Currently Funded NEUP - MRP

NEUP Nuclear Energy University Program
U.S. Department of Energy

MRP Microreactor Program

MRP – NEUP Collaboration

Project ID: 19-1680 (Year Awarded 2019)

Title: Determining the Effects of Neutron Irradiation on the Structural Integrity of Additively Manufactured Heat Exchangers for Very Small Modular Reactor Applications

PI: Prof. Barton Prorok, Auburn University

TPOC: Dr. Stu Malloy, Los Alamos National Laboratory

Determining the Effects of Neutron Irradiation on the Structural Integrity of Additively Manufactured Heat Exchangers for Very Small Modular Reactor Applications

MICROREACTOR PROGRAM STAKEHOLDERS WORKSHOP
May 12, 2021

Auburn University
Tahmina Keya
Ashley Romans
Greyson Harvill
Bart Prorok

3D Printing,
Microstructure and
Mechanical Properties

Kansas State University
Mohanish Andurkar
Scott Thompson

3D Printing,
Thermodynamic
Analysis and Modeling

University of Missouri
Valentina O'Donnell
John Gahl

Neutron and Proton
Irradiation and Analysis

AM Compact HeXs – Project Goals

AM enables novel geometry, materials & performance

- part/joint consolidation,
- non-uniform cross-sectioned channels,
- asymmetric core architecture,
- fully-circular channels (as opposed to semi-circular),
- reduced wall thicknesses,
- stream-tailored (cold/hot channel) designs,
- etc.

https://www.metal-am.com/

www.renishaw.com

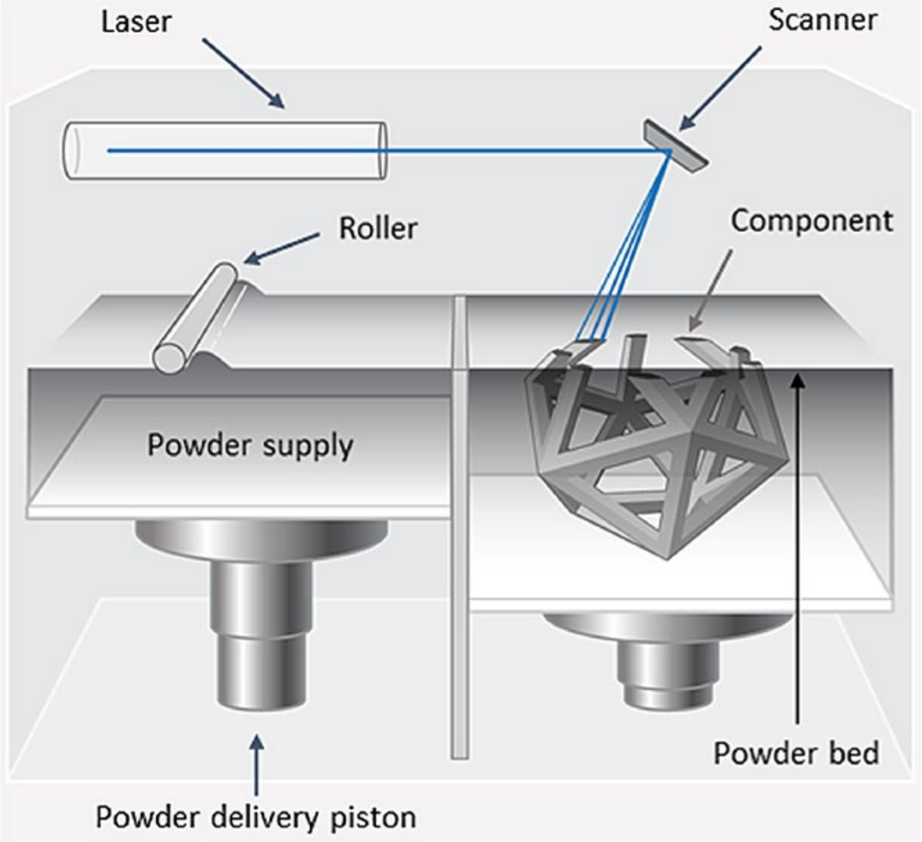
Determine effects of neutron irradiation on L-PBF nickel-based super alloys (Inconel 625 & 718)

- Nuclear Attenuation
  - Swelling
  - Porosity
  - Hardening & embrittlement
- AM Processing Characteristics
  - AM porosity (lack-of fusion, entrapped gas)
  - Inclusions (un-melted particles)
  - Complex residual stress fields
  - Build orientation
- Microstructure/mechanical properties
  - As-printed microstructure
  - Chemical segregation from high cooling rates
  - ppt formation
  - Heat treatments (stress anneal, ppt hardening, equiaxed grain structure)
  - New AM TTT diagrams.

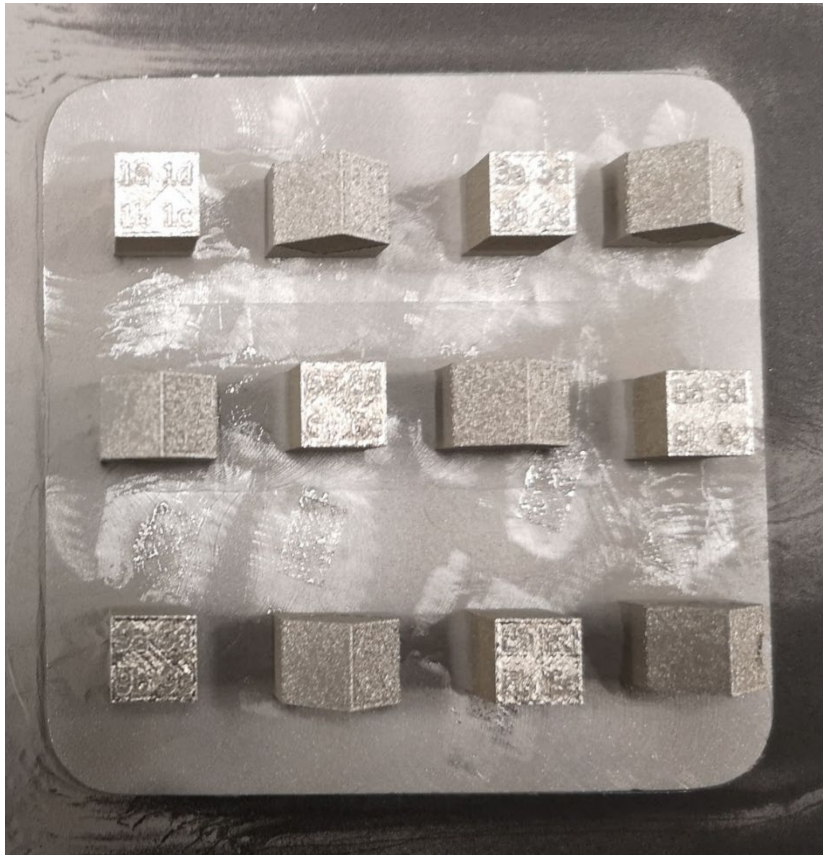
AM Inconel 625 – Laser Powder Bed Fusion (LPBF)

- Geometric Freedom, High Res.
- Complex Thermal History
- Anisotropic and Heterogeneous Microstructure

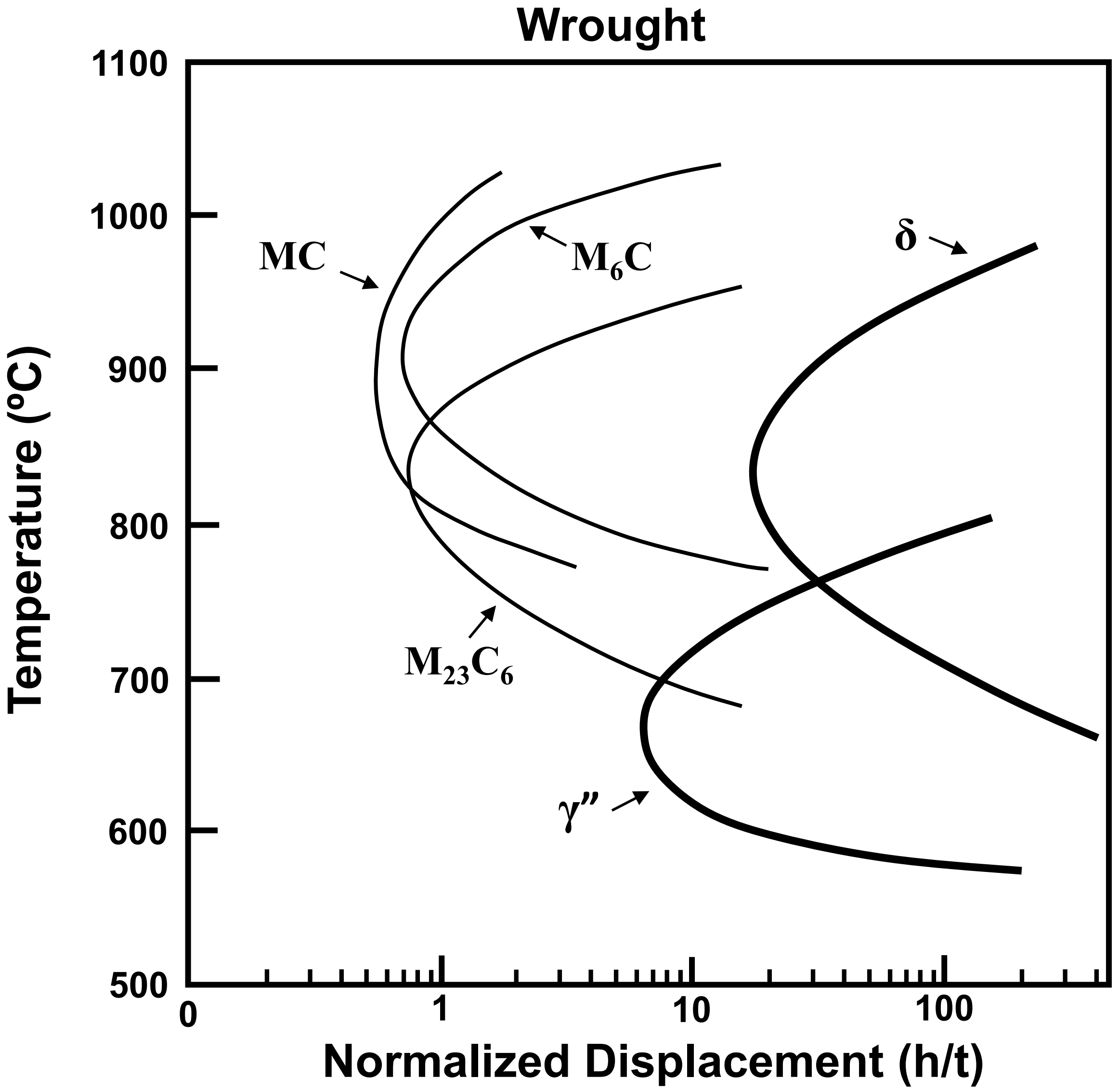
- Laser Power 90 W
- Scan speed 800 mm/s
- Layer thickness 25 µm
- Hatch spacing 60 µm



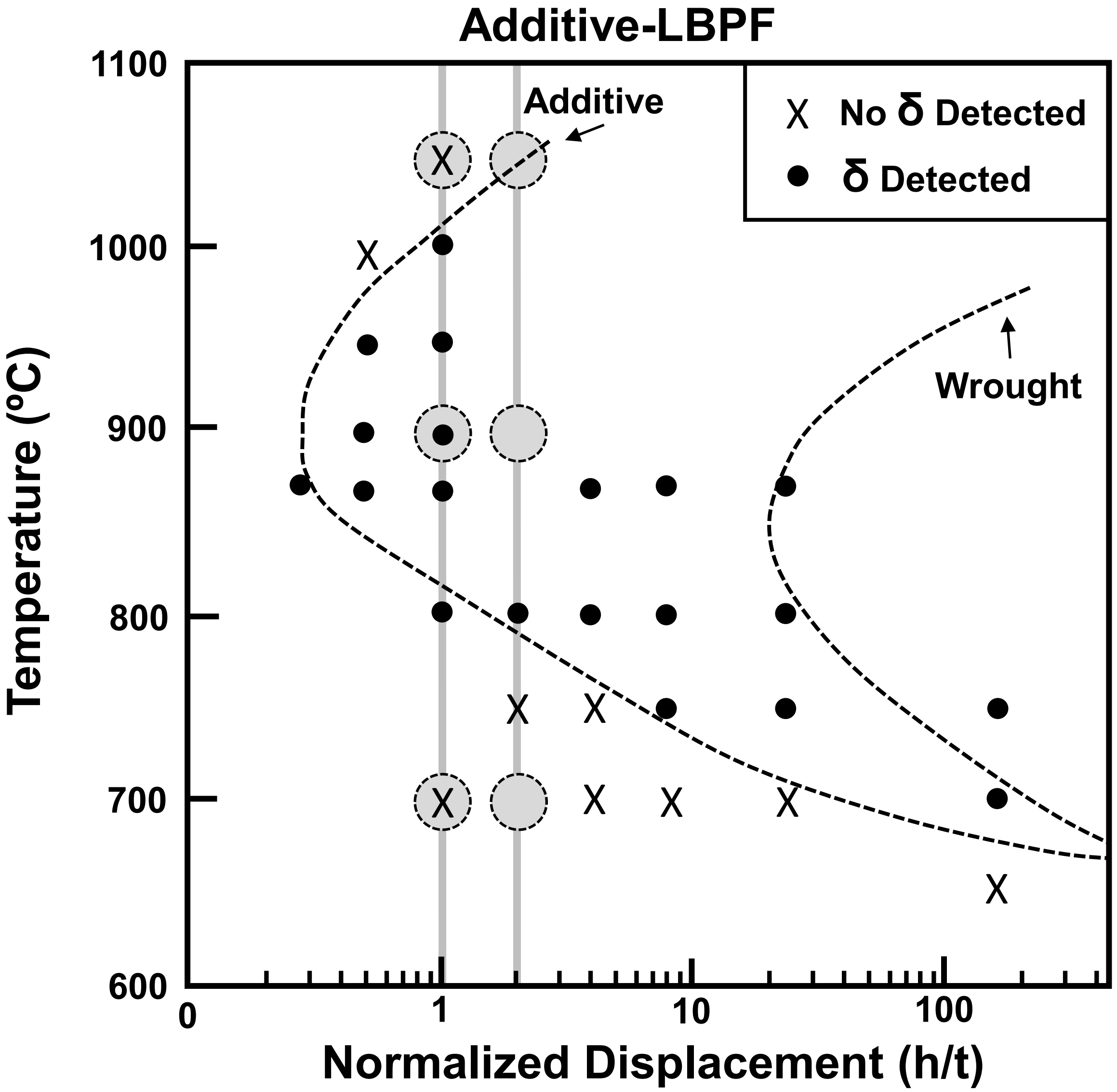
*O'Brien, Optical Engineering **58**(1), 010801 (2019)*



Inconel 625 – TTT Diagram

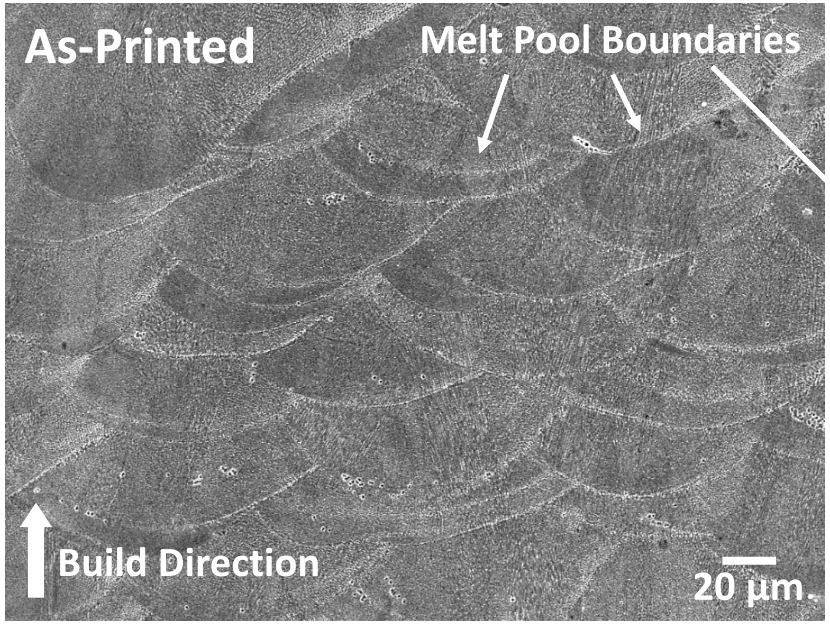


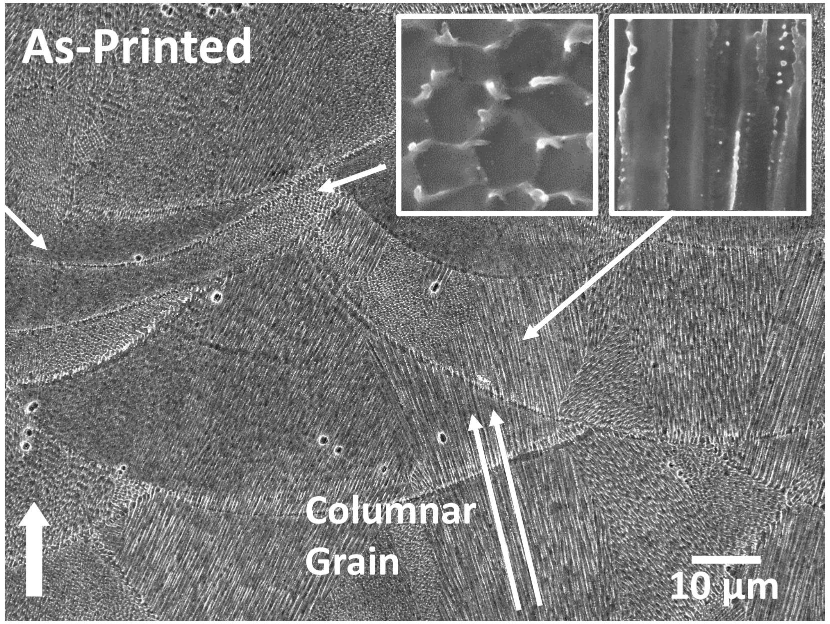
*Shoemaker,Superalloys **718** (625), 409 (2005)*

