Intermediate Temperature Oscillating Heat Pipe Radiators for Lunar Fission Surface Power

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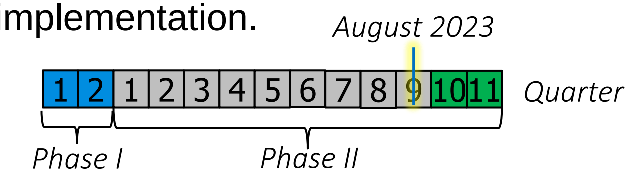
Thermal & Fluids Analysis Workshop
TFAWS 2023
August 21-25, 2023
NASA Goddard Space Flight Center
Greenbelt, MD

Presentation Outline

- SBIR framework
- Background
- Alcohol Mixture Compatibility
- Alkane Test Results
- Water Mixture Test Results
- Final Phase II Hardware
- Summary
- Acknowledgements

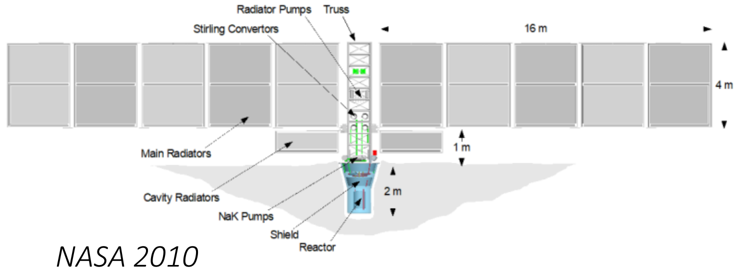
NASA Fission Power SBIR

- 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:

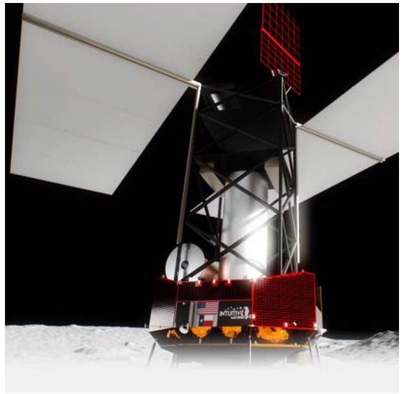


- Solicitation target:
  - Freeze tolerant heat pipe radiators that can operate through lunar night (-173 ºC) and day (127 ºC) temperature swings. Heat pipes must start-up from lunar night temperature and begin transferring heat within several thermal cycles.
- Proposed solution:
  - Develop intermediate 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

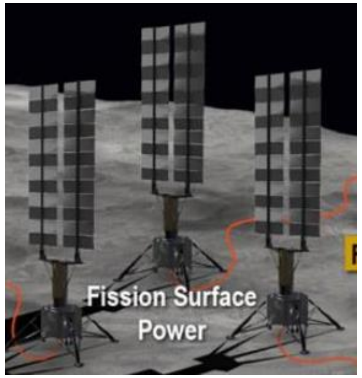
FSP Concept Art presented at JHU APL LSIC, Jan '23



