THERMAL & FLUIDS ANALYSIS WORKSHOP

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Hybrid Wick Heat Pipes for Planetary Surface and High Heat Flux Applications

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Presentation Outline

- Motivation
- Background
- Hybrid Wick Development
- Hybrid Heat Pipes Fabrication
- Performance Testing
- Conclusions
- Acknowledgments

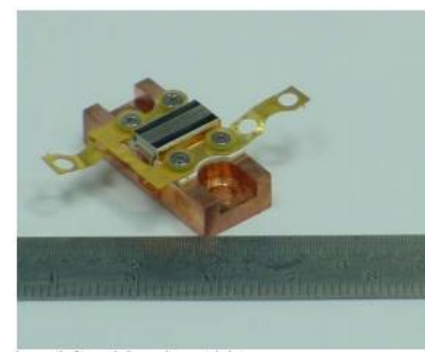
Motivation

- Examples of applications demanding high-heat-flux cooling schemes*:
  - Computer,
  - Medical,
  - Transportation,
  - Energy,
  - Aerospace,
  - Defense.

Mudawar, Issam. "Recent advances in high-flux, two-phase thermal management."** ***Journal of Thermal Science and Engineering Applications **5.2 (2013): 021012.**

Motivation

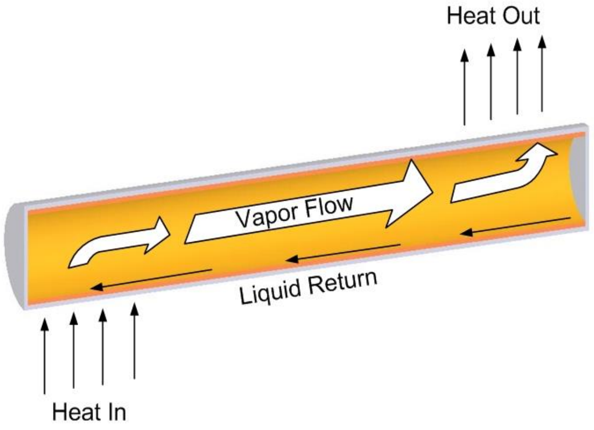
- Future spacecraft and instruments for NASA's Science Mission Directorate:
  - Can involve high power electronics with heat fluxes approach ~ 50 W/cm^2.
  - High heat flux limitation for future high power electronics such as laser diodes.
- High heat flux (~ 50 W/cm^2) is a severe limitation for:
  - Standard grooved CCHPs.
  - Loop heat pipes (LHPs).
- ACT is proposing a novel hybrid wick CCHP for:
  - **Lunar and Martian landers and rovers.**
  - **Solving the high heat flux limitation for future highly integrated electronics.**



High power laser diode arrays (LDAs)

Background Information – Heat Pipes

- Constant Conductance Heat Pipes (CCHPs)
  - Vacuum tight device
    - Working fluid
    - Wicking structure
  - Transports heat by two-phase circulation of working fluid
    - Enthalpy of vaporization
  - Working fluid
    - Vaporizes at evaporator
    - Condenses at condenser
    - Liquid returned to evaporator by capillary action
  - Thermal superconductor
    - Small ΔT required to drive cycle
    - Effective thermal conductivity ≈ 30000 W/m-K (copper ≈ 400 W/m-K)



Background Information – Axial Grooved CCHPs

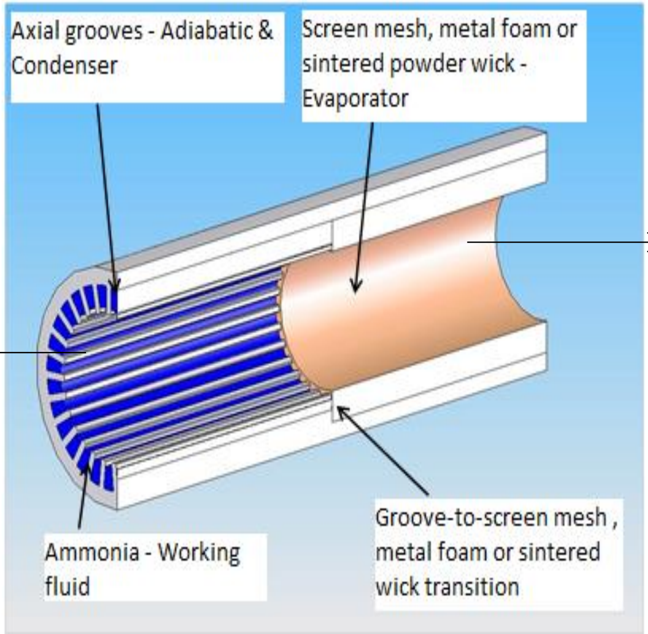
- Axial Grooved CCHPs
  - Standard for spacecraft HPs
    - Very high permeability.
    - Allows for very long heat pipes (up to ≈3.5 m).
  - Only suitable for zero-g / gravity-aided operation
    - Low capillary pumping capability.
    - 0.1” against earth gravity.
  - *Drawbacks:*
    - *Low heat flux limitation in the evaporator*
    - *No pumping capability against gravity on planetary surfaces*

ACT’s solution – Hybrid wick CCHP

Hybrid Heat Pipes - Concept

- Heat pipe with a hybrid wick that contains screen mesh, metal foam or sintered evaporator wicks for the evaporator region.
  - Can sustain high heat fluxes.
- The axial grooves in the adiabatic and condenser sections
  - Can transfer large amounts of power over long distances due to their high wick permeability and associated low liquid pressure drop.

Adiabatic and Condenser sections:
Large pore size responsible for the:
- **high permeability.**
- **low pumping capability.**
- **Relatively low heat flux limitation.**



Evaporator section:
Small pore size responsible for the:
- **Low permeability.**
- **High pumping capability.**
- **Relatively high heat flux limitation.**
- **eliminate start-up problems.**

Hybrid Heat Pipes

- Advantages of hybrid/grooved wicks:
  - Operate against gravity
    - Adverse inclination acceptable in evaporator on planetary surface
    - Grooved condenser permits reflux mode (thermosyphon) operation on planetary surface for landers and rovers.
  - Allows higher heat fluxes in the evaporator than axial grooves
    - Potential wicks in the evaporator are:
      - Sintered powder
      - Metal foam
      - Screen mesh
  - Operate in space
    - Grooved condenser has greater permeability than sintered powder, metal foam, or screen mesh
    - Transports heat over longer distances
  - Greater heat transport capability than all-sintered wick.
  - Because of the large number of nucleation sites in the metal foam or sintered wick, startup problem in vertical heat pipes will be eliminated.