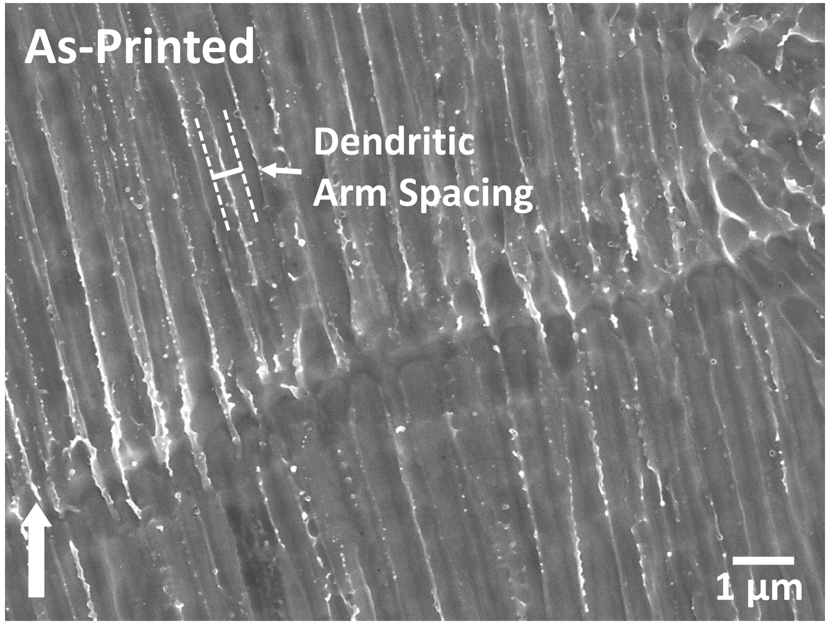


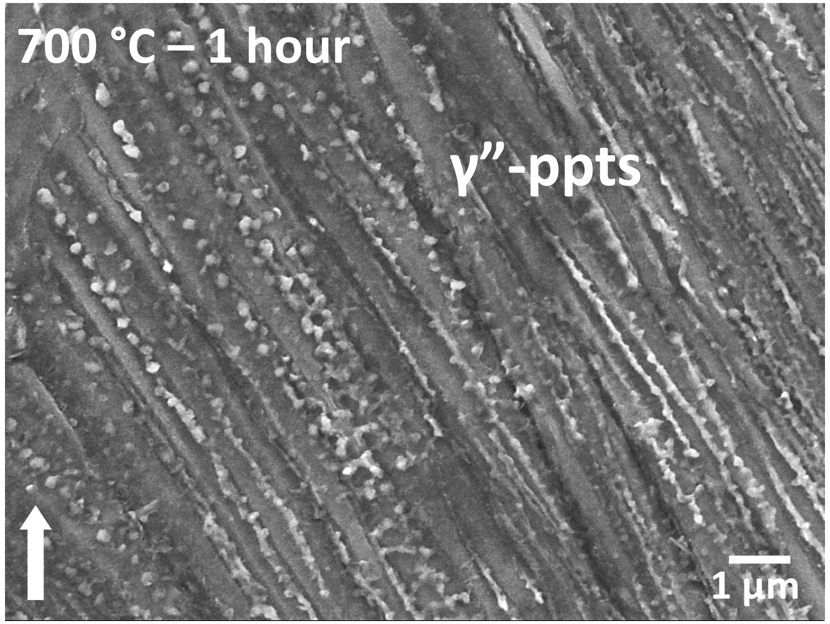
*NIST – Stoudt, et al., Met. Trans. **49A**, 3028 (2018)*

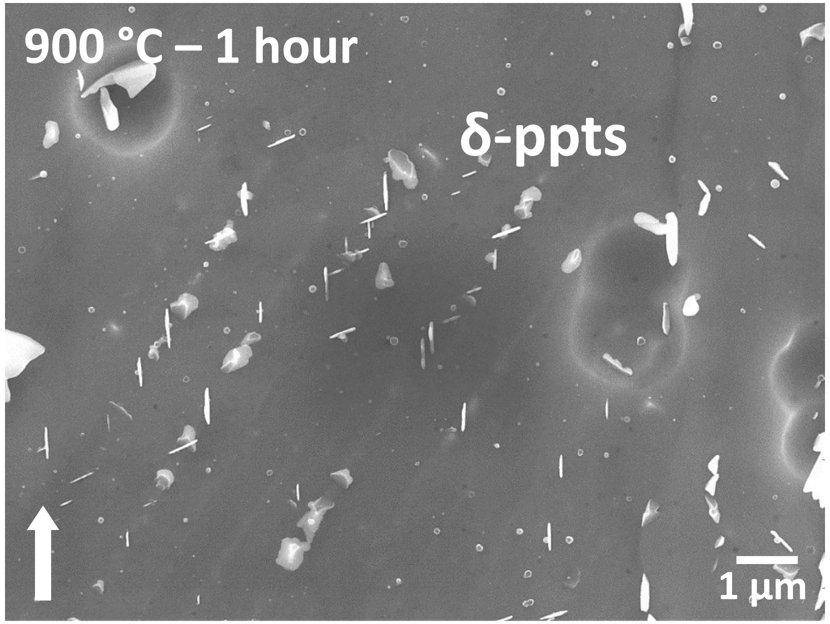
Inconel 625 - Heat Treatment and Microstructure

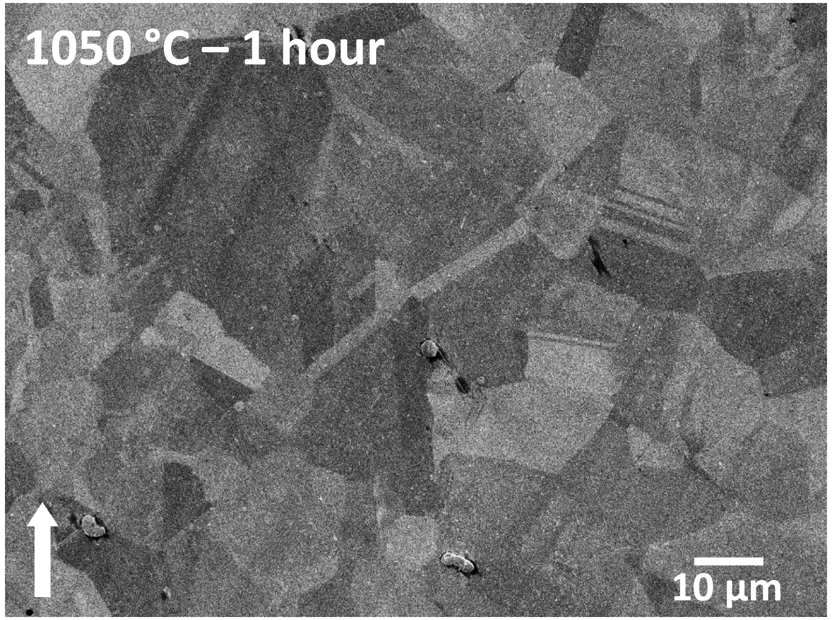






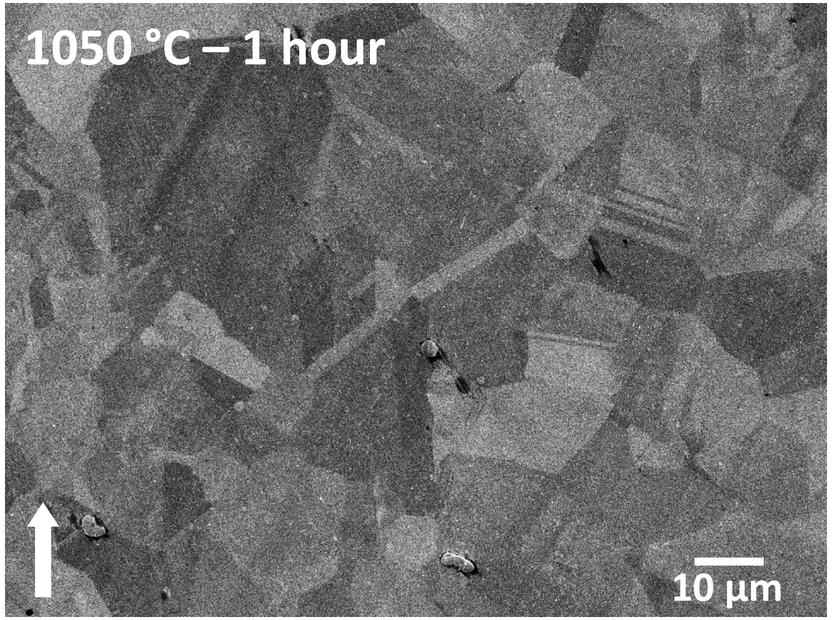


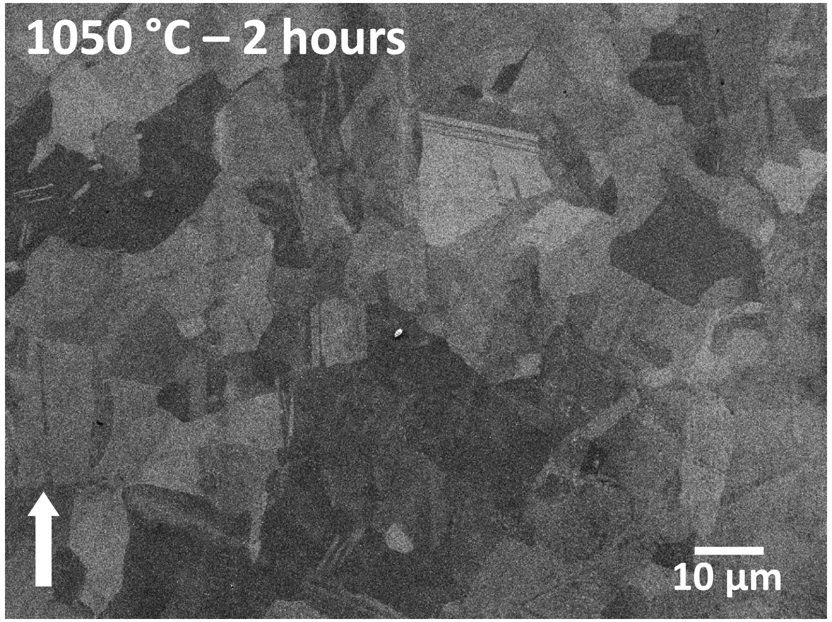




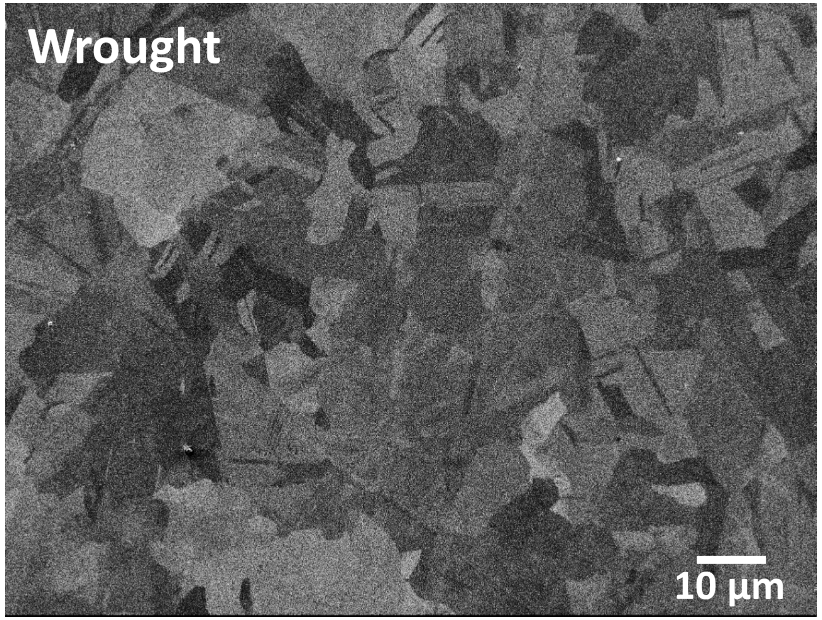
Inconel 625 – AM vs. Wrought Microstructure

