Jet Propulsion Laboratory
California Institute of Technology

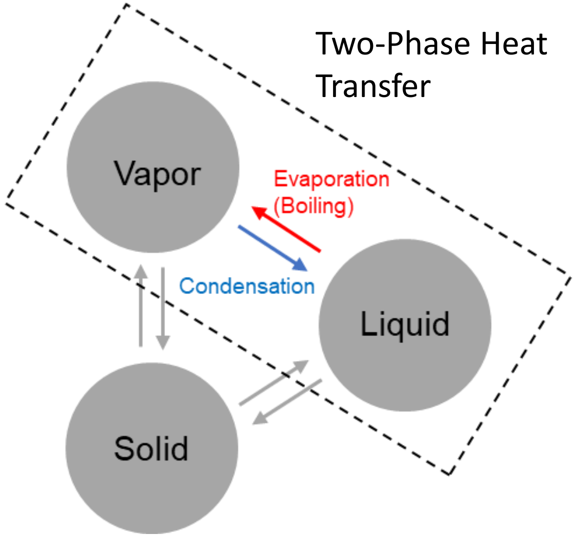
Two-Phase Thermal Technology Laboratory

Two-Phase Thermal Technology Development at JPL

Taku Daimaru
Thermal Engineer / PI of JPL Two-Phase Lab

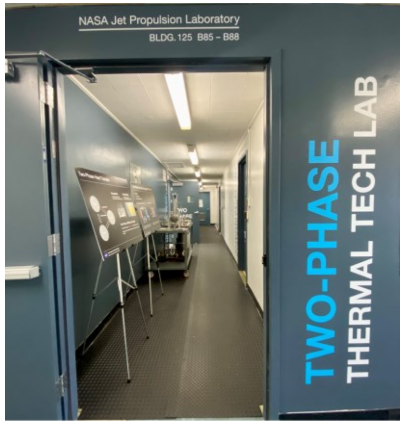
JPL Two-Phase Thermal Technology Laboratory

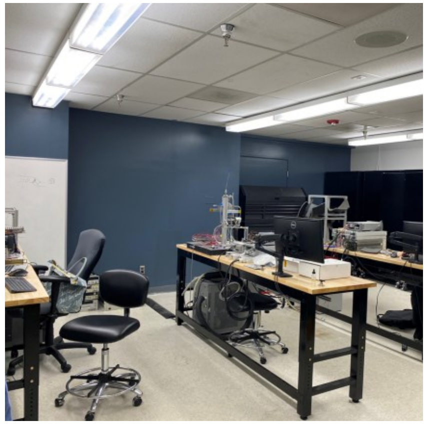
- Utilizing Evaporation (Boiling) and Condensation Heat Transfer
- More Efficient Comparing to Single (Liquid) Phase
  - 1g of Water: Evaporation >> **500 times** >> 1^{o}C Temperature Increases
    ➡ System can be much lighter or Larger heat rejection
  - Fluids stays at the constant temperature when Evaporation/Condensation happens.
    ➡ Isothermal / Precise temperature control by controlling pressure



Primary research areas in JPL

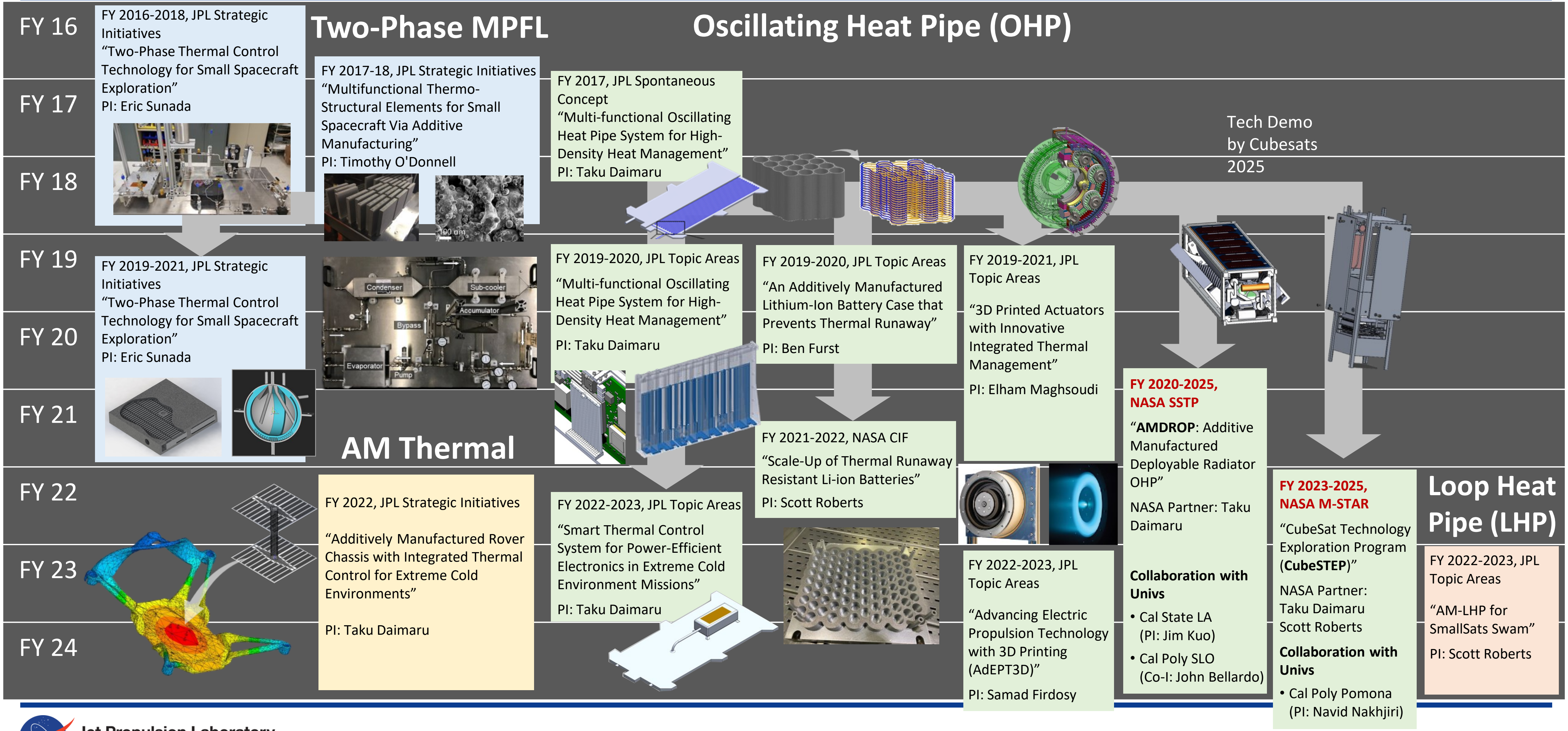
- Two-Phase Mechanically Pumped Fluid Loop (2016-2022)
- Oscillating Heat Pipe (2017-2025)
- AM Rover Chassis with Integrated Thermal Control (2022-2024)
- Loop Heat Pipe (2023-2025)





JPL Two-Phase Thermal Technology Laboratory (2024)

JPL Two-Phase Thermal Technology Lineage

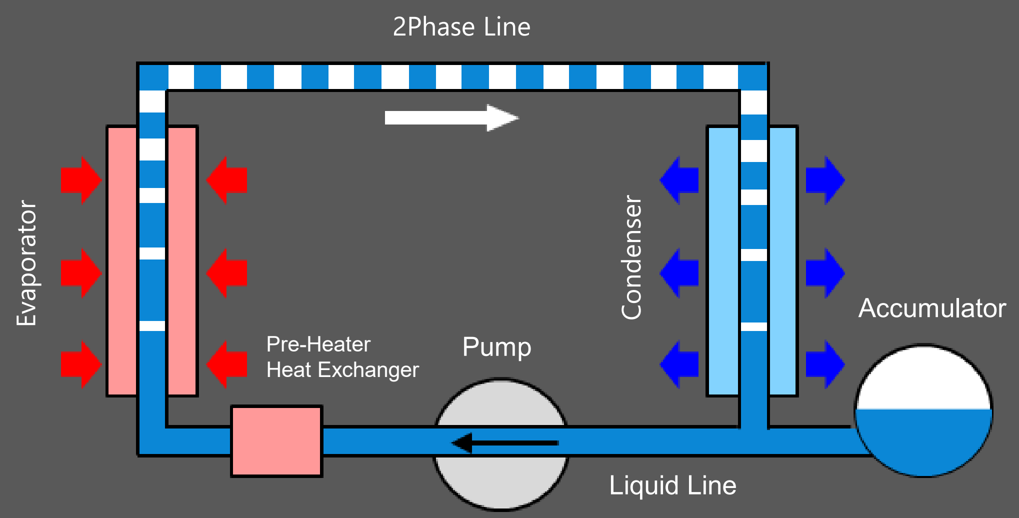


Primary Two-Phase Thermal Technologies

Key Words

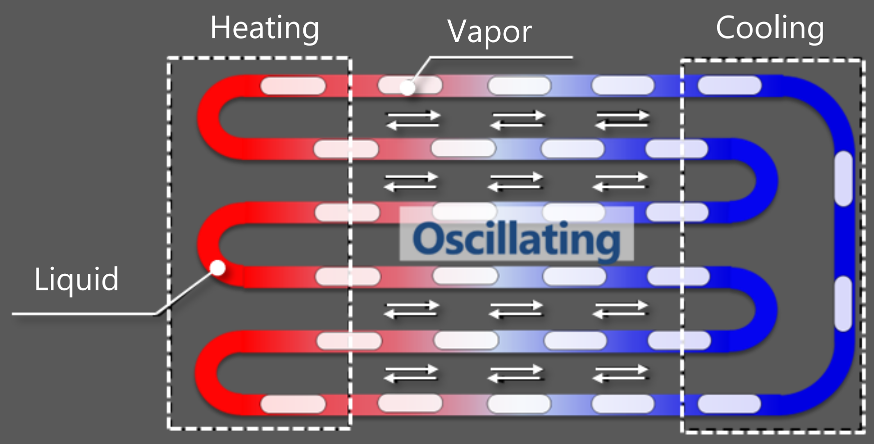
- Two-Phase Flow: More Efficient Heat Transport
- Additive Manufacturing: Integrate Thermal Control into Structure

Two-Phase Mechanically Pump Fluid Loop



- Circulate fluid by a pump, heat transport in long distance > 10m
- Evaporation in Evaporator and Condensation in Condenser

Oscillating Heat Pipes (OHPs)

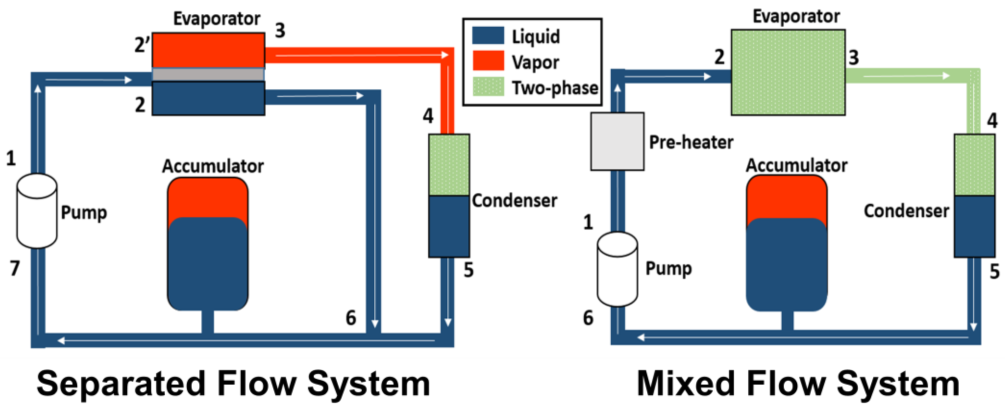


- Heat pipe using self-excited oscillation of fluid, heat transport < 1m
- Heat transport by evaporation/condensation of micro liquid film

