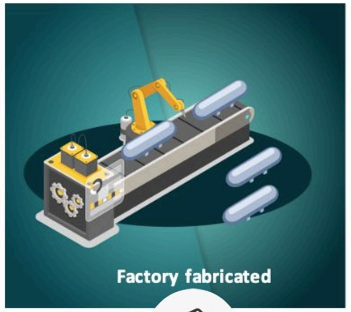
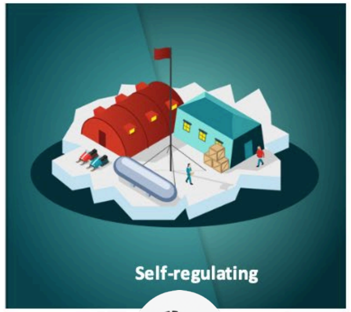
Microreactor Program FY2022

John Jackson, Ph.D.
National Technical Director

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

Microreactors
Megawatt-scale Advanced Nuclear Reactors



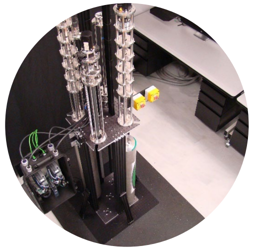


ENABLING TECHNOLOGIES

Fuel & Moderator

- Small Core,
- Long life,
- HALEU
- High-T Moderator

Reactor Controls



- Automation
- Compact, in-core sensors
- AI/ ML
- Remote Control

Power Conversion

- Skid mounted
- High Temp.
- Robust
- Flexible operation

Structural Material

- Creep resistance
- ASME Sec III, Div. 5 compliant
- NQA-1 supply chain

Neutron Reflector

- Low cost
- Manufacturability
- High moderating ratio
- High temperature

Transport & Siting

- NEPA
- Vibration isolation
- Transport shielding
- Licensing modernization

DOE Microreactor Program

Dr. John Jackson (INL), National Technical Director

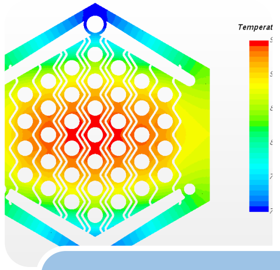
Program Vision

Through cross-cutting research and development and technology demonstration support, by 2025 the Microreactor Program will:

- Achieve technological breakthroughs for key features of microreactors
- Empower initial demonstration of the next advanced reactor in the US
- Enable successful demonstrations of multiple domestic commercial microreactors.

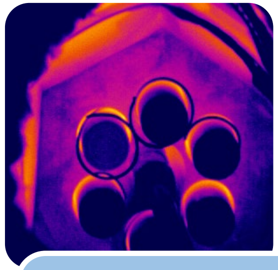
Program Objectives

- Address critical cross cutting R&D needs that require unique laboratory/university capability or expertise
- Develop R&D infrastructure to support design, demonstration, regulatory issue resolution, and M&S code validation
- Develop advanced technologies that enable improvements in microreactor viability



System Integration & Analyses

- Economics & Market Analysis
- Integrated Systems Analysis
- Applications of NEAMS Computational Tools
- Technoeconomic Analyses
- Regulatory Development



Technology Maturation

- Advanced Heat Pipes
- Advanced Moderators
- Heat Exchangers
- Instrumentation & Sensors
- Advanced Materials and Material Code cases

Demonstration Support Capabilities

- Single Primary Heat Extraction & Removal Emulator (SPHERE)
- Microreactor Agile Non-nuclear Experimental Testbed (MAGNET)
- Primary Coolant Apparatus Test (PCAT)
- Validation of NEAMS tools

Microreactor Application

- Applied R&D
- Microreactor Applications Research, Validation and Evaluation (MARVEL)

