DOE-NE Microreactor Meeting–
Sodium heat pipes; design and failure mode assessment for micro-reactor applications (NEUP 24-31551)

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Contents

Project Collaborators and Background

- Collaborative effort between:
  - **University of Wisconsin-Madison (UWM)**
    - Mark Anderson (PI), Tiago Moreira (Co-PI), Paul Brooks, Nikona Rousseau, Erik Tillman
  - **Texas A&M University (TAMU)**
    - Yassin Hassan (Co-PI), Joseph Seo, Hansol Kim
  - **Westinghouse (WEC)**
    - Michael Shockling (Co-PI), John Lojek, Rachel Riley, Harold Maguire, Jennifer Sassaman, Hayley Wagreich
  - **Los Alamos National Laboratory (LANL)**
    - Katrina Sweetland (Co-PI), Bob Reid
- Collaborators meet monthly to disseminate information and provide progress updates
- Goal: ***Understand the performance of sodium heat pipes with the following conditions to support Westinghouse eVinci development***
  - Physical failures (pinhole breech, weld failures, manufacturing flaws, etc.)
  - Prescence of high oxygen concentration
  - Prescence of non-condensable gases

MRP Microreactor Program

Project Goals & Timeline

Tasks/Milestone:	Deliverable	Responsible	2024		2025						2026						2027				
			10	12	2	4	6	8	10	12	2	4	6	8	10	12	2	4	6	8	10
	Final Report	UW-THL	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Failure modes and their effects on heat pipes	Construction of instrumented sodium heat pipes	UW-THL/WEC and LANL	■	■	■	▨	▨														
	Characterization of theoretical heat pipe performance through numerical modelling and CFD	UW-THL/ TAMU/WEC and LANL	■	■	■	▨	▨														
	Characterization of the performance and limits of the sodium heat pipes	UW-THL/ TAMU/WEC and LANL					▨	▨	▨												
	Assessment of heat pipe failure modes and their effects on heat pipe performance	UW-THL/ TAMU/WEC and LANL							▨	▨	▨	▨									
Performance degradation with different non-condensable gases	Design and construction of liquid sodium heat pipes with access for vacuum level control	UW-THL/WEC and LANL					▨	▨	▨												
	Characterization of the effects different non-condensable gases have on heat pipe performance	UW-THL/ TAMU/WEC and LANL							▨	▨	▨	▨	▨	▨							
Effect of sodium oxygen content on heat pipe performance	Corrosion assessment of heat pipe candidate materials in liquid sodium at different oxygen concentrations	UW-THL/ TAMU/WEC and LANL			■	▨	▨	▨	▨	▨	▨	▨	▨								
	Evaluation of the effect that sodium oxygen concentration has on heat pipe performance	UW-THL/ TAMU/WEC and LANL											▨	▨	▨	▨	▨	▨	▨		
Wick optimization and heat pipe performance	Development of optimized wicks based on CFD and water experiments considering water-sodium scaling methodologies	TAMU/ UW-THL/WEC and LANL	■	■	■	▨	▨	▨	▨	▨	▨	▨									
	Construction and testing of heat pipes with optimized wicks from start-up up to their limits of operation	UW-THL/WEC and LANL					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Heat Pipe Development – Task 1

- ***Design and manufacture sodium heat pipes with reasonably prototypic dimensions and performance***

Initial tube parameters

- Dimensions
  - OD: 0.75”
  - Condenser Length: 9”
  - Adiabatic Length: 17.7”
  - Evaporator Length: 9”
- Materials
  - Tube: Inconel 625
  - Wick: Stainless 316
- Wicks
  - Porous sintered tube
  - Wrapped mesh
- Fill ratio
  - 110% - 150%

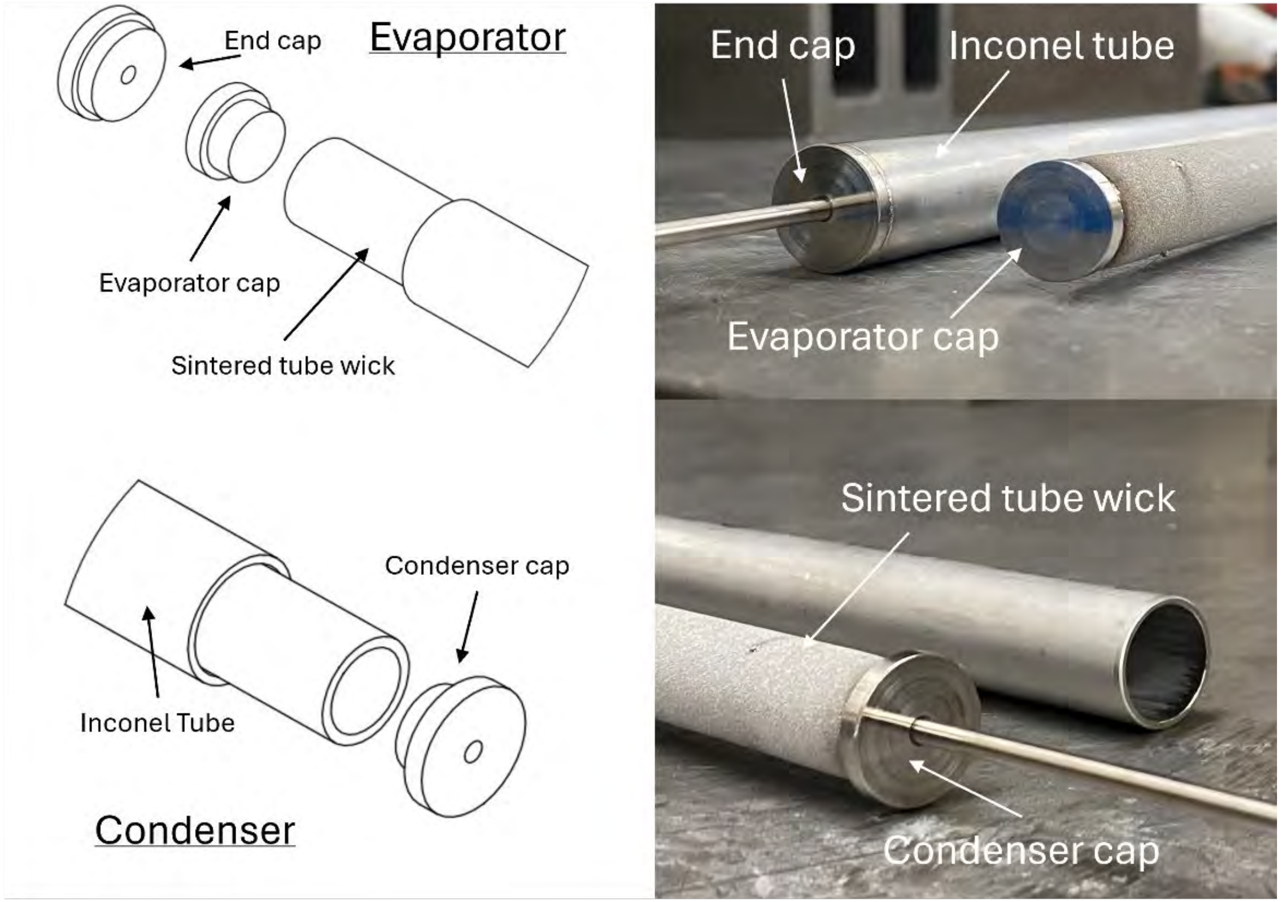


Figure 1. Heat pipe design.

Wick Development – Task 1

- Two wick design options
- Wick 1: Porous Sintered Tubes:
  - Custom manufactured porous sintered tubes (316 stainless)
    - Dimensions chosen to optimize heat pipe performance based on heat pipe limit analysis and manufacturability.
  - Dimensions
    - 14 µm pore size
    - 0.063” thick
    - 0.625” OD (0.014” gap size)
- Wick 2: Wrapped wire Mesh
    - CNC laser weld seam
    - High pressure resistive local diffusion bond seam
  - Material
    - Stainless 316 - 250 x 250 mesh
    - Opening size: 60 µm
    - 0.614” OD (0.019” gap size)

Figure 2. Porous sintered wick.