Two-Phase Mechanical Pump Fluid Loop

System Architecture

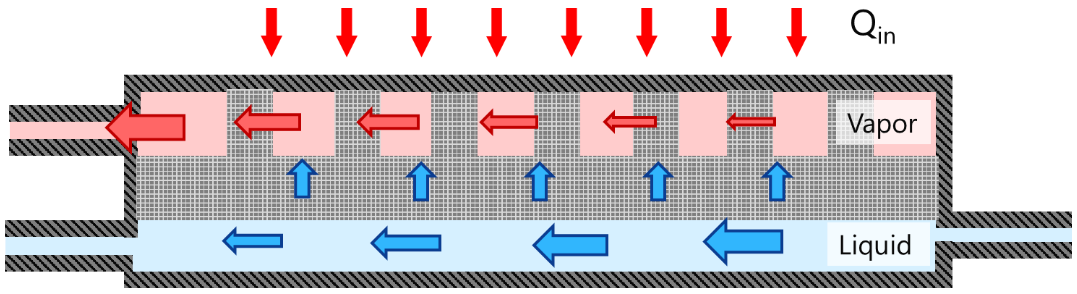
- Mixed Flow System
  - ➢ Preheating / Two-Phase flow
- **Separated Flow System**
  - ➢ No Preheating / Vapor Flow



System Architecture
(Furst 2017)

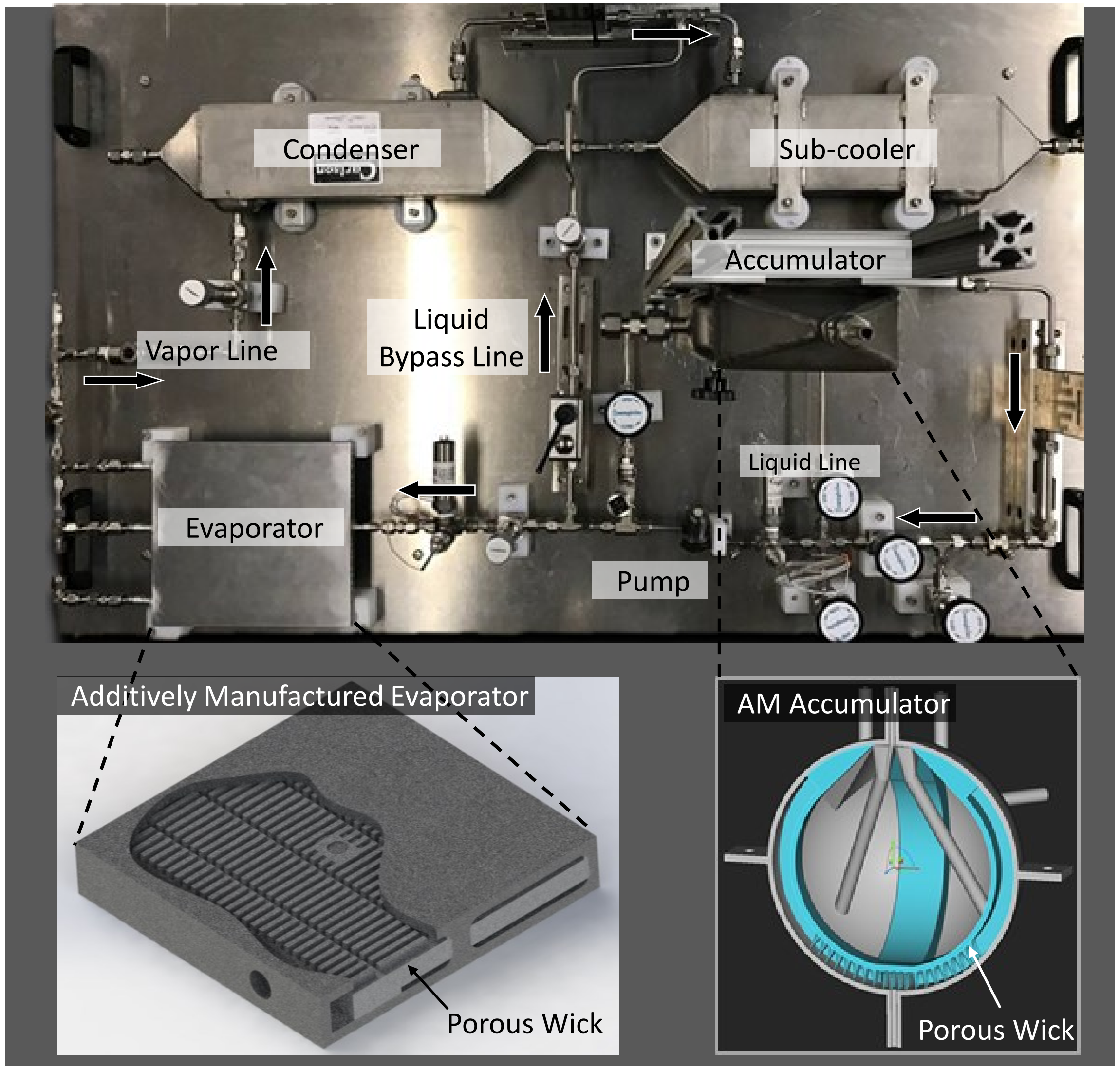
Wick-Type Evaporator

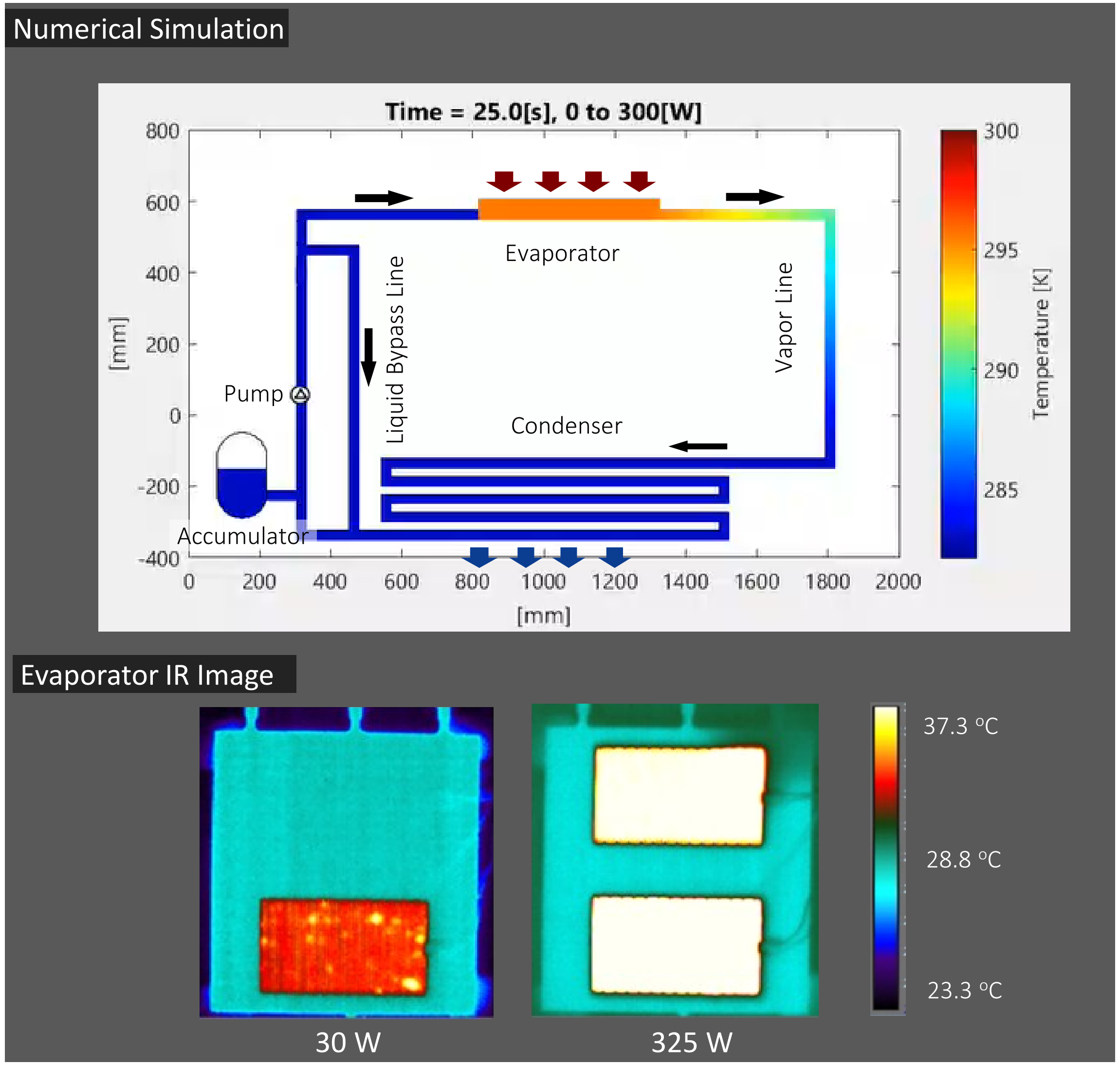
- Working in Separated Flow System
- Phase Separation
- Ability to Adjust Mass Flow Rate to Q
  - ➢ Wick pulls liquid up as needed



Wick-Type Evaporator

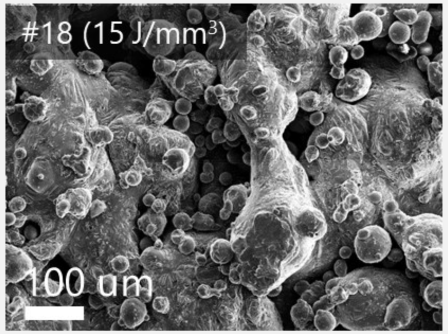
Two-Phase Mechanical Pumped Fluid Loop (TRL 4~5)





Evaporator Development

Porous Material Development in AM



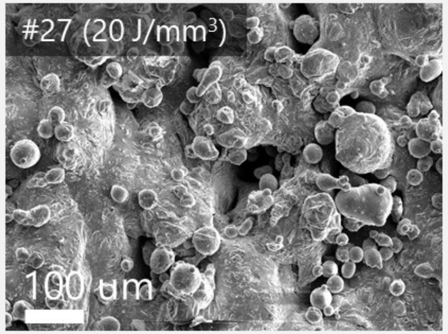
Baseline

#23 (15J/mm³)

Pore Radius: 18.0 um

Permeability: $3.2{*}10^{-13}$

Porosity: 22.3 %



Challenge

#30 (20J/mm³)

