An Experimental Investigation of a High Temperature Oscillating Heat Pipe for Leading Edge Applications

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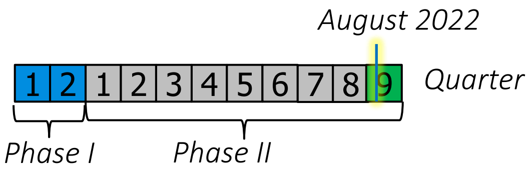
Presentation Outline

- NASA Hypersonic SBIR: Goal, Targets, and Proposed Solution
- Phase I Overview
  - Case Study
  - OHP Design and Manufacturing
  - Laboratory Testing
  - Achievements
- Phase II Ongoing Efforts
  - Objectives and Requirements
  - Breadboard Testing
  - Wedge Testing
  - Summary
- Acknowledgement

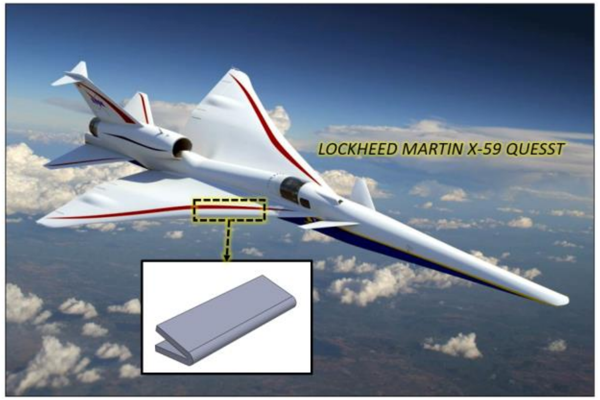
NASA Hypersonic SBIR

- Goal:
  - Develop a wing leading edge skin structure with novel integrated thermal management capability using the company's flagship technology; the Oscillating Heat Pipe (OHP).
- SBIR Timeline:

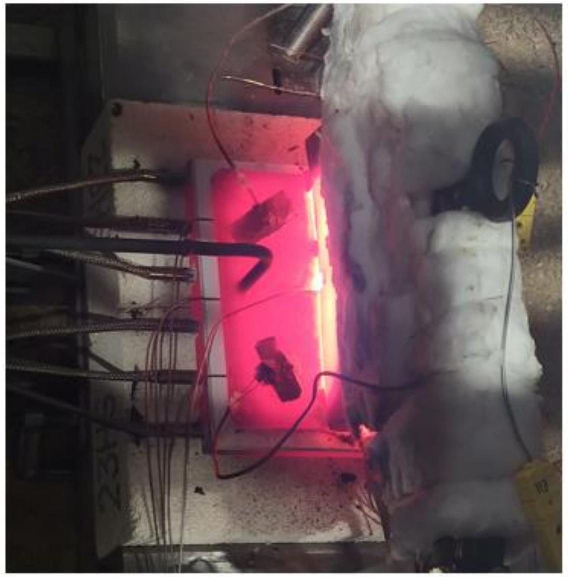


- Solicitation targets:
  - Manufacturing approaches that can fabricate complex thermal management devices, such as heat-pipe-cooled leading edges
  - Materials lighter in weight but capable of repeatedly reaching service temperatures up to and exceeding 1,000 deg-C
  - Capabilities that can fabricate complex geometry, such as incorporating integral heat pipes for thermal management
  - Provide multi-functionality, incorporating thermal management and structural load capabilities into an integrated component
- Proposed solution:
  - Develop the first high temperature OHP, e.g. 600 to > 1,000 deg-C
  - High heat flux capacity, e.g. 100's W/cm^2
  - Low thermal resistance, matching liquid-metal CCHP's
  - Multifunctional / integrated thermal-mechanical structure

Conceptual end use of "leading edge OHP" being developed with NASA

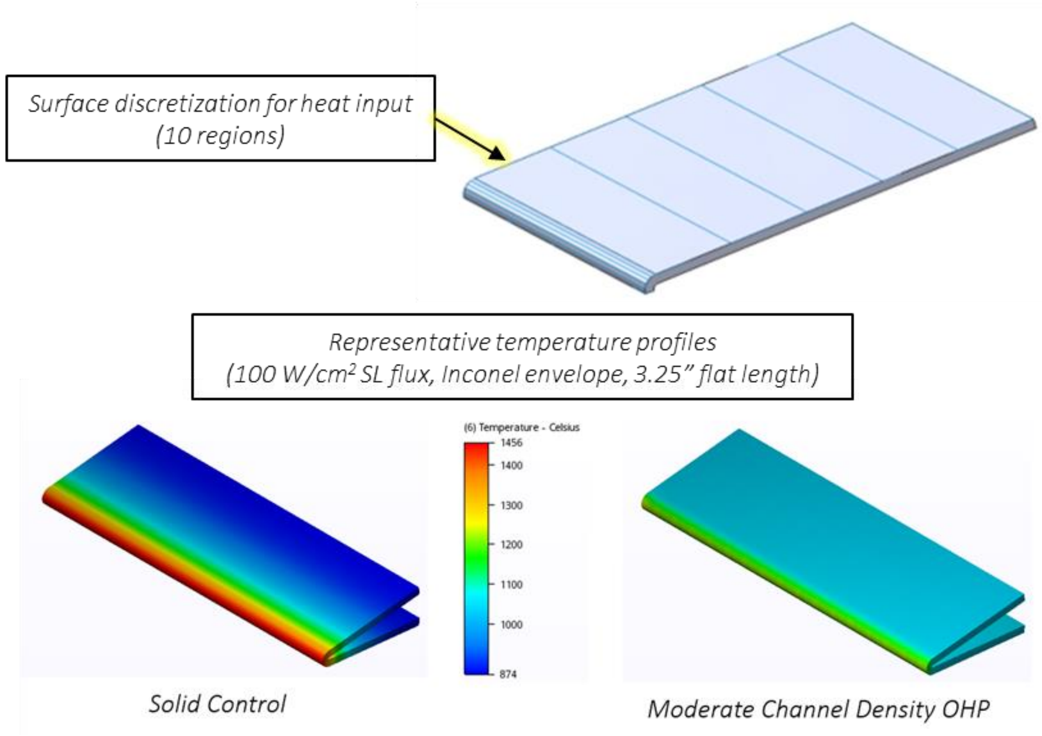


Photograph of Phase 1 flat plate OHP operating at ~1,000°C at ThermAvant Technologies, LLC



Phase I Case Study

- A case study was conducted to highlight the benefit likely provided in the end use - with notional phase II leading-edge ‘V’ geometry (0.25” radius), and boundary conditions from literature



- For a 0.25” (6.4mm) radius edge and 48kPa dynamic pressure, expected heat fluxes on the stagnation line are:
  - 61 W/cm^2 at Mach 6
  - 163 W/cm^2 at Mach 8

Adapted from Steeves, J. Appl. Mech (2009)

- Three important relationships:
  Anderson, “Hypersonic and high-temperature gas dynamics”

$$\frac{du_e}{dx} = \frac{1}{R}\sqrt{\frac{2(p_e - p_\infty)}{\rho_e}} \qquad (6.121)$$

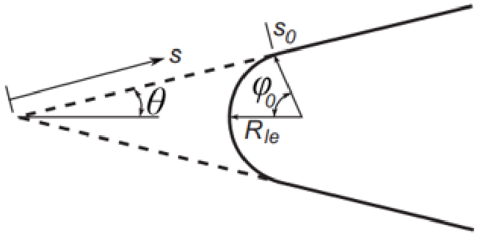
Examine Eqs. (6.106) and (6.111) in light of Eq. (6.121). We see that

$$\boxed{q_w \propto \frac{1}{\sqrt{R}}} \qquad (6.122)$$

This states that *stagnation-point heating varies inversely with the square root of the nose radius; hence, to reduce the heating, increase the nose radius.* This is the

$$\boxed{q_w \approx \tfrac{1}{2}\rho_\infty V_\infty^3 C_H} \qquad (6.167)$$

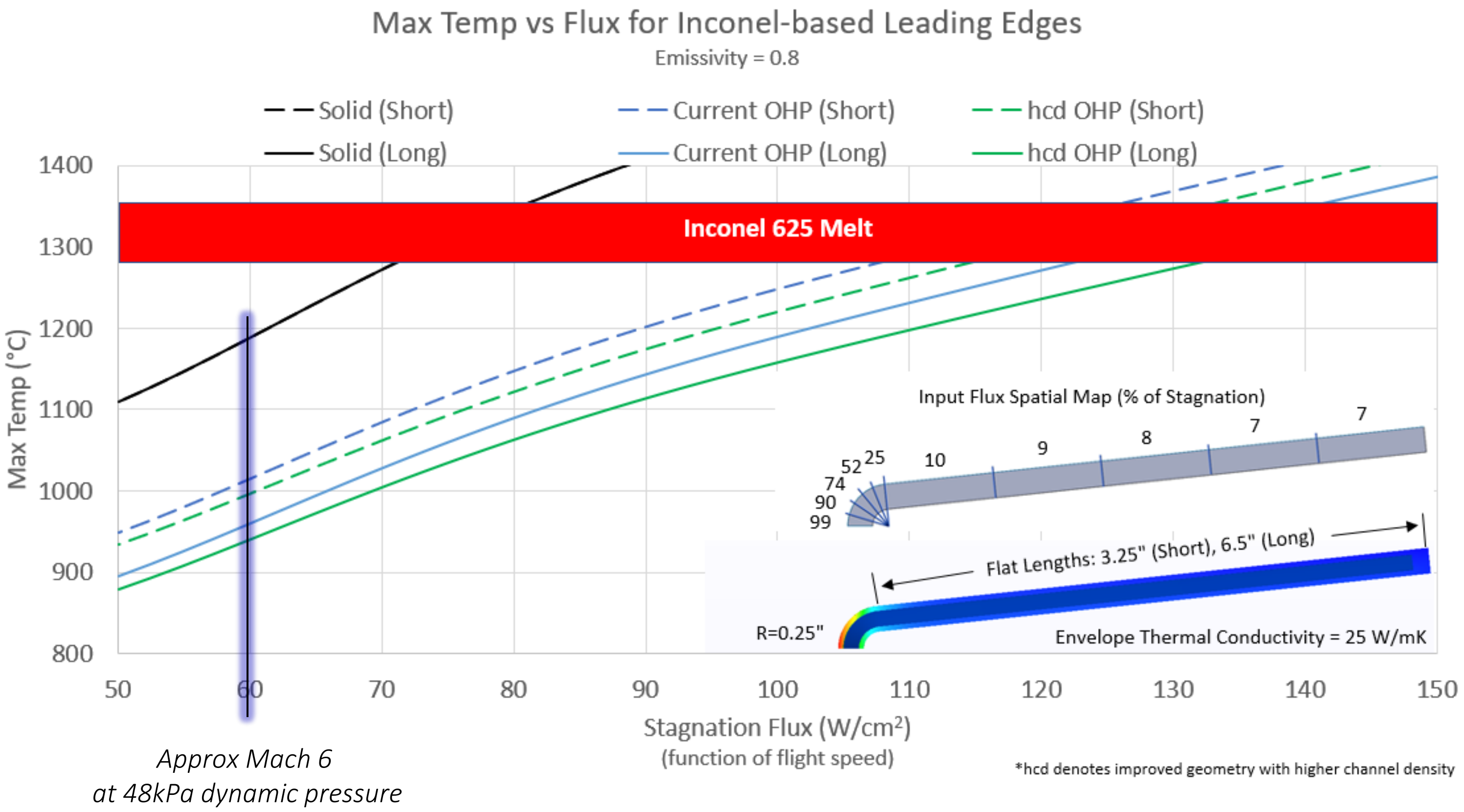
The main purpose of Eq. (6.167) is to demonstrate that aerodynamic heating increases with the *cube* of the velocity and hence increases very rapidly in the hypersonic flight regime. By comparison, aerodynamic drag is given by



