Intermediate Temperature Oscillating Heat Pipe Radiators for Lunar Fission Surface Power

Prime Contract no. 80NSSC21C0545
Project no. TD180
Prepared for: LSIC Surface Power
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August 24, 2023

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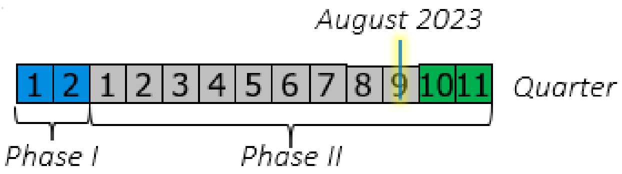
Presentation Outline

- SBIR framework
- OHP 101
- Alcohol Mixture Compatibility
- Alkane Test Results
- Water Mixture Test Results
- Final Phase II Hardware
- Summary
- Backup Slides

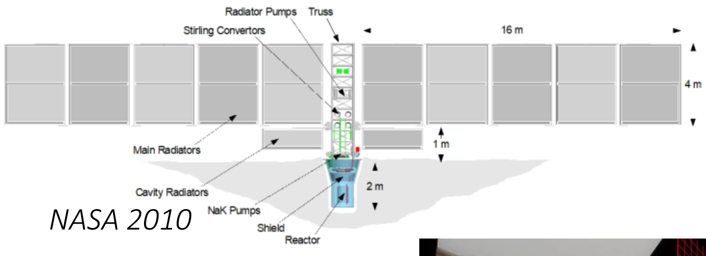
NASA Fission Power SBIR

- 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:

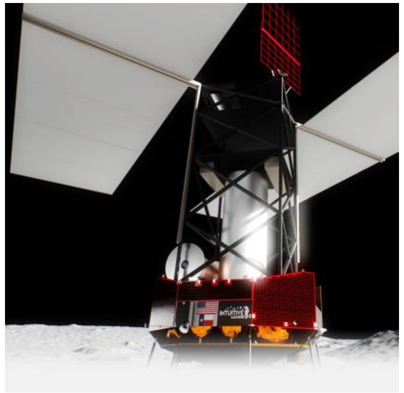


- Solicitation target:
  - Freeze tolerant heat pipe radiators that can operate through lunar night (-173 ºC) and day (127 ºC) temperature swings. Heat pipes must start-up from lunar night temperature and begin transferring heat within several thermal cycles.
- Proposed solution:
  - Develop intermediate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

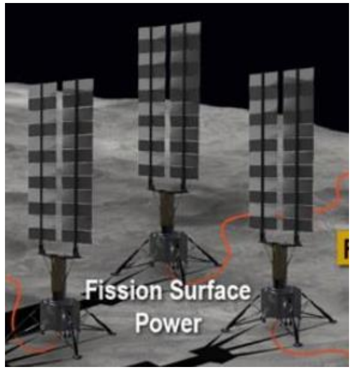
FSP Concept Art presented at JHU APL LSIC, Jan ‘23



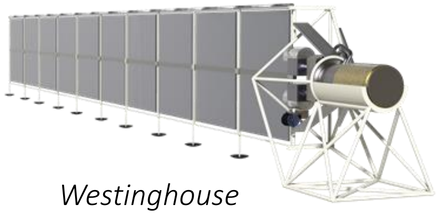
NASA 2010



Intuitive Machines



Lockheed Martin



Westinghouse

OHP 101

OHP Operating Principles

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

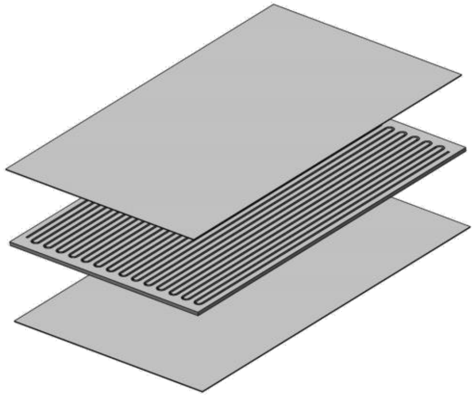
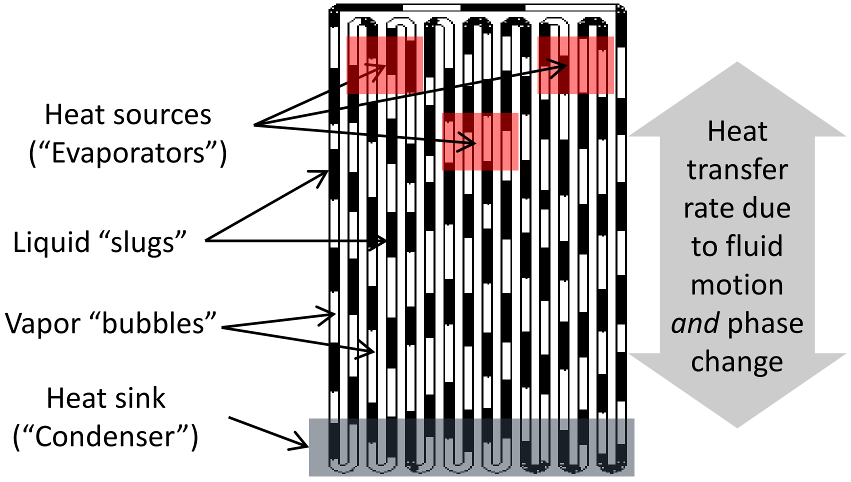


