Advanced Passive Thermal Experiment for Hybrid Variable Conductance Heat Pipes and High Conductivity Plates on the International Space Station

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As NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architectures will be challenged with unprecedented thermal environments in deep space. In addition, there is a need to extend the duration of the missions in both cold and hot environments, including cis-lunar and planetary surface excursions. The heat rejection turn–down ratio of the increased thermal loads in the above-mentioned conditions is crucial for minimizing vehicle resources (e.g. power). Therefore, future exploration activities will have the need of thermal management systems that can provide higher reliability and performance, and power and mass reduction. In an effort to start addressing the current technical gaps in thermal management systems, novel new passive thermal technologies have been selected to be included as part of a suite of experiments to be tested on the board of the International Space Station (ISS), tentatively in 2017. Advanced Cooling Technologies, Inc. (ACT), together with NASA Marshall Space Flight Center and NASA Johnson Space Center, are working to test and validate hybrid wick Variable Conductance Heat Pipes (VCHPs) with warm reservoir and high conductivity plates on the ISS under the Advanced Passive Thermal experiment (APTx) project. The APTx consists of two separate payloads that will be tested sequentially: 1) Payload 1 contains a VCHP/high conductivity plate assembly: a hybrid wick copper-Monel-water VCHP design consists of a copper evaporator (with sintered wick inside), a monel adiabatic section and a condenser both with grooved wick inside and a non condensable gas (NCG) reservoir thermally and physically attached to the evaporator. In turn, the VCHP evaporator is mounted on an aluminum high conductivity plate. 2) Payload 2 contains a high conductivity plate and the ElectroWetting Heat Pipe (EWHP) experiment, developed by the University of Texas at Austin.

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
APTx	=	Advanced Passive Thermal experiment
CCHPs	=	Constant Conductance Heat Pipes
EWHP	=	Electrowetting Heat Pipe
ISS	=	International Space Station

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LHPs	=	Loop Heat Pipes
NASA	=	the National Aeronautics and Space Administration
NCG	=	Non Condensable Gas
VCHPs	=	Variable Conductance Heat Pipes
WEB	=	Warm Electronics Box

I. Introduction

Hybrid wick heat pipes have a porous wick (e.g. sintered wick) in the evaporator section, and a grooved wick in the adiabatic and condenser sections. The sintered-powder-metal evaporator wick is capable of operating against gravity on the planetary surface and can also operate at higher heat fluxes. The grooved condenser/adiabatic wick in the hybrid heat pipes allows the heat pipe to operate in space, carrying power over long distances.

The next generation of polar rovers and equatorial landers is among the near-term NASA applications. A hybrid variable conductance heat pipe (VCHP) is required which can operate during large tilts, shut down during the long Lunar night and operate over a wide range of sink temperature fluctuations on the Lunar surface. The next generation of landers and rovers have a Warm Electronics Box (WEB) and a battery, both of which must be maintained in a fairly narrow temperature range. This requires a variable thermal link between the WEB and the radiator. During the Lunar day, the thermal link must transfer heat from the WEB to the radiator as efficiently as possible, to minimize the radiator size. On the other hand, the thermal link must be as thermally isolating as possible during the Lunar night to preserve the electronics and battery warm with minimal power, even if the sink temperature is very low. This variable thermal link also requires hybrid wick to allow liquid return during operation under unfavorable orientation of the evaporator. After testing on earth, the heat pipes will be tested in micro-gravity environment on the International Space Station (ISS) for two reasons:

1. To ensure that the hybrid wick works in microgravity condition.
2. To raise the overall TRL of the hybrid wick heat pipes and high conductivity (HiK™) plates [1,2].

The ISS as shown in Figure 1 is the only long-duration platform existing in the relevant space environment with an integrated space systems construction that can be used to validate operations concepts and advanced technologies. The ISS program offers an infrastructure capable of demonstrating and validating prototypes and systems that may advance spaceflight technology readiness. The space station, the in-orbit crew, the launch and return vehicles, and the operation control centers are all supporting the demonstration of advanced systems and operational concepts that will be needed for future exploration missions. (Hornyak, 2013[3])

Figure 1. The International Space Station (Photo: NASA/ESA).