MRP Microreactor Program

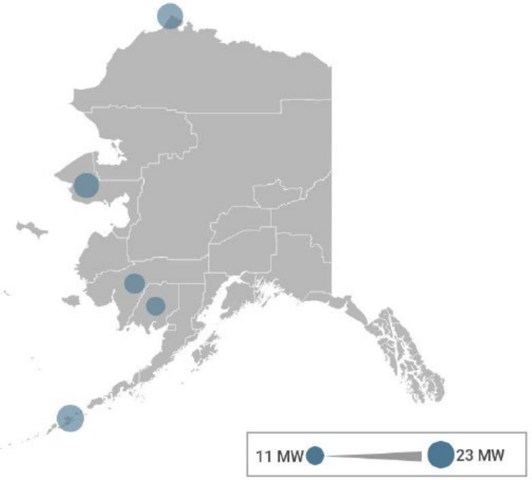
Preliminary FY22 Program Outcomes

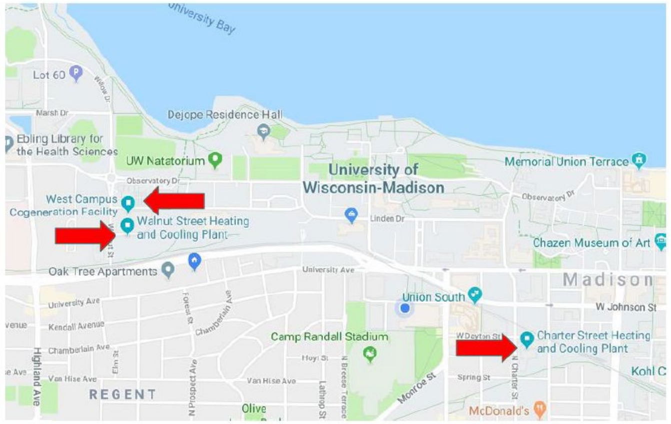
1) Complete MARVEL design and initiate procurement of fuel and major components
2) Perform testing on MARVEL Primary Coolant Apparatus Test
3) Complete MARVEL Preliminary Safety Analysis Report
4) Complete YH PIE and investigate other advanced moderator technologies (e.g. encapsulation)
5) Complete initial integrated YH handbook with both TCR and MRP data (including all PIE).
6) Complete legacy metallic fuel data qualification
7) Complete assembly of the 37 heat pipe microreactor test article.
8) Complete MAGNET procurements and modifications to enable power cycle testing such as 37 heat pipe test article
9) Embed structural health monitoring equipment into a test object during fabrication and evaluate results
10) Support NRIC He-CTF modifications to MAGNET and conceptualize high temp/high pressure (~9 MPa) SPHERE adaptation
11) Guidance for manufacturing license and recommendations to NRC
12) Investigate appropriate automation in MR control systems for inherent safety using MAGNET and with an eye toward MARVEL

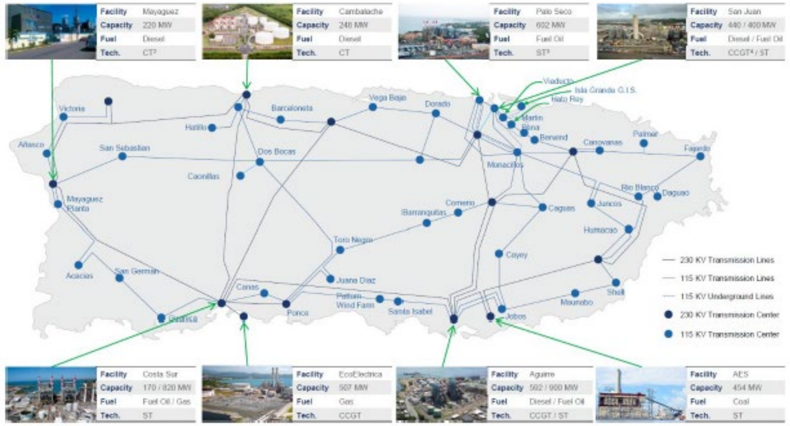
MRP Microreactor Program

Microreactor Economic Analysis - Overview

- Scope overview. This work supports the understanding of the market and economic potential for microreactors in the U.S. and internationally.
- Why? Economic Performance and Market Analysis provides a techno-economic basis for support to industrial microreactor deployment and operation.
- How? Three studies managed by INL were independently conducted
  - U Alaska-Anchorage, U Wisconsin-Madison, and the Nuclear Alternatives Project in Puerto Rico.
  - INL summarized 3 studies and added international perspective in global market report. https://www.osti.gov/biblio/1806274







MRP Microreactor Program

FY22 Activities: Manufacturing Licenses and Transportation

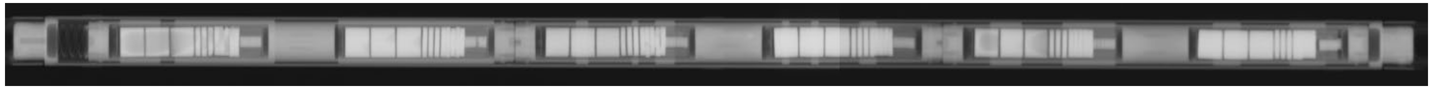
- Some microreactor vendors have stated the desire to construct their entire reactor in a factory setting under a manufacturing license (some including factory fueling)
  - Reduces complexity of on-site assembly and construction
  - These microreactors would then be shipped (fueled or unfueled) to an operating site licensed under 10CFR Part 50/52/53
- Currently, the draft regulation for 10CFR Part 53 Subpart E addresses traditional manufacturing licenses but does not address Part 70 (SNM possession and use), Part 71 (transportation), or Part 72 (spent fuel storage)
- NEI White Paper from July 2021 provided recommendations to NRC staff on how to address these needs
- INL report (February 2022) provided a recommendation from INL/ORNL staff on how to address these needs
  - INL/ORNL staff will draft a report (due September 2022) that discusses and provides recommendations for transportation of a fueled or unfueled microreactor from the factory to the operational site

