Methane Cryogenic Oscillating Heat Pipe Thermal Strap

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Presentation Outline

- Abstracts
- Inputs and Targets
- ‘Generation 0’ Testing
- Transient Analysis
- Phase I OHP Hardware
- Thermal Testing
- In-Situ Charging
- Results
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- Acknowledgements

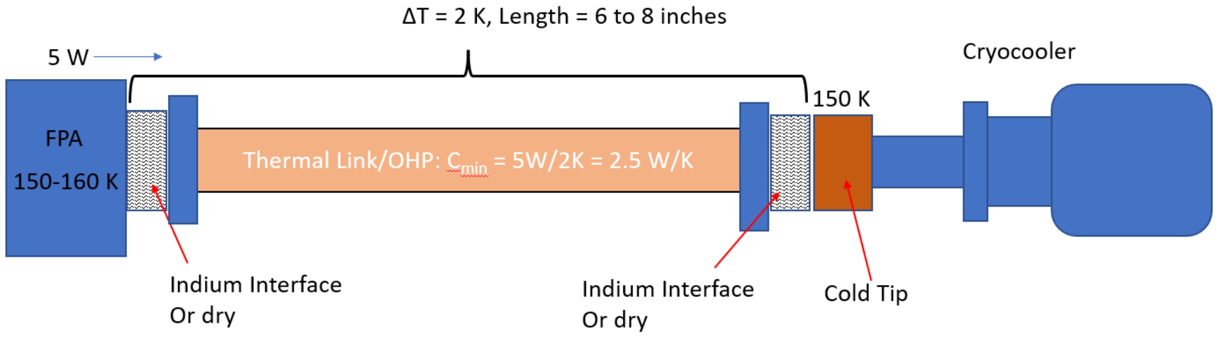
NASA Cryo OHP SBIR

- Phase I Proposal Abstract:
  - In response to NASA SBIR Topic S16.07, ThermAvant Technologies, LLC proposes to develop high conductance cryogenic oscillating heat pipes for space applications. Working fluids will be investigated at temperatures between 77 K and 230 K. The oscillating heat pipes will be developed in a range of geometries to demonstrate high effective thermal conductivities in complex 3D geometries and small form factors, and demonstrate ambient storage conditions.

- TFAWS Abstract:
  - On a recent Phase I effort with NASA JPL, ThermAvant Technologies developed and demonstrated an additively manufactured cryogenic oscillating heat pipe (OHP) thermal strap, operating between 100 K and 150 K. Requirements were aligned with an established satellite application, aiming to transport a 5W heat load from a focal plane array (FPA) to the cold tip of a cryocooler. The OHP met primary thermal and mass requirements, achieving a thermal conductance of 4W/K, spatial gradient <2K, at half the available mass budget. In-situ passive charging was demonstrated with a remote fluid reservoir held at supercritical conditions (room temp). Temporal stability was measured at ±100's mK at the evaporator interface, and stiffness was considered regarding the viability of OHPs as rigid cryogenic thermal transporters.

Inputs and Targets

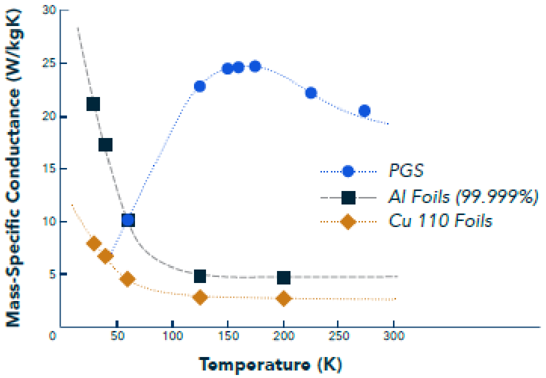
- Assume focal plane array (FPA) dissipates 3-5W
- FPA (OHP evaporator) operational limit: 150-160K
  - Stability requirement ±100mK
  - FPA contact area: 1 in^2
- Cryocooler cold tip (OHP condenser) at 150K during normal operation
  - Cold tip contact area: 2 in^2
- Non-op exposure (survival) temp: 323K