$$\boxed{Q(\Phi) = Q_{stagnation\ line} * \cos(\Phi)}$$

Phase I Case Study – Trends for OHP Geometry and Flight Condition

- With a solid Inconel reference, an OHP may reduce peak leading edge temp by 250K at Mach 6
- Sensitivity to channel density and extent of the rejection region shown by the blue/green and solid/dashed series, respectively.
- Key take-away: OHP enables more aggressive heat input conditions (higher Mach #) for a given material's working temperature ceiling



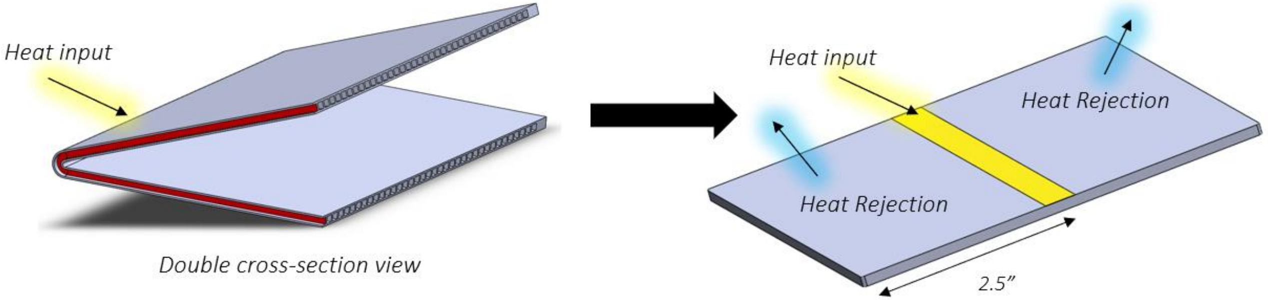
This case study was performed prior to phase I experimental data available, hence characterization of the 2-phase heat transfer performance in the finite element model was not empirically based on the high temperature demonstration. The fluid properties were extrapolated from lower temperature data (conservatively) – to be updated in phase II.

Phase I Hardware

- Phase I hardware was produced in a planar form factor at 6” scale, to demonstrate the OHP technology in a new temperature regime – decoupled from the manufacturing complexity of a V-leading edge
- Inconel 625 was selected for the envelope material due to relatively high service temperature and maturity of relevant manufacturing processes: vertical milling, vacuum brazing, and welding
- High temperature working fluids are proprietary; take-away is that two were successfully demonstrated during phase I
- Three prototypes were manufactured to completion, with two different channel hydraulic diameters, three braze materials, and three braze vendors. All three were charged and successfully tested (100% yield)

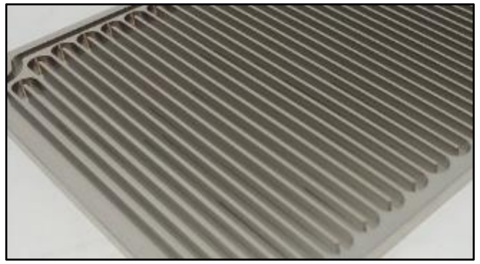
Phase I form:
- Easier to manufacture and test
- Similar OHP performance (bend is negligible regarding fluid motion[1])

Notional future form



Double cross-section view

Gen 1 OHP channel body



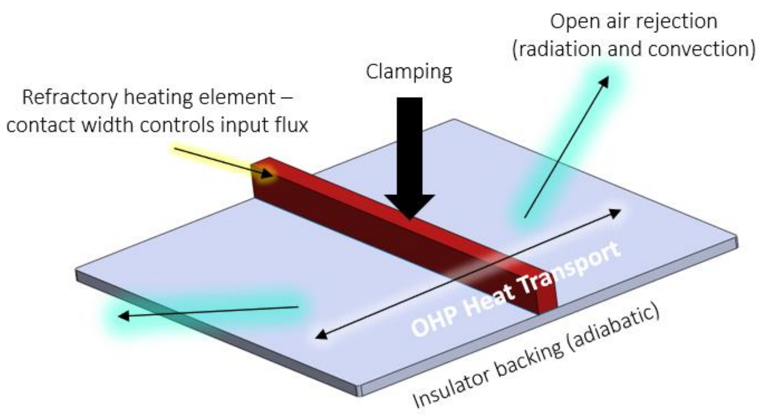
Gen 1 OHP photograph prior to charge tube attachment

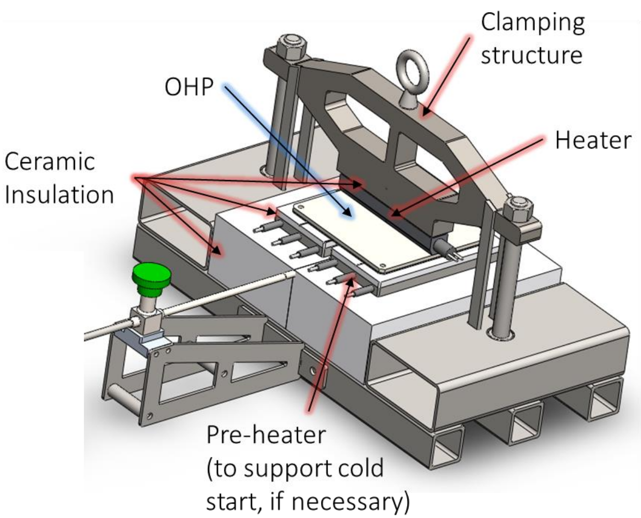
Phase I Testing – Test Bed

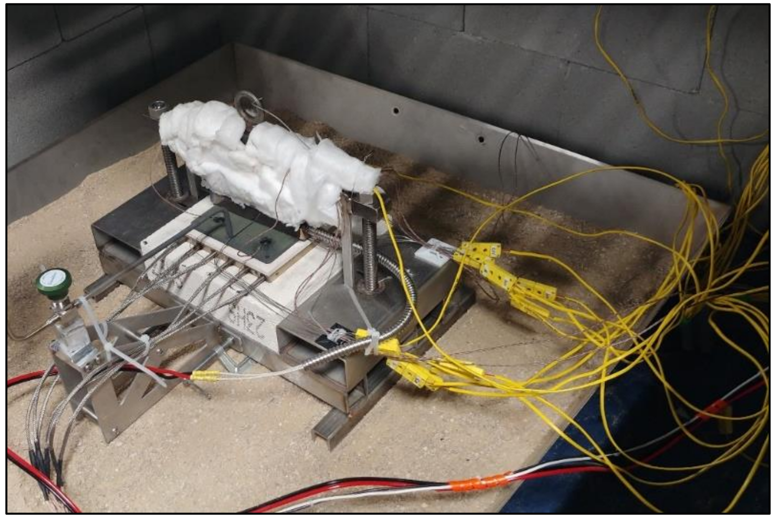
- Gen 1 breadboards were tested in the ‘unfolded V’ configuration, with centerline heat input, rejection from the adjacent surfaces, and adiabatic backside

- Test were intended to run from a soak above the working fluid melt point up to pressure containment limitations of the envelope (essentially never achieved due to limitations of COTS cartridge heaters)

- Two different heater geometries used: ¼” and ½” contact length x full width of the part. Uniform flux produced vs cosine spatial profile around a cylindrical leading edge, but length scales are relevant

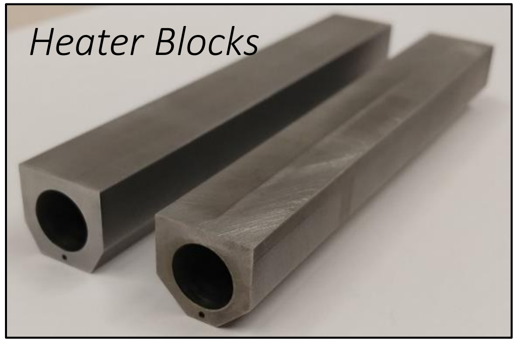


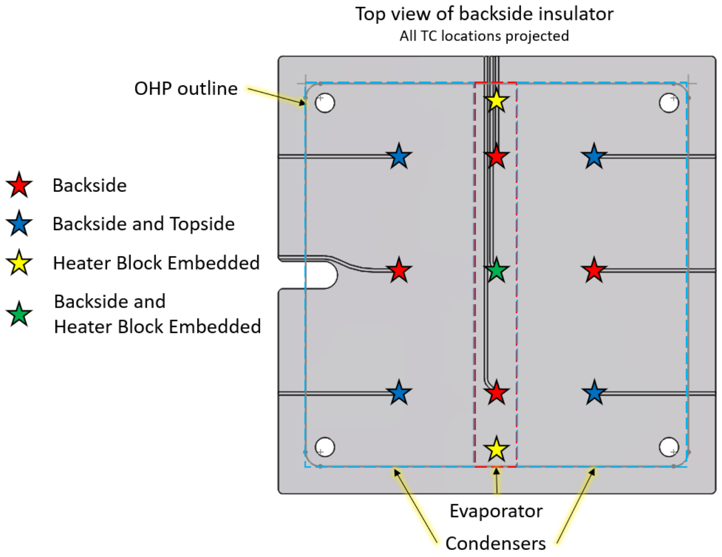




Phase I Testing – Test Description

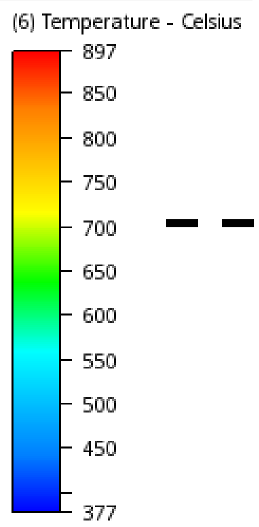
- Heat rejection via radiation + natural convection to the room
  - Forced convection utilized in one test to drive higher rejection flux, to showcase the OHP's transport capacity
- Primary test variables include:
  - Working fluid type
  - Heat input level
  - Heat input width (low and high flux blocks produced)
- Data acquisition:
  - Heater temperature, rejection surface temperature, temperature profile on the adiabatic backside of the part, electrical input power



