High Temperature Oscillating Heat Pipe Heat Rejection Radiators for Management of Fission Power Generation

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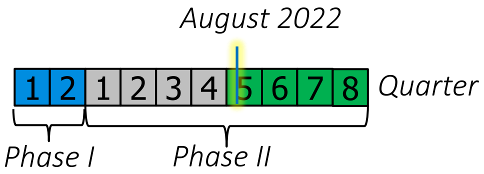
Presentation Outline

- NASA Fission Power Background
  - SBIR Project Overview
  - Related Work
  - Roadmap
  - Phase I Trade Study

- Phase II Ongoing Efforts
  - Analysis and Design
  - Manufacturing
  - Performance Testing
  - Summary

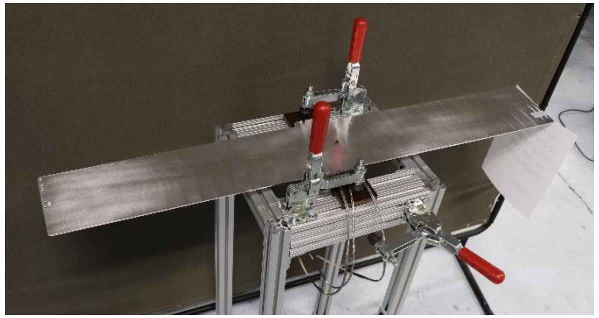
NASA Fission Power SBIR

- Goal:
  - Continue the development of thin-profile Oscillating Heat Pipe (OHP) radiator panels, e.g., m^2 scale x 2-3 mm thick, to reject waste heat from the Fission Surface Power reactor system at intermediate temperatures, and position the technology for implementation.
- SBIR Timeline:

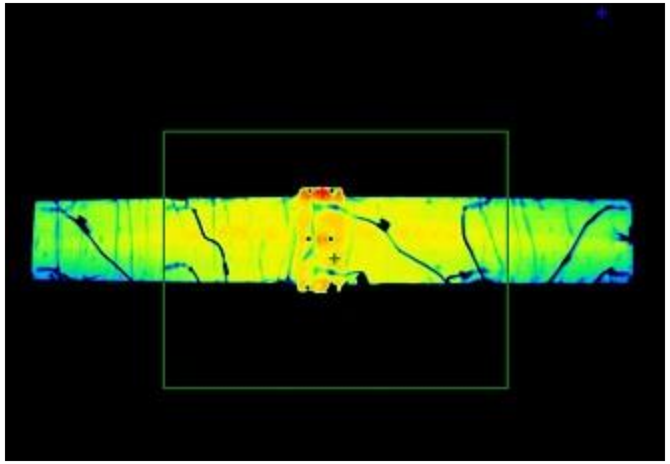


- Solicitation target:
  - Freeze tolerant heat pipe radiators that can operate through lunar night (-173 ºC) and day (127 ºC) temperature swings. Heat pipes must start-up from lunar night temperature and begin transferring heat within several thermal cycles.
- Proposed solution:
  - Develop intermediate temperature OHP radiator, by quantifying limits of operation, better predicting conductance turndown ratio and optimal fill ratio
  - Demonstrate more working fluid options capable of operating over a broad range of temperatures (100-300 ºC) without detriment to the envelope material, i.e., long-term reliability
  - Elevate the TRL by testing subscale prototypes
  - Elevate the MRL by maturing manufacturing processes, capable of building reliable radiator panels with high thermal conductance and specific power

Example of OHP radiators being developed with NASA



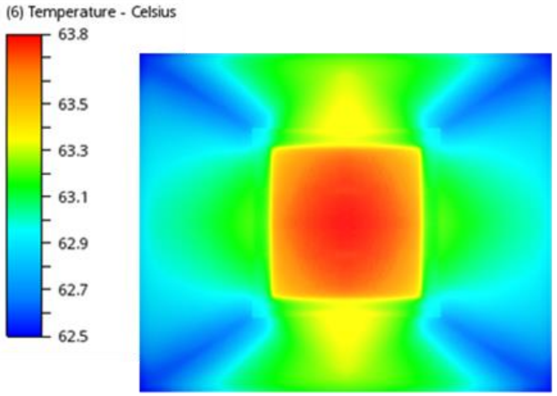
IR image of flat plate OHP radiator operating at ~175°C at ThermAvant Technologies



Phase I/II: Next Gen Spacecraft Heat Rejection System

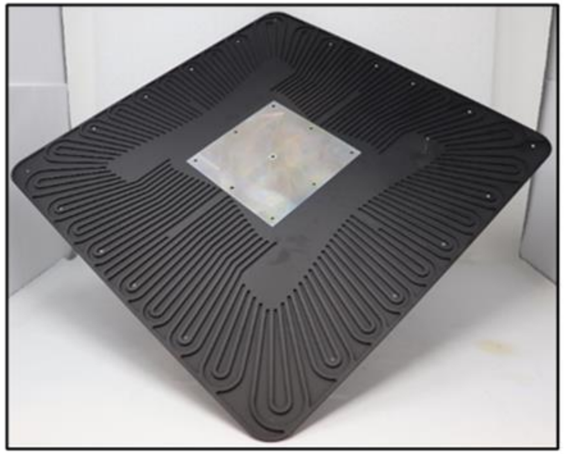
- OHP-embedded aluminum radiators, focused on applications up to 360 K (Si-based electronics payloads)
- 2D spreading of point loads, with less than 2 °C gradient in all cases tested, on panel sizes from 0.25 to 0.50 m^2
- Thermal resistance as low as 0.005 K/W at up to 600 W
- No adverse effects of gravitational orientation
- Demonstrated increased thermal capacitance by embedding solid-to-liquid PCM to dampen transient loading and ΔT's