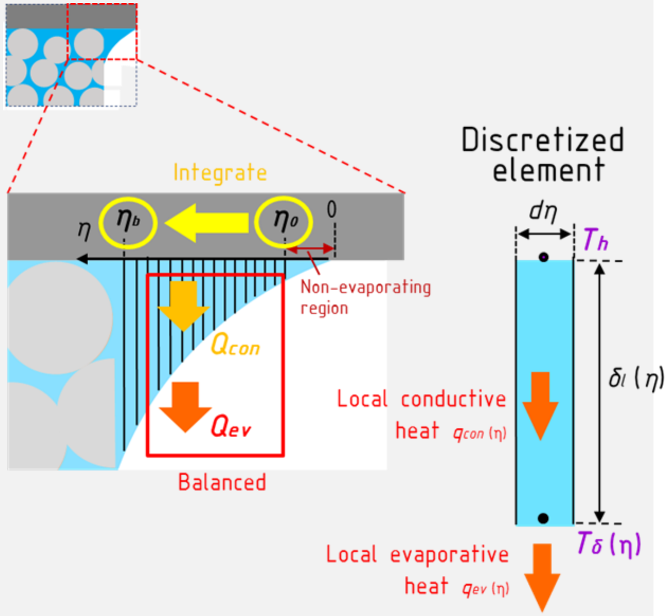
Pore Radius: 2.9 um

Permeability: $1{,}2{*}10^{-14}$

Porosity: 12.2 %

Aluminum

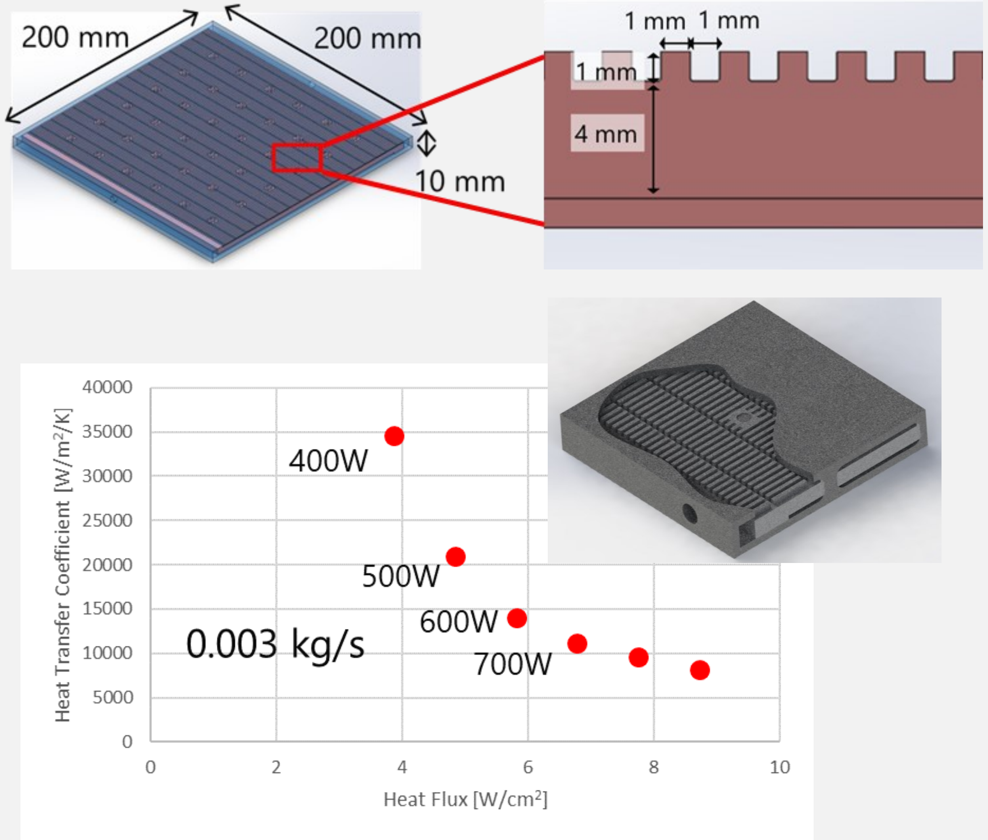
Theoretical Modeling



Heat Transfer Coefficient Model

Odagiri (2017)

Designing

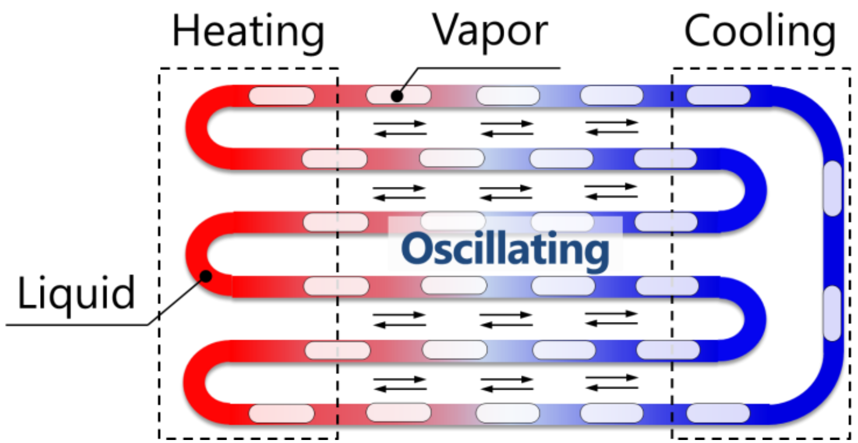


Heat Transfer Coefficient

Oscillating Heat Pipe (OHP)

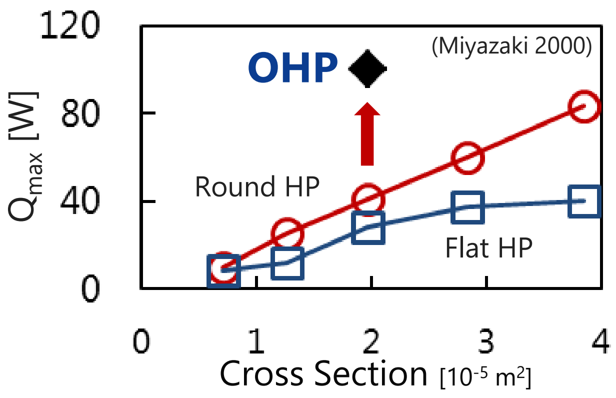
Operational Principle

- Metal Pipe, Working Fluid (Liquid Slug – Vapor Plug)
- Transport heat by Self-Excited Oscillation of working fluid
- Utilizes pressure-driven, two-phase fluid flow to rapidly transfer heat between heat sources and heat sinks.
- Heat transferred by Phase Change in Liquid Films

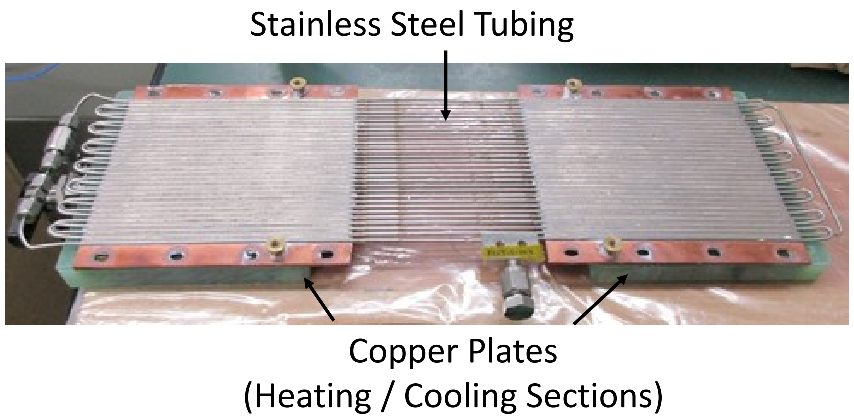


Merits and Challenge

- Can handle higher Maximum Heat Input Q_{max}
- Thinness・Light Weight・Flat-Plate
- No Porous Structure (Wick)
- Flexibility in Channel Arrangement
  - ➡ **Additive Manufacturing (AM)**
- Complex Physics
  - ➡ **Numerical Simulation**

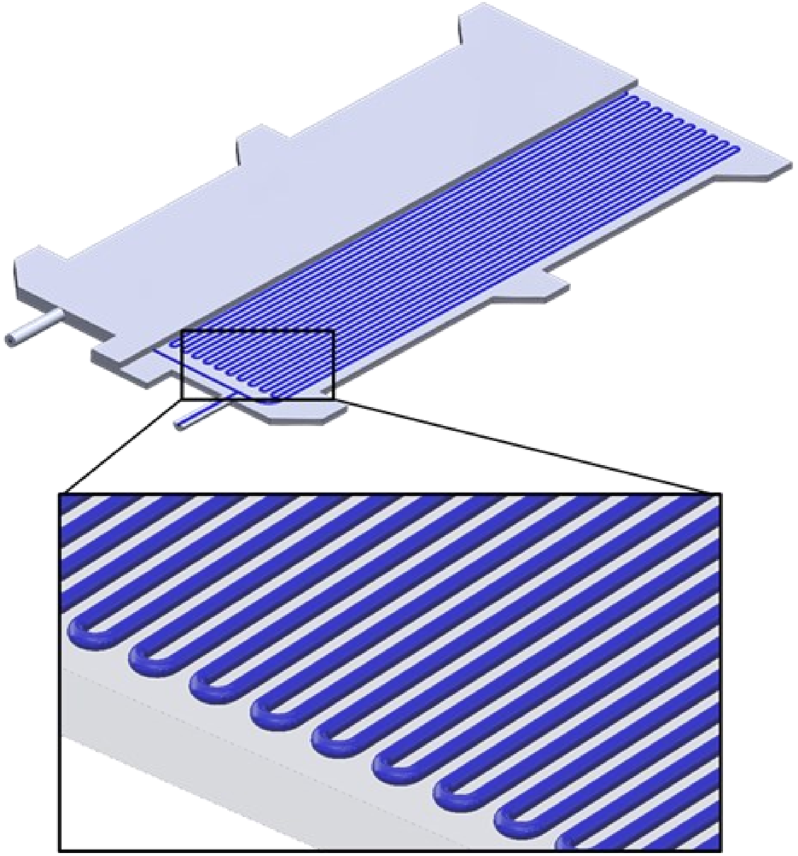


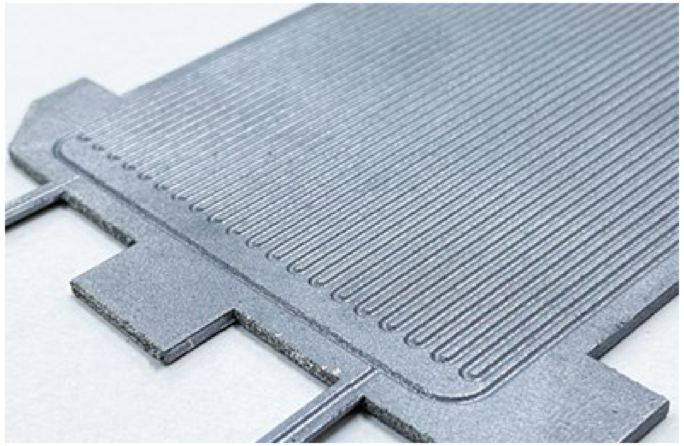
Comparison of Q_{max}

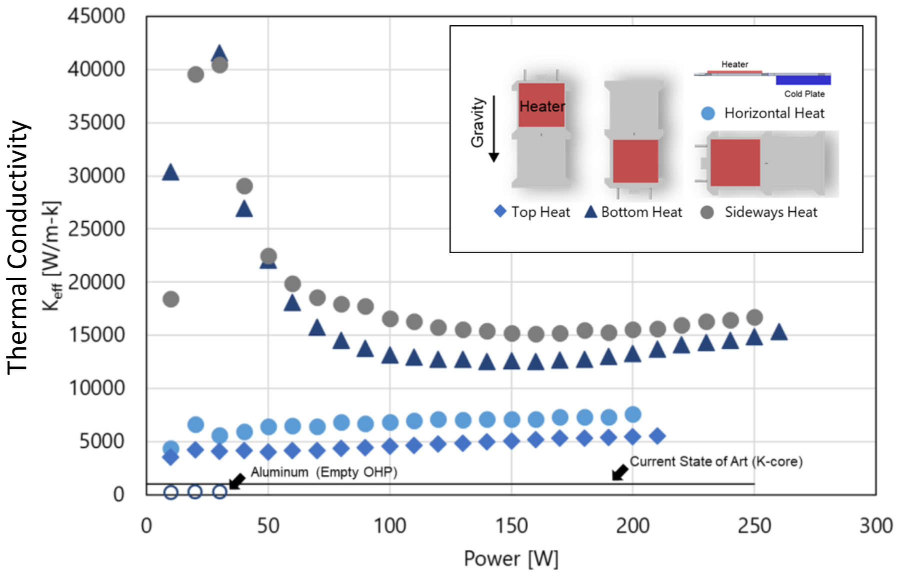


Example of Conventional OHP (JAXA)

