ADVANCED COOLING TECHNOLOGIES

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Qualifying Hybrid Variable Conductance Heat Pipes (VCHPs) and Copper-Water Heat Pipes in Microgravity

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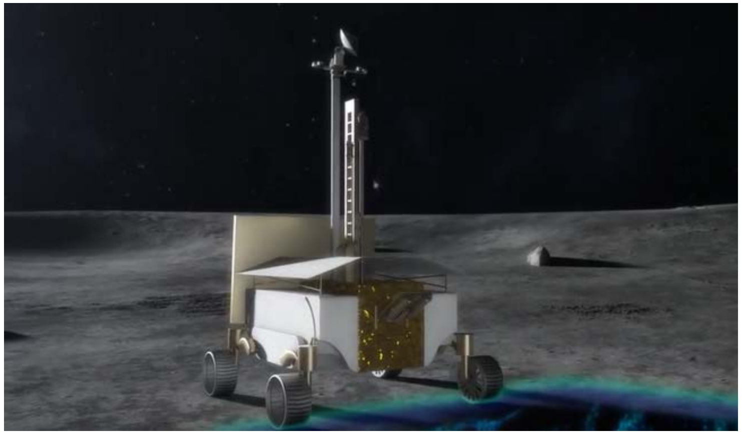
Presentation Outline

- Motivation
- Background
- Hybrid Wick Heat Pipes
- ISS Flight APTx Experiment
- Conclusion

Motivation

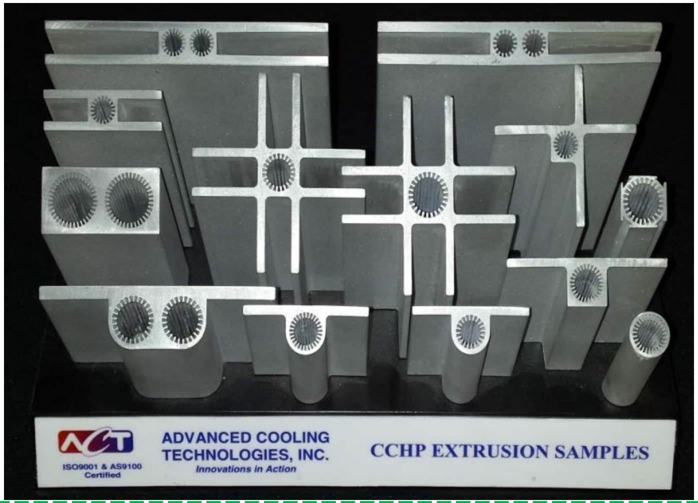
- Next generation of polar rovers and equatorial landers is the immediate NASA application.
- Planetary surface applications require against gravity operation in the evaporator:
  - The traditional grooves do not have the pumping capability.
  - Dissipate the heat flux generated by these electronics.
- 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.**
  - **Vertical startup**



NASA's RP polar rover design toward 2020 Launch

Background – 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***



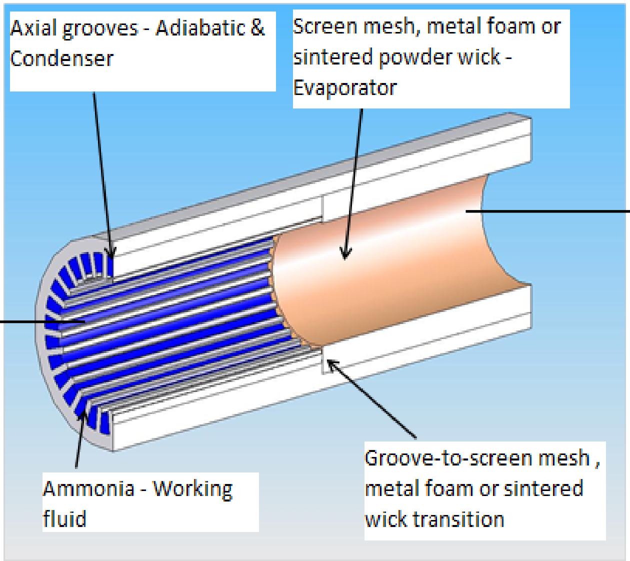
ACT'S CCHP SPACE FLIGHT HOURS: 23,268,268.6

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.

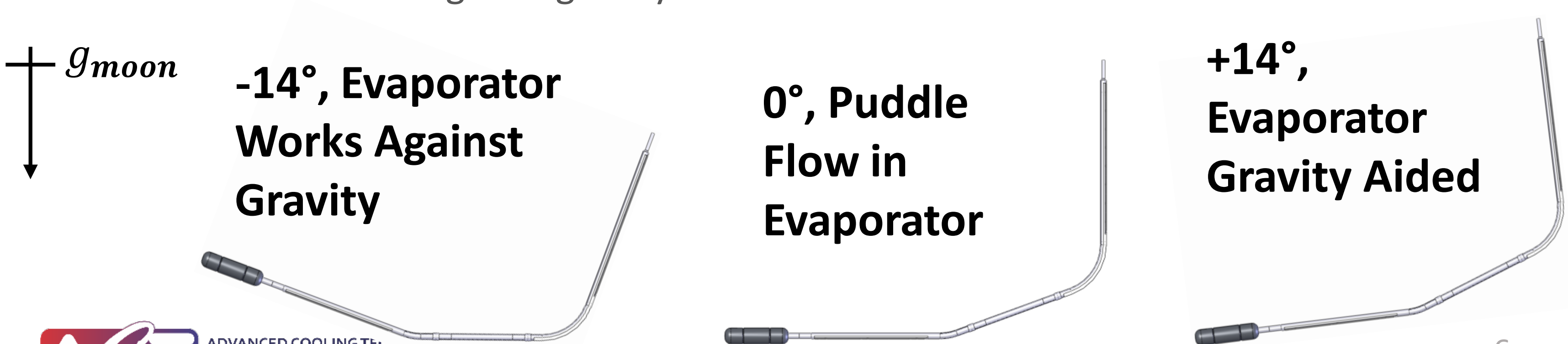
Adiabatic and Condenser sections:
Large pore size responsible for the:
- **high permeability.**
- **low pumping capability.**
- **Relatively low heat flux limitation.**



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

Hybrid Wick Heat Pipes Applications

- Two related applications can benefit from using hybrid wicks:
  - For Planetary Surface:
    - Operation against gravity of VCHPs for Lunar Landers and Rovers
      - Sintered wick in evaporator to accommodate tilt and grooves in condenser and adiabatic sections.
      - Test against gravity 4.2° (only the evaporator) while the rest of the pipe is gravity aided.
      - Test 0.1” against gravity (for operation in space).
  - For Spacecraft:
    - High Heat Flux in evaporator
      - Sintered wick in evaporator and grooves in condenser and adiabatic sections.
      - Test 0.1” against gravity.