AM

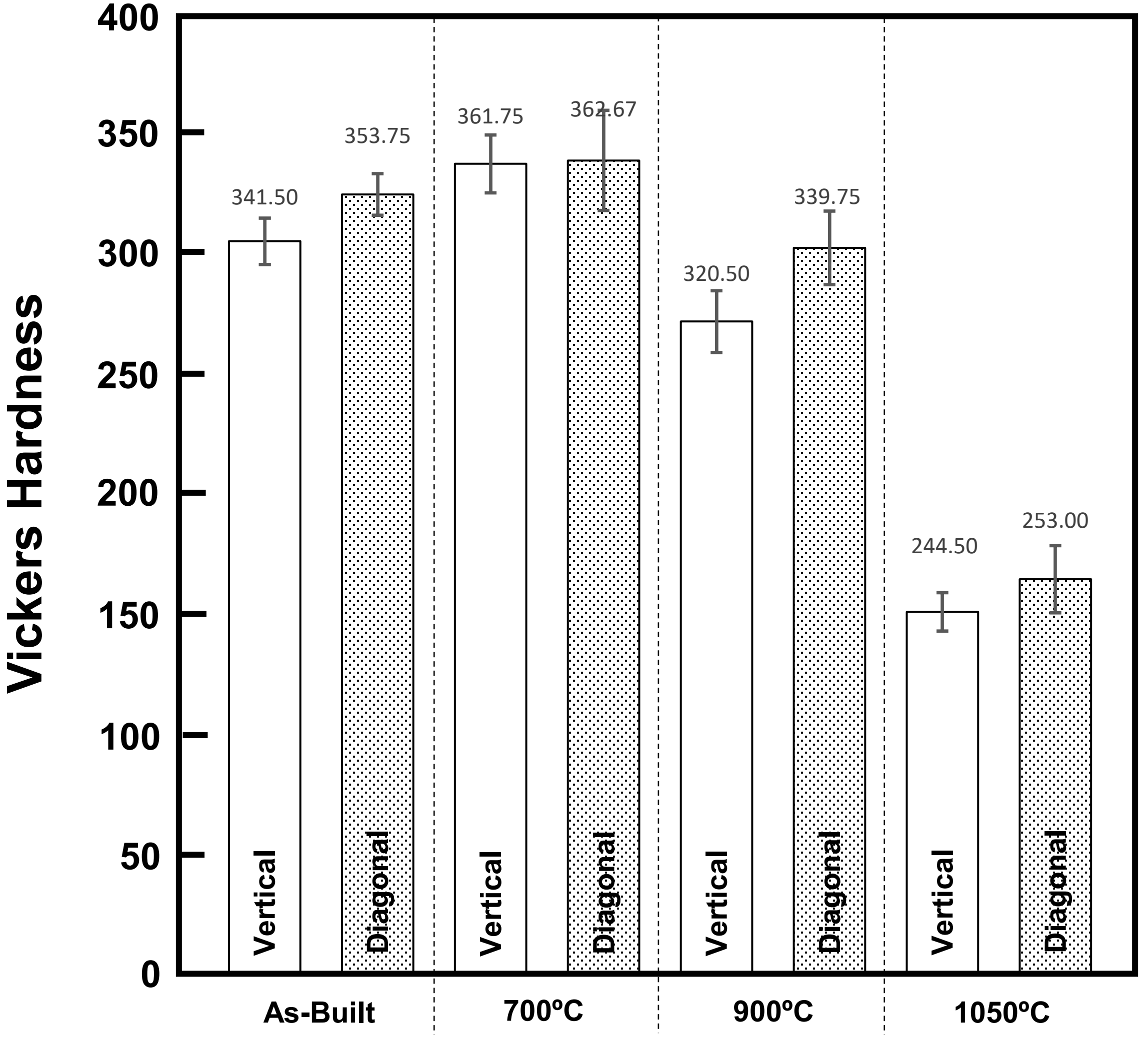


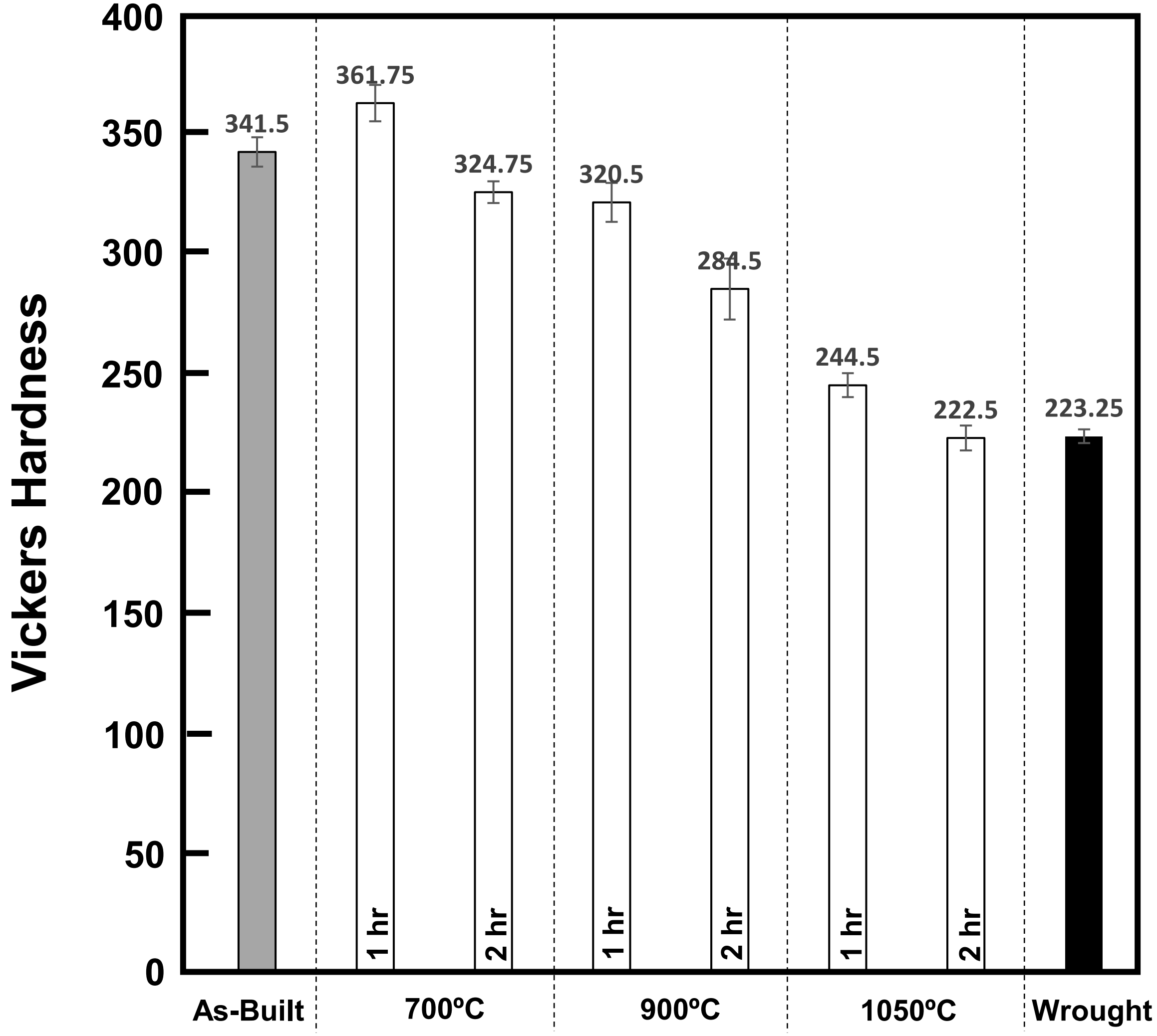


Wrought



Inconel 625 – Pre-Irradiation Mechanical Properties



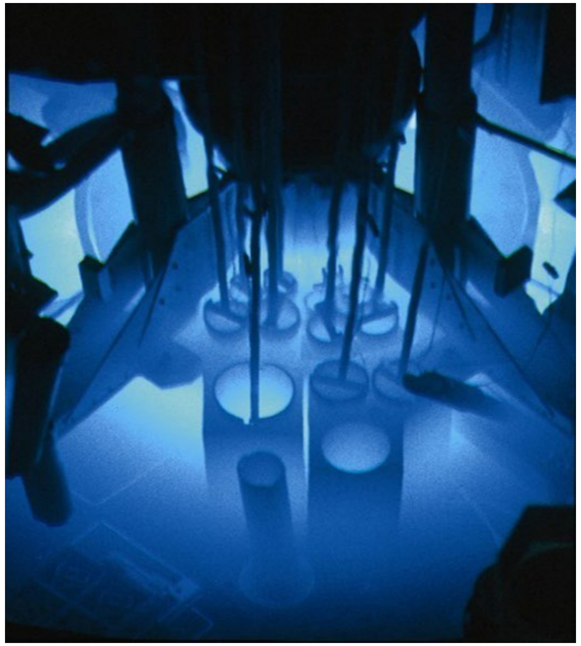


MURR

Have hot cell hardness measurements for AM and wrought Inconel 625

Thermal Neutrons

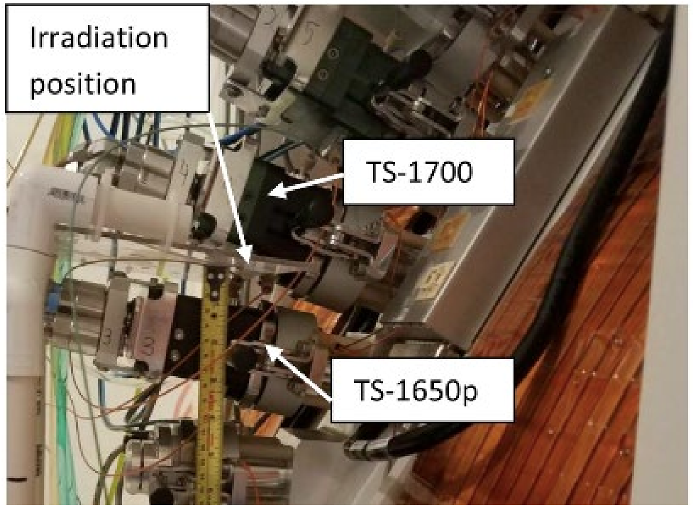
- 10 MW_{th}
- 6 x 10^{14} n/cm^2s



16 MeV Cyclotron

(Fast) Neutrons

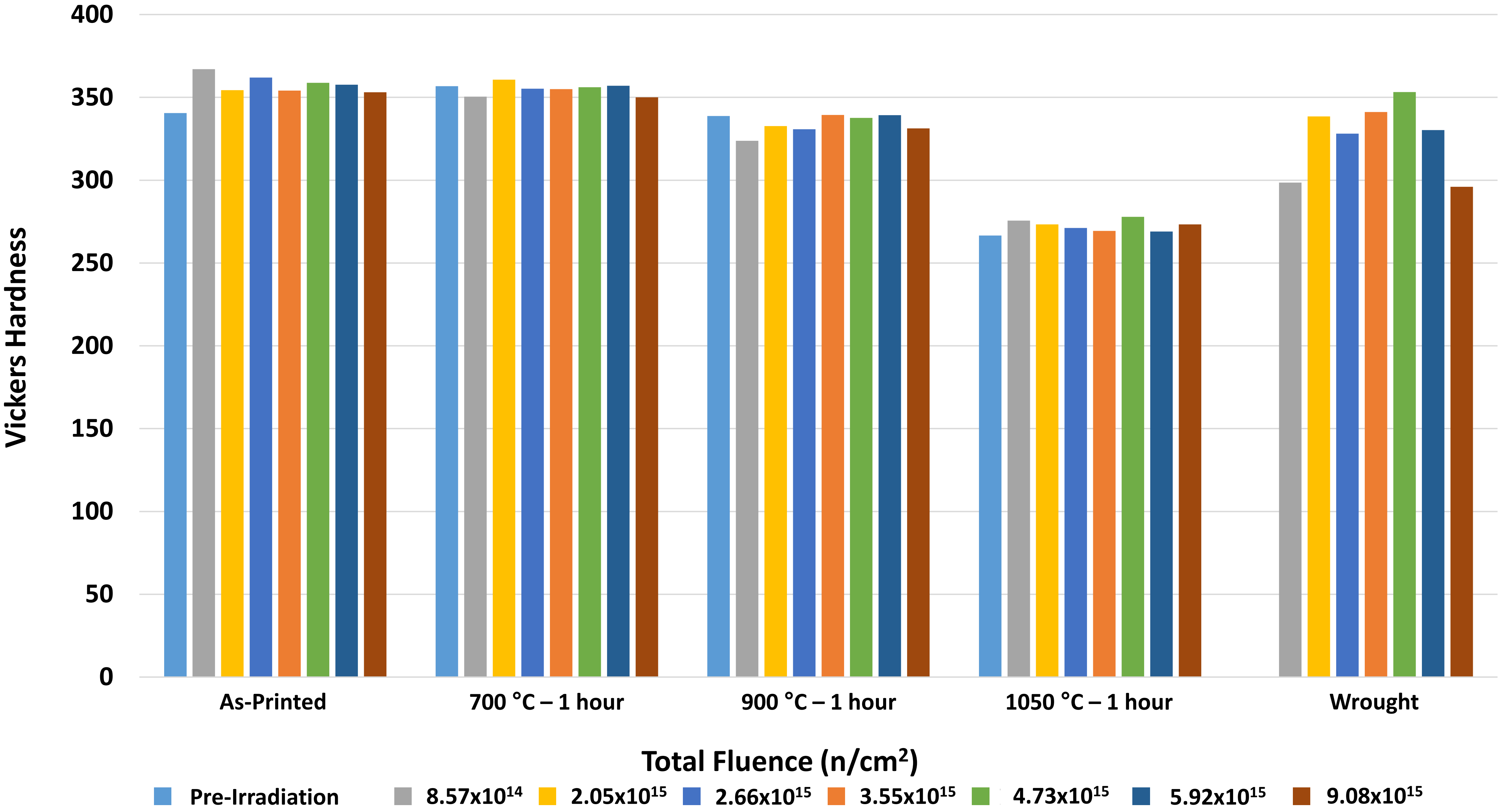
- Radio-isotope pharmaceutical prod.
- 1 MeV
- 4 x 10^9 n/cm^2s



Protons

- 16 MeV Cyclotron
- 80 uA beam

Inconel 625 - Fast Neutron Mechanical Properties



Forward

Inconel 625

- Expand and finish Microstructure of non-irradiated specimens
- Perform microstructure analysis on post-irradiated fast neutron specimens
- Finish feasibility of proton on the wrought specimens – potentially perform on AM specimens

Inconel 718

- Complete the TTT-microstructure study on non-irradiated specimens
- Perform fast neutron exposures and follow up with post-irradiation microstructural analysis
- Potentially perform proton exposure on 718 AM specimens

Other

- Continue to assess thermal neutron specimens and method

MRP – NEUP Collaboration

Project ID: 19-16802 (Year Awarded 2019)

Title: Evaluation of Semi-Autonomous Passive Control Systems for HTGR Type Special Purpose Reactors

PI: Prof. Brendan Kochunas, University of Michigan

TPOC: Dr. Pradeep Ramuhalli, Oakridge National Laboratory

MRP Microreactor Program

NEUP Nuclear Energy University Program
U.S. Department of Energy

Evaluation of Semi-Autonomous Passive Control Systems for HTGR Type Special Purpose Reactors

Prof. Brendan Kochunas
In collaboration with: Victor Petrov, Nicolas Stauff, Changho Lee, and Claudio Filippone

Microreactor Program Workshop
May 13th-14th 2021

COLLEGE OF ENGINEERING
NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

HolosGen™

Argonne NATIONAL LABORATORY

Project Overview

Purpose The purpose of this project is to characterize the dynamic behavior of HTGR like special purpose reactors (e.g. microreactors) and consider the feasibility of design elements that support some inherent, passive control of the system to support semi-autonomous operation. Both traditional reduced order models (e.g. point kinetics) and state of the art modeling and simulation (e.g. PROTEUS) will be used in the characterization and design of passive control elements for dynamic reactor response.

Objectives

- Characterize dynamic behavior of HTGR like micro reactors by assessing global and local reactivity feedback mechanisms and overall range of stability for dynamic behavior.
- Develop and apply model predictive control (MPC) algorithm to assess controllability of reactor and define control system requirements for load follow.
- Evaluate potential passive control systems to support semi-autonomous operation using traditional reduced order models and high-fidelity simulations.

Task #	Description	End Date
~~2a~~	~~Assessment of local temperature reactivity response~~	~~4/30/2020~~
~~2b~~	~~Assessment of variable reflector reactivity envelope~~	~~7/31/2020~~
~~2c~~	~~Global and Local Reactivity Assessments for Passive Control Systems~~	~~9/30/2020~~
~~1a~~	~~Point Kinetics Model Development with MPC~~	~~12/31/2020~~
2b	**Passive Feedback Model Development and Integration**	**6/30/2021**
2c	**CFD and FEM Analysis of Passive Variable Flow Controller**	**9/30/2021**

Outcomes: The main outcomes of this project will be the characterization of the dynamic behavior of HTGR type micro reactors, and subsequent design and evaluation of passive reactor features for inherent semi-autonomous control with respect to meeting a variable power demand.

Research Objectives

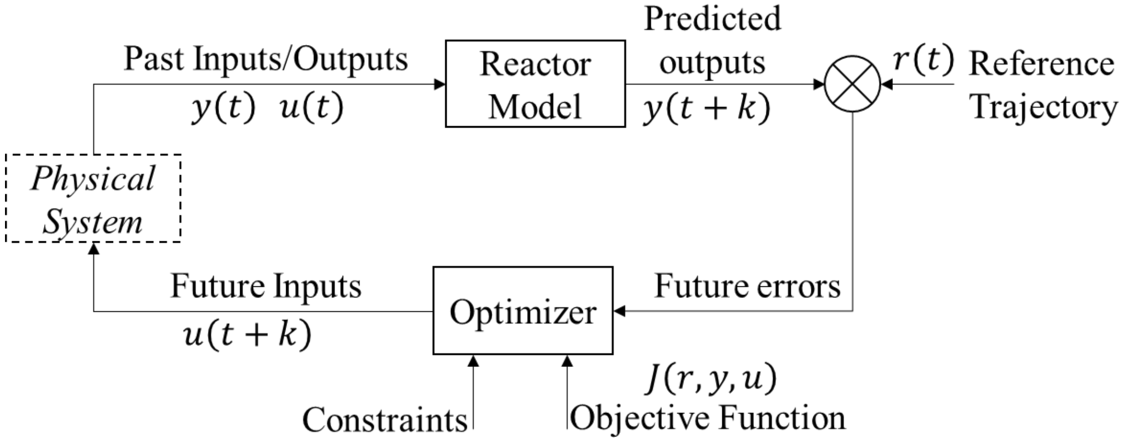
Can reactor components be designed to give a certain dynamic response?

- Reactor Dynamics are well known
    - Point Kinetics and two or three temperature equations
    - Spatial kinetics & high-fidelity

$$\delta\rho(t) = \delta\rho_{cr}(t) + \delta\rho_{T_{inlet}}(t) + \delta\rho_{\dot{m}}(t) + \delta\rho_{Xe}(t) + \alpha_f\left(T_f(t) - T_{f0}\right) + \alpha_m\left(T_m(t) - T_{m0}\right)$$

- Demand More Power → ? → increase reactivity
- Demand Less power → ? → decrease reactivity

How good do model-based controllers have to be, and can they learn?



Past Inputs/Outputs

$y(t)$ $u(t)$

Reactor Model

Predicted outputs

$y(t+k)$

$r(t)$ Reference Trajectory

Physical System

Future Inputs

$u(t+k)$

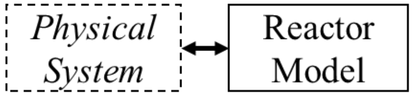
Optimizer

Future errors

Constraints

$J(r,y,u)$

Objective Function



Physical System

Reactor Model

Research Objectives

Can reactor components be designed to give a certain dynamic response?

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$$\delta\rho(t) = \delta\rho_{cr}(t) + \delta\rho_{T_{inlet}}(t) + \delta\rho_{\dot{m}}(t) + \delta\rho_{Xe}(t) + \alpha_f\left(T_f(t) - T_{f0}\right) + \alpha_m\left(T_m(t) - T_{m0}\right)$$

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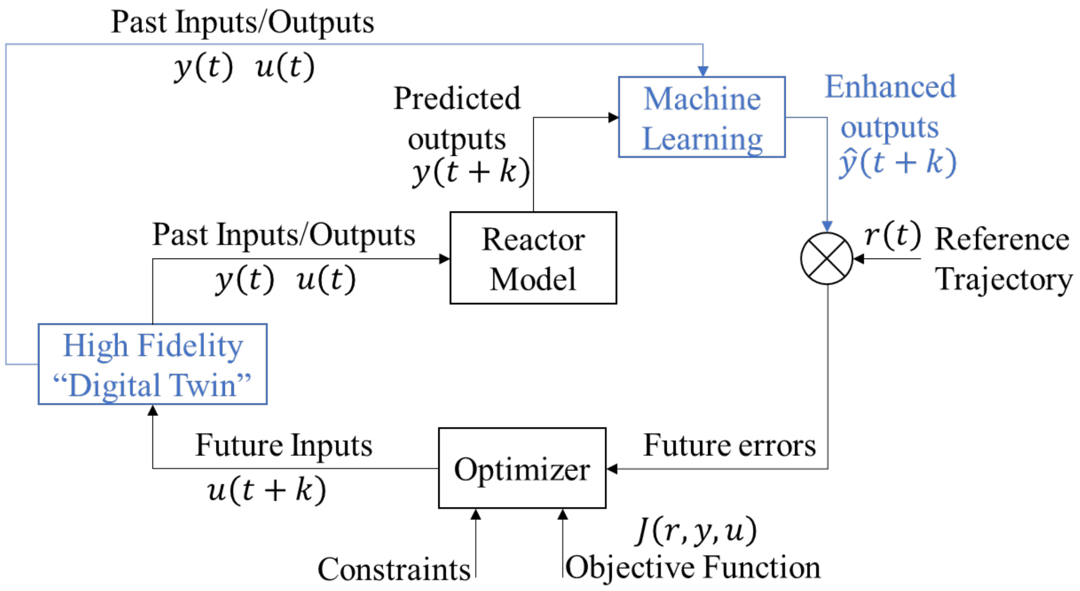
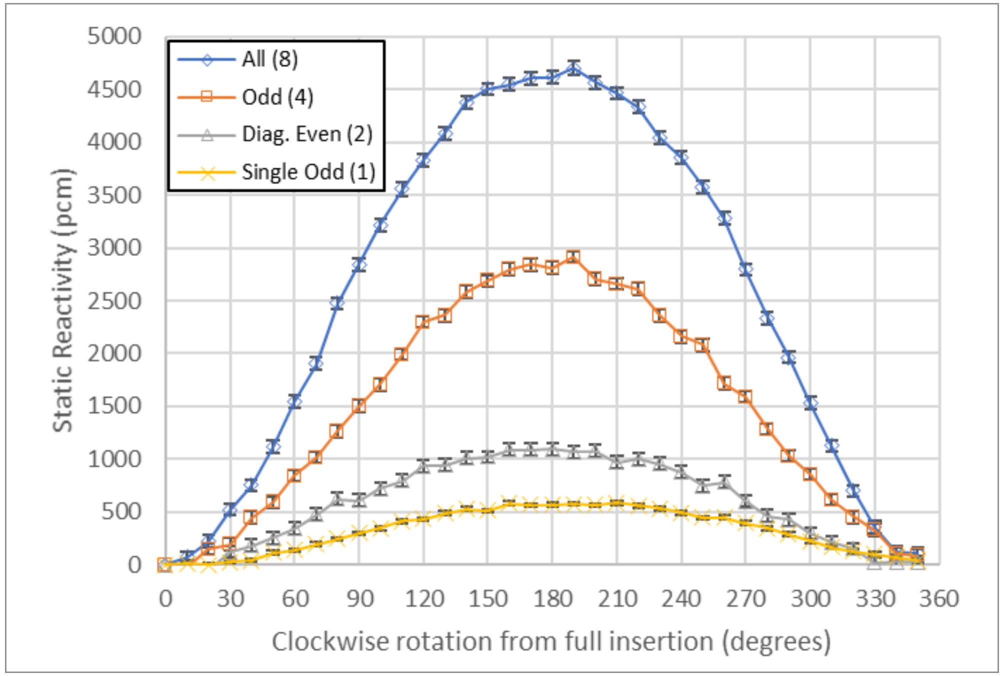
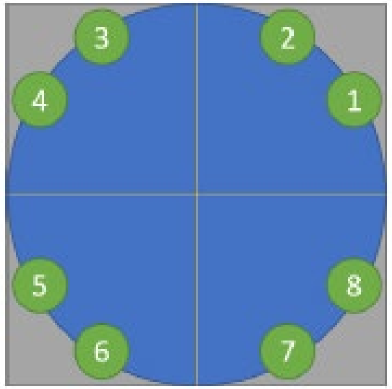


Summary of Reactivity Envelope for "Variable Reflector"

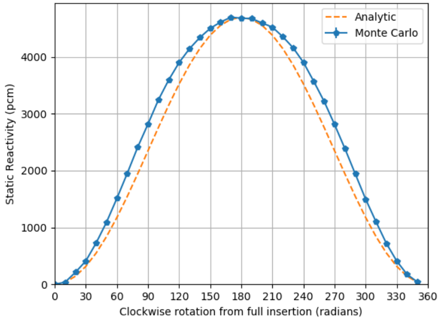
- 12 patterns, 10-degree drum increments
  - 432 Serpent calcs, each on 24 threads, 6 hours
  - Presently developing some data driven reduced order models

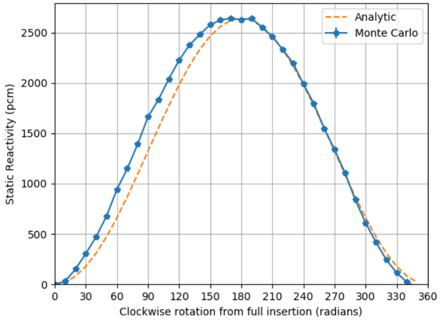


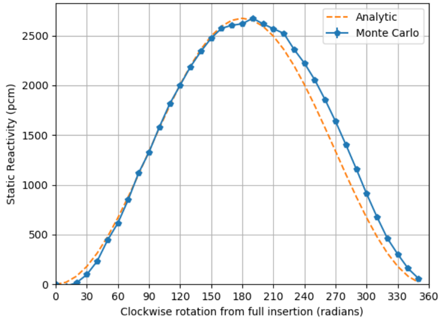
Integral Drum Worth



Consider 12 different patterns



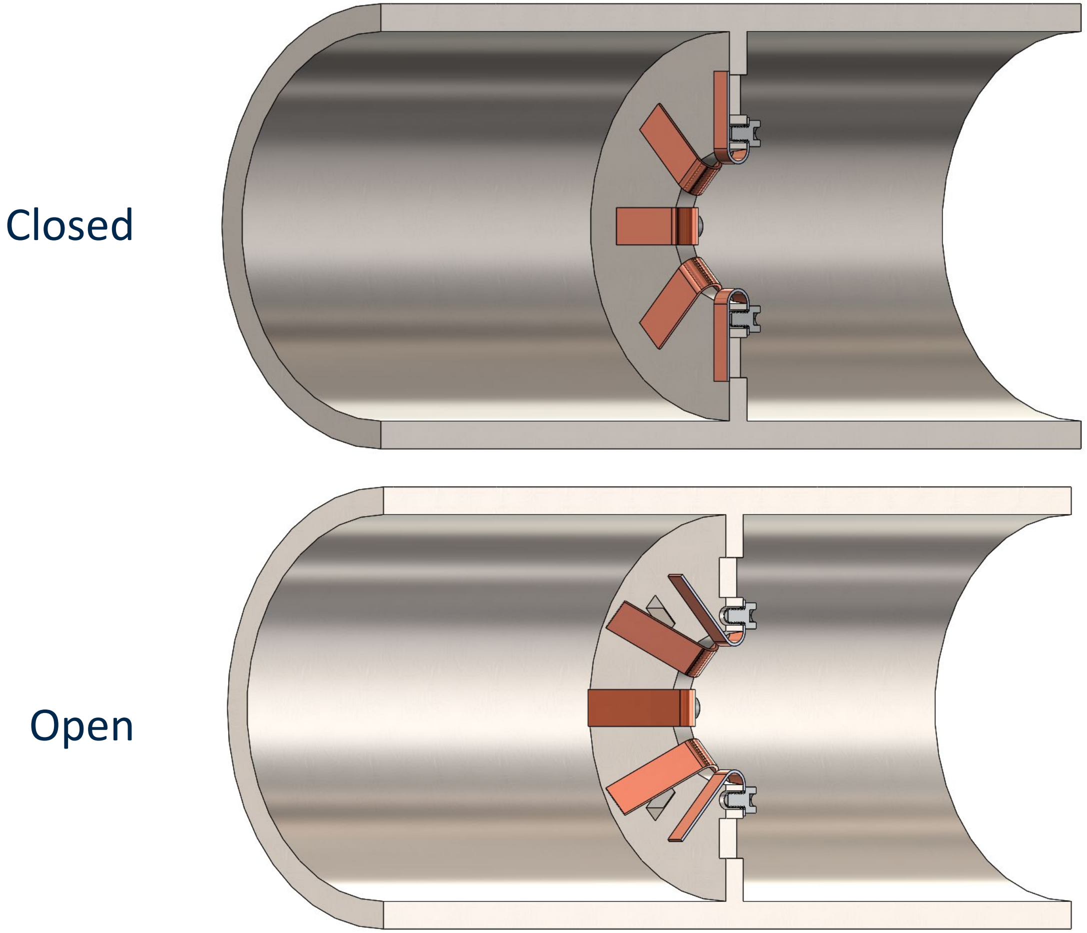




Passive Variable Flow Controller Concept (Design in Progress)