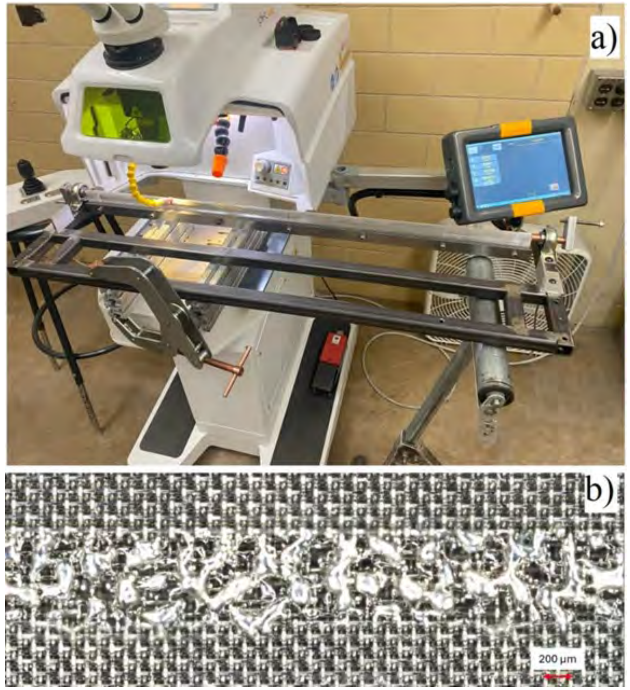


Figure 3. a.)Laser weld station, b.)Microscope image of laser weld .

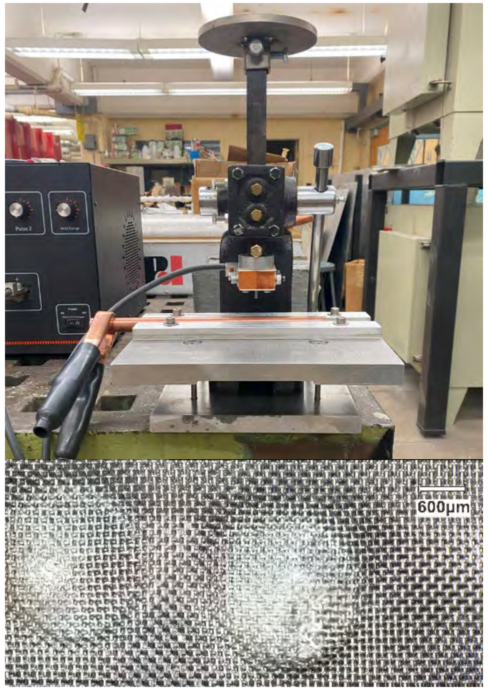


Figure 4. a.)Diffusion bond station, b.)Microscope image of bond.

Wick Characterization – Task 2

- ***Bubble test characterizes pore size***
- Relates pressure to pore size:

$$\frac{2\sigma}{r_{pore}} = P_{gas} \text{ (Young-Laplace)}$$

- Visual observation of largest pore location
  - Determines condenser end of wick
- Proper characterization improves modeling and limit calculations
- Effective Pore Size:
  - Porous Sintered Wick: 15 µm
  - Wrapped Mesh Wick: 50 µm

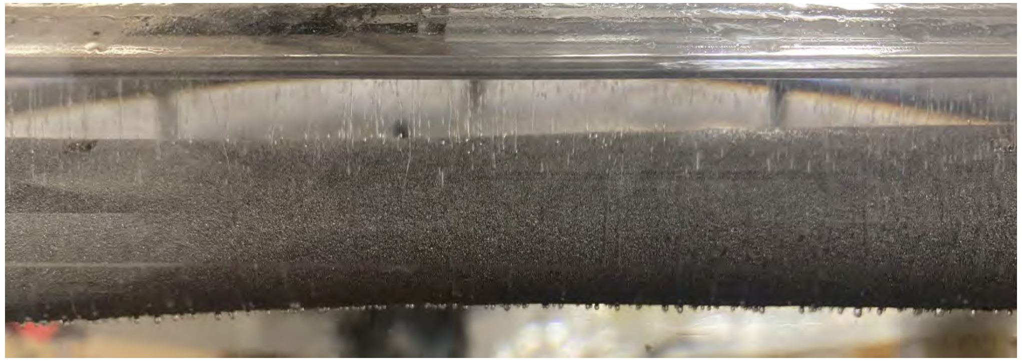


Figure 6. Porous sintered tube wick bubble test.

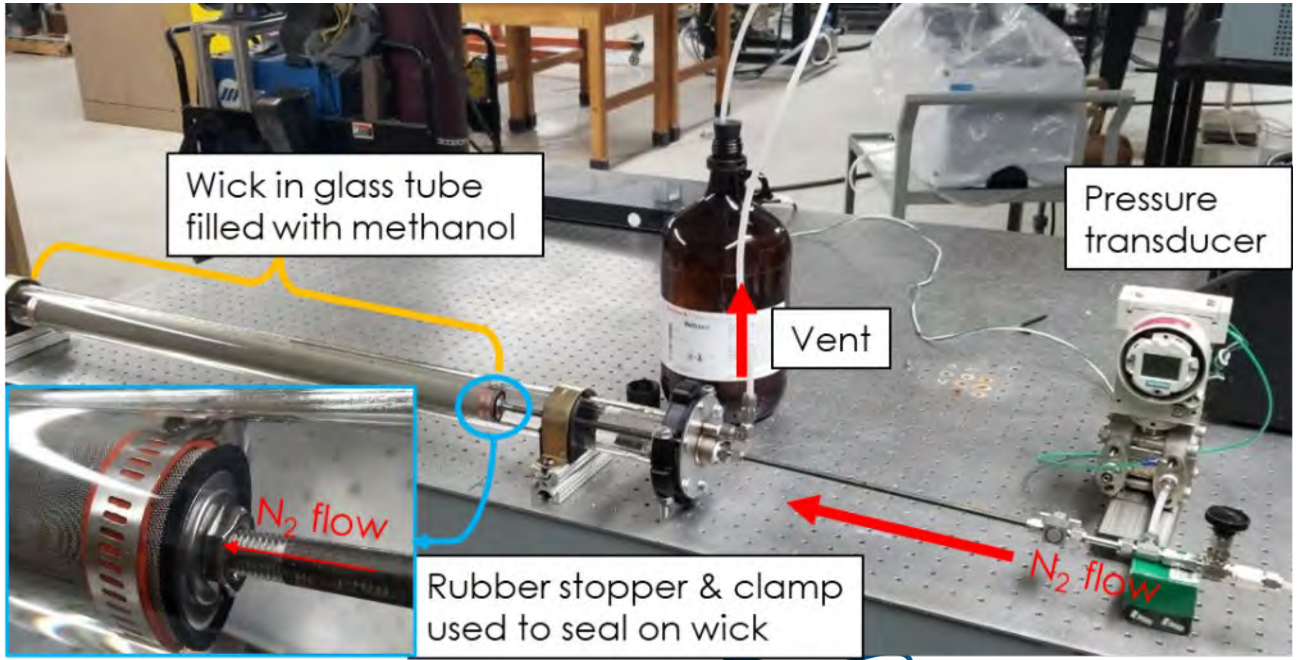


Figure 7. Bubble test setup.