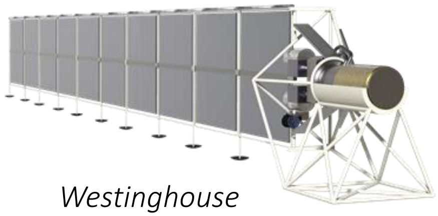
NASA 2010



Intuitive Machines



Lockheed Martin

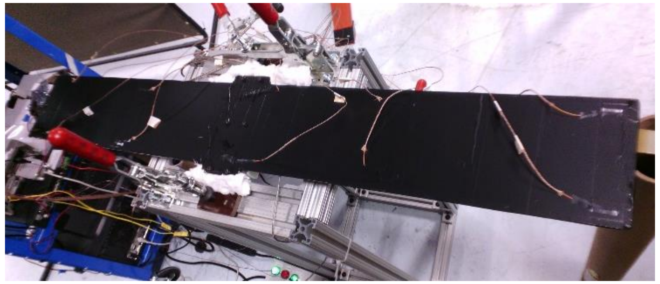


Westinghouse

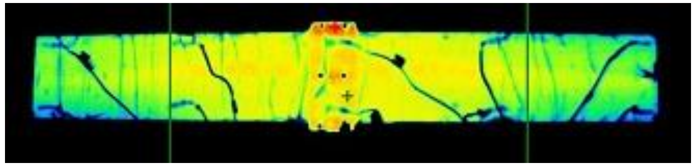
Background

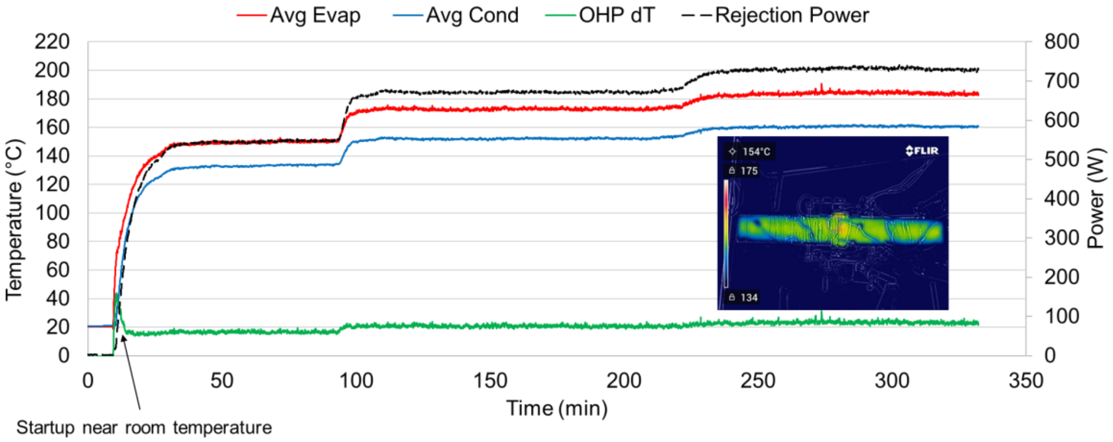
- Phase II key specs from NASA:
  - 175-deg C evaporator interface
  - 6 freeze/thaw cycles to 50K
  - Minimize areal density <3kg/m^2
- Progress presented at TFAWS 2022:
  - 6” x 44” aluminum breadboard OHP radiators, with alcohol mixture working fluid
  - 3.1 kg/m^2, 36 W/K, stable from 150-185-deg C
  - 40X performance of mass equivalent Al control
  - https://tfaws.nasa.gov/index.php?gf-download=2022%2F08%2FTFAWS-2022-Fission-Power-OHP-Miller.pdf&form-id=20&field-id=42&hash=413fb61ea5d761517d5bd10a42fda315daaca55ed9b39ada6ac00e68e04f2028
  - https://www.youtube.com/watch?v=Znyoikz-ckg