Illustration of OHP construction with "lids" bonded to "channel body" to embed a meandering micro-channel pattern within the monolithic structure (channels can run in 3D planes see slide 3/3)

Photograph of CuMo OHP with liquid slugs and vapor bubbles (without lid)



Heat sources ("Evaporators")

Liquid "slugs"

Vapor "bubbles"

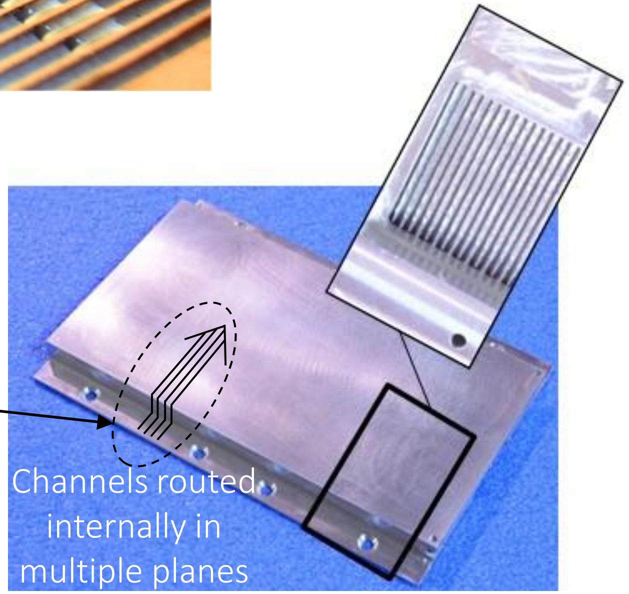
Heat sink ("Condenser")

Heat transfer rate due to fluid motion *and* phase change

OHP Benefits:

- Capable of accepting high fluxes >100 W/cm^2
- 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

Photograph of Al OHP with cutaway of the OHP microchannel pattern inside Al base material



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)

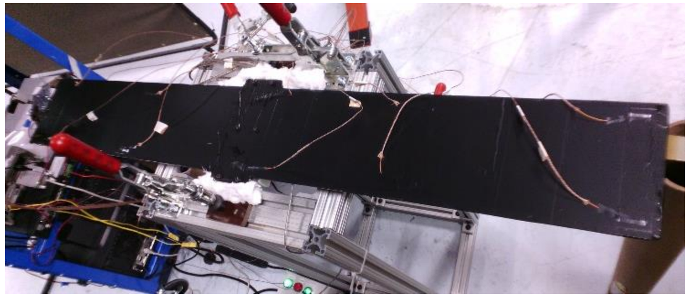
Funded by AFRL/RV Contract No. FA9453-17-C-0423; ThermAvant Technologies' SBIR Data Rights

Project Background

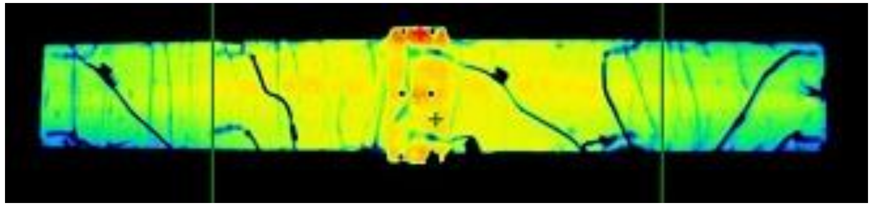
- Phase II key specs from NASA:
  - 175-deg C evaporator interface
  - 6 freeze/thaw cycles to 50K
  - Minimize areal density <3kg/m^2

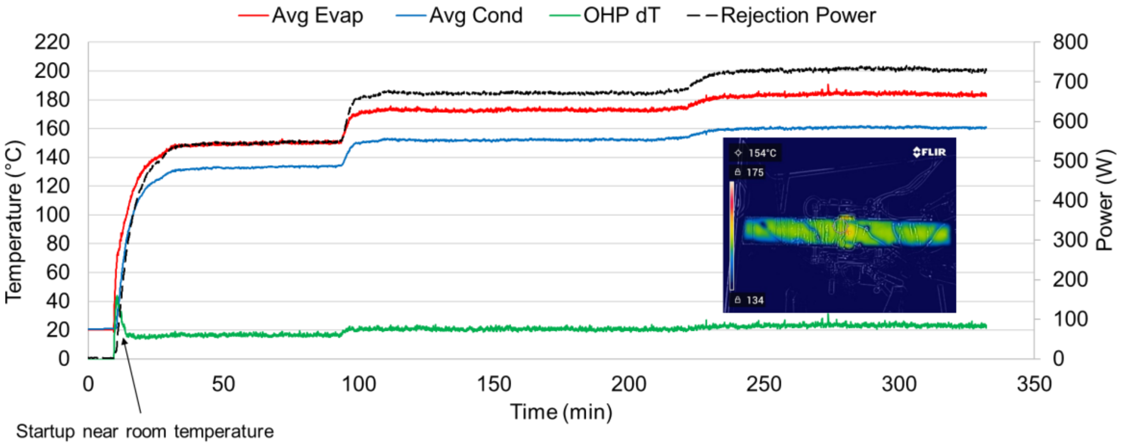
- Progress presented at TFAWS 2022:
  - 6” x 44” aluminum breadboard OHP radiators, with alcohol mixture working fluid
  - 3.1 kg/m^2, 36 W/K, stable from 150-185-deg C
  - 40X performance of mass equivalent Al control
  - https://tfaws.nasa.gov/index.php?gf-download=2022%2F08%2FTFAWS-2022-Fission-Power-OHP-Miller.pdf&form-id=20&field-id=42&hash=413fb61ea5d761517d5bd10a42fda315daaca55ed9b39ada6ac00e68e04f2028
  - 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