Limits of wicks – Task 2 & 9

- ***Applied heat pipe theoretical limits to design wick geometry***:
  - Thickness
  - Gap size (OD)
  - Pore size
- Chose geometry that maximized operating limits
- Comparing analytical limits to numerical models
  - HTPIPE
  - NASA GLENN
- Targeting reasonable heat pipe limits for microreactor applications
  - ~ 5 kW
- Capillary limit is typically the most difficult limit for microreactor scale heat pipes

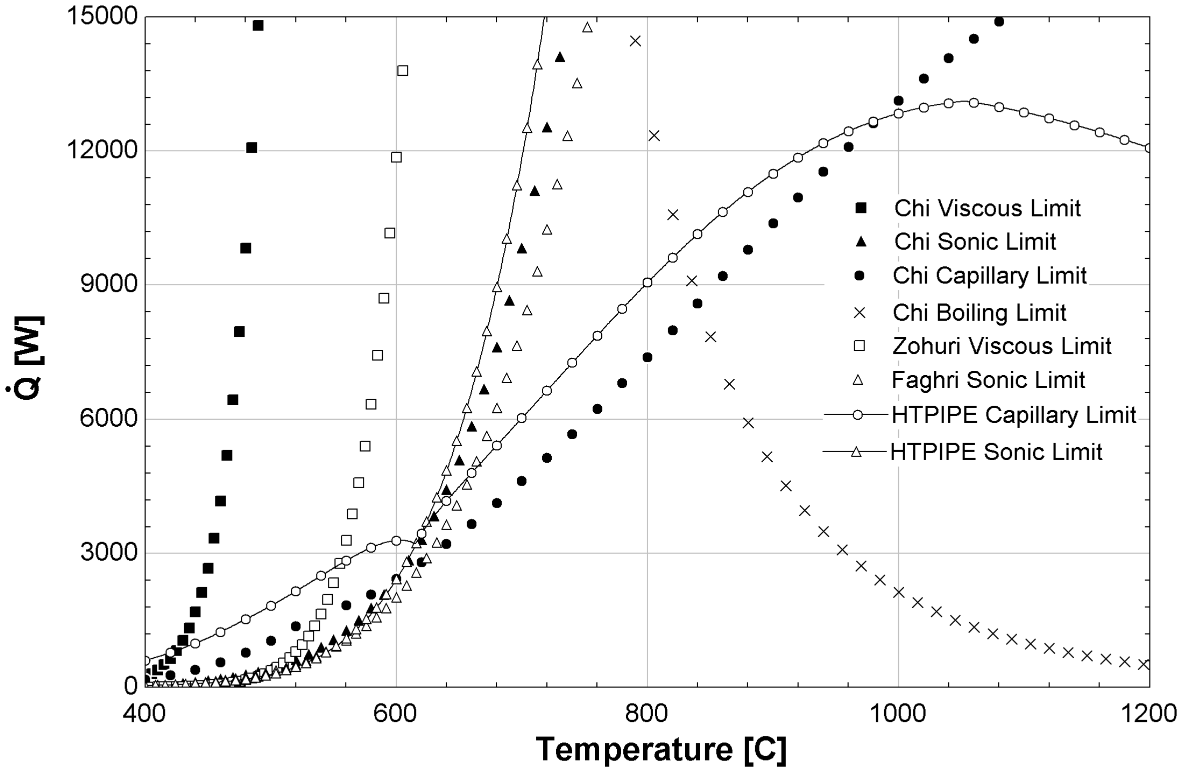
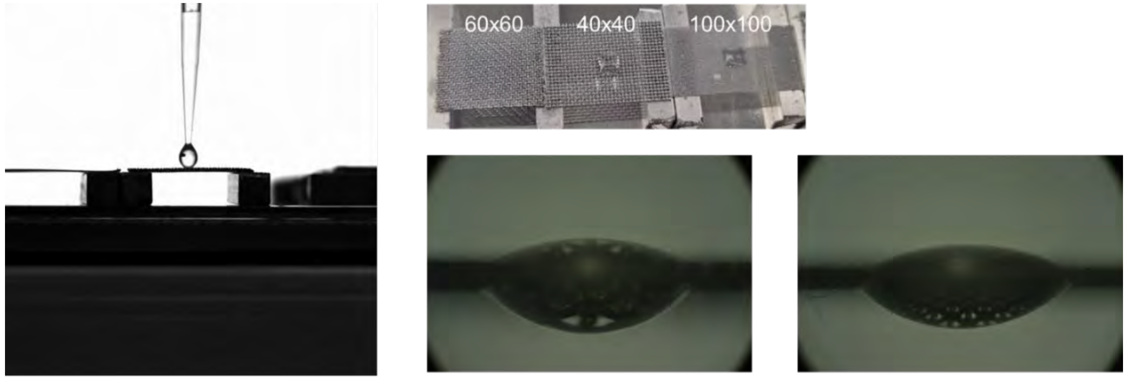


Figure 5. Porous sintered wick heat pipe limits.

TAMU Contact Angle Measurements – Task 9

- ***TAMU measuring fluid-porous media contact angles***
  - Important for modelling and predicting heat pipe behavior
- Using water as a baseline fluid prior to using sodium
- Visual measurements of contact angle between fluid and wick material
- Also taking X-ray images of sodium-porous media interactions
  - Challenges in making sure we achieve similar wetting characteristics as an operational heat pipe



Water
40x40

Water
100x100

Figure 8. Water-mesh contact angle measurements.

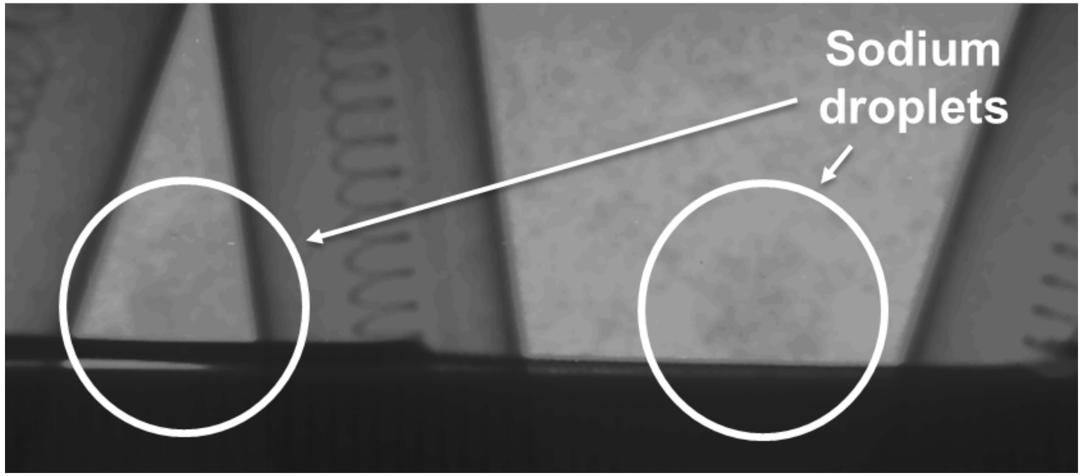
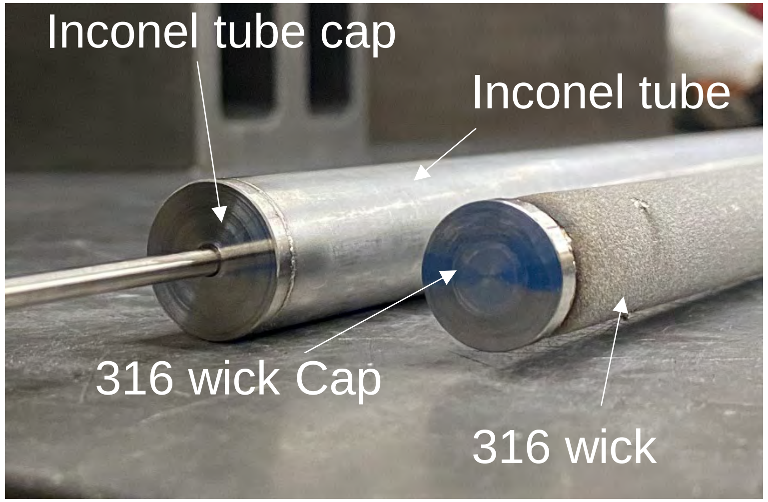