Example of OHP radiators being developed with NASA GRC



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

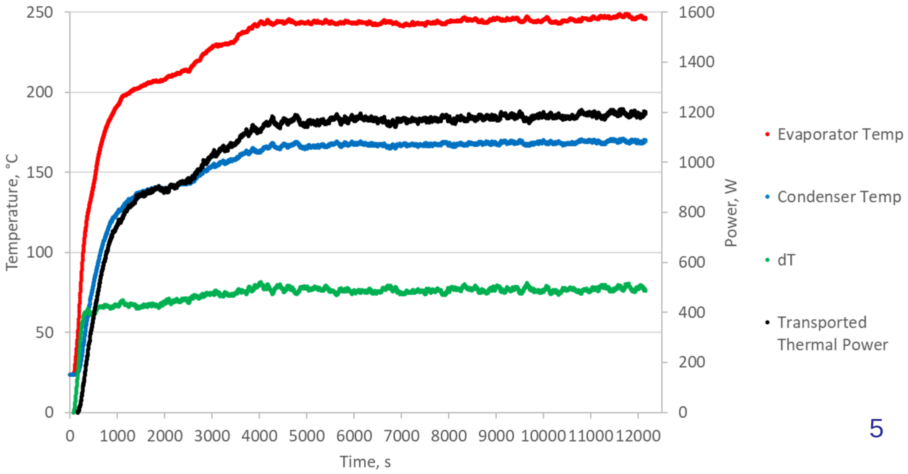




Alcohol Mixture Compatibility

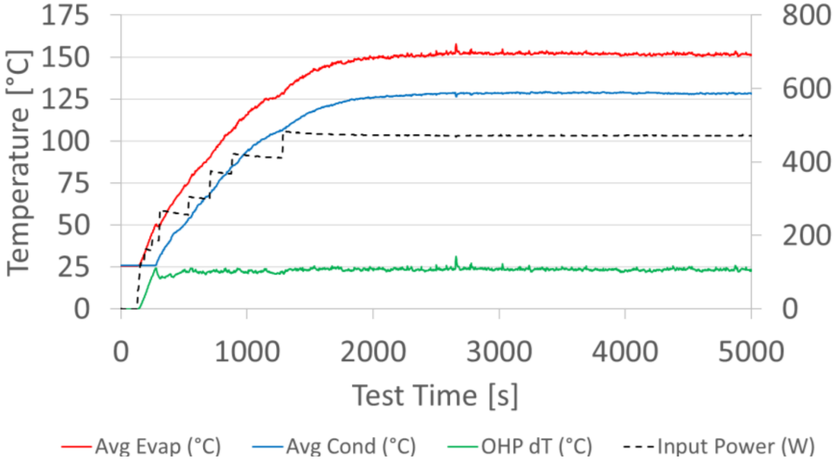
- The alcohol mixture which showed good performance initially was put on full scale life test at 175-deg C and failed at 330 hours due to a pin hole leak formed in the evaporator.
- A more fundamental corrosion experiment was performed for six different alcohol mixture compositions charged into tubular coupons with the same alloys present as a brazed aluminum OHP. All of the samples failed this screening, by pin hole leak, or production of significant levels of hydrogen or oxides – as identified by mass spec vapor analysis
- Fluid development efforts for aluminum envelopes transitioned to fluids for which fluid thermal stability and aluminum compatibility has already been established in historical literature, e.g. alkanes (straight-chain saturated hydrocarbon)
- The alcohol mixtures are expected to be long term copper compatible, and were operated successfully in a large bent tube Cu OHP up to 1.2kW at 250-deg C evaporator. Copper is not a competitive candidate for low density radiators, but trades well in less mass-sensitive applications. Evaluation in Ti radiator scheduled this quarter

44” long copper bent tube OHP
Photograph taken prior to silicone-ceramic black coating



Alkane Test Results

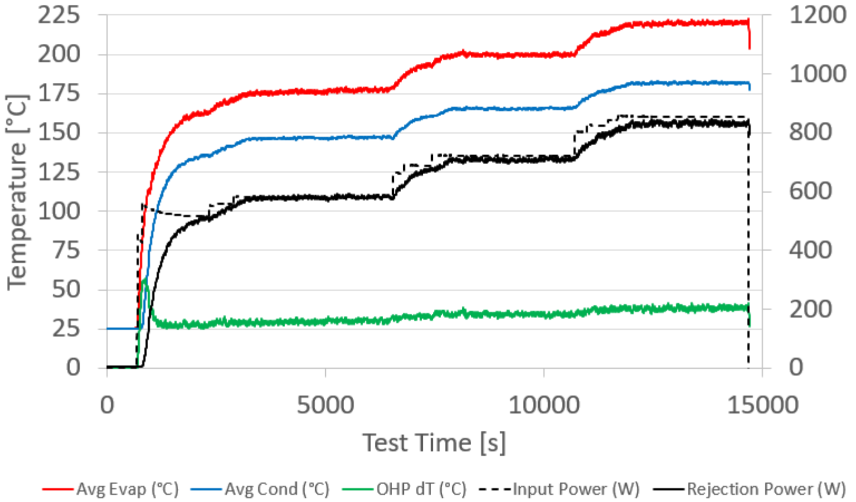
- Shorter alkane
  - 25 W/K at 150-deg C
  - Unstable at application-specific temperature targets (≥175-deg C)