Hybrid Heat Pipes

- Heat Flux (Boiling) Limitation
  - Working fluid within evaporator wick starts to boil
  - Vapor bubbles form, blocking liquid return and causing dryout

- Heat Flux Limits
  - Up to 15 W/cm^2 for axial groove wicks (space CCHPs)
  - Up to 75 W/cm^2 for screen mesh wicks (ILN VCHP)
  - Up to 75 W/cm^2 for sintered powder wicks (terrestrial CCHPs)
  - Up to 500 W/cm^2 for sintered wicks (specialized wick for vapor chambers)

- Many applications currently exceed heat flux limit for axial grooves
  - Laser diode: 5 to 10 W/cm^2 (expected to increase to 50 W/cm^2)

Design Parameters for Lunar Rover Application

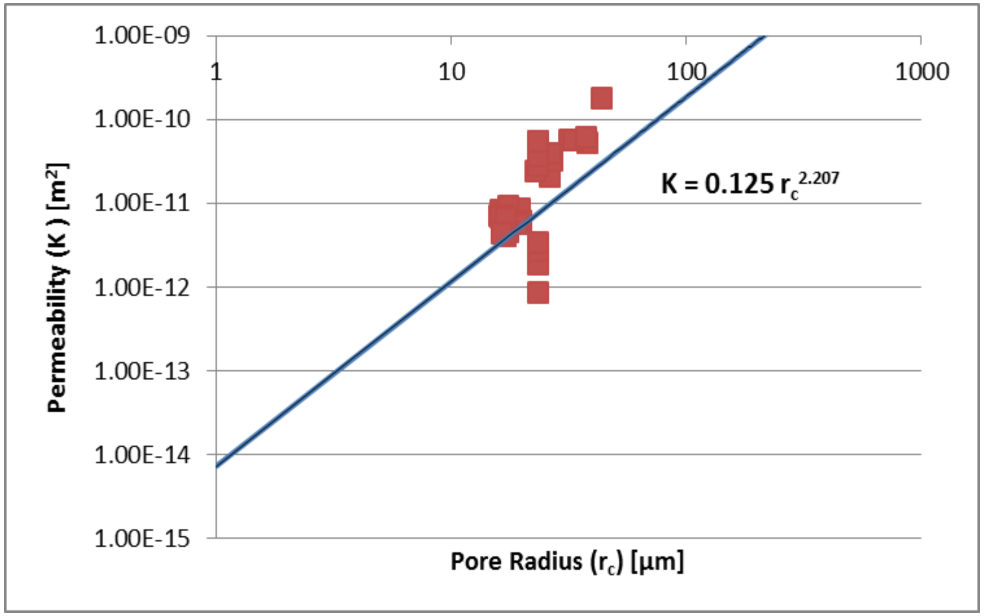
Attribute	NASA Requirements
Min. Electronics Temp.	-10 °C
Max. Electronics Temp.	50 °C
Max. Radiator Load (Moon)	100 W to 150 W, 150 W preferred
Power During Transit (Space)	100 W to 150 W, 150 W preferred
Mission Duration	~ 6 years
WEB/Bus Geometry	24” x 41” x 14” (height)
Max. Tilt	14° (lander), 25° (rover), 25 ° preferred
Radiator Emissivity	0.8
Min. Radiator Sink Temp. (Moon)	96 K (parasitic heating from lander)
Max. Radiator Sink Temp. (Moon)	269 K
Cruise Sink Temp. (Space)	168 K
Min. Soil Temp.	100 K
Max. Soil Temp.	390 K
Condenser Length	12”
Adiabatic Section Length	18.6”
Evaporator Length	9”

Hybrid Wick Development

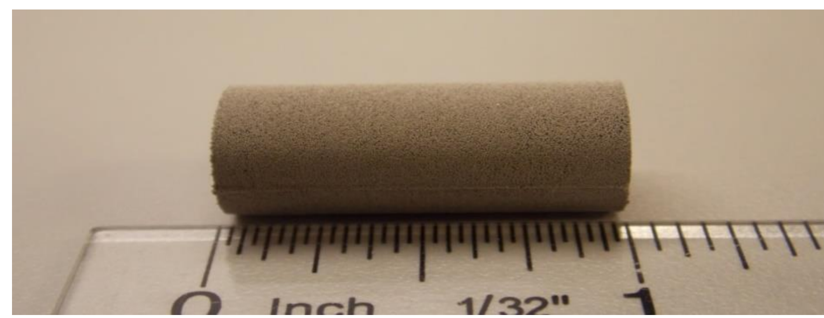
- Develop and enhance techniques for:
  - Sintering powder metal (e.g. nickel)
    - Insertion into the aluminum envelope based on insertion technique used for the previous project
    - ***<u>Sintering within the stainless steel envelope</u>***
  - Stainless steel grooved heat pipe development.
- Design and evaluate wick characteristics and materials
  - Sinter small test slugs from different powders and sintering schedules
  - Experimentally measure wick parameters: pore size and permeability
  - Modeling effort shows that the current screen mesh and metal foam **Not** doing the job!
- Select the best wick characteristics based on heat pipe models :
  - **Pore size/permeability combination**
  - ~~Metal foam porosity/pore density combination~~
  - ~~Screen mesh number~~

Sintered Wick Development

- Spherical nickel metal powder after sintering.