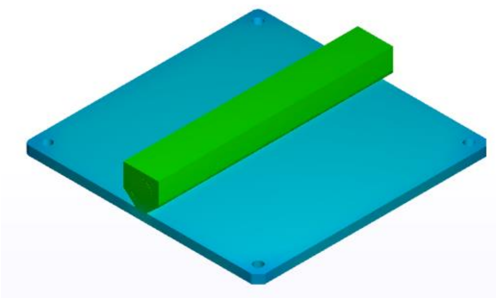


Test Description	Interface Material Type	Air Temperature	Heat Input	Expected Limit
Control Testing & Debugging (Phase A)	.002" copper foil	20°C (R.T.)	200 W to limit, 200W increments Wide Heater Design	Cartridge Heater Safe Op Limits
Fluid 1 Testing (Phase B)	.002" copper foil	20°C (R.T.)	200 W to limit, 200W increments Both heater designs	Fluid temperature of 850°C (pressure containment)
Fluid 2 Testing (Phase C)	.002" copper foil	20°C (R.T.)	200 W to limit, 200W increments Narrow Heater Design	Envelope temperature of 1,050°C (safe service temp of braze joint)

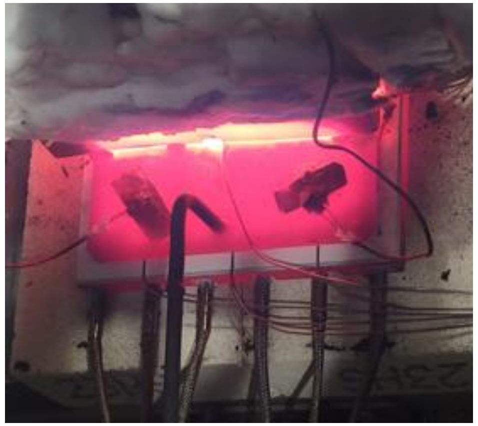
Phase I Testing – OHP vs Control

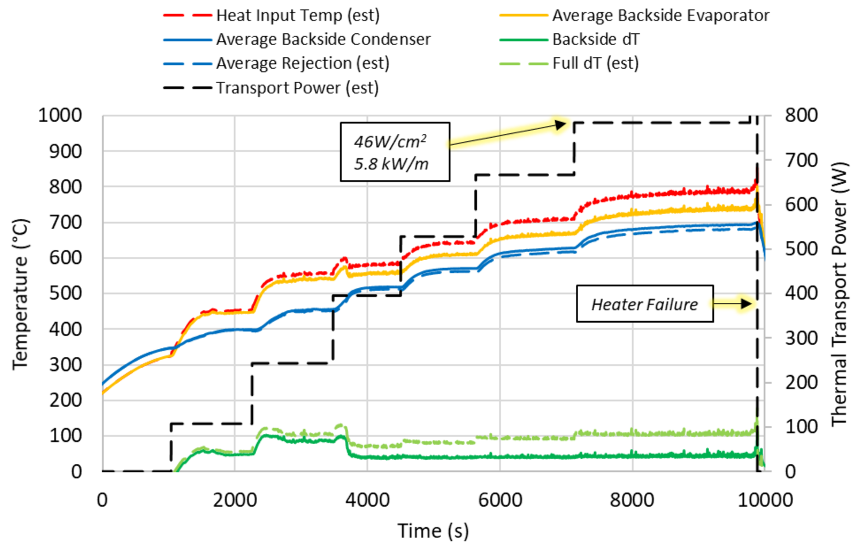


Oscillating Heat Pipe

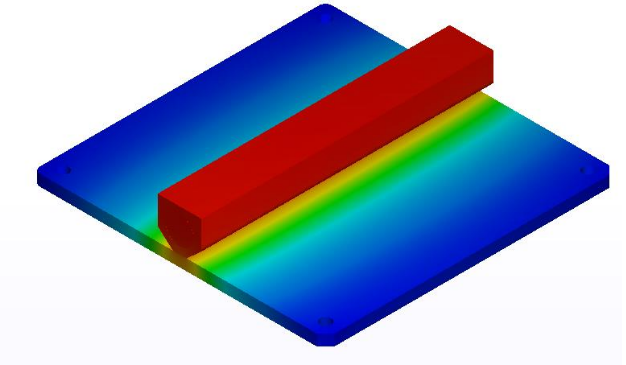


Transport Δ T: 57 °C
Conductance: 8.8 W/°C

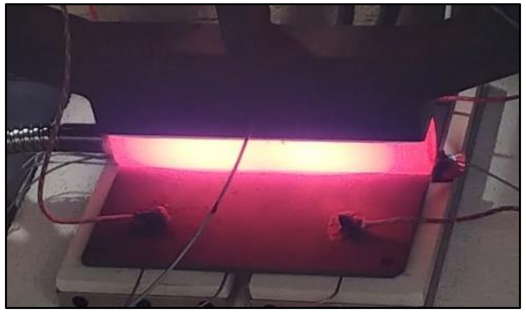




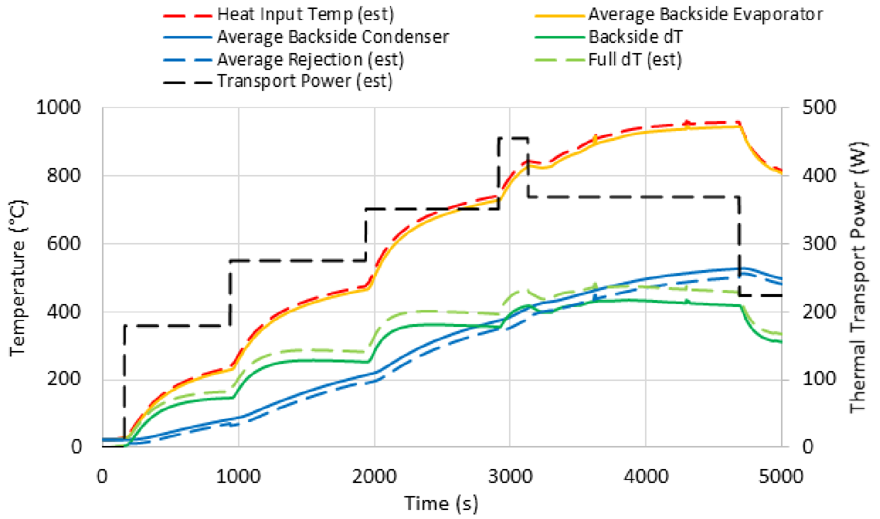
Solid Inconel Control



Transport ΔT: 377 °C
Conductance: 1.0 W/°C

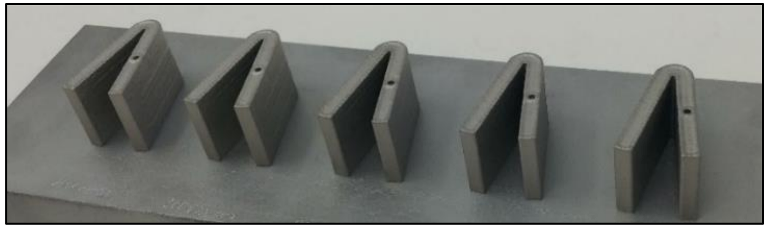


Initial turn-on test with solid control, before insulation was applied.
Early cartridge heater with 'cold ends'