Hybrid wick VCHP with warm reservoir and HiK™ plate (i.e. heat spreaders with embedded heat pipes) has never been tested in micro-g environment. ACT, NASA Marshall Space Flight Center, and the International Space Station office at NASA's Johnson Space Center will test the hardware in Low-Earth Orbit, aboard the International Space Station.

II. Heat Pipe Background

Constant conductance heat pipes (CCHPs) transport large amounts of heat from a heat source to a heat sink with a very small temperature difference. Axial groove capillary wick structures are utilized because of the relative ease of manufacturing (aluminum extrusions) and their demonstrated heritage in spacecraft and instrument thermal control applications. CCHPs can transport heat in either direction and are typically used to transfer heat from specific thermal loads to a radiator panel or as part of an integrated heat pipe radiator panel.

Grooved Aluminum/Ammonia Heat Pipes

Grooved wicks are typically used in spacecraft CCHPs and VCHPs. Typical aluminum grooved extrusions are shown in Figure 2. These grooves have a very high permeability, allowing very long heat pipes for operation in micro-gravity, typically several meters long. One of their weaknesses is that they are suitable only for space, or for gravity aided sections of a heat pipe. The reason is that the same large pore size responsible for the high permeability results in low pumping capability.

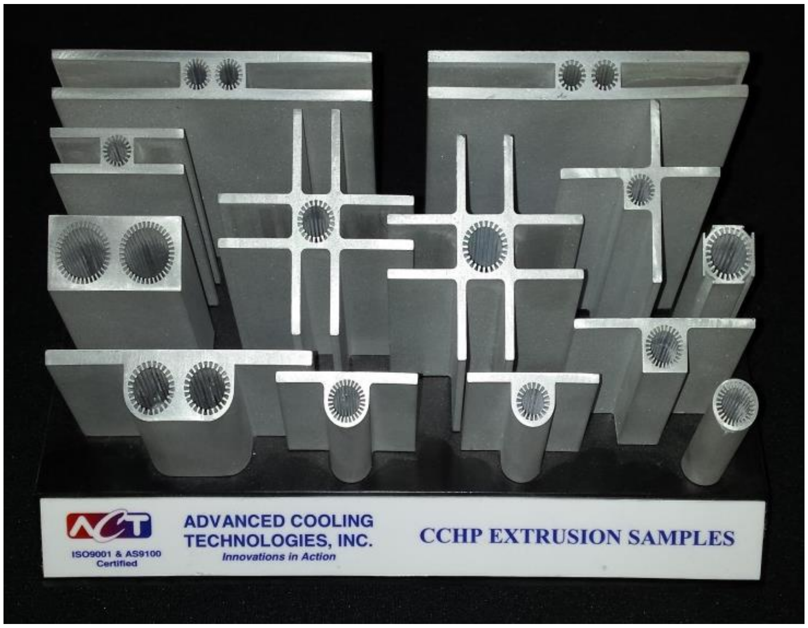


Figure 2. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow long heat pipes for spacecraft applications, but only work about 0.10 inch (0.00254m) against gravity for earth-based testing (ACT Inc., 2013[4]).

Grooved aluminum/ammonia heat pipes are designed to work with a 0.10 inch (0.25cm) adverse elevation (evaporator elevated above the condenser). This allows them to be tested on earth prior to insertion in a spacecraft. However, they are very sensitive to adverse elevation. In our previous work, it was shown experimentally that increasing the heat pipe elevation by 0.010 inches (0.0254cm) will significantly decrease the power[1]. For heat pipes operating on the Moon or Mars, grooves can only be used in gravity-aided portions of the heat pipe. Another wick must be found for sections with adverse elevations, e.g. sintered powder, screen mesh, or metal foam wicks.

Variable Conductance Heat Pipe (VCHP)

A VCHP is similar to a conventional heat pipe, but has a reservoir and a controlled amount of non-condensable gas (NCG) inside the reservoir. This NCG is used to regulate the overall thermal conductance of the heat pipe. By regulating the thermal conductance, the temperature at which the VCHP operates can be controlled even with variations in the heat load. Information on VCHPs can be found in (Brennan and Kroliczek[5], 1979), and (Marcus[6], 1971). When the VCHP is operating, the NCG is swept toward the condenser end of the heat pipe by the flow of the working fluid vapor. The NCG then blocks the working fluid from reaching a portion of the condenser. The VCHP works by varying the amount of condenser available to the working fluid for heat transfer. As the evaporator temperature increases, the vapor temperature (and vapor pressure) rises, the NCG compresses (Figure 3, top) and more of the condenser is exposed to the working fluid. This increases the effective conductivity of the heat pipe and drives the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expands (Figure 3, bottom). As the NCG begins to fill the condenser, the heat pipe effective conductivity decreases, and the evaporator temperature decrease is minimized.

