



Advanced Passive Thermal Experiment (APT_x) for Hybrid Heat Pipes and HiK™ Plates on board the International Space Station (ISS)

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Presentation Outline



- Motivation
- Background
- Hybrid Heat Pipes Applications
- International Space Station (ISS) Flight Experiment
- Thermal Control Analysis and Results
- Conclusions





Motivation



- The following hardware has never been tested in micro-g environment :

1. Hybrid wick heat pipe

- Higher heat fluxes (e.g., lasers)
- Operation against gravity for Lunar landers and rovers

2. Variable Conductance Heat Pipe (VCHP) with a passive, warm reservoir

- Eliminates electricity required to heat a standard cold reservoir
- Minimizing electrical use required for Lunar landers/rovers, some deep space missions

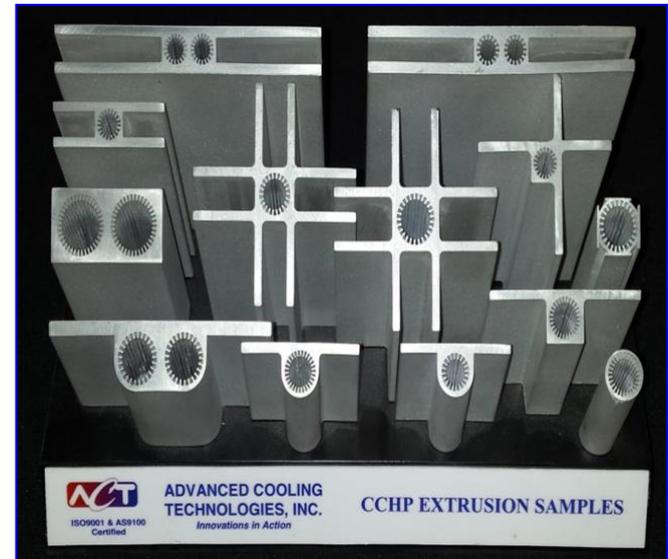
3. High Conductivity (HiK™) plates with embedded copper/water heat pipes

- Higher effective thermal conductivity than encapsulated pyrolytic graphite
- Up to 2500 W/m K for a 1 m long plate
- Lower cost and lead time, no reduction in thermal conductivity with thermal cycling
- Can bend around corners



➤ 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 ($\sim 10\text{-}15$ W/cm²)
 - ❑ No pumping capability against gravity on planetary surfaces

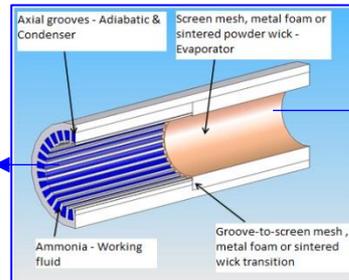


ACT'S CCHP SPACE FLIGHT HOURS: 19,183,335.0

ACT's solution – Hybrid wick CCHP

Adiabatic and Condenser sections:

- Large pore size responsible for the:
- High permeability.
 - Low liquid pressure drop
 - Transfer large amounts of power over long distances
 - Low pumping capability.
 - Relatively low heat flux limitation.

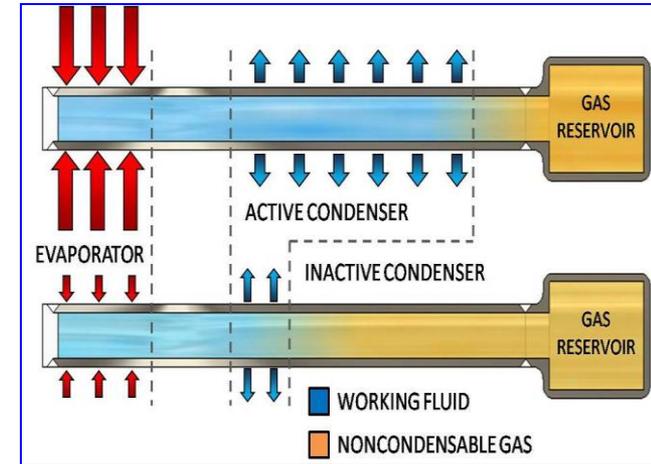


Evaporator section:

- Small pore size responsible for the:
- Low permeability.
 - High liquid pressure drop
 - High pumping capability.
 - Relatively high heat flux limitation.
 - Eliminate start-up problems.