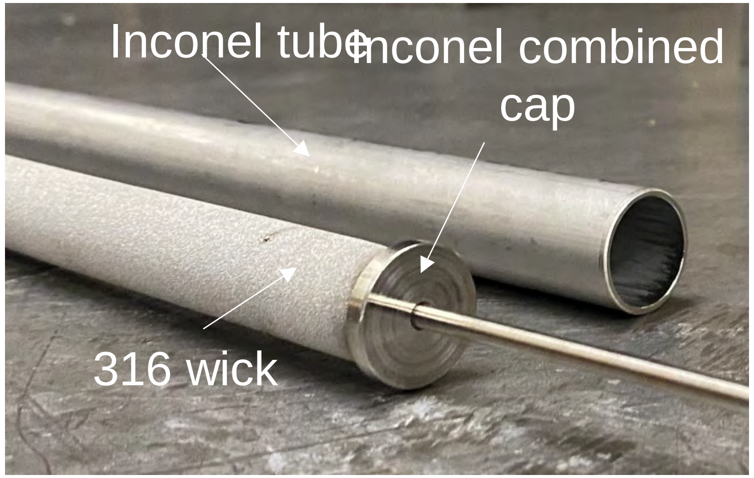
Figure 9. X-ray images of sodium-mesh interaction.

Heat Pipe Fabrication – Task 1

- Remove any contaminants on wick (Clean with acid bath)
- Bubble test to measure actual pore size and QA check on manufacturing.
- Laser weld caps on wick & tubing
- Laser weld wick to Inconel tube and cap
- Final clean with ethanol

Evaporator

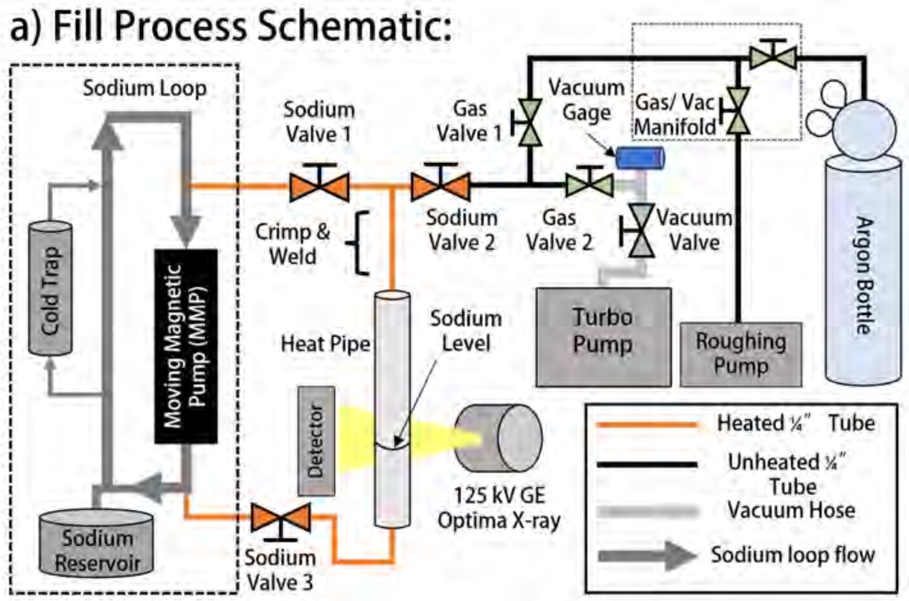




Condenser

Sodium Fill – Task 1

1. Vacuum bake-out HP
2. Circulate sodium through heat pipe and cold trap to wet and reduce any oxide presence in heat pipe
3. Slowly drain HP of sodium, using X-ray system and weight measurement to monitor sodium fill volume
4. Measure final change in sodium mass to verify fill volume
5. Crimp/bond lower fill tube to seal
6. Pull vacuum (~1E-05 torr) on heat pipe
7. Crimp/bond upper fill tube for final seal
8. Conduct XRCT to verify sodium fill volume and obtain as fabricated complete 3D model


a) Fill Process Schematic:

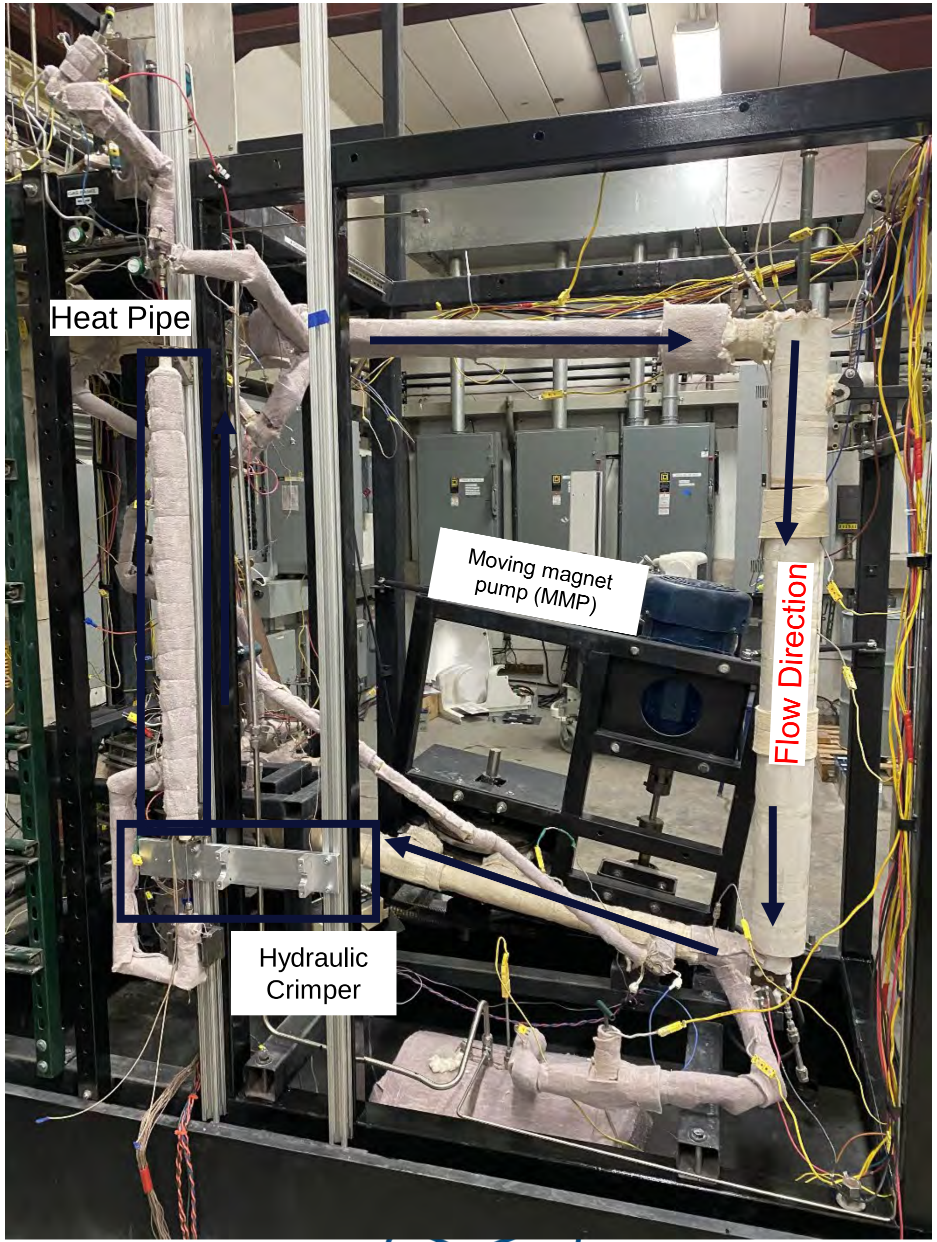


Figure 10. Sodium fill loop.