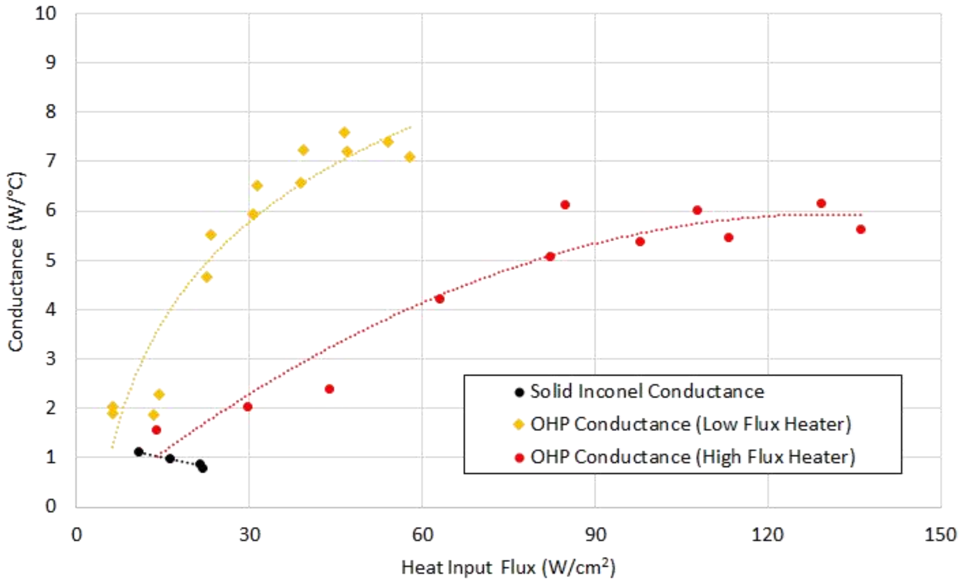


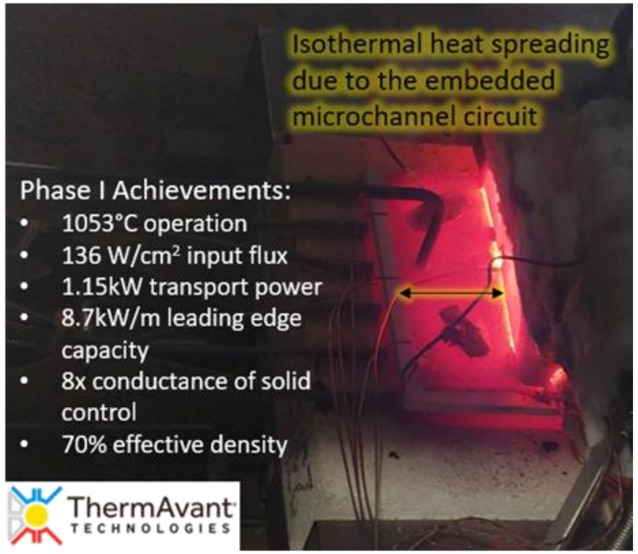
Phase I Achievements

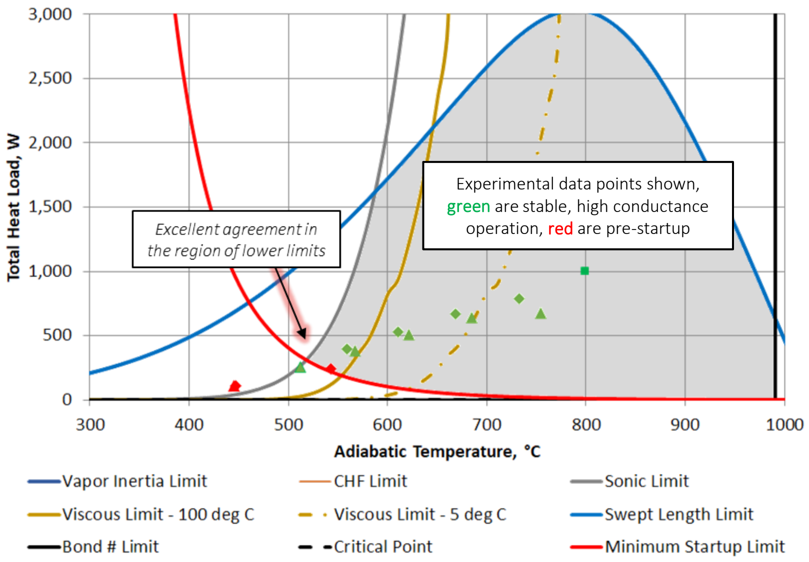
- Built and tested the first high performance, high temperature OHP (HT-OHP)
- Validated Startup Limit for first HT-OHPs
- Demonstrated two working fluids (elemental fluids with high vapor pressure, not metals!)
- Demonstrated one additive manufacturing process
- Expands ThermAvant's thermal skin product portfolio
- Generated significant interest from existing major defense contractor (MDC) customers



Additive MRL coupons on build plate







Peak performance limited by phase I test bed, did not reach OHP transport limits

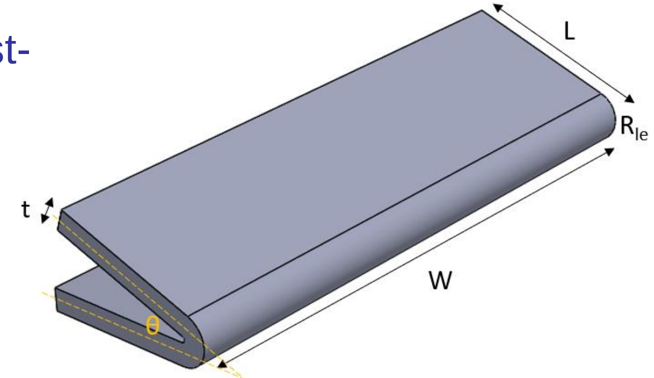
Phase II Objectives, Tasks, and Requirements

Technical Objectives

A. Improve predictive modeling capabilities through exhaustive breadboard testing
B. Optimize the HT-OHP performance, stability and external mechanical features
C. Develop reliable manufacturing processes for real-world LE-OHPs
D. Create clear technology transition paths for LE-OHPs post-Phase II

Task Descriptions

1. Formalize specifications for design activities
2. Conduct an engineering design and analysis
3. Manufacture OHP prototypes
4. Experimental investigation into performance, limits of operation and reliability
5. Transition of LE-OHPs (or similar form factor) to commercial and military programs

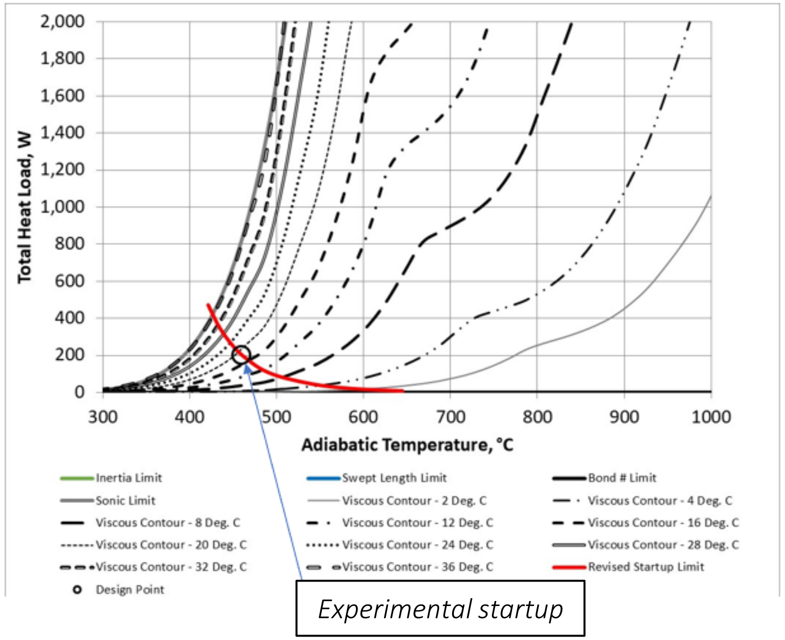


Program Targets

Characteristic	Proposed for Program
Width (in)	≥ 4
Length (in)	4 – 8
Thickness (in)	N/A
Leading edge radius (in)	0.12
'V' angle (°)	10
Integration / attachment features	As required for testing
Envelope CTE (ppm/K)	5 – 20
Surface roughness (microinch)	30-100
Structural / mechanical	As required for testing
Surface emissivity	≥ 0.8
Input heat flux (W/cm2)	200 – 500
Peak input temperature (°C)	1200 – 1500 +
Thermal performance	Specific conductance 25x base material
Baseline	CMC
Oxidation protection and high emissivity	Coatings suitable to survive ground testing
Storage	4 years at 50°C
Mission life	10 min to 10s of hours

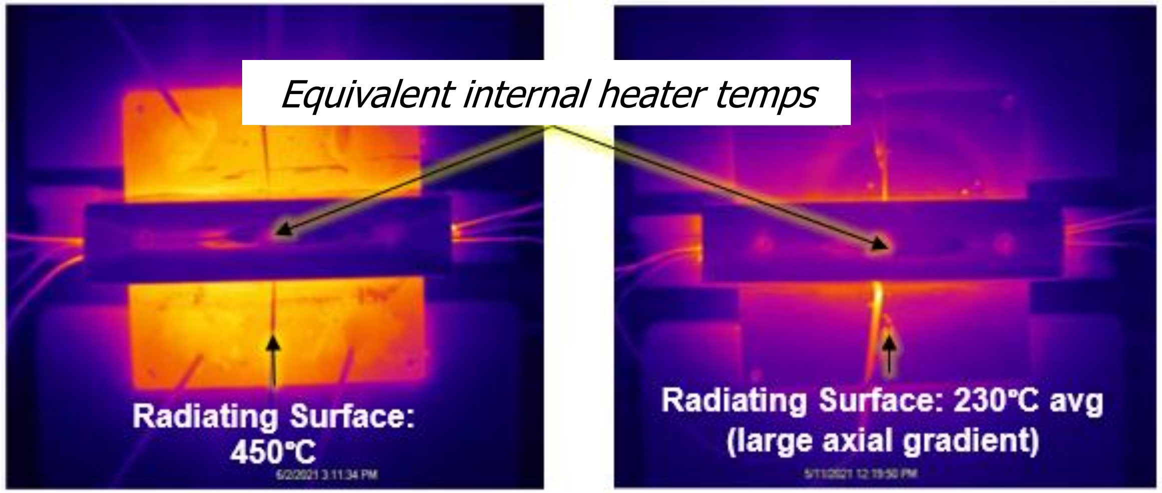
PhII: Single Heater Testing – Centerline Input

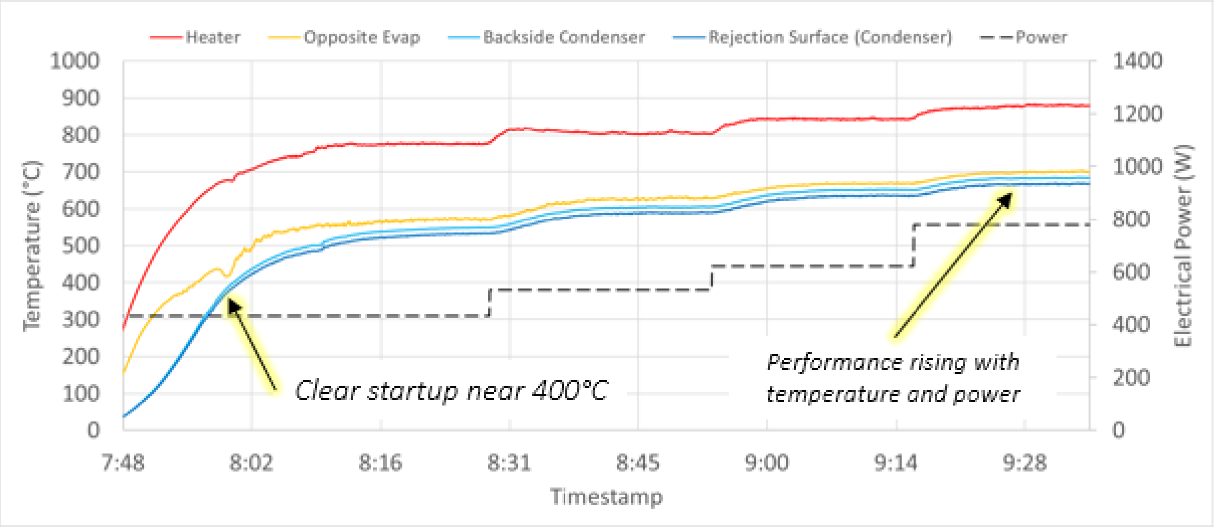
- New working fluid demonstrated in phase II (liquid metal), with:
  - Improved chemical compatibility with envelope materials
  - Wider operating range (higher critical point)
  - Lower freeze/thaw risk (lower freeze point)
  - Predictable startup: limits chart vertical axis on basis of instantaneous rejection power (calculated from condenser surface temp)