- VCHPs are most often used for temperature control in spacecraft applications

- During operation, the working fluid drives the NCG to the condenser
- The portion of the condenser blocked by NCG is not available for heat transfer by condensation
- Low blockage – high power, high sink temperature
- High blockage – low power, low sink temperature
- Electrically heat reservoir to change blockage amount

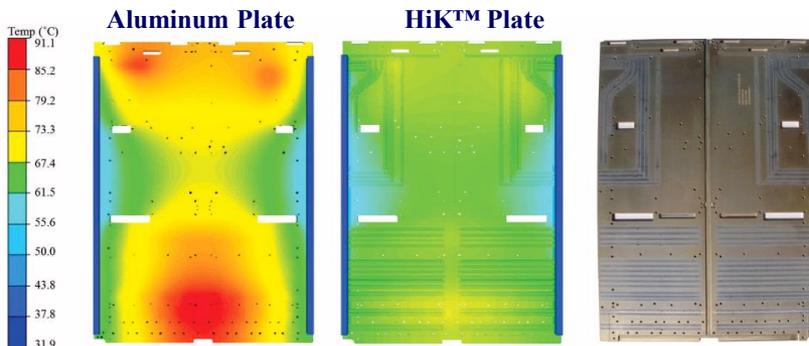
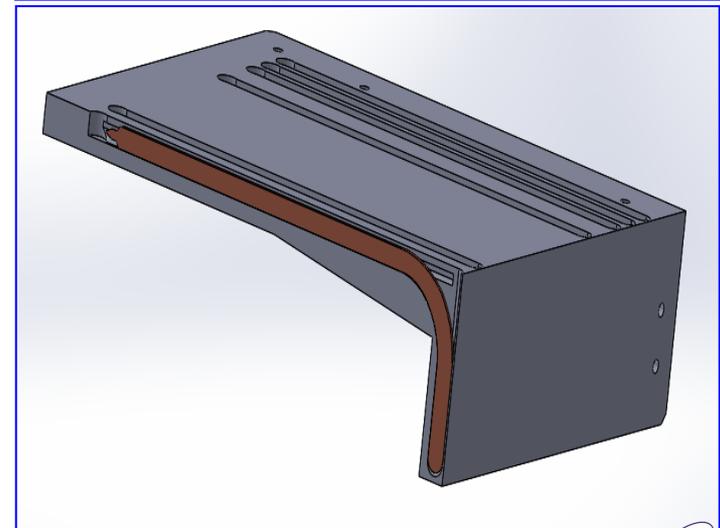
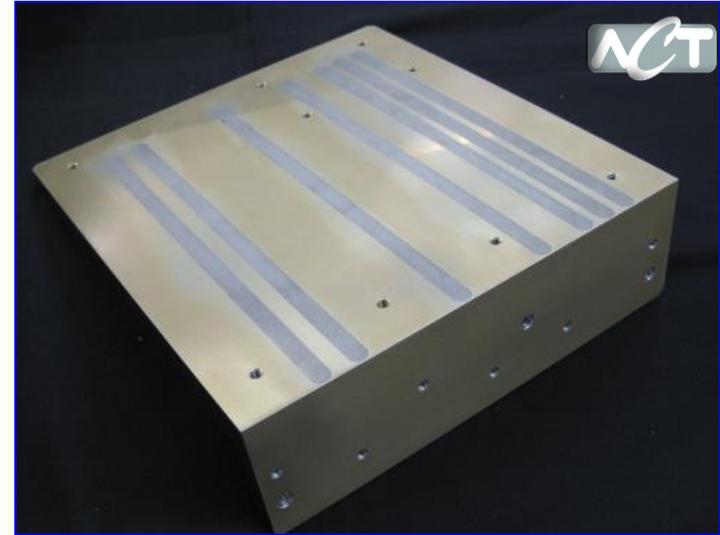


- Standard VCHP has an evaporator, a condenser, and a reservoir for Non-Condensable Gas (NCG)

- Cold-biased reservoir is located next to the condenser.
- Electrical heaters control the reservoir temperature
- Typically maintain evaporator temperature control of $\pm 1-2$ °C
- over widely varying evaporator powers and heat sink temperatures
- Roughly 1-2 W electrical power required for the reservoir heaters



- 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 (versus ~ 500 W/m K for encapsulated pyrolytic graphite)
- Identical Dimensions, 22 °C Reduction in Peak Temperature Measured





ISS Flight Hardware

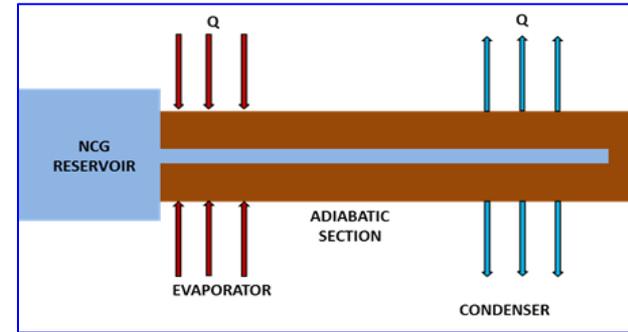


- NASA are working on an ISS flight experiment with components supplied by ACT under the Advanced Passive Thermal experiment (APT_x) project.
- The APT_x consists of two separate payloads that will be tested sequentially:
 - Payload 1 contains a VCHP/HiK™ plate assembly.
 - Payload 2 contains a HiK™ plate and the ElectroWetting Heat Pipe experiment, developed by the University of Texas at Austin.
- Objectives for ISS Experiment:
 - Demonstrate VCHP operation and its thermal control capability.
 - Show the gas front dynamics as a function of thermal contexts
 - Demonstrate VCHP shutdown at the shutdown temperature.
 - Show that heat leaks are minimized
 - Demonstrate the efficiency of the hybrid wick heat pipe in micro-gravity.
 - Demonstrate startup and capability to address working fluid location anomalies (e.g. in the reservoir) of the VCHP.
 - Demonstrate turndown ratio for the VCHP.
 - Demonstrate the operation and flight worthiness of the HiK™ plate.
 - Demonstrate the ability of the HiK™ plate to survive multiple freeze/thaw cycles.
 - Demonstrate the ability of the HiK™ plate to start-up from a frozen state