	Description	Specification	Compliance Method
Thermal Performance	Goal thermal conductance	2 W/K minimum	Test
Heat Input	Heat load from focal plane array (FPA)	3-5 W on a 29 x 24 mm^2 footprint	Test
Heat Rejection	Heat rejection to cryocooler tip	6-8 inches from heat input at 150 K to 160 K	Test
Temperature Differential	Maximum differential from FPA to cryocooler tip	<2 K	Test
Temporal Stability	Maximum temperature variance on the FPA rejection surface	<+/- 100 mK over 260 s	Test
Maximum Excursion Temperature		50 °C	Test
Mass		150 g max on cryocooler tip	Test
Stiffness	Flexibility of OHP thermal strap	Target similar to pyrolytic graphite thermal straps	Analysis
Design Factor of Safety		4X FOS to burst pressure at 50 °C	Test and analysis

- Baseline: SDL PGS straps
  - SDL: Space Dynamics Lab (Utah State University)
  - PGS: Pyrolytic Graphite Sheets
  - .025" thick sheets
  - 1.92 g/cc
  - 1750 W/m-K in-plane
  - 18 W/m-K thru-plane
  - https://hpmsgraphite.com/pyrolyticgraphitesheet

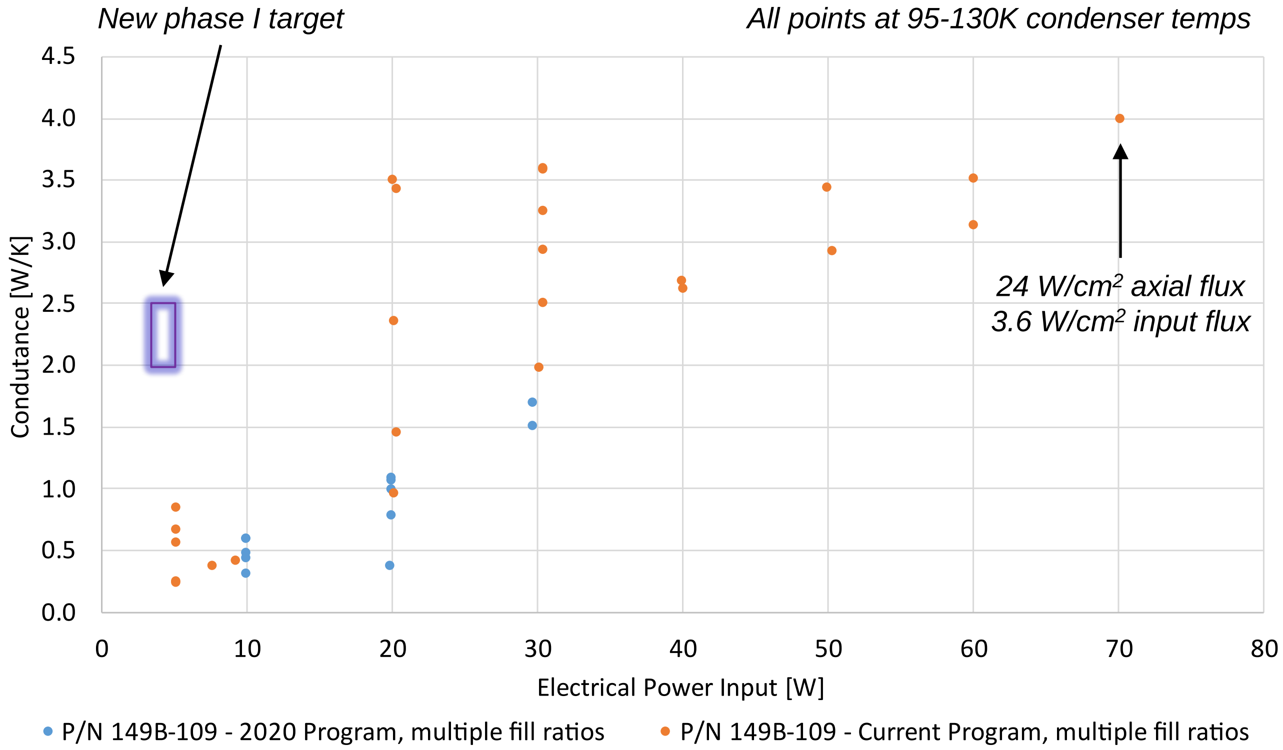
Large SDL PGS thermal strap

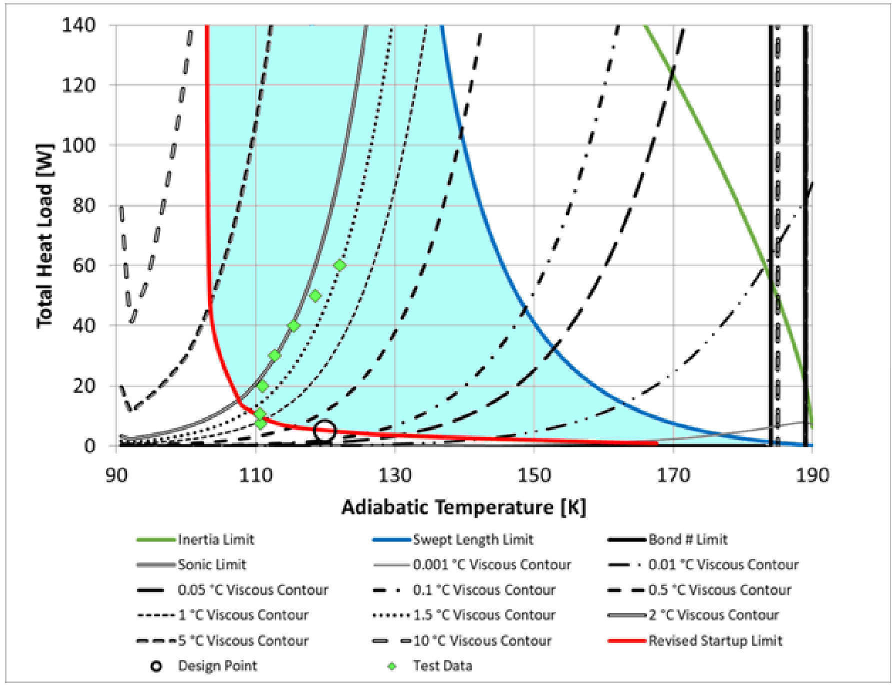


https://www.sdl.usu.edu/downloads/brochures/pgs-thermal-solutions.pdf

‘Generation 0’ Testing

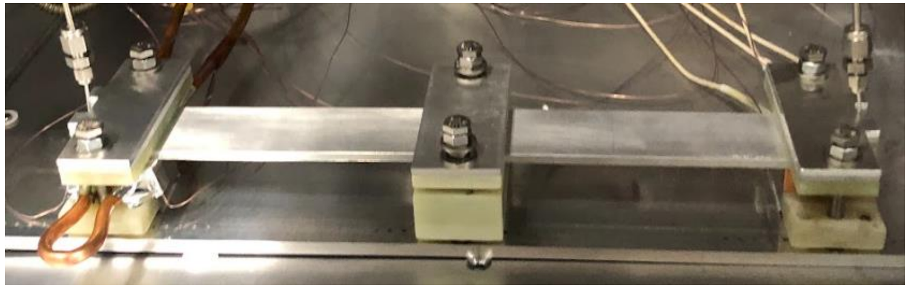
- Existing hardware asset with relevant physical geometry was re-evaluated with methane working fluid
- Phase I target not met, but significantly higher powers were demonstrated for the first time in this temperature range
- Additional validation of Startup Limit near 10W and 110K





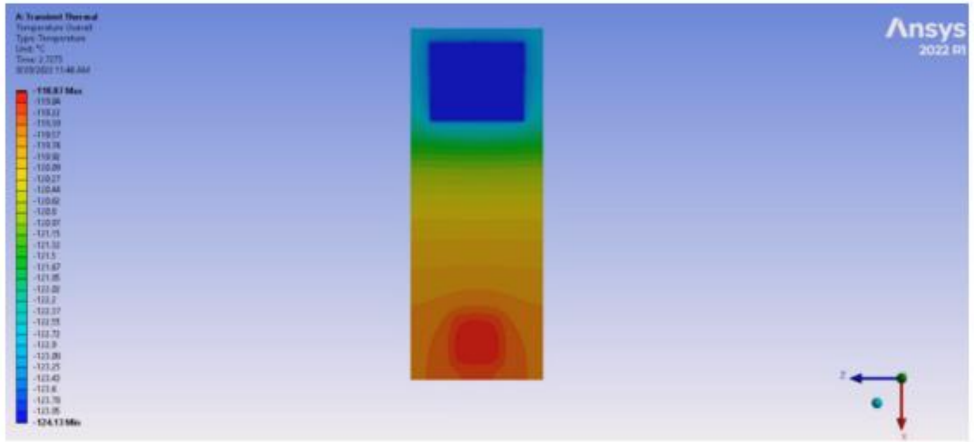
. *Methane limits chart for G0 design with new test points overlaid*