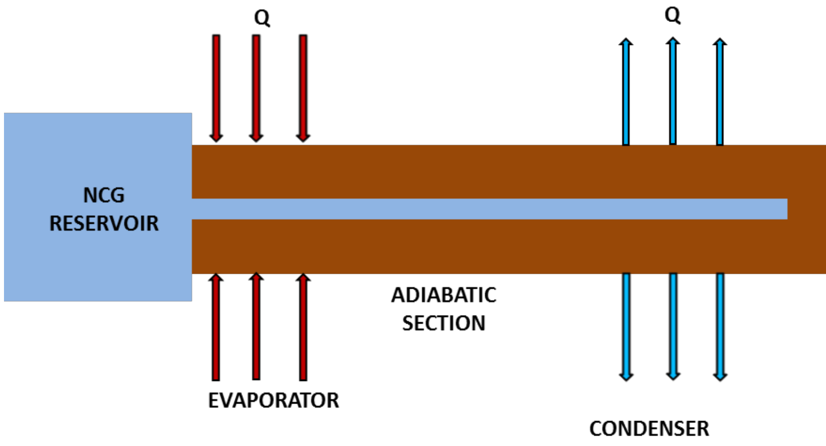


VCHPs for Variable Thermal Links

- Variable Conductance Heat Pipes (VCHPs) can be used for variable thermal links
  - Maintain evaporator temperature range in a fairly broad temperature range with large variations in sink temperature
  - Transmit heat readily during hot sink conditions
  - Minimize heat transmission during cold sink conditions
- Variable Thermal Link useful when
  - Variable system loads resulting from intermittent use
  - Large changes in environment temperature
    - Lunar surface temperature range: -140 °C to 120 °C
  - Limited electrical power
    - Lunar Application: 1 W = 5 kg of energy storage and generation
- Applications that can benefit from using VCHPs as variable thermal links include
  - **Lunar and Martian Landers and Rovers**
  - Research Balloons (fly near Poles in winter)
  - Lunar and Space Fission Reactors

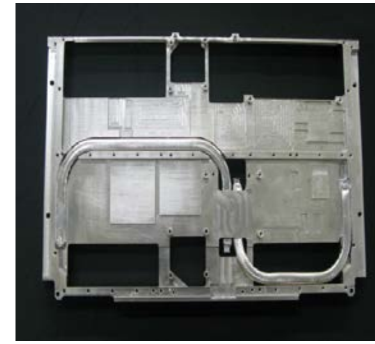
Hybrid Wick Warm Reservoir VCHP

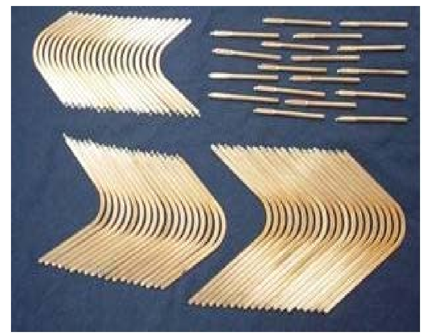
- In contrast to the standard cold VCHP, the hybrid wick VCHP has a warm reservoir located adjacent to the evaporator.
- The warm reservoir is mainly follow the payload (i.e. evaporator) temperature.
- The warm reservoir provided tighter temperature control than standard cold reservoir.
  - Although it is slightly more complicated.
- Based on this concept, the 1-2 Watts required keeping the reservoir at the correct temperature will be eliminated.
  - This is a necessity for Lunar applications, where it is estimated that supplying 1 W over the 14-day long Lunar night requires 5 kg of solar cells, batteries, etc.



Copper-Water Heat Pipes

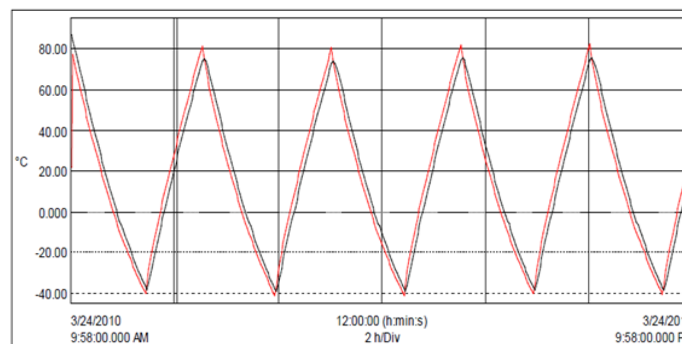
- Benefits:
  - Reliable, proven
  - High performance
  - Ground testable
  - Easy integration
  - Cost effective





- ACT Capabilities
  - Proven prototype & volume
  - Demonstrated capacity > 250,000 per year

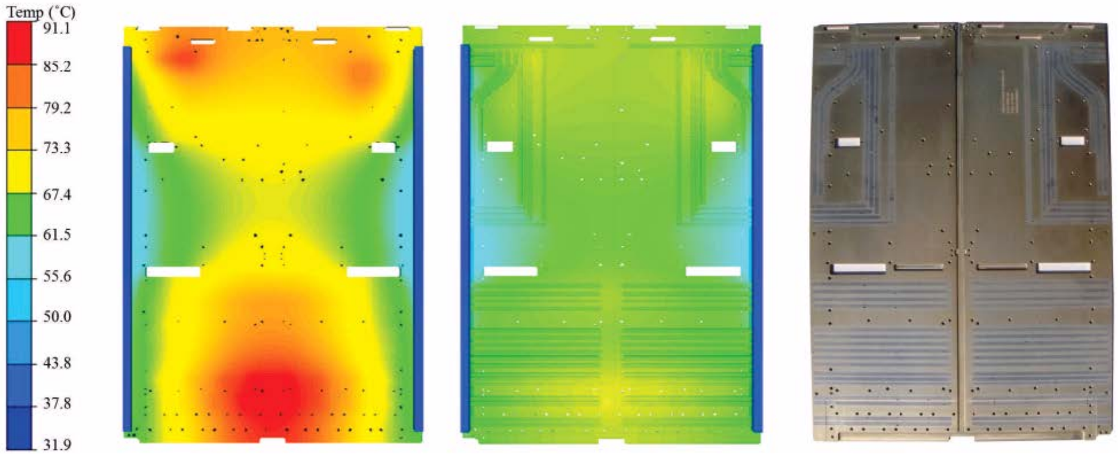
- Qualification / Space Readiness
  - Freeze/Thaw tolerant
  - Shock/Vibe tolerant
  - **Flight hardware tested on the ISS**

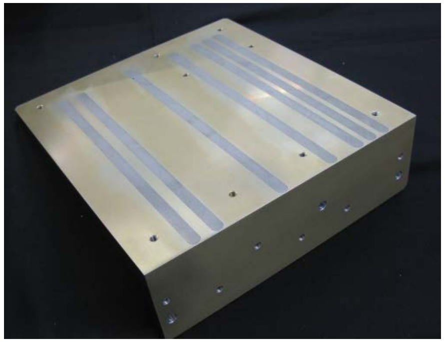


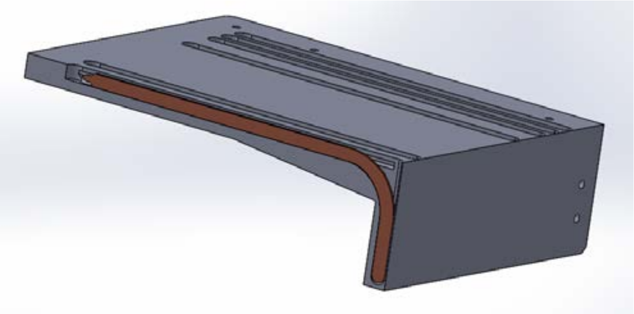
Embedded Heat Pipe Plates (HiK™)