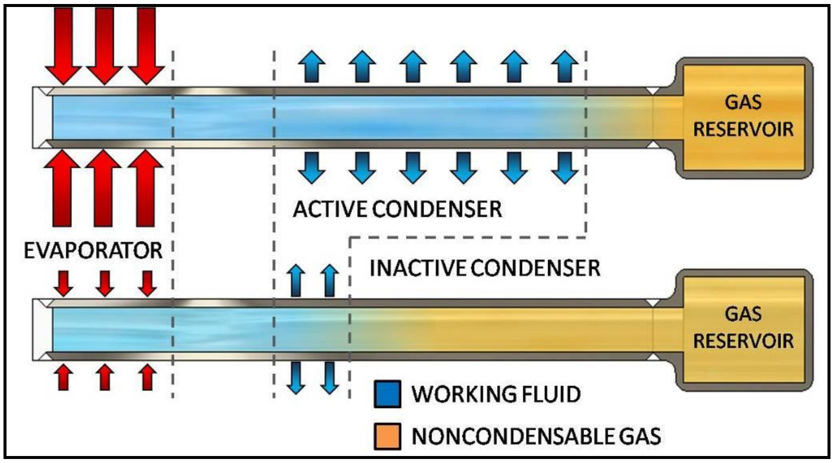


Figure 3. Operation of a VCHP. As heat load increases, the temperature dependent saturation pressure of the working fluid increases and the NCG is compressed into the reservoir (top). As heat input decreases, the working fluid saturation pressure decreases and the non-condensable gas is allowed to expand into the condenser (bottom).

For the simple VCHP illustrated in Figure 3, the reservoir is cold-biased in most spacecraft applications. Electric heaters on the reservoir are then used to control the temperature to within ±2°C. During the long Lunar day, the thermal management system must be capable of removing the waste heat from the WEB and ensuring the WEB does not get too warm. During the long Lunar night, the variable thermal link for the WEB must limit the amount of heat that is removed from the WEB and radiated to space. This will keep the electronics and battery warm with minimal power, even with the very low temperature (100 K) environment. A variable thermal link (typically a VCHP) is needed which can operate during large tilts, over a wide sink temperature swings on the Lunar surface and shut down during the long Lunar night.

High Conductivity Plates (HiK™ Plates)

The HiK™ or high conductivity plate as shown in Figure 4 represents a technology developed at ACT (ACT Inc., 2013[7]) that consists of heat pipes embedded in a plate to transfer of heat from one location to another. The embedded heat pipes are soldered in place, and then the surface is fly-cut to provide a smooth surface. The weight of a HiK™ plate is roughly similar to its solid counterpart; however, effective thermal conductivities range from 500 to 1200 W/m.K (versus ~ 200 W/m.K for aluminum). In some spacecraft applications, the effective thermal conductivity can be as high as 2500 W/m.K, equivalent to diamond. For applications with large variations in heat load across a surface, such as electronics boards, the embedded heat pipes can be customized to provide controlled heat transfer across the plate. The addition of HiK™ plates to the electronics enclosure would further decrease the temperature gradient within this device by eliminating hot spots and improving overall heat transfer.

Analysis of a HiK™ Plate is shown in Figure 5 using finite element analysis to compare the performance of a solid aluminum plate and potential improvements using an aluminum plate with embedded copper/water heat pipes. The conventional aluminum plate's highest temperature was 90.3° C whereas the HiK™ aluminum plate is 69.1°C. This is a considerable performance improvement. HiK™ can contain both copper/water and copper/methanol heat pipes. Note that the copper/water heat pipes drop in efficiency below about 20°C, due to the water properties. At

0°C, the water heat pipe will freeze and will make no contribution to the thermal conductivity until they thaw again. By controlling the water inventory so that no free liquid is available, HiK™ plates have been shown to withstand thousands of freeze/thaw cycles[8].