Heat Pipe Sealing – Task 1

- ***Developed repeatable sealing technique***
  - In-line diffusion bond
- Leak proof against:
  - 30 psi helium leak detection
  - 5000 psi of H2O
- Heat pipe sealed in fill-loop
- Quick and repeatable filling and sealing of heat pipes

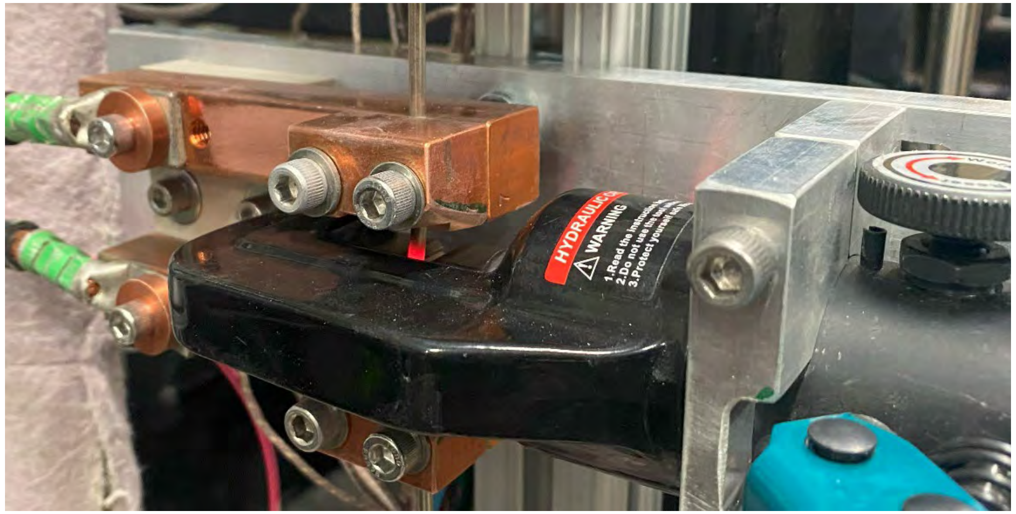


Figure 11. In-line diffusion bond.

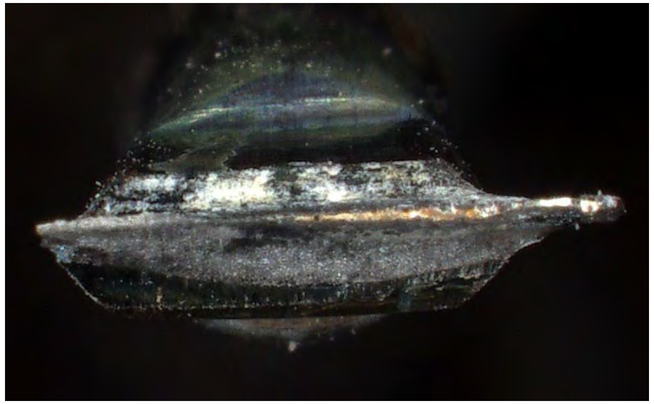
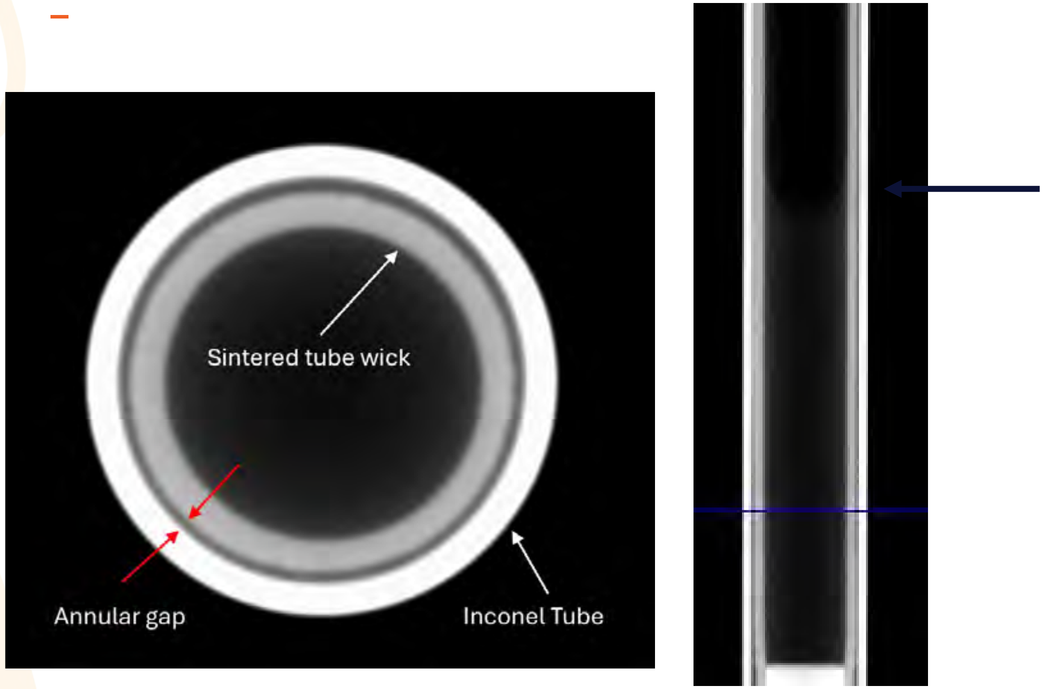
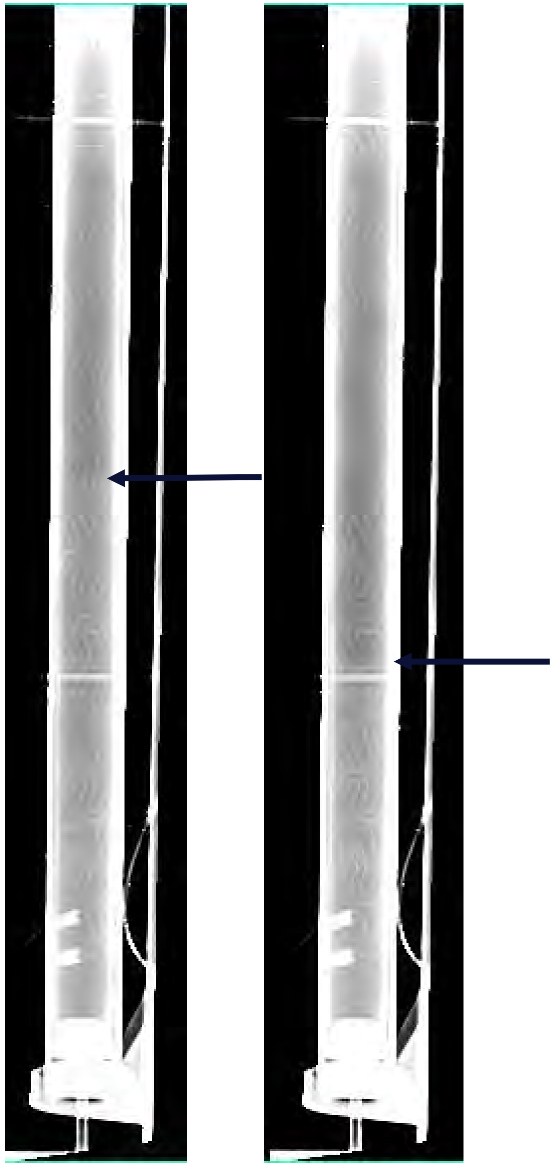


Figure 12. Microscope image of seal.