1.0m x 0.5m x 3.5mm OHP

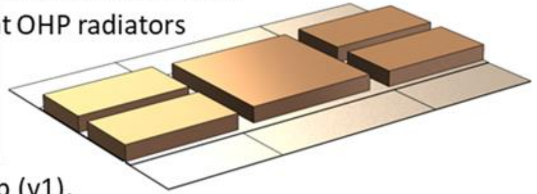


Simulation of single-component heat acquisition on 0.25m² panel

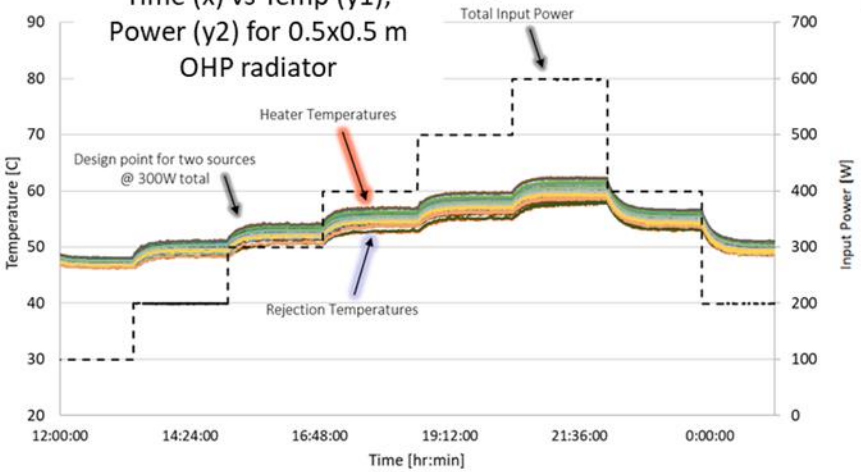
Phase II 'Qual Panel' with material removal (lightweighting) between channels



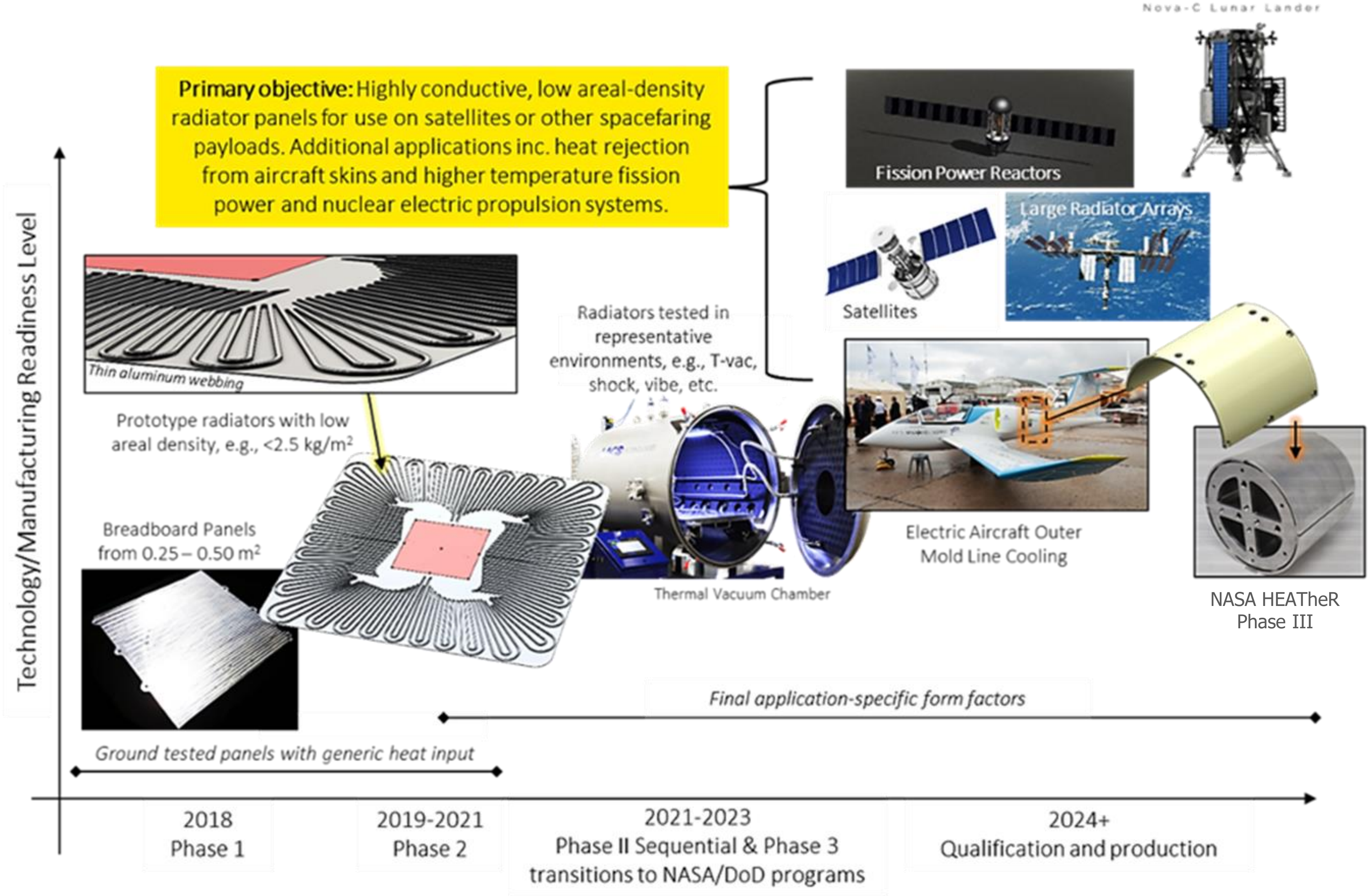
Conceptual layout of electronics on large-format OHP radiators



