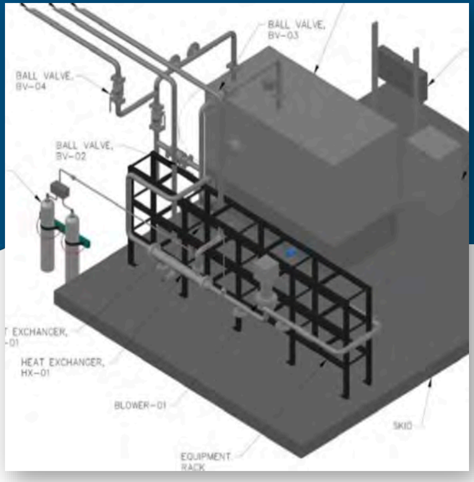
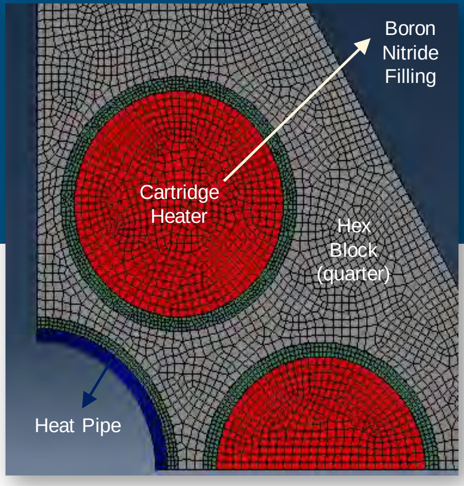
Microreactor Program

DOE-NE Microreactor Program Winter Review Meeting

Demonstration & Support Capabilities





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March 5th 2024

INL Idaho National Laboratory | Los Alamos NATIONAL LABORATORY | OAK RIDGE National Laboratory

MRP Microreactor Program

Focus Areas – *Enabling non-nuclear demonstration to support microreactor development and deployment.*

Single Primary Heat Extraction and Removal Emulator

- Update and current status

Microreactor Agile Non-nuclear Experiment Testbed (MAGNET)

- Update and current status

HElium Component Testing Out-of-pile Research (HECTOR) Facility

- Update and current status

Idaho National Laboratory

Piyush Sabharwall, TJ Morton, Jeremy Hartvigsen, Zachary Sellers, Troy Unruh, Sunming Qin, Mauricio Retamales, Silvino Balderrama Prieto, Ilyas Yilgor, Brad Couch, and Edward Beverly

Los Alamos National Laboratory

Bob Reid, Katrina Sweetland and Holly Trellue

Oak Ridge National Laboratory

Christian Petrie and Holden Hyer

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Demonstration Support Capabilities – *Subdivided into four main areas to support testing needs to deploy microreactors*

- **SINGLE PRIMARY HEAT EXTRACTION AND REMOVAL EMULATOR (SPHERE) –** Development of a platform to support non-nuclear thermal and integrated systems testing capabilities. This capability shall provide a better understanding of **thermal performance of the heat pipe under a wide range of heating values and operating temperatures**, enhancing the understanding of heat pipe during startup, shutdown and transient operation.

- **MICROREACTOR AGILE NON-NUCLEAR EXPERIMENTAL TESTBED (MAGNET) –** Development of a thermal-hydraulic and integrated systems testing capability, called MAGNET, to simulate core thermal behavior, heat pipe and primary heat exchanger performance, and passive decay heat removal **will support verification and validation of detailed microreactor thermal hydraulic models**. **This is applicable under startup, shutdown, steady-state, and off-normal transient behavior in steady-state operation, transient operation, and load-following conditions**. This testing will be done before nuclear system demonstration. The test bed will ultimately be integrated into the INL Systems Integration Laboratory, which includes thermal and electrical energy users such as steam electrolysis, real-time digital simulators for power systems emulation, a microgrid test bed, and renewable energy generation.

- **EVOLVING DEMONSTRATION SUPPORT –** Demonstration and testing infrastructure needs are expected to evolve as technology readiness of microreactors advance. **Development of capability necessary to support this evolution is covered under this subarea**. MAGNET was modified to support component testing for gas cooled systems.
  - High Pressure and High Temperature Helium Facility (HECTOR; 8MPa and 800 C)

- **VERIFICATION AND VALIDATION SUPPORT –** This subarea focuses on targeted testing supporting verification and validation to meet industrial and licensing organization (such as NRC) needs to **enhance understanding of a phenomenon of interest and reduce uncertainty**.

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Single Primary Heat Extraction and Removal Emulator

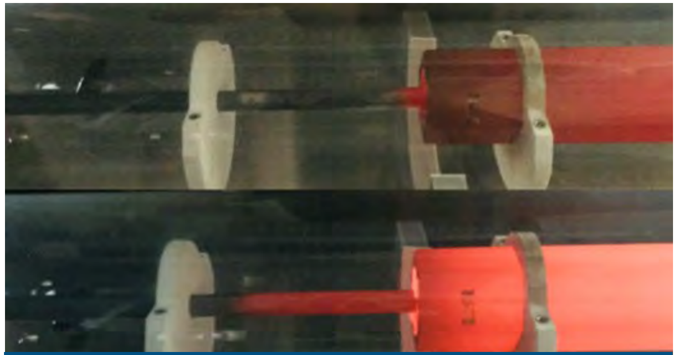
Provide capabilities to perform steady-state and transient testing of heat pipes and heat transfer:

- Wide range of heating values and operating temperatures
- Observe **heat pipe startup and transient operation**

Develop effective thermal coupling methods between the heat pipe outer surface and core structures

Measure heat pipe axial temperature profiles during **startup, steady-state, and transient operation** using thermal imaging and surface measurements

SPHERE
Test BED



Optical image of the block and heat pipe operations

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

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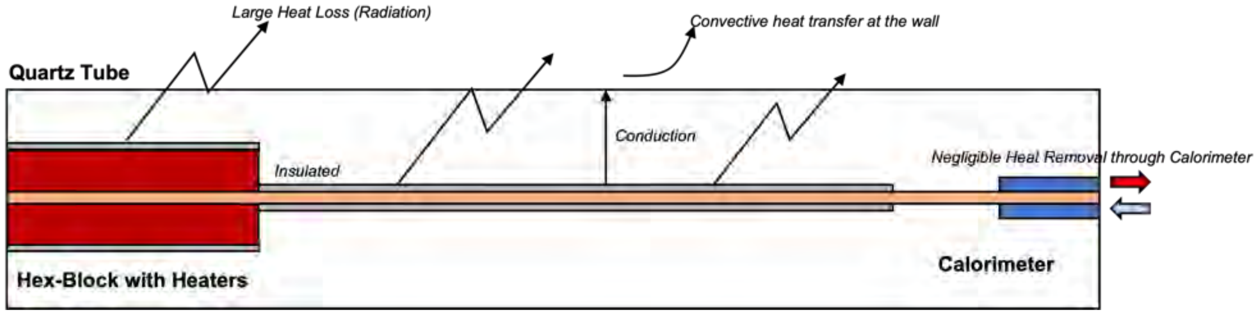
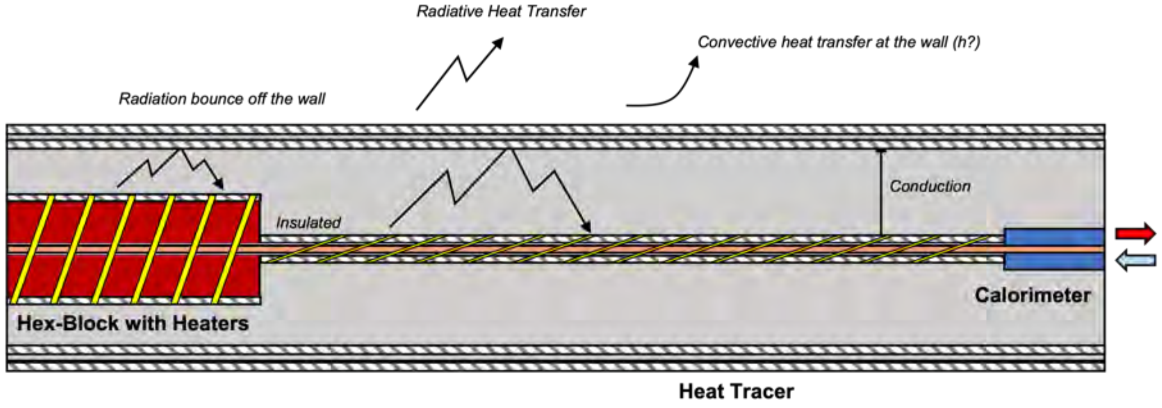
Experimental Setup Changes

- Quartz tube to stainless steel tubing
- Wrapped the hex block and adiabatic section of the heat pipe in heat trace to limit heat loss in those regions
- Wrapped inside of the stainless tubing with a layer of insulation to further reduce heat loss