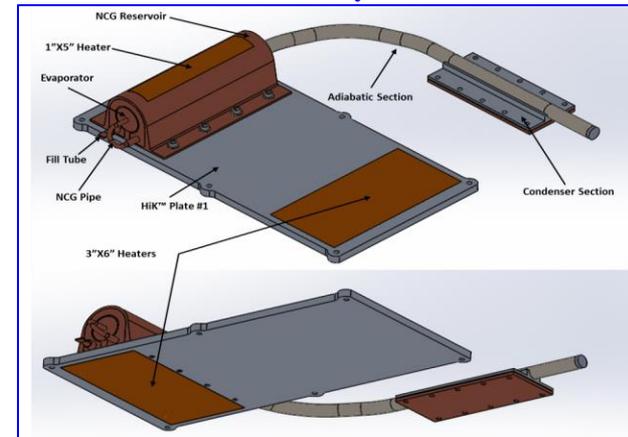


- 3 heaters (will operate one heater at a time)
 - ❑ A 90W (3"x 6"): Primary heater located remotely on the HiK™ plate (to demonstrate the operation of both systems)
 - ❑ A 90W (3"x 6"): Secondary heater located directly below the evaporator (to demonstrate the operation of VCHP without HiK™ plate)
 - ❑ A 50W (1"x 5"): Heater located on the NCG reservoir.
 - ❑ The actual applied power is ~ 100 W (assuming the power losses is ~ 30 W)
- Temperatures are monitored using 45 thermocouples (TCs) which will be attached to the VCHP and the HiK™ plate
- A chiller block attached to the VCHP condenser to offer sink temperature that will be sweeping between -10 to 50 °C.