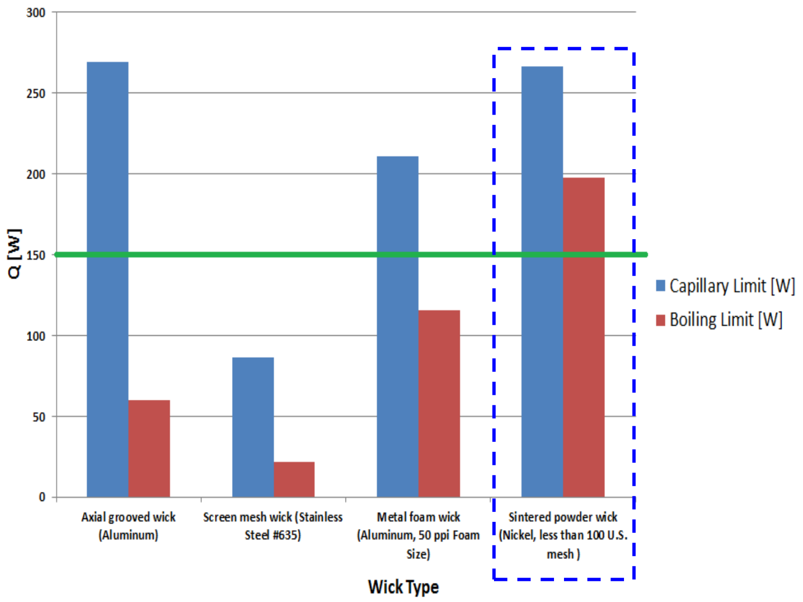


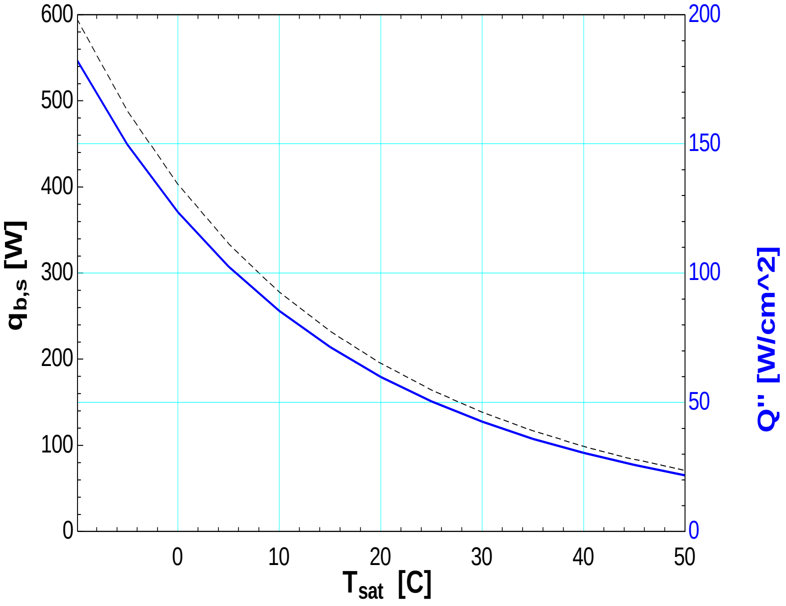
Anderson Pore Size/Permeability Curve



Sintered nickel powder (-100 US sieve size, OD = 0.5", length = 1")

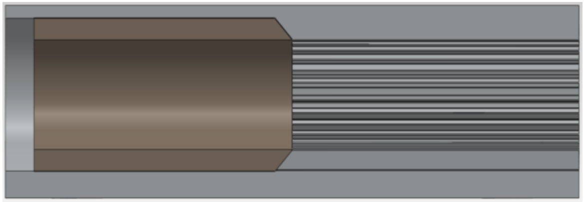
Sintered Wick Development



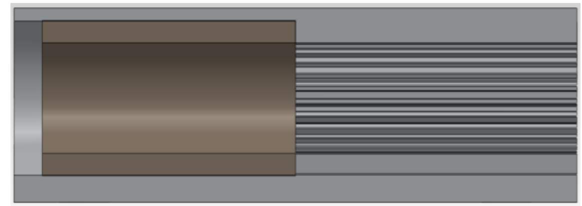


Sintered Wick Development

- Wick Interface design for high heat flux hybrid CCHPs



Aluminum CCHP 45° (Angled)



SS CCHP 90° (Angled)

- Wick Interface design for Planetary hybrid CCHPs

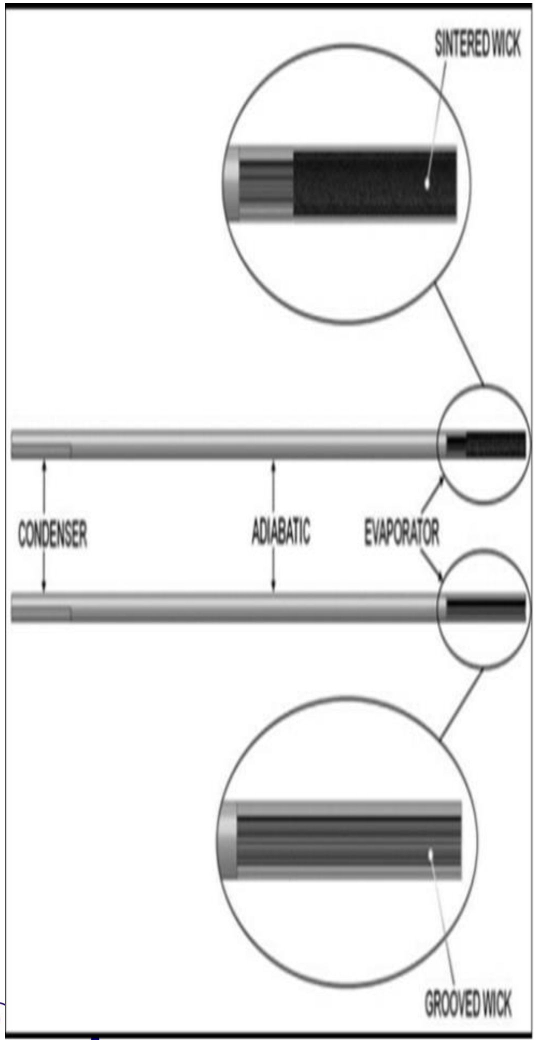
- Nickel powders have very low permeability, too low for 0.43" ID pipes.
- This 1" ID evaporator increases cross-sectional area, reducing liquid flow resistance and thereby allows for a longer evaporator with a low permeability wick.

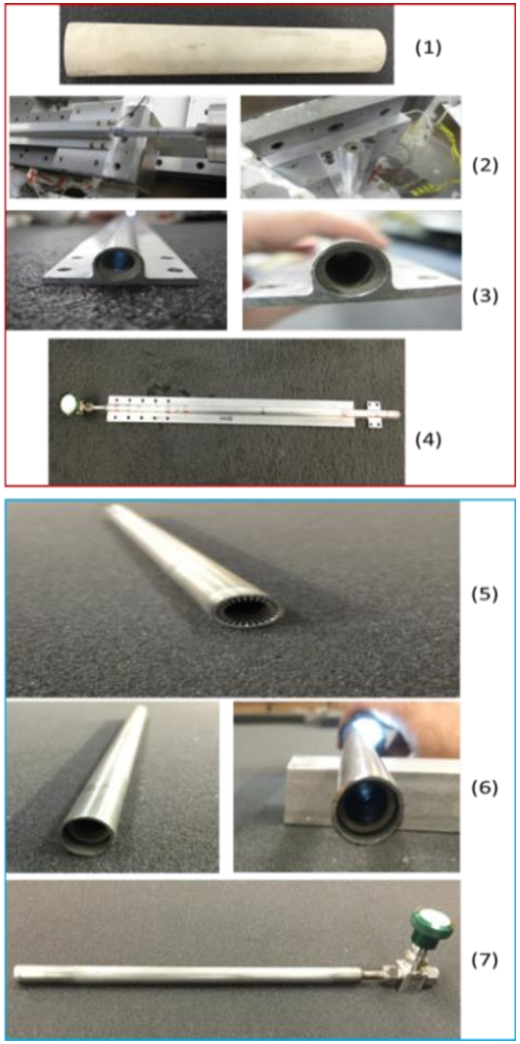
Hybrid Heat Pipe Fabrication

- Five constant conductance heat pipes were fabricated:
  - Two CCHPs to demonstrate high heat flux operation
  - Two CCHPs to demonstrate operation against gravity
  - The benchmark conventional Aluminum/Ammonia CCHP with all-grooved wicks