- HiK™ plates have copper/water or copper/methanol heat pipes
  - Flatten, solder in machined slots
  - Can withstand thousands of freeze/thaw cycles
  - Operate up to 12 inches against gravity (if water is used)
  - Effective thermal conductivity of 500 – 1200 W/m K for terrestrial applications, up to 2500 W/m K for spacecraft
- Identical dimensions, 22°C reduction in peak temperature measured

Aluminum Plate HiK™ Plate







The Advanced Passive Thermal eXperiment (APTx) on board the ISS

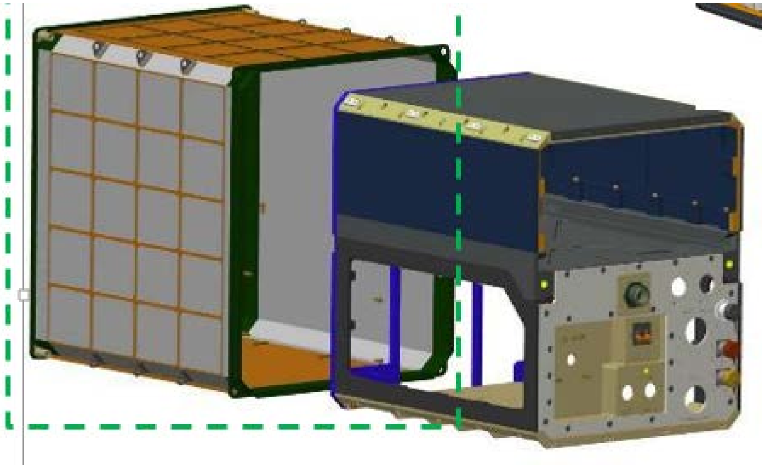
- NASA Marshall and NASA Johnson worked on an ISS flight experiment with components supplied by ACT.

- Experimental configuration – 2 experiments
  - Payload #1: VCHP with HiK^{TM} plate – designed so that heat is delivered to the VCHP, whether or not the HiK^{TM} plate works.
  - Payload #2: Separate HiK^{TM} plate

- Envelope/Working Fluid Selection
  - Monel-Copper/water for VCHP
  - HiK^{TM} plates with embedded copper/water heat pipes

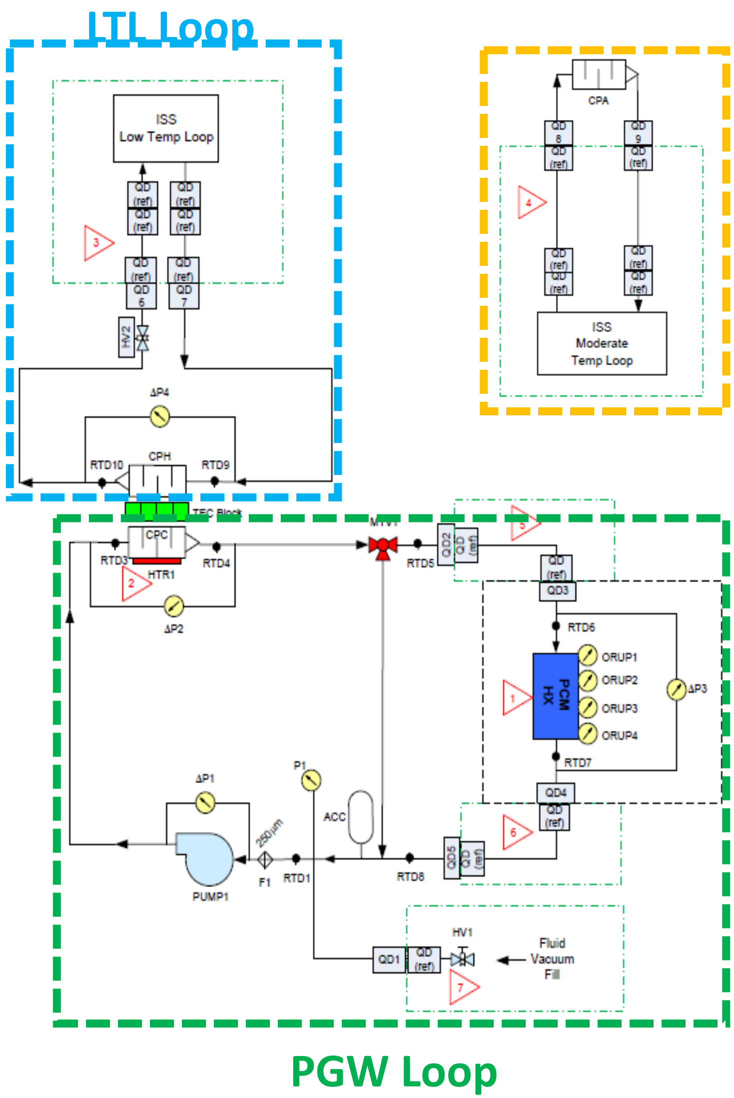
ISS Flight Hardware

- The ISS test rack has a lower and an upper section.
  - The lower section has the a PCHX fluid loop from a previous PCM module test.
  - PCHX loop currently on the ISS, with duplicate loop on ground
  - The dimensions of the upper section, where our experiment would fit is 14” x 13.5” x 7.5” high