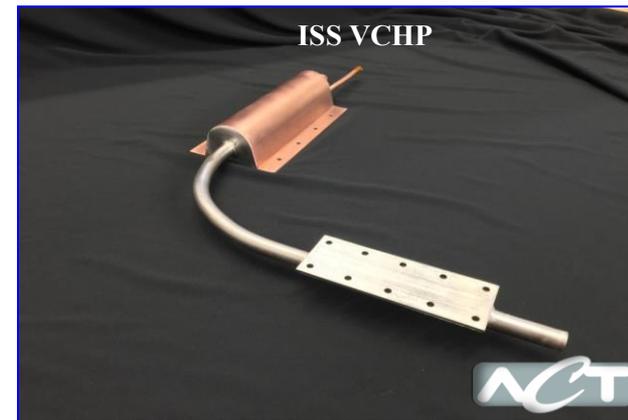
Warm reservoir VCHP



APT-X-Payload #1

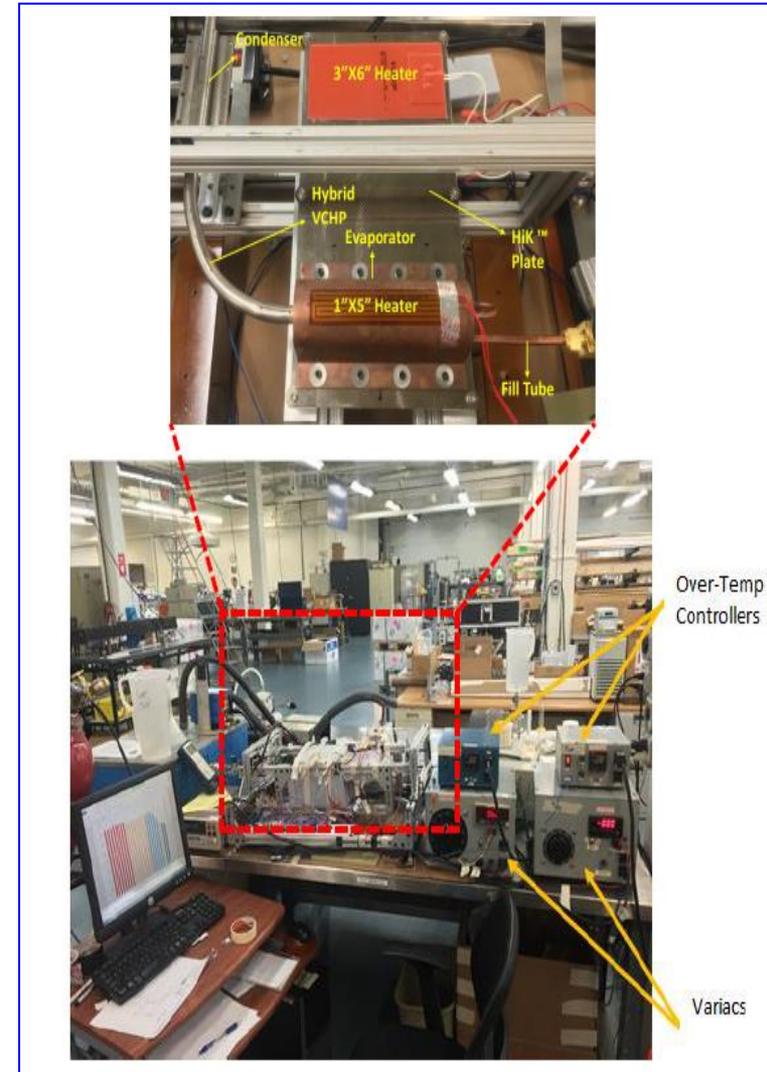


ISS VCHP

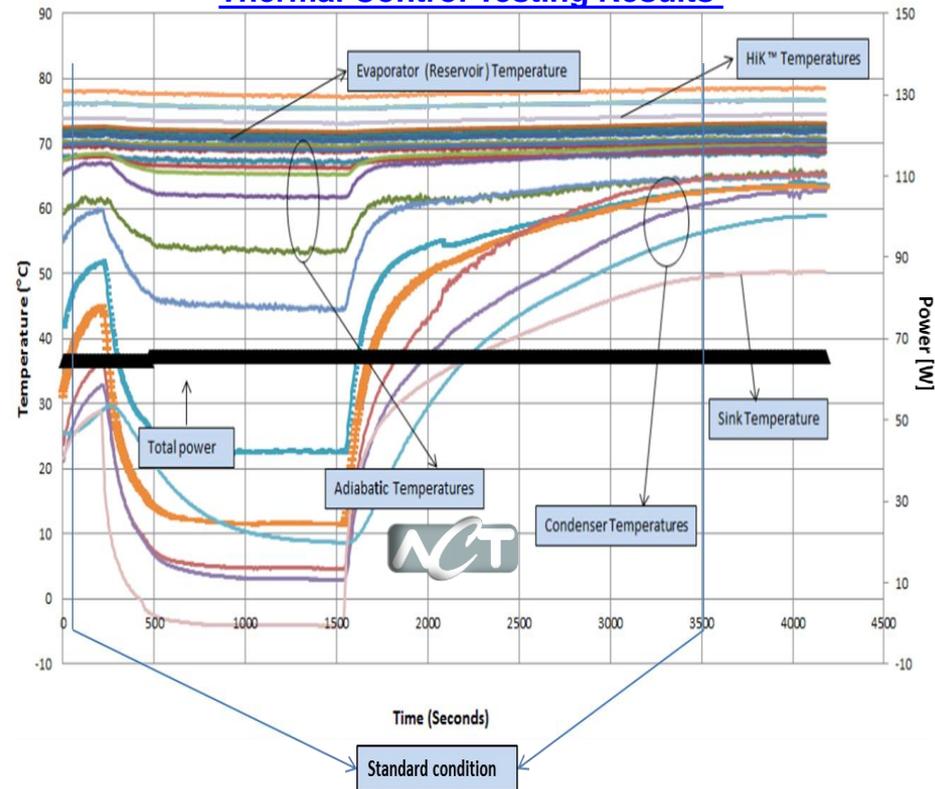


- The testing procedure is as follows:
 - ❑ Turn the chiller on and start pumping propylene glycol through the system.
 - ❑ For reference, the propylene glycol temperature set point was 32 °C
 - ❑ Power the 1"x5" heater to full power.
 - ❑ When the temperatures on the NCG reservoir reach 65 °C, turn off the 1"x5" heater power and immediately power the 3"x6" heater to 66W.
 - ❑ Adjust the chiller temperature to achieve a 50 °C sink temperature
 - ❑ Monitor the adiabatic temperatures and adjust power until they are around 70 °C.