Design Parameter	Hybrid Wick Aluminum/Ammonia CCHP Design	Hybrid Wick Stainless Steel/Ammonia CCHP Design	Standard CCHP Design
Overall Length	22 inches (55.9 cm)	11.25 inches (28.6 cm)	22 inches (55.9 cm)
Evaporator Length	1 inch (2.54 cm)	1 inch (2.54 cm)	1 inch (2.54 cm)
Condenser Length	5 inches (12.7cm)	5 inches (12.7cm)	5 inches (12.7cm)
Heat Input Area	3.26cm^2	3.26cm^2	3.26cm^2
Wick Structure – Condenser and Adiabatic	Axial Grooves	Axial Grooves	Axial Grooves
Wick Structure – Evaporator	Sintered Nickel Powder	Sintered Nickel Powder	Axial Grooves
End Detail in Evaporator	45° Angled	90° Angled	NA
Envelope Material	6063 Aluminum	304 Stainless Steel	6063 Aluminum
Ammonia Fluid Charge	9.1 grams	4.8 grams	8.5 grams

High Heat Flux Hybrid Heat Pipe Fabrication





High Heat Flux Hybrid Wick Aluminum/Ammonia Heat Pipe Fabrication

High Heat Flux Hybrid Wick Stainless Steel/Ammonia Heat Pipe Fabrication

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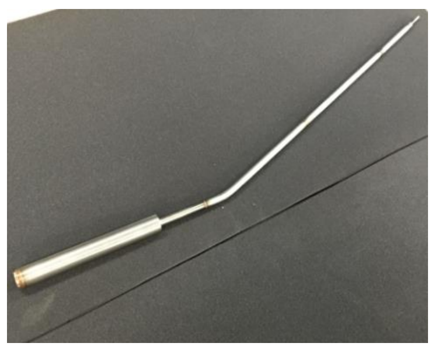
Planetary Hybrid Sintered/Grooved Wick Fabrication

Aluminum Planetary CCHP



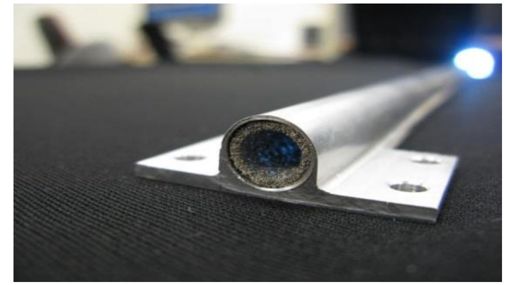
Stainless Steel Planetary CCHP

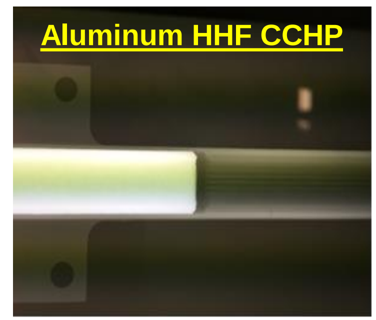
Design Parameter	Planetary CCHPs
Overall Length	40 inches (101.6 cm)
Evaporator Length	9 inches (22.9 cm)
Condenser Length	12 inches (30.5cm)
Wick Structure – Condenser and Adiabatic	Axial Grooves
Outside Diameter – Condenser and Adiabatic	0.5 inch (1.27 cm)
Wick Structure - Evaporator	Sintered Nickel Powder
Outside Diameter - Evaporator	1.18 inch (3.0 cm)
End Detail in Evaporator	45° Angled
Envelope Material	6063 Aluminum and 304 Stainless Steel
Ammonia Fluid Charge	27.7grams

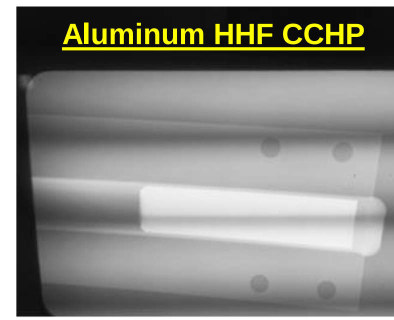
ISO9001:2008 & AS9100C Certified

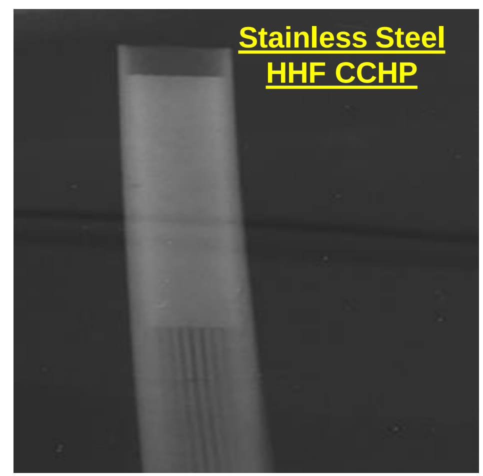
Hybrid Heat Pipes Challenges

- The interface between the CCHP wall and wick.
- Interface between the axial groove and the sintered wicks.
- Interface between evaporator grooves to adiabatic grooves in planetary CCHPs .
- Gaps or voids will form areas where liquid return is limited resulting in “hot spots”
  - Define wall and wick machine tolerances to avoid gaps or voids
  - Evaluate methods to align and connect the wicks to assure the proper interface









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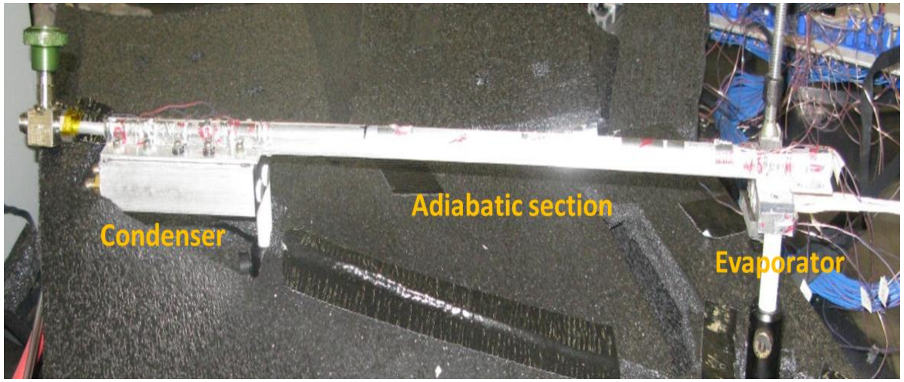
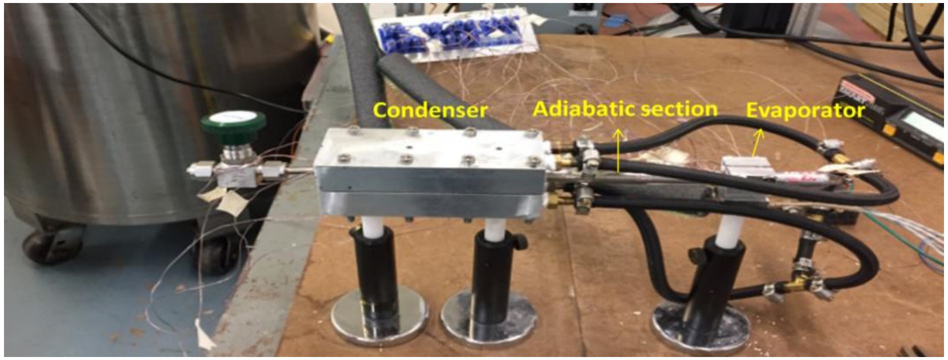
Performance Testing