Parameter	Value
Length	10 ft
Diameter	12 in
Tube material	Stainless steel
Connections	Flanged for gas flow and instrumentation feedthrough
Maximum power	20 kW
Max temperature	900 C
Heat removal	Passive radiation or water-cooled gas gap calorimeter

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SPHERE – PROGRESS *(from initial startup)*

- Demonstrate initial startup (shake-down testing) and operation of a single heat pipe experiment in the SPHERE test bed
- Develop coupled thermal and structural analysis for high temperature heat pipe experiments
- Complete engineering design of test article, develop test plan and instrumentation needs for gap conductance testing
- Complete fabrication and procurement of test article, perform test for gap conductance testing and report on findings (worked closely with NRC)
- Create, maintain and add experimental data to shareable database on transient heat pipe performance in coordination with NEUP heat-pipe projects
- Work with industry under WFO Program – Heat Pipe Performance
- Advanced internal characterization of in operando heat pipes
  - In operando heat pipe testing to begin shortly
- Procure, operate and test advanced heat pipes for SPHERE test bed

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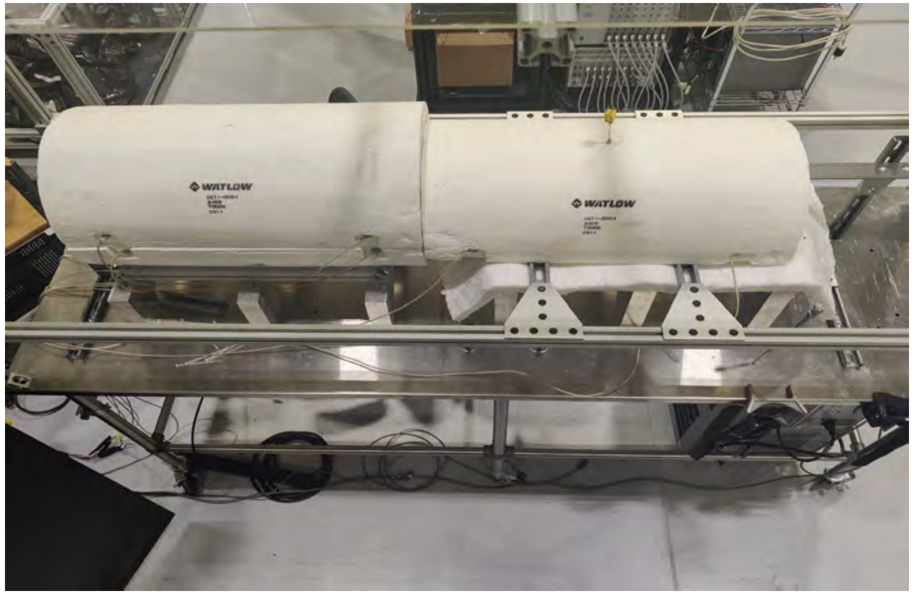
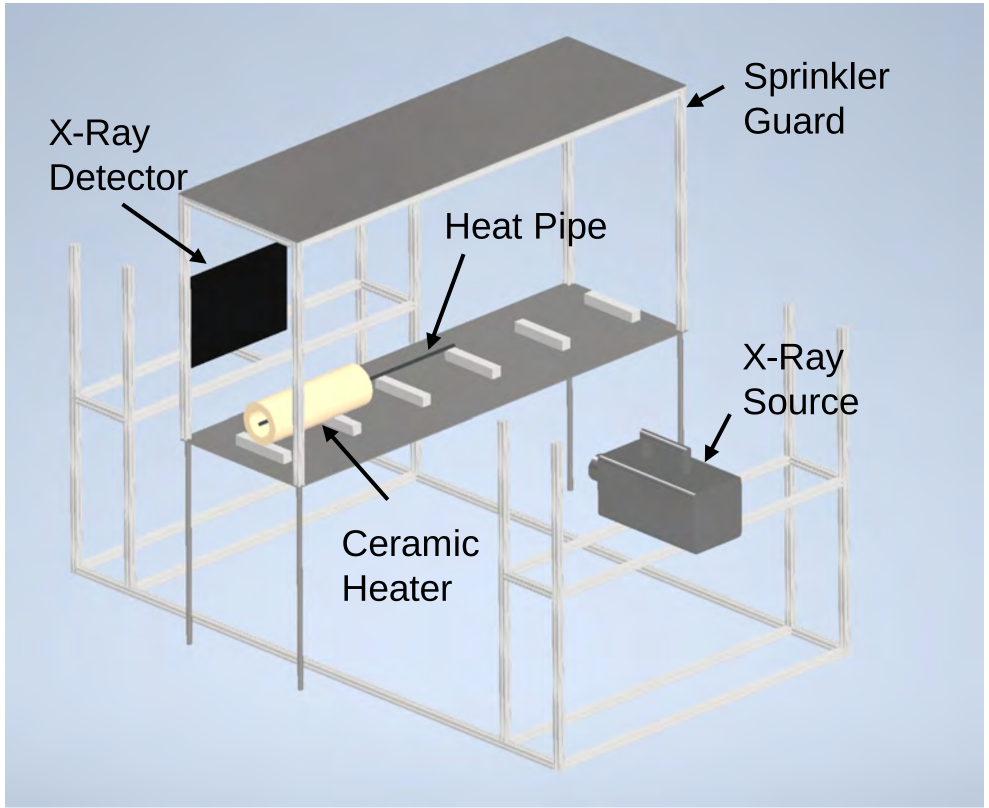
In-Operando X-ray Test Stand

- Open-air setup for x-ray flow visualization
  - Flow visuals could be highly beneficial in understanding heat pipe operation
    - There is no conventional way for obtaining flow visuals of liquid metal heat pipes
    - Will be especially useful for frozen startup and limit conditions





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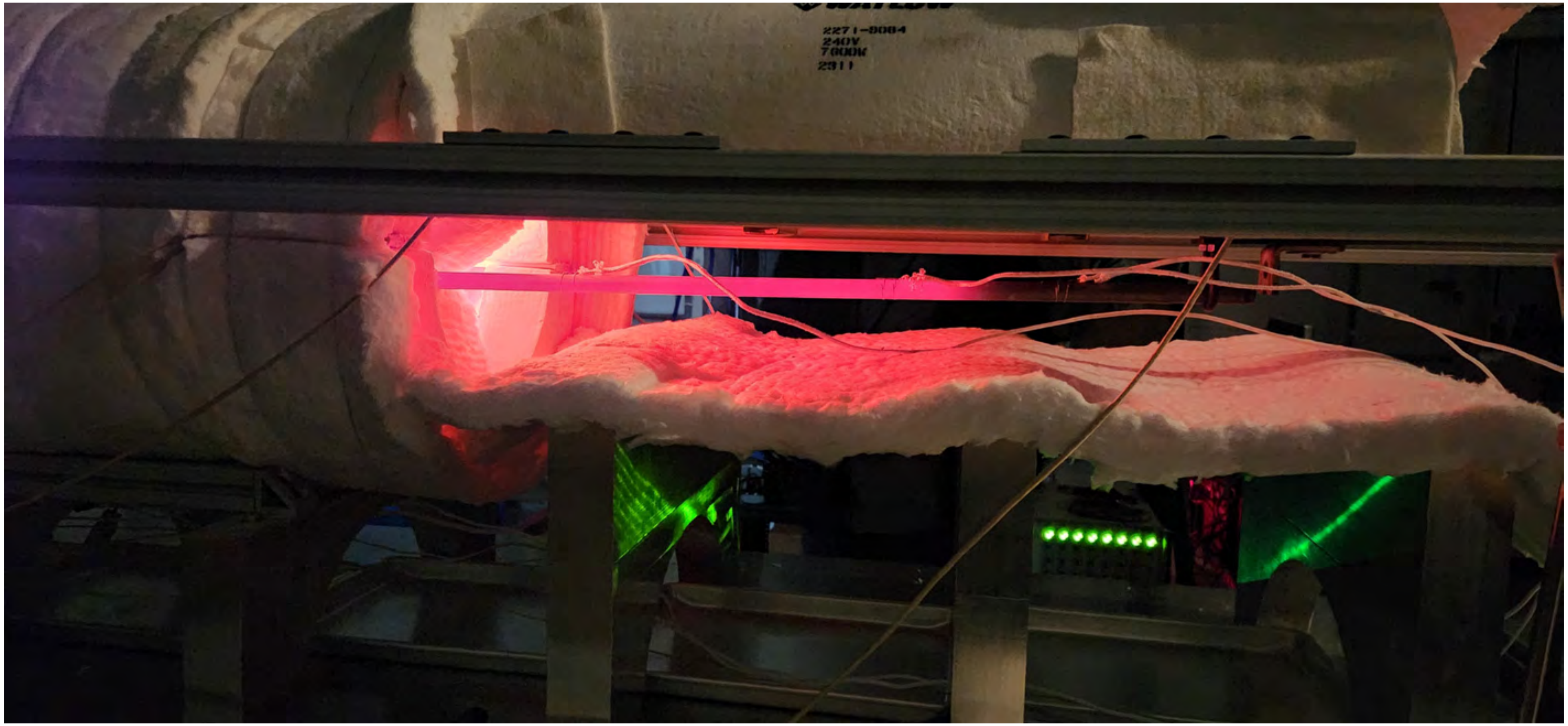
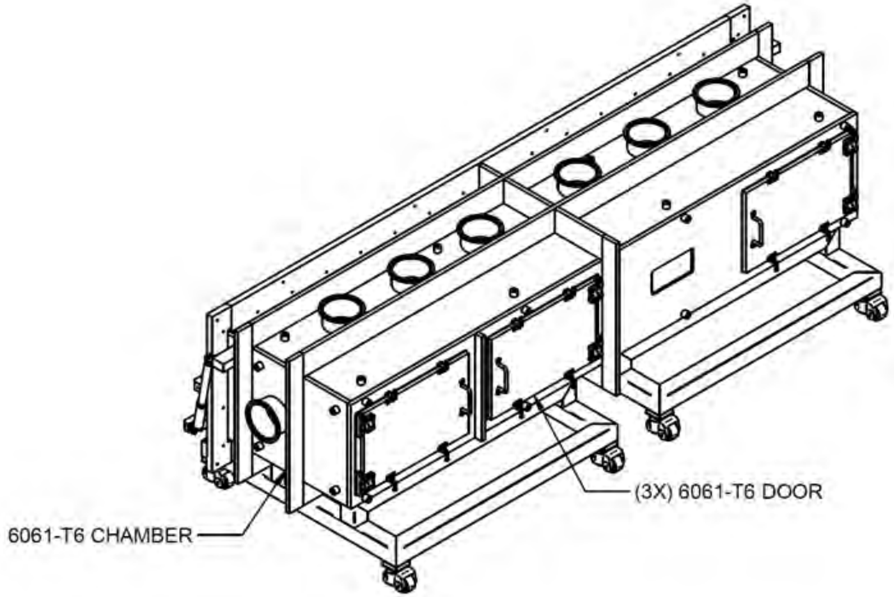
In-Operando X-ray Test Stand