‘G0’ existing hardware: 2” x 14” 0.23”
(2x transport distance of new target)

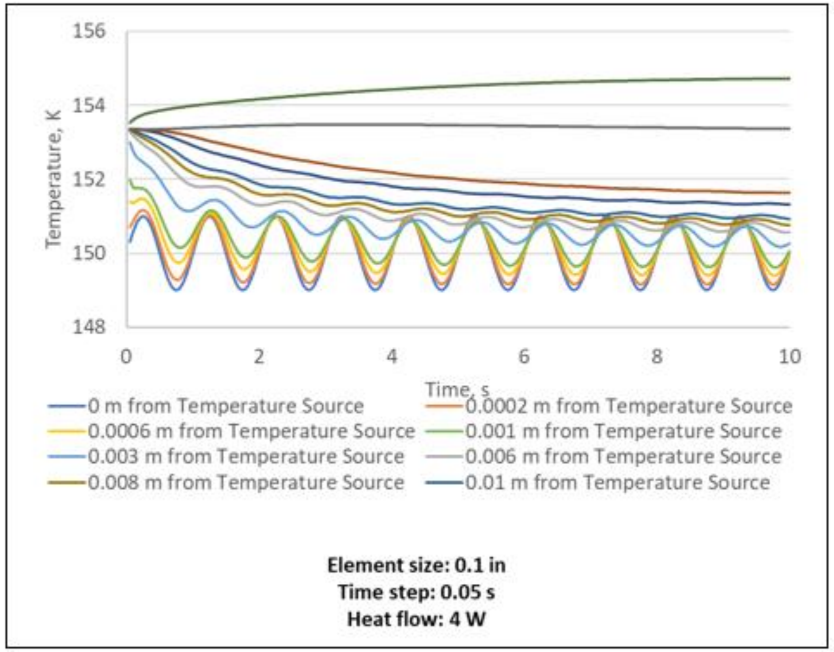


Transient Analysis

- The application requirement for **±100mK transient stability was perceived as high-risk**, due to amplitude of temperature oscillations observed at OHP interfaces across historical demos at widely varying conditions
- Interpretation of the stability target was refined, to determine if the criteria was properly applied at the OHP evaporator interface, vs a remote sensor interface - capturing the influence of the thermal mass of other thermally coupled structures
- JPL communicated that there is an additional FPA support structure, 4.5” long, lying between the OHP interface and the position truly sensitive to temperature fluctuation
- Provided with the geometry and material properties, transient finite-element simulations were performed to characterize the **temporal damping, spatially across this support structure**
- The FEA setup conservatively assumed a 1Hz ±1K boundary condition at OHP interface driving the temperature profile of the support structure
- Convergence was found for mesh sizes below 0.1” (45 elements axially) and time steps <0.05s (20 per sinusoidal period)
- **At a conduction distance of only 0.007m (0.28”) from extent of the heat input area, the amplitude of surface temperatures dropped an order of magnitude, within target ±100mK. Hence, ‘noise’ induced by an OHP is expected to be insignificant for this application**