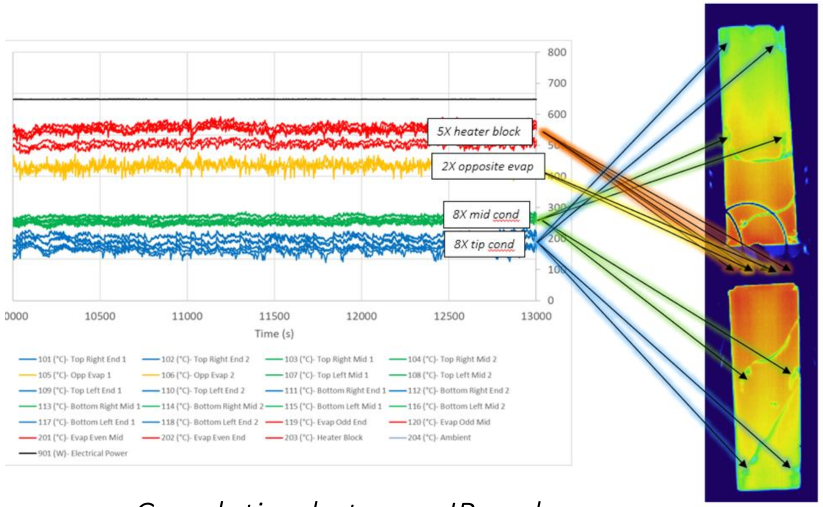


Updated heater clamping (bolted -> pneumatic) for improved contact uniformity and test repeatability

Test article references: 1.0kg charged, 0.9 W/K vented performance (Al control)

- Longer alkane
  - 19 W/K at 175-deg C
  - 22 W/K at 220-deg C
  - Likely the hottest Al OHP demo ever
    - Haven't performed an exhaustive lit survey, please forward a link to the contrary!
  - 840 W/kg specific power



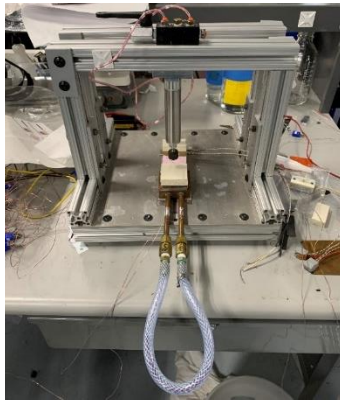


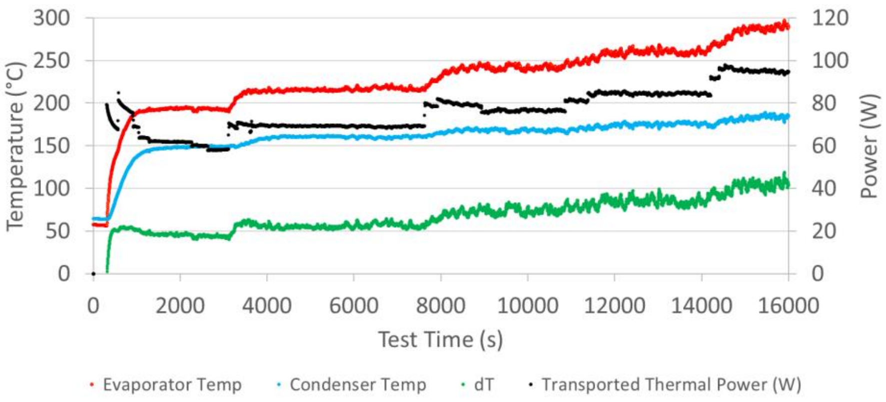
Correlation between IR and qty 25 TC measurements