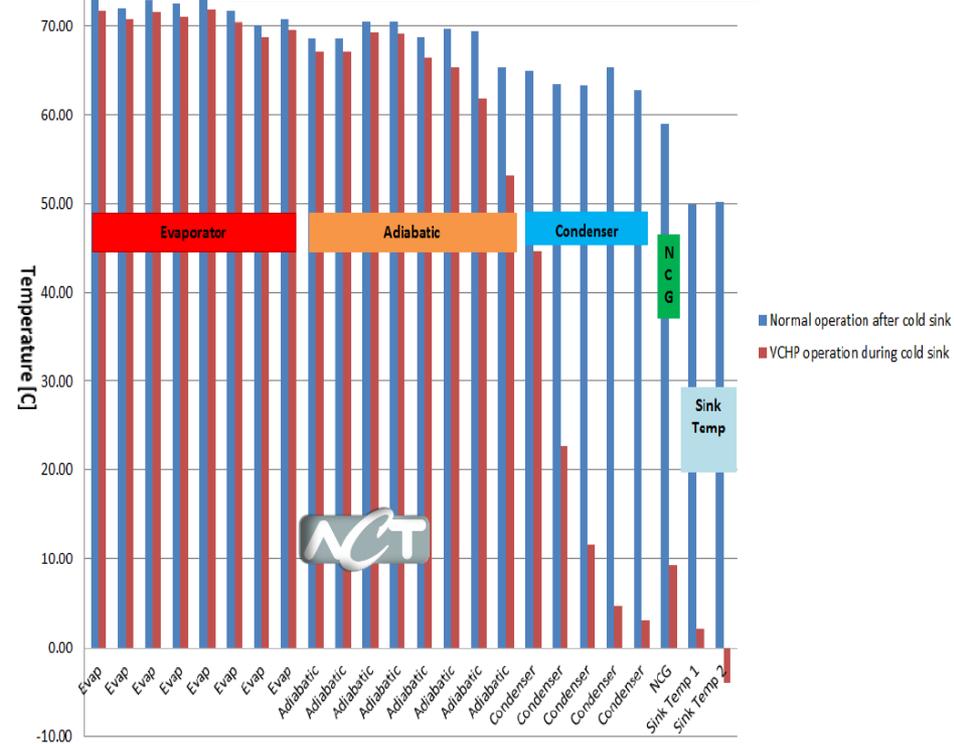
- NCG charge: The NCG (argon) charge is calculated, and then applied to the VCHP



Thermal Control Testing Results



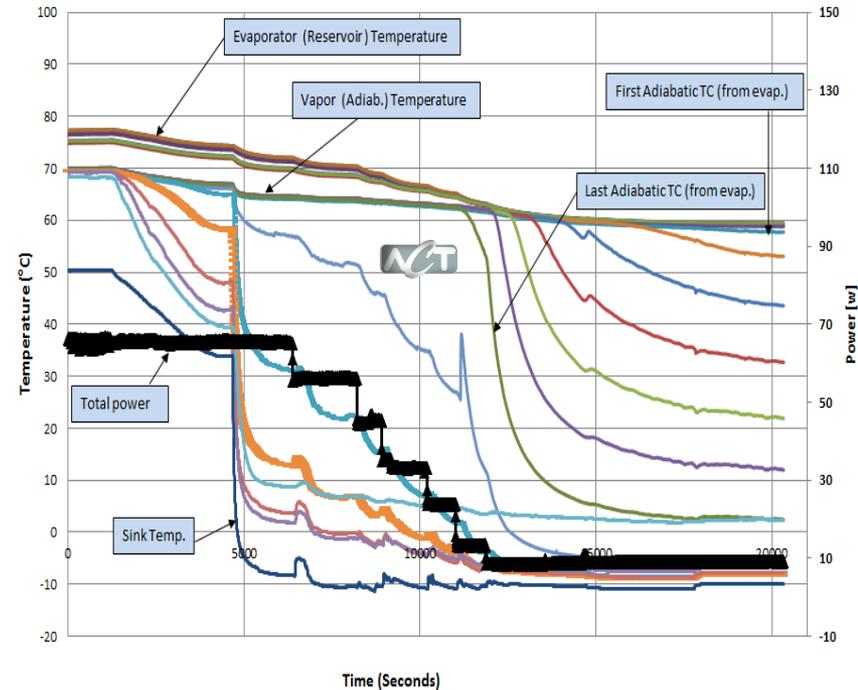
Instantaneous Temperature Profile



- The “standard” condition of rejecting 50 W into a 50 °C sink with vapor at ~ 70 °C.
- The power was maintained constant at 66W while sink temperature was incrementally decreased at about 1500 seconds then the sink temperature increased back again to ~ 4500 seconds (i.e. steady state condition).
- The evaporator (payload) temperature only varies from 69 °C to 67 °C as the sink temperature swings between 50 and – 4 °C.
- Demonstrating the capability of the VCHP to keep the evaporator temperature within 2 °C over the entire sink temperature range, from 50 °C to – 4 °C.

- 0-1220s, steady state at standard condition where the total power is 66 W (50W nominal and a measured power loss to the ambient of 16W) with maximum sink temperature of 50 °C and vapor temperature of ~70 °C.
- 1220s-4650s, total power is constant (and maximum) while sink temperature is decreased however being controlled only by the coolant temperature (thermoelectric modules are off).
- 4650s-6300s, total power is still constant while sink temperature further decreased (to - 8.3 °C) being driven by the thermoelectric modules that now are on. As a result, vapor temperature decreased to ~66 °C.
- 6300s-12000s, total power is incrementally decreased to 15W while sink temperature further decreased and stabilized at -10 °C. Slightly before the 12000s mark (at ~11500s), the last adiabatic TC separates from the other vapor temperatures showing that the NCG front starts to move into the adiabatic section towards the evaporator, announcing the approaching of the survival mode.
- 12000s to the end, the total power was further reduced to 10W allowing the first adiabatic TC to separate from the other vapor temperatures meaning that the survival mode is reached. Vapor temperature in this case is ~58 °C. The authors believe that the total applied power of 10W mainly represents the losses to the ambient. The real survival power, consisting by conduction through the adiabatic wall and diffusion, is less than 1W (based on calculations) and is embedded in the 10W of total power.