Hybrid Heat Pipes Description	Lunar Application		Space Application	
	Operating Temperature	Adverse Orientation	Operating Temperature	Adverse Orientation
Hybrid Wick CCHPs for HHF Applications	–	–	25°C	0.1 inch
Hybrid Planetary CCHPs	25°C	4.2°	25°C	0.1, 0.2, 0.3 inch

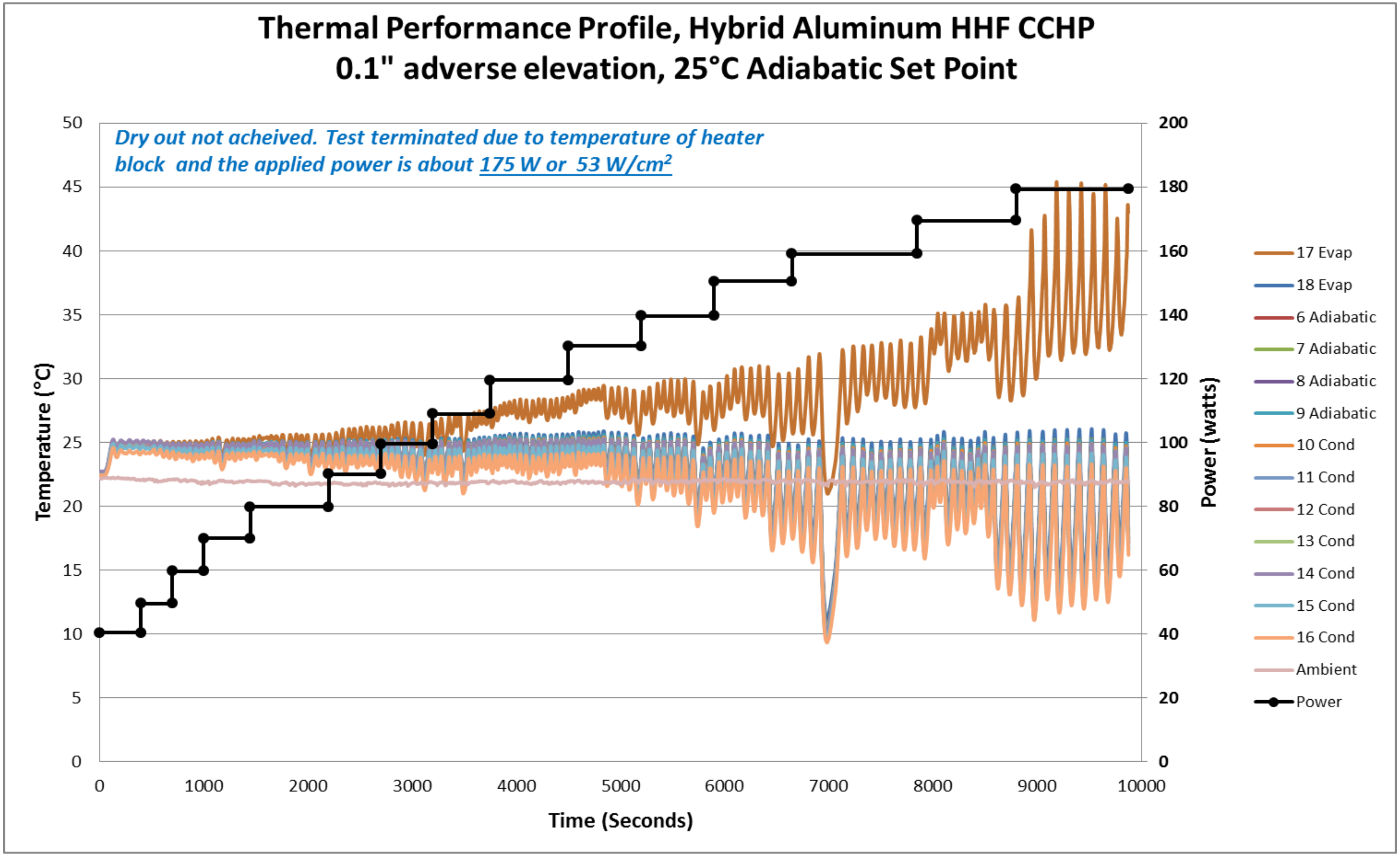


The overall test assembly for the aluminum/ammonia high heat flux CCHP testing set up.



The overall test assembly for the stainless steel/ammonia high heat flux CCHP testing set up.

Thermal Performance Profile for the Aluminum/Ammonia Hybrid Wick High Heat Flux CCHP