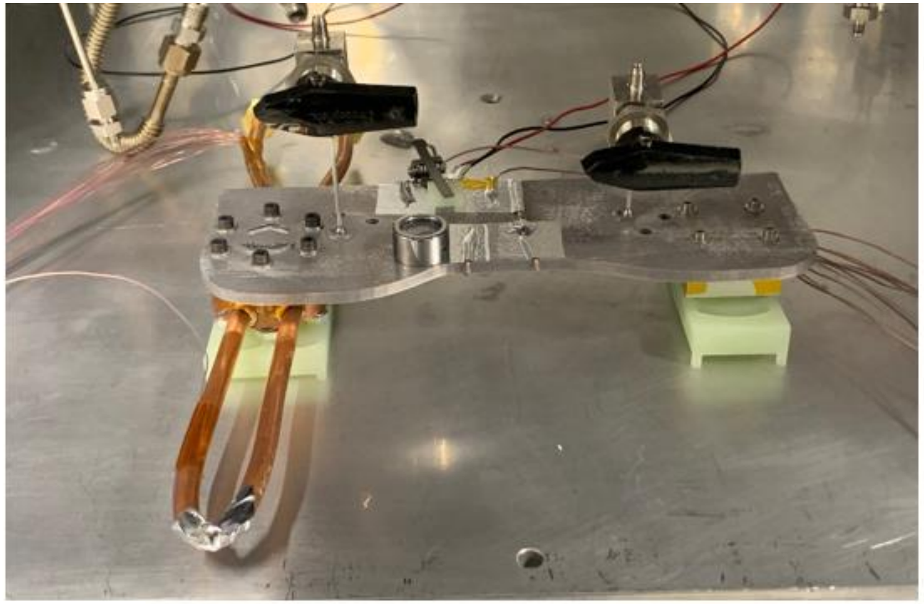


FEA transient thermal simulation



Phase I OHP Hardware

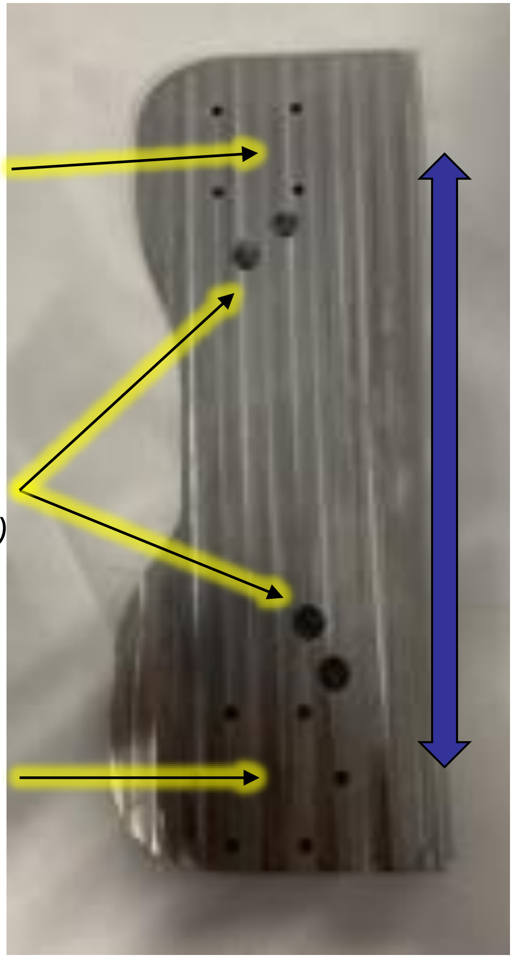
- Five unique OHP designs were additively manufactured by SLM/LPBF in AlSi10Mg
- Variants included different hydraulic diameters, and different general routing of the channel field between evaporator and condenser interfaces
- Hardware passed test readiness checks (hermeticity by helium leak check, and 5ksi proof pressure at RT)
- Due to time constraints on phase I, only one test article was thermally tested