Time (x) vs Temp (y1), Power (y2) for 0.5x0.5 m OHP radiator



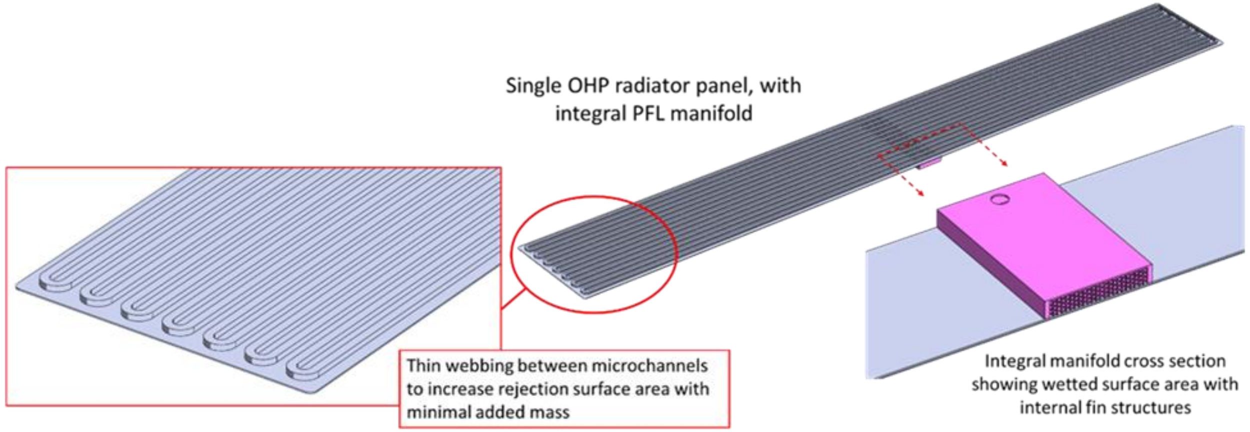
Roadmap for TAT's OHP Radiator Technology



Phase I Trade Study

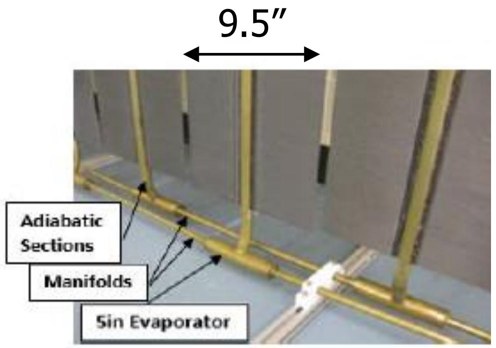
- A case study was performed comparing a sparse channel OHP concept to the concept described by Tarau, et al using a titanium water VCHP with carbon fin

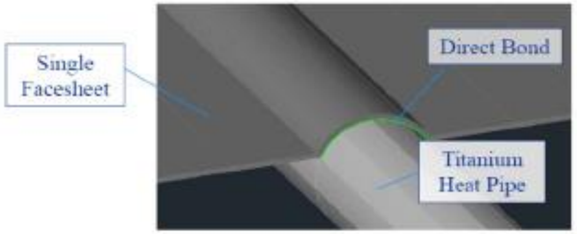
- Increased rejection capacity driven by improved uniformity of the panel and reduced ΔT at the heat input interface through use of high-performance, integrated PFL manifold



	OHP Radiator	Tarau et al [7] Heat Pipe Radiator
Radiator Area (both sides)	0.44 m^2	0.44 m^2
Working fluid	Acetone, Ethanol or another Ketone	Water
Envelope Material	All aluminum	Titanium CCHP with stainless plumbing
PFL Inlet Temperature	110 °C	127 °C
Radiator Temperature	100 °C	100 °C
Thermal Capacity	416 W	416 W
Dry Mass, not including manifold	0.367 kg	Not reported
Dry Mass, including manifold	0.433 kg*	0.685 kg
Areal density	0.98 kg/m^2	1.55 kg/m^2
Specific Power	960 W/kg	608 W/kg

Obsolete target temps (see next slide)





[7] Calin Tarau, "*Status of the Development of Low Cost Radiator for Surface Fission Power II*," Nuclear and Emerging Technologies for Space (NETS) 2016, Huntsville, AL, February 22-25, 2016.

*Estimated based on CAD model

Phase II Key Specifications

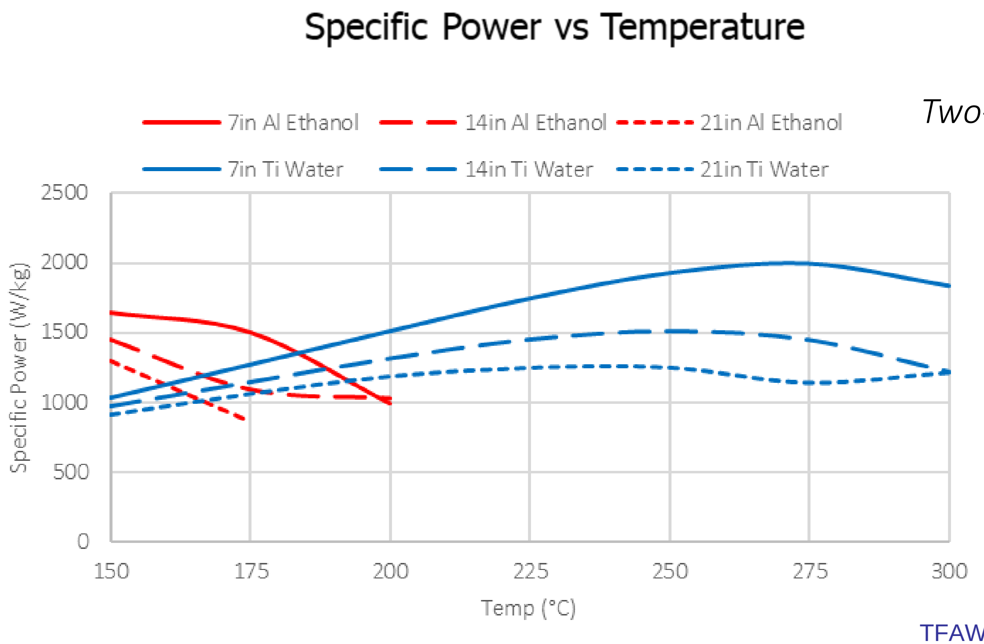
Specifications	***NASA Phase II***
Max Allowable Cold Side Temperature (inlet temperature to the interface with the OHP)	175 °C
Reactor Electrical Output	10 kW
Reactor Waste Heat	50 kW
Pump Efficiency	
Pressure Drop through PFL	best effort/pump motor losses
Parasitic electrical losses from the pump	<5%
Target Specific Power (kW/kg) and/or Areal Density (kg/m^2); temperature uniformity vs. areal density	areal dens = 1-3 kg/m^2 (panel + manifold + structure)
Incident Solar Radiation Load (W/m^2) and Surface Absorptivity; variability with lunar cycle	DSNE targeting South Pole Lunar
Min/Max Sink Temperatures and View Factors; single- or two-sided rejection; variability with lunar cycle	50K-250 K (& DSNE)
Environmental testing requirements (e.g., shock, vibe, thermal cycling, etc.)	TBD/ GEVS and SMC-S-016 are good places to start
Surface Finish or Coating Requirements	
Desired variable conductance or thermal switching	
Acceptance temperature range for qualification testing	
Redundancy requirements	50% power with 1 credible failure
Static loads – strength requirements	TBD/ GEVS and SMC-S-016 are good places to start
Stiffness requirements	TBD/ GEVS and SMC-S-016 are good places to start
MMOD shielding requirements	

