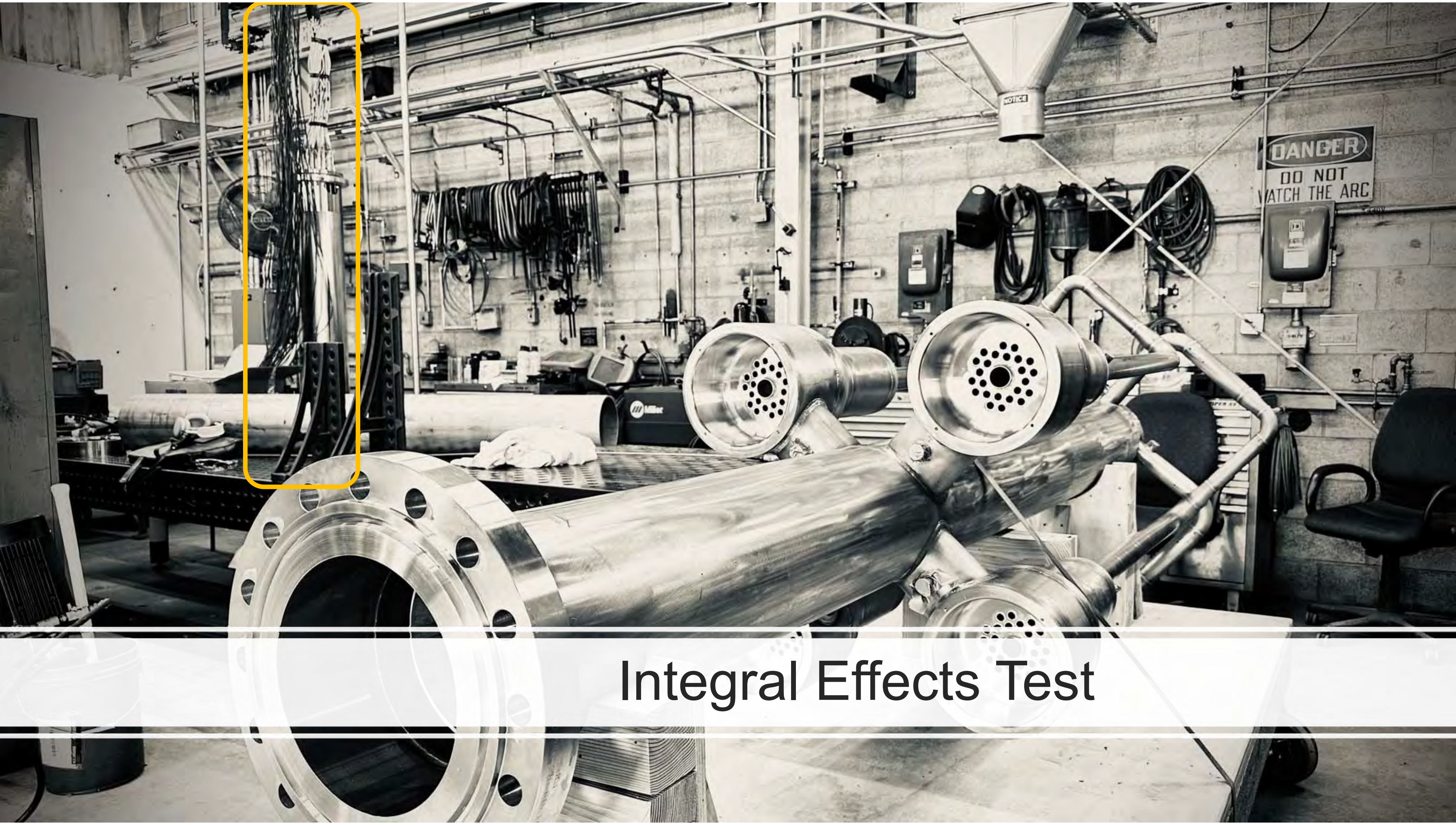
- Researchers refined the MARVEL Control Drum system design and developed and validated methods which will be leveraged in listed system qualification procedures needed prior to MARVEL startup:
  - Phase I: Assembly and Checkout
  - Phase II: Functional Testing
  - Phase III: Acceptance Testing