Additive Manufactured OHP (AMOHP) (TRL 5)







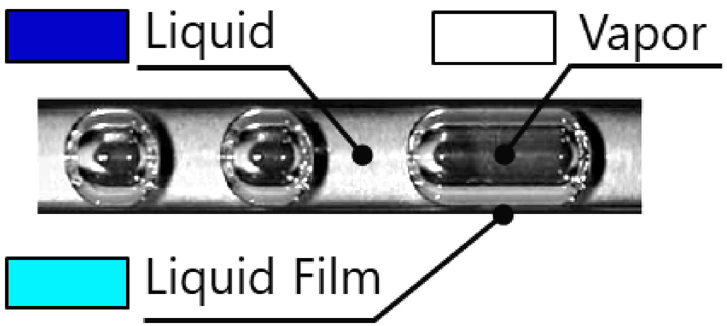
- Material : AlSi10Mg
- Number of Turns : 42
- Chanel Diameter : 1 mm
- Turn Radius : 1 mm
- Plate Length : 20 cm
- Plate Width : 9 cm
- Plate Thickness : 4 mm

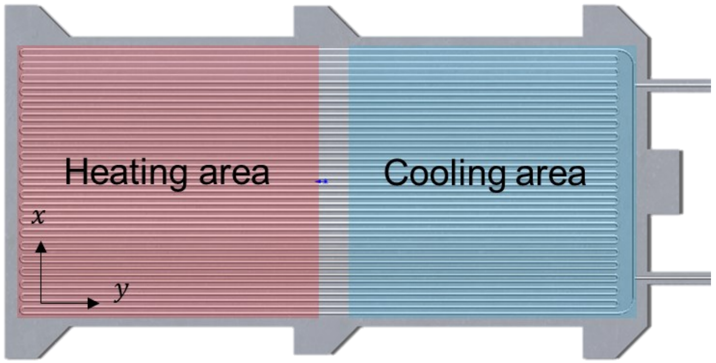
- **Collaboration with JPL Additive Manufacturing Center**
- **High Thermal Conductivity**
  - **7,500 W/m/K (Horizontal Heat)**
  - **40,000 W/m/K (Bottom Heat)**
  - **5-15X higher than Current State of the Art (K-core)**

OHP Numerical Simulation Model

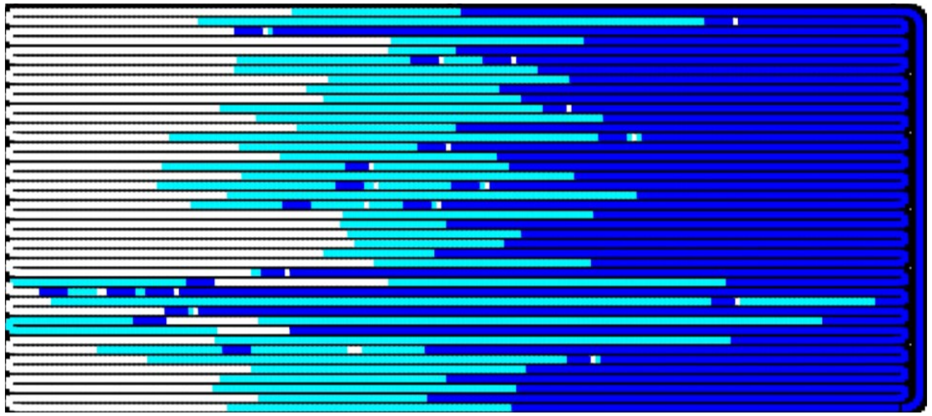
100 W

Time = 30 sec
Steady-state
1.0 x speed

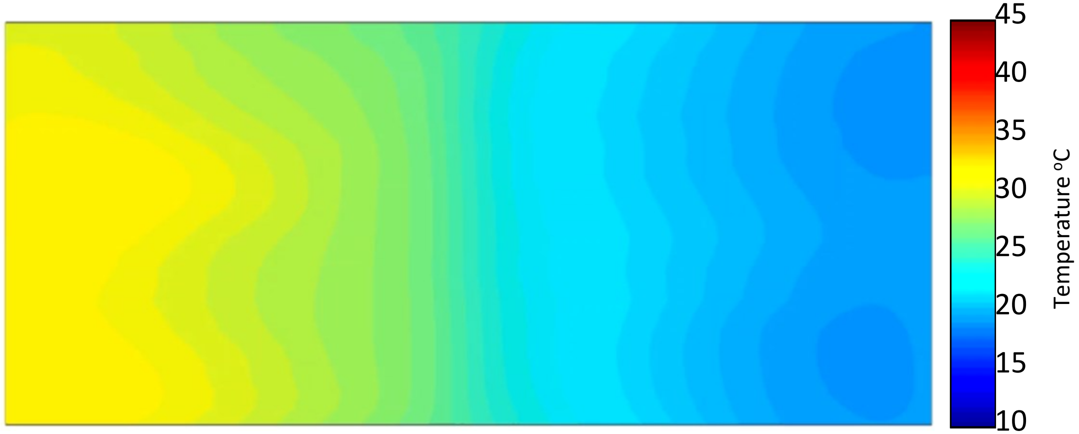


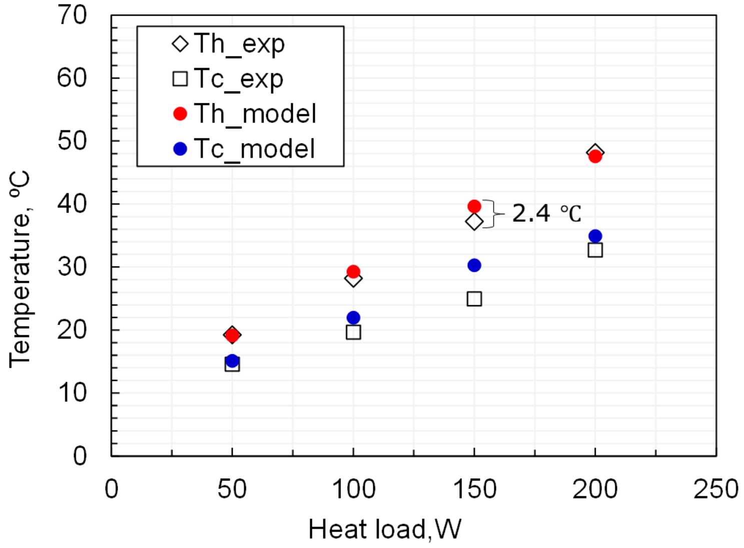


Change in liquid-vapor distribution



Change in temperature distribution

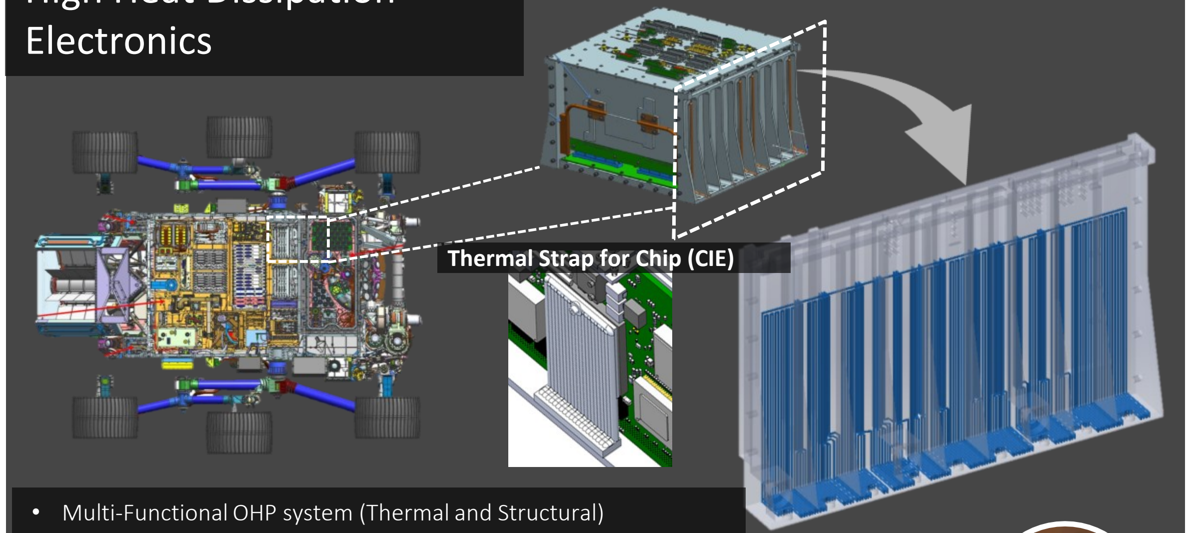




- **High precision numerical model based on Two-Phase Physics**
  - **Movement of Liquid/Vapor**
  - **Boiling, Liquid Film Evaporation**
  - **Heat Transfer in Structure**
- **Being used as OHP design tool**

Applications of AMOHPs in JPL

High Heat Dissipation Electronics

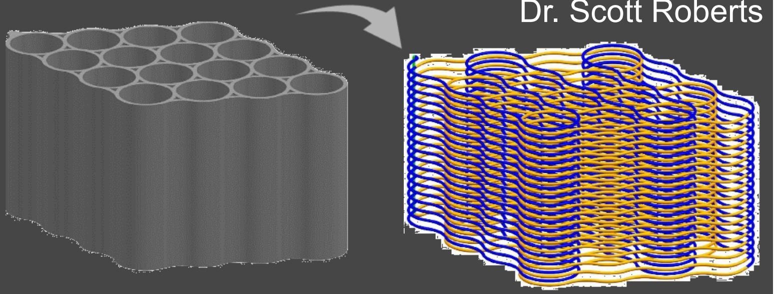


- Multi-Functional OHP system (Thermal and Structural)
- Enables more powerful operation of high-power electronics

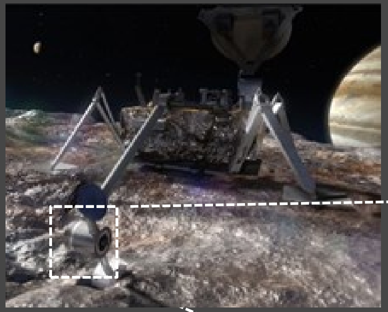
Dr. Scott Roberts

Li-Ion Battery Case

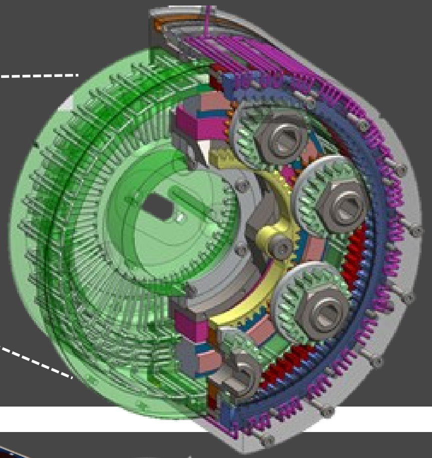
- Thermal Management of entire Battery Unit
- Preventing Thermal Run-away which generate high heat-density dissipation