222A-101A OHP integrated with thermal test vehicle in the TVAC Chamber

Prior to MLI insulation

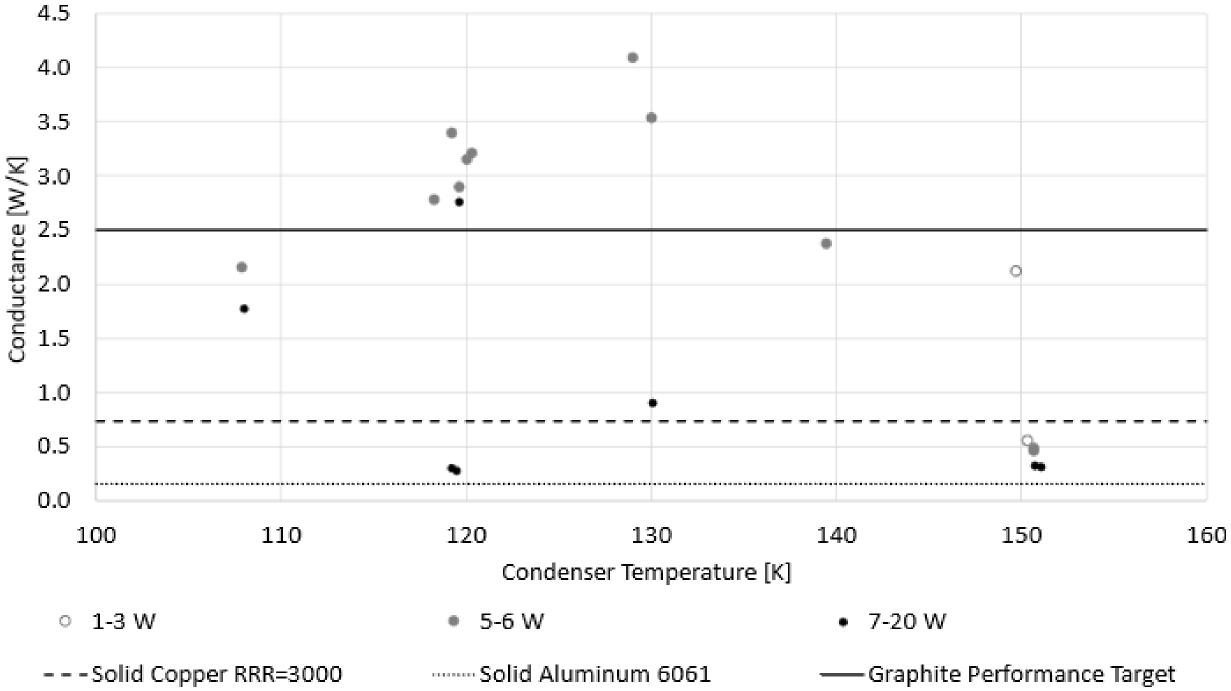
CNC cleanup of native additive surface for improved interfaces (contact resistance)



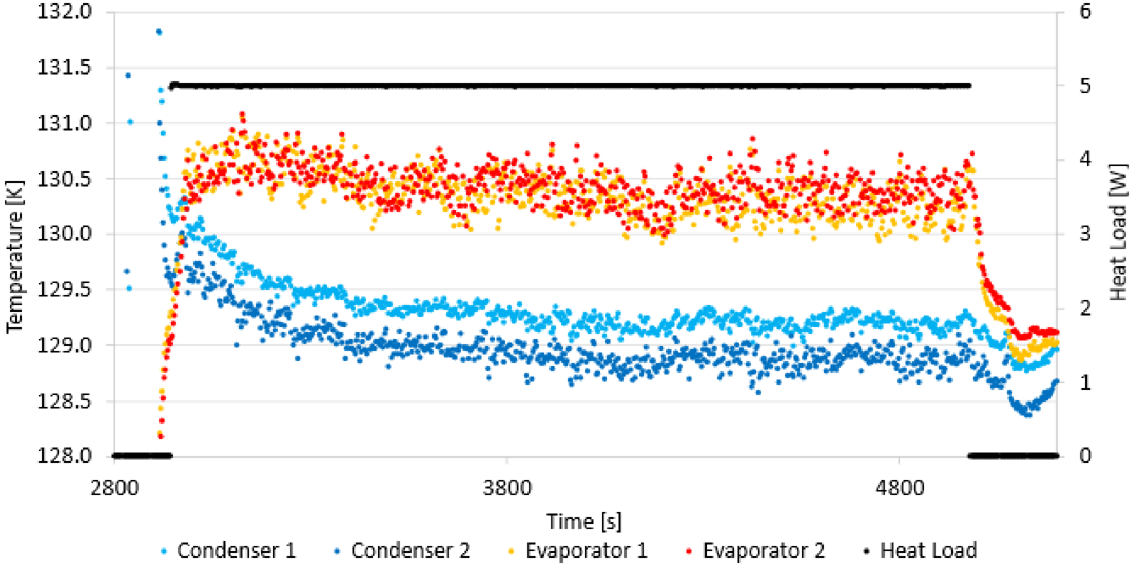
0.165” thick, 125 grams (<50% of mass req)

Thermal Testing

- Peak conductance >4W/K (2x target), at 5W and 130K condenser
- Lower conductance at original target temp (150K) - JPL communicated a pivot to similar applications at 130K
- Good temporal stability: ±385mK peak to peak, near ±100mK target with spatial and temporal averaging (still on evap surface)
- After maximum transport capacity was observed lower than ‘G0’ hardware, x-rays were examined and some evidence of residual powder from additive manufacturing was found