Gen 1 OHP, retested on phase II after 18mo storage

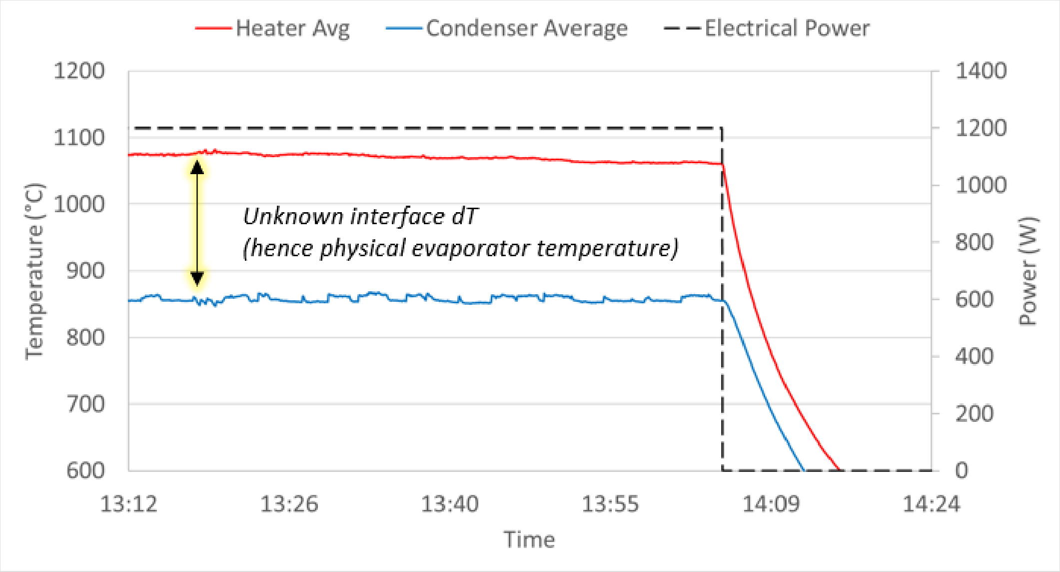
Solid Inconel Comparison

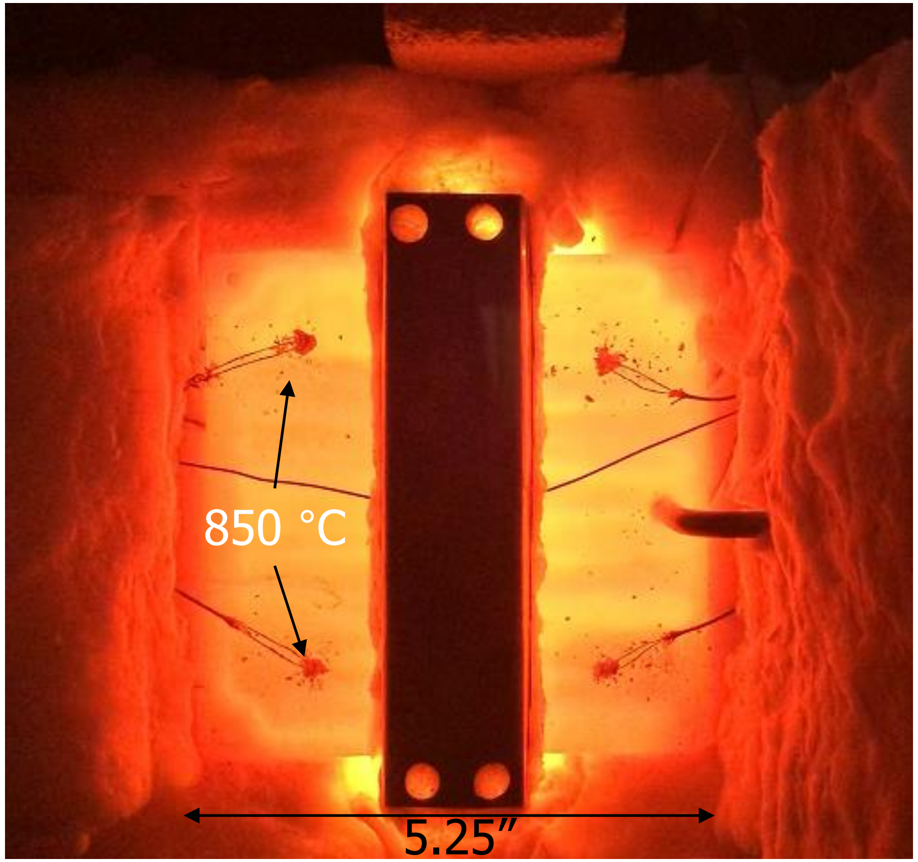




PhII: Dual Heater Testing – Centerline Input

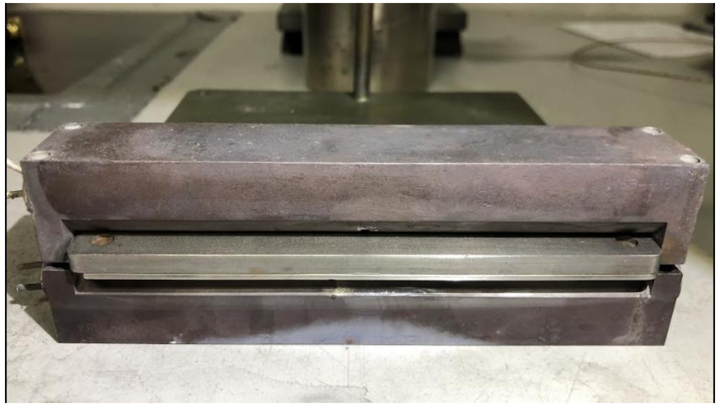
- Testing performed with two opposing heaters to achieve higher power
- 850 deg-C average rejection surface at $1.2kW_e$
- Conductance values not reported due to unknown true evaporator temperature (TCs probes located on hot side of copper interface in heater block grooves)

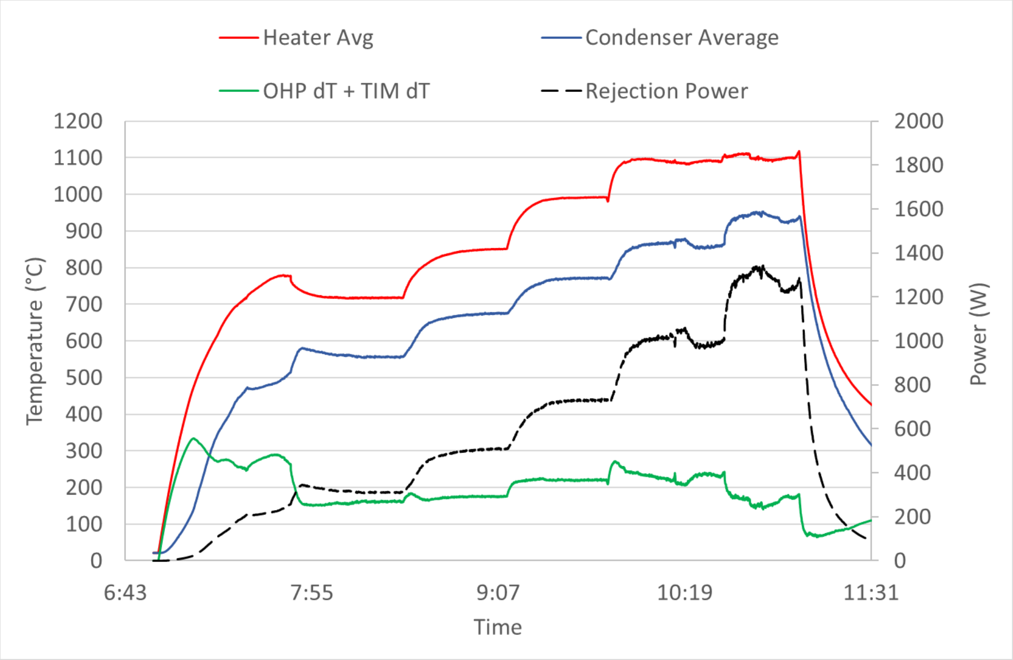


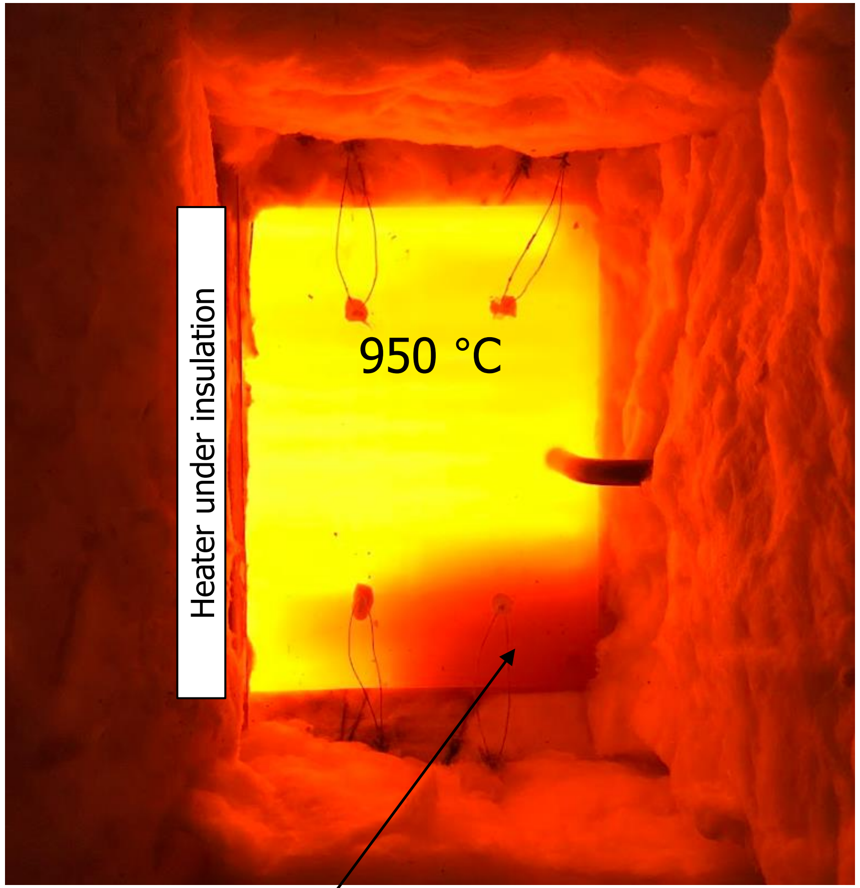


PhII: Dual Heater Testing – Edge Input

- Dual heaters moved from centerline to edge of Gen 2 breadboard
- Heaters survived up to 1100 deg-C measured at the OHP interface, resulting in 950 deg-C avg rejection surface
- ~4” transport distance approaching envelope service limits.