- Use bimetallic valve based on thermal expansion
- Temperature increases—flow area increases
- Temperature decreases—flow area decreases

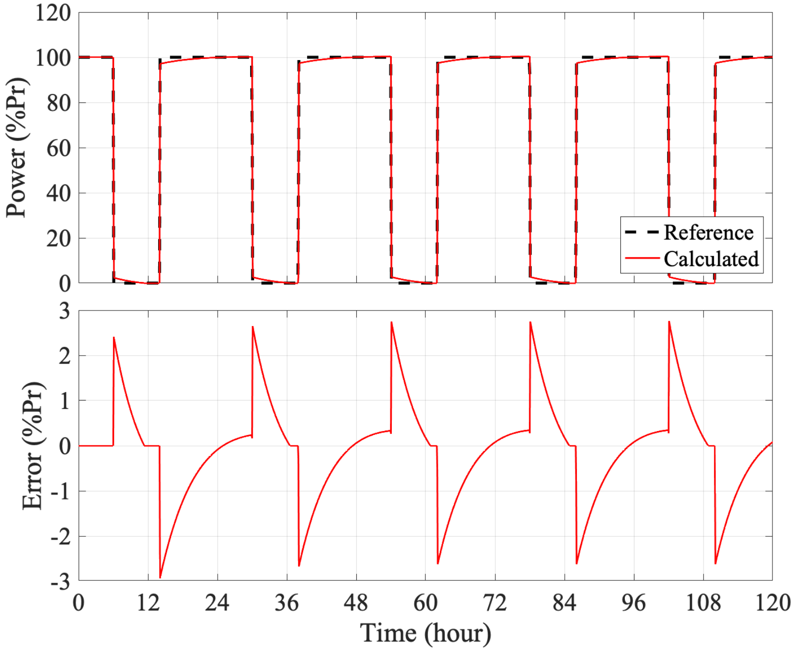
Analogous to turbine throttling
Concept could be implemented for valves for turbine bypass, compressor throttling, or inventory control

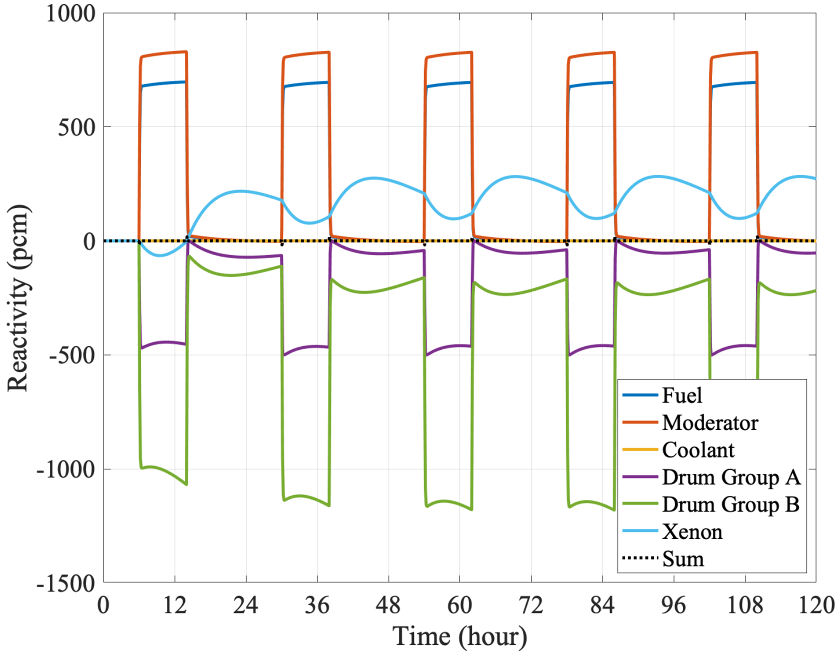


Conceptual Illustration

Model Predictive Control Assessment (How good is a controller without Xe Dynamics?)

- Real-time model-based controllers will necessarily have approximations and uncertainties
  - Known approximations for lumped parameter models
  - Known uncertainties from expected operation variation in coefficients
- Can we simulate and provide reactor control for load follow when we purposefully ignore "first order physics"?





Publications

1. S. Choi, S. Kinast, V. Seker, C. Filippone, and B. Kochunas, "Preliminary Study of Model Predictive Control for Load Follow Operation of Holos Reactor," ***Trans. Am. Nucl. Soc.***, vol. 122, pp. 660–663, 2020, doi: 10.13182/T122-32327.
2. D. Sivan *et al.*, "Linear Stability Analysis of HTR-like Micro-reactors," ***Trans. Am. Nucl. Soc.***, vol. 122, pp. 664–667, 2020, doi: 10.13182/T122-32399.
3. V. Seker and B. Kochunas, "Assessment of Variable Reflector Reactivity Envelope in Multi-Module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-002-00, Ann Arbor, MI, Apr. 2020.
4. B. Kochunas, K. Barr, and S. Kinast, "Assessment of Variable Reflector Reactivity Envelope in Multi-Module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-003-00, Ann Arbor, MI, Jul. 2020.
5. B. Kochunas, K. Barr, S. Kinast, and S. Choi, "Global and Local Reactivity Assessments for Passive Control Systems of Multi-module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-005-00, Ann Arbor, MI, Sept. 2020.
6. S. Choi, S. Kinast, and B. Kochunas, "Point Kinetics Model Development with Predictive Control for Multi-Module HTGR Special Purpose Reactors," **Tech. Report**, NURAM-2020-006-00, Ann Arbor, MI, Dec. 2020.
7. S. Kinast, D. Sivan, S. Choi, C. Filippone, and B. Kochunas, "Frequency Domain Analysis of HTR-Like Microreactors," **Proc. M&C 2021**, accepted.
8. S. Choi, S. Kinast, K. Barr, C. Filippone, and B. Kochunas, "Comparative Study of Control Algorithms for Load-Follow Operations of the Holos Microreactor," **Proc. of M&C 2021**, accepted.

MRP – NEUP Collaboration

Project ID: 19-17416 (Year Awarded 2019)

Title: Experiments and Computations to Address the Safety Case of Heat Pipe Failures in Special Purpose Reactors

PI: Dr. Victor Petrov, University of Michigan

TPOC: Dr. Donna Guillen, Idaho National Laboratory

Experiments and computations to address the safety case of heat pipe failures in Special Purpose Reactors.

DOE NEUP Project 19-17416

Victor Petrov, Annalisa Manera, Pei-Hsun Huang, Taehwan Ahn, Julio Diaz

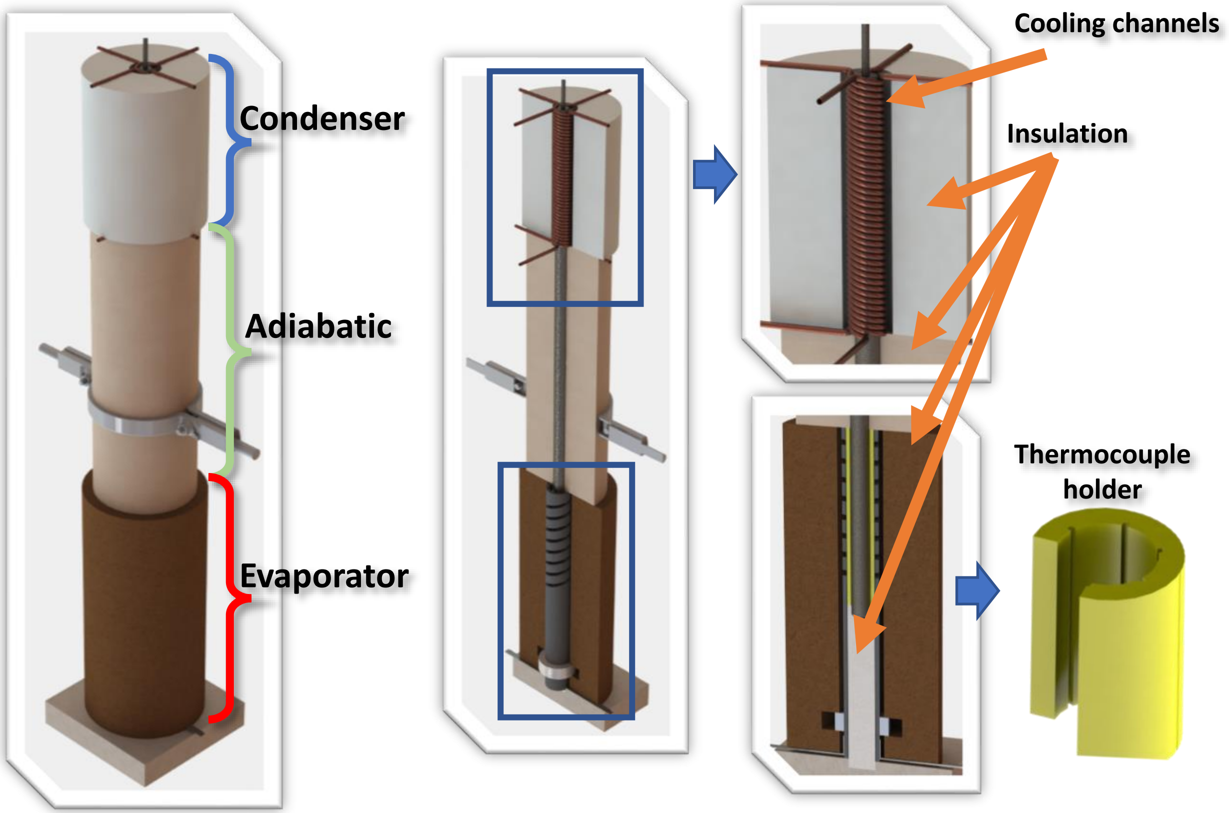
Microreactor Program Workshop

May 13th-14th 2021

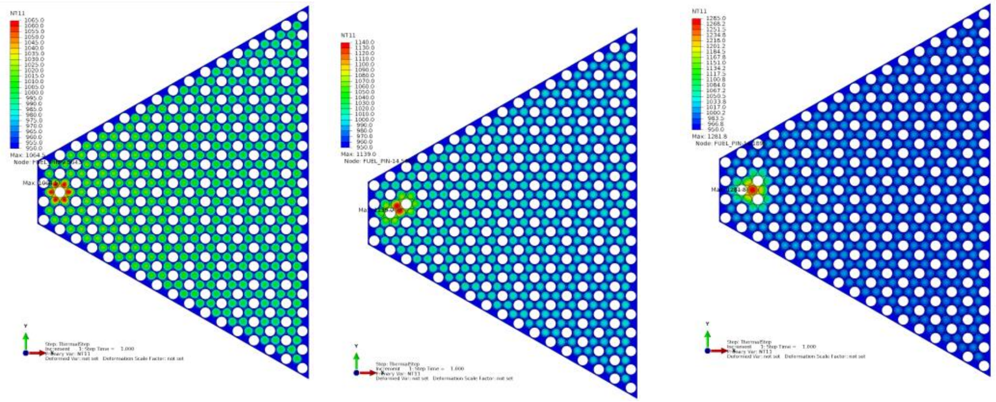
Project tasks

Task 1 Scaling study and pre-test simulations for the design of the experimental facility (sub core).
Task 2 Construction of the experimental facility.
Task 3 Definition and execution of experimental campaign.
Task 4 Validation (and further improvement) of the code's suite.
Task 5 Development of set of recommendations for heat pipe micro-reactors safety case.

Single heat pipe facility

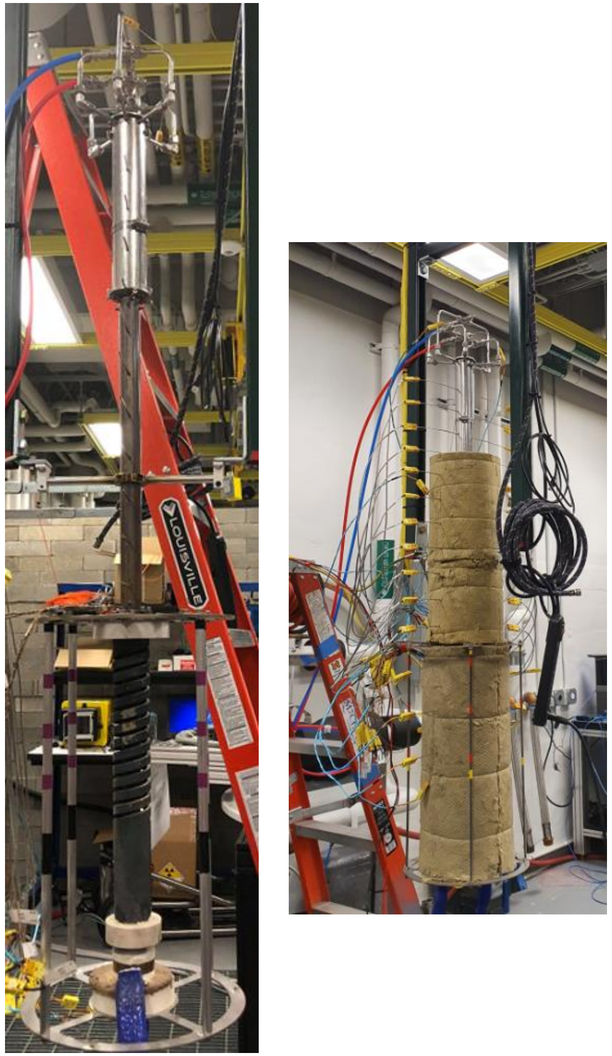


Multiply heat pipe failure scenario.



Transverse cross-section of monolith and fuel mid-plane temperature distribution for 1 failed heat pipe condition (left), 2 failed heat pipes (center) and three failed heat pipes (right) [Sterbentz et al.,2017].

Single heat pipe characterization facility



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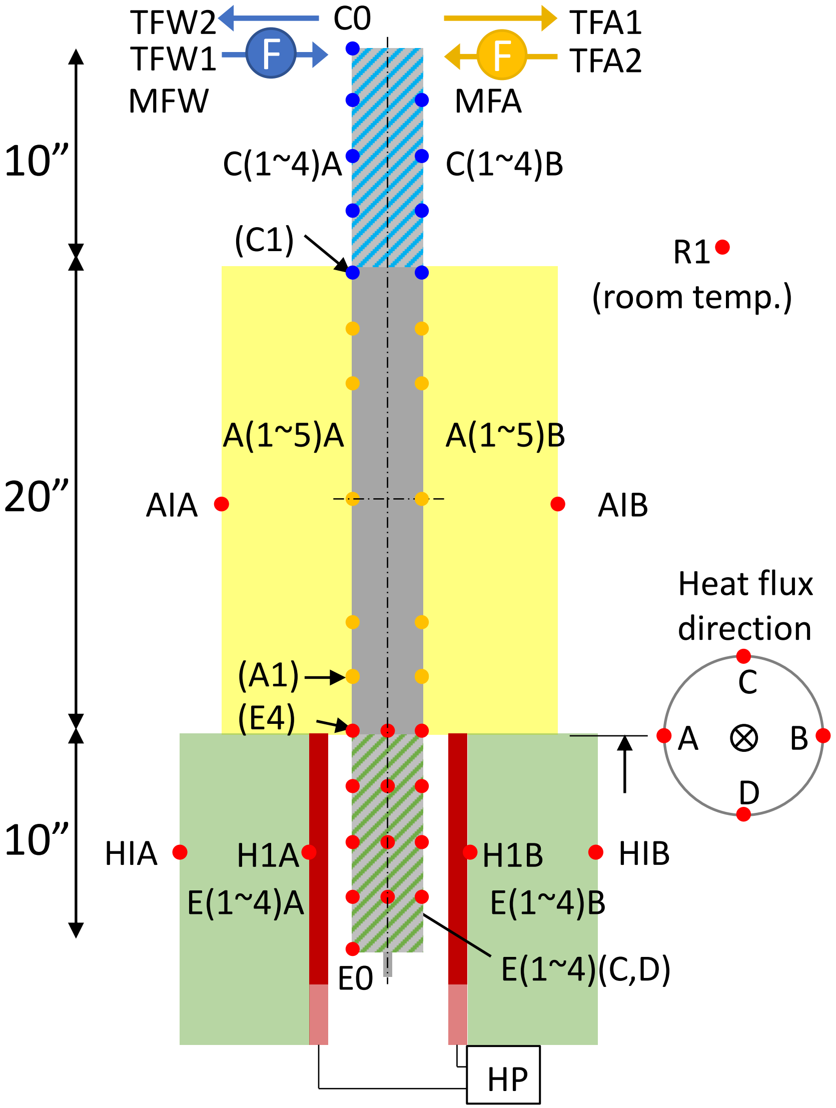

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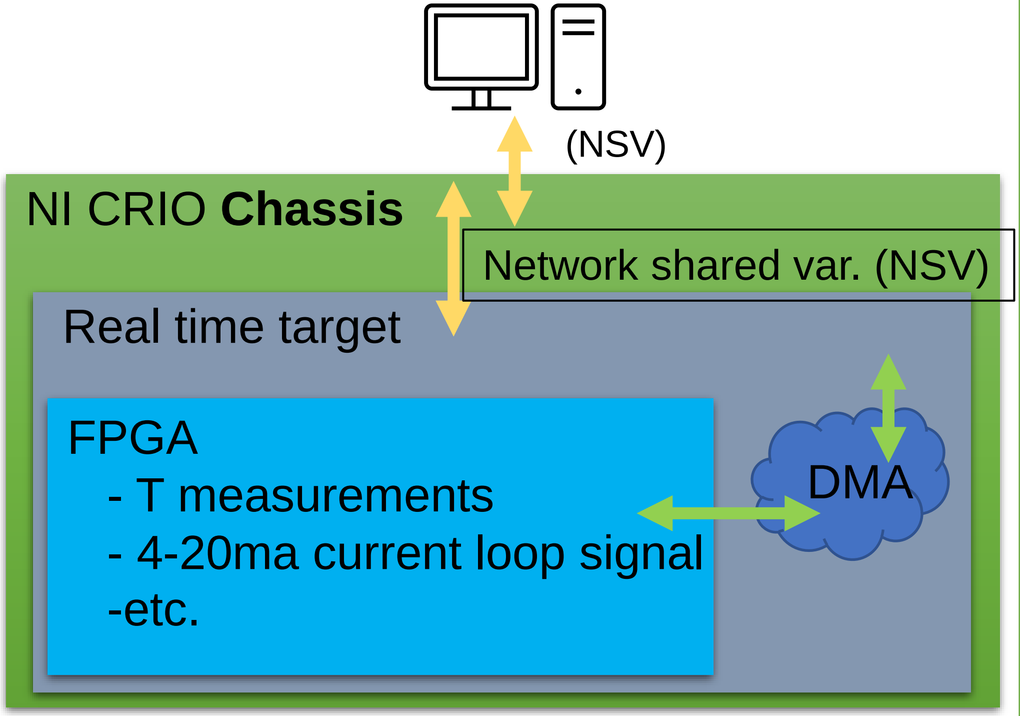


(NSV)

NI CRIO **Chassis**

Network shared var. (NSV)

Real time target

FPGA
- T measurements
- 4-20ma current loop signal
-etc.