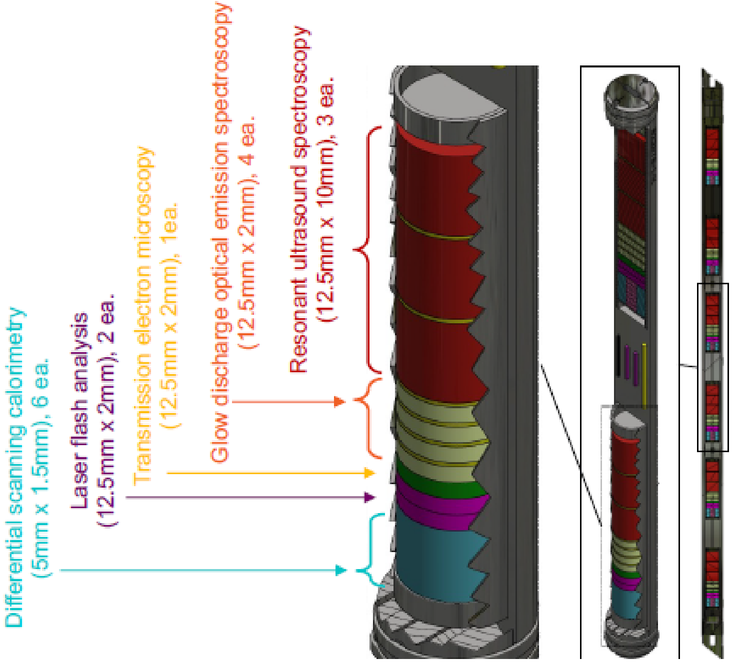
MRP Microreactor Program

DOE-NE Microreactor Technology Maturation

- Main focus of FY22 work is:
  - High Temperature Moderator Material (yttrium hydride)
    - Post irradiation examination (PIE) of samples irradiated in the Advanced Test Reactor (ATR) – see picture to right for PIE starting soon.
    - Hydrogen diffusion analyses using neutron imaging
  - Fabrication of a Heat Pipe Test Article for non nuclear testing at MAGNET
- Instrumentation and Sensors for testing at MAGNET

Neutron radiography of irradiated YH





- Most important:
  - Hydrogen stability with temperature and fluence.
  - General integrity of samples.
- Determine thermophysical/ mechanical properties
  - Swelling
  - Elastic properties
  - Heat capacity
  - Thermal diffusivity
  - Microstructure
  - Thermal expansion
  - Hardness

High Temperature Moderator Material

- FY20: Fabricated samples of yttrium hydride.
- FY21: Samples were irradiated in ATR.
- FY22: Initiated PIE on irradiated samples.
- FY22: Performed neutron imaging to understand hydrogen migration with temperature
- FY21:   Initiated cladding and containment analysis for hydrides.
- FY21: Performed critical experiment on YH.