X-ray Fi

- In





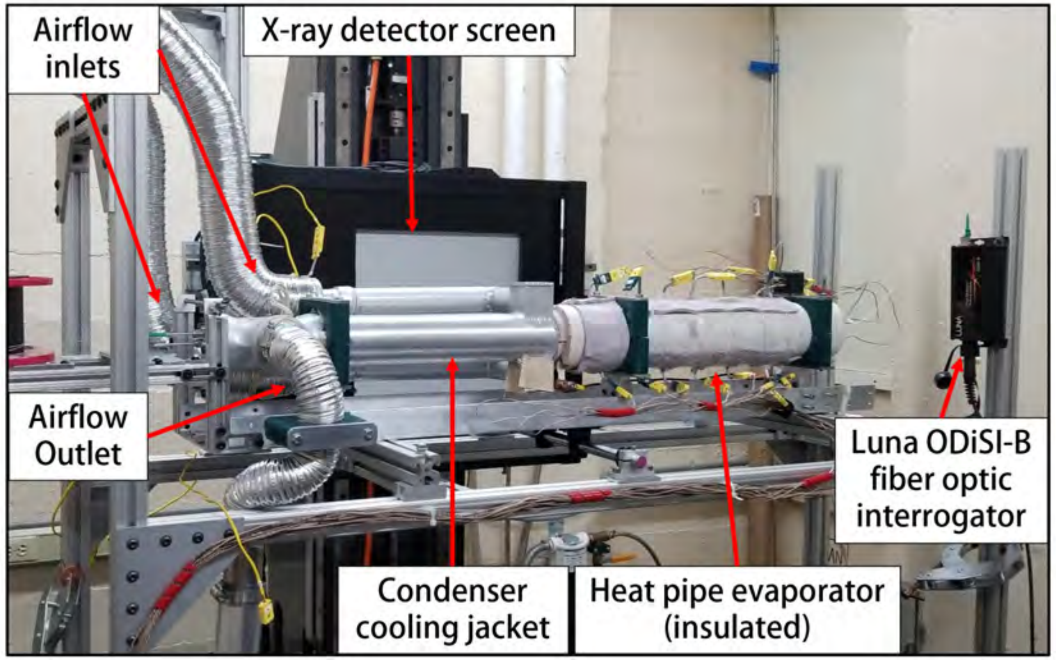
Summary of Heat Pipe Development – Task 1

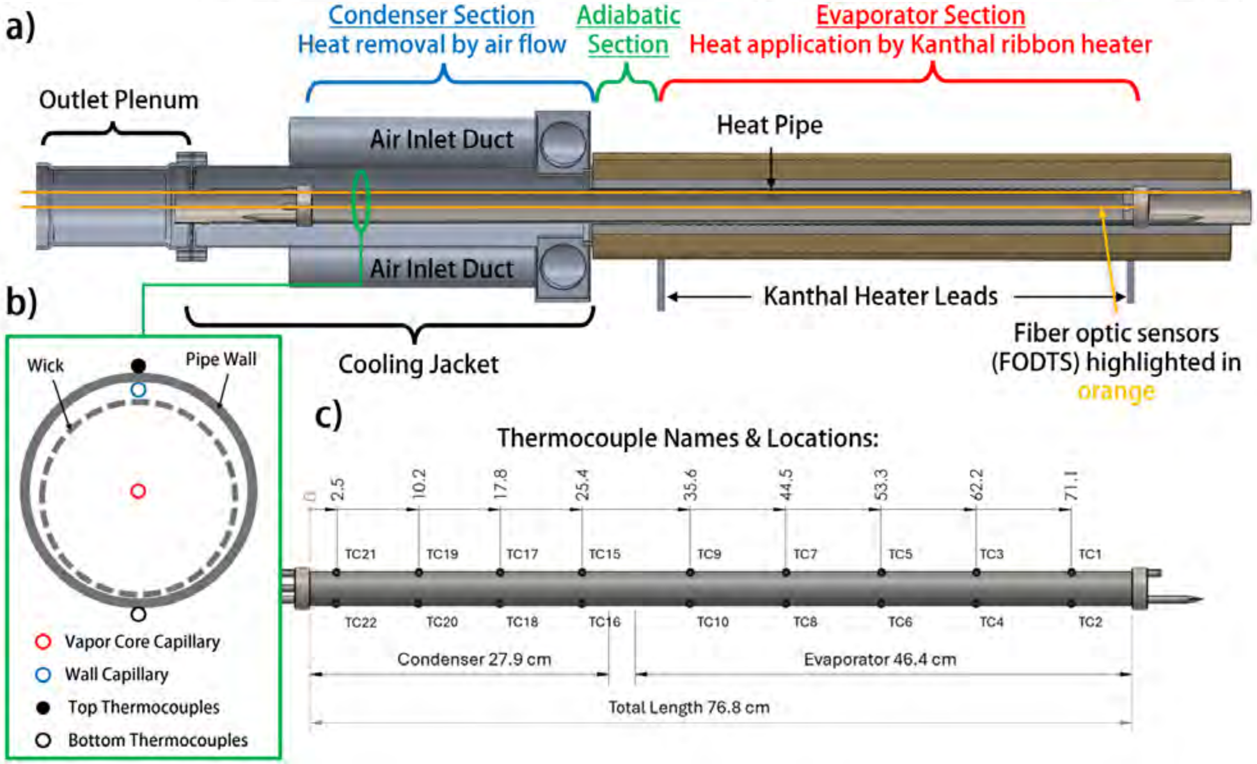
- Development of a repeatable heat pipe manufacturing process.
- Initial design of heat pipe with two different wick geometries.
  - Designed wicks to maximize theoretical performance
  - Manufactured wicks and characterized performance with bubble test.
  - Fabricated heat pipes
  - Filled to desired volume
  - Developed repeatable and effective sealing method

Now to testing, presented by Erik Tillman →

Heat Pipe Testing and Characterization Facility

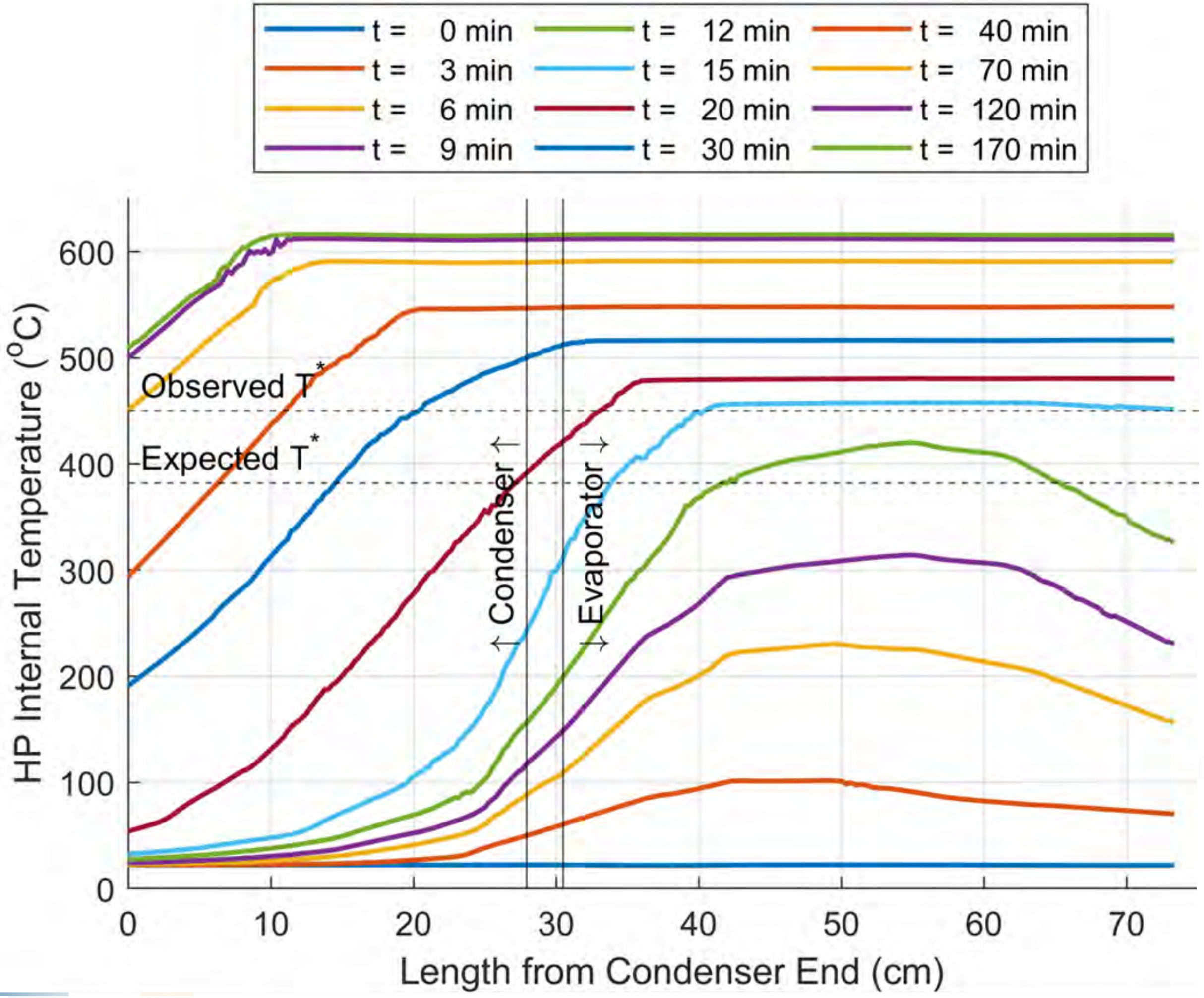
- Heat pipe installed in 450 kV X-ray facility for imaging
  - Up to 30 fps acquisition speed
  - 2048 x 2048 pixel array (41 cm x 41 cm)
- TCs measure external evaporator and condenser temperatures
- Luna ODiSI B system records internal FODTS temperature data
  - 0.5mm gauge length
  - Up to 100 Hz acquisition frequency
- Evaporator heated using resistive heating element (measure DC power input)
- Condenser cooled by forced airflow (measured using hotwire anemometer)