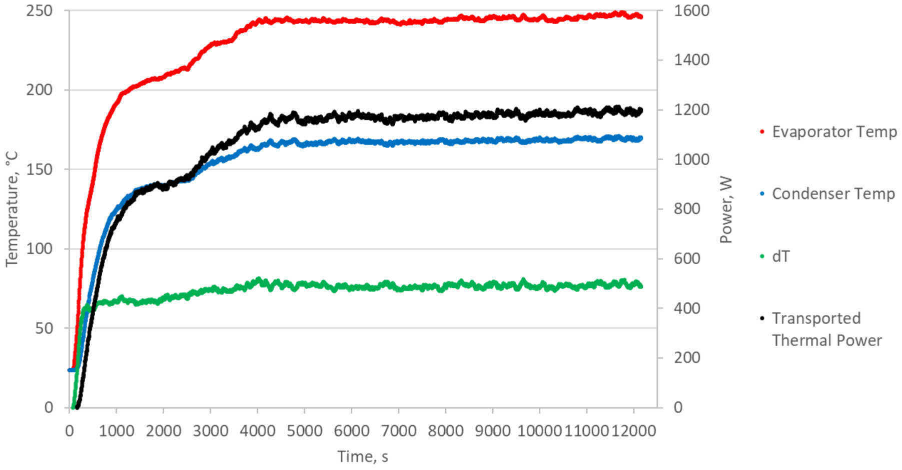
- The alcohol mixture which showed good performance initially was put on full scale life test at 175-deg C and failed at 330 hours due to a pin hole leak formed in the evaporator.

- 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

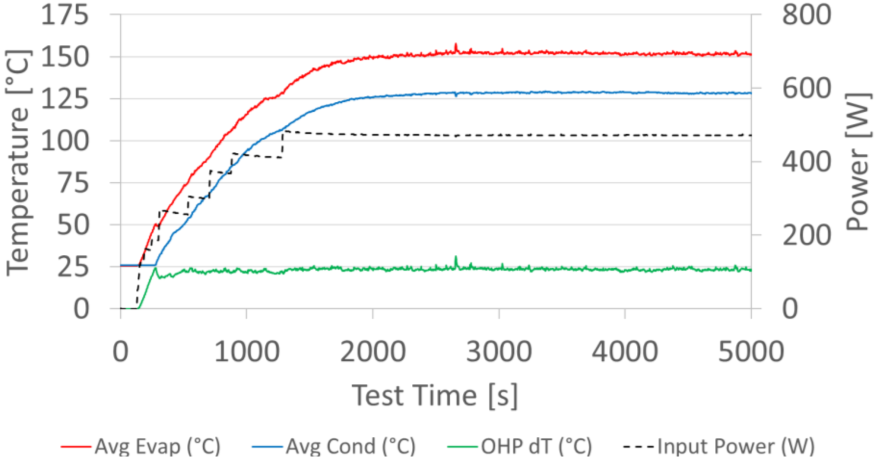
- Fluid development efforts for aluminum envelopes transitioned to fluids for which fluid thermal stability and aluminum compatibility has already been established in historical literature, e.g. alkanes (straight-chain saturated hydrocarbon)

- 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



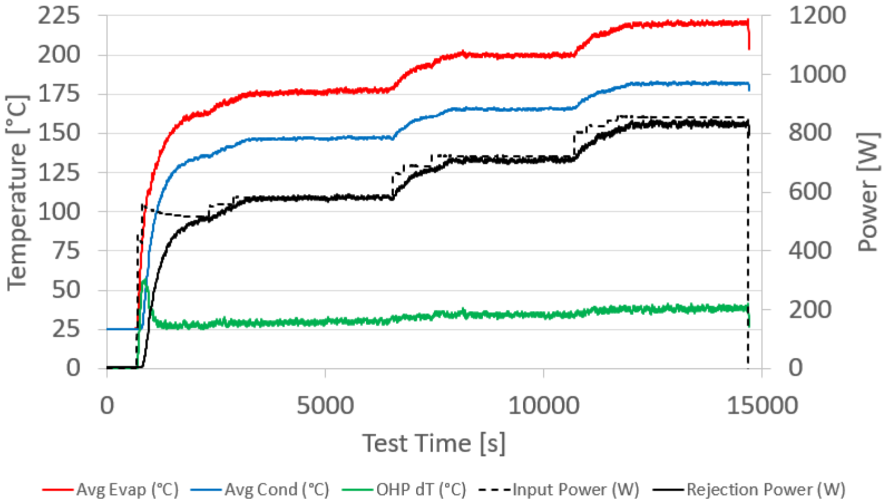
- Shorter alkane
    - 25 W/K at 150-deg C
    - Unstable at application-specific temperature targets (≥175-deg C)