DMA

<Data acquisition>

Test Conditions

TEST	Date	Objective	Max. heater power
003-011	2/04 – 3/05	Heat exchanger optimization (HX1 and HX2, ceramic fiber and RESCOR 750 casting material fillers)	1300 W
012	3/08	Horizontal	1776 W (700°C)
013-016	3/18-4/01	Heat exchanger optimization (HX2, copper filler)	1300 W
017-019	4/16	Inclination angle, HX3 check	1500 W
020-024	4/22 - 4/23	Heat exchanger optimization (HX3 and HX4)	2100 W

HX 1

Single Channel HX

HX 2

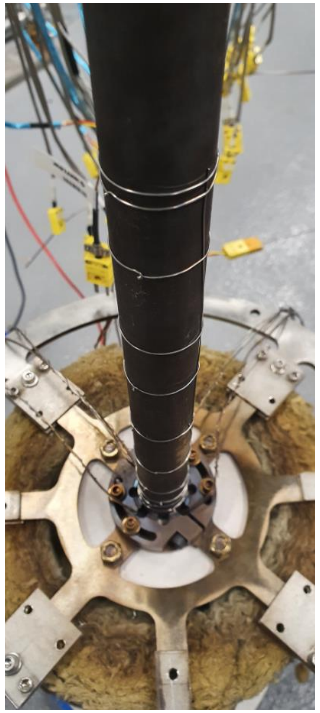
Double Channel HX

HX 3

Double Channel HX with Straight fins & outermost water channel

HX 4

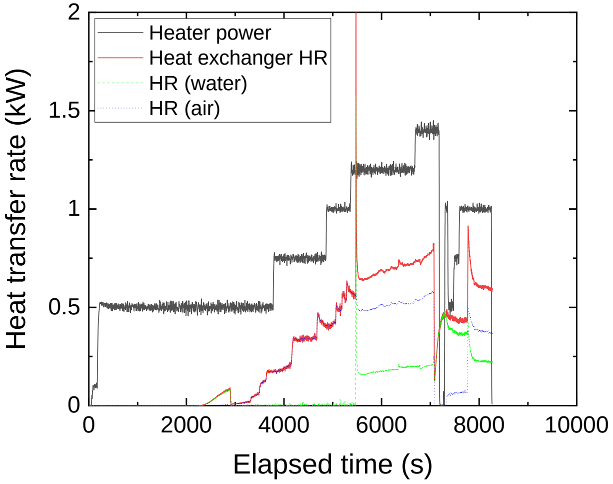
Double Channel HX with Spiral fins

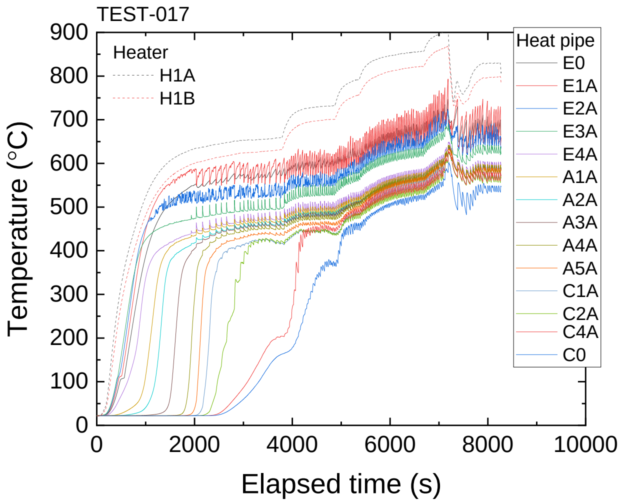


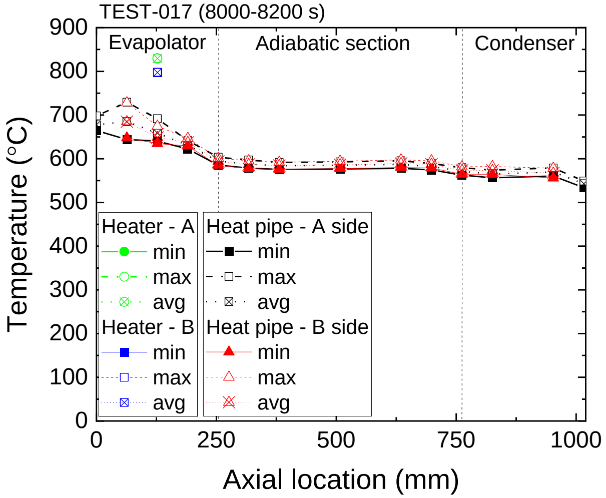
<Measurement>

Results

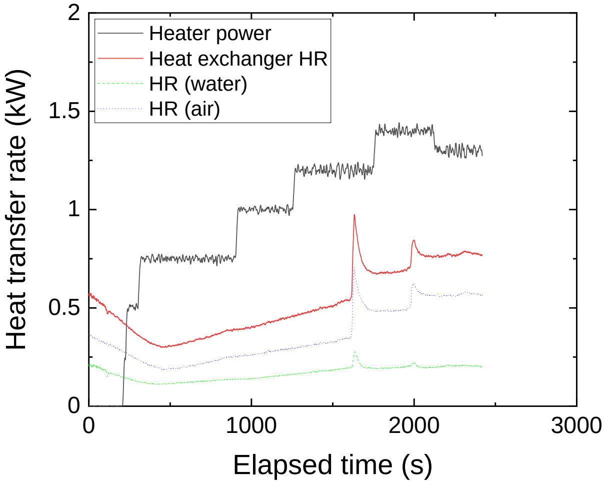
TEST-017: Vertical orientation (HP: 1000 W, Condenser HX: 602 W)

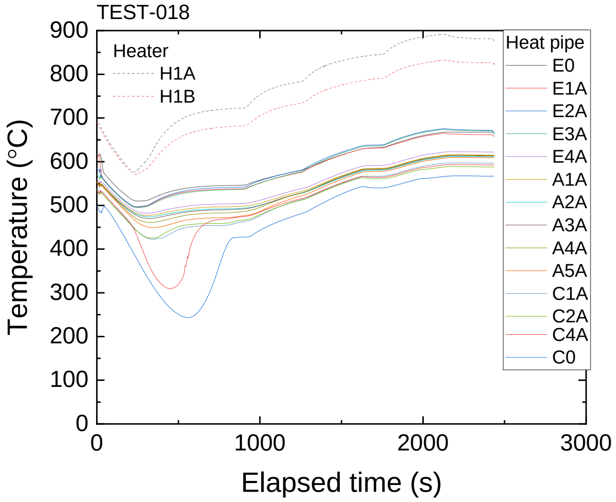


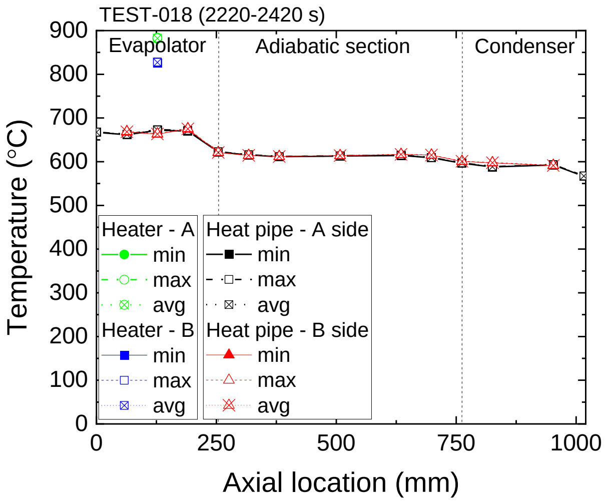




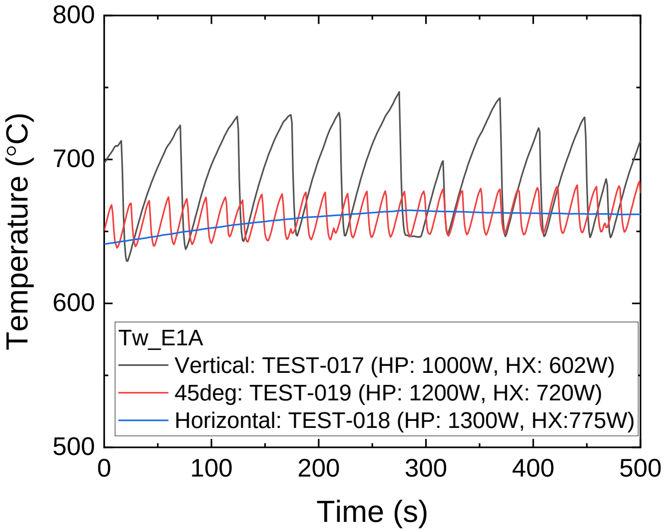
TEST-018: Horizontal orientation (HP: 1300 W, Condenser HX: 775 W)



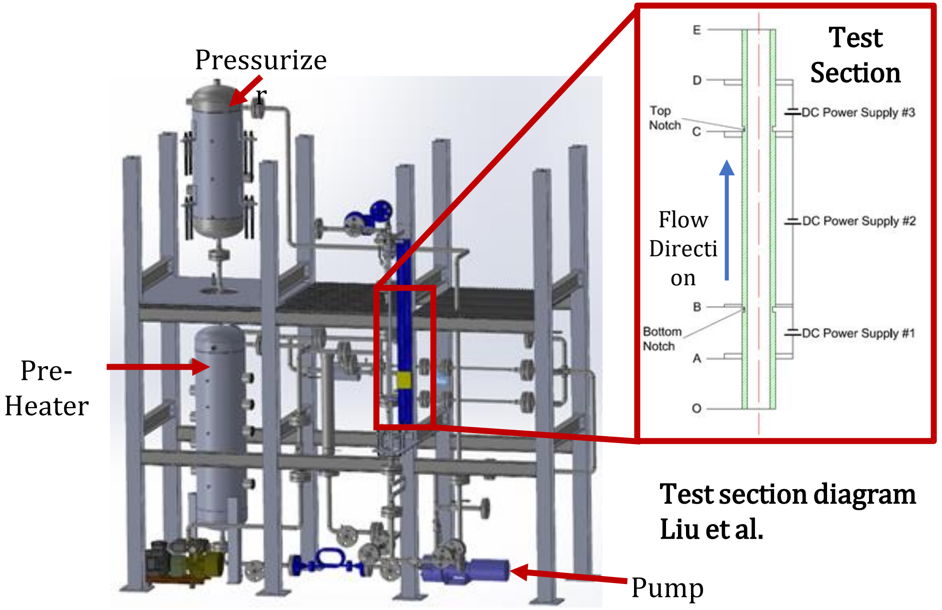




Vertical vs. Horizontal vs. Inclined



High speed X-ray imaging system (tomography /radiography)



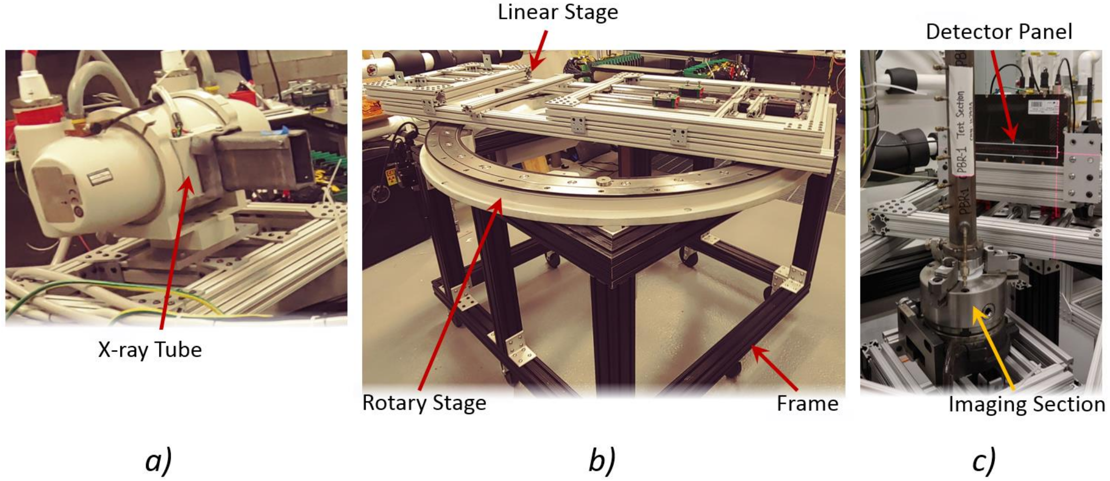
Test section diagram Liu et al.

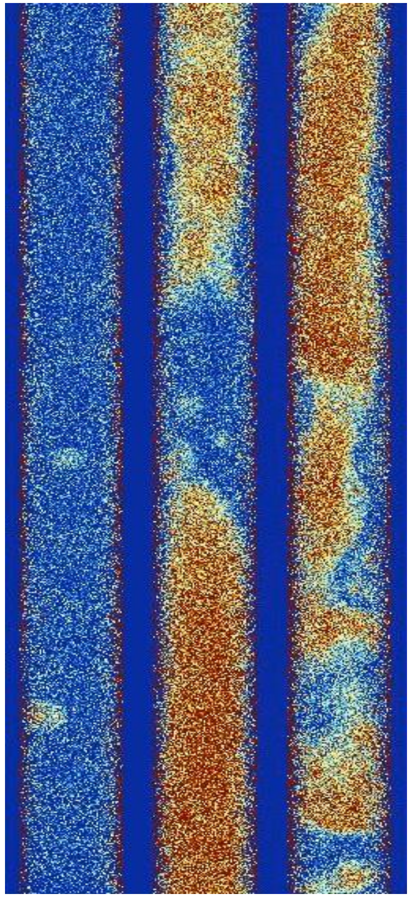
Liu, Q., Shi, S., Sun, X., & Kelly, J. (2018). Thermal hydraulic performance analysis of a post-CHF heat transfer test facility. Nuclear Engineering and Design, 339, 53-64.

The test section is designed to be heated by means of DC power with a max amperage 2500A.

- Cylindrical geometry test section
- Incoloy 800H
- Test section 1.0 m length
- Outer diameter of 19.05 mm
- Inner diameter of 12.95 mm
- Operational pressure of 20 to 1000 psi
  - T_{sat} of 100 to ~285 ^{o}C

Imaging system





J. Diaz, “Radiation Transmission Imaging Applications for Nuclear Reactor Systems”
Prospectus slides

Publications/Future plans

- P.-H. Huang , T. Ahn, A. Manera, V. Petrov “Design of a sodium heat pipe experimental setup for the Special Purpose Nuclear Reactor” ANS student conference 2021. **Best Paper Award**
- T. Ahn, P.-H. Huang, J. Diaz, A. Manera, V. Petrov, “An experimental study on startup characteristics of a sodium-filled heat pipe, using in-house high-resolution and high-speed radiation-based imaging system.” NURETH-19, accepted.

Future plans:

- Continuation of experimental campaign;
- High-speed x-ray “insitu” heat pipe imaging;
- Construction of multi heat pipe facility.

MRP – NEUP Collaboration

Project ID: 20-19042 (Year Awarded 2020)

Title: Flexible Siting Criteria and Staff Minimization for Microreactors

PI: Prof. Jacapo Buongiorno, Massachusetts Institute of Technology

TPOC: Jason Christensen, Idaho National Laboratory

MRP Microreactor Program

Microreactor Program Stakeholders Workshop

Flexible Siting Criteria and Staff Minimization for Micro-Reactors

May 12-13, 2021

MITei
MIT Energy Initiative

NSE
Nuclear Science
and Engineering
science : systems : society

THE PROJECT TEAM


Isabel Naranjo
(grad)


Edward Garcia
(grad)


Leanne Galanek
(UG)


Katherine Zhao
(UG)


Lucy Nester
(UG)

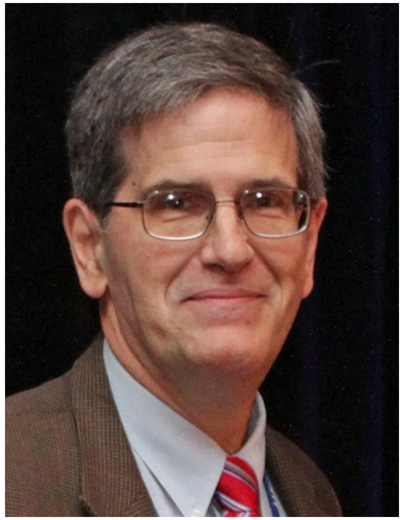

Jacopo Buongiorno
(PI, NSE)


Edward Lau
(NRL)


Sara Hauptman
(NRL)


Neil Todreas
(NSE)

THE ADVISORY COMMITTEE



Michael Corradini
(U-Wisconsin)

Matthew Smith
(Westinghouse)

James Kinsey
(INL, Coastal Technical Services)

ECONOMIC IMPERATIVES FOR MICROREACTORS

- To access large markets, microreactors must be licensable for deployment near and within population centers ⇐

- LCOE and LCOH analysis suggests that microreactors can meet the heat and electricity cost targets for large markets, if:
  - ➢ Power output is maximized, within microreactor constraints (e.g., truck transportability, passive decay heat removal)
  - ➢ Staff is in the 0.5-1.5 FTE/MW range ⇐
  - ➢ Enrichment <10% and burnup >20 MWd/kg_U
  - ➢ Microreactor fabrication cost (excluding fuel) <5000 $/kW
  - ➢ Discount rate <10 %/yr

⇐ focus of this project

PROJECT OBJECTIVES

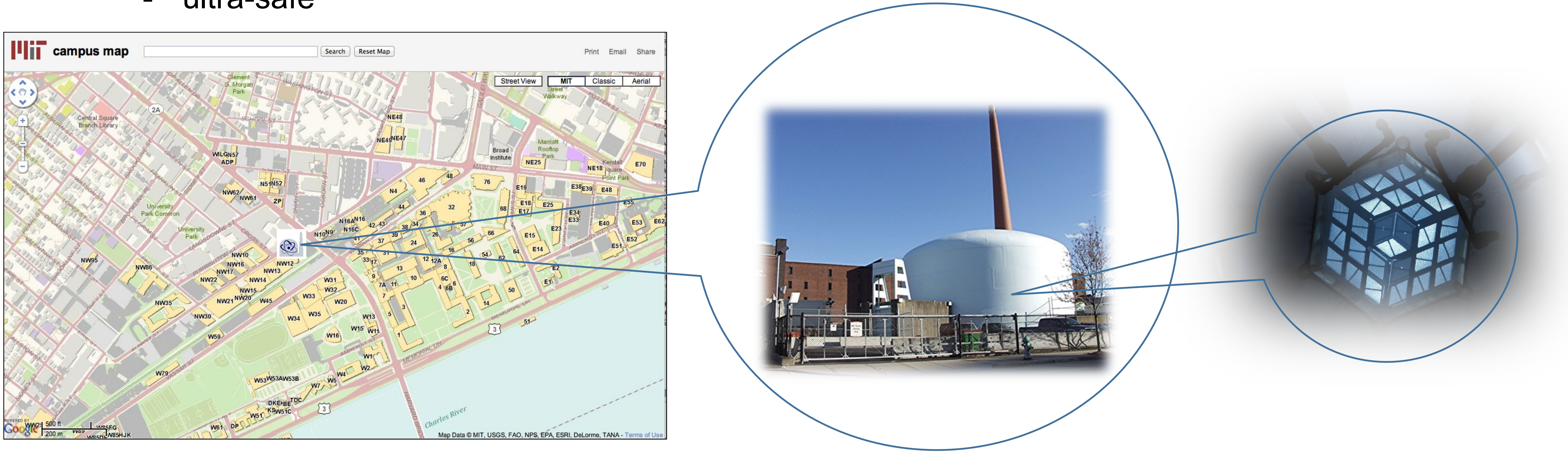
- Develop siting criteria that are tailored to micro-reactors deployable in densely-populated areas, e.g., urban environments.
- Conceptualize a model of operations and security for micro-reactors that would minimize the staffing requirements, and thus reduce the cost of electricity and heat generated by these systems.

APPROACH

- Compare MIT nuclear reactor (MITR) with leading micro-reactor concepts, and evaluate whether and how the MITR design basis (e.g., inherent safety features, engineered safety systems, source term, emergency planning and emergency operating procedures) and associated regulations may be applicable to micro-reactors.
- Review the MITR experience and requirements, as well as survey the innovations in autonomous control technologies (e.g., machine learning) and monitoring (e.g., advanced sensors, drones, robotics) that may permit a dramatic reduction in staffing at micro-reactor installations.