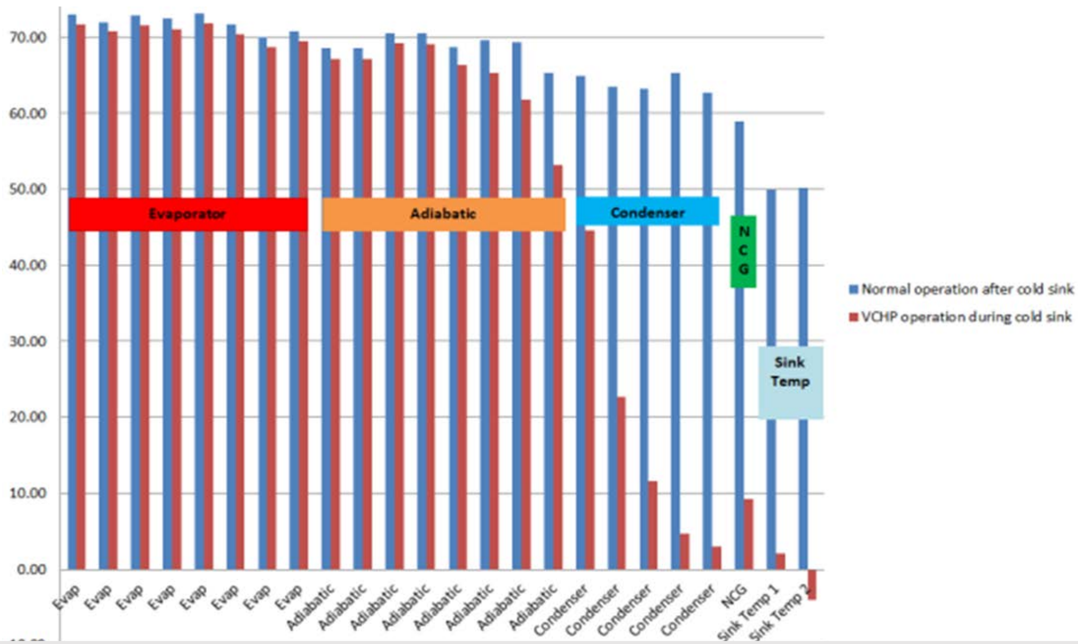
PCHX Flow Loop Schematics

- The fluid system includes a primary PGW Loop with 50/50 Propylene glycol water and an MDP 95 psia (Green Section).
- PCHX flight loop is connected to ISS Low Temp Loop via fluid jumpers
- ISS MTL loop is used to provide cooling to the avionics system (Yellow Section)
- Loop can supply fluid from -10 to 30ºC, and remove up to 150 W
- Fluid Temperature set by thermoelectrics

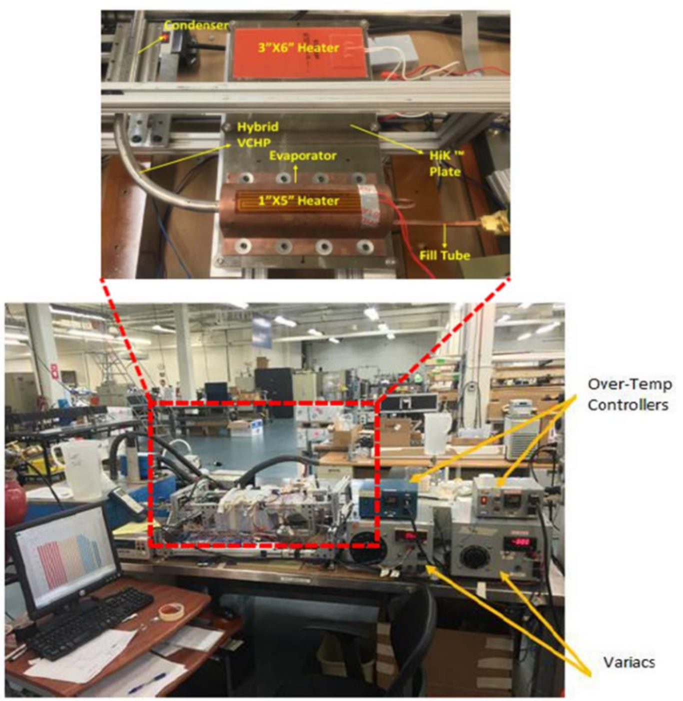


VCHP for ISS Experiment-Payload#1: Ground Testing

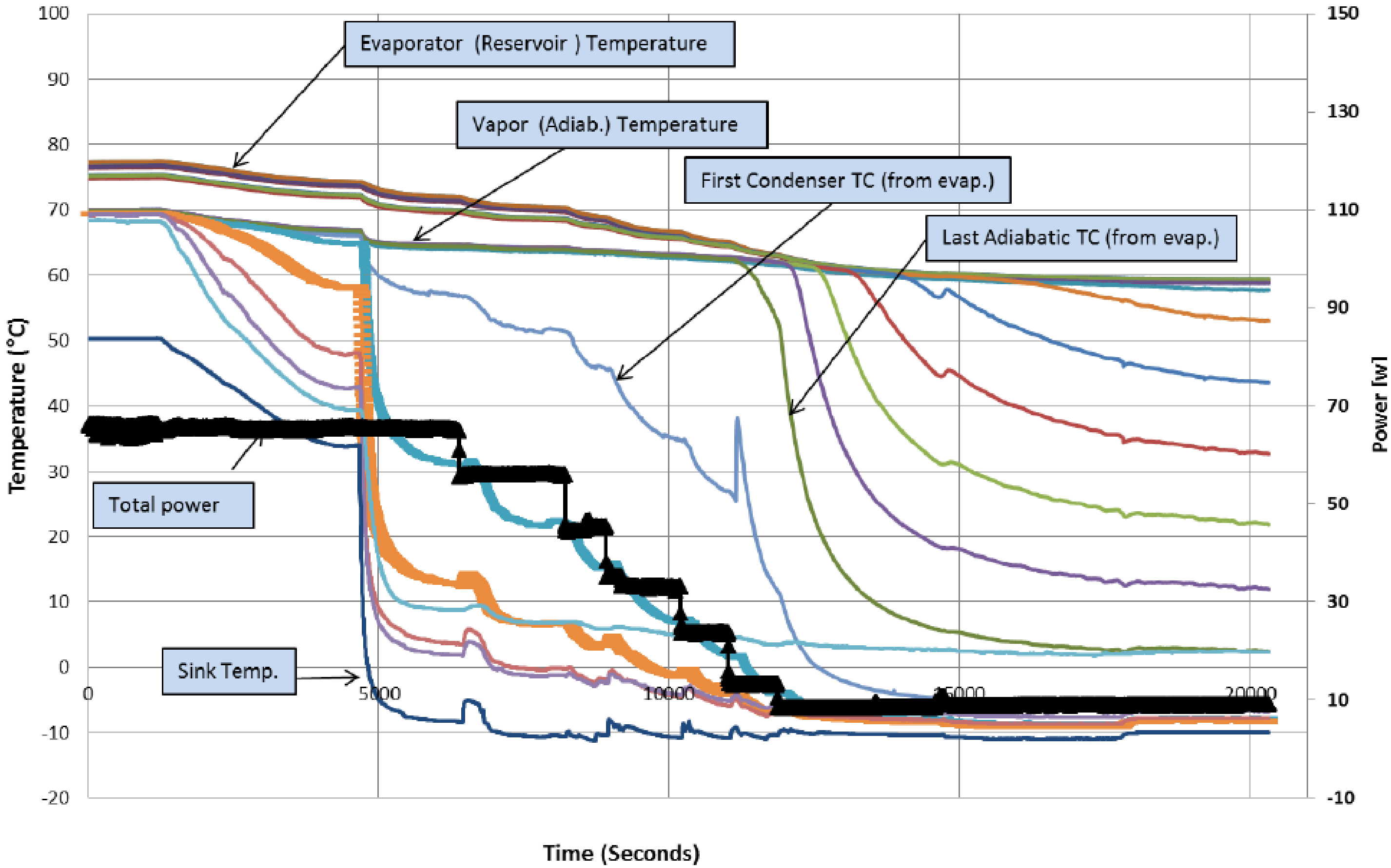
- The HiK™ plate in payload 1, which was attached to the copper-monel-water hot reservoir VCHP were tested on ground and on-board ISS.
- The HiK™ plate showed the expected performance in the ISS test and results showed excellent agreement with both predictions and ground testing results.
- The thermal control test on ground at ACT for the hybrid wick VCHP with warm reservoir shows that vapor temperature varies from 69ºC to 67ºC over widely varying sink temperatures between 50 and - 4°C. (See ICES-2017-272: Ababneh et.al for the full details).