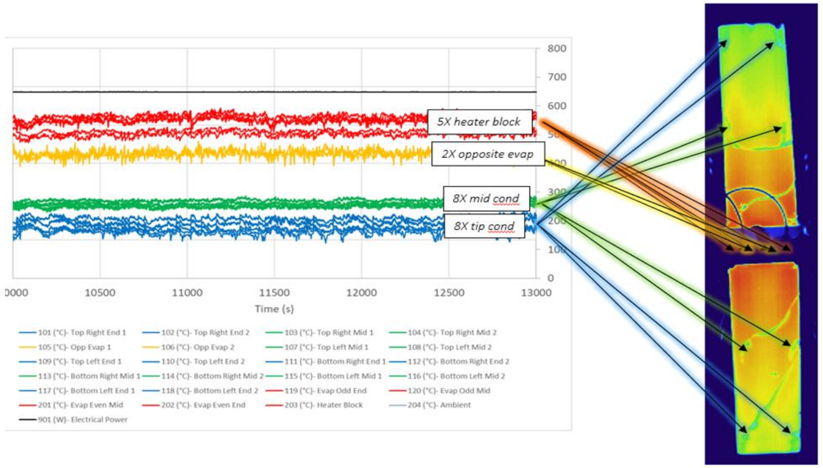


Updated heater clamping (bolted -> pneumatic) for improved contact uniformity and test repeatability

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

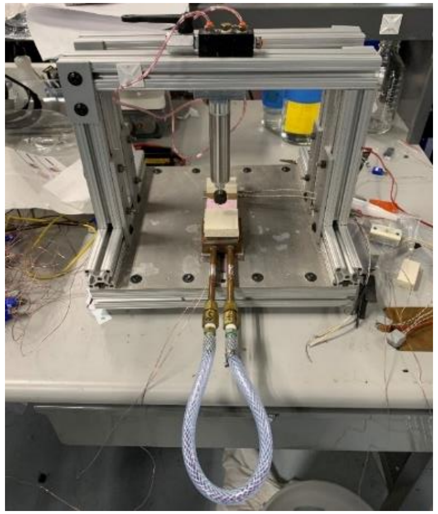


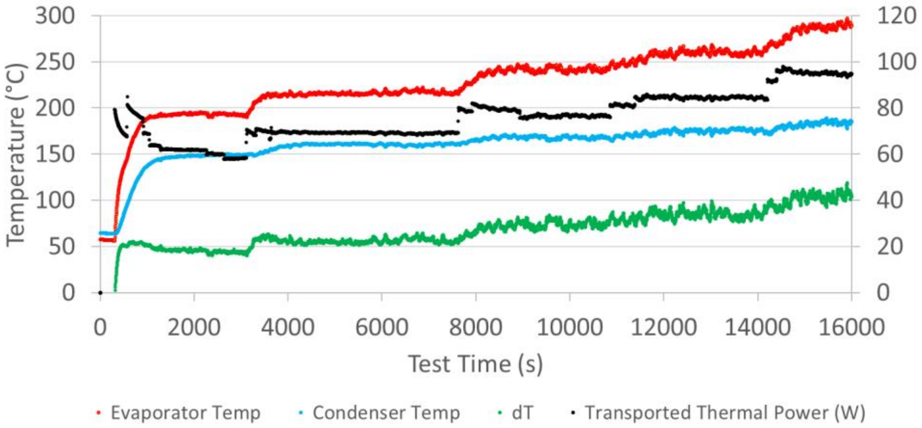


Correlation between IR and qty 25 TC measurements

Water Mixture Test Results

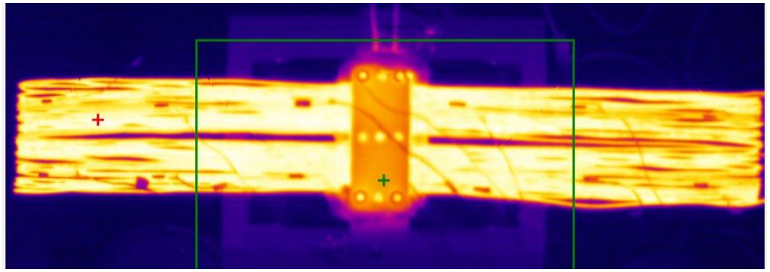
- Novel water mixture with significantly improved freeze tolerance - no sharp crystalline expansion at phase transition. Particularly relevant in Ti envelope applications

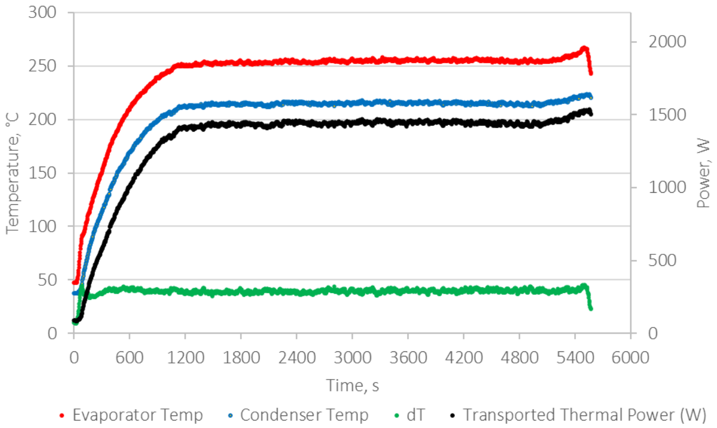




- Stainless Steel 2” x 6” breadboard
  - Stable to 300-deg C evaporator
  - Peak conductance >20X vented control