- Added requirement: minimum exposure temperature (50 K) and 6 freeze/thaw cycles

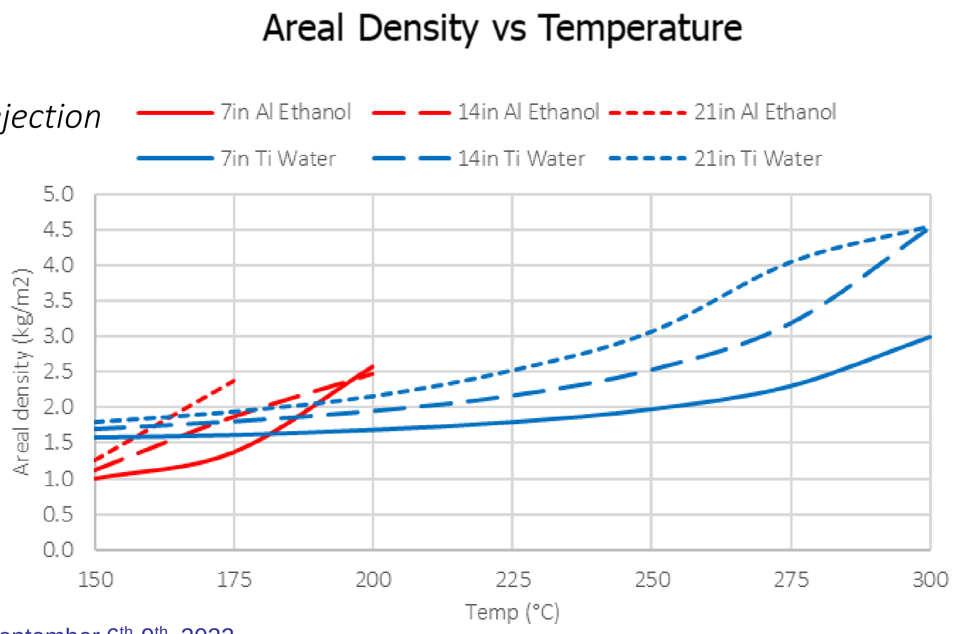
Preliminary Trade Study

Setup:

- Assumes isothermal rejection surfaces: neglects OHP transport gradient and facesheet fin efficiency
- Ignores low channel count instabilities (min. width required at effective channel pitch)
- Wall and lid thicknesses set to .025”, a reasonable value from a manufacturability perspective – currently ignores pressure containment (fluid vapor pressure and FoS to yield)
- Length in legend is transport distance (half panel length if center heated)
- Channel density required is based on 10% margin to predicted transport capacity hot limit (vapor-inertia), <u>however these capacity predictions were not experimentally verified across a full range of temperatures and length scales at time of chart creation (2021)</u>
- A primary output of the Phase II will be updated versions of these charts, validated and anchored by experimental data



Two-sided rejection

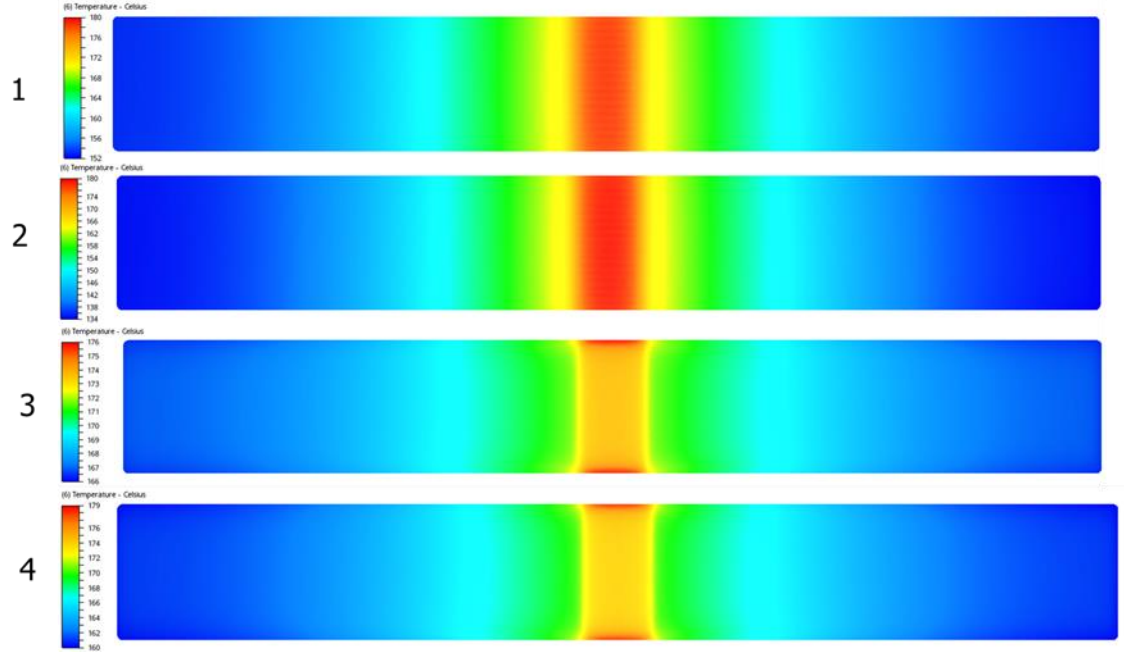


Preliminary FEA Analysis

Geometry and Boundary Conditions

- 6" x 44" aluminum OHP
- 3" long evaporator, with constant input flux applied
  - Not PFL-analog isothermal BC
- Emissivity = 0.95
- 50 K sink temperature
- Channel characterization extrapolated from testing at lower temps in smaller parts with a traditional (pure) fluid