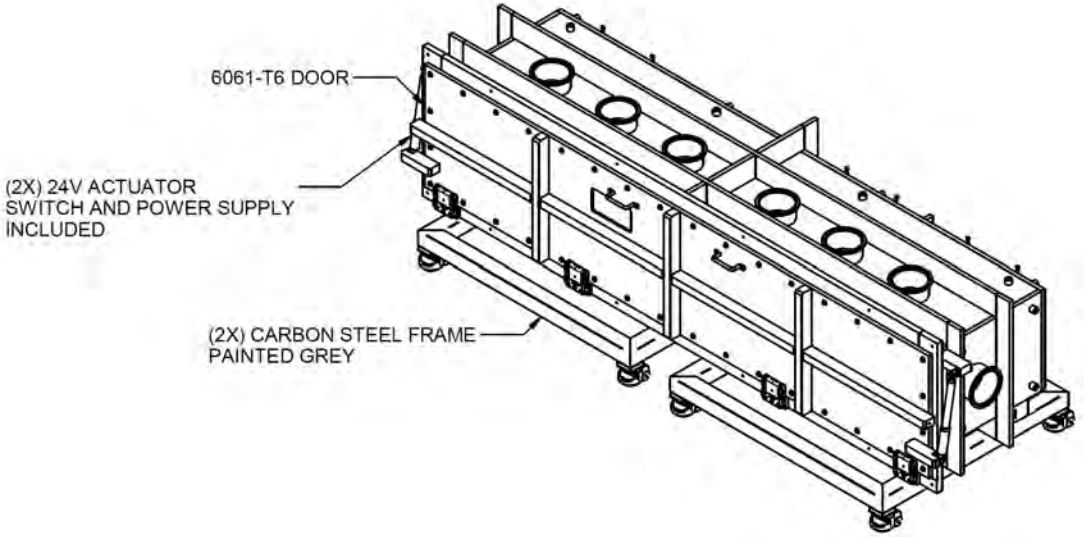
- Open-air heat pipe operation



Environmental Chamber

- New environmental chamber from Kurt J. Lesker
  - Allows x-ray visualization under vacuum through aluminum 6061 walls
    - Enhances repeatability
    - Enables more robust calculations of condenser output power
  - Extensive space for fluid, power, and instrumentation lines
  - Can accommodate test articles other than heat pipes





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Summary of Expanded Capabilities

- Testbed Upgrades
  - SS casing with insulation linings significantly reduces radiation heat loss compared to the original design
  - Heat trace wrapped around the insulation in the evaporator and adiabatic section compensates for heat losses
  - The open-air x-ray test stand will be used to demonstrate the x-ray flow visualization technology
  - The new environmental chamber allows for x-ray flow visualization under vacuum and inert gas atmosphere conditions

- Instrumentation Upgrades
  - Fiber optic sensors, ultrasonic sensors, and multi-point thermocouples provide high spatial resolution temperature measurements

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Impact of Expanded Capabilities

- Greater accuracy and repeatability of experiments via improved design which minimizes losses
  - Repeatability of experiments is crucial especially for V&V, the evaluation of manufacturing methods, and the investigation long-term performance degradation
- Extremely high-resolution temperature measurements
  - Provides a more comprehensive dataset for V&V efforts
- Flow visuals provide imperative data on heat pipe operation
- Expanded testing capabilities allows for high resolution in measurement for heat pipe testing

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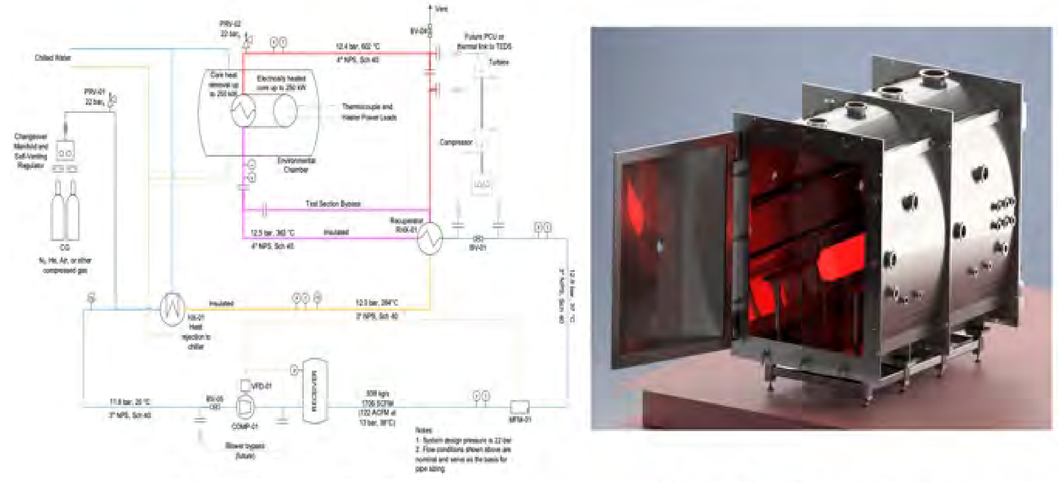
Microreactor AGile Non-nuclear Experimental Testbed *(MAGNET)*

- General purpose test bed for performance evaluation of microreactor design concepts (heat pipe, gas-cooled, other)
- Provide detailed reactor core and heat removal section thermal hydraulic performance data for prototypical geometries and operating conditions
- Demonstrate interface of heat removal section to power conversion system for power generation
- Provides for integrated materials, instrumentation testing
- Co-located with integrated energy systems R&D capabilities

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 feedthrough 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



a) MAGNET Process Flow Diagram

b) MAGNET Environmental Enclosure

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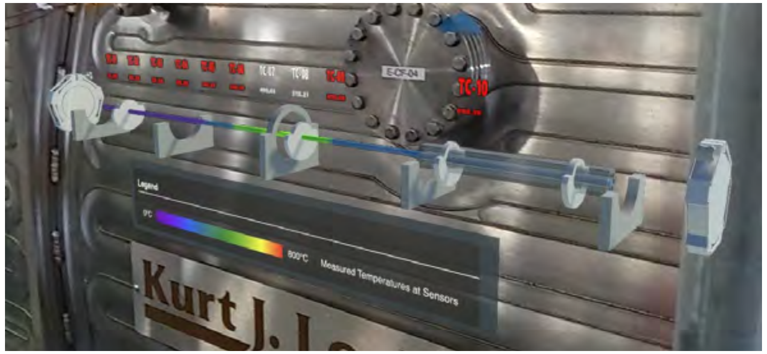
Single Heat Pipe Test Digital Twin Collaboration

MAGNET Control Station



Virtual Image of Test Article via Microsoft HoloLens for Digital Twin Effort

- Single heat pipe testing in MAGNET to demonstrate MAGNET's operation (heater control, instrumentation, and gas cooling flow rate control were all validated)

- Collaborated with researchers from across INL to demonstrate a small-scale digital twin using machine learning to maintain steady state.