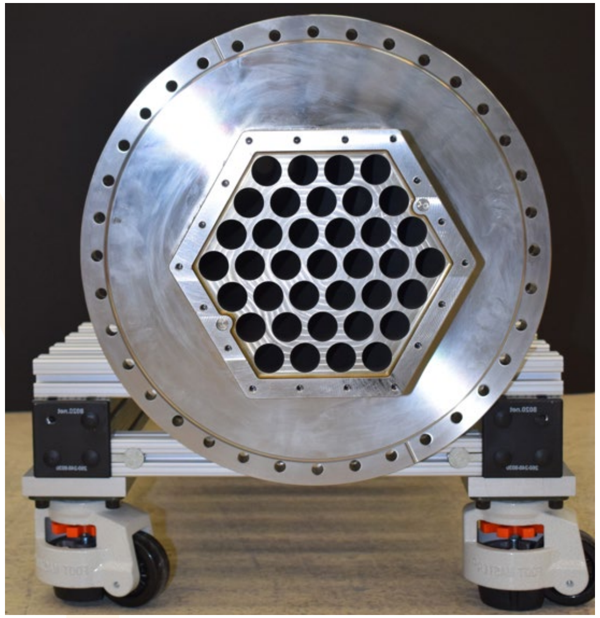
MRP Microreactor Program

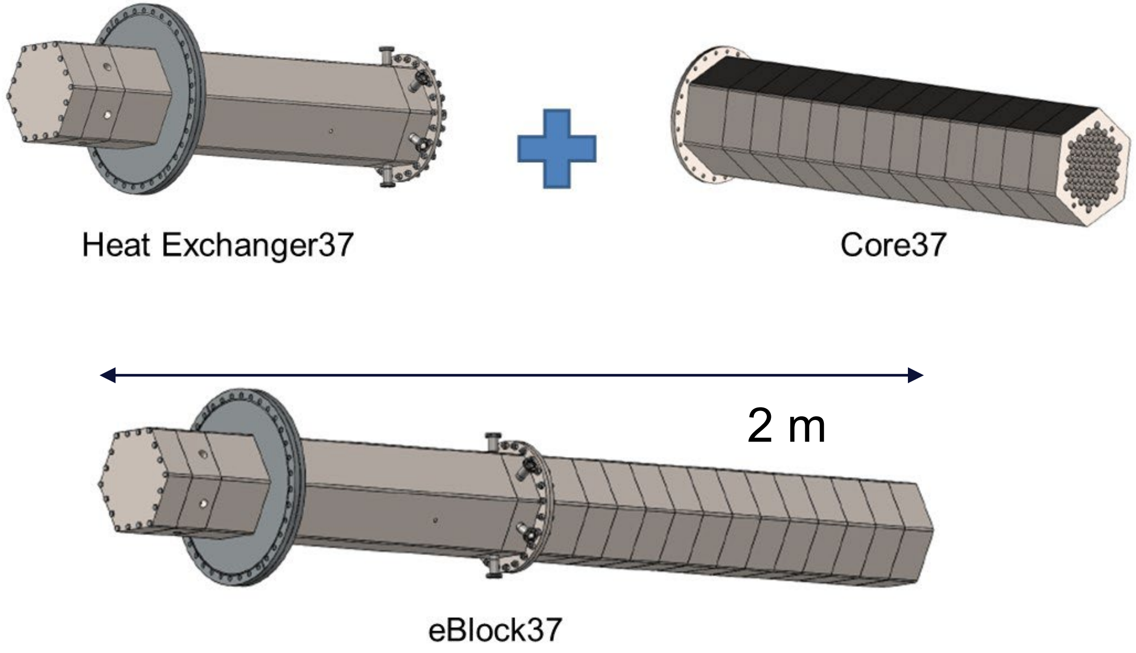
Instrumentation and sensors scope

- Instrumentation and Sensors activities funded at levels that allow simple demonstrations that leverage other MRP-funded or NE-funded activities to maximize productivity
  - MRP Capability Development: SPHERE, MAGNET testbeds
  - Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation (NEET ASI) Program: Various sensor development activities
  - Transformational Challenge Reactor (TCR) Program: AM-embedded sensors
- Programmatic focus
  - Health monitoring of microreactor components using embedded sensors, distributed sensors and other advanced sensing technologies during electrically-heated testing in SPHERE and MAGNET
  - Enhanced diagnostics to detect and mitigate issues and prevent unplanned shutdowns for maintenance
  - Advanced control strategies to support semi-autonomous operation

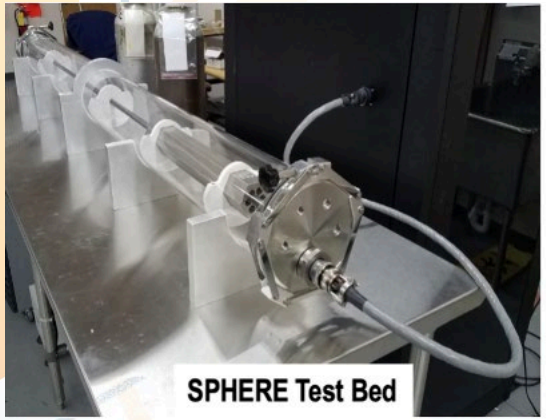
37 Heat Pipe Test Article

- 91 holes: 37 of these holes house sodium heat pipes linked to a heat exchanger; 54 holes are intended for electrical cartridge heater installation. Three-inch sections are still in the process of being joined (see picture to right where they are assembled on a cart).
- Heat exchanger consists of a main body containing holes through which the heat pipe array passes (see picture to left).
- High fidelity wicks in heat pipe array will be filled with sodium in the latter part of 2022.