(variable temperature scales – each set to part)



Summary Table

Simulation #	Channel Count	Radiation BC	Power	AVG Evaporator	AVG Condenser	OHP dT
1	Low	Single sided	325 W	178 °C	159 °C	19 °C
2		Double Sided	550 W	177 °C	144 °C	33 °C
3	High	Single sided	350 W	174 °C	168 °C	6 °C
4		Double sided	650 W	174 °C	163 °C	11 °C

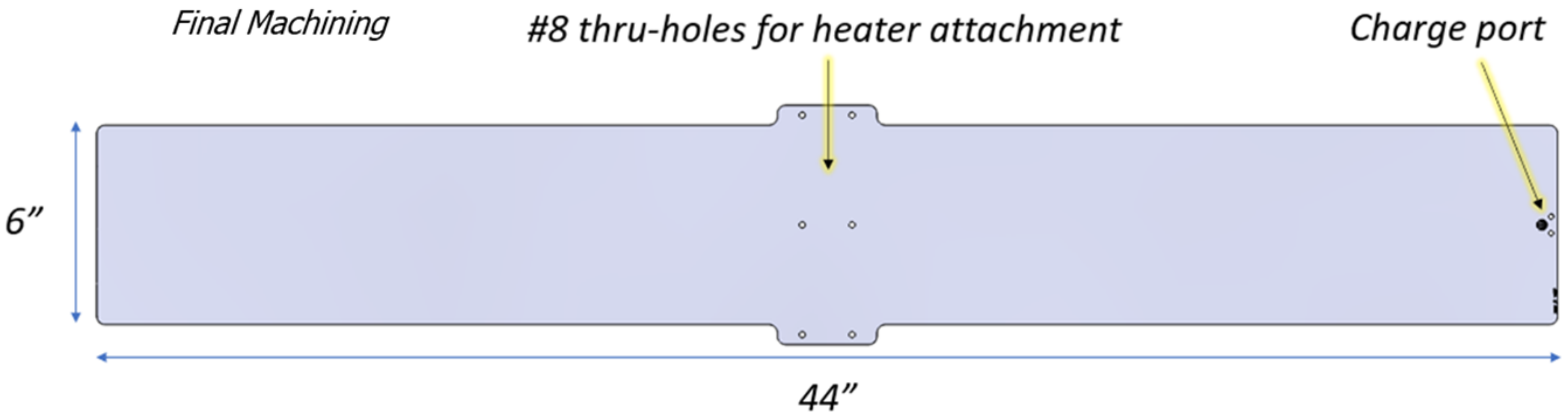
Manually iterated applied power to hit target 175 °C evap

- Simulations predicted conductance of 17-59 W/K for two-sided rejection, as function of channel count (low to high)
- Experimental testing has resulted in 21-36 W/K for breadboards with low to moderate channel counts
- Sensitivity to channel count in the simulations is primarily due to proportionally higher physical evaporator channel area (at fluid interface), hence lower flux and lower dT at assigned convective film coefficient (h_{2p})

Gen 2 Prototype Manufacturing

Aluminum breadboard OHPs with bolt-on electrical heater block

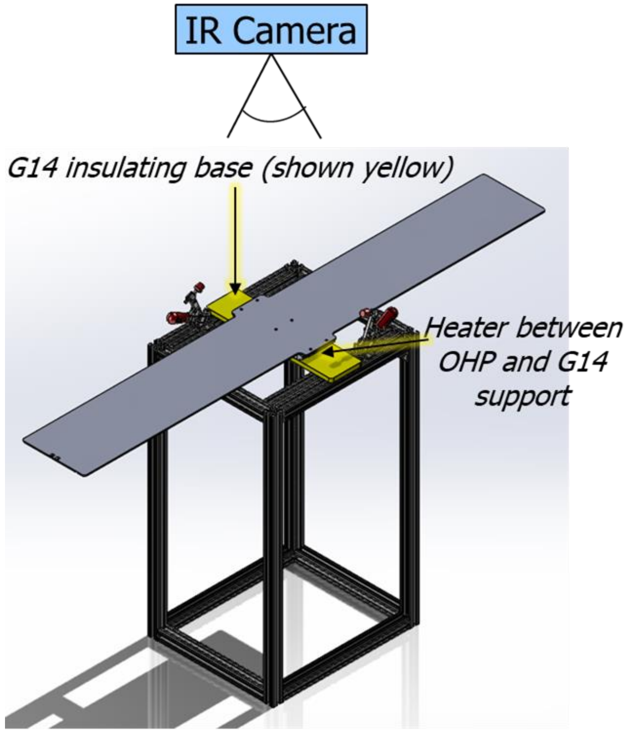
- 8 baseline designs manufactured with different internal channel geometries
- Thickness range: 0.08 - 0.14 inch (2 – 3.5 mm)
- Areal density range: 2 – 4 kg/m^2