- The employed Advanced Sensor and Instrumentation (ASI) program's double delta deflection/force/torque application platform applied deflections commensurate of those expected by MARVEL's operating environment to a Control Drum prototype of commensurate geometry, inertias, boundary conditions, and resistances.
- Investigation results revealed that spherical bearings better accommodated the expected deflections.
- Time response data validated component sizing calculations and demonstrated the system's control and passive insertion capabilities as achieved via torsional spring under the following conditions:
  - Clutch disengaged
  - Back drive motor (clutch engaged)
  - Laterally deflect at the top of drum up to ½"

MARVEL Control Drum Prototype in ASI Double Delta Platform

Full-In to Full-Out to Release Steps and Response Profile

MRP Microreactor Program



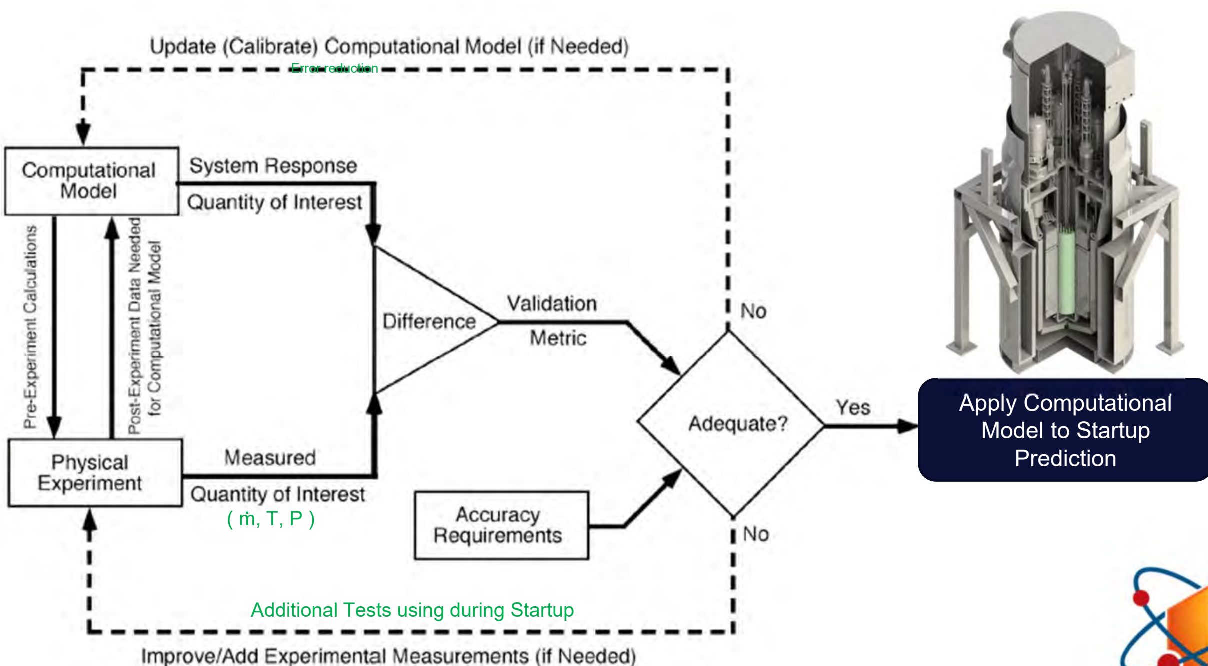
Integral Effects Test

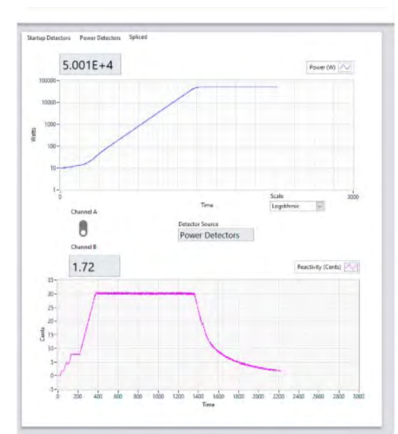
THERMAL HYDRUALIC VALIDATION GOALS

- ***Strategic goal****: Increase confidence in the quantitative predictive capability of the computational model → Initial MARVEL Startup*
- ***Tactical goal****: Characterization and minimization of uncertainties and errors in both, the computational model and the experimental data*