Actuator Thermal Control For Planetary Sampling

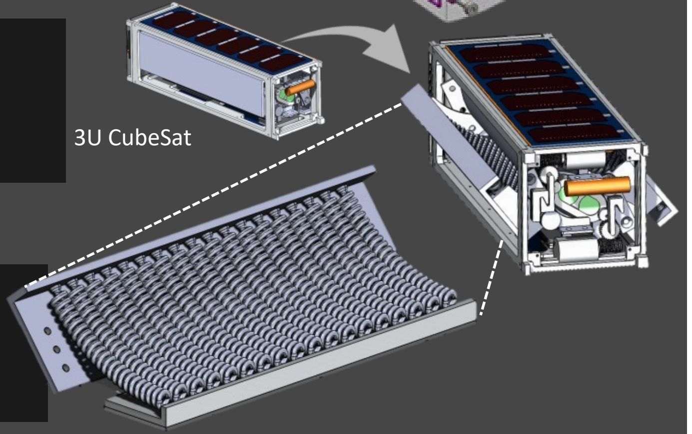


- More efficient worming-up in cold environment
- Enables high-power heat dissipation during actuator operation



Deployable Radiator for CubeSat (AMDROP)

- NASA SSTP CSLA/Cal Poly SLO/JPL



- AMDROP allows high power instrumentation/computation in CubeSats by enabling 100W class heat removal

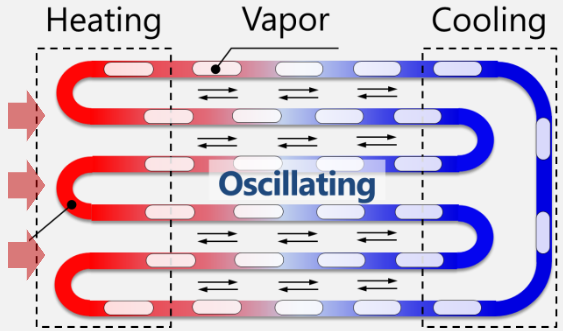
OHP Performance Prediction Model
(Collaboration with University of Michigan)

Prof. Massoud Kaviany

1

Q [W]

Heat Input

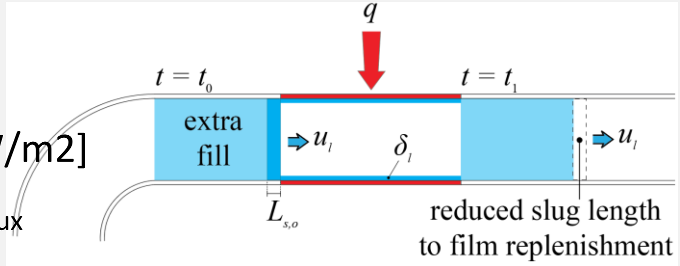


Simplify

2

q [W/m2]

Heat Flux



u_l [m/s]

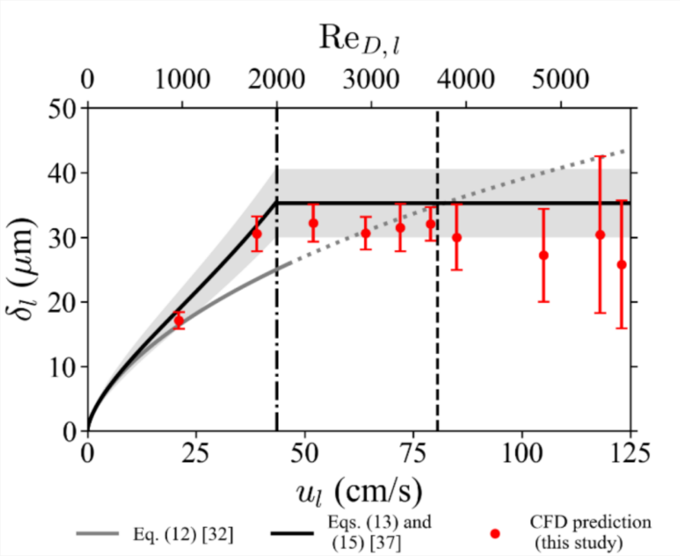
Liquid Velocity

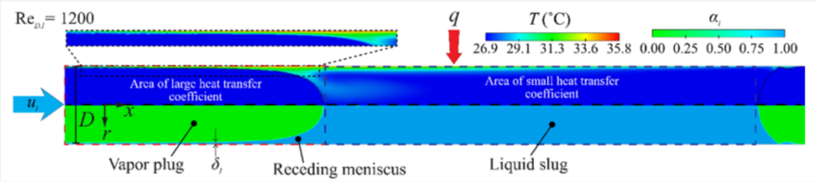
$$q = \frac{\rho_l D L_{s,o} \Delta h_{lg}}{4 L_e^2} u_l$$

3

δ_l [um]

Liquid film thickness



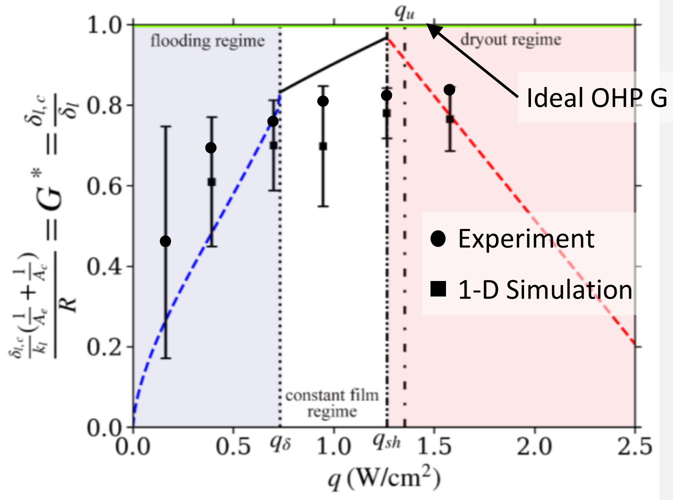


4

G_{ideal} [W/K]

Thermal Conductance

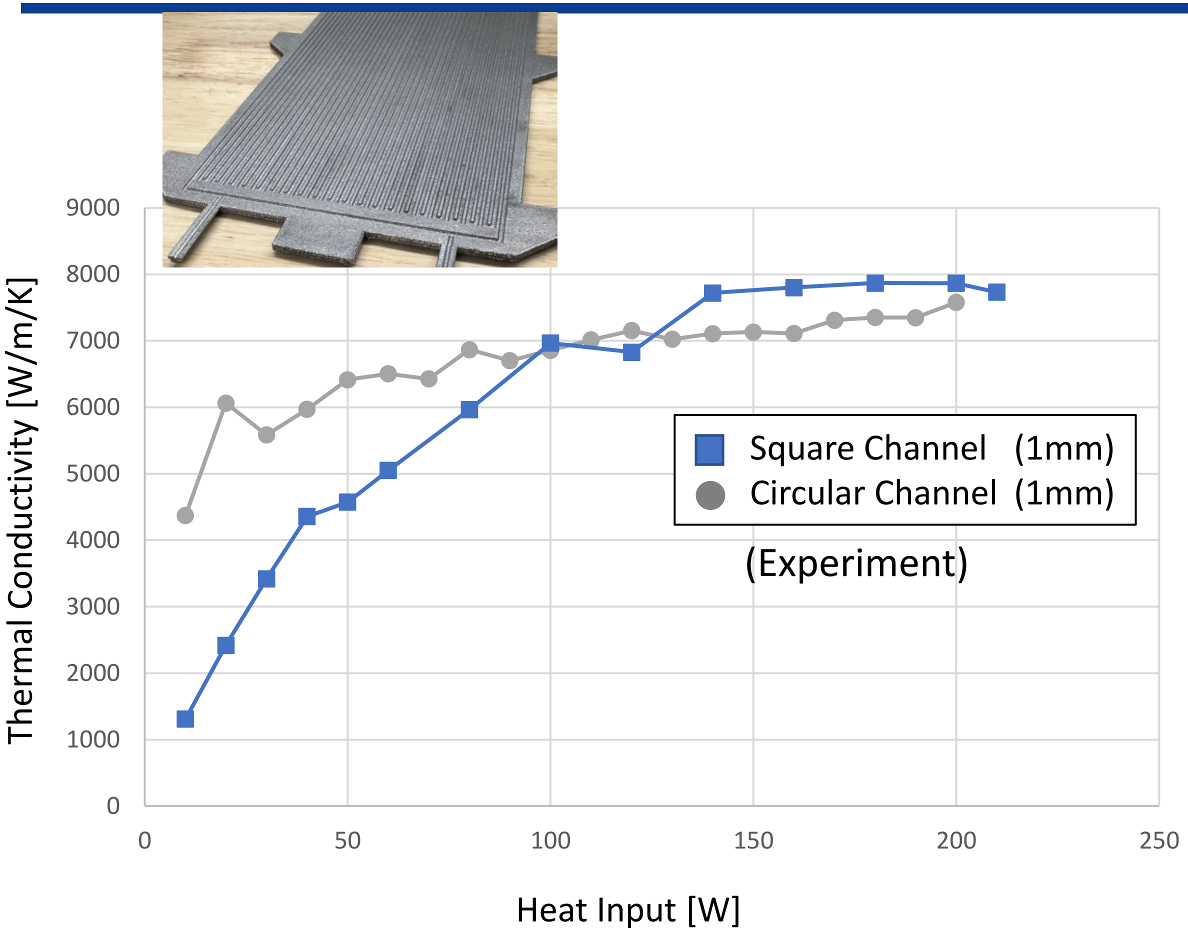
$$G = \frac{k_l}{\delta_l}\left(\frac{1}{A_e} + \frac{1}{A_c}\right)^{-1}$$

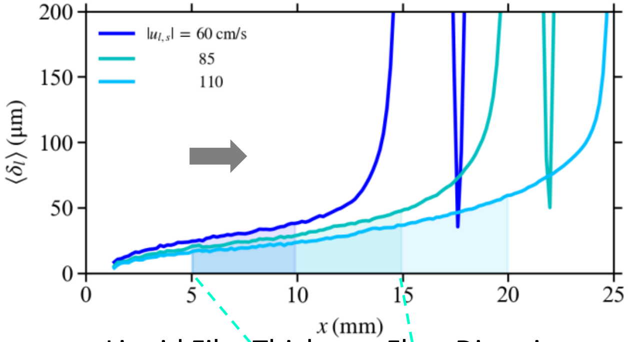


Experimental Result is about 80% of G_{ideal}

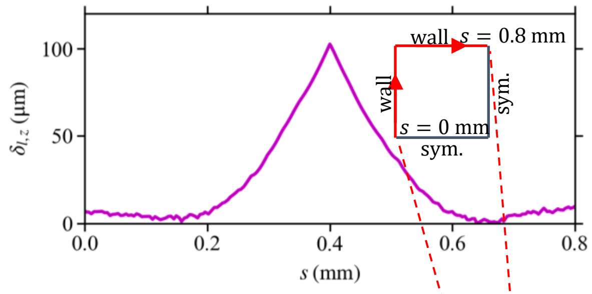
OHP Channel Geometry
(Collaboration with University of Michigan)

Prof. Massoud Kaviany

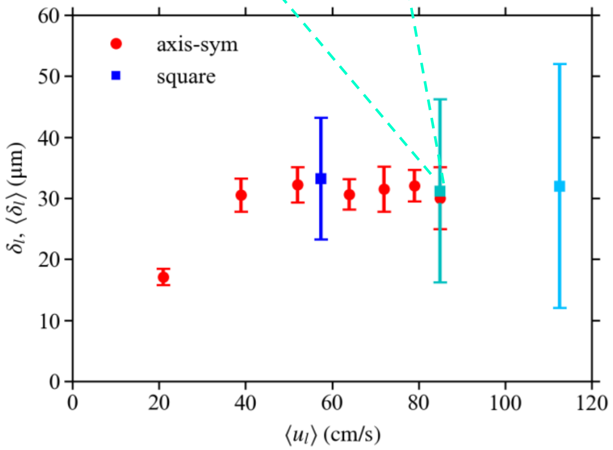


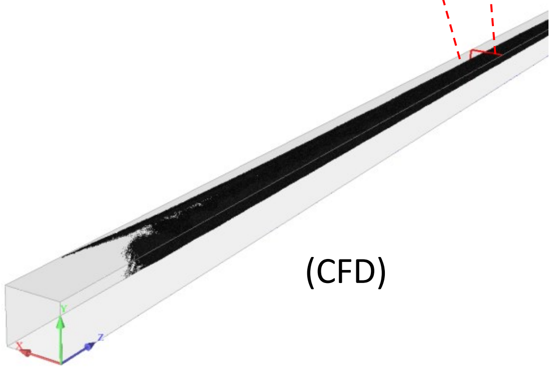


Liquid Film Thickness Flow Direction



Liquid Film Thickness Circumferential Direction





(CFD)