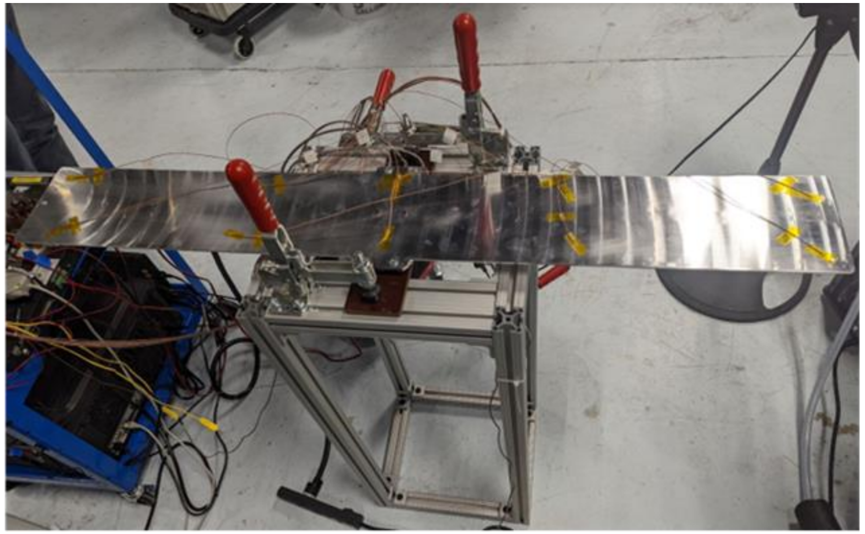


Vacuum brazed and final machined

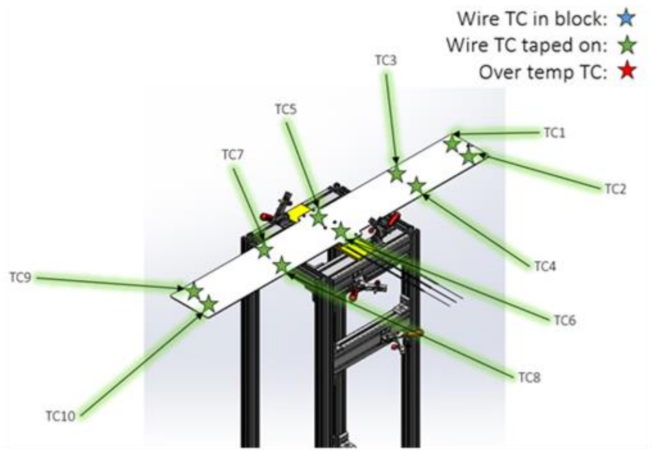
Open-air Test Bed

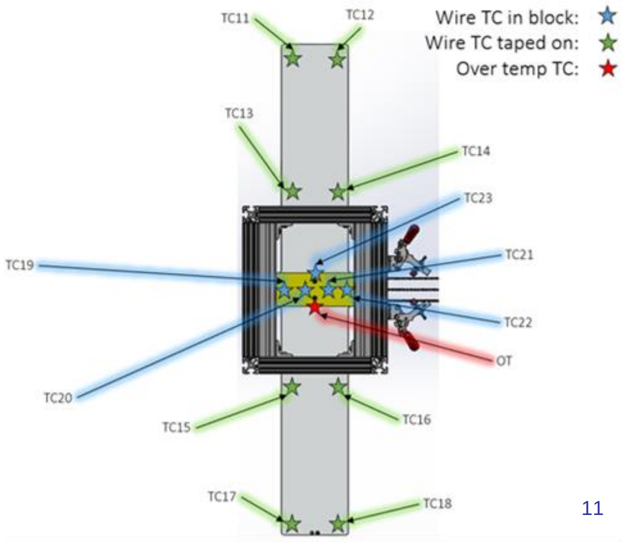
- Initial performance evaluation
- Higher throughput than TVAC
- Rejection flux at 165 °C ($T_{s,avg}$) is 15% higher than the radiative lunar environment due to natural convection