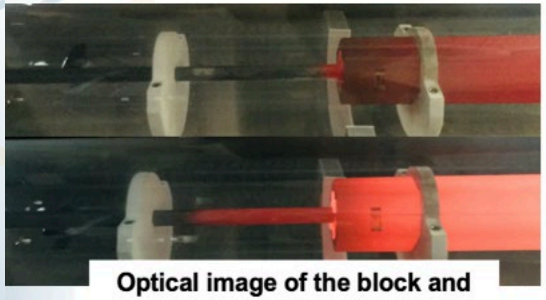




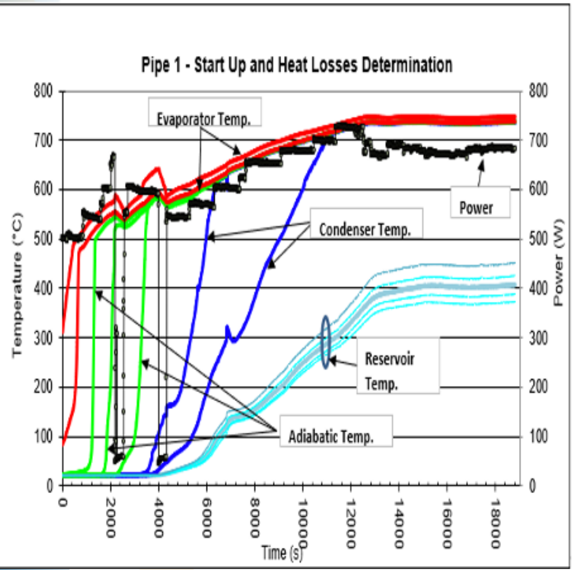
Single Primary Heat Extraction and Removal Emulator (SPHERE)



SPHERE Test Bed



Optical image of the block and heat pipe operation



Objectives

- Provide **capabilities** to perform steady state and transient testing of heat pipes and heat transfer:
  - Wide range of heating values and operating temperatures
  - Observe **heat pipe startup and transient operation**
- **Measure** heat pipe axial temperature profiles during **startup, steady-state, and transient operation** using thermal imaging and surface measurements

Parameter	Value
Length	243 cm
Diameter	15 cm
Tube material	Quartz
Connections	Flanged for gas flow and instrumentation feed through
Maximum power	20 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter

Key Accomplishments

- SPHERE Initial Startup and Operation
- Complete Engineering Design of Gap Conductance Test Article

In Progress

- Gap Conductance Testing for NRC
- Working for Industrial Partner on understanding the effect of orientation on heat pipe performance

Challenges

- Testbed chamber is inadequate for accessibility and assembly
- TC routing too tight
- Secondary test article creates additional complexity
- Contact resistances are significant source of model error

External Vendor Testing

- Evaluation of heat pipe performance for external microreactor vendor
- Heat pipe limit testing
- Compare vertical and horizontal performance

MRP Microreactor Program

Microreactor AGile Non-Nuclear Experimental Test Bed (MAGNET)

- Completed construction in November 2020
- Pressurized, started, and slightly heated system in January of 2021 for ASME B31.3 pressure testing
- A change in Engineer of Record for design and construction resulted in removal of insulation from all joints for a new B31.3 pressure test
- Final pressure testing of reworked section of piping

Parameter	Value
Chamber Size	5 ft x 5 ft x 10 ft
Heat Removal	Liquid-cooled chamber walls, gas flow
Connections	Flanged for gas flow and instrumentation feed through and viewing windows
Coolants	Air, inert gas (He, N2)
Gas flow rates	Up to 43.7 ACFM at 290 psig
Design pressure	22 barg
Maximum power	250 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter

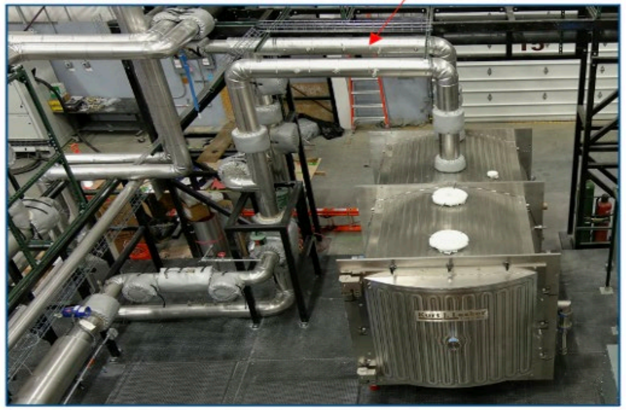
Objective

- General-purpose, non-nuclear microreactor test bed
- Thermal-hydraulic and materials performance data for design performance verification and analytical model validation (V&V)
- Expandable design with capability to demonstrate an integrated power conversion unit (PCU)
- Advanced sensors identification, development, and testing for potential autonomous operation

Lessons Learned

- System design in parallel with equipment procurement presents challenges
  - General arrangement drawings sometimes differ from final fabrication drawings
- Include instrumentation and control (I&C) in scope of construction
  - Allows installation contractor to perform complete system commissioning and turn over a fully operational system to INL
- Installation discrepancies with construction drawings resulted in significant re-work not communicated to project
- Near miss while starting up co-located system (thermal energy distribution system (TEDS)) resulted in changes to operations in facility

Thermal expansion loop added to this section



MARVEL Can Enable a New Class of Nuclear Reactors

(Microreactor Applications Research, Validation & EvaLuation)