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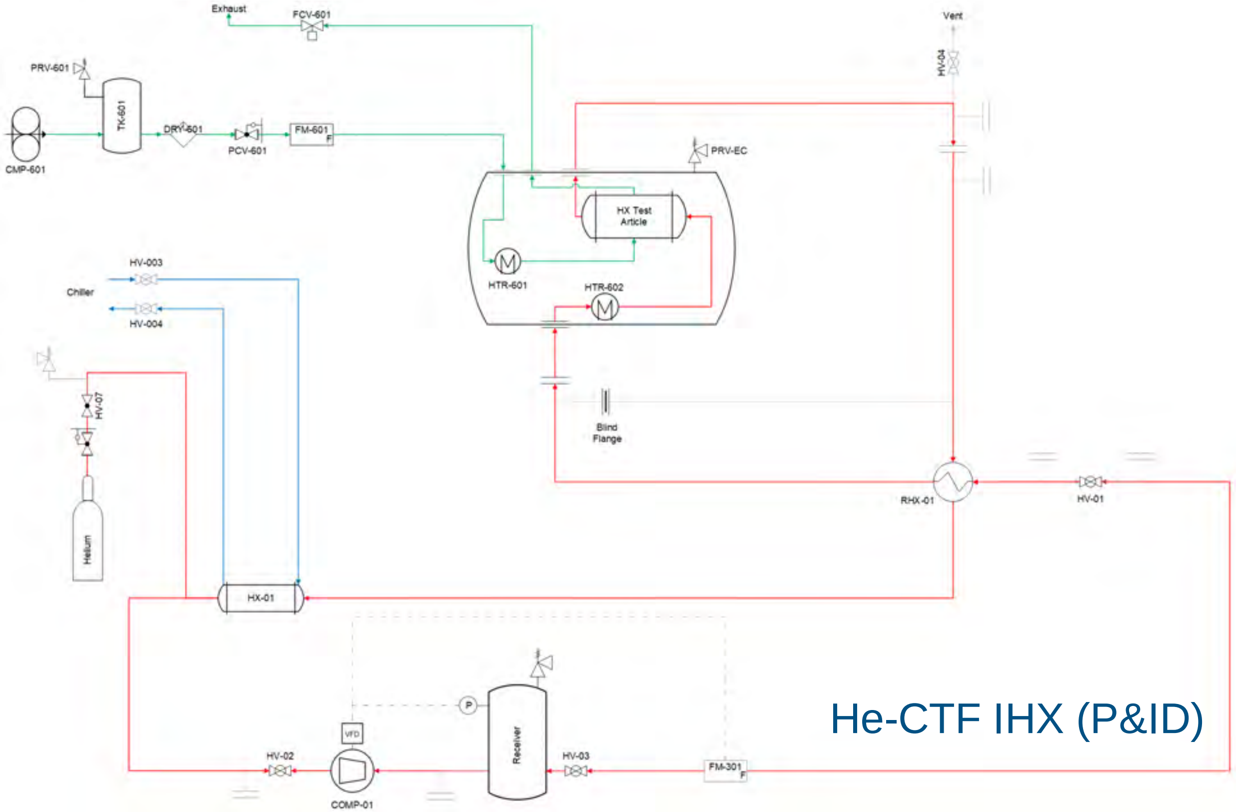
MAGNET / He-CTF
Commercial Developer HX Testing

- Successfully tested proprietary HX design for commercial microreactor developer
- Ran helium at 70 g/s at design temperature and pressure (650°C and 22 bar)



He-CTF IHX (P&ID)

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MAGNET Facility

- MAGNET Deployment in the INL Energy Systems Laboratory (ESL) building, Systems Integration Laboratory
- Co-located with the Thermal Energy Distribution System (TEDS) and the High-Temperature Steam Electrolysis (HTSE) System

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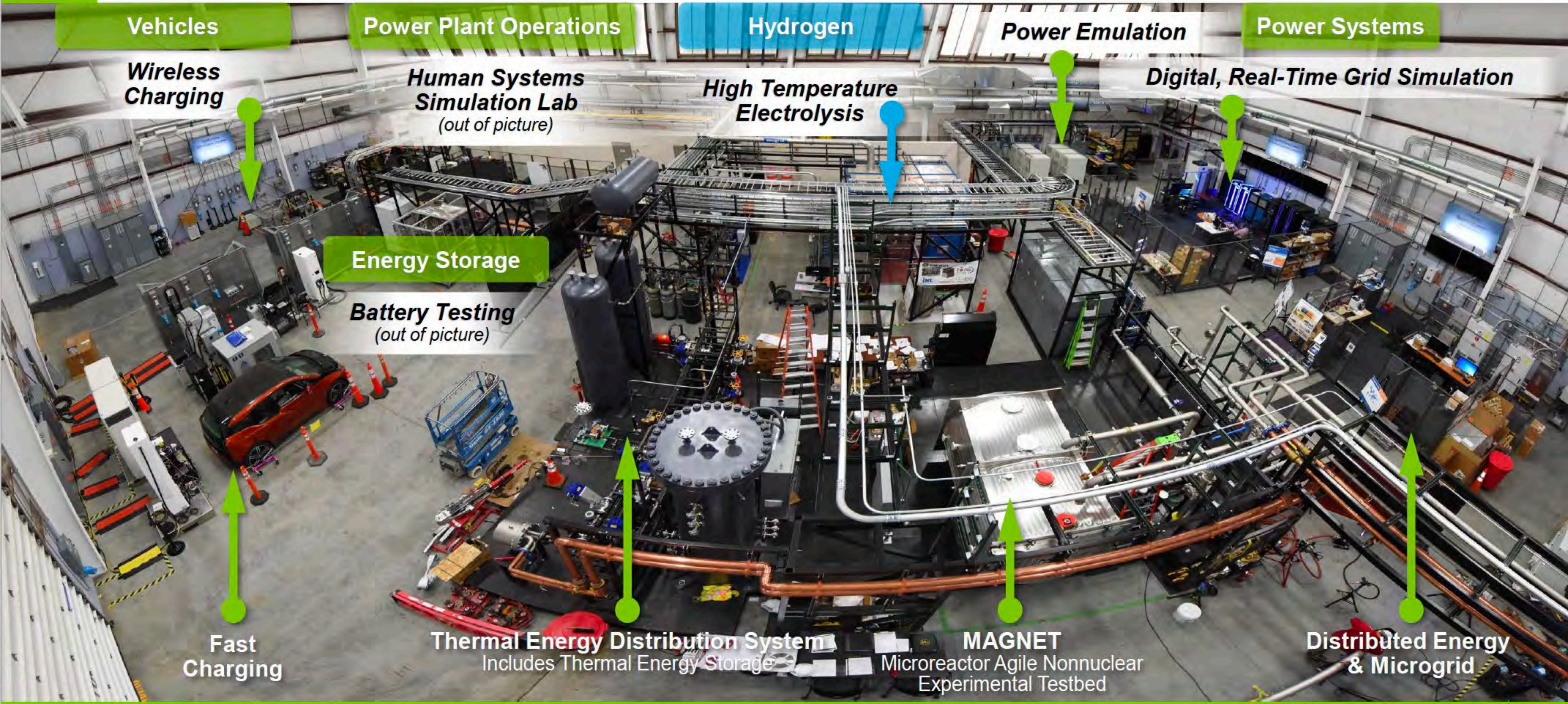
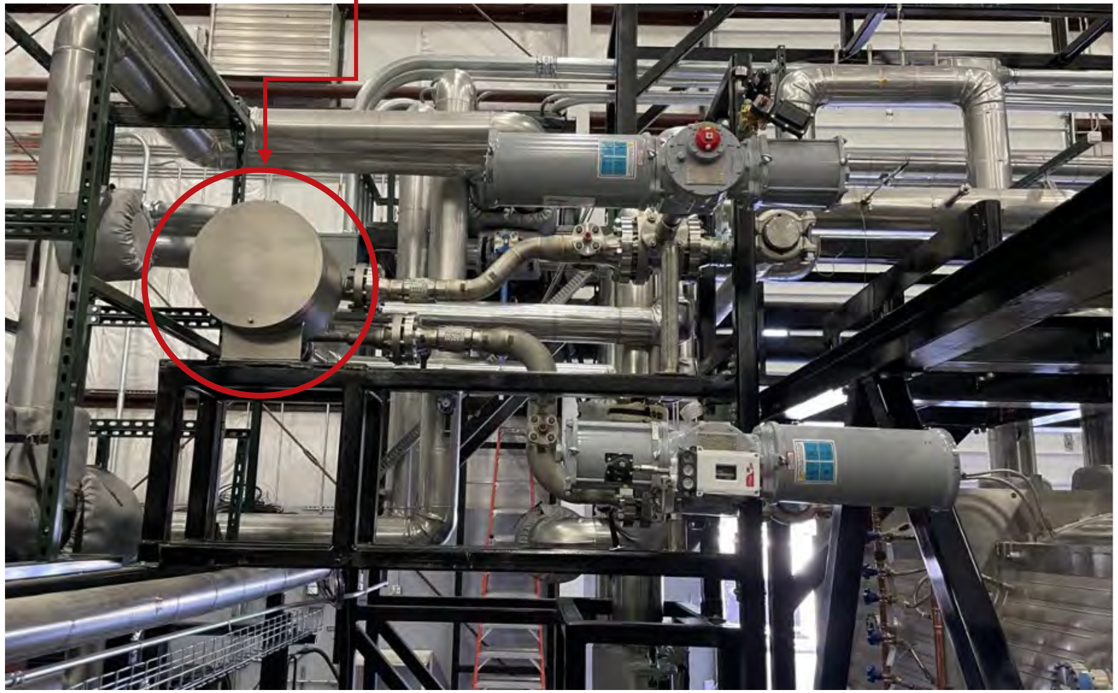
Integrating systems for the nation's net-zero future