Thermocouple map





Analysis equations

$$Input\ Power = Electrical\ Power - Losses$$

$$Rejection\ Power = Natural\ convection + Radiation$$

$$Avg\ Evap = Avg\ Heater - TIM\ dT$$

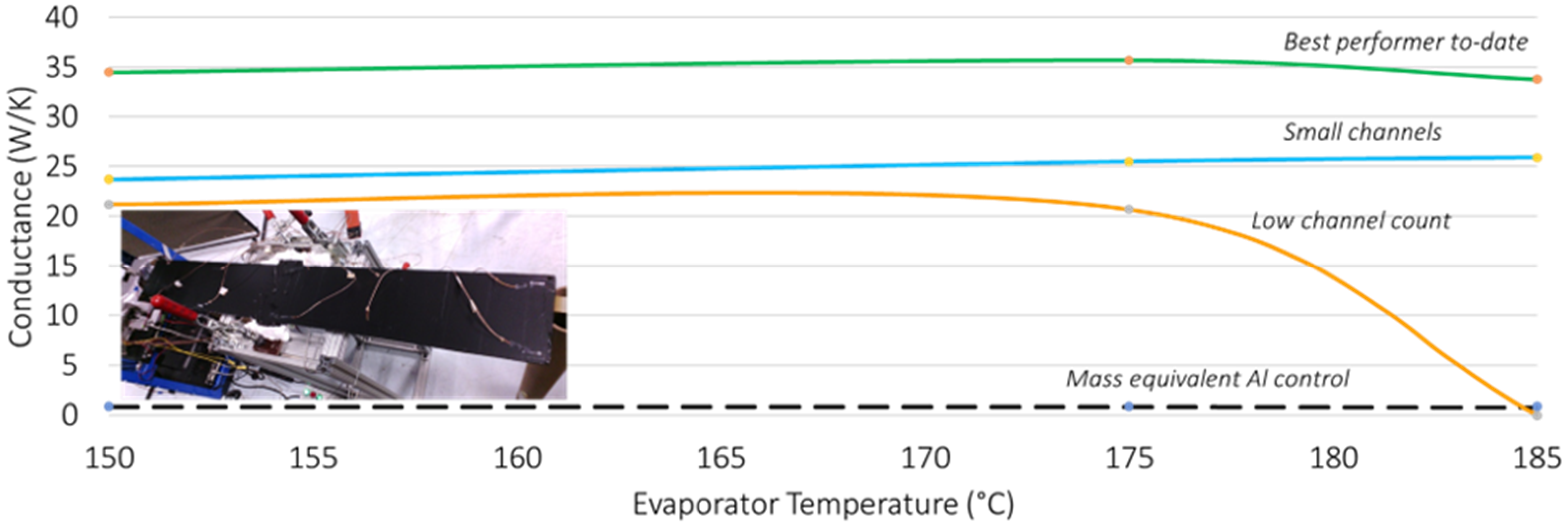
$$OHP\ dT = Avg\ Evap - Avg\ Cond$$

$$Conductance = {Power}/{OHP\ dT}$$

Gen 2 Performance Testing – Conductance Summary

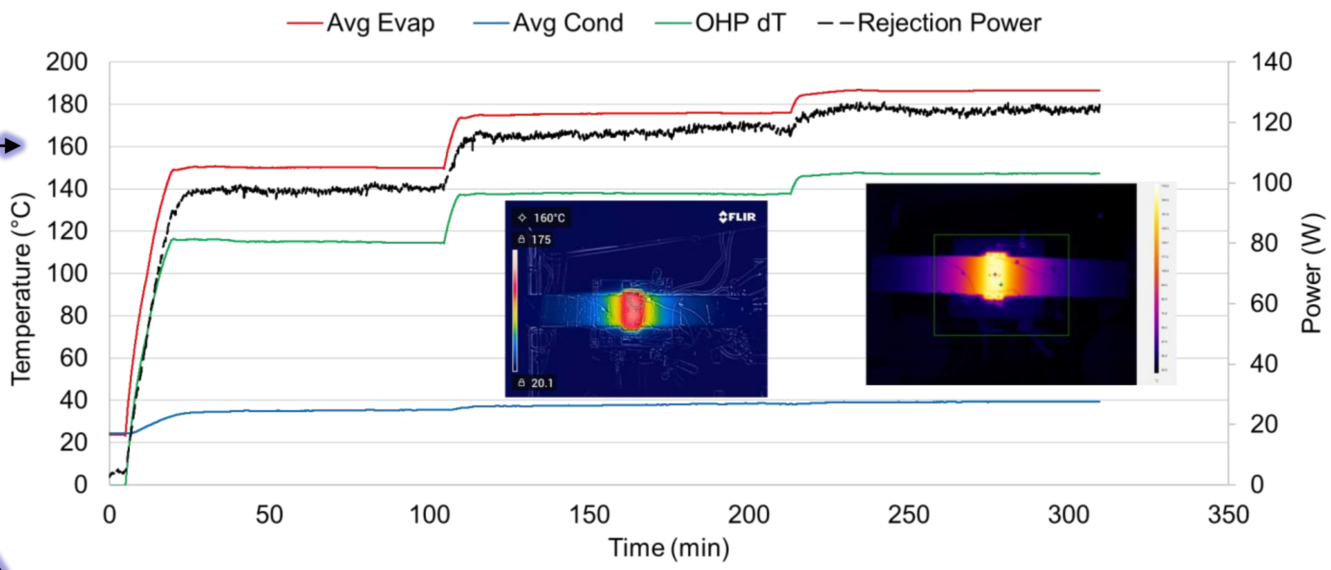
Results
- 3.1 kg/m^2 areal density
- 36 W/K conductance at 175 ℃ evaporator temp
- 40X performance of mass-equivalent Al control radiator

Test details
- Alcohol binary mixture
- OHP coated with high emissivity tape
- Varied liquid fill fraction to optimize performance

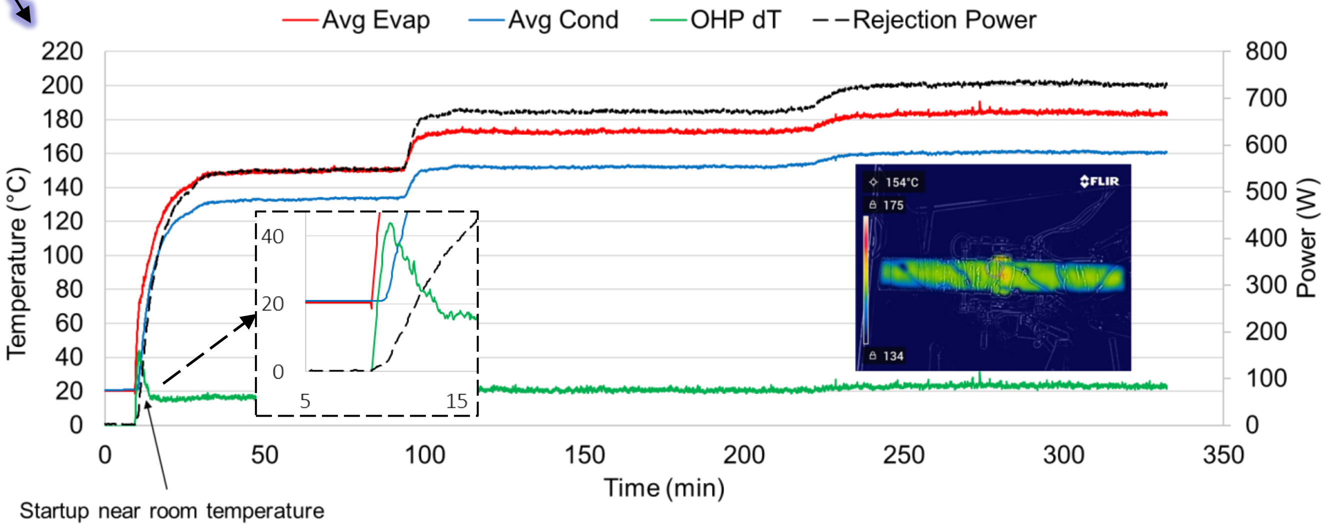


Gen 2 Performance Testing – OHP vs Control

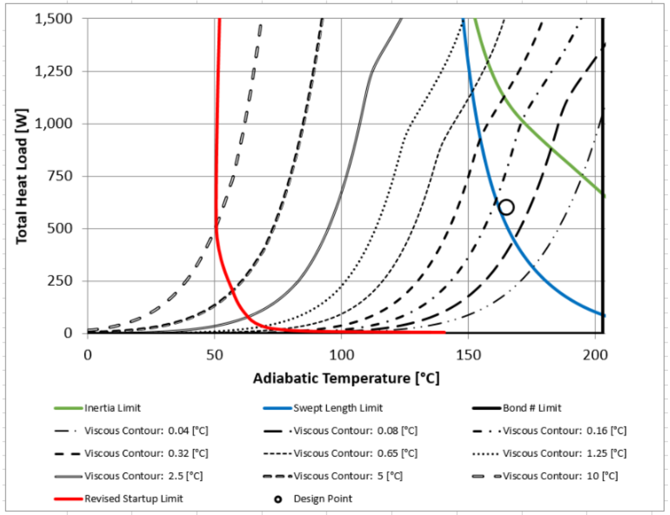
- (Near) mass equivalent aluminum control: OHP envelope vented of working fluid
- Cold tips, low thermal conductance: 0.85 W/K