Project Goals:

- Rapid development of a small-scale microreactor that provides a platform to test unique operational aspects and applications of microreactors

Primary Objectives:

- Operational microreactor in the most **accelerated timeline** possible
- Produce **combined heat and power (CHP)** to a functional **microgrid**
- **Share lessons learned** with commercial developers

U.S. DOE Sponsor Program:

MRP Microreactor Program

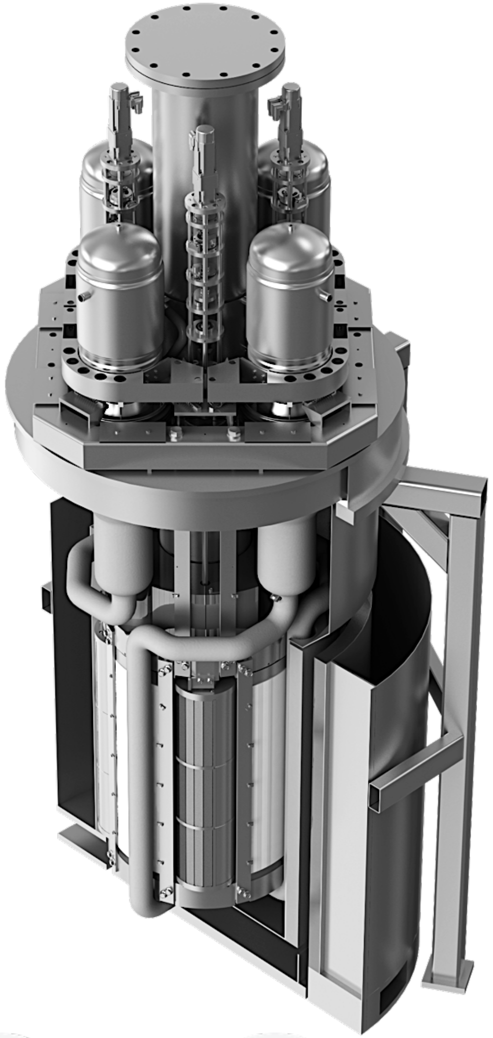
Create momentum,
Champion rapid technology maturation to de-risk industry
Collaborate and engage microreactor end-user companies

MRP Microreactor Program

MARVEL - Test Microreactor

Microreactor Application Research, Validation and EvaLuation Project

Key Design Features	
Thermal Power	100 kW
Electrical Power	20 kWe (QB80 Stirling Engines)
Weight	< ~10 US ton
Primary Coolant	Sodium-Potassium eutectic
Intermediate Coolant	Lead-Bismuth eutectic
Coolant Driver	Natural Convection, single phase
Fuel	HALE(UZrH), 304SS clad, end caps
Moderator	Hydrogen
Neutron Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary	SS316H



Factory Fabricated

transportable

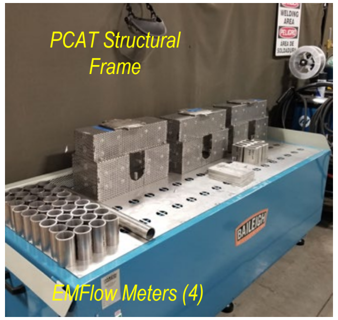
Self-regulating

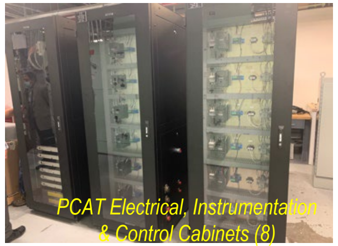
MRP Microreactor Program

MARVEL Full-Scale, Electrically Heated Prototype for Integral Effects Testing

- Successfully completed design, fabrication and assembly of a full-scale, electrically heated prototype of the MARVEL reactor <u>within nine months</u>.
- **Test goals:**
  - Validate flow and heat transfer characteristics of MARVEL technology
  - Benchmark modeling and simulation parameters
  - Train operators.
  - De-risk supply chain
- **The test hardware includes:**
  - Primary and secondary Loop test article, designed and built to ASME Boiler and Pressure Vessel Code
  - Four Stirling Engines, engine control, and heat rejection units
  - Electrical, instrumentation and control cabinets (8 total)
  - Electromagnetic flow meters
  - Structural test frame