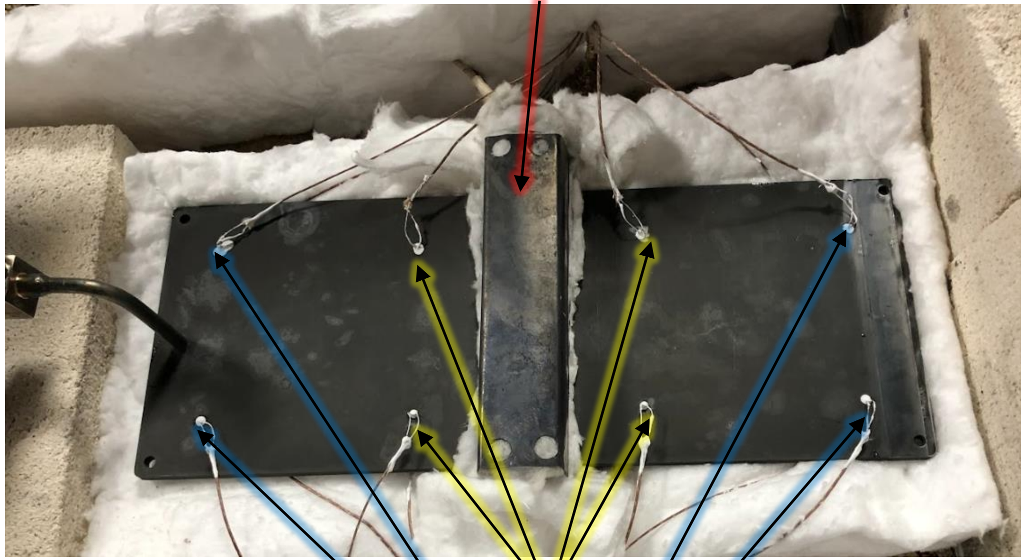


Corner region transitioning dark/cold on slow period (10 min) above 800°C – possibly tip of heater going out at last power step and not heating bottom channels

PhII: Larger Breadboard Test Setup

- 'G2 Long' OHP envelope: 5.25" x 13.5" x 0.20"

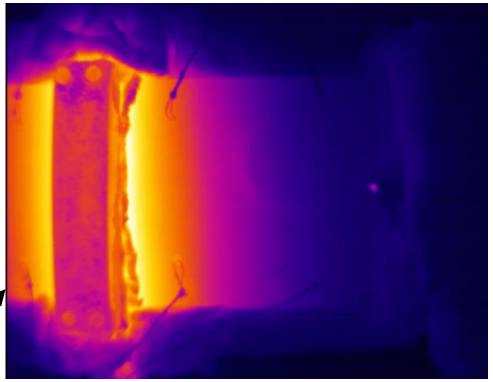
Radiation shield over central heater



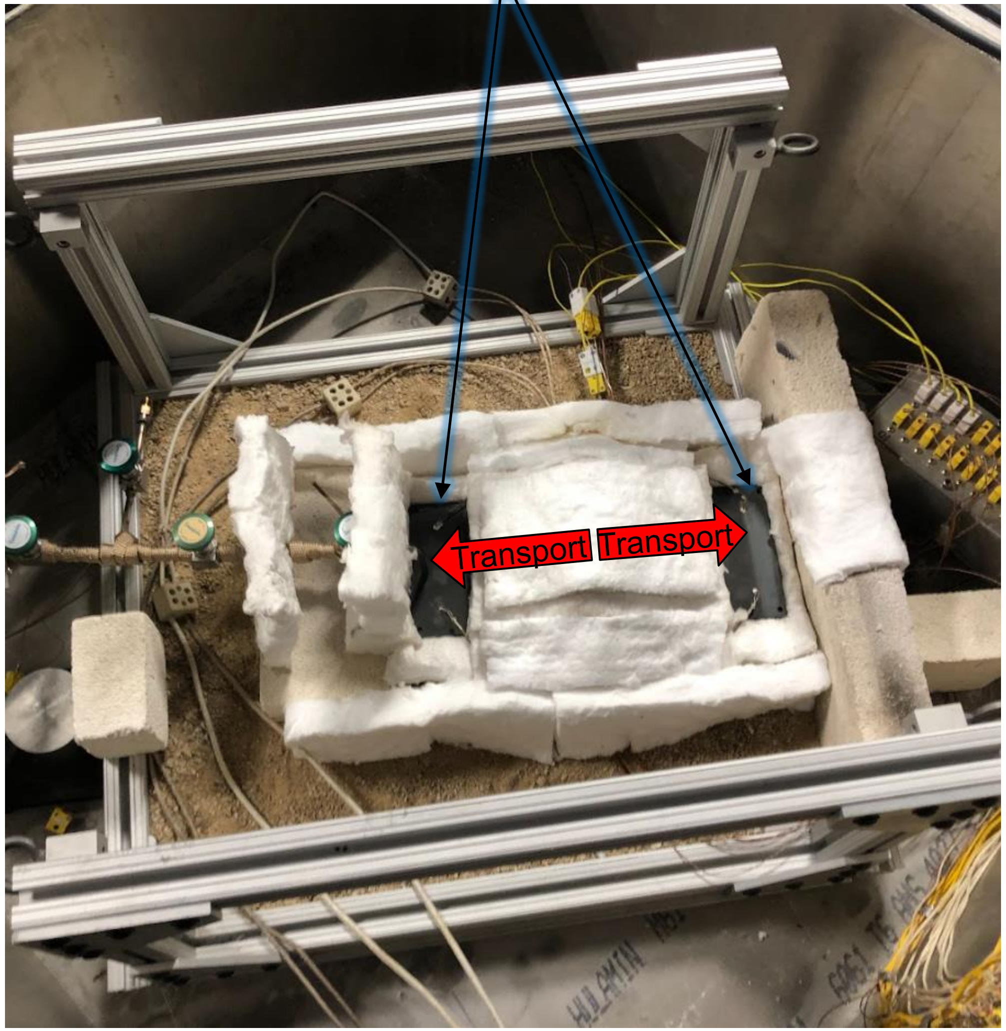
Adiabatic TCs

Condenser TCs

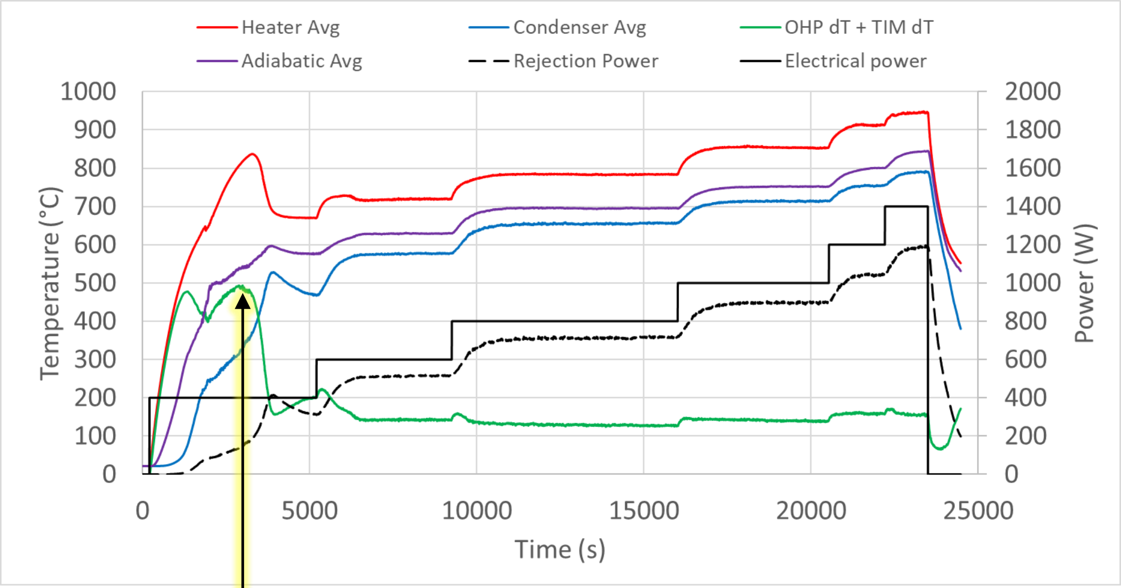
IR profile for ~near mass equivalent control test (empty OHP), run initially without additional insulation for adiabatic transport