Water Mixture Test Results

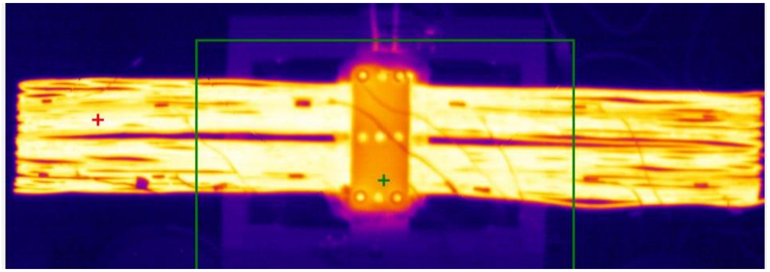
- Novel water mixture with significantly improved freeze tolerance - no sharp crystalline expansion at phase transition. Particularly relevant in Ti envelope applications

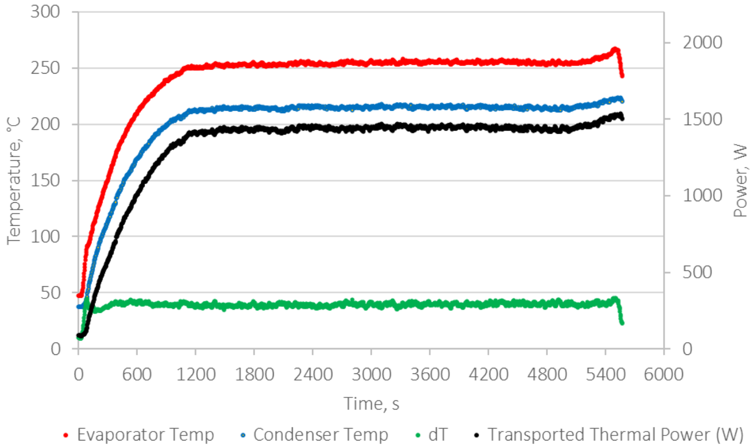
- Stainless Steel 2” x 6” breadboard
  - Stable to 300-deg C evaporator
  - Peak conductance >20X vented control





- 44” copper bent tube (same test article used for alcohol mixture demo)
  - 1.5kW at 250-deg C evaporator
  - 40 W/K @ 37K dT