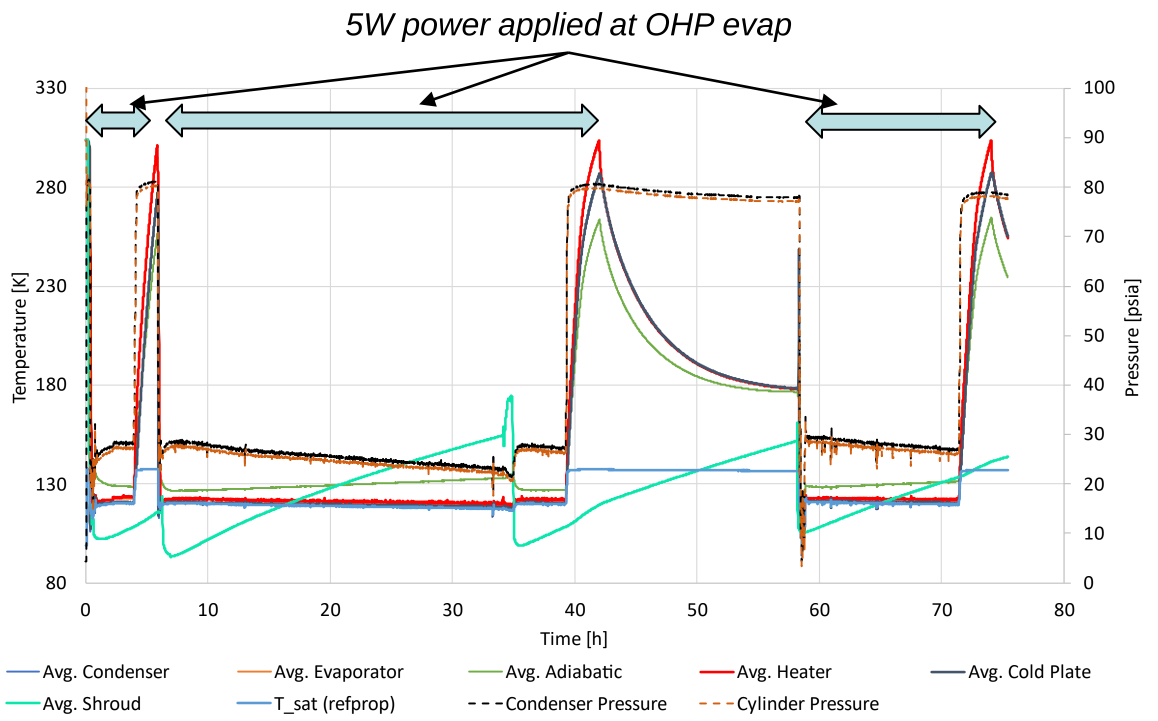
Summary of G1 OHP Testing: Conductance vs Condenser Temp, with power-banded series formatting. Cu RRR=3000 k=482 W/m-K at 100 K and Al6061 k=104 W/m-K at 100 K



Highest performance G1 OHP time series; at 20% fill, 5 W heat load, and 128 K cold plate

In-Situ Charging

- There are practical hurdles regarding the delivery and storage of cryogenic OHPs, prior to operational service (working fluid is in a supercritical state)
- Two primary paths exist to addressing the vapor pressure during these high temperature exposure periods
  1. Structurally design the OHP envelope to survive these high pressures, via pivot from flat plate aluminum to tubular SS/Inconel architectures. This carries very significant local mass, performance, and integration penalties
  2. Include an expansion vessel, the volume of which can be calculated for a target 'hot non-op' OHP pressure, and target OHP liquid fill fraction at some reference temp. When the OHP is brought to cryogenic service temperature, the necessary liquid condenses into the channel volume. This path also carries a significant mass penalty (the gas cylinder), however many larger satellites can accommodate this remote mass and have temperature regulating systems in place for other components near RT (electronics, batteries, etc).
- Path #2 was demonstrated, with a large methane source cylinder located outside the TVAC test chamber at supercritical conditions (295K RT). The plumbing between this expansion volume and the OHP was fully passive (no valves) and 'open' for the entire demo.
- OHP was brought from RT down to 120K, operated for long durations (4-40 hours) and returned to RT, for 3 cycles.