(a) blue column or after cold sink (i.e. sink temperature = 50 °C) (b) red column or during cold sink (i.e. sink temperature = - 4 °C).



Survival Testing of the VCHP: Ground Testing



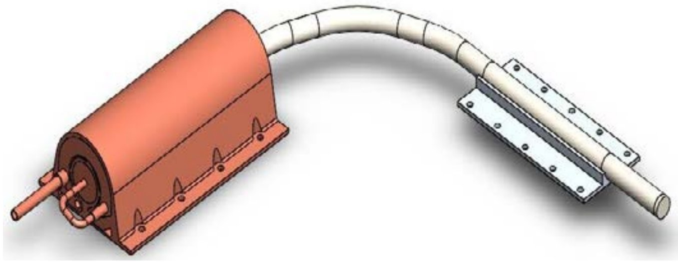
- ➢ **Thermal control survival testing results for the hybrid VCHP /HiK™ plate.**

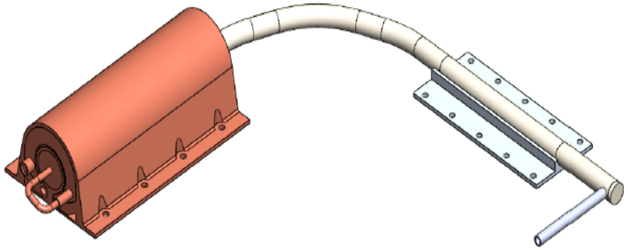
Microgravity Testing of Payload 1 on the ISS

- The VCHP worked on-board ISS, but at higher temperatures than expected.
  - The different behavior in microgravity are primarily due to the lack of natural convection.
- From on orbit testing, valuable insight into integrated reservoir design, concentric return tube, and heat pipe was gained.
- In addition, the first few days of testing demonstrated functionality of the dual wicked system,
  - Providing confidence in the redesigned VCHP for future microgravity operations.
- A new design of the warm reservoir VCHP was developed.

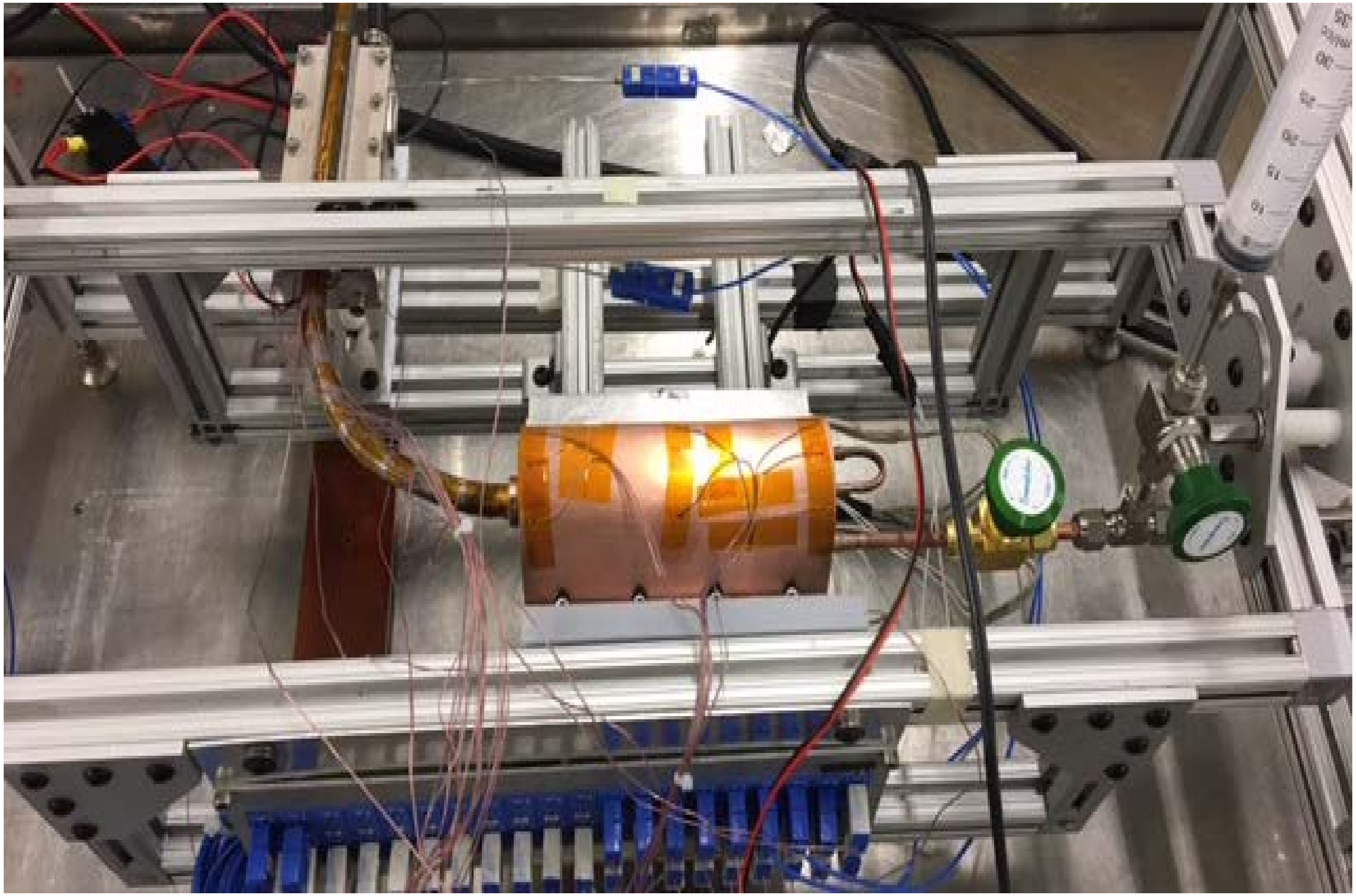
The Modified Warm Reservoir VCHP

- The preliminary thermal testing for the modified VCHP was focused on purging procedure.
  - ➢ The new design is considered the lack of natural convection on orbit.
- The fill tube (i.e. that attached to the VCHP's reservoir) accumulates liquid.
  - ➢ Therefore, the results are misleading (i.e. purging point of view).
- In order to eliminate this source of instability the fill tube was moved to the of the monel section at the end of the pipe