Square channel is low-performing at lower heat, but slightly higher at high heat

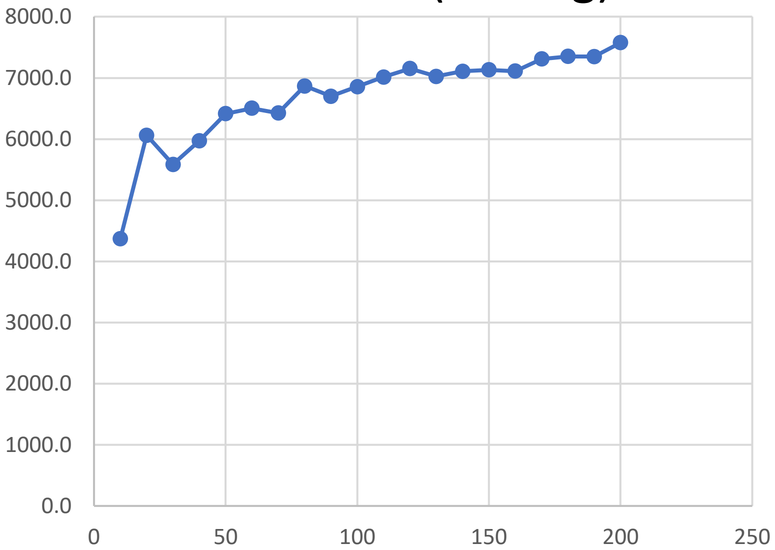
- More Liquid Mass -> Higher Pressure Difference
- Thinner Liquid Film Section, Larger Surface Area

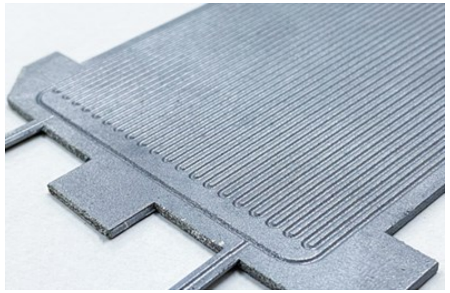
OHP in Various Material (All 3D Printed)

Michael Cox

Tomas Wexler

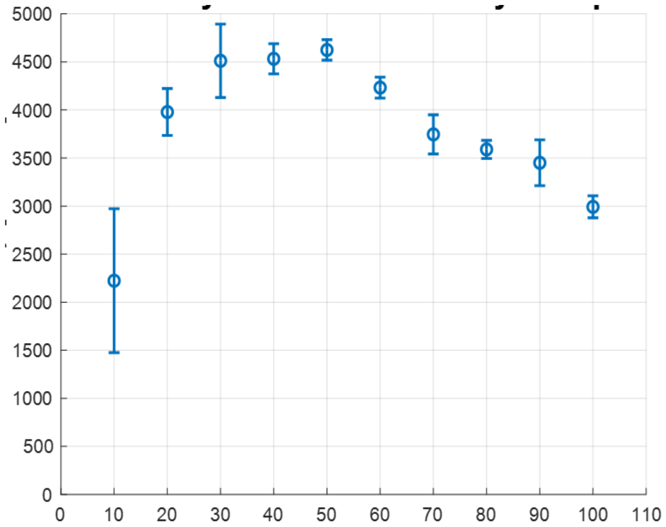
Aluminum (AlSiMg)





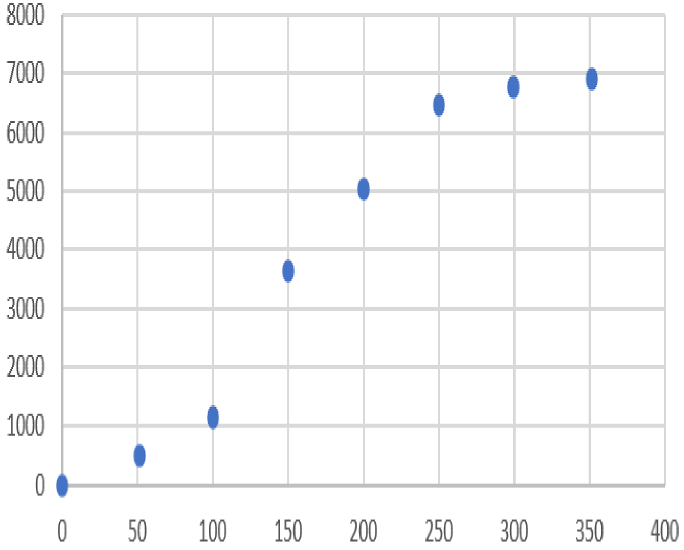
- Working Fluid: R134a
- 1mm Diameter Channel
- Operation Range
  -10 ~ 60C
- Material k: 180 W/m/K

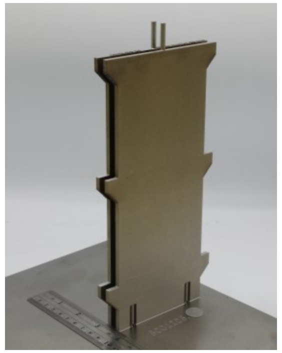
Titanium



- Working Fluid: R134a
- 1mm Diameter Channel
- Operation Range
  -10 ~ 60C
- Material k: **6.7 W/m/K**

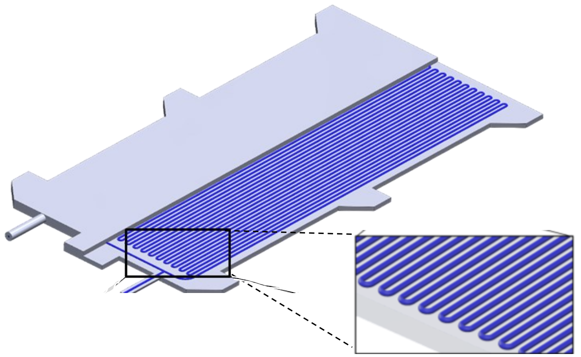
Hiperco 60

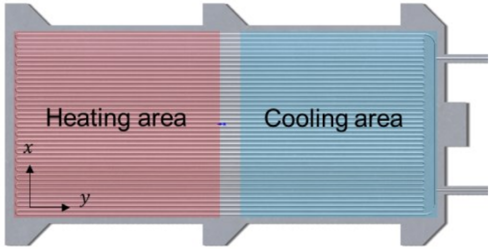


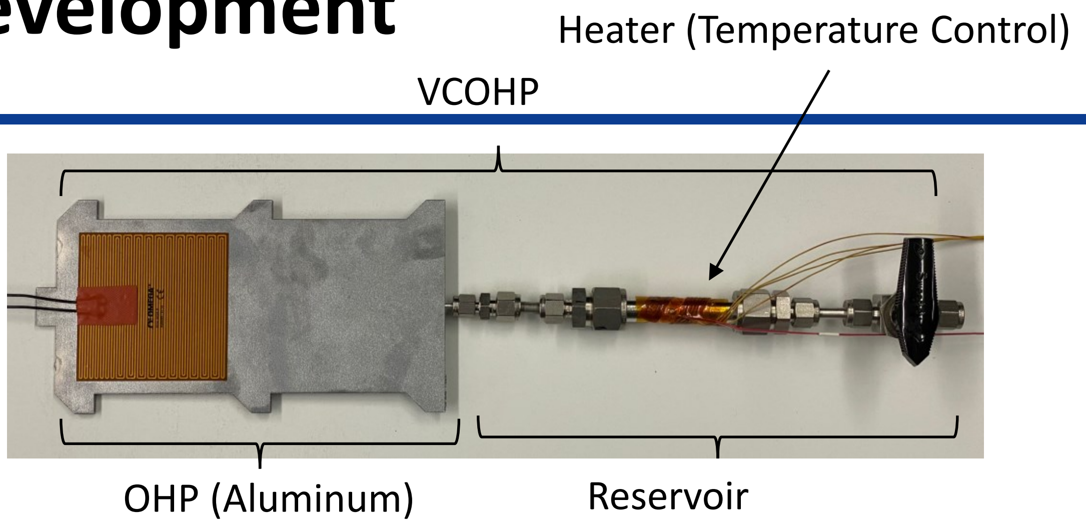


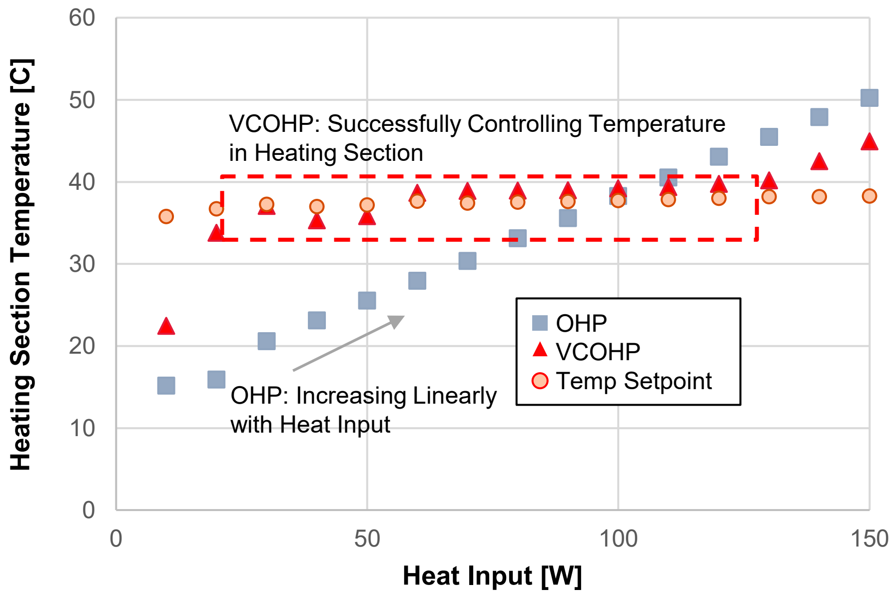
- Working Fluid: Water
- 2mm Diameter Channel
- Operation Range
  25 ~ 300C
- Material k: **30 W/m/K**