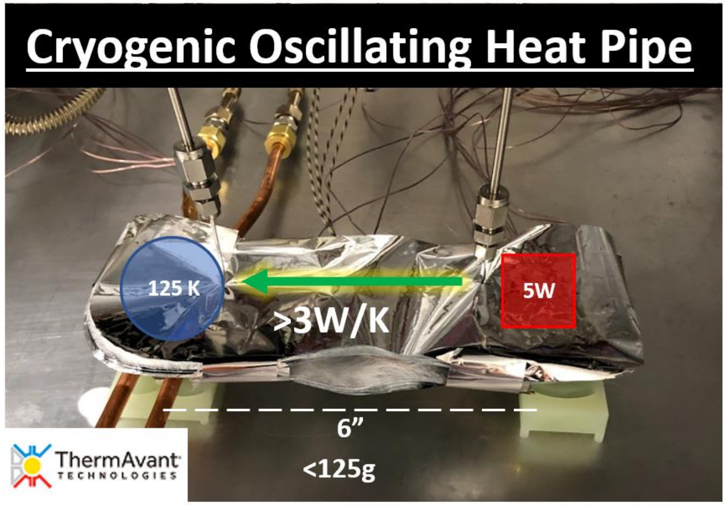
- *PID control on shrouds turned off while system unattended by technician, hence the gradual rise of ~1K/hr*
- *PID control on nitrogen cold plate drifting colder while unattended by technician, observable in TC data and saturated pressure*
- *Adiabatic temps biased high due to heat leak from adjacent charge tubes*

Results

- Improved understanding of OHPs for 100-150K applications
  - No published examples of OHPs in this temp range outside TAT (significant work in academia at 65-80K with nitrogen working fluid)
- Met primary phase I targets: mass and conductance competitive against PGS straps for cryocooler FPA applications with 2.5-3.2um sensors (120-150K)
- Feasibility demonstrated for ‘real-world’ implementation of a cryogenic OHP (delivery / storage / non-op in supercritical state)
- Mechanical isolation (vibration transmission) remains a risk area for OHPs to replace PGS thermal straps – possibly addressed by hybrid solution:

PGS-embedded conductor bar with integrated thermal strap

https://www.sdl.usu.edu/downloads/brochures/pgs-thermal-solutions.pdf



i. Summary of Phase I requirements and results

	Description	Specification	Compliance Method	Phase I Results	Phase I Metric [Passed/ Not Achieved]
Thermal Performance	Goal thermal conductance	2 W/K minimum	Test	4.09 W/K	Passed
Heat Input	Heat load from focal plane array (FPA)	3-5 W on a 29 x 24 mm² footprint	Test	1-20 W	Passed
Heat Rejection	Heat rejection to cryocooler tip	6-8 inches from heat input at 150 K to 160 K	Test	100-150 K	Partially passed
Temperature Differential	Maximum differential from FPA to cryocooler tip	<2 K	Test	1.26 K [60 second time avg] 1.51 K [60 second peak-peak]	Passed
Temporal Stability	Maximum temperature variance on the FPA rejection surface	<+/- 100 mK over 260 s	Test	+/- 385 mK over 260 s [instantaneous maximum minus instantaneous minimum over time period]	Not achieved directly. Mitigated by analysis
Maximum Excursion Temperature		50 °C	Test	22 °C [ambient excursion of charged OHP]	Not evaluated
Mass		150 g max on cryocooler tip	Test	63 g on cryocooler tip 125 g OHP total [additional expansion reservoir required for ambient excursions; currently 1700.61 g]	Passed
Stiffness	Flexibility of OHP thermal strap	Target similar to pyrolytic graphite thermal straps	Analysis	Not evaluated	Not evaluated
Design Factor of Safety		4X FOS to burst pressure at 50 °C	Test and analysis	>56X	Passed (sensitive to expansion vessel volume selection)

Potential Applications

- 2.5-3.2μm sensors (120-150K)
- WFIRST (Wide Field Infrared Survey Telescope)
  - Ethane and methane heat pipes <170K & Al-encapsulated APG thermal bus
- Lunar Flashlight
  - Detectors <200K via cold finger in close proximity to cryoradiator on a CubeSat
- Reach
  - SPHEREx (FPA <80K)
  - TIRS-2 (FPA <95K)
  - LXM (Lynx X-ray Microcalorimeter) (?)
  - Astrophysics Decadal Survey: Origins Space Telescope (?)
- Commercial
  - Cryo coolers, MRI machines, Maglev, superconducting systems, quantum computing, liquid production, fuel survival/transfer systems

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