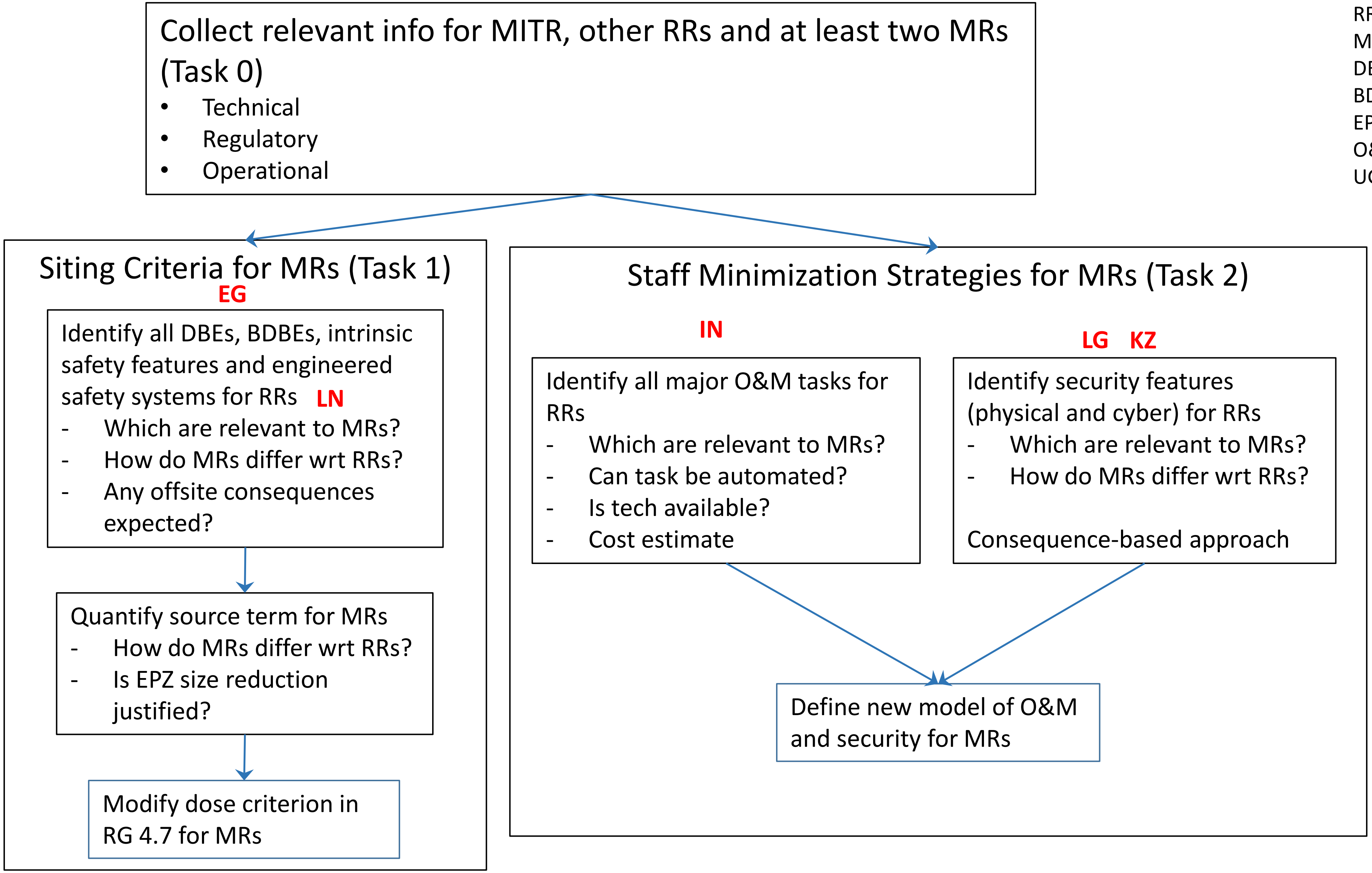
THE MITR

MITR is an urban micro-reactor:
- low power (6 MWt)
- 24/7 ops
- ultra-safe



But there are major differences:
- the mission is research (vs. commercial)
- unsuitable for heat utilization and electricity generation (<60°C core outlet temperature)
- frequent refueling (every 10 weeks)
- non-transportable
- large staff (operations + research + admin = 60 FTEs)

PROJECT SCOPE OF WORK



Collect relevant info for MITR, other RRs and at least two MRs (Task 0)

- Technical
- Regulatory
- Operational

Siting Criteria for MRs (Task 1)

EG

Identify all DBEs, BDBEs, intrinsic safety features and engineered safety systems for RRs **LN**

- Which are relevant to MRs?
- How do MRs differ wrt RRs?
- Any offsite consequences expected?

Quantify source term for MRs

- How do MRs differ wrt RRs?
- Is EPZ size reduction justified?

Modify dose criterion in RG 4.7 for MRs

Staff Minimization Strategies for MRs (Task 2)

IN

Identify all major O&M tasks for RRs

- Which are relevant to MRs?
- Can task be automated?
- Is tech available?
- Cost estimate

LG KZ

Identify security features (physical and cyber) for RRs

- Which are relevant to MRs?
- How do MRs differ wrt RRs?

Consequence-based approach

Define new model of O&M and security for MRs

Legend

MITR = MIT Reactor

RR = Research Reactor

MR = Micro-Reactor

DBE = Design-Basis Event

BDBE = Beyond Design Basis Event

EPZ = Emergency Planning Zone

O&M = Operation & Maintenance

UG = Under-Graduate Student

Student Names

EG = Edward Garcia

IN = Isabel Naranjo

LG = Leanne Galanek

LN = Lucy Nester

KZ = Katherine Zhao

RG 4.7 Revision Example

Current:

- A reactor should be located so that, at the time of initial plant approval within about 5 years thereafter, the population density, including weighted transient population, averaged over any radial distance out to 20 mi (cumulative population at a distance divided by the circular area at that distance), does not exceed 500 persons per square mile. A reactor should not be located at a site where the population density is well in excess of this value.

MR Addition:

- A microreactor can be sited in an environment in which the population density exceeds 500 persons per square mile on the basis that the EPA early-phase PAG minimum of 1 rem projected dose to a member of the public over the course of 4 days is not exceeded for any credible accident release including the MCA. Additionally, the outer perimeter of the microreactor must serve as the boundary of the EA, EPZ, and LPZ. Additional EPA PAGs must be met (working on this still).

PAG = protective action guidelines; EA = Exclusion Area; EPZ = Emergency Planning Zone; LPZ = Low Population Zone; MCA = Maximum Credible Accident

MRP – NEUP Collaboration

Project ID: 20-19693 (Year Awarded 2020)

Title: Evaluation of microreactor requirements and performance in an existing well characterized micro-grid

PI: Prof. Caleb Brooks, University of Illinois

TPOC: Dr. Scott Greenwood, Oakridge National Laboratory

MRP Microreactor Program

Evaluation of micro-reactor requirements and performance in an existing well-characterized micro-grid

Project 20-19693

Caleb S. Brooks, Kathryn D. Huff, Tomasz Kozlowski
University of Illinois

Jacob DeWitte
Oklo Inc.

May 12, 2021

Project Purpose:

to quantify the opportunities and challenges of operating micro-reactors in decentralized power generation environments and the potential for deployment in established micro-grids with diverse power generation sources.

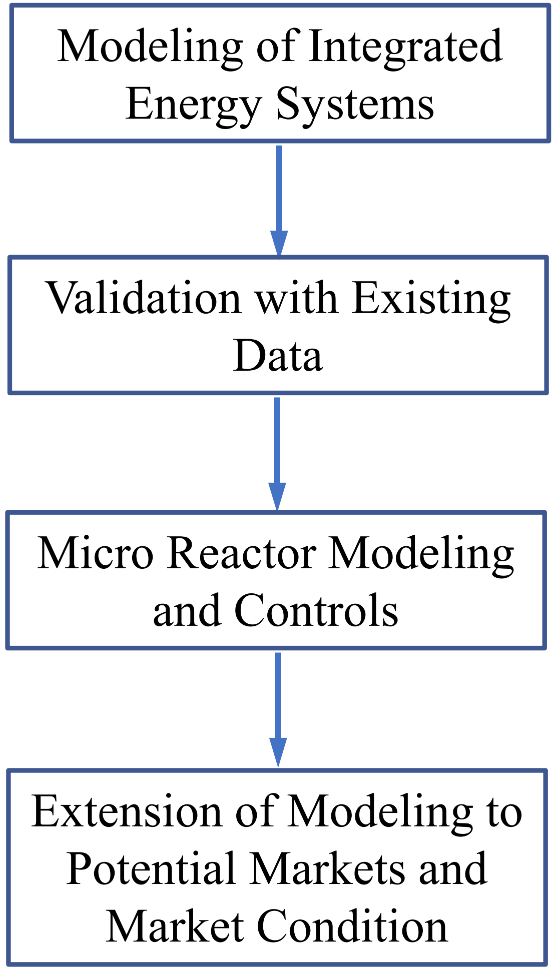
Project Objectives:

1) Develop integrated systems modeling of micro-reactor applications,
2) Incorporate available data to validate modeling,
3) Simulate normal and bounding events
4) Determine economic performance requirements across applications,
5) Identify operational requirements and opportunities across applications.
6) Determine the scalability of micro-reactor deployment at campuses and other existing micro-grids.

Expected Project Outcomes:

1) detailed analysis of the market potential for micro-reactors in existing micro-grids
2) expansion of the Modelica-based hybrid energy system modeling to include the existing well-characterized environment of a functioning micro-grid with diverse energy generation and dispatch portfolio,
3) economic target for micro-reactors deployed as electricity producers, thermal energy producers, and hydrogen producers,
4) identification of specific economic and technical opportunities to guide technology development efforts,
5) foundational training of the next generation of nuclear engineers in the critical path for the wide adoption of clean, safe, reliable nuclear power.

Project flow chart



Modeling of Integrated Energy Systems

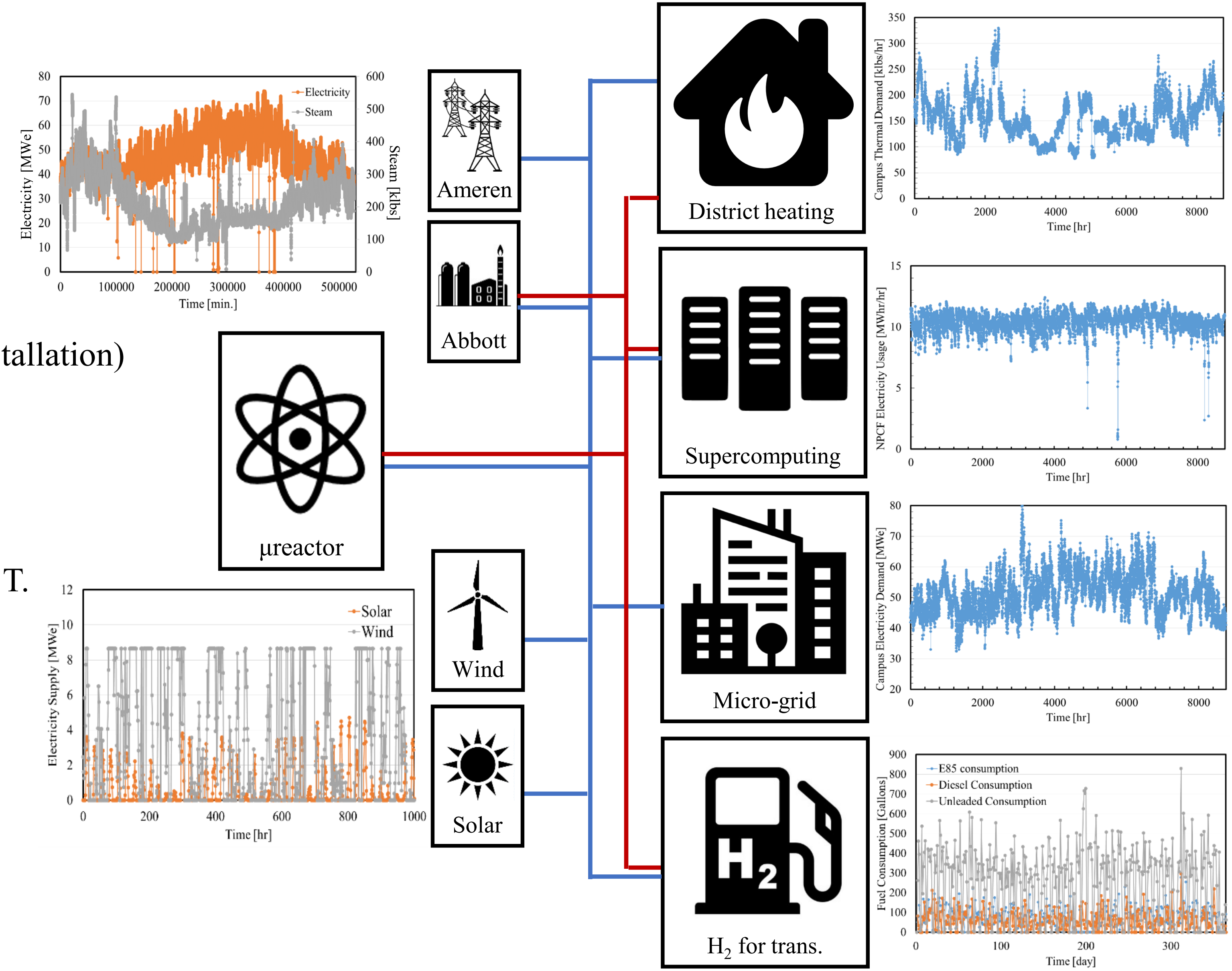
Validation with Existing Data

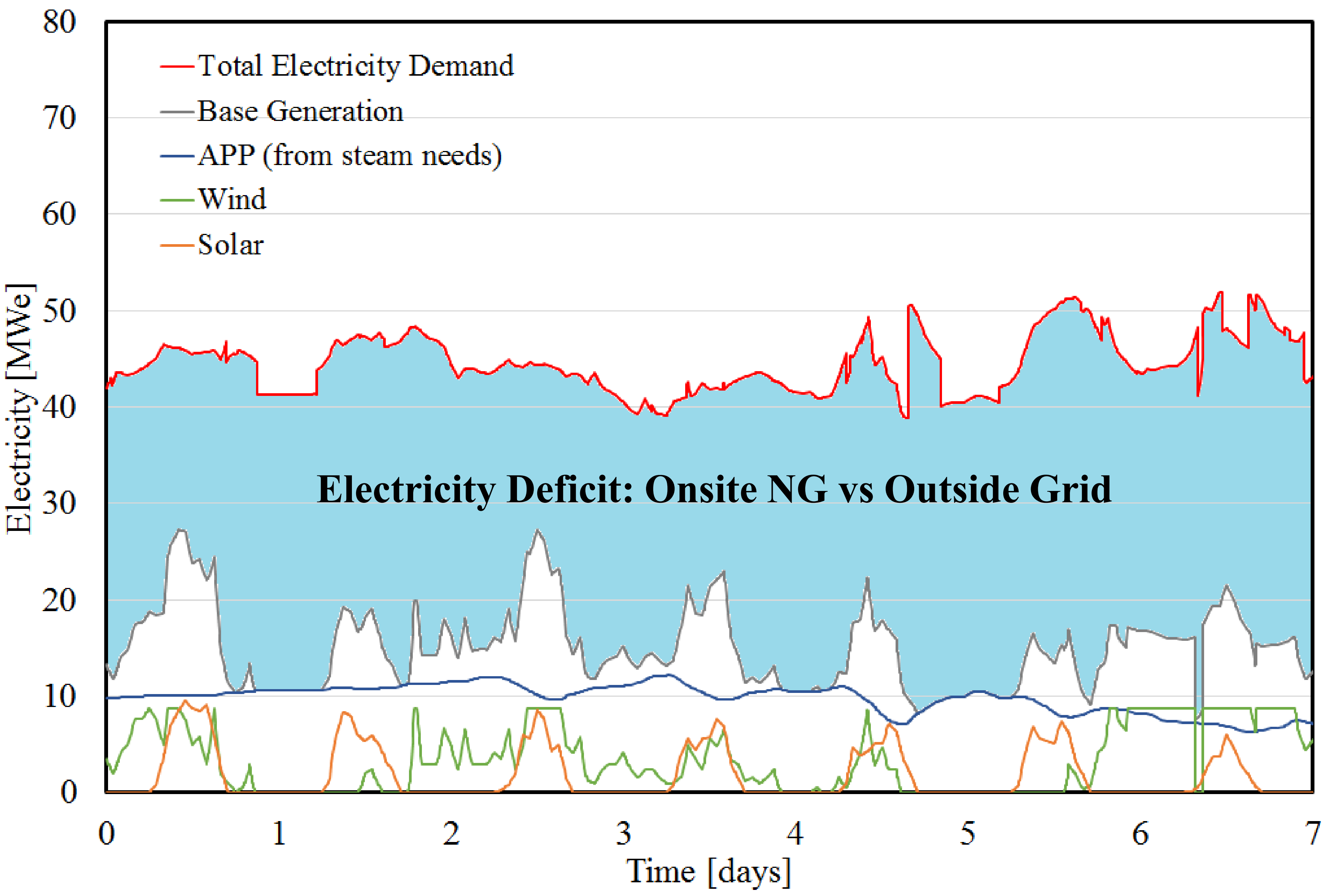
Micro Reactor Modeling and Controls

Extension of Modeling to Potential Markets and Market Condition

Model development: UIUC Campus

- Electrical
  - 55 MWe average demand
  - Blue Waters Supercomputer up to 15 MWe
  - Wind: ~25,000 MWh/yr
  - Solar: ~8,000 MWh/yr (25,000 MWh/yr new installation)
  - Chillers: ~8.5 MWe peak
- Thermal
  - 50 MWt average demand
  - High P steam constant, Low P steam varies with T.
  - 7 Chilled water plants (2 steam, 5 electric)
  - Energy storage (37,500 tons chilled water)
- Transportation
  - Campus fleet ~ 800 gallons/day
  - Campus bus system: up to 3,400 gallons/day
  - Bus system already investing in H_2 busses




Total Electricity Demand
Base Generation
APP (from steam needs)
Wind
Solar
Electricity Deficit: Onsite NG vs Outside Grid
Electricity [MWe]
0
10
20
30
40
50
60
70
80
Time [days]
0
1
2
3
4
5
6
7

Modelica: is an object-oriented, equation-based programming language built to assist design and analysis of applications with high complexity. Integration of mechanical, electrical, electronic, hydraulic, thermal, and control components. With Modelica the separation of physical models and the solvers of the models enables rapid generation of complex physical systems and control design in a single language.

Energy Production

Energy Demand

Economic, environmental, and other market factors

Planned markets: Data centers, hospitals, federal installations, remote outposts, etc.