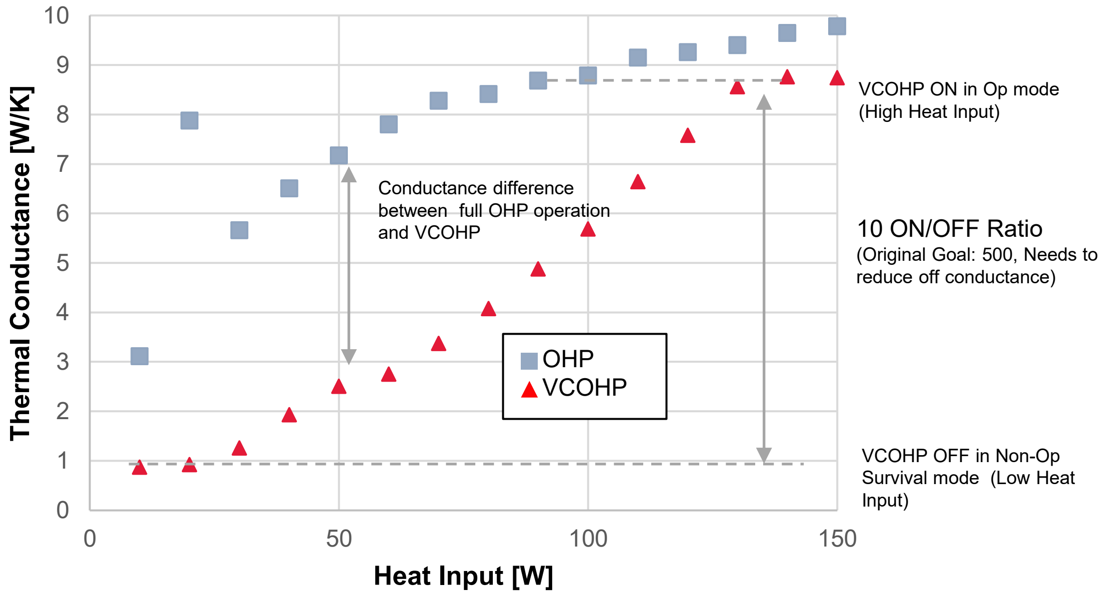
Temperature Controllable OHP Development



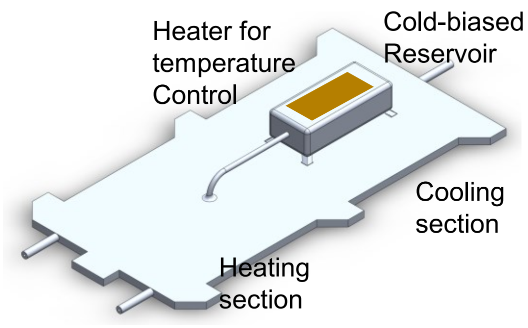


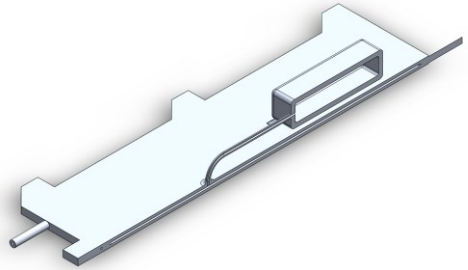


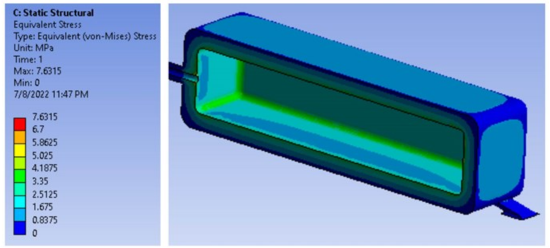


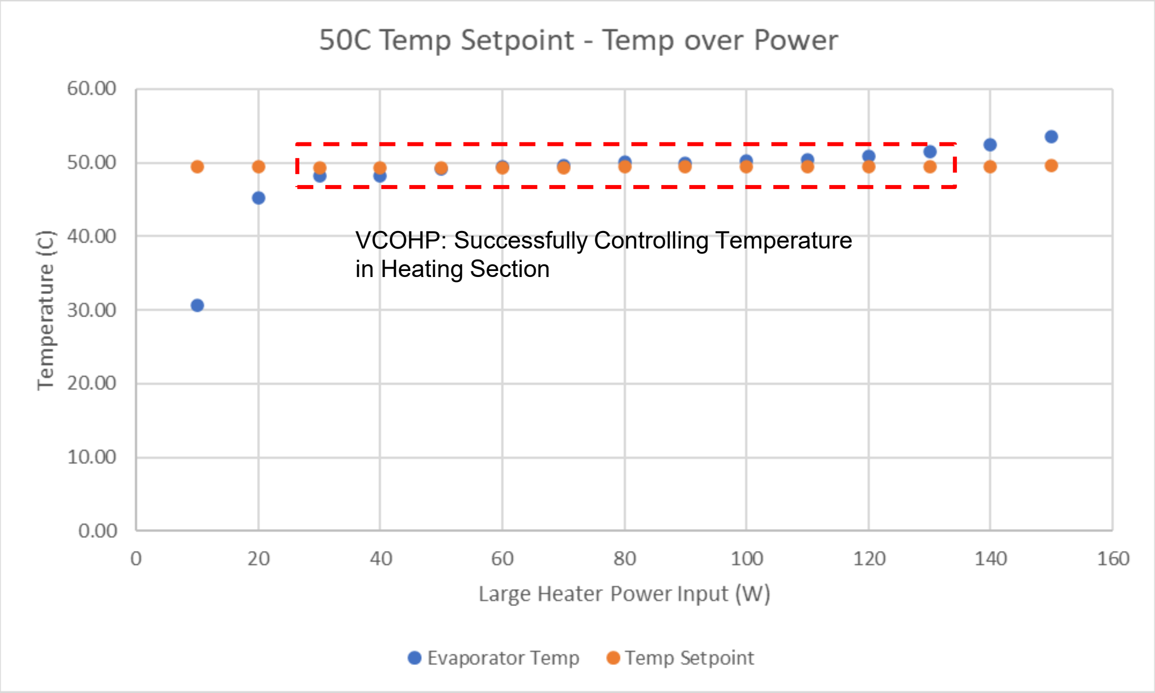


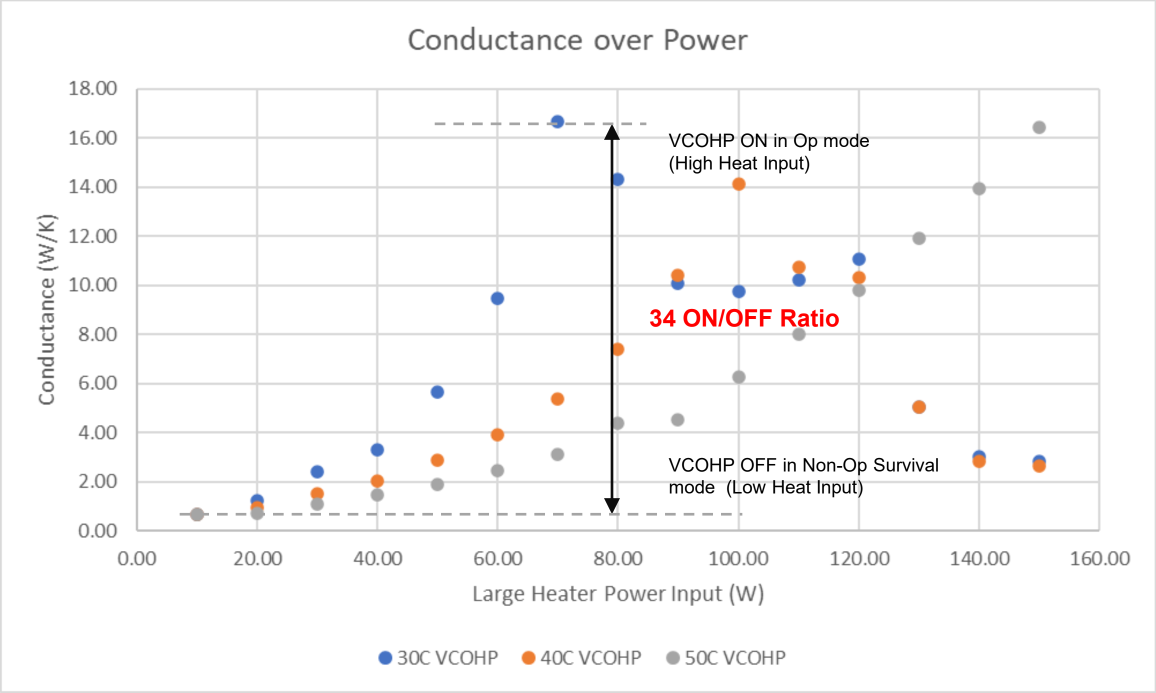
AM-VCOHP Development





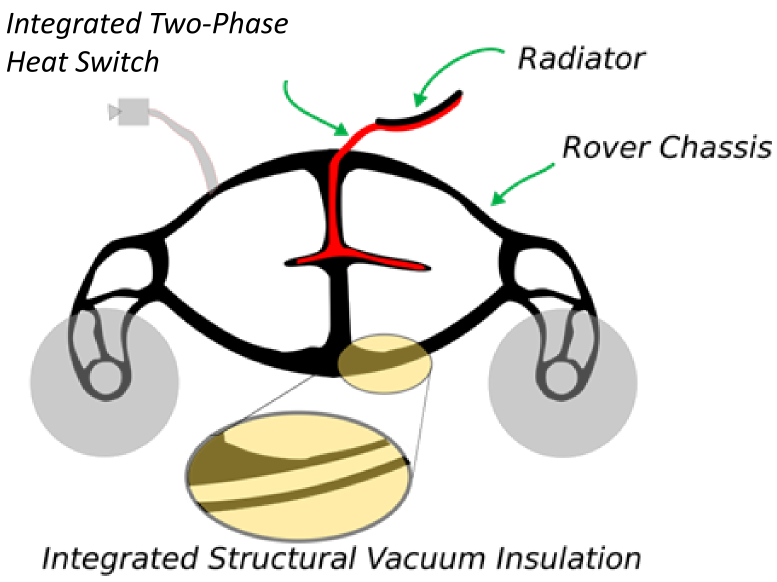






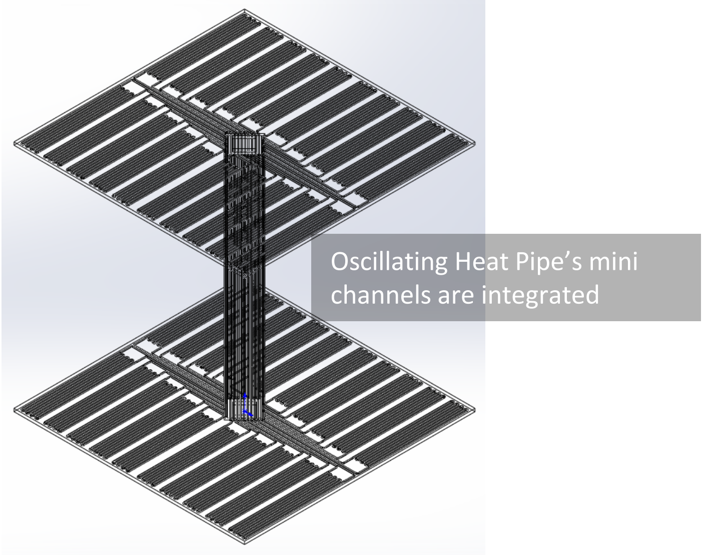
Additive Manufacturing Rover Chassis

with Topology Optimization and Integrated Two-Phase Thermal Control



Concept of AM Rover Chassis

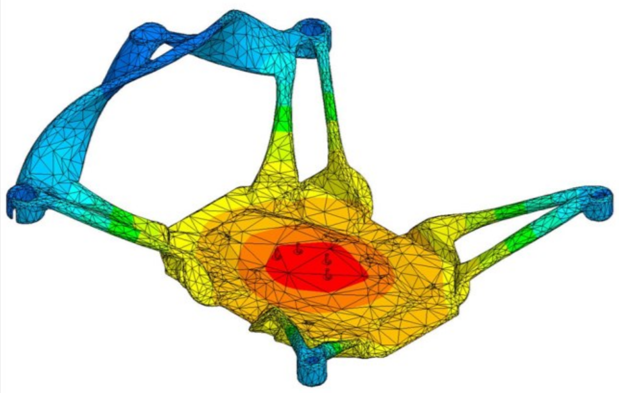
Mechanical and Thermal Topology Optimization