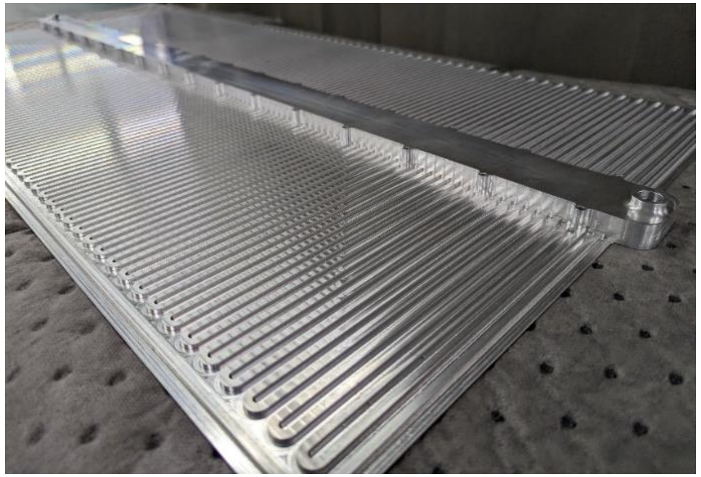
- 44” copper bent tube (same test article used for alcohol mixture demo)
  - 1.5kW at 250-deg C evaporator
  - 40 W/K @ 37K dT

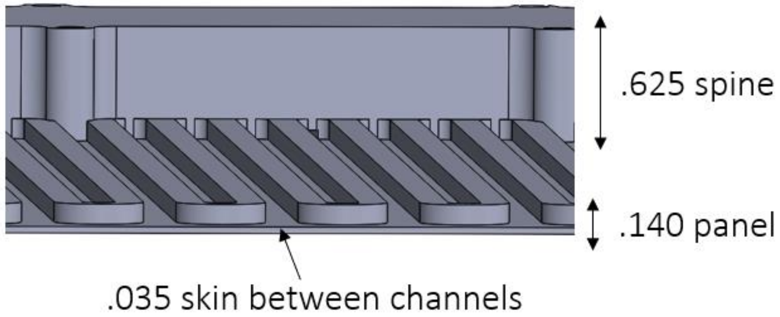




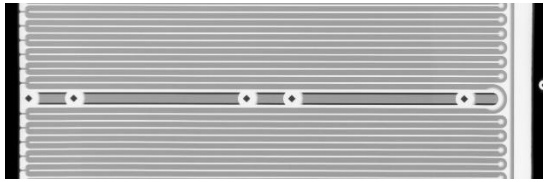
Final Phase II Hardware

- 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

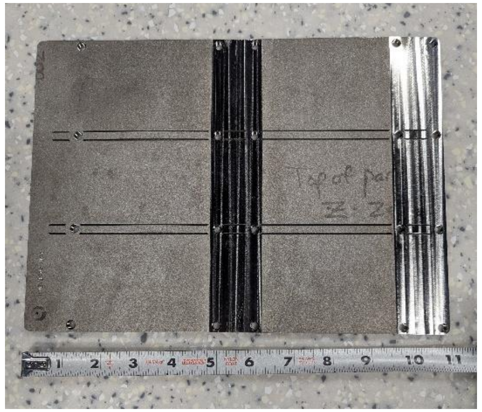




- Titanium OHP Radiator
  - Ti-6Al-4V, 8” x 11” x 0.185”
  - 4.9 kg/m^2 two-sided
  - ThermAvant’s first Ti radiator and first additively manufactured Ti OHP



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

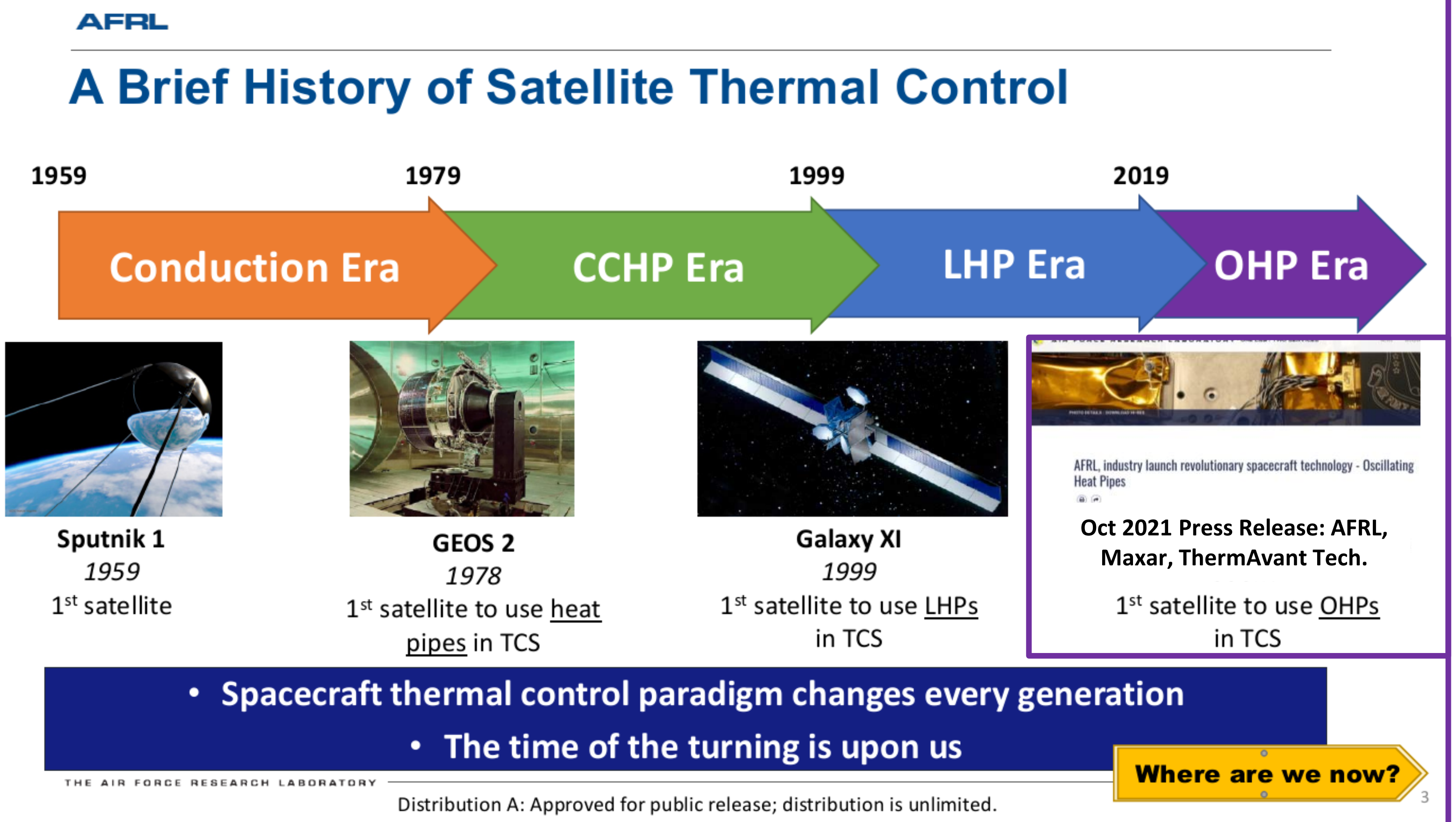
- Alcohols have been previously demonstrated in academia in SS and Cu bent tube OHPs, and by ThermAvant in short tests (tens hours) in aluminum hardware. Passivation of the known reactivity with aluminum was attempted with a variety of mixtures, unsuccessfully