Survival Testing Results



- The standard condition of operation of the VCHP, where power is 50W, vapor temperature is 70 °C and sink temperature is 50 °C shows a conductance of 2.5 W/ °C.
- The actual survival power is assumed as less than 1W, based on calculations.
 - In these conditions, the survival mode conductance is given by the survival power of 1W, and the measured temperatures of vapor (58 °C) and sink (-10 °C). The result is 0.0147 W/ °C and the turndown ratio is ~ 170.
- The functional hybrid VCHP was delivered to NASA for further testing and qualification and currently is under testing on the ISS.

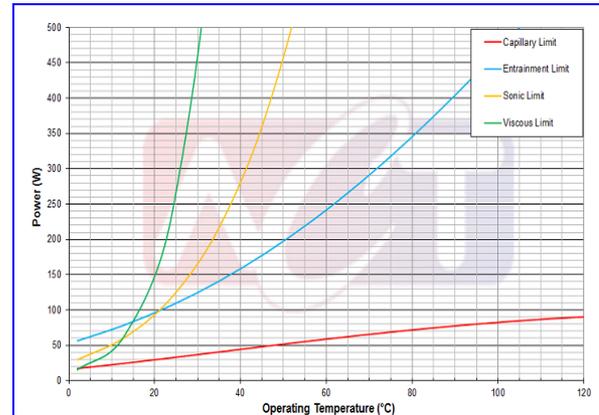


Payload #1: Fully Assembled Heat pipe Test Article

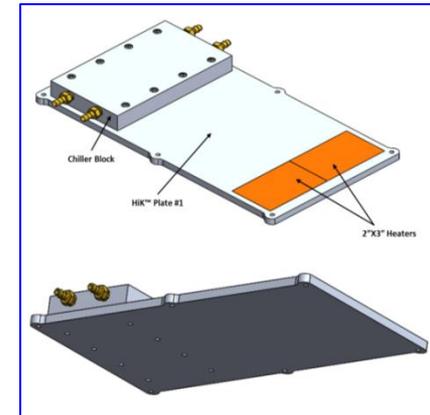
- Freeze thaw tests were conducted from temperature ranging from -30 to +70° C for two of the ISS HiK™ plates.

- ❑ The plates were subjected to 15 freeze/thaw cycles.
- ❑ The embedded copper/water heat pipes can sustain these freeze/thaw cycles without damage.

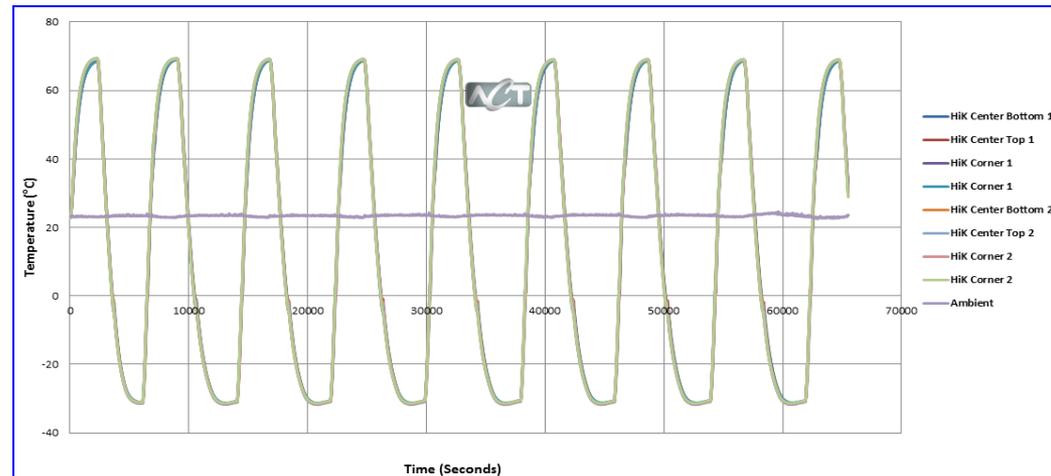
- Two 53W (2"×3") silicon heaters will be used as a heat source on the top of the HiK™ plate;
- A chiller block will be used to impose sink temperatures between -10 to 50° C
- 30 TC's are used.