MARVEL Project de-risked Reactor Construction





MRP Microreactor Program

Small Reactor...Big Opportunities

Idaho National Laboratory
NS&T| MFC

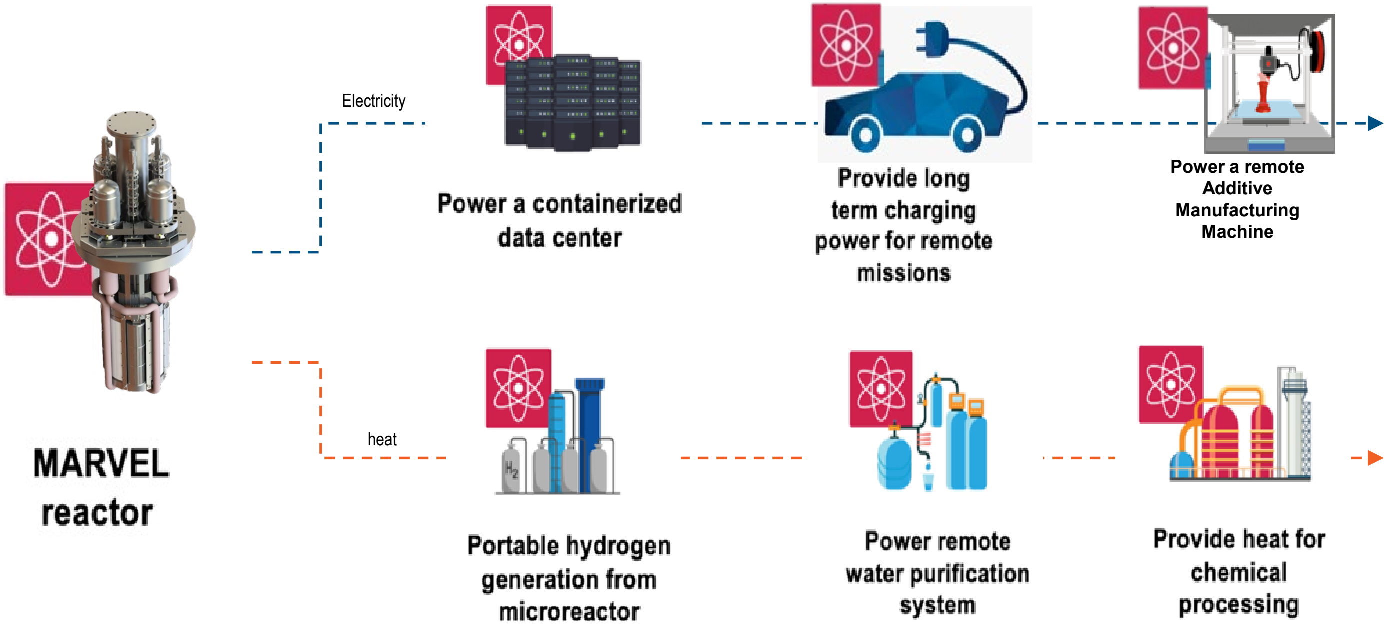
WALSH Engineering Services
Los Alamos National Laboratory EST. 1943
Argonne National Laboratory
Qnergy Reliable Remote Power
Creative Engineers, Inc. United States | Canada | International
NC STATE UNIVERSITY
Idaho State University
U.S. Department of Energy Idaho Operations Office

Integrated with Private Industry

OKLO, Westinghouse, BWXT, X-energy, RADIANT, GENERAL ATOMICS, LOCKHEED MARTIN

NQA-1 & Commercial Supply Chain

Premier Technologies, Petersen Inc., American Fabrication, Materion, TRIGA International



External Program Collaborators

INL Net-Zero; DOE System Integration & Analysis; DOE Research Reactor Infrastructure Program

End-user companies engaged:

- ✓Dell
- ✓Tesla
- ✓Electrify America
- ✓Chargepoint
- ✓ExxonMobil
- ✓Oxeon
- ✓Bloom
- ✓Fuelcell Energy
- ✓Envoy Public Labs
- ✓Eastman/Kodak
- ✓GSE
- ✓Shell
- ✓Chevron
- ✓AVEC
- ✓Idaho Power
- ✓Southern Company
- ✓Holtec
- ✓Battery 500
- ✓Proton Conduction H2
- ✓LIFEPo4