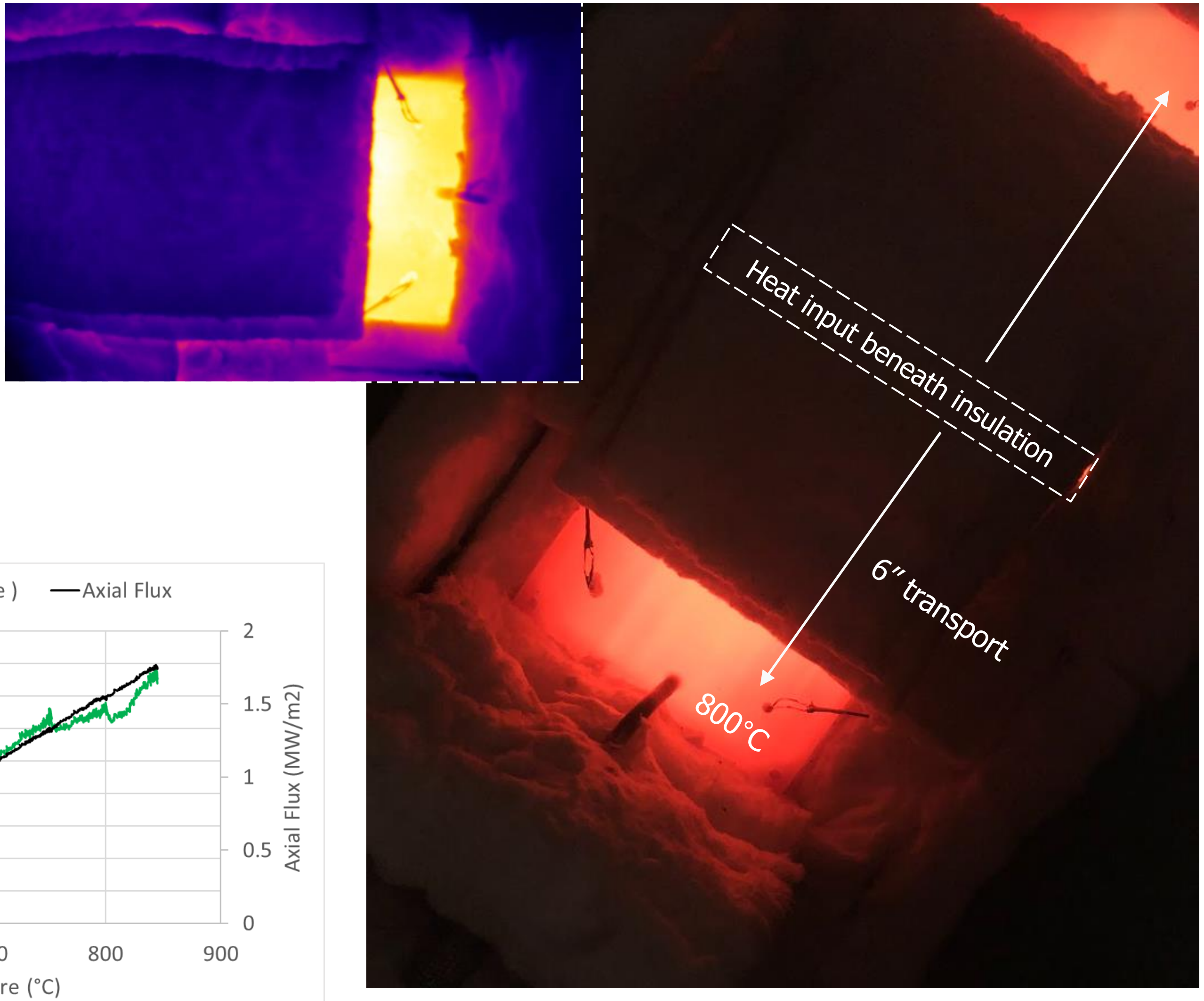


Rejection only from tips of top surface



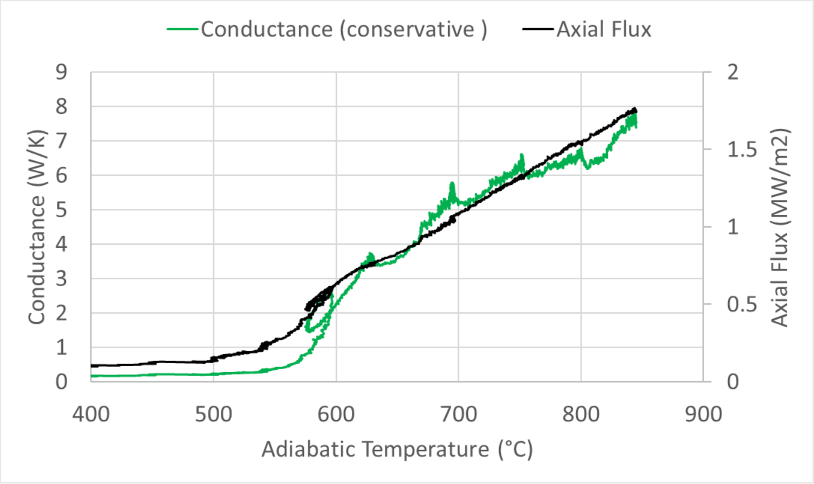
- Successful first demo at 1/3-m scale, and first demo of liquid metal in smaller channels (<3mm)





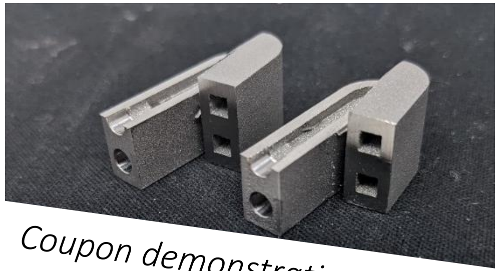
- Clear startup at 550 deg-C adiabatic temp and low power (~200W instantaneous transport power based on rejection temp). Accurately predicted by Limits Chart (not shown)

- Performance continues to rise sharply with increasing temperature and power
  - Denominator in conductance calculation includes unknown evap TIM dT (conservative)

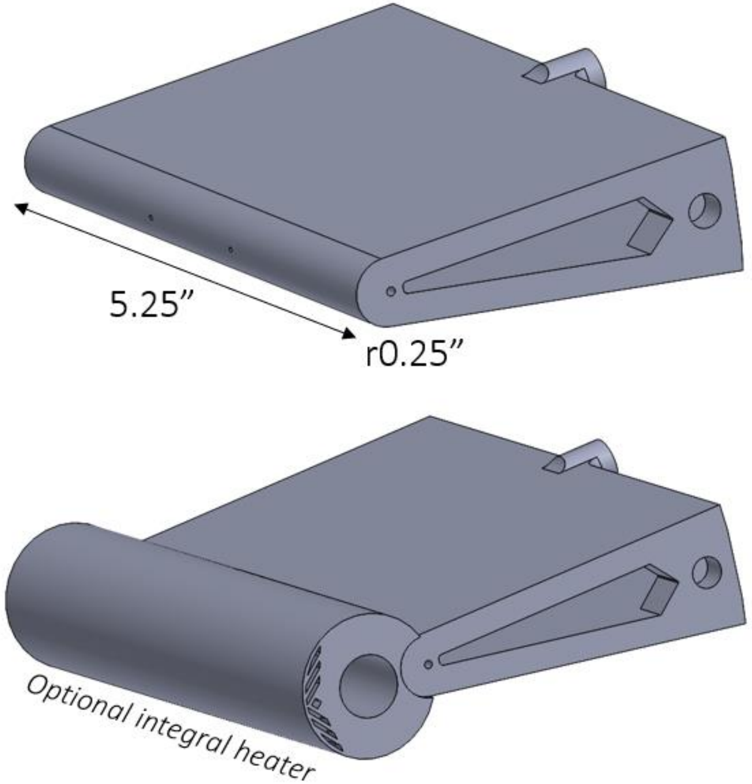


PhII Hardware – G5 Engineering Models

- Final generation of hardware on the phase II program are additively manufactured Inconel 625 wedges (SLM/LPBF), demonstrating the complex geometry required by real-world leading edge applications
- Multiple designs were manufactured, with various internal channel geometry, leading edge radii, and integral heaters for testing
- These parts were ThermAvant's first functional OHPs additively manufactured in superalloy material: completed with 100% yield (6/6)



Coupon demonstrations prior to full-scale print



G5 CAD Concepts

Test ready G5 hardware

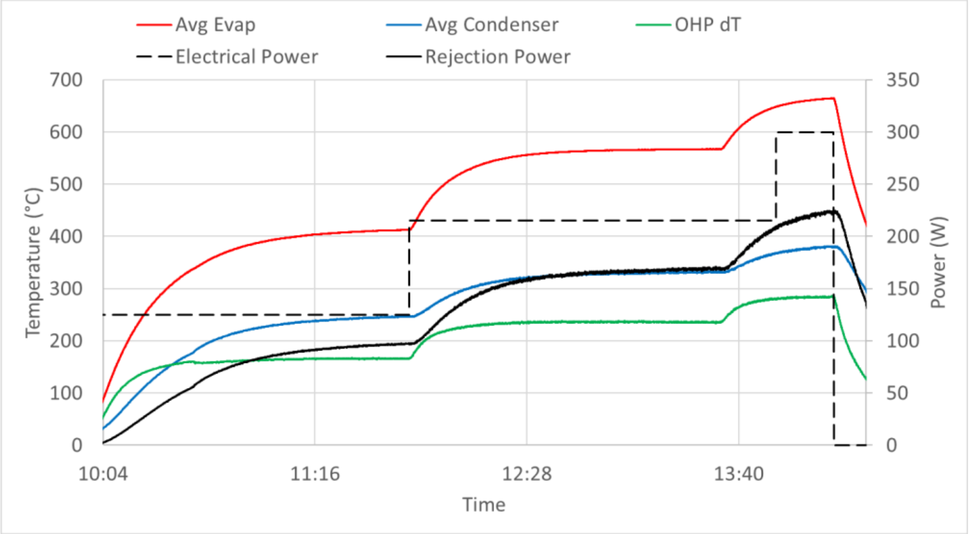
PhII Hardware – G5 Wedge OHP Test Results

- G5 wedge OHPs charged with liquid metal working fluid exhibit good thermal performance – similar to planar breadboards with equivalent boundary conditions

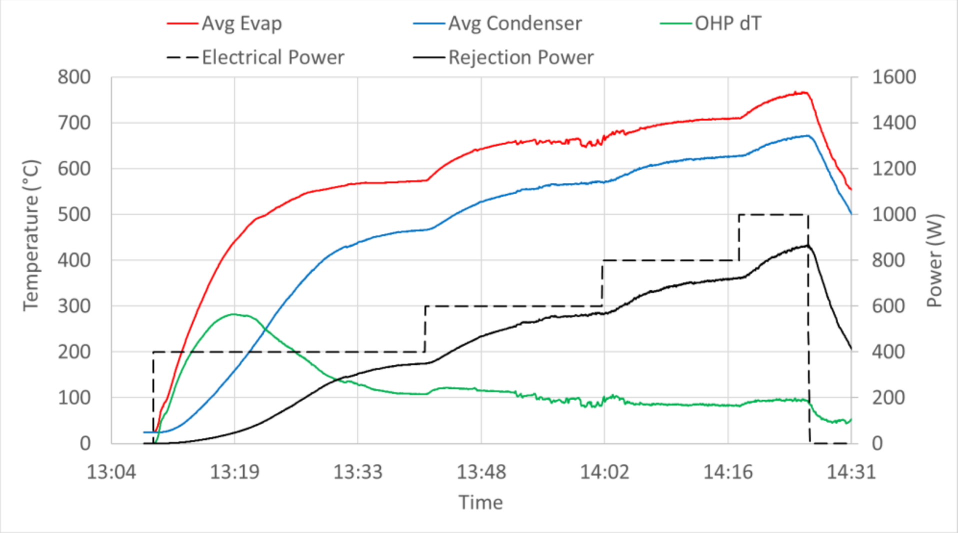
- Reliance on COTS cartridge heater limited demonstration to $1kW_e$, 850W transported @ +50 W/cm^2 input flux

Side profile images of the G5 OHP wedge taken within the test chamber with a borescope. Top: room temperature. Bottom: 750°C peak input (evaporator), 670°C rejection surfaces (condenser).