Installed TEDS to MAGNET Heat Exchanger

- Allow for interfacing between the thermal storage unit at INL
- This coupling improves MAGNET's capability to provide data on excess heat offloading
- Allows for integrated energy system testing with IES program
  - Expands cooperatives efforts across INL

TEDS to MAGNET Heat Exchanger



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MAGNET – PROGRESS *(from initial startup)*

- Complete shakedown and preliminary testing of MAGNET facility with test article bypass
- Complete test matrix for seven-hole test article
- Complete engineering design for PCU integration
- MAGNET modification to support proprietary HX testing (from a commercial developer).
- Demonstrated digital twin of a single-heat-pipe test article in MAGNET with autonomous, self-adjusting capability.
- Mezzanine construction completed (replaced temporary scaffolding)
- Advanced Heat pipe Interface Heat Exchanger Testing (NEUP with University of Wisconsin)

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HElium Component Testing Out-of-pile Research *(HECTOR)* Facility

Test bed being designed to enable testing of components such as heat exchangers, valves, circulators, etc., at operating conditions up to 8MPa and at 800 C.

US Reactor Design Concepts

Developer	Name	Power Output (Mwe/NWth)	Fuel	Coolant	Moderator	Gas Pressure	Outlet Temperature
BWXT	BANR	17/50	TRISO	He	Graphite	–	–
HolosGen	Holos Quad	10-13/–	TRISO	He/CO_2	–	7 MPa	620ºC
NuGen, LLC	NuGen Engine	2-4/–	TRISO	He	–	–	–
Radiant Nuclear	Kaleidos	1.2/–	TRISO	He	Graphite	–	700ºC
Ultra Safe Nuclear	Micro Modular Reactor	5/15	TRISO	He	Graphite	3 MPa	565ºC
X-energy	Xe-100	80/200	TRISO	He	Graphite	6 MPa	750ºC
General Atomics	GA-EMS	50/112	UO_2	He	–	7 MPa	800ºC

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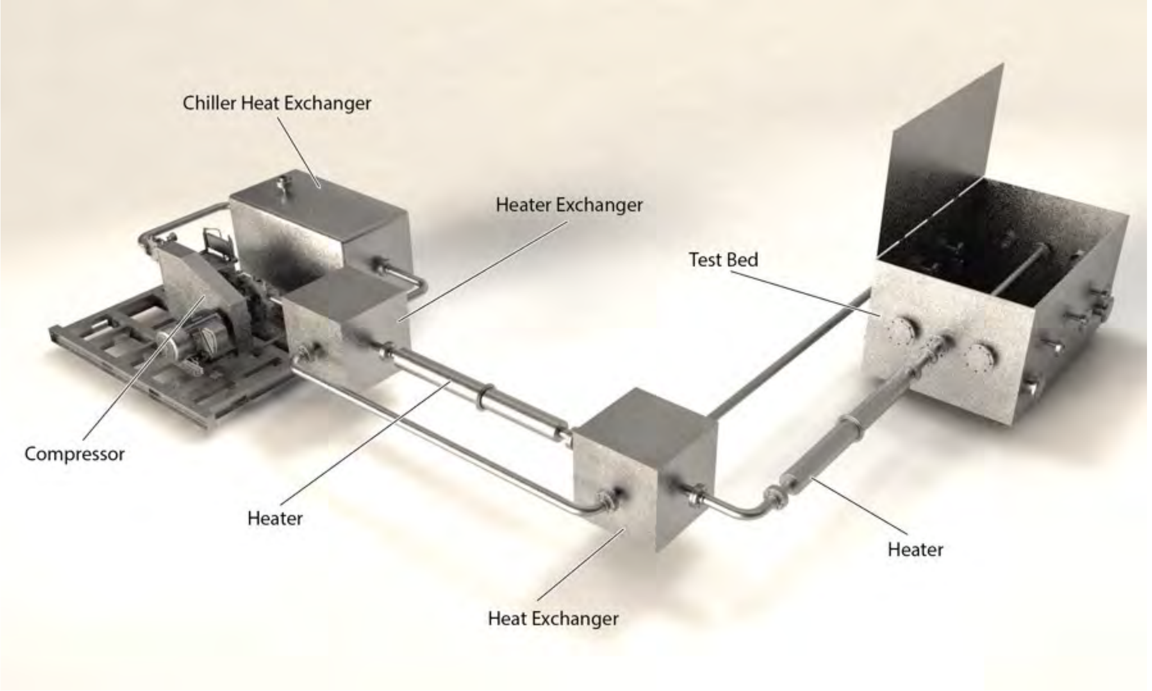
HElium Component Testing Out-of-pile Research Facility

Operating Conditions	
Pressure	8MPa
Temperature	Up to 800 C
Mass Flow	0.01 – 0.15 kg/s
Reynold's Number Range	11,700 – 1,610,000



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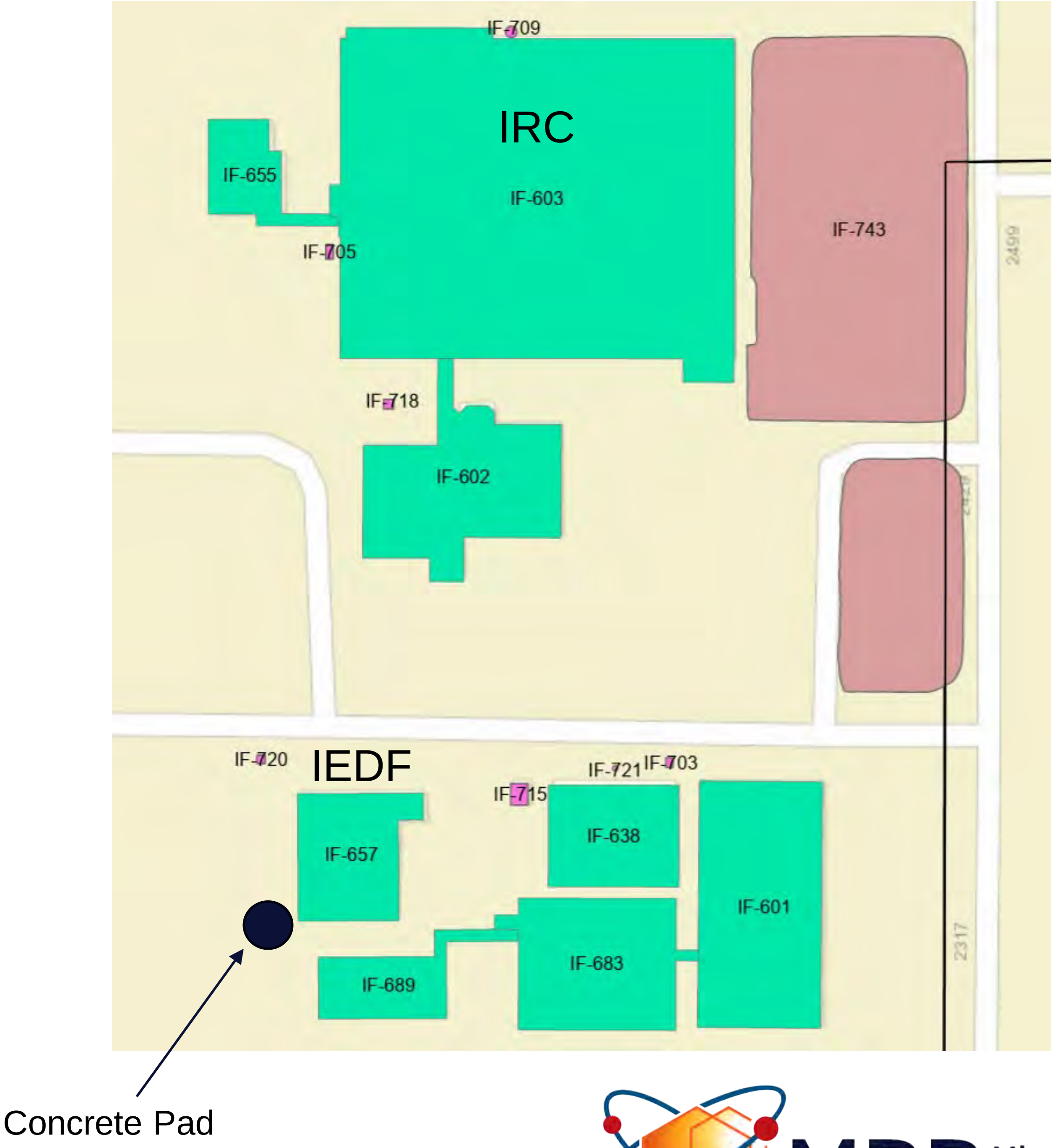
Remaining Challenges