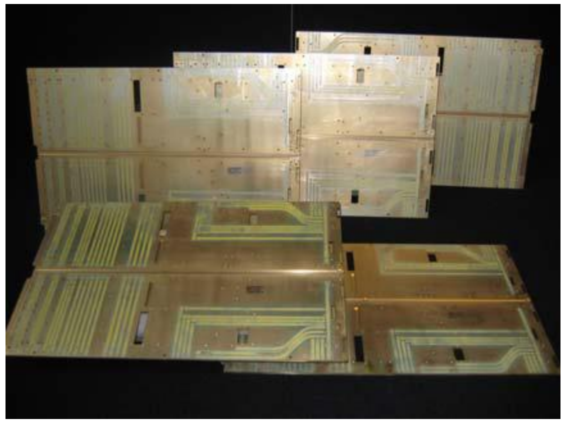
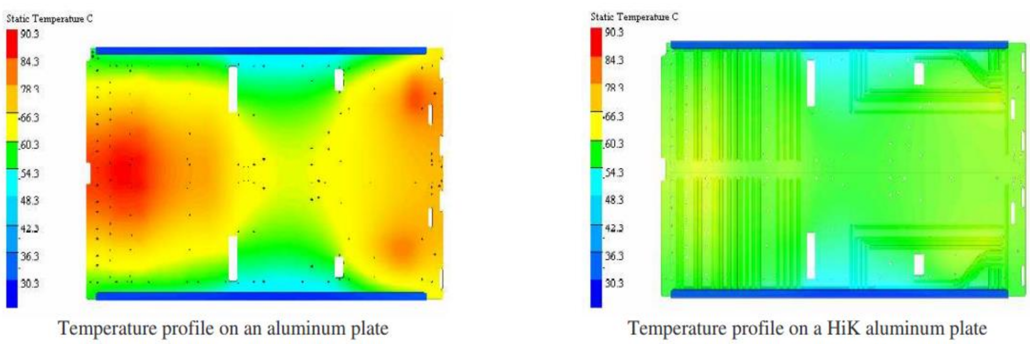


Figure 4. **High conductivity aluminum (HiK™ Aluminum) plates with embedded heat pipes.**



(a) **(b)**

Figure 5. FEA for a particular application with multiple heat sources across the plate. For a) Temperature distribution on the standard aluminum plate b) Temperature distribution on the HiK™ plate. A reduction in peak temperature of 21°C can be observed.

III. Heat Pipes Advanced Features

- **<u>Hybrid wick heat pipes</u>**

Heat flux limit in axial grooved heat pipe evaporators normally starts at 5-15 W/cm^2. In order to increase the heat flux limit to more than 50 W/cm^2, the concept as shown in Figure 6 is to develop heat pipes with a hybrid wick that contains screen mesh or sintered evaporator wicks for the evaporator region, which can sustain high heat fluxes, where 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.

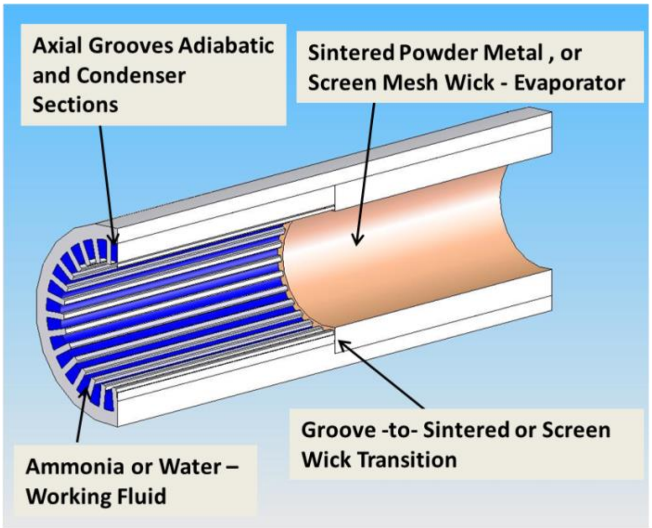


Figure 6. Hybrid CCHPs: axial grooved adiabatic and condenser sections - screen mesh or sintered evaporator wick.