Top view of G5 OHP during testing. Cartridge heater possibly offset 'to the left' causing reduced heat delivered to channels on the right and hence colder condenser corner.

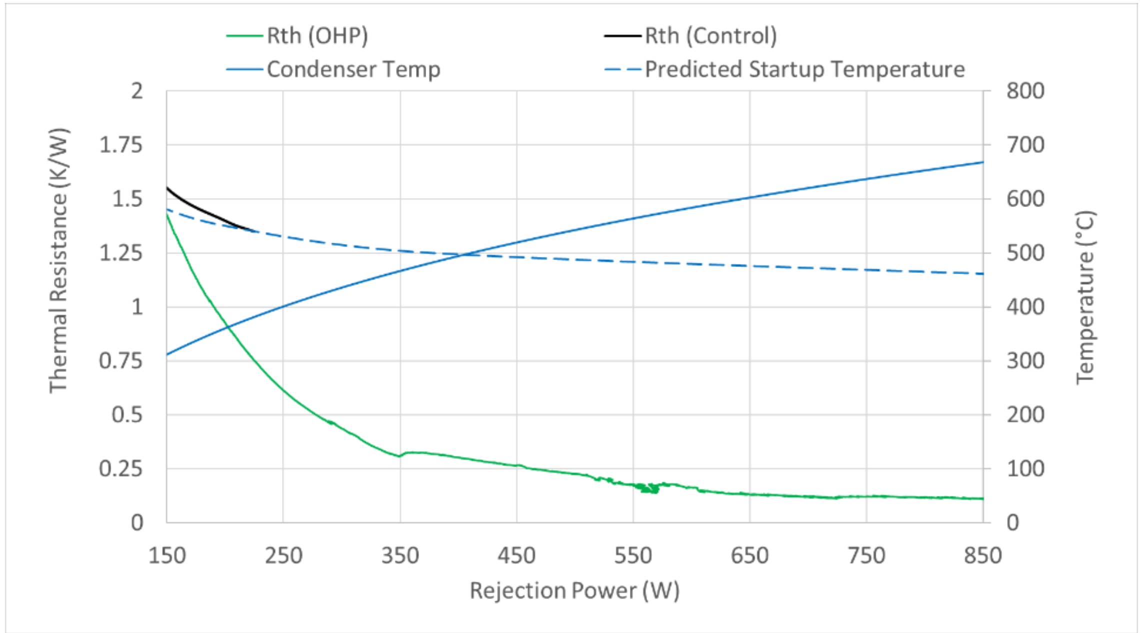


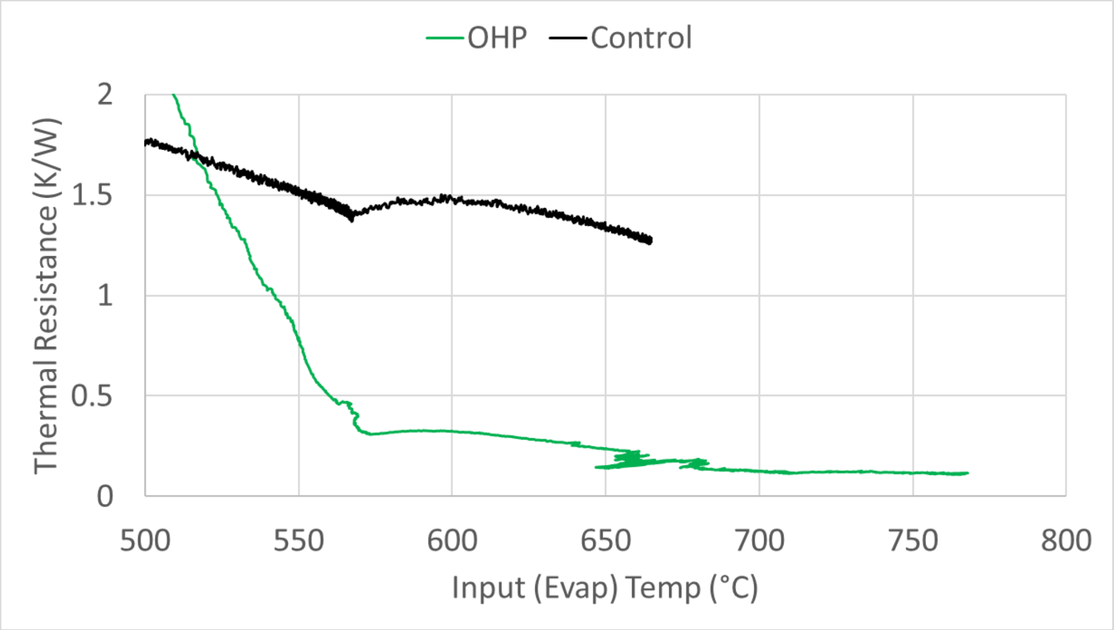
G5 mass equivalent control test (empty OHP)



G5 OHP test, with liquid metal working fluid

PhII: G5 Wedge OHP Test Results





- G5 OHP performance sensitivity to rejection power and condenser temperature (proxy for fluid temp), with comparison to vented control. Predicted startup temperature included on secondary axis for reference.

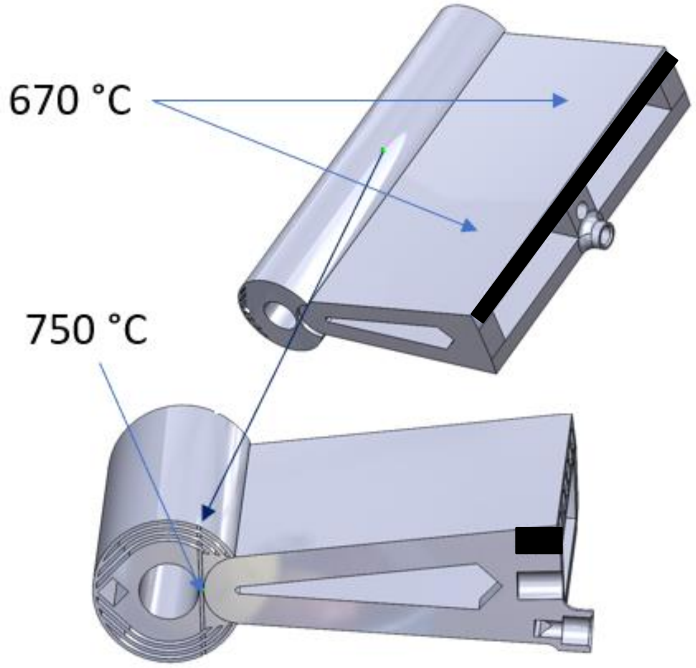
- G5 OHP comparison to vented control: thermal resistance vs input temperature

- The OHP performance improves with temperature and achieves an order of magnitude improvement over the mass-equivalent conductor above ~675°C.

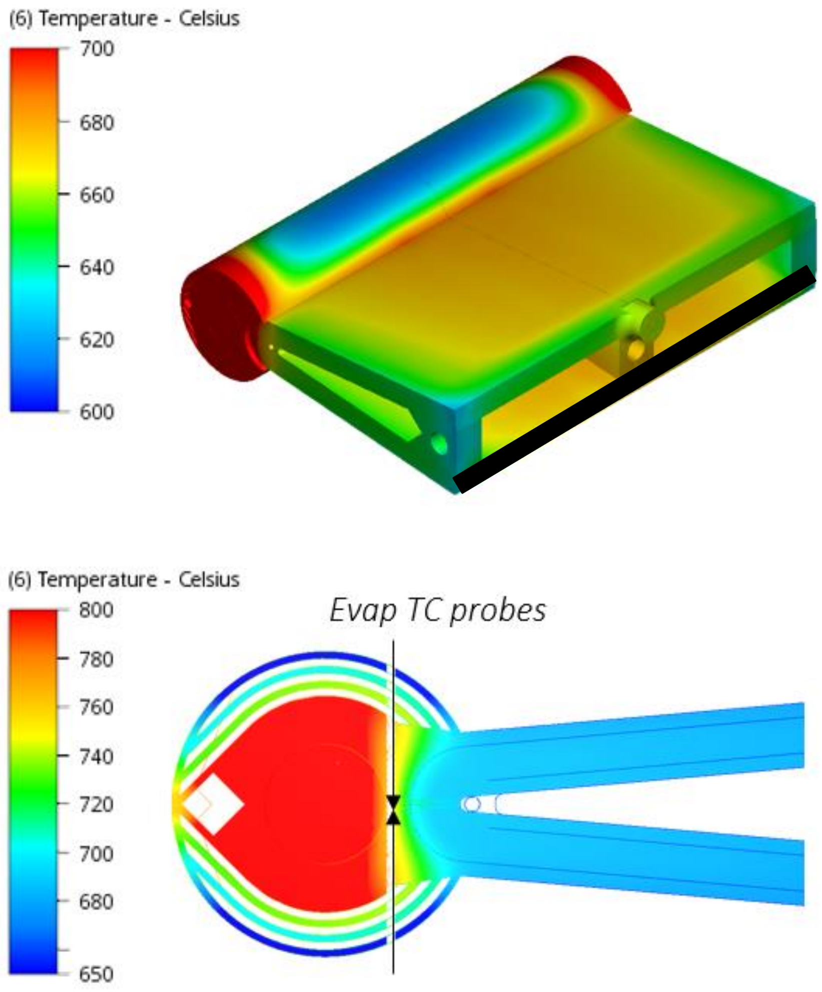
PhII: G5 OHP Simulation Tuning

- Levering these experimental results which aren’t obscured by unknown interface gradients, a finite element analysis was performed to match experimental measurements and extract effective properties of channels and fluid

- The validated characterization (effective thermal conductivity of the channel volume, and convective film coefficients applied to channel walls) can be utilized for predicting performance of new designs and/or varying boundary conditions



Three experimental measurement values and positions for tuning of finite element model.



Temperature profiles from steady-state finite element simulation, matched to experimental results

Phase II Summary

- High temperature (400-1100 deg-C) oscillating heat pipes in superalloy envelopes are at TRL/MRL 4
- Complex, additively manufactured, and 1/3-m scale geometries have been successfully demonstrated
- Phase II demonstrations with a new liquid metal working fluid are very promising, with good thermal performance, manageable freeze point, and known compatibility with superalloy envelopes
- No ‘hot-limit’ (transport capacity limitation) has been observed in any testing to-date, due to existing test bed power limitations <2kW$_e$ and service ceiling of the Inconel envelope (~1100 deg-C)
- Modeling of high temperature OHPs is improving rapidly as we generate empirical data to verify, validate, and anchor models

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