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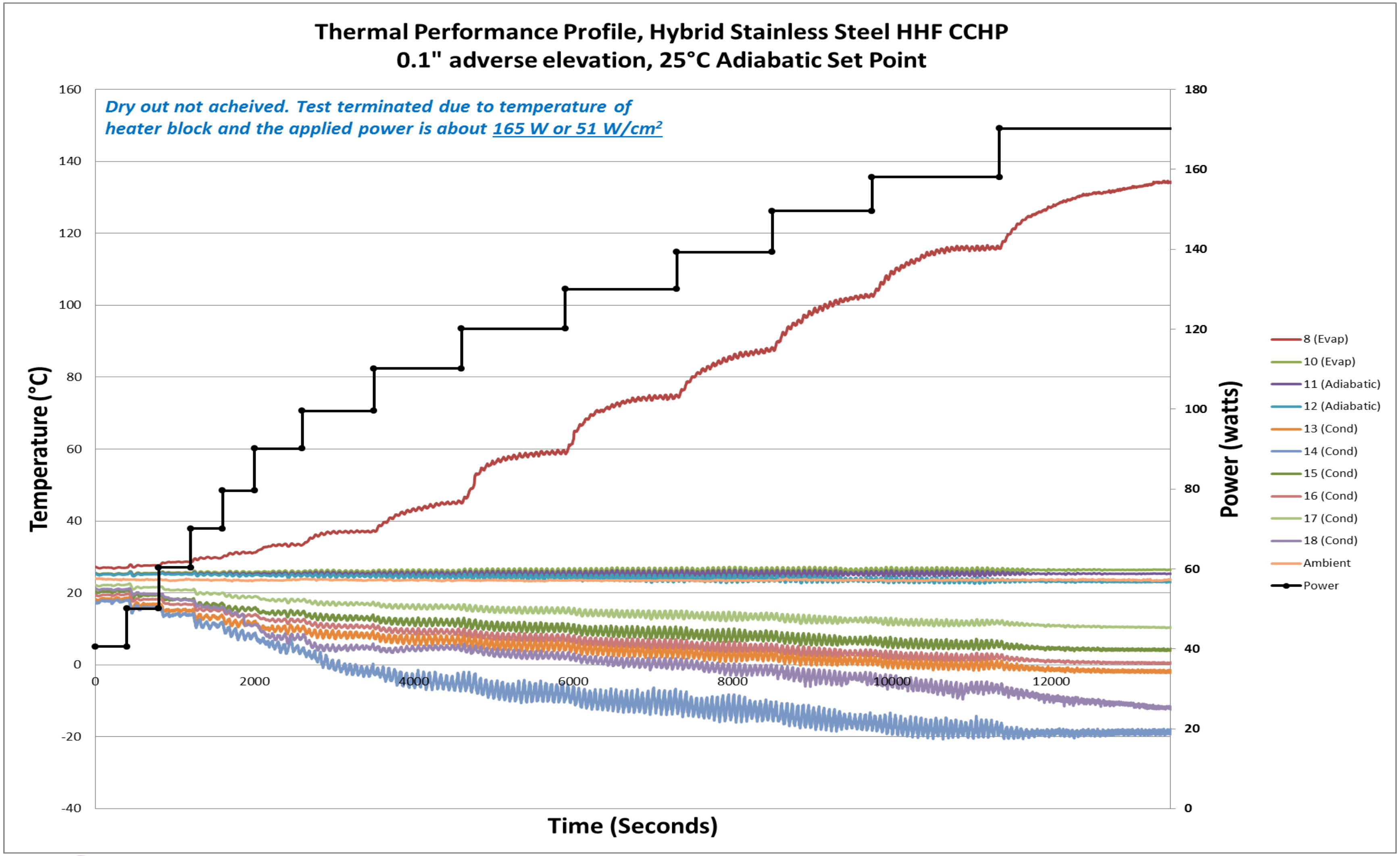
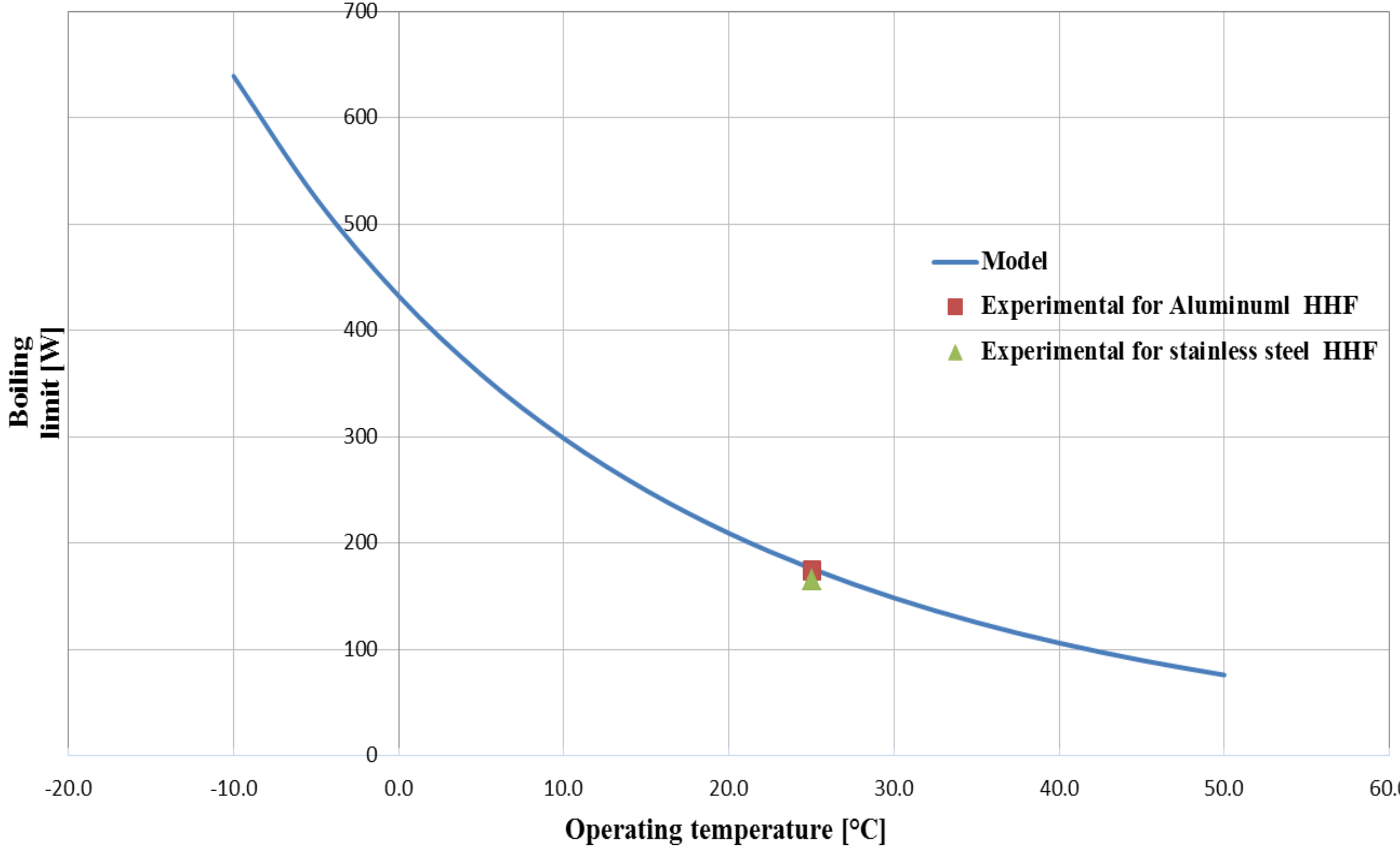
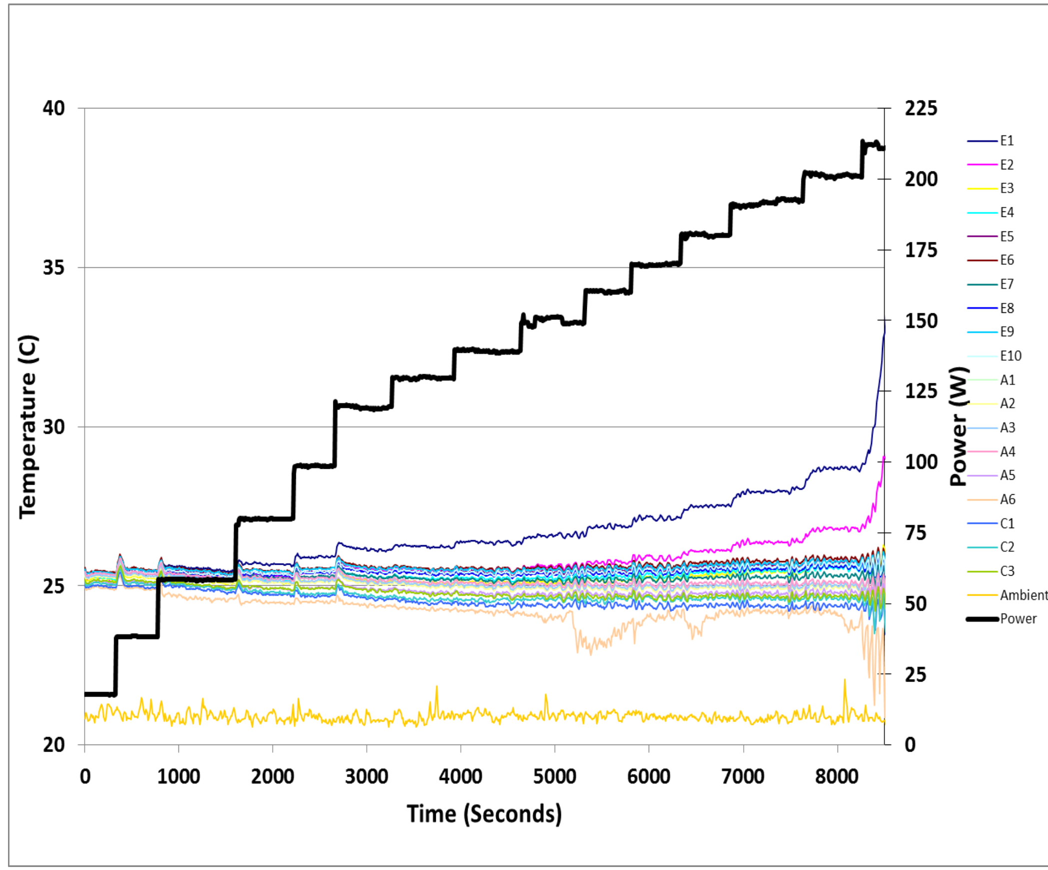
Thermal Performance Profile for the Stainless Steel/Ammonia Hybrid Wick High Heat Flux CCHP