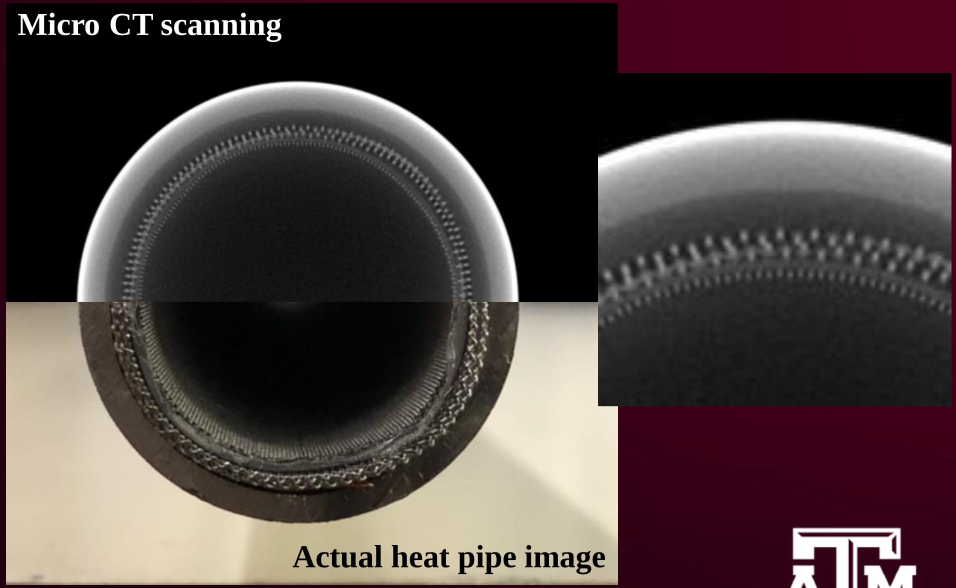
MRP – NEUP Collaboration

Project ID: 20-19735 (Year Awarded 2020)

Title: Experiments for Modeling and Validation of Liquid- Metal Heat Pipe Simulation Tools for Microreactor

PI: Prof. Yassin Hassan, Texas A&M University

TPOC: Dr. Piyush Sabharwall, Idaho National Laboratory



Experiments for Modeling and Validation of Liquid-Metal Heat Pipe Simulation Tools for Micro-Reactors

Joseph Seo
Rodolfo Vaghetto
Yassin Hassan

MECHANICAL ENGINEERING
TEXAS A&M UNIVERSITY

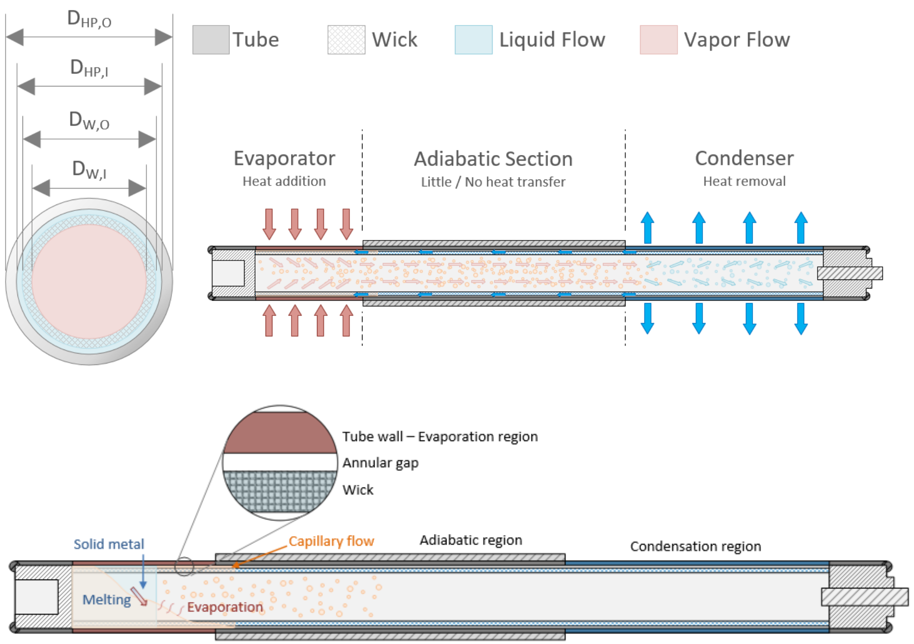
NUCLEAR ENGINEERING
TEXAS A&M UNIVERSITY
Thermal-Hydraulic Research Laboratory

Overview of the Project

Purpose: The proposed work aims to produce high-fidelity liquid-metal heat-pipe experimental data for the validation of the simulation tool, Sockeye, through both single heat-pipe and integrated heat-pipe experiments.

Objectives:

- **Single Liquid-Metal Heat-Pipe Experiment**
  Measurements of internal temperature, pressure, and phase distribution for validation/development of heat transfer and flow models in Sockeye.
- **Single Heat-Pipe Hydraulic Experiment**
  Measurements of the hydraulic resistance for validation/development of wall friction, wick friction/form loss models.
- **Multiple Liquid-Metal Heat-Pipes Experiment in Hexagonal Arrangement**
  Investigate the integrated system performance under various operational scenarios such as partial failure of constituent heat pipes and non-uniform cooling/heating.



Sodium heat pipe with targeted design

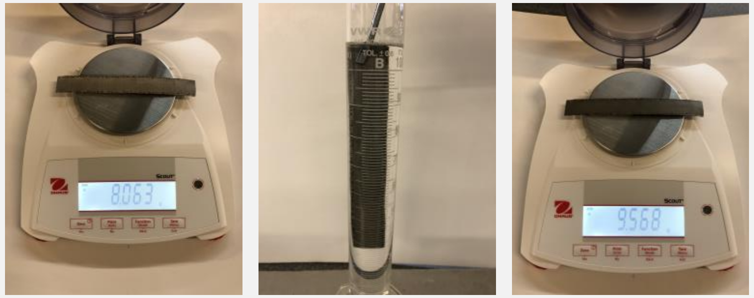
Wick Characteristics Experiment

The wick with the best performance

composite wick structures were characterized

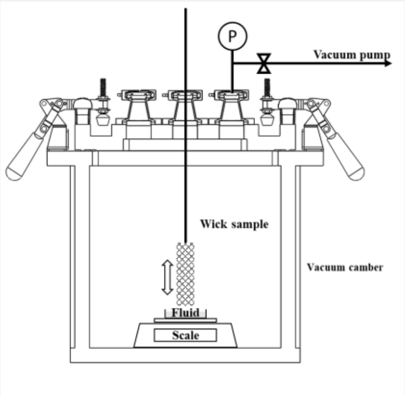
Case #	Total number of layers	Mesh composition			Measurement result			
		100-mesh (inside layer)	400-mesh (middle layer)	60-mesh (outside layer)	Porosity (ε [−])	Permeability (K [μm^2])	Effective Pore Radius ($r_{eff}[mm]$)	$\frac{K}{r_{eff}}$ [μm]
1	6	6	0	0	0.642	0.815×10^3	0.266	3.064×10^3
2		0	6	0	0.767	0.825×10^3	0.232	3.556×10^3
3		0	0	6	0.626	0.745×10^3	0.419	1.778×10^3
4		2	2	2	0.634	0.985×10^3	0.252	3.909×10^3
5		1	3	2	0.653	1.435×10^3	0.213	6.737×10^3
6		2	3	1	0.667	1.205×10^3	0.264	4.564×10^3
7		2	1	3	0.637	0.300×10^3	0.188	1.596×10^3
8		3	2	1	0.671	0.635×10^3	0.169	3.757×10^3
9		3	1	2	0.682	1.080×10^3	0.284	3.803×10^3

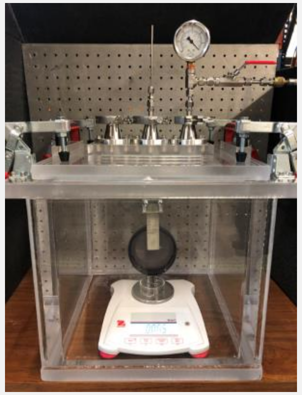
Porosity measurement

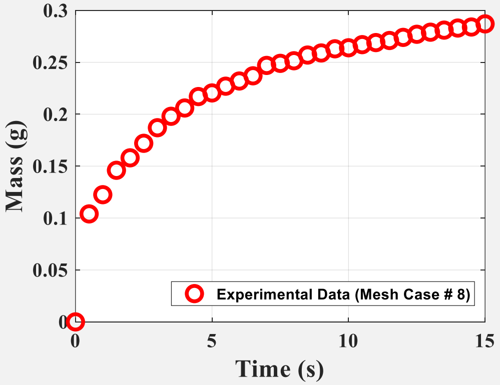


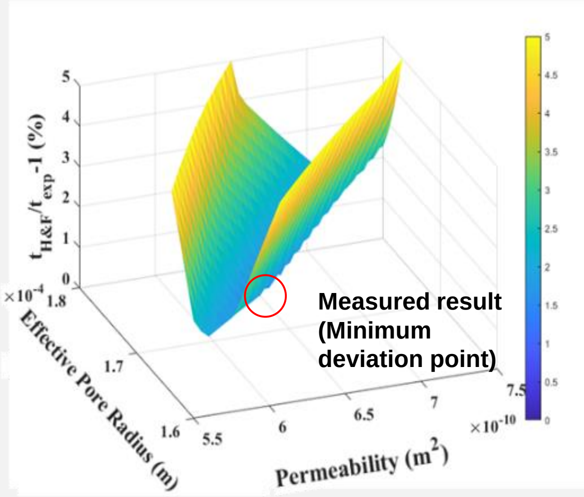
Porosity is calculated from the mass and density of the liquid filling void space of the mesh.

Permeability and **effective pore radius** measurements







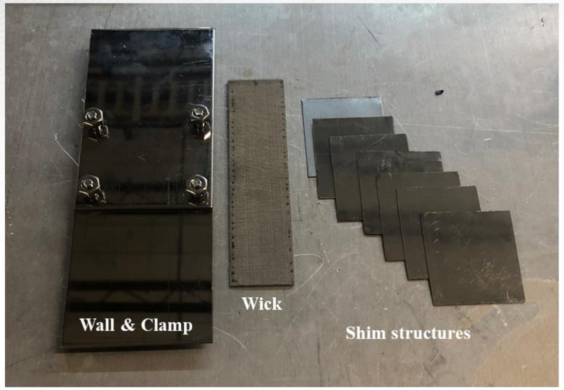


Measured result (Minimum deviation point)

The method by Holley and Faghri (2004) is used.

Gap Effect Experiments

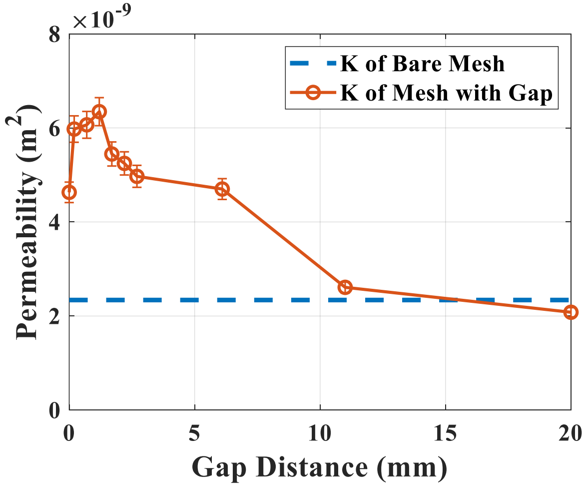
Wick assembly with adjustable gap between the wall

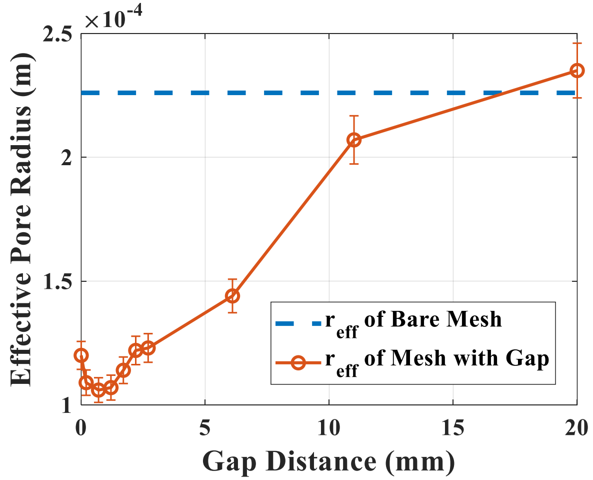


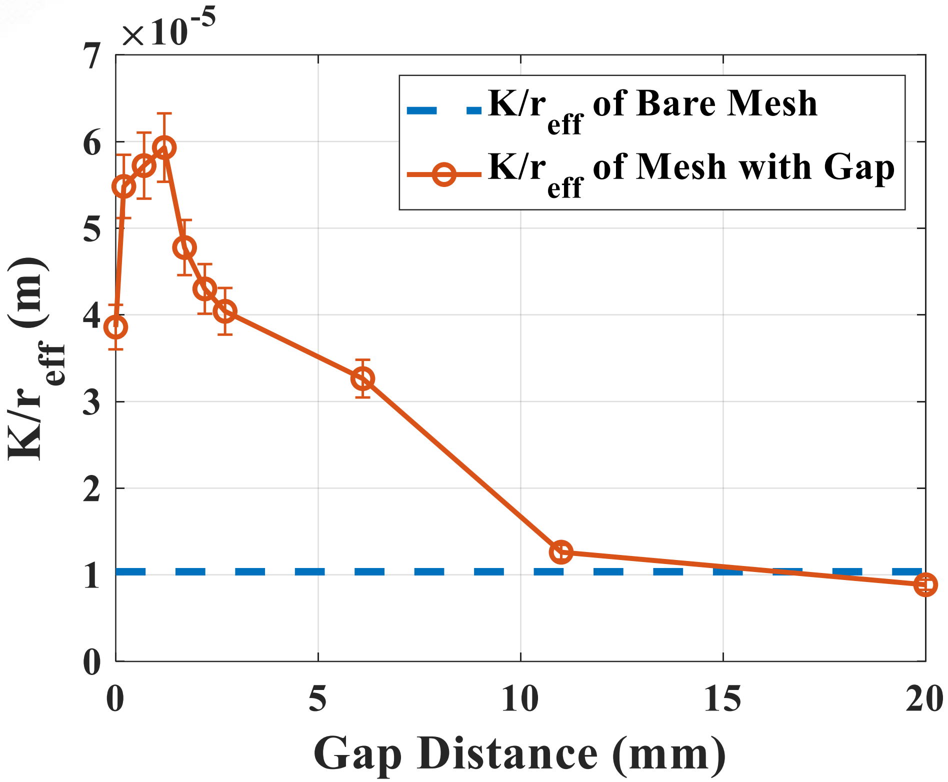

Front view


Side view

Wick samples were prepared to measure permeabilities and effective pore radius with different sizes of gap (0.0 mm ~ 20.0 mm) between stainless steel wall.





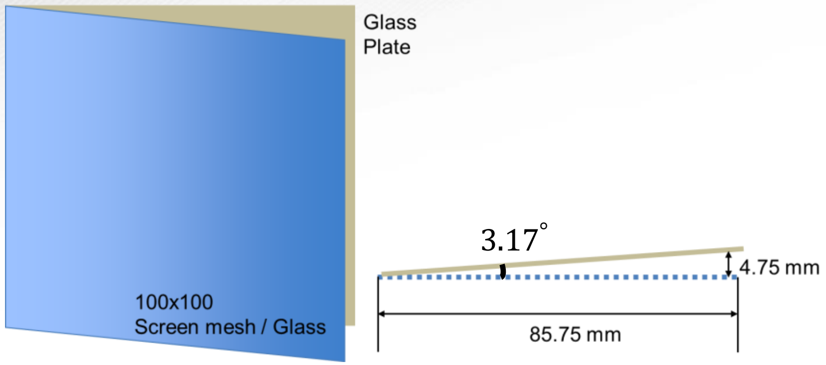


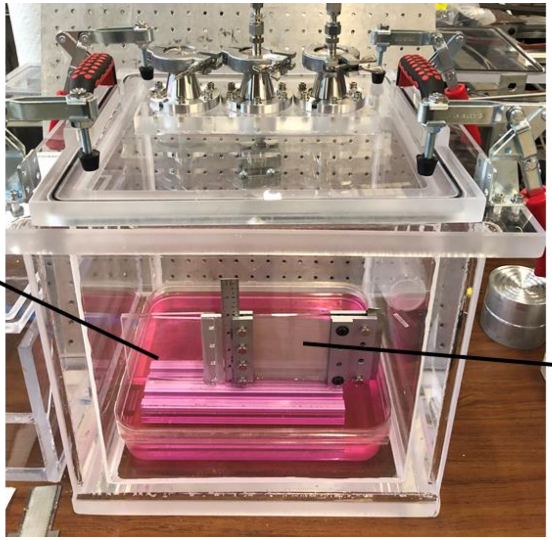
Optimal distance of the gap for the annular type heat pipe was found

The result of the measurement is plotted to the gap distance. An interesting trend can be found from the result. The K/R_{eff} increases as the gap become wider, making a peak **at 0.7 to 1.2 mm.** As the gap increases, the measured value converges to the bare mesh case.

Angled Mesh-Plate Experiment

Experimental setup of angled mesh-plate experiment





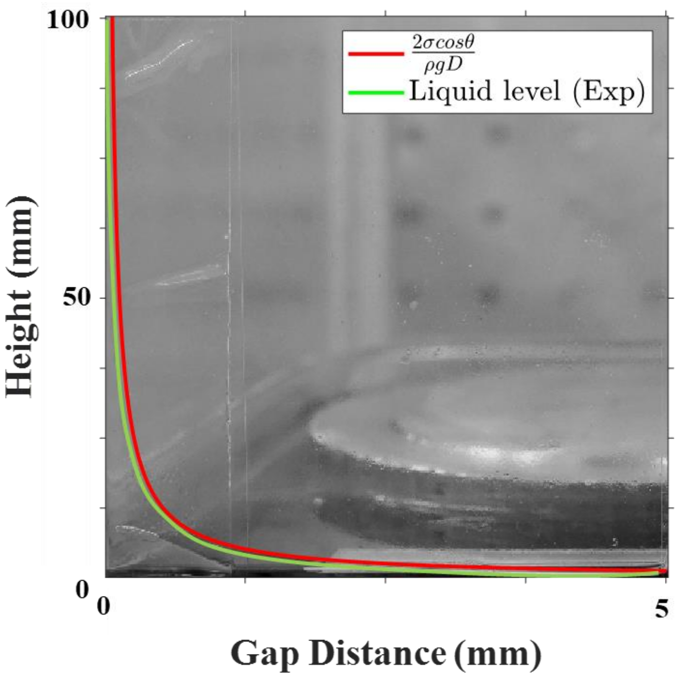
Glass/ Glass

Glass/ Mesh

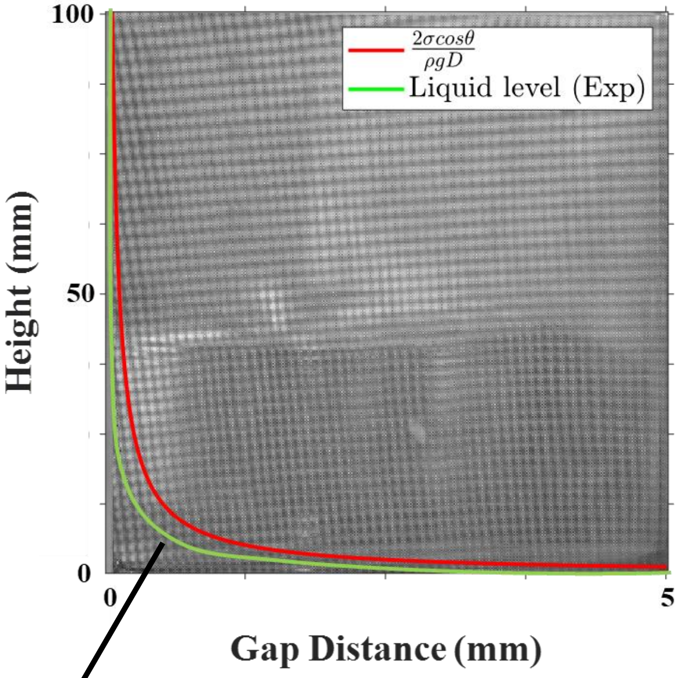
Experimental result

Contact angle of ethanol on a glass surface

Glass/Glass experiment ($\theta = 30^\circ$)



Glass/Mesh experiment ($\theta = 30^\circ$)

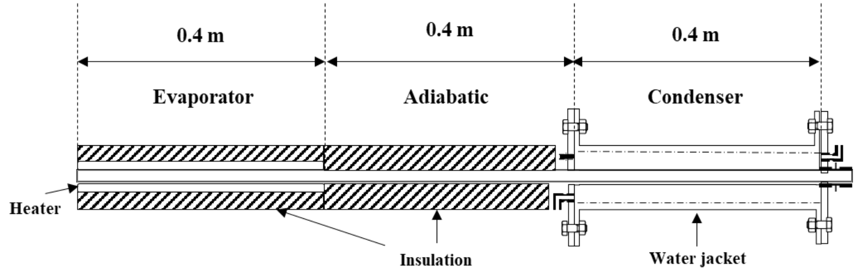


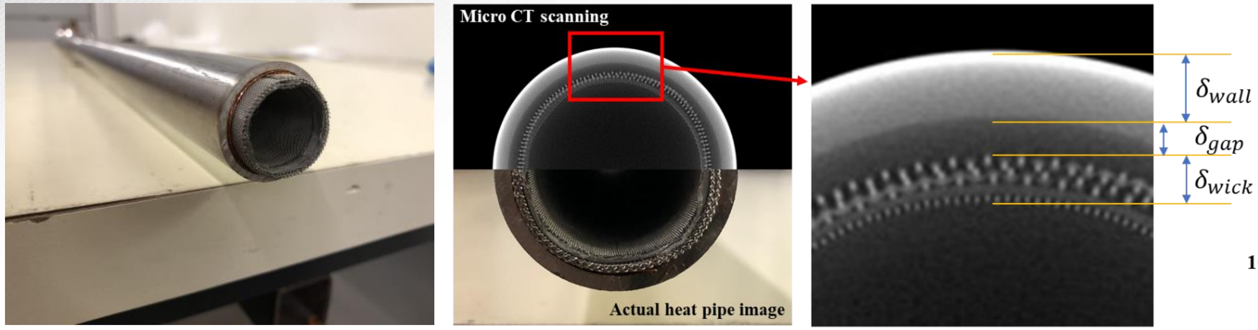
The rising height of the liquid in a gap between solid/mesh differs from solid/solid case.