MRP Microreactor Program

MARVEL Value Statement for Public/End Users

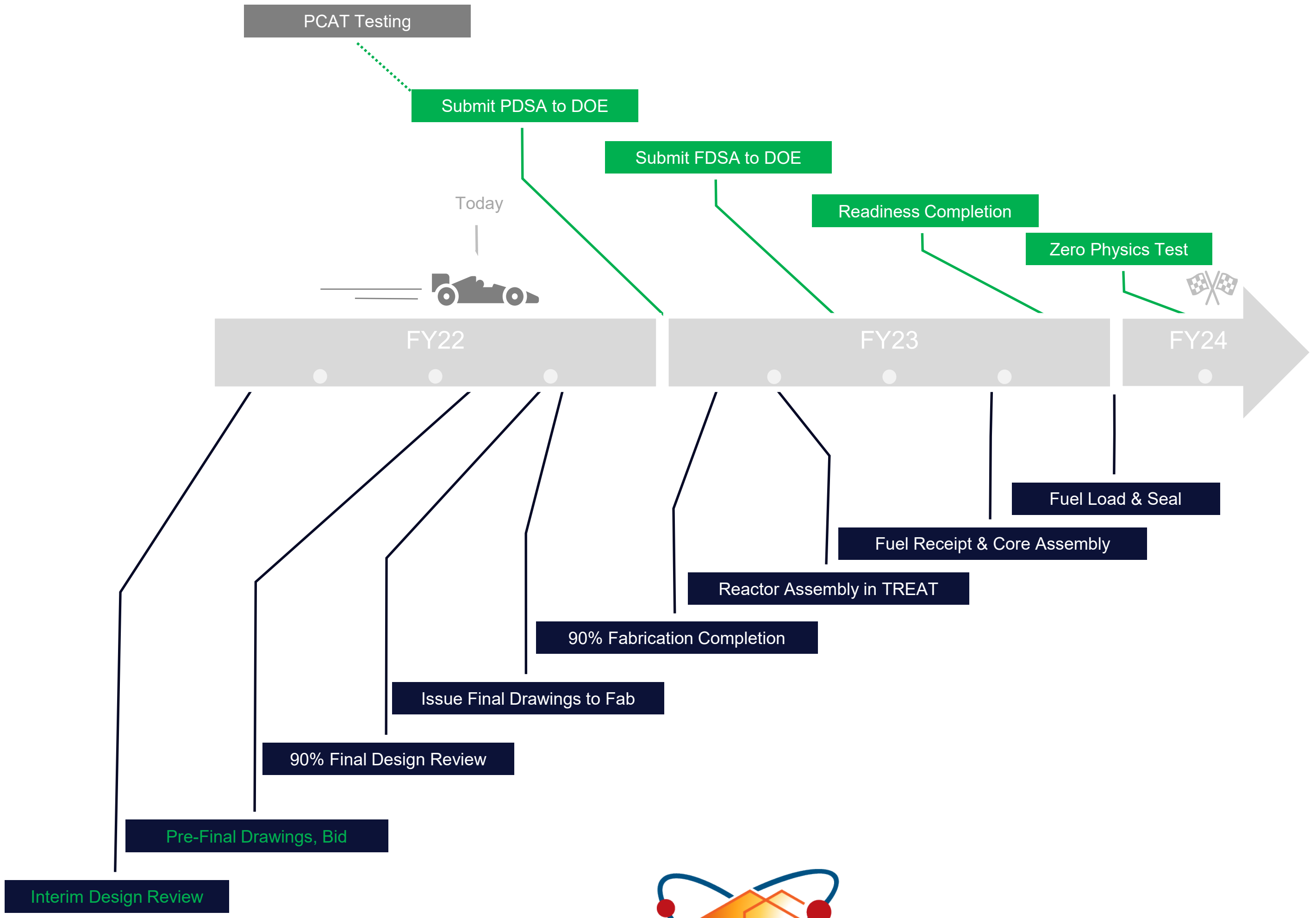
- Nuclear Energy is <u>new</u> to microreactor entry market
  - Operation complexity
  - Fear of colocation
  - Training needs
  - Reliability
- Customers reluctant to adopt microreactor technology unless they “see one” first (not willing to be the first in their backyard)
- <u>Having no real test reactor is a barrier to market entry</u>
  - End users deem it necessary to “interact” with a microreactor prior to providing customer requirements
  - End users unsure of technology potential prior to interaction

MARVEL will be the first microreactor to achieve criticality to power end user applications

MRP Microreactor Program

Key Accomplishments up to FY22 & Upcoming Milestones

- **Completed 9+ separate effects tests** to increase technology readiness levels
- **Completed accident analyses** on expected performance on normal operation and postulated accident analyses
- **Safety Design Strategy** approved by DOE-ID
- **Final EA and FONSI** approved by DOE-ID
- **Completed design, fabrication and assembly of full-scale electrically heated test system** (aka PCAT).
- **Fuel** Supplier finalized
- **Completed Interim Design Reviews**
- **Entered Final Design Stage-** Completed Interim Design Reports and interim design review (I&C and Structural Design pending)
- **Released Pre-Final Drawings** to request for proposals on procurement packages



MRP Microreactor Program

MARVEL is highlighted among the Department of Energy's "Top Accomplishments" in the department's "Biden-Harris Year One Summary," for leading the world in science & technology

Summary on Key Opportunities

- **First Nuclear Microgrid**: collaborating with INL Net Zero
- **First Contemporary Microreactor**: collaborating with developers on lessons learned
- **First Advanced Reactor**: establishing regional (i) nuclear supply chain (ii) resource pipeline