- 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)

Backup Slides

AFRL/RV leadership in achieving OHP TRL 8/9

Built from AFRL/RV presentation and press releases in 2021



AFRL

A Brief History of Satellite Thermal Control

1959 1979 1999 2019

Conduction Era → CCHP Era → LHP Era → OHP Era

Sputnik 1
1959
1st satellite

GEOS 2
1978
1st satellite to use heat pipes in TCS

Galaxy XI
1999
1st satellite to use LHPs in TCS

AFRL, industry launch revolutionary spacecraft technology - Oscillating Heat Pipes

Oct 2021 Press Release: AFRL, Maxar, ThermAvant Tech.

1st satellite to use OHPs in TCS

- **Spacecraft thermal control paradigm changes every generation**
- **The time of the turning is upon us**

Where are we now?

THE AIR FORCE RESEARCH LABORATORY

Distribution A: Approved for public release; distribution is unlimited.

3

Slide presented by Air Force Research Laboratory Technology Roadmap presented at the Spacecraft Thermal Control Workshop 2021

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.

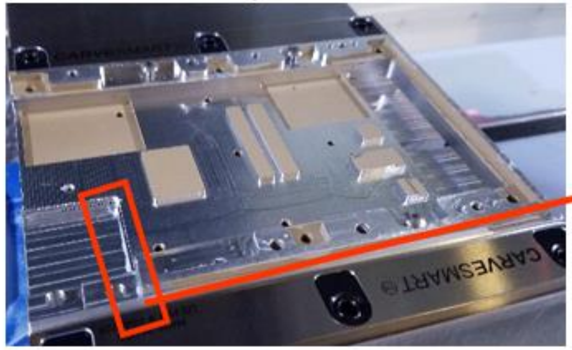
“We expect OHPs to be the linchpin thermal control technology on satellites from 2020 to 2040,” Allison said. “It’s my proposition that the fourth era is defined by oscillating heat pipes, and that the revolution that OHPs enable will be not so much focused on larger and more powerful spacecraft, but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

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

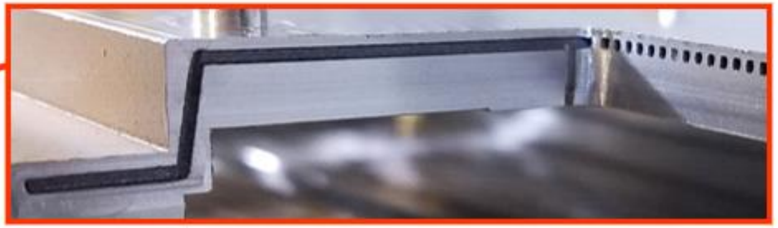
Basics

Examples of OHP form factors

Autopsied OHP heat sink and frame for military circuit card for [redacted]