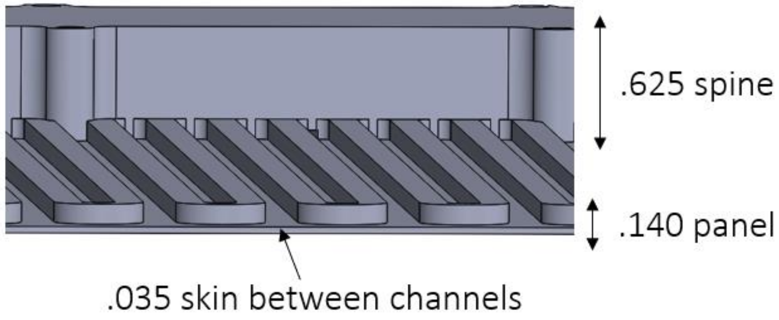


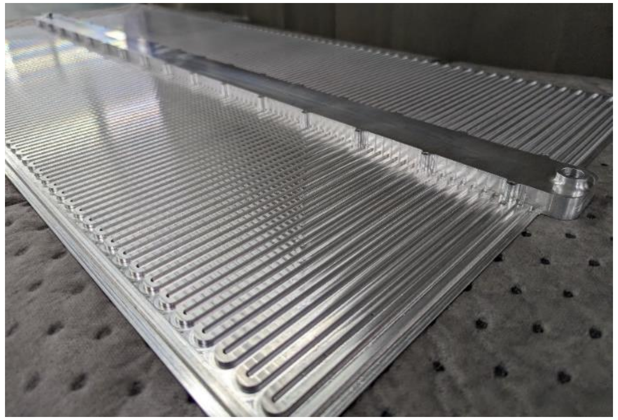


Final Phase II Hardware

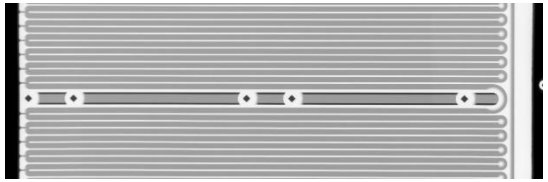
- Engineering Model: Aluminum OHP Radiator with Integrally Brazed PFL HEX | Manifold
  - Al6061, 20” x 40” (1m^2 rejection area)
  - 2.3 kg/m^2 two-sided (charged panel only, ignoring PFL HEX)
  - 2.9 kg Al total with PFL HEX (no fluids)
  - Photos right off the CNC for final machining, prior to cleaning and coating

Business card for scale

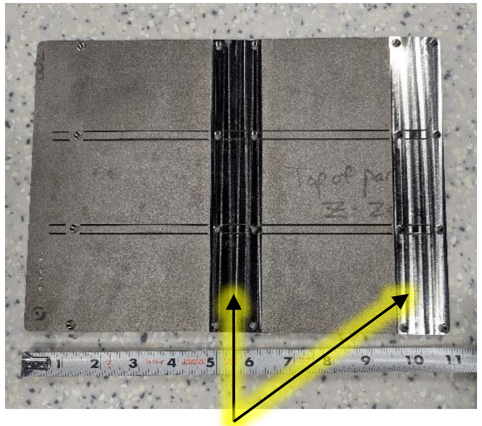




- Titanium OHP Radiator
  - Ti-6Al-4V, 8” x 11” x 0.185”
  - 4.9 kg/m^2 two-sided
  - ThermAvant’s first Ti radiator and first additively manufactured Ti OHP



Xray to verify complete powder removal



Heater contact areas post-machined

Summary

- OHP solutions for intermediate temperature applications have matured in terms of working fluid options with improved envelope compatibility, and generation of experimental datasets for model tuning and verification (thermal conductance and transport limits)

- Aluminum + alkanes demonstrated for applications <500K (limited by Al yield strength for pressure containment)
  - Panel areal densities below 2.5 kg/m^2 (two-sided) manufacturable by traditional CNC and vacuum brazing
  - Lower panel densities are possible for shorter transport distances (fin length)

- Novel freeze tolerant water mixture demonstrated for applications <600K (hot limits approaching critical temp)
  - Predicted to be compatible with titanium, however long duration life testing has not yet been conducted

- Alcohols have been previously demonstrated in academia in SS and Cu bent tube OHPs, and by ThermAvant in short tests (tens hours) in aluminum hardware. Passivation of the known reactivity with aluminum was attempted with a variety of mixtures, unsuccessfully

- On TRL/MRL: OHP radiators have been tested in relevant TVAC environment, however previous work was <375K with traditional fluids. Near-term demonstrations will constitute several ‘firsts’:
  - Aluminum alkane demo at 450K with PFL heat input boundary condition, vs constant flux electrical heating (ThermAvant, Q3 2023)
  - Aluminum alkane TVAC at 400-500K (NASA GRC, Q1 2024)
  - Titanium additive manufacturing | welding | workmanship verifications: hermeticity and pressure testing (ThermAvant, Q3 2023)
  - Ti OHP TVAC at 400-600K (NASA GRC, Q1 2024)
  - Freeze/thaw testing (20 cycles) of both OHP designs, prior to delivery to NASA (ThermAvant vendor, Q3 2023)

Thanks

The authors would like to thank NASA for their support and sponsorship, and recognize the team members who have contributed to content herein (Contract 80NSSC21C0545)

ThermAvant Technologies

- Alex Miller (PI & Technical Lead)
- Dr. Shane Hilsenbeck (PM)
- Berto Aviles (Engineering Support)
- Jacob Norris, Trenton Post, and Michael Dunn (Laboratory Testing)

NASA

- Greeta Thaikattil, GRC (Technical Monitor)
- James Sanzi, GRC
- Lee Mason, GRC