Performance results for ISS copper/water HPs



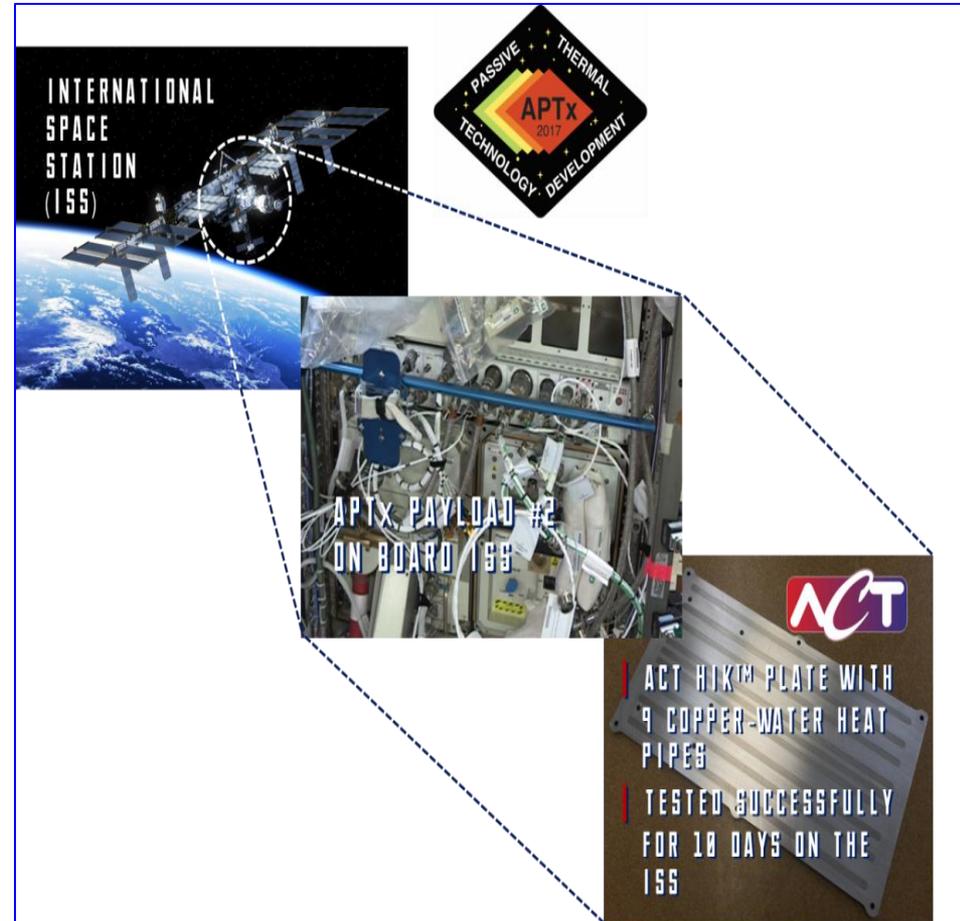
APT_x – Payload #2



Ground Freeze/thaw cycles for ISS HiK™ plates

- In the ISS test, the heat pipes were embedded in a HiK™ plate, and subject to a variety of thermal tests over a temperature range of -10 to 38 °C for a **ten-day** period
 - ❑ Results showed excellent agreement with both predictions and ground testing results.
 - ❑ The HiK™ plate underwent **14** freeze-thaw cycles successfully during the ISS test.

- After 10 days of testing on the ISS:
 - ❑ Demonstrate the successful operation of the copper/water HPs and HiK™ plate.
 - ❑ Demonstrate the ability of the copper/water HPs and HiK™ plate to survive multiple freeze/thaw cycles.
 - ❑ Demonstrate the copper-water heat pipes are capable of carrying the required power.
 - ❑ Demonstrate the ability of the copper/water HPs and HiK™ plate to start-up from a frozen state.





Conclusion



- ACT Inc., NASA Marshall Space Flight Center and NASA Johnson Space Center, are working to test and validate hybrid wick VCHP with warm reservoir and HiK™ plates on the ISS microgravity environment.
- The flight test verifying :
 - The operation of the hybrid wick VCHP at the maximum and shutdown temperatures
 - The HiK™ plates with the embedded copper/water heat pipes in micro-gravity environment.
- A hybrid wick VCHP and two HiK™ plates were developed and tested successfully in ground.
 - The thermal control test for the hybrid wick VCHP with warm reservoir shows that vapor temperature varies from 69 °C to 67 °C over widely varying sink temperatures between 50 and – 4 °C.
 - The VCHP can protect the payload against extremely low sink temperatures during survival.
 - Overall conductances for the hybrid VCHP during “ON” and “OFF” modes are 2.5 and 0.0147 W/ °C respectively, show that the heat pipe operates as a variable thermal link with large turn down ratio (i.e. 170).
- Two HiK™ plates were designed, fabricated, tested, and shipped to NASA.
 - Each HiK™ plate has 9 copper/water heat pipes.
 - Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit.
 - Also, freeze/thaw test is conducted successfully for both HiK™ plates from temperature ranging from -30 to +70 °C for 15 cycles.