The previous work[1] showed that the hybrid screen/grooved wicks CCHP did not meet the goal for Lunar landers and rovers program (i.e. the required total power that should be dissipated for the high heat flux applications is 150 W or higher). Thus the screen mesh wick was ruled out. Instead, the sintered wicks offer the highest operating heat flux capability and height against gravity compared to screen, foam, and grooved wicks. Hybrid wick heat pipes have the following advantages:

- The sintered-powder-metal evaporator wick is capable of operating at higher heat fluxes in comparison to the axial groove design and can also operate against gravity on the planetary surface.
- The grooved condenser wick in the hybrid CCHPs allows the heat pipe to operate in space, carrying power over long distances.
- The grooved condenser wick in the hybrid CCHPs allows the heat pipe to act as a thermosyphon on the planetary surface for Lunar and Martian landers and rovers. Thus, it is valuable for Lunar/Martian rover and lander applications.
- The combination has a higher transport capability than a porous wick.

Figure 7 depicts the planetary hybrid VCHP evaporator design. The wick design has a cross-sectional flow area over five times larger than that of the standard wick without increasing the ΔT through the wick (i.e., ΔT from evaporator wall to vapor).

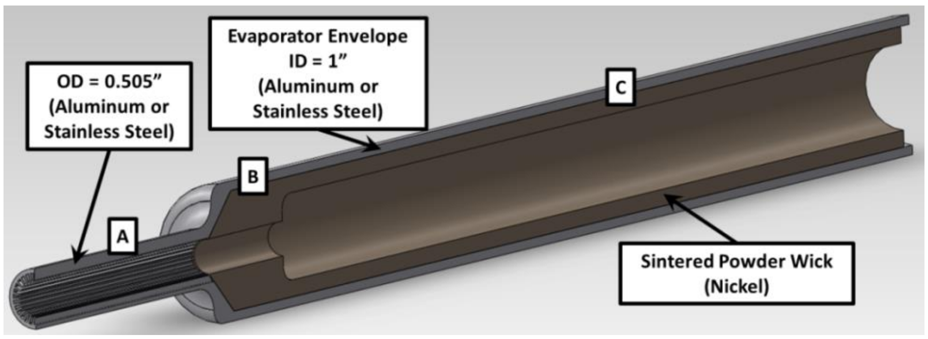


Figure 7. Planetary VCHP evaporator design (sintered wick after insertion into evaporator).

Working fluid returning from the condenser is pumped by the grooves (section A) to the beginning of the sintered wick. A 45° conical interface hydraulically joins the axial grooves to the sintered metal powder wick. There is a 1.25 inch (0.031m) length of adiabatic section (section B) within the sintered wick, which has a vapor core diameter nearly identical to that of the grooves. The evaporator begins at the start of the large diameter cavity (section C) in the sintered wick and has a total length of 9.25 inches (0.23m). Figure 8 contains a cross sectional right view and detail view (inset) of the grooved wick to sintered wick interface. The flow path of the liquid return is shown. This 45° conical interface utilizes a relatively thick amount of sintered powder material to ensure a structurally robust feature (Ababneh et al.[1], 2015).

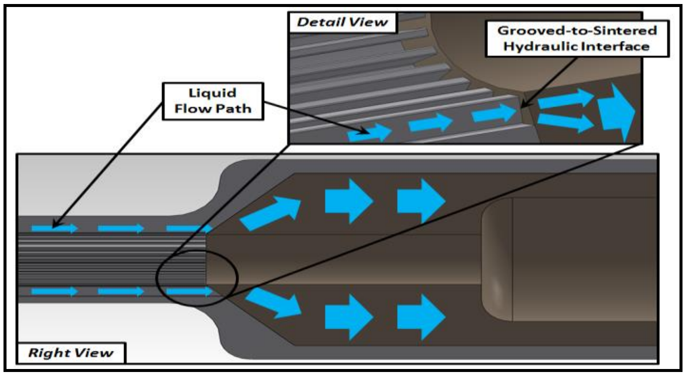


Figure 8. Planetary VCHP evaporator 45° conical interface (cross sectional right view and detail view).

- **<u>Warm reservoir heat pipes</u>**

In contrast to the standard cold, electrically-heated reservoir at the end of the condenser, the hybrid wick VCHP has a warm reservoir located adjacent to the evaporator as shown in Figure 9. In this case the warm reservoir will mainly follow the payload (i.e. evaporator) temperature. As will shown later in section IV, the warm reservoir will provide 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. (Anderson et al., 2010 [9]).