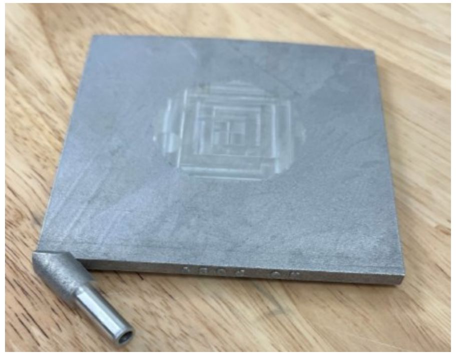
OHP Heat Switch Design

Benefits compared to SOP/SOA:

- For extremely cold environment missions
  - ✓ Lunar Surface
  - ✓ Mars Polar Region
  - ✓ Ocean-Worlds
- AM two-phase heat switch (THS) enables high heat rejection
- AM structural vacuum insulation (SVI) reduces heat loss
- Integrated AM thermal/structural design reduces mass and heat loss

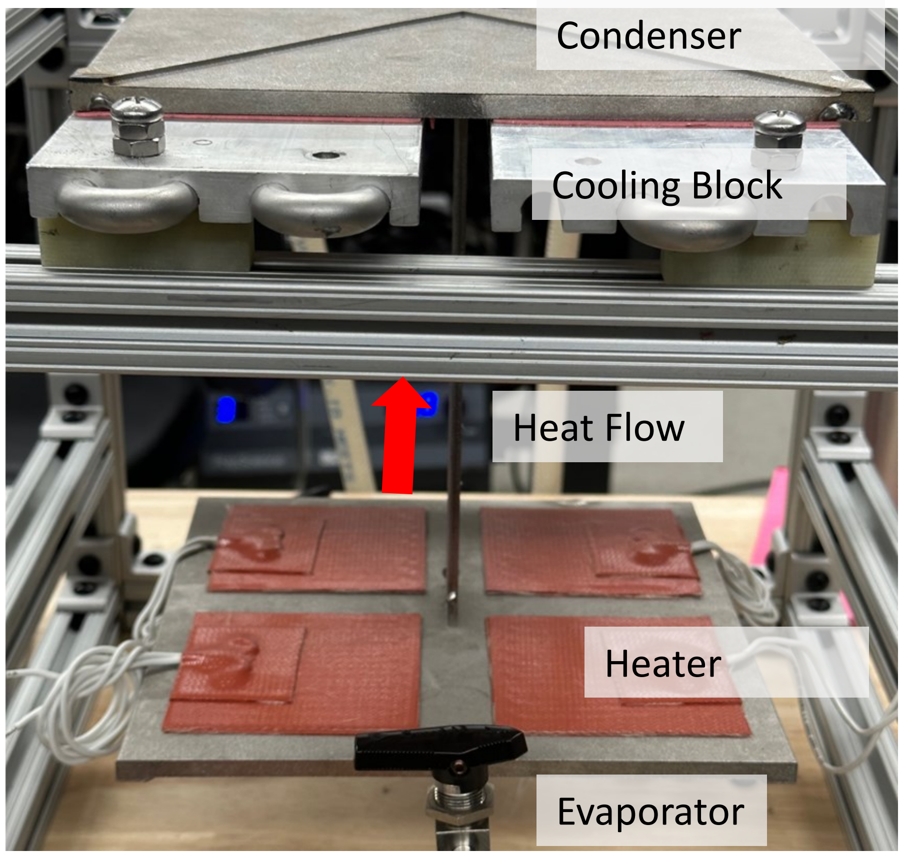


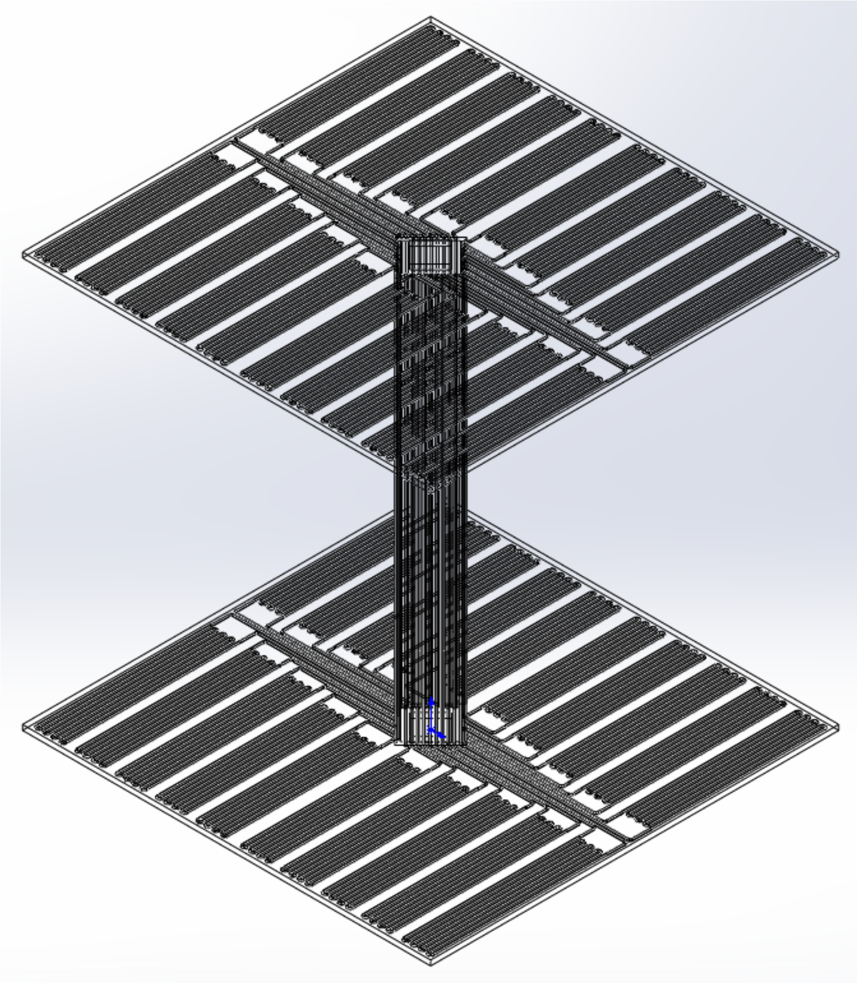
Thermal Simulation



Vacuum Insulation Coupon

OHP Heat Switch

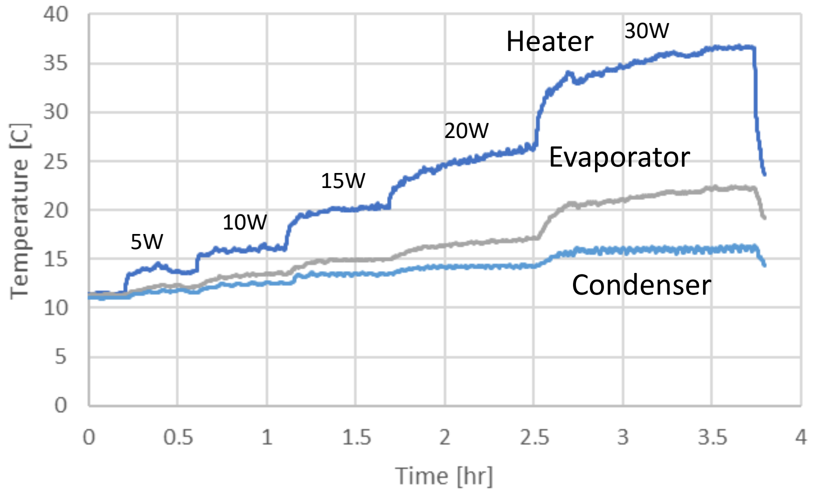


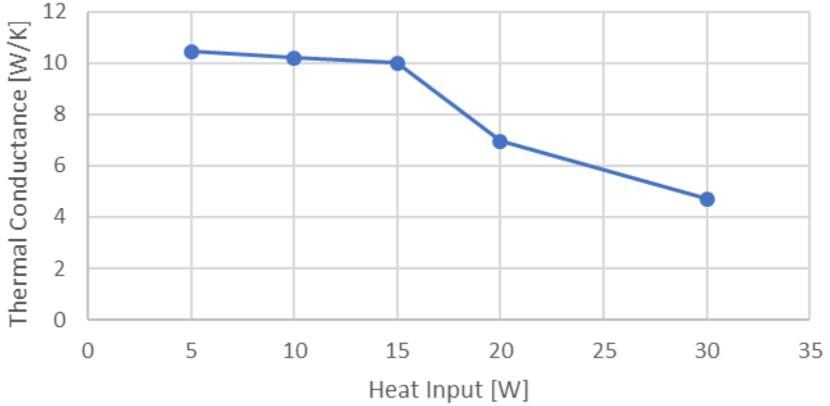


Internal Channel Design

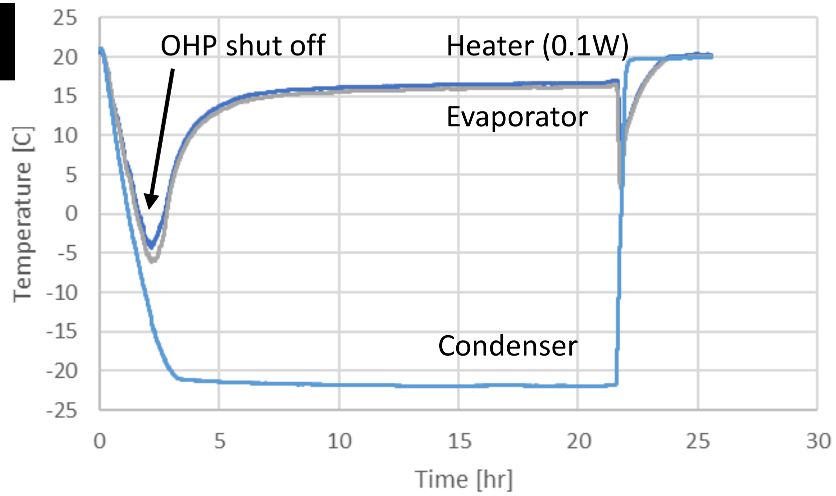
OHP Heat Switch

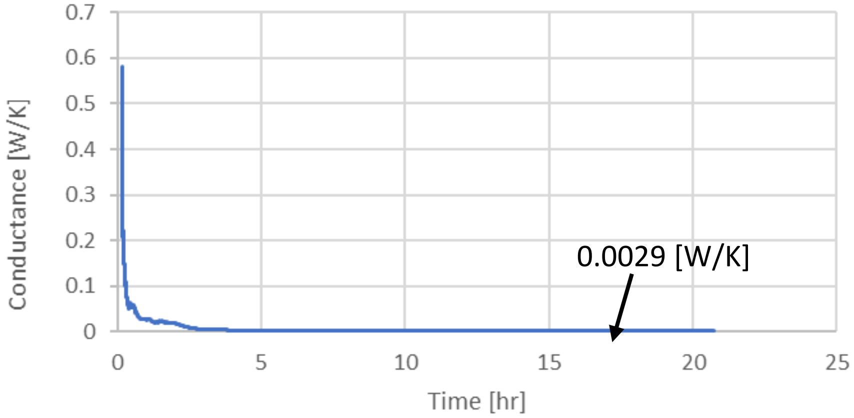
ON





OFF





Successful Demonstration

- Stable operation over 3.5 hrs and 20hrs
- **ON Conductance: 10.4 W/K** (Goal 10W/K), Ti-OHP Thermal Conductivity is ~30472 W/m/K (vs 16 W/m/K, Titanium)
- **OFF Conductance: 0.0029 W/K** (Goal 0.001 W/K)

Jet Propulsion Laboratory
California Institute of Technology

Two-Phase Thermal Technology Laboratory

Thank you!