- Highest performing OHP to-date: same aluminum structure, charged with working fluid
- 20 K spatial gradient (input surface to avg rejection surface) at 700 W: 36 W/K



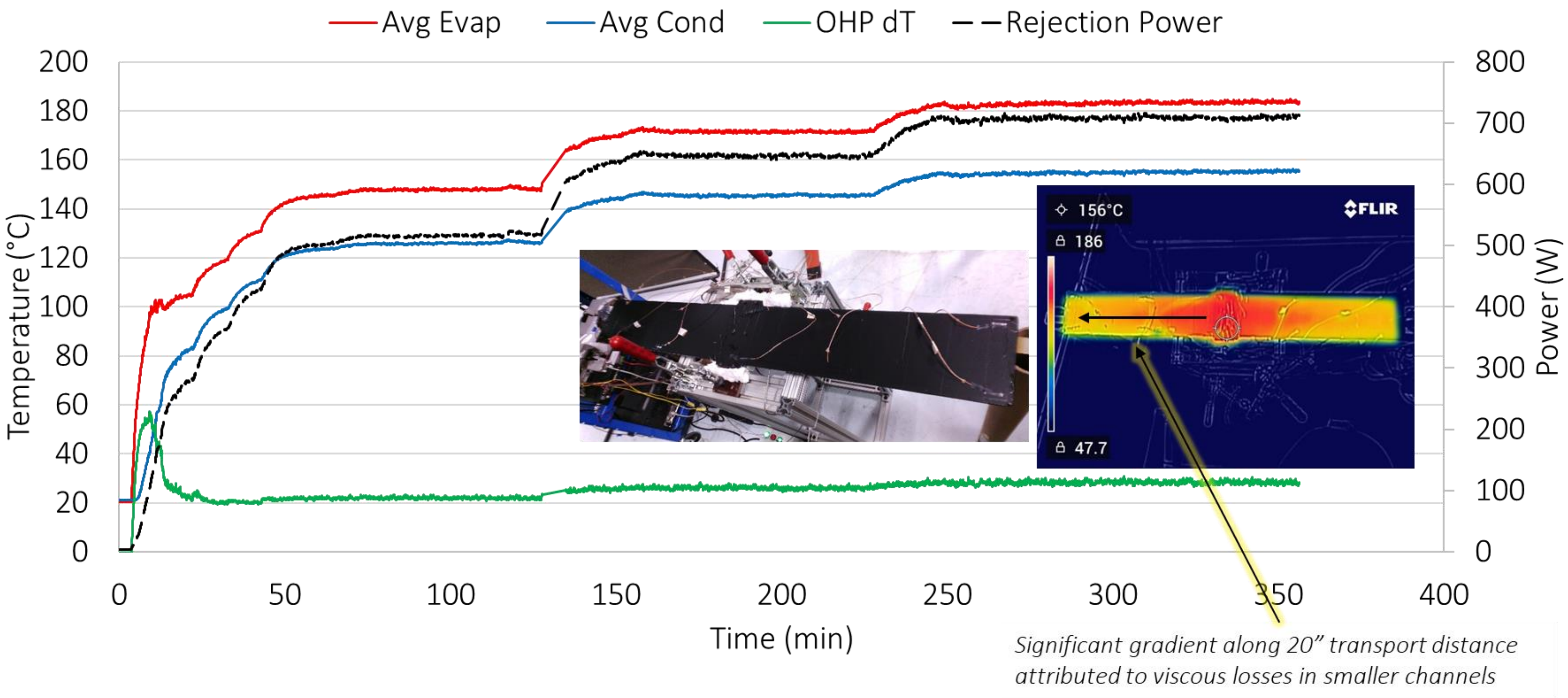
- OHP Limits Chart[1] predicts Startup near experimental observation and margin to Vapor-Inertia Limit
- Swept length for OHP spreaders with ‘full backside cooling’ is still in development

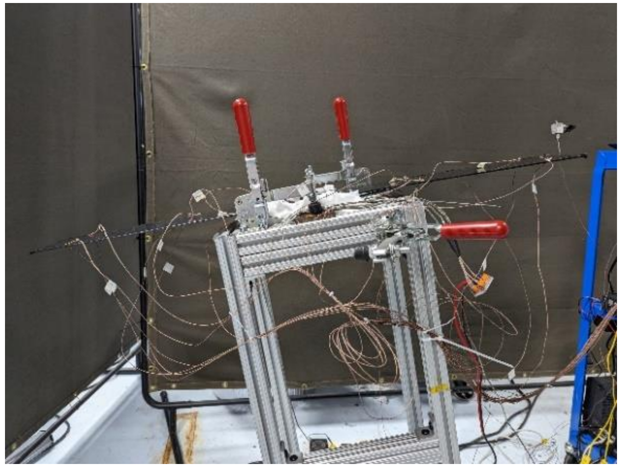


[1]Drolen, Smoot, “Performance Limits of Oscillating Heat Pipes: Theory and Validation” (2016)

Gen 2 Performance Testing – Small Channels and Gravity

- A variant with smaller channels had lower performance (26 W/K) with viscous penalty clear in IR profile
- Tested gravity neutral and tilted for dz=L/6 with negligible performance impact (orientation analogous to vertical operation on lunar surface)





Summary

- Demonstrated, for the first time, high performance meter-scale Al OHPs (Gen 2) relevant for rejection of waste heat from Sterling cycles (150-185 °C)
- Performance (thermal conductance) 40x that of mass-equivalent Al radiators
- First candidate working fluid (alcohol binary mixture) has shown initial compatibility with Al-6061 envelopes throughout breadboard testing
  - Long term compatibility is still a primary risk
- OHP Limits Charts have been produced for the first time for fluid mixtures
  - Initial limits charts predict experimental Startup (onset of nucleate boiling) and Vapor Inertia Limit (maximum transport capacity), reasonably well without any tuning parameters
- Novel freeze-tolerant working fluids are being developed for higher temperature applications (200-350 °C)
- Actively pursuing multiple post-Phase II opportunities for insertion/commercialization

Thanks

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<u>ThermAvant Technologies</u>

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