Intermediate Temperature Oscillating Heat Pipe Radiators for Lunar Fission Surface Power

Prime Contract no. 80NSSC21C0545
Project no. TD180
Prepared for: LSIC Surface Power
Prepared by: Alex Miller (Alex.Miller@ThermAvant.com)
August 24, 2023
Presentation Outline

• SBIR framework
• OHP 101
• Alcohol Mixture Compatibility
• Alkane Test Results
• Water Mixture Test Results
• Final Phase II Hardware
• Summary
• Backup Slides
• **Goal:**
  - Continue the development of thin-profile Oscillating Heat Pipe (OHP) radiator panels, e.g., m² 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 °C) and day (127 °C) 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 °C) 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
OHP Basics

1. Form microchannels on base material
2. Hermetically bond/seal and manufacture to final form factor
3. Partially fill/seal with saturated working fluid
4. Fluid oscillates due to phase change events (axial expansion, contraction)
5. Heat transfer by latent and sensible heat

OHP Benefits:

- Capable of accepting high fluxes >100 W/cm²
- Integrated into existing structural components (i.e. drop in replacement part with high thermal performance)
- Reduced mass from channel formation
- Structural OHP channels form “I-beam” cross section retaining material strength
- Channel routing in multiple planes (3D)
- Designable to negate external forces (G-Loading)
- Predictable operating ranges (proprietary modeling tools)
- Formable or designable in complex shapes
OHP 101
40-sec OHP Start-Up Video with AFRL

Short video of transparent OHP during start-up and operation with visible two-phase “Taylor Flow”

Transparent OHP (R134a in plated Kovar) in operation with visible start-up
Left (warm vapor, evaporator) and Right (cool vapor, condenser)

Funded by AFRL/RV Contract No. FA9453-17-C-0423; ThermAvant Technologies’ SBIR Data Rights
Project Background

• Phase II key specs from NASA:
  o 175-deg C evaporator interface
  o 6 freeze/thaw cycles to 50K
  o Minimize areal density <3kg/m^2

• Progress presented at TFAWS 2022:
  o 6” x 44” aluminum breadboard OHP radiators, with alcohol mixture working fluid
  o 3.1 kg/m^2, 36 W/K, stable from 150-185-deg C
  o 40X performance of mass equivalent Al control
    o https://tfaws.nasa.gov/index.php?gf-downloads=2022%2F08%2FITAWS-2022-Fission-Power-OHP-Miller.pdf&form-id=26&field-id=42&hash=41fb63ea9c763517d56b210a27b3a32a6a5cedb3f9ad6ae00e66e04f2028
    o https://www.youtube.com/watch?v=3nyokz-og
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.

Photograph taken prior to silicone-ceramic black coating.
• Shorter alkane
  o 25 W/K at 150-deg C
  o Unstable at application-specific temperature targets (≥175-deg C)

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

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

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

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
  o Stable to 300-deg C evaporator
  o Peak conductance >20X vented control

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

• Engineering Model: Aluminum OHP Radiator with Integrally Brazed PFL HEX | Manifold
  o Al6061, 20” x 40” (1m² rejection area)
  o 2.3 kg/m² two-sided (charged panel only, ignoring PFL HEX)
  o 2.9 kg Al total with PFL HEX (no fluids)
  o Photos right off the CNC for final machining, prior to cleaning and coating

• Titanium OHP Radiator
  o Ti-6Al-4V, 8” x 11” x 0.185”
  o 4.9 kg/m² two-sided
  o ThermAvant’s first Ti radiator and first additively manufactured Ti OHP

X-ray 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)
  o Panel areal densities below 2.5 kg/m² (two-sided) manufacturable by traditional CNC and vacuum brazing
  o 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)
  o 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’:  
  o Aluminum alkane demo at 450K with PFL heat input boundary condition, vs constant flux electrical heating (ThermAvant, Q3 2023)
  o Aluminum alkane TVAC at 400-500K (NASA GRC, Q1 2024)
  o Titanium additive manufacturing | welding | workmanship verifications: hermeticity and pressure testing (ThermAvant, Q3 2023)
  o Ti OHP TVAC at 400-600K (NASA GRC, Q1 2024)
  o Freeze/thaw testing (20 cycles) of both OHP designs, prior to delivery to NASA (ThermAvant vendor, Q3 2023)
The Air Force Research Laboratory has partnered with ThermAvant Technologies and Maxar Technologies to develop and deploy the next generation of spacecraft thermal control technology.

“We have seen how every generation heralds a new era in spacecraft thermal control by introducing a new, revolutionary technology,” Allison said. “The first generation used only thermal conduction, the second generation introduced heat pipes, and the third generation introduced loop heat pipes. The advent of each new generation enabled larger, more powerful spacecraft.”

Allison believes now is the time for the next generation, and OHPs are the perfect technology to enable future missions.

“We expect OHPs to be the linchpin thermal control technology on satellites from 2020 to 2040,” Allison said. “It’s my proposition that the fourth era is defined by oscillating heat pipes, and that the revolution that OHPs enable will be not so much focused on larger and more powerful spacecraft, but smaller and more powerful spacecraft.”

AFRL, industry launch revolutionary spacecraft technology
Published Oct. 25, 2021
Basics

Examples of OHP form factors

3D Rigid Structural Heat Sinks for...

Small scale heat spreaders developed with Navy

Battery Packaging for NASA

Flexible 1.2m OHP strap/transporter developed with AFRL/RV

Autopsied OHP heat sink and frame for military circuit card for...

Cross-section of internal OHP microchannels

OHP Radiator for Small Satellites developed with NASA
Limits of Operation

Illustrated description and comparison to constant conductance heat pipes (CCHPs)

Heat Pipe Limits of Operation

OHP Limits of Operation [2]

Heat Pipe cross-section (axial view)

OHP cross-section (axial view)


Limits of Operation

Detailed descriptions of current limits

- Used to define channel microchannel cross-section for a given fluid type and operating conditions
- Viscous Contours
  - Due to viscous loss, temperature rise will increase until the viscous drag is overcome by $\Delta P$ to create fluid movement – contours show isotherm lines, e.g. $5^\circ C \Delta T$ (within fluid space) along this line
- Sonic Limit
  - Fluid velocity is choked at the speed of sound for the two-phase mixture
- Startup Minimum
  - Incident heat flux must be sufficiently high to create a large enough superheat at the wall to begin nucleation
- Swept Length Limit (SLL)
  - Nucleation frequency becomes sufficiently high enough to prevent full liquid return
- Vapor Inertia Limit (VIL)
  - Vapor generation rate is high enough to allow vapor to penetrate liquid plugs
- Bond Number (Bo)
  - Surface tension decreases and can no longer span the capillary channel, and fluid movement cease