- Material Selection
  - **Alloy 230**
  - Alloy 625
  - Alloy 617
- B31.3 Piping analysis completed
- Finding location
  - PermaCon/Conax Container
  - IEDF area is ideal
    - Concrete pad ready for container placement
  - Potential lab space in IRC



Potential Location – PermaCon

- Most likely solution is a PermaCon

Demonstration Support Capabilities – *Activities & Milestones Planned (FY-24)*

- **SINGLE PRIMARY HEAT EXTRACTION AND REMOVAL EMULATOR (SPHERE)**
  - Complete power transient testing matrix (will support V&V of Sockeye by providing the results of heat pipe performance under various power transients): Due May 31st 2024
  - Complete testing on LANL high capacity heat pipes for steady state thermal heat transfer characterization: Due August 31st 2024

- **MICROREACTOR AGILE NON-NUCLEAR EXPERIMENTAL TESTBED (MAGNET)**
  - **Integrate PCU with MAGNET to allow Integrated Microreactor Heat T/F System Testing (M2; Due Aug 30th 2024)**
    - Award Construction Contract for Integrating PCU (M3; 28th March 2024)
    - Complete Enclosure Installation (M4; 20th June 2024)
    - Complete Piping Installation (M4; 31st July 2024)
  - Integrate PCU with MAGNET (M3; Due Sept 30th 2024)

- **HELIUM COMPNENT TESTING OUT-OF-PILE RESEARCH (HECTOR) FACILITY**
  - Complete Engineering Design for High Temperature and High Pressure Gas Test Loop (8MPa and 800 deg C) – M3 Milestone (Completed 11/30/2023)
    - Manuscript being drafted

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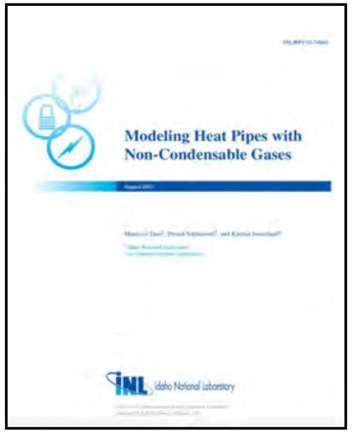
Modeling Efforts

Modeling Summary (From FY-23)

- Advance modeling of heat pipes with and without non-condensable gases
  - Two distinct models were compared:
    - Conduction model in Sockeye (NEAMS tool)
    - Two-phase Euler-Euler Computational Fluid Dynamics developed with STAT-CCM+
  - Both models were tested against Katrina Sweetland's Ph.D. experiments for copper-water heat pipes with a single condenser
  - Advantages and disadvantages of both models are driven from experiment comparison and runtime assessments


Modeling Heat Pipes with
Non-Condensable Gases

Credit: Mauricio Tano Retamales (INL)

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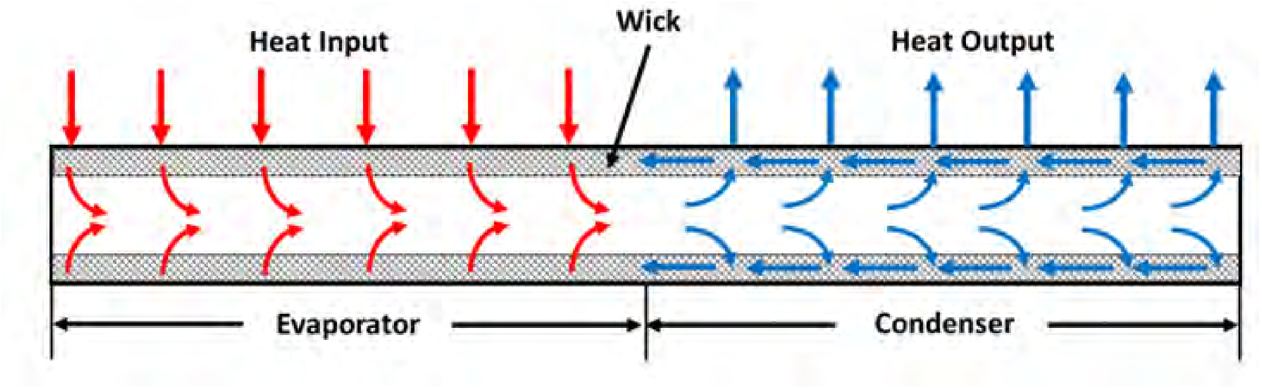
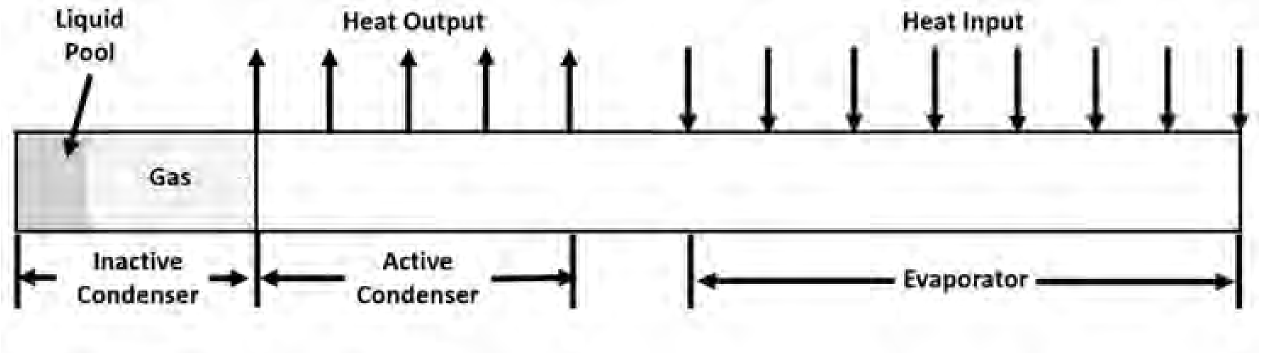
Tano, M., P. Sabharwall and K. Sweetland, *Modeling Heat Pipes with Non-Condensable Gases*, INL/RPT-23-74866, August 2023.

Operating basis of heat pipes with and without non-condensable gases

- In a regular heat pipe, flow evaporates from the wick into the core at the evaporator and condenses from the core into the wick at the condenser
- Non-condensable gases are transported by the core vapor flow into the end of the condenser, where they accumulate
- This accumulation reduces the effective active length of the condenser but introduces a gas buffer that regulates temperature
- A liquid pool may form at the end of the condenser due to the non-condensable gas insulation





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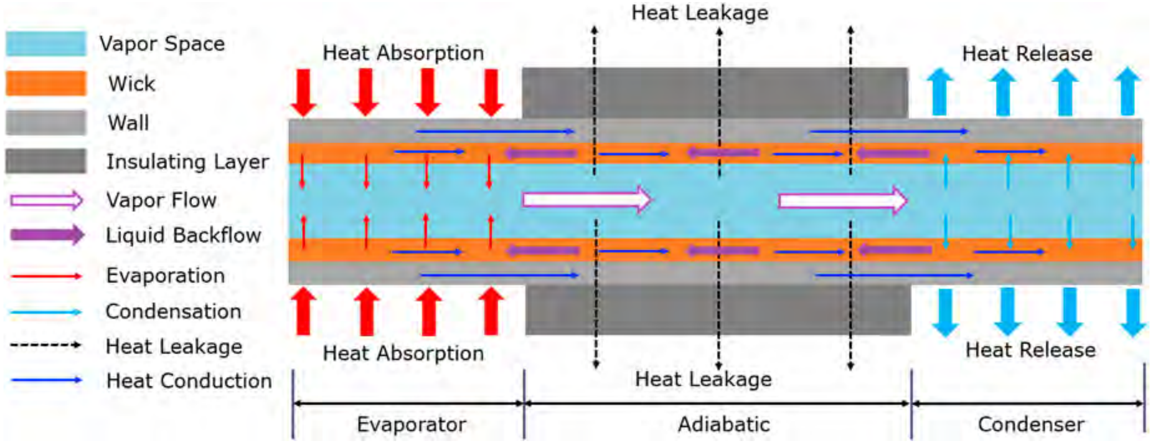
Modeling non-condensable gases (NCGs) in heat pipes