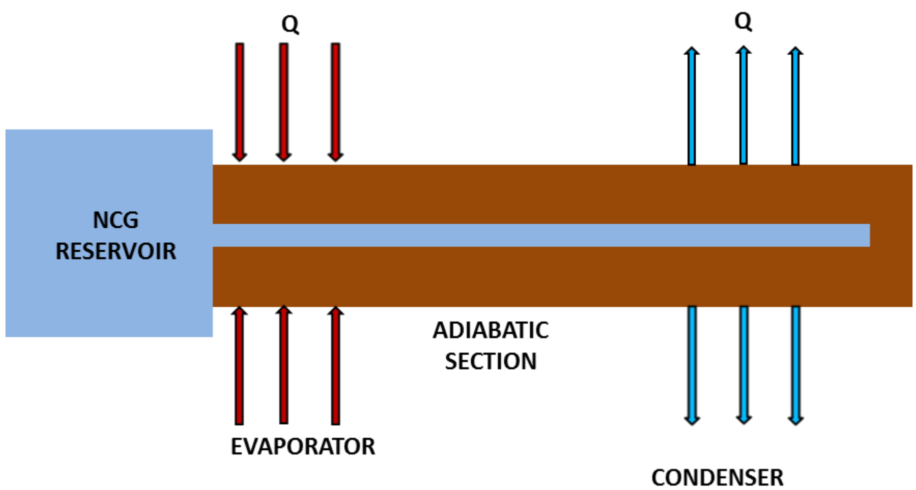


Figure 9. Schematic diagram of thermally coupled warm reservoir heat pipe.

- **<u>Technology Readiness Level Assessment</u>**

The TRL of the high conductance plate (HiK™ plate) is currently TRL 9 for terrestrial applications, and TRL 6 for space applications. The micro-gravity tests on this plate will raise the TRL level of the plates to TRL 8, since the plate tested is will be very similar to those used in the actual application. The TRL is lower for the hybrid VCHP. We believe that it is TRL 6 for operation on Earth, and in a Lunar or Mars environment (based on other tests conducted at ACT and NASA, on aluminum/ammonia versions of the design) it is closer to TRL 5 for operation in space (note that both the Lunar lander and the lunar rover also need to function in microgravity). The ISS VCHP tests will demonstrate that the two major innovations will also work in microgravity: 1. Hybrid wick, and 2. Warm reservoir. This will raise the TRL for operation in microgravity to TRL 7 (same design, different materials and working fluid).

IV. ISS Flight Hardware

As NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architectures will be challenged with unprecedented thermal environments in deep space. In addition, there is a need to extend the duration of the missions in both cold and hot environments, including cis-lunar and planetary surface excursions. The heat rejection turn–down ratio of the increased thermal loads in the above mentioned conditions is crucial for minimizing vehicle resources (e.g. power). Therefore, future exploration activities will have the need of thermal management systems that can provide higher reliability and performance, and power and mass reduction. In an effort to start addressing the current technical gaps in thermal management systems, novel new passive thermal technologies have been selected to be included as part of a suite of experiments to be tested on the board of the ISS, in 2017 [2].

As discussed before, the systems will need to operate in microgravity, during transit to the moon or Mars. We cannot test the VCHP using either parabolic flights or sounding rockets, since the time period is much too short. The principal mechanism that has not been tested is on the moon or Mars is the flooding limit. Our design used a lunar flooding limit for thermosyphons, validated by NASA Glenn with parabolic flights[10]. Consequently, ACT Inc., together with 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 under the Advanced Passive Thermal experiment (APTx) project. The hybrid wick VCHP is used as a thermal link between Warm Electronics Box (WEB) electronics or avionics and the radiator for landers and rovers. The objectives for testing flight hardware on the ISS are:

- Demonstrate VCHP operation at the maximum temperature.
    - 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 environment.
- Demonstrate startup and capability to address working fluid location anomalies (e.g. in the reservoir).
- Demonstrate turndown ratio for the hybrid VCHP.
- Demonstrate the operation and flight worthiness of the HiK™ plate.