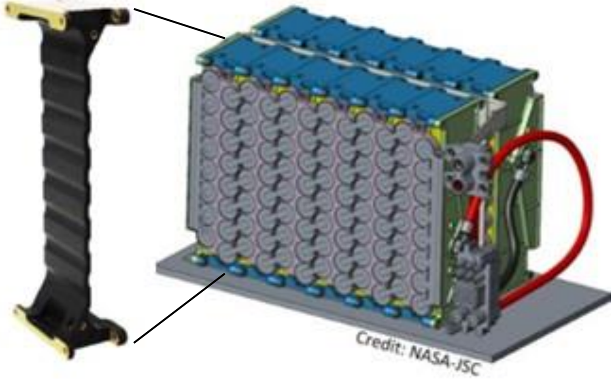


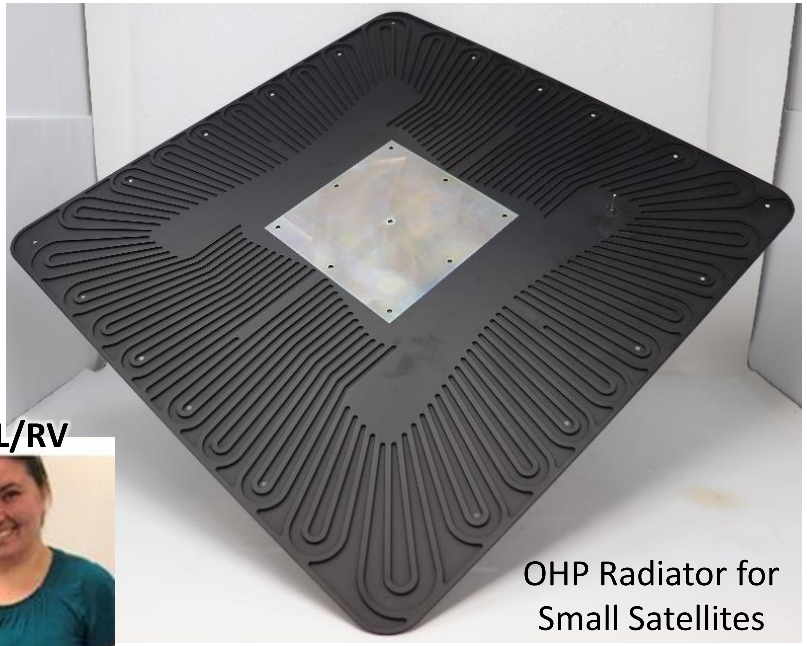
Cross-section of internal OHP microchannels

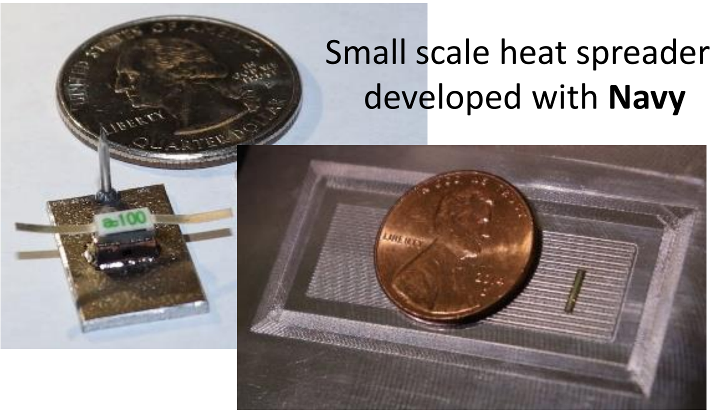



3D Rigid Structural Heat Sinks for [redacted]

Battery Packaging for **NASA**


Credit: NASA-JSC


OHP Radiator for Small Satellites developed with **NASA**

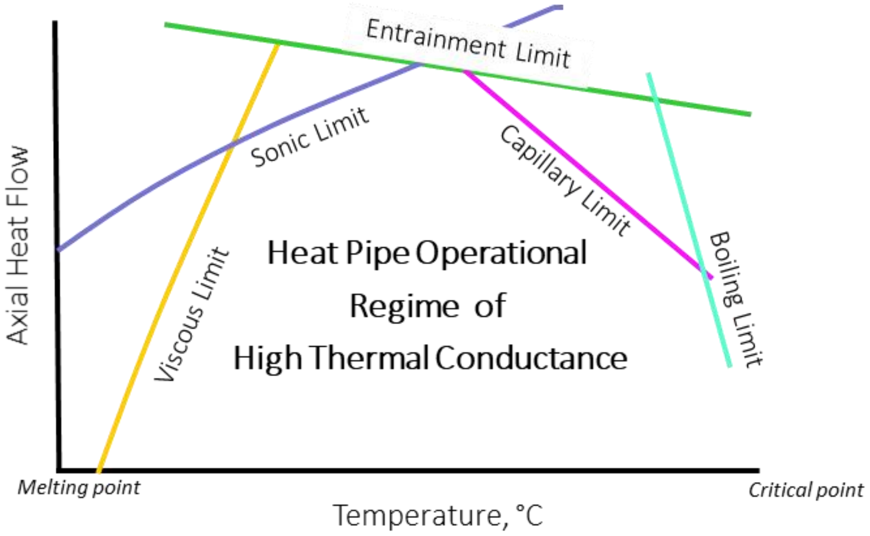

Small scale heat spreaders developed with **Navy**

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

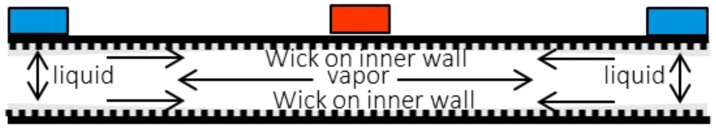
Limits of Operation

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

Heat Pipe Limits of Operation

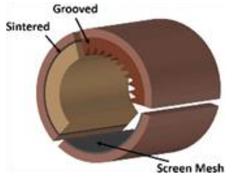


Heat Pipe cross-section (axial view)