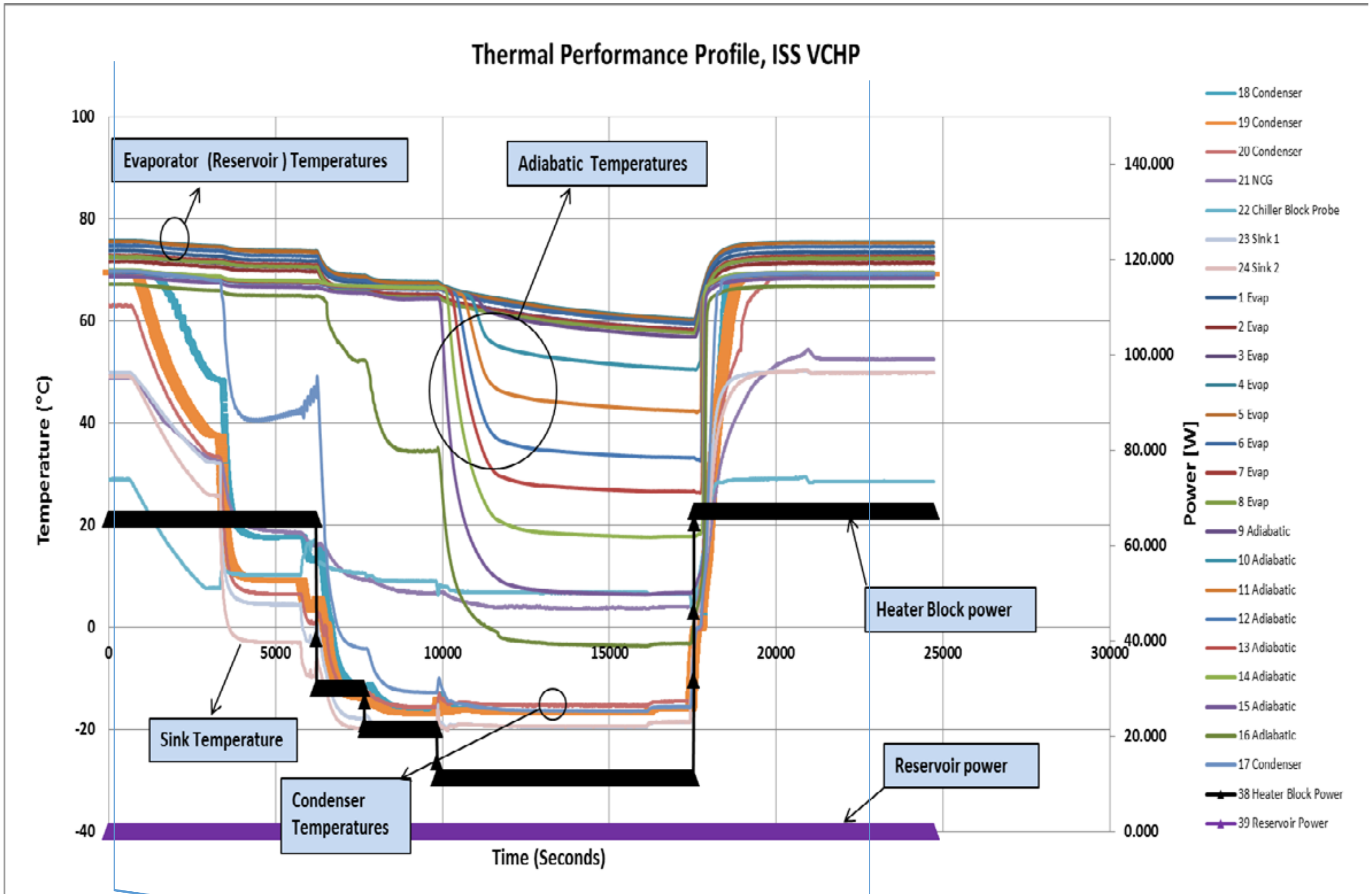




Modified VCHP Testing

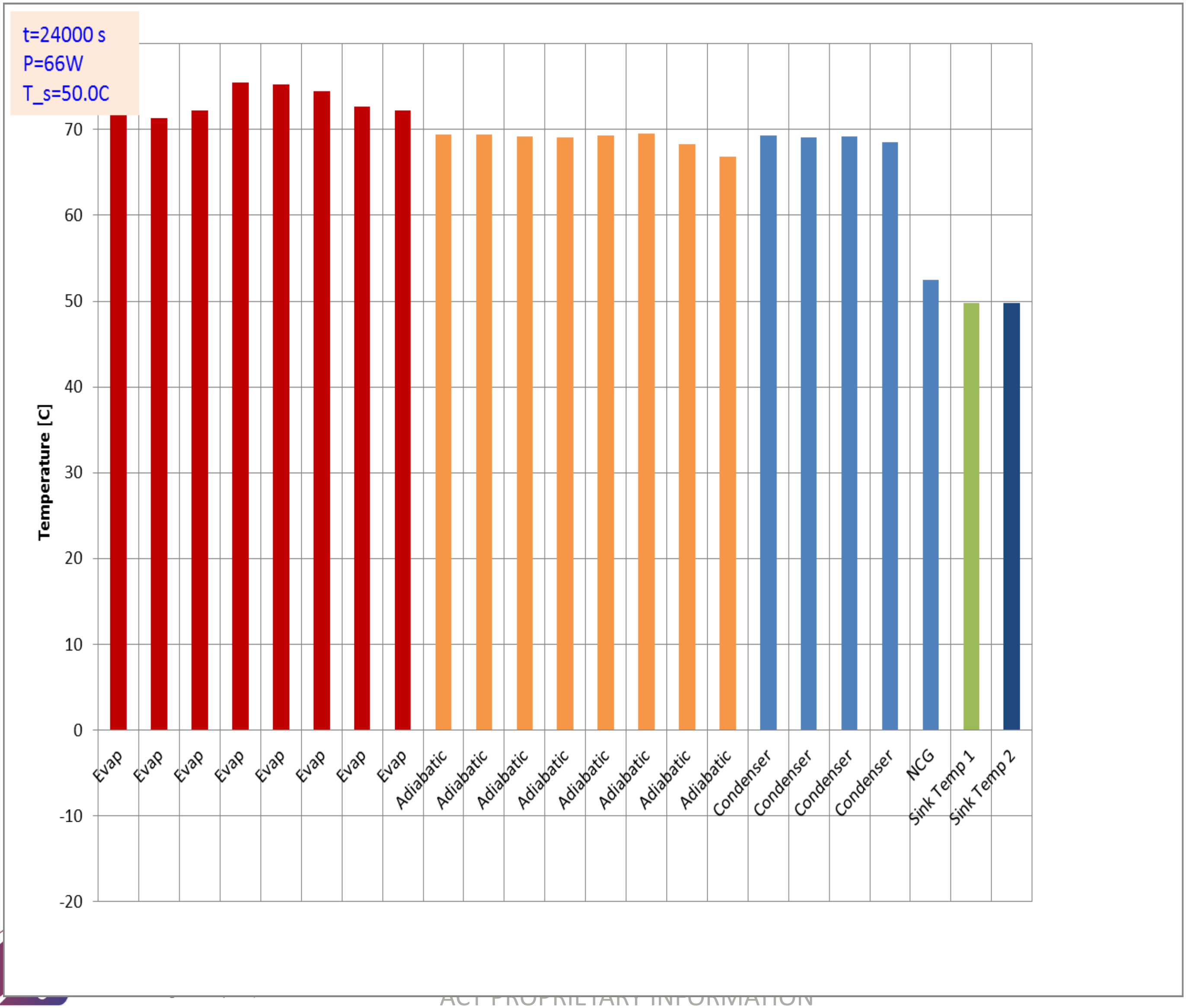


VCHP Testing Results



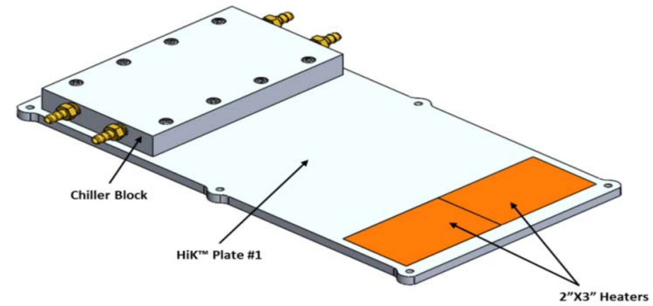
Standard Condition:
The "standard" condition of rejecting 50 W into a 50 °C sink with vapor at ~ 70°C.

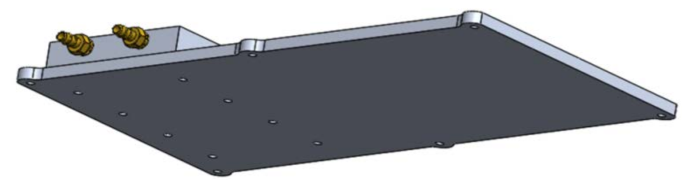
Instantaneous Profile for the VCHP

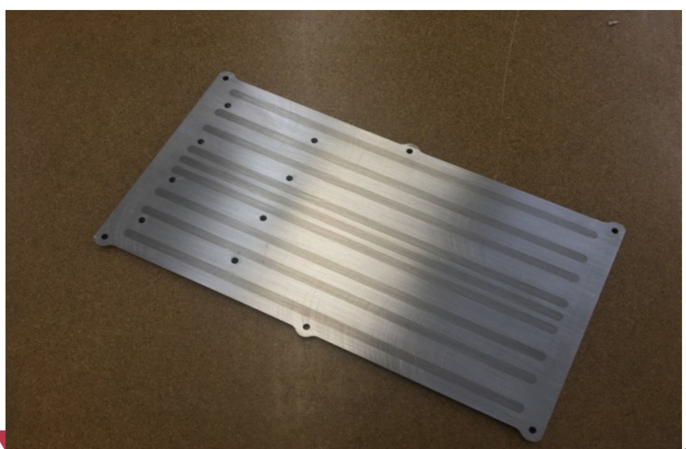


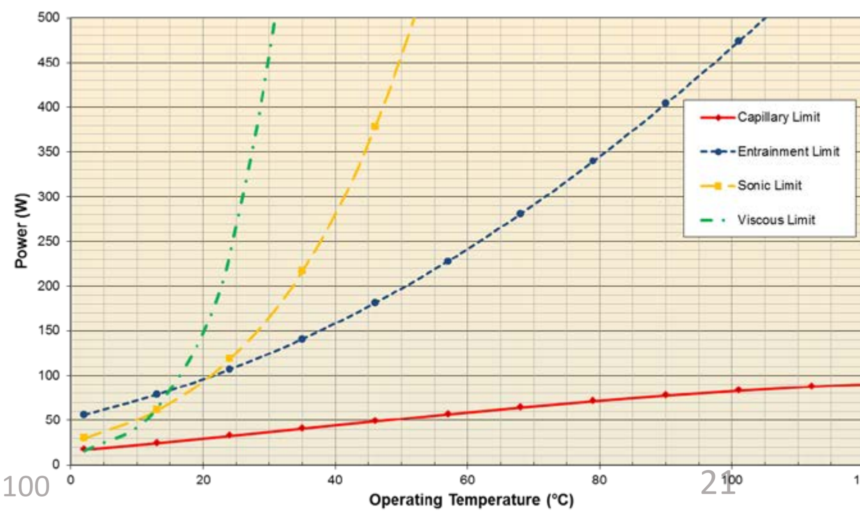
HiK™ Plate for the ISS Experiment in Payload 2: Ground Testing

- Two 53W (2”x3”) silicon heaters will be used as a heat source on the top of the HiK™ plate;
- A chiller block was used to impose sink temperatures between -10 to 40°C
- Freeze/thaw testing was performed for the HiK™ plate on the ISS.
- Each HiK™ plate had 9 copper/water heat pipes. Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit