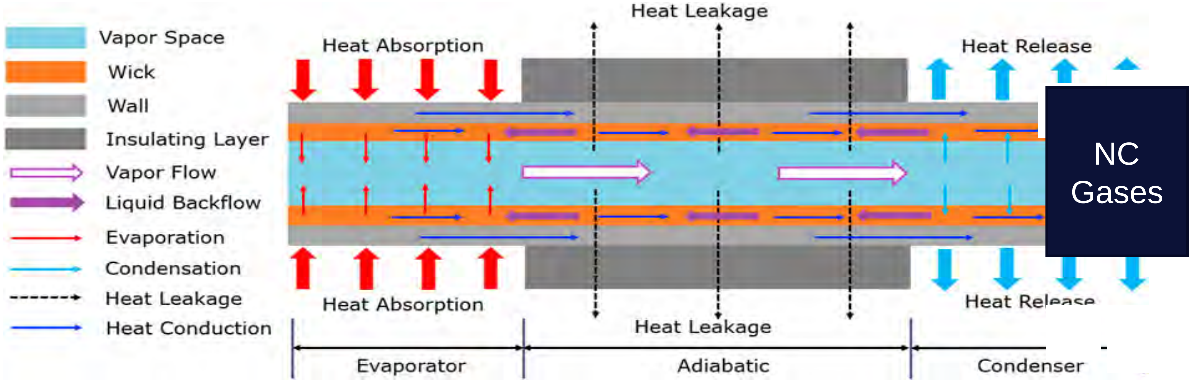
- The effective thermal conductivity model in Sockeye uses adapted thermophysical parameters for each region

	ρ	c_p	k
Vapor Space	$\rho_v(p_{sat}, T)$	$c_{p,v}(p_{sat}, T)$	$k_{core}(T)$
Wick	$\rho_l(p_{sat}, T)$	$c_{p,l}(p_{sat}, T)$	$k_l(p_{sat}, T)$
Wall	$\rho_{wall}(T)$	$c_{p,wall}(T)$	$k_{wall}(T)$



- Non-condensable gases shorten the active condenser length and increase the pressure in the heat pipe ($p_{eq} = p_{sat} + p_{nc}$). The modified

	ρ	c_p	k
Vapor Space	$\rho_v(p_{eq}, T)$	$c_{p,v}(p_{eq}, T)$	$k_{core}(T)$ Only for active length
Wick	$\rho_l(p_{eq}, T)$	$c_{p,l}(p_{eq}, T)$	$k_l(p_{eq}, T)$
Wall	$\rho_{wall}(T)$	$c_{p,wall}(T)$	$k_{wall}(T)$



Active Inactive

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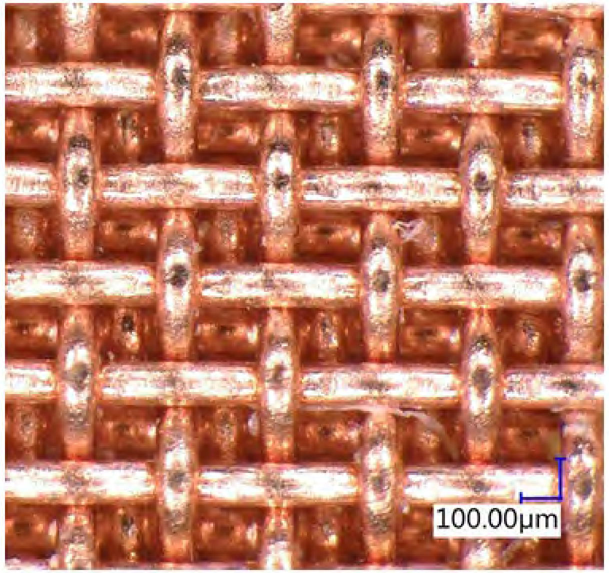
Katrina Sweetland's heat pipe experiment

- Copper-water heat pipe system
- Wick made from rolled copper mesh
- Heating by a set of controlled thermal resistances and cooling by natural convection and thermal radiation
- 16 reported thermocouples measurements places axially on the clad are used for model validation

Images from Katrina Sweetland's Ph.D. manuscript



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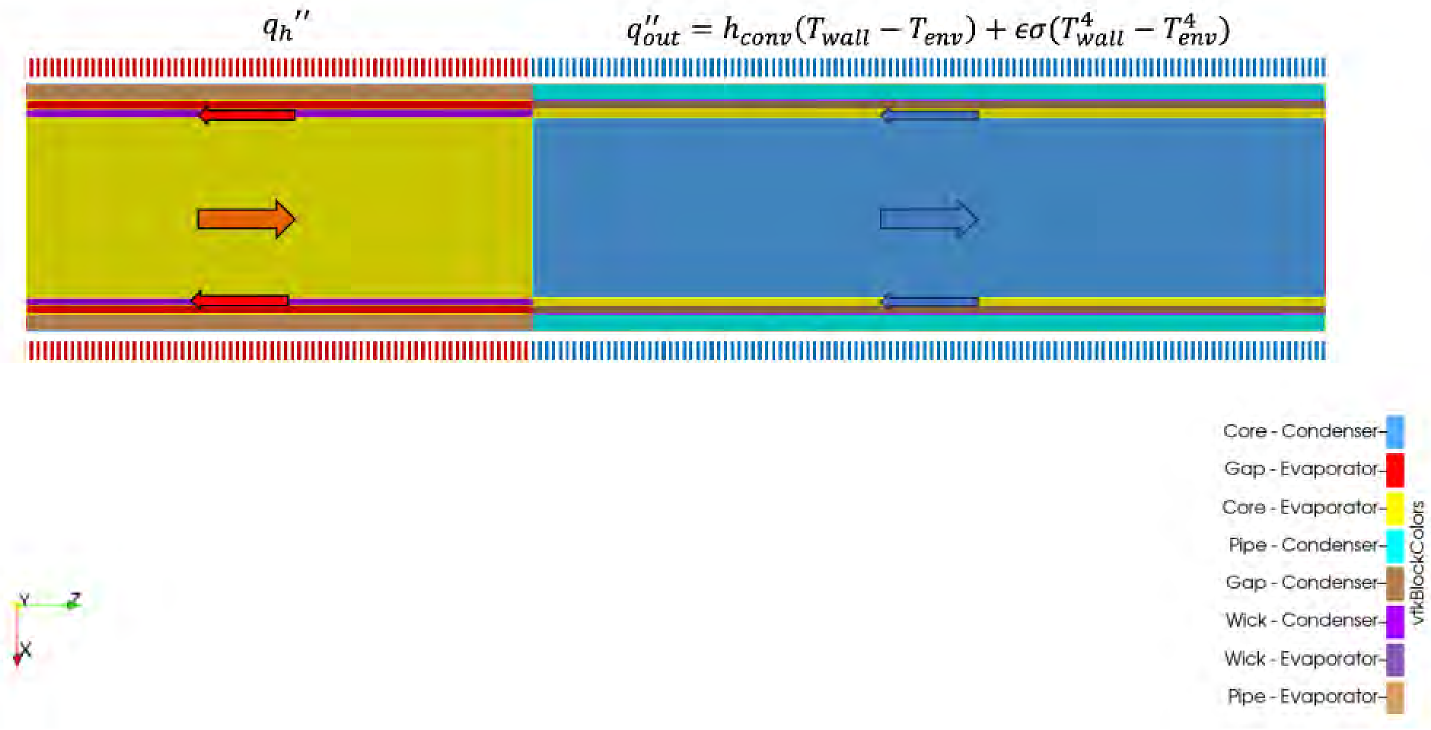
Credit: Katrina Sweetland (LANL)

Experiment model

- Heat pipe model includes evaporator and single condenser
- Radially, the model includes:
  - Core
  - Wick
  - Gap
  - Clad
- Evaporator power is set as a constant heat flux
- Natural convection cooling is modeled by mixed convection-radiation heat transfer
- Same model used for Sockeye and STAR-CCM+



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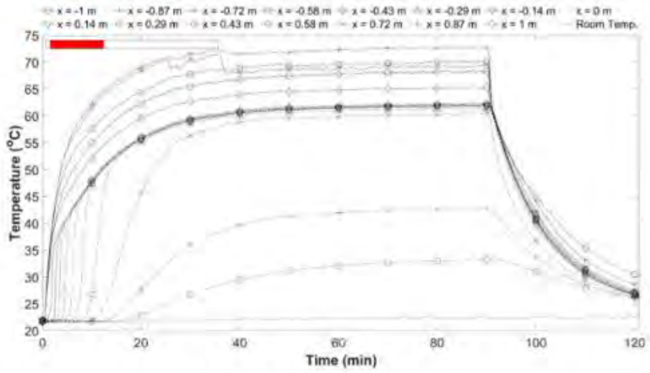
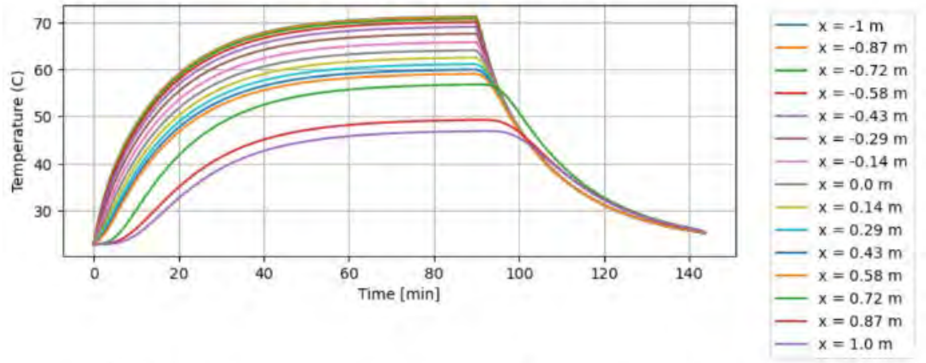
Credit: Katrina Sweetland (LANL)