Conclusion



- Flight testing aboard the ISS for the APTx payloads:
 - **Payload 1 contains a VCHP/HiK™ plate assembly:**
 - ❑ The HiK™ plate, which is assembled with the copper monel water hot reservoir VCHP is currently under testing.
 - ❑ The HiK™ plate shows the expected performance.
 - ❑ The VCHP works at higher temperatures than expected.
 - ❑ Currently, we are working to improve the thermal control of the warm reservoir VCHP.
 - **Payload 2 contains a HiK™ plate and the ElectroWetting Heat Pipe (EWHP) experiment, developed by the University of Texas at Austin:**
 - ❑ The HiK™ plate successfully tested as a separate heat transfer device.
 - ❑ Thermal resistance was evaluated for low, medium and high temperatures for symmetrically and non-symmetrically applied loads.
 - ❑ The results in microgravity show excellent agreement with both predictions and ground testing results.
 - ❑ The HiK™ plate underwent 14 freeze-thaw cycles successfully during the ISS test.



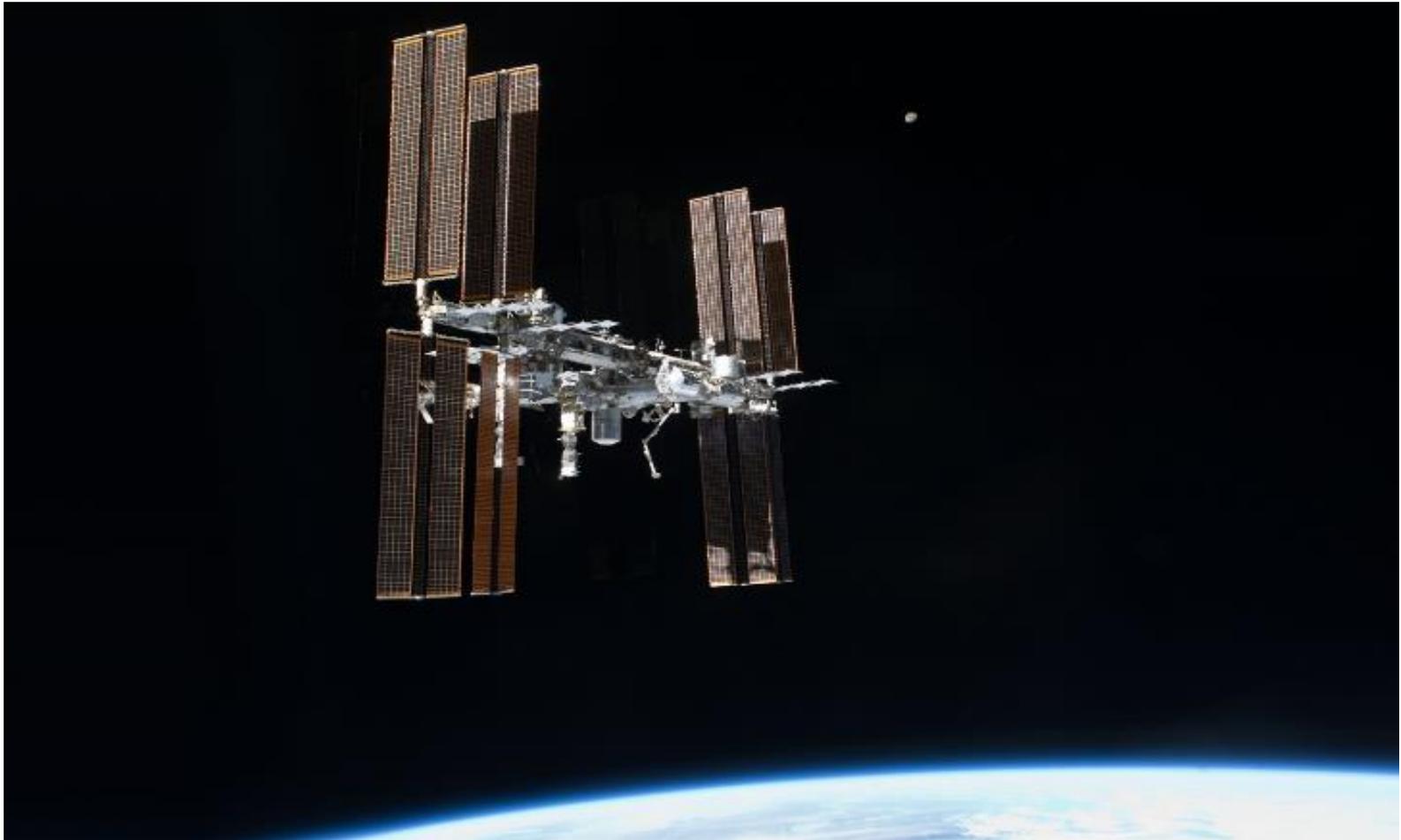


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- Joel Wells and Corey Wagner were the laboratory technicians responsible for the fabrication of the heat pipes.







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