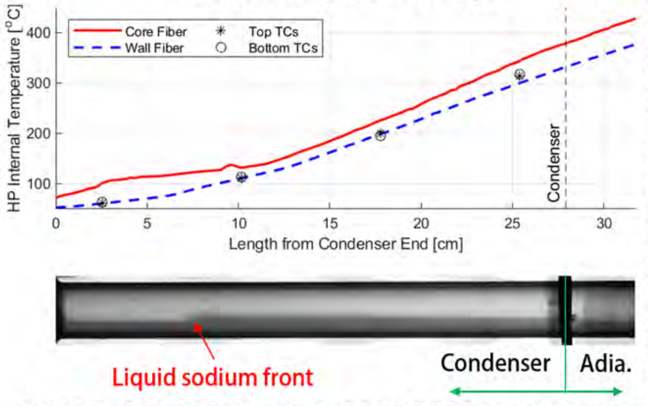
Example: Startup Characteristics

Vapor Core FODTS measurements, 500W startup

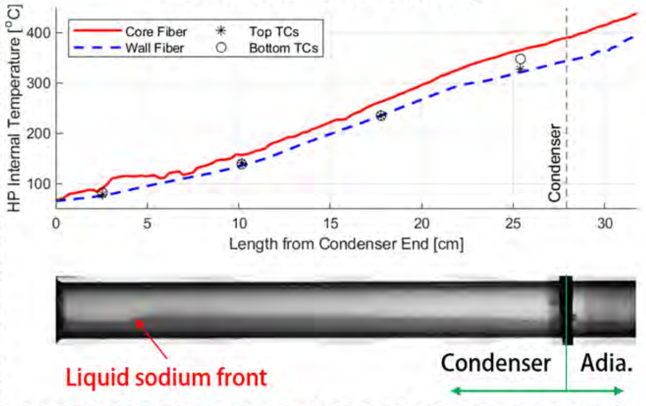


Parameter	Value
Pipe OD / ID	1.25 [in] / 1.12 [in]
Vapor Core Dia.	1.00 [in]
Evaporator Length	18 [in]
Adiabatic Length	1 [in]
Condenser Length	11 [in]
Wick Thickness	0.045 [in]
Wick Composition	6 Layers of 316 mesh: Inside: 1x 100x100 Middle: 3x 400x400 Outside: 2x 60x60
Max. Annular Gap	0.030 [in]
Sodium Fill	150% of wick + gap volume

21 minutes after startup

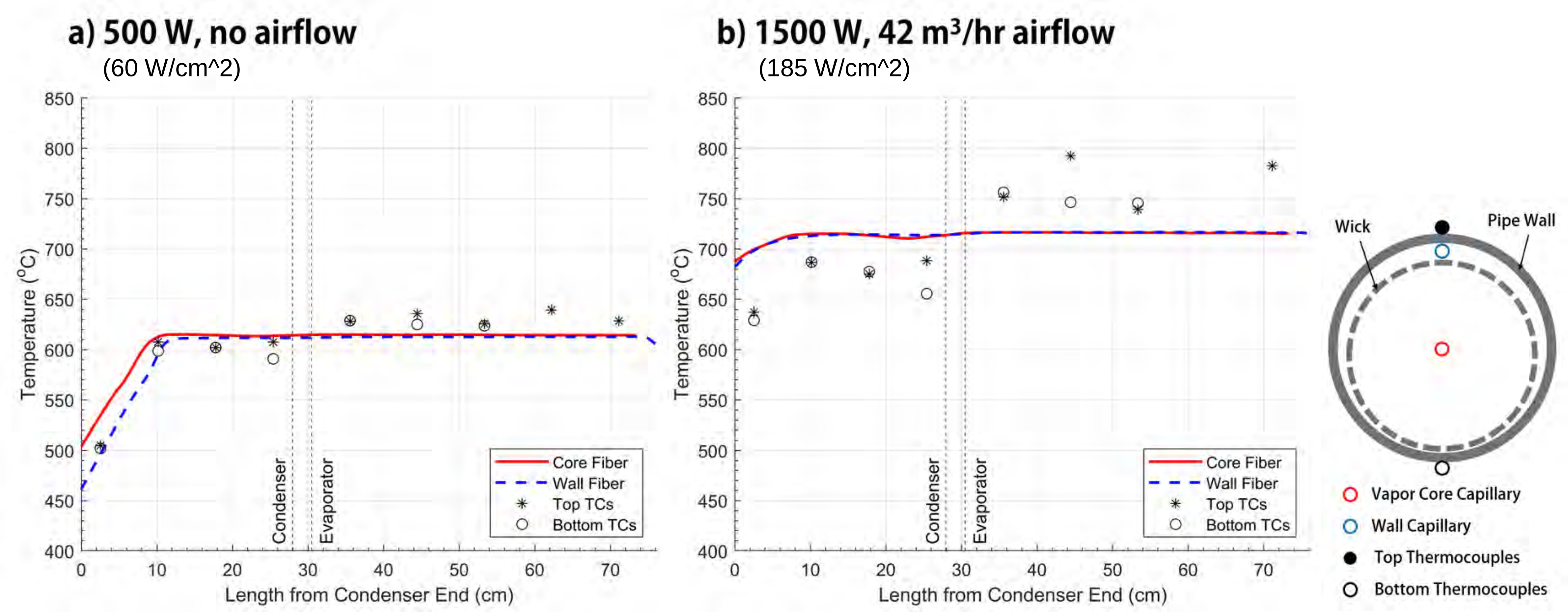


23 minutes after startup



E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes." Applied Thermal Engineering, 2025 [submitted, under revision]