Results with non-condensable gases

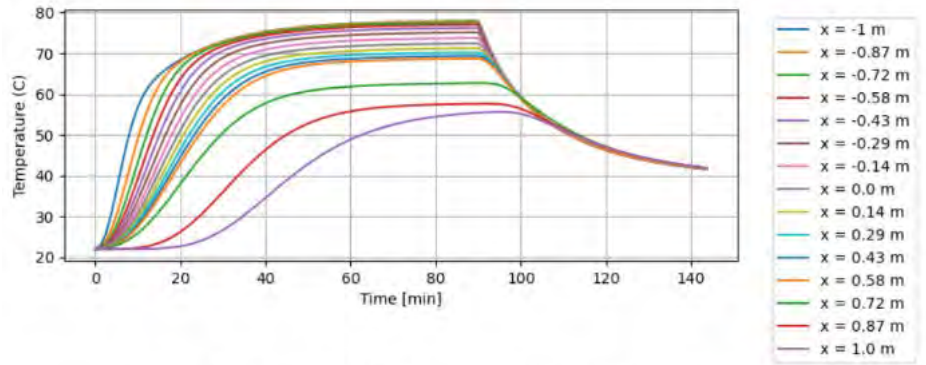
- Good qualitative agreement between STAR-CCM+ and Sockeye model
- Start-up and shutdown dispersion in thermocouple readings is better predicted by STAR-CCM+ model
- Temperature behavior of cold thermocouples next to condenser better predicted by STAR-CCM+ model
- The main reason is that the pressure stabilization hypothesis in the shorten condenser conduction model does not consider thermal gradients across the non-condensable gas region



(a) Experimental Results.



(b) Results Obtained by the Heat Conduction Calculations.



(c) Results Obtained by the two-phase CFD Calculations.

Average L2 errors in Kelvin

	Conduction Model	CFD Two-Phase Model
Without Non-Condensables	3.7	0.9
With Non-Condensables	5.4	1.7

Runtime comparison

Runtime	Without non-condensable gases	With non-condensable gases
Sockeye	16 seconds	26 seconds
STAR-CCM+	1.6 hours	2.2 hours

Both Sockeye and STAR-CCM+ model present a good agreement with copper-water heat pipes with and without non-condensable gases. Sockeye’s conduction model presents a significantly faster runtime that makes it more apt for the expectations of microreactor simulations

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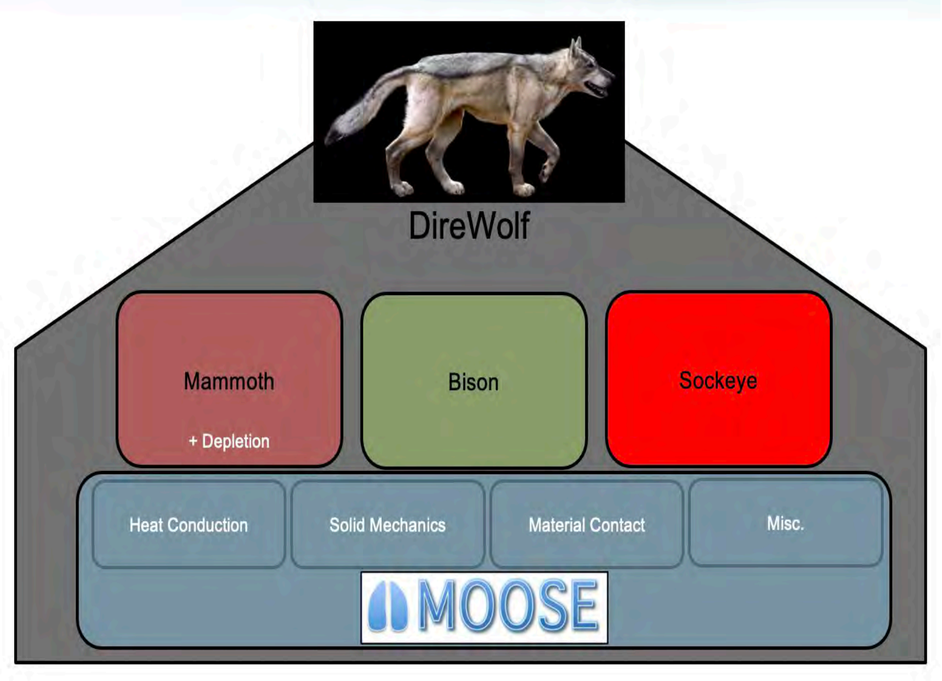
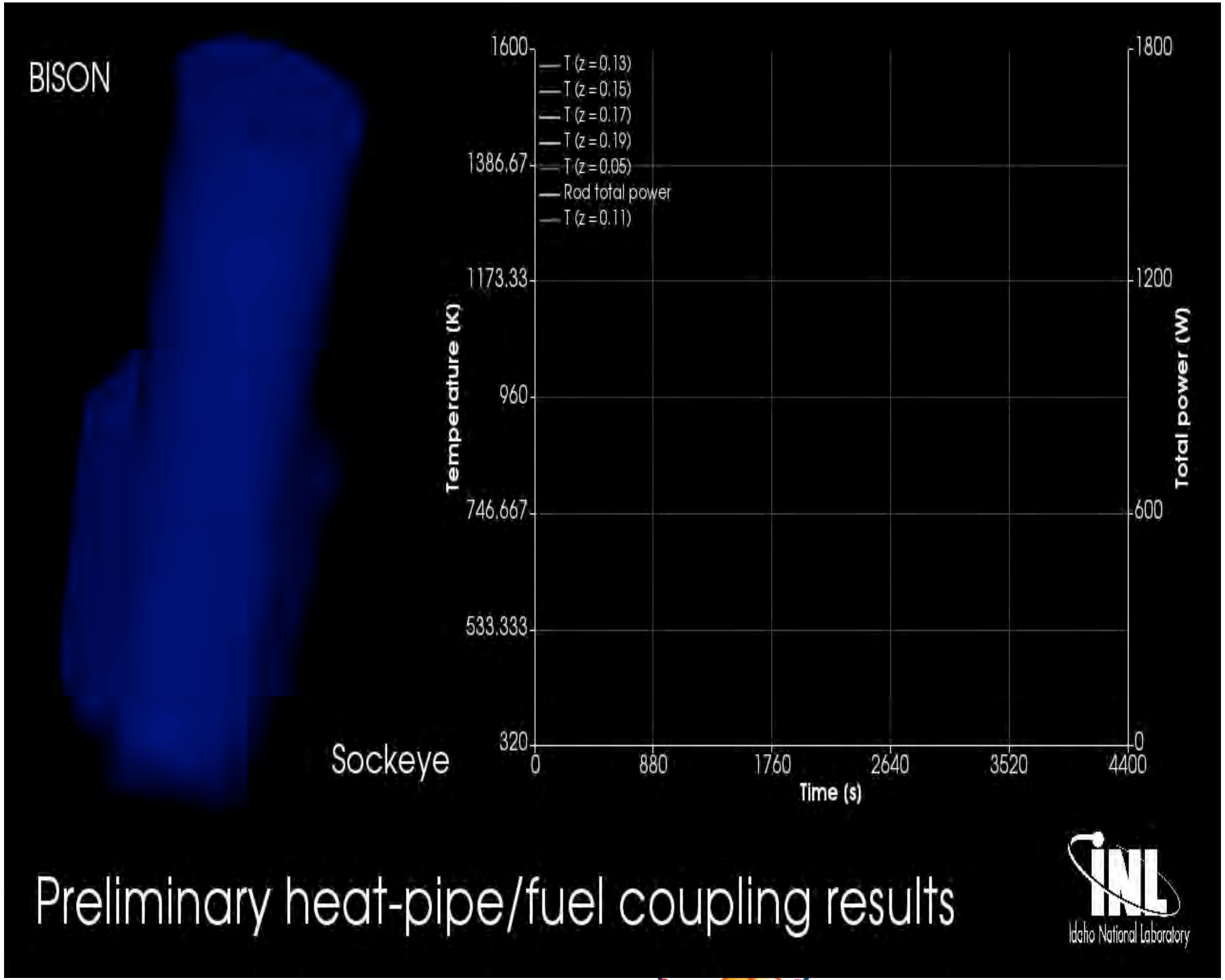
Modeling Informed Designs





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