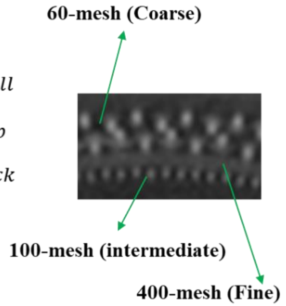
There is no previous study on the capillary pressure acting on solid surface/mesh surface.

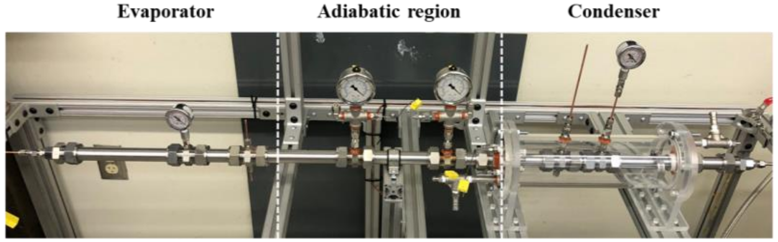
These results are needed for high-fidelity gap effect modeling.

Heat Pipe Fabrication and Experiment
Micro Computed Tomography (Micro CT)

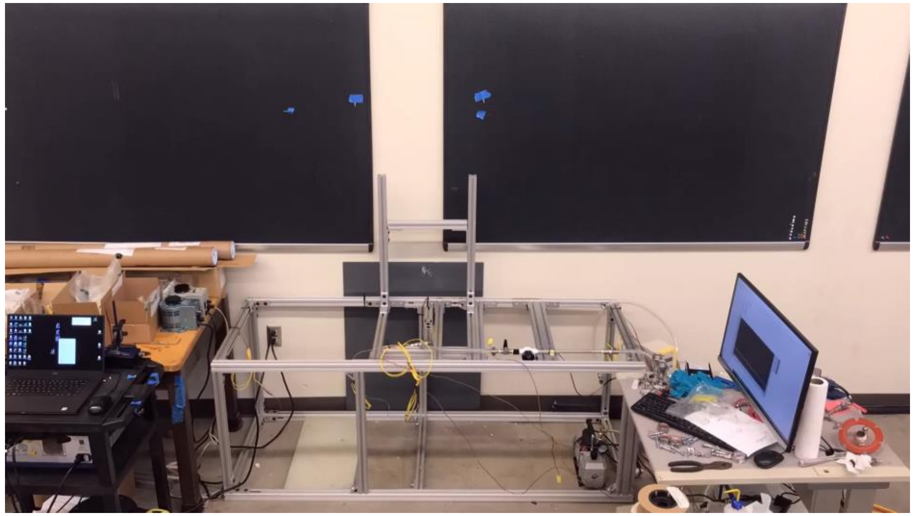


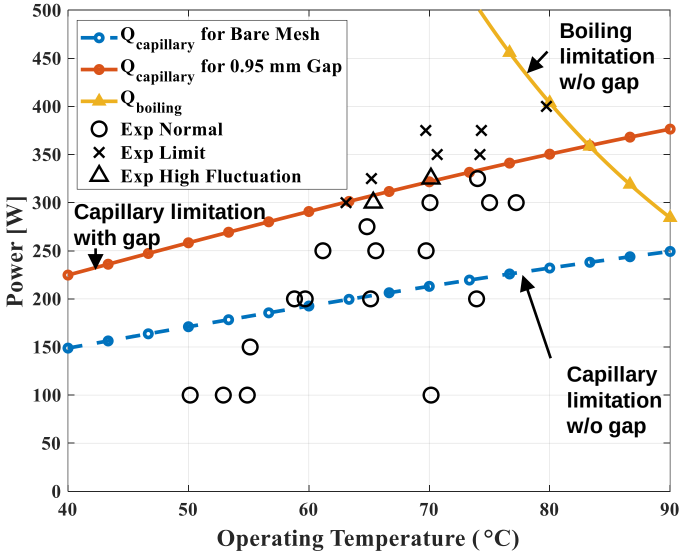




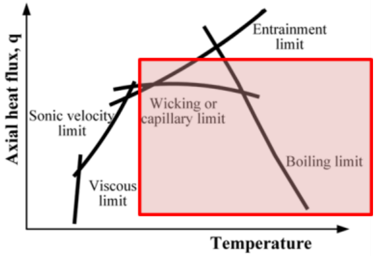


Multi-layered composite screen wick mesh was fabricated (Water as a working fluid).

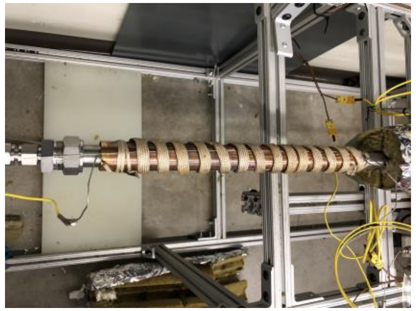




The operating limitation of the heat pipe matches well with the prediction calculated from the result of the wick characterization and gap effect experiment.

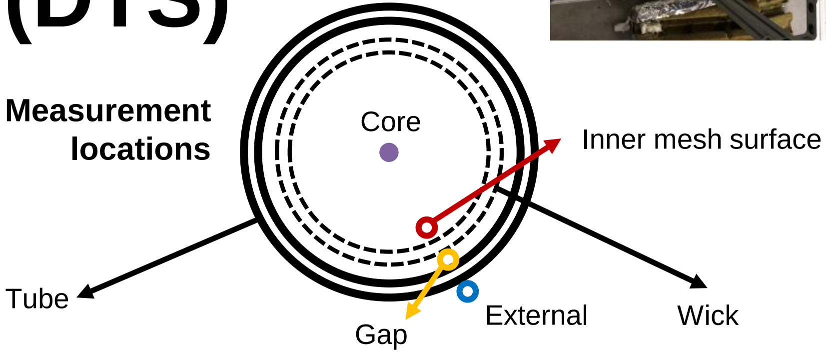


Heater was wrapped on the copper tube for uniform heat transfer to the heat pipe.

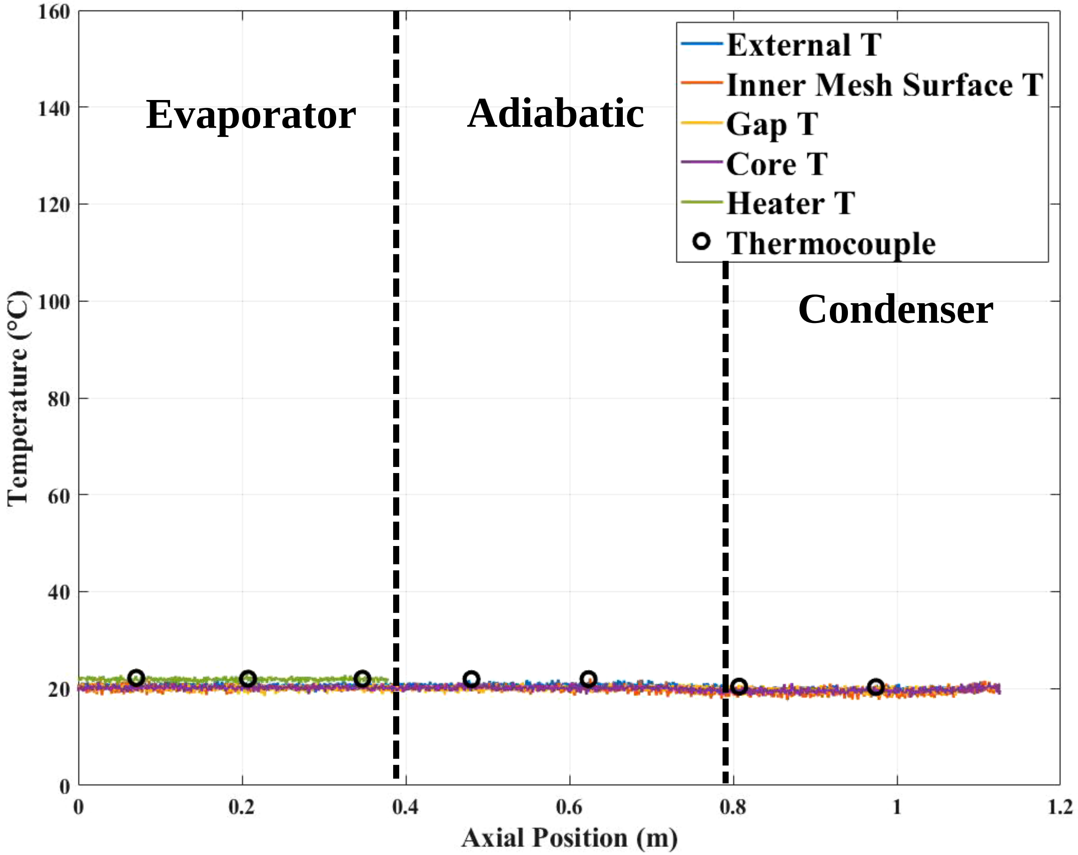


Distributed Temperature Sensing (DTS)

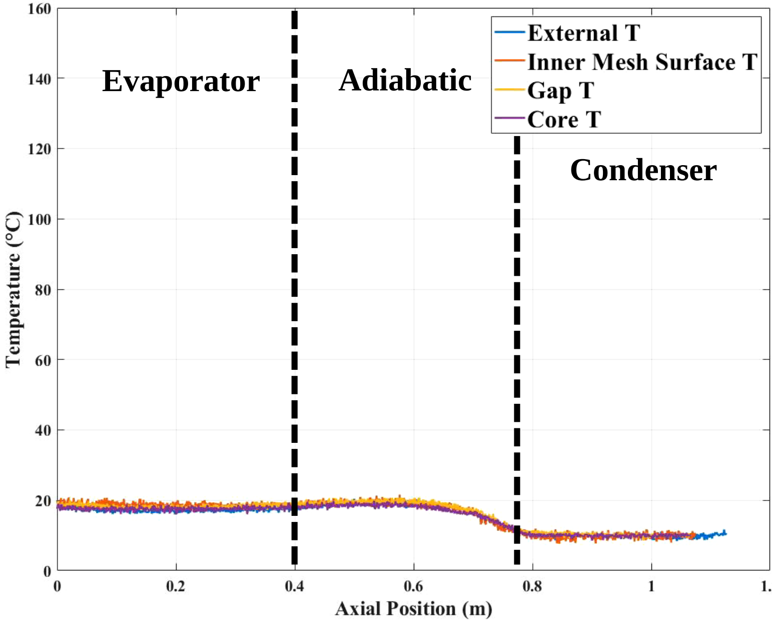
Measurement locations



Slow start (30W, ~60 mins) of the heat pipe



Rapid start (75W, ~60 mins) of the heat pipe

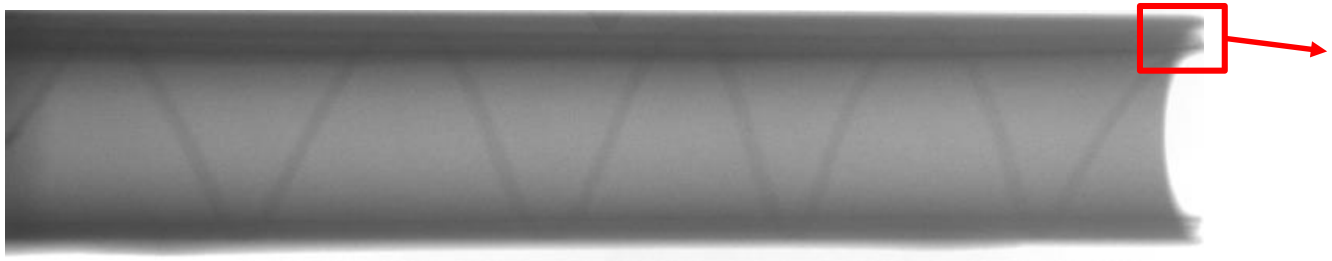


Imaging
Work in Progress

X-ray Imaging for the visualization of the fluid distribution

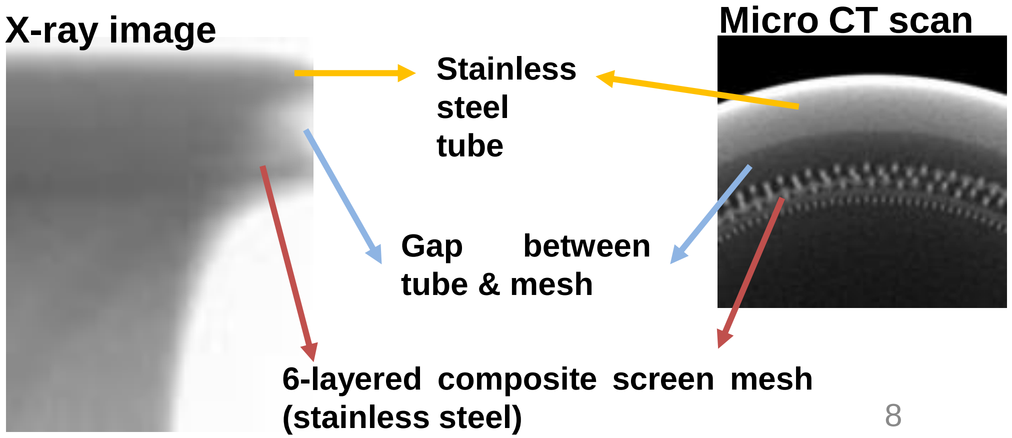

X-ray machine


Tube-mesh sample


X-ray image tube-mesh sample

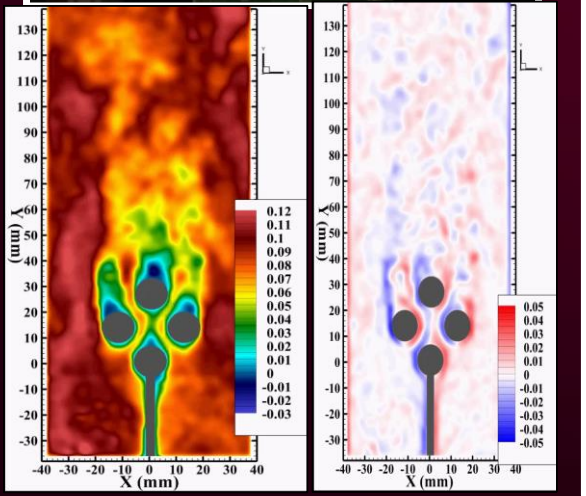

Glove box for handling alkali metals

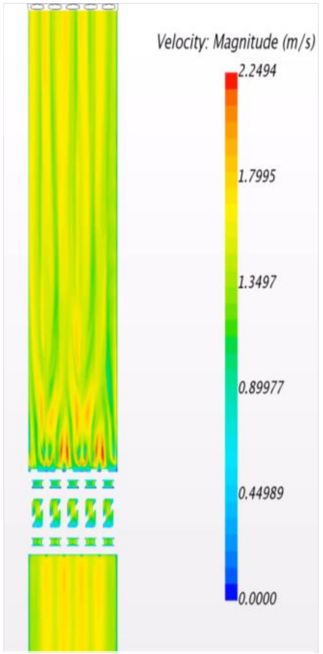
Constructing a liquid metal handling system
A glove box to achieve oxygen and moisture-free environment.



Thermal-Hydraulic Research Laboratory (thrlab.tamu.edu)
Advanced Computational & Experimental Techniques

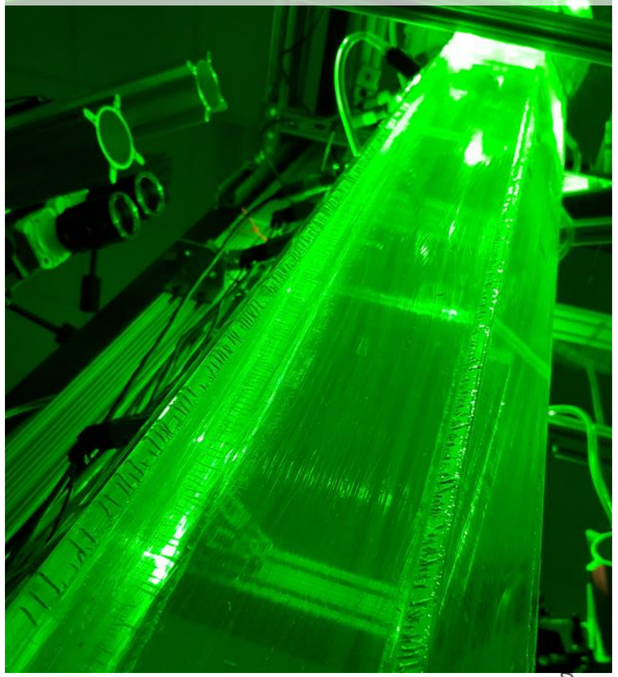
Pebble Bed Flow Experiments

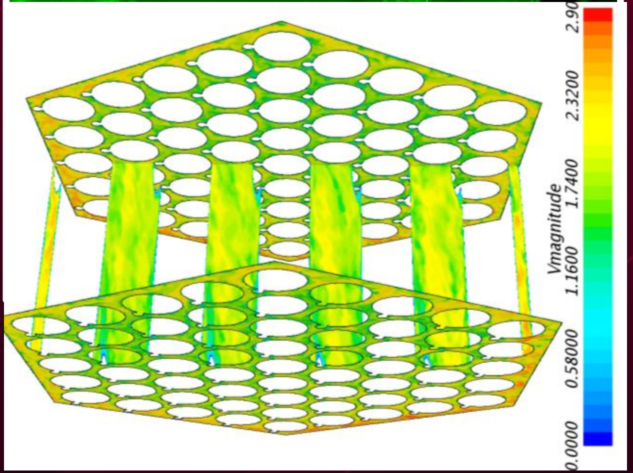




5x5 Bundles

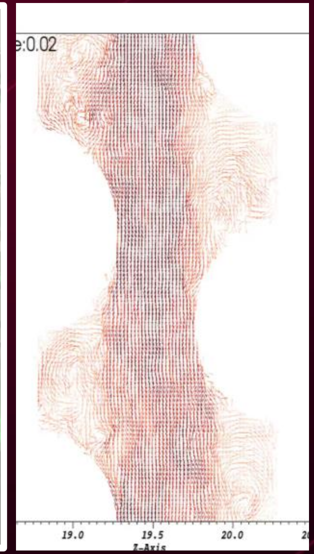
The largest MIR Wire Wrapped Bundle In the World





Passive Safety Systems

Helical Coil Steam Generators



MRP Microreactor Program

NEUP Nuclear Energy University Program

U.S. Department of Energy

MRP – NEUP Collaboration

Project ID: 19-17185 (Year Awarded 2019)

Title: Demonstrating Reactor Autonomous Control Framework using Graphite Exponential Pile

PI: Prof. Bren Phillips, Massachusetts Institute of Technology

TPOC: Dr. Holly Trellue, Los Alamos National Laboratory

MRP Microreactor Program