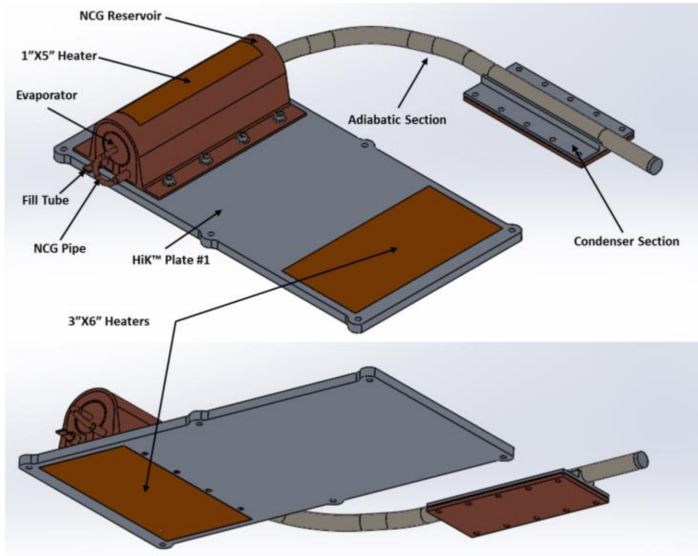
The APTx consists of two separate payloads that will be tested sequentially:

- Payload 1 contains a VCHP/HiK™ plate assembly.
- Payload 2 contains a HiK™ plate and the ElectroWetting Heat Pipe (EWHP) experiment, developed by the University of Texas at Austin.

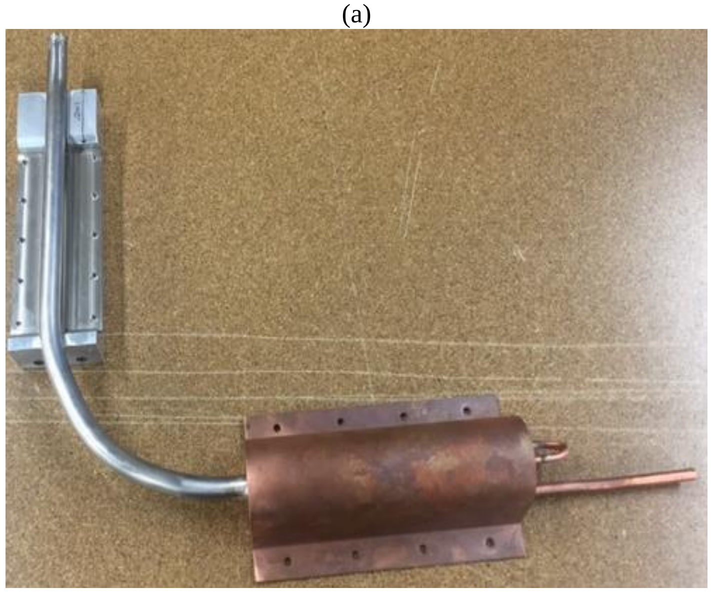
Payload 1:

The hybrid wick VCHP design would typically have an aluminum envelope, with ammonia as the working fluid. The HiK™ plate design for aerospace applications would typically include copper/water and copper/methanol heat pipes. All of the heat pipes in the APTx will have water as the working fluid, due both to the short time to develop and test the experiments before they must be flight ready, and the fact that the experiment will be tested inside the ISS. Since water is not compatible with aluminum, the flight test VCHP will have copper and Monel as the envelope.

A hybrid-wick copper-Monel-water VCHP design consists of a copper evaporator (with sintered wick inside), a monel adiabatic section and a condenser both with grooved wick inside and a NCG reservoir thermally and physically attached to the evaporator. In turn, the VCHP evaporator is mounted on an aluminum HiK™ plate. Figure 10 shows the CAD model and the fabricated hybrid wick VCHP and HiK™ plate for the ISS experiment in payload 1.



(a)



(b)

Figure 10. The hybrid wick VCHP and the HiK™ plate for the ISS experiment in payload 1: (a) The CAD model, (b) The fabricated VCHP.

After that, the fabricated VCHP was tested to demonstrate VCHP operation/shutdown and its thermal control capability. Therefore, a chiller block attached to the VCHP condenser provides the sink temperature that will be varied between -10 to 50°C. Three heaters will be used as heat sources:

- 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 maximum applied power is ~ 100 W (assuming the power loss is ~ 30 W). Temperatures are monitored using 45 thermocouples (TCs) which will be attached to the VCHP and the HiK™ plate. The condenser sink conditions were established using an aluminum block connected with a