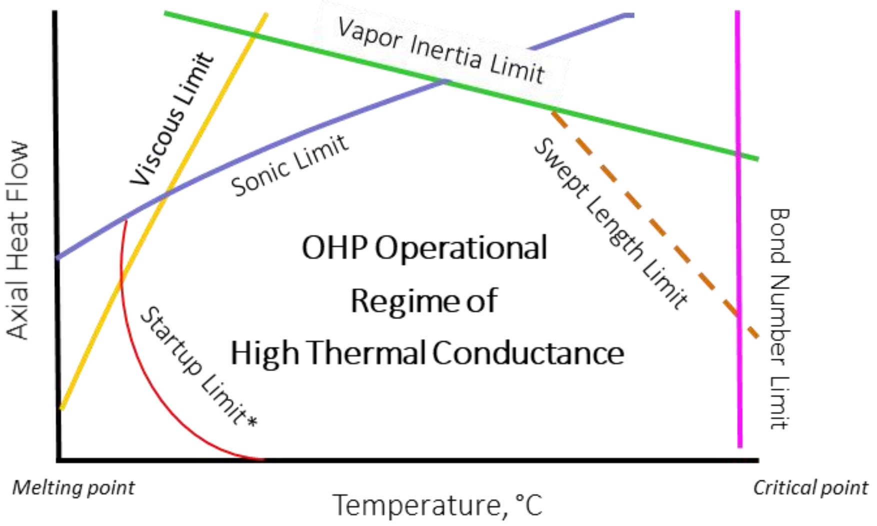
Counter-current *two-phase flow*

Cross-section of heat pipe wick structures [1]



[1] Bumataria, et al "Current research aspects in mono and hybrid nanofluid based heat pipe technologies" Heliyon, Elsevier May 2019

OHP Limits of Operation [2]



OHP cross-section (axial view)

Co-current *two-phase flow*

Cross-section of 3D OHP microchannel pattern

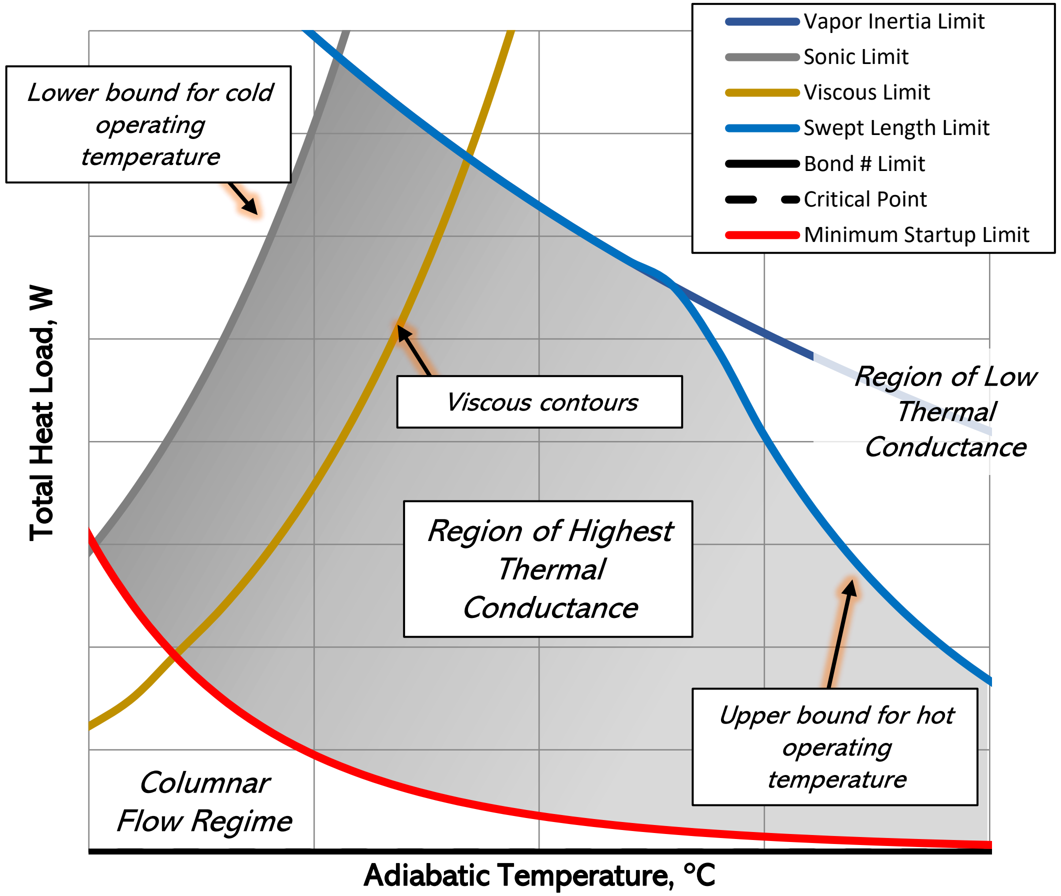
[2] *"Performance Limits of Oscillating Heat Pipes: Theory and Validation"* 2016, by Drolen, Smoot; Startup Limit presented at Spacecraft Thermal Control Workshop, 2018

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 ΔP to create fluid movement – contours show isotherm lines, e.g. 5°C ΔT (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*

Example limits chart



Reference: B.L. Drolen and C.D. Smoot, "The Performance Limits of Oscillating Heat Pipes: Theory and Validation," Journal of Thermophysics and Heat Transfer, 31, 4, pp. 920-936 (2017)