STAR-CCM+ RELAP5-3D

SETs IET





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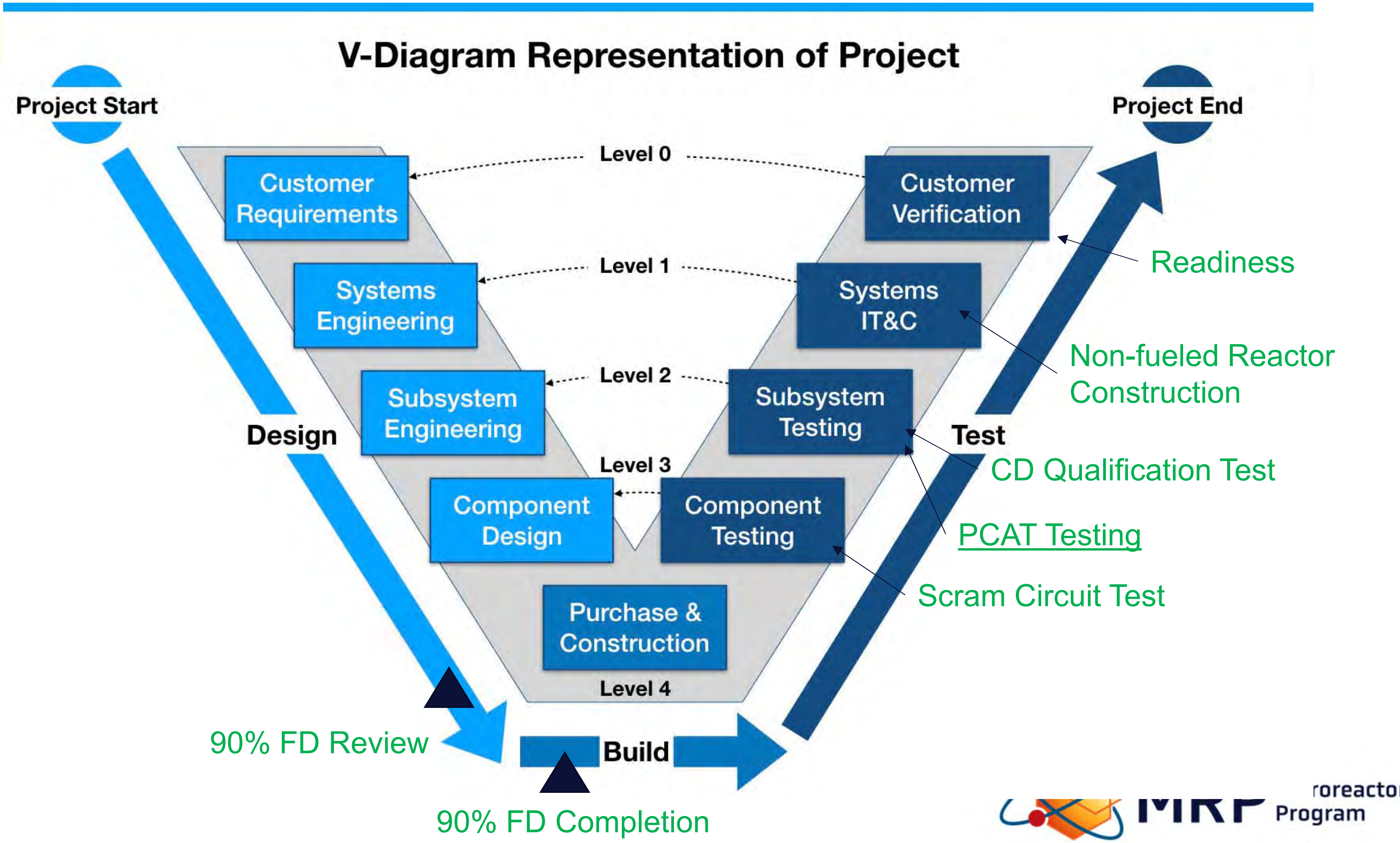

V-Diagram Representation of Project
Project Start
Project End
Level 0
Customer Requirements
Customer Verification
Level 1
Systems Engineering
Systems IT&C
Level 2
Subsystem Engineering
Subsystem Testing
Level 3
Component Design
Component Testing
Purchase & Construction
Level 4
Design
Test
Build
Readiness
Non-fueled Reactor Construction
CD Qualification Test
PCAT Testing
Scram Circuit Test
90% FD Review
90% FD Completion