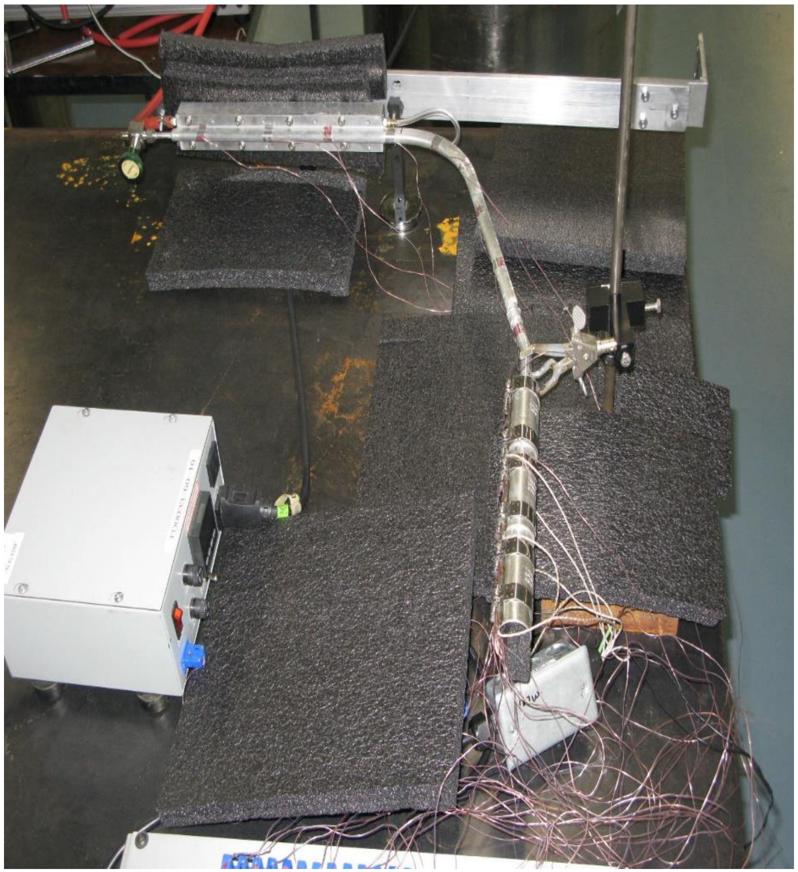
Experimental and Theoretical Thermal Performance for the Hybrid Wick High Heat Flux (HHF) CCHPs Comparison

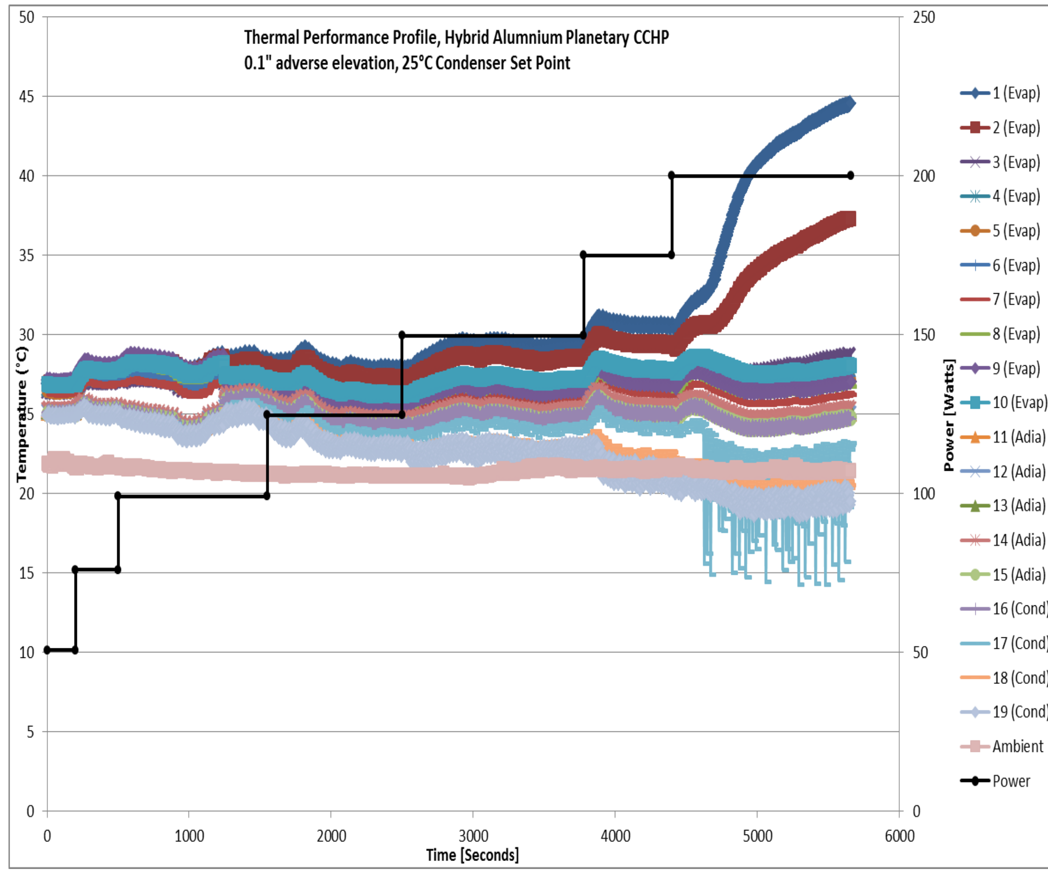


Thermal Performance Profile for the Aluminum Planetary Hybrid CCHP, Lunar Surface at 4.2° Adverse Elevation