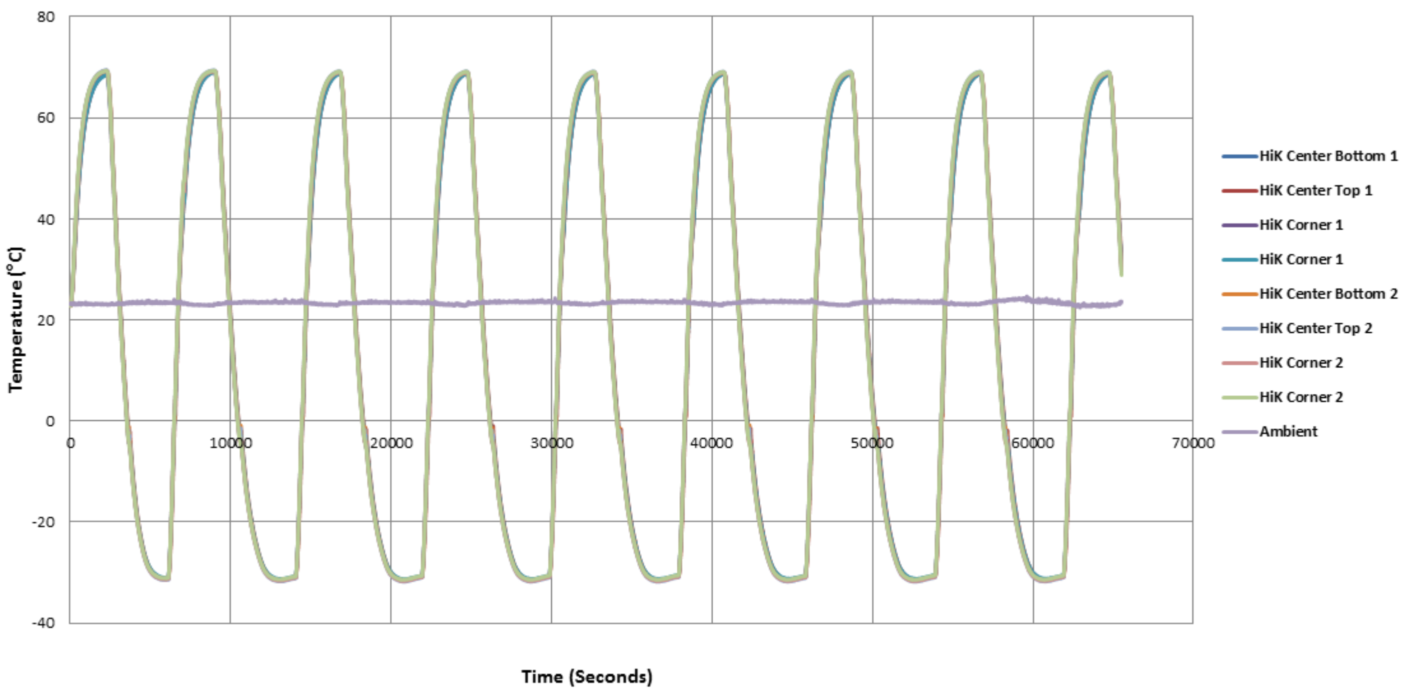






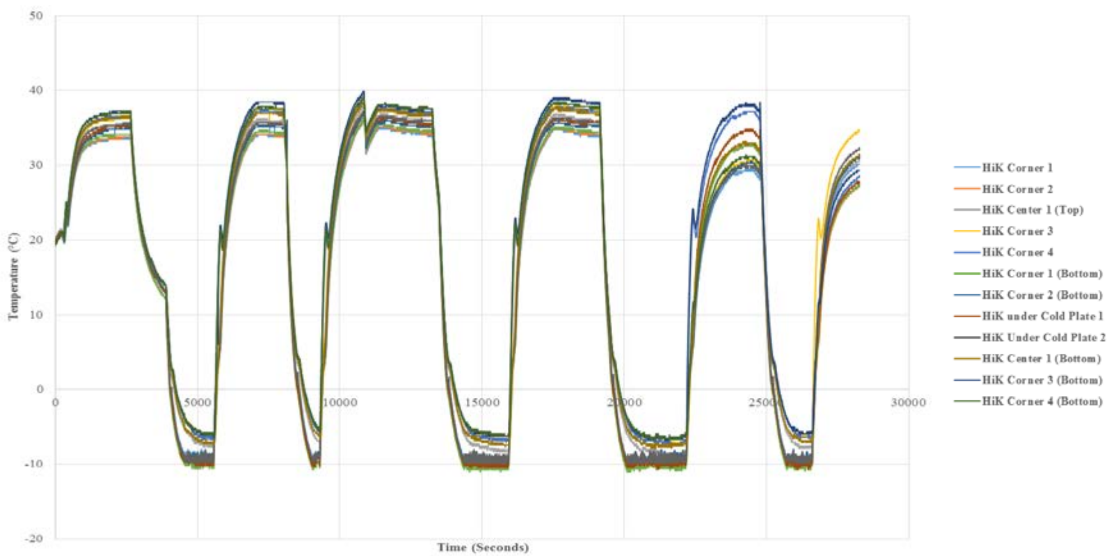
Ground Freeze/Thaw Cycle for HiK™ Plates

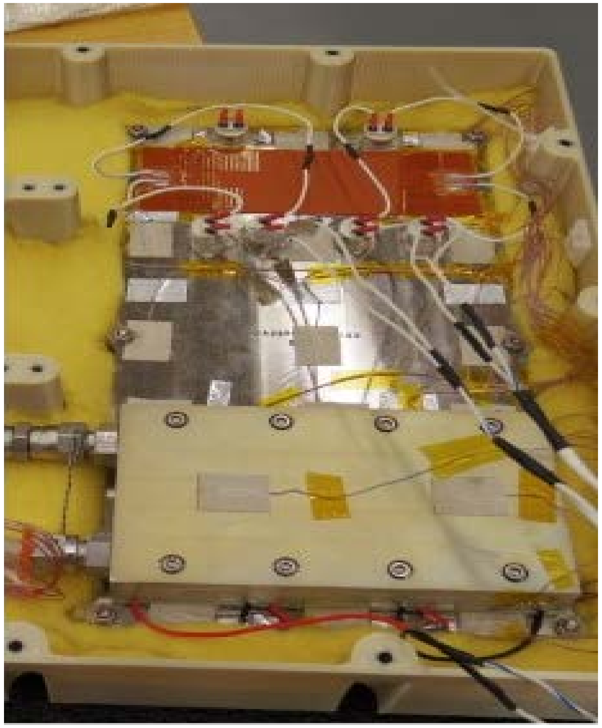
- Freeze thaw tests were conducted from temperature ranging from -30 to +70°C for two of the HiK™ plates.
- The plates were subjected to 15 freeze/thaw cycles.
- The embedded copper/water heat pipes can sustain these freeze/thaw cycles without damage.



Microgravity Testing of Payload 2 on the ISS

- Freeze/thaw testing was performed successfully for the HiK™ plate on orbit.
- The freeze/thaw tests were conducted for the HiK™ plate from temperature ranging from -10°C to approximately 40°C.
- Fourteen cycles of freeze-thaw and freeze-startup-thaw cycles were performed on orbit.





The assembled HiK™ plate integrated in Payload 2

Conclusion

- ACT Inc., NASA Marshall Space Flight Center and NASA Johnson Space Center, worked together to test warm reservoir hybrid VCHP and HiK™ plates in the ISS microgravity environment.
- A hybrid wick VCHP and two HiK™ plates were developed and tested on ground and on board ISS.
- The VCHP worked at higher temperatures than expected on ground test due to the evaporator's design that not appropriate for micro-g environment.
- Hence, a new modified warm reservoir hybrid VCHP was developed.
- The thermal control ground test of the modified hybrid wick VCHP with warm reservoir showed that vapor temperature varies from 70ºC to 68ºC over widely varying sink temperatures between 50 and - 7°C.
- The modified warm reservoir hybrid VCHP will be tested in Low-Earth orbit, aboard the ISS tentatively in 2018.

Conclusion

- The flight test verified the operation of the HiK™ plates with the embedded copper/water heat pipes in micro-gravity environment.
- Two HiK™ aluminum base plates were designed, fabricated, and tested successfully in ground and on the ISS.
- In the ISS test for payload 2, the copper-water heat pipes were embedded in a HiK™ plate, and subject to a variety of thermal tests over a temperature range of -10 to 40 ºC for a ten-day period.
- Results showed excellent agreement with both predictions and ground testing results.
- The HiK™ plate underwent 15 freeze-thaw cycles between -30 and 70 ºC during ground testing, and an additional 14 freeze-thaw cycles during the ISS test.
- This flight test on-board ISS is an important step toward qualifying copper/water heat pipes as a passive thermal management solution in support of future human and robotic space exploration missions by NASA.

Acknowledgements

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- We would like to acknowledge the help of Ryan Spangler at ACT.

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