Steady-State Operating Conditions



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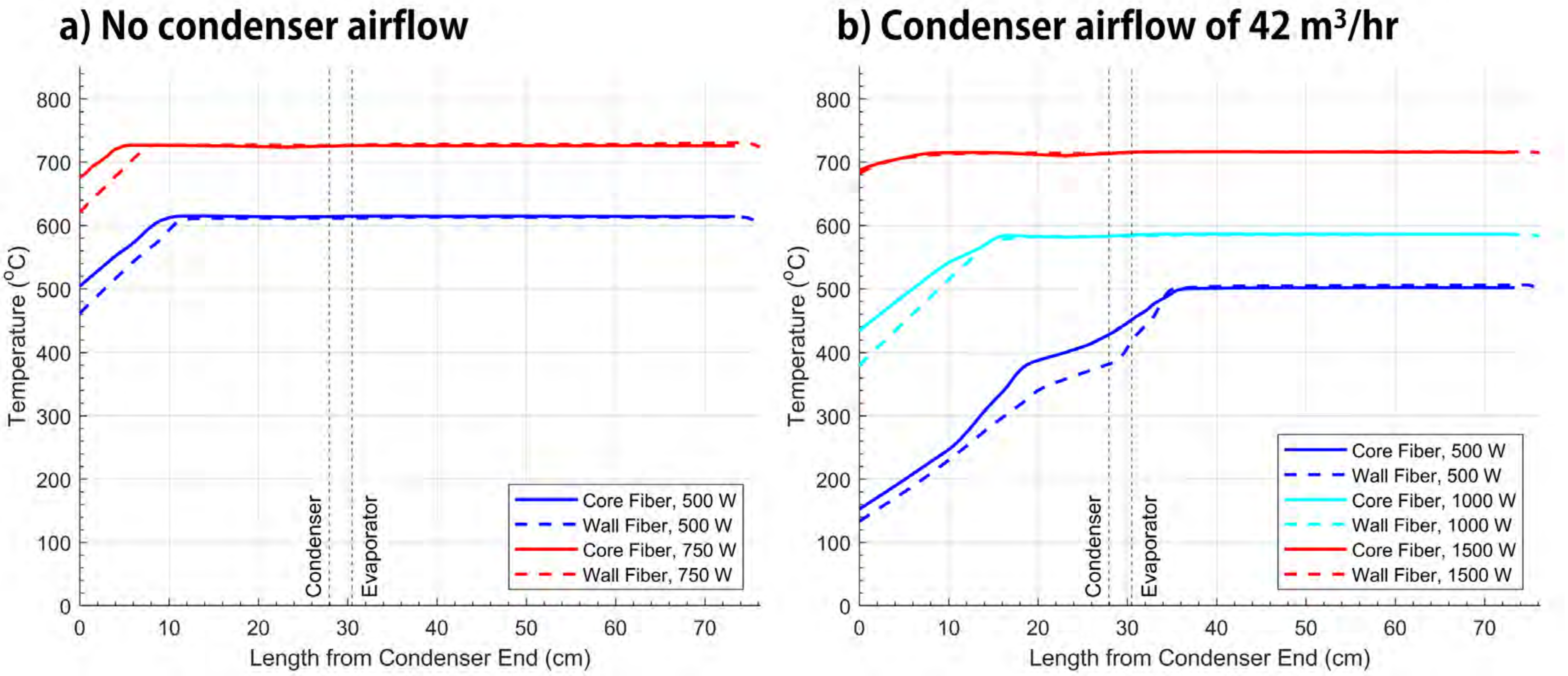
Effect of Heat Flux on Steady-State Operating Conditions



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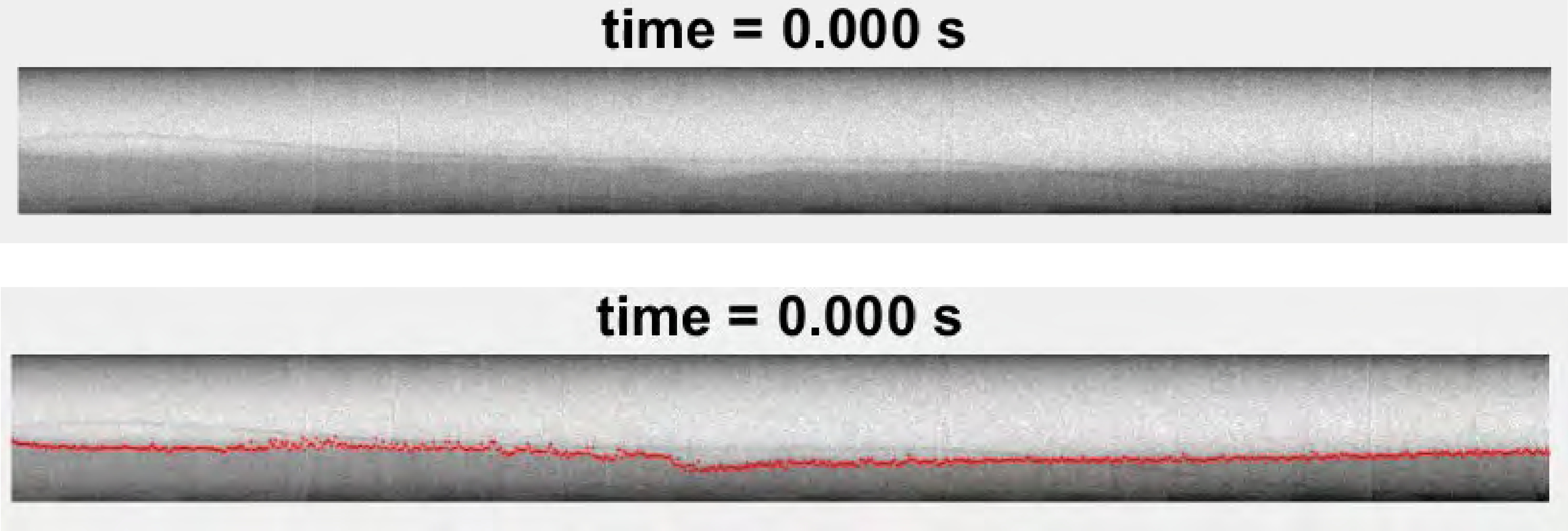
Time-Resolved X-ray Imaging

- Developed algorithm to track the liquid-vapor interface for every axial position



Both videos show condenser, 1000 W steady-state, 1/3x speed

E. Tillman, T. Moreira, G. Nellis, & M. Anderson. “High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes.” Applied Thermal Engineering, 2025 [submitted, under revision]

Next steps

- Complete characterization tests on heat pipes – Task 3
- Expand heat pipe testing facility
  - Add ability to due induction heating on evaporator
  - Helium gas-gap calorimeter condenser
- Perform corrosion tests on heat pipe candidate materials – Task 7
  - Materials likely used for microreactor heat pipes (Inconel, Kanthal, FeCrAl, etc.)
- Develop methodology to test heat pipes during failure – Task 4
  - Pinhole breach, pipe fracture, etc.
  - Active discussions among collaborators on test matrix
- Explore performance degradation from
  - Non-condensable gases – Task 6
  - High oxygen content – Task 8

Questions for the Community

1. Considering that we are able to obtain high resolution X-ray images and internal temperature measurements, what are the most important measurements we could make that would help with code validation?
2. Are there available heat pipe models that consider the effects of heat pipe fill ratios?
3. What methods of sodium heat pipe failure are of particular interest to the community?
4. Are heat pipes with longer or shorter adiabatic regions more representative of microreactor scale heat pipes?
5. What limits are most relevant and least relevant to reactor scale heat pipes?

Publications

- Journal papers

E. Tillman, T. Moreira, G. Nellis, & M. Anderson. “High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes.” *Applied Thermal Engineering*, 2025 [submitted, under revision]

- Conference Papers:

E. Tillman, T. Moreira, G. Nellis, & M. Anderson. “High-Resolution Temperature Measurements on Sodium Heat Pipes Applied to Microreactors.” Presented at the ANS Winter Meeting 2024.

E. Tillman, G. Nellis, & M. Anderson. “X-ray Imaging of Flow Phenomena Within Sodium Heat Pipes for Microreactor Applications.” *Transactions of the American Nuclear Society,* 2023. doi.org/10.13182/T128-42068

E. Tillman, G. Nellis, & M. Anderson. “Manufacturing and X-ray Imaging of Kilowatt-Scale Sodium Heat Pipes for Microreactor Applications.” *Proceedings of the ANS Winter Meeting 2022*. doi.org/10.13182/T127-39763

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