Thermal Performance Profile for the Aluminum Planetary Hybrid CCHP, 0.1" Adverse Elevation





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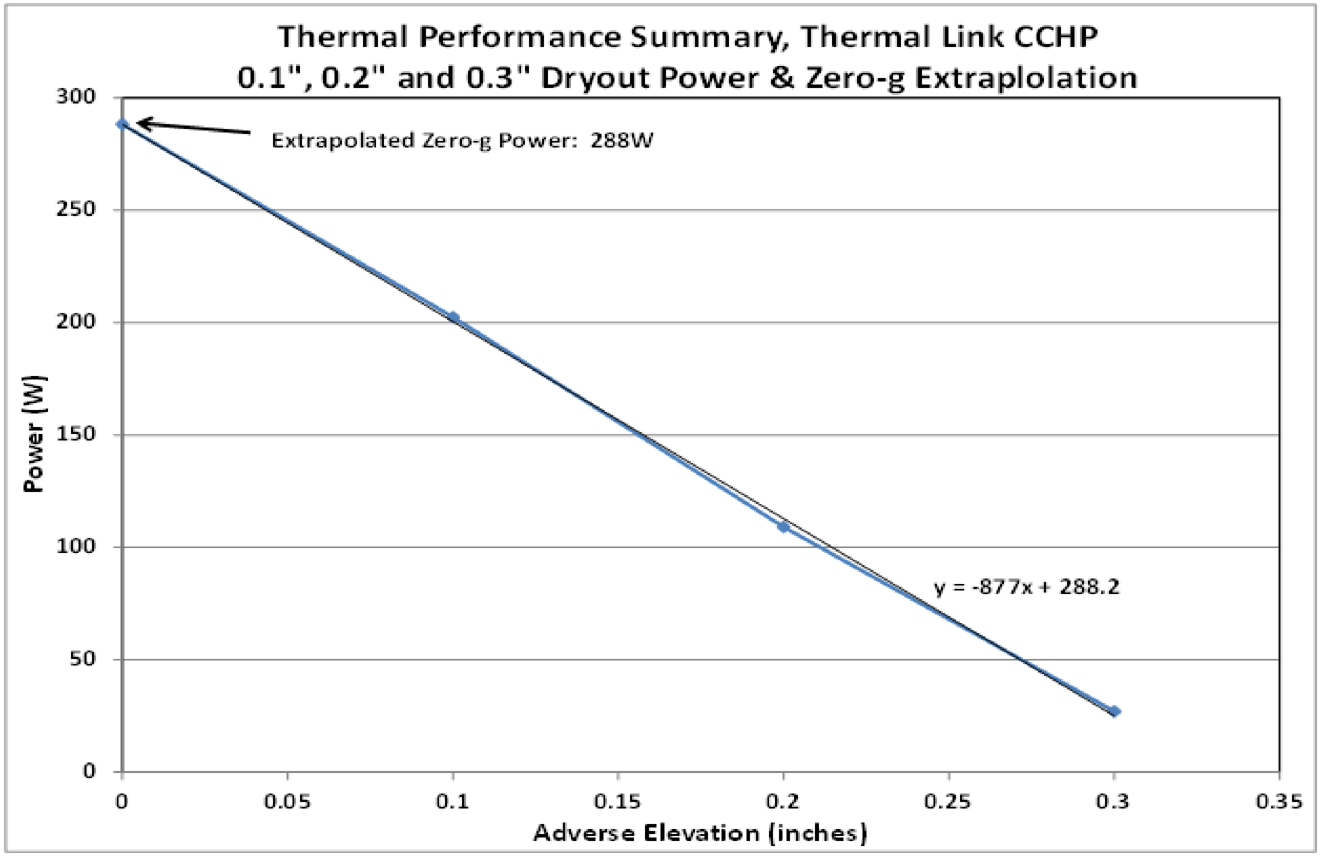
Thermal performance summary for the Thermal Link CCHP

- The maximum powers measured at 0.1”, 0.2” and 0.3” are used to extrapolate the zero-g performance for space based operation.



Conclusions

- The innovation is to develop CCHPs with a hybrid sintered, metal foam, or screen mesh in the evaporator section and grooved wick in the adiabatic and condenser sections for: 1)Planetary surface, 2) High heat flux applications.

- A hybrid wick CCHP design allows operating at:
  - higher heat fluxes as compared to axial groove design
  - operate in space and against gravity on the planetary surface,
  - Carrying power over long distances,
  - Act as a thermosyphon on the planetary surface for Lunar and Martian landers and rovers.
  - Demonstrate a higher transport capability than an all-sintered wick.

- The standard axial groove CCHP transported approximately 58 watts, or 17.8 W/cm^2 at 0.1 inch adverse elevation before dryout.

Conclusions

- The hybrid wick high heat flux aluminum/ammonia CCHP transported a heat load of 175 watts with heat flux input of 53W/cm^2 at 0.1 inch adverse elevation.
  - The test was terminated not because it reached the heat pipe limit but rather because it reached a safety limit on the heater block.
  - This demonstrates an improvement in heat flux capability of **3 times** over the standard axial groove CCHP design.

- The hybrid wick high heat flux stainless steel/ammonia CCHP transported a heat load of 165 watts with heat flux input of 51 W/cm^2 at 0.1 inch adverse elevation.
  - The test was terminated because it reached a safety limit on the heater block.

- The theoretical model showed agreement with the experimental results in estimating the boiling limit for the hybrid CCHPs.

Conclusions

- The Thermal Link planetary aluminum/ammonia CCHP transported approximately 202 watts at a 4.2° adverse inclination before dryout, exceeding the 150W target.

- The planetary aluminum/ammonia CCHP was tested for maximum transport power at three different adverse elevations to extrapolate zero-g power. The maximum power at zero-g is 288 watts, exceeding the 150 watt target.

- The X-ray micrographs for the interface between the sintered powder metal wick and the axial grooves in the stainless steel hybrid CCHPs shows much better contact in comparison to the aluminum CCHPs because of the successful internal sintering technique developed during this project.

Acknowledgments

- This research was sponsored by NASA Marshall Space Flight Center under Contract No. NNX14CM13P.
- Sincere appreciation is expressed to Jeffery Farmer (the contract technical monitor) for his valuable comments and help.
- Corey Wagner was the laboratory technician.

Questions ?

INNOVATIONS IN ACTION

The Thermal Management Experts

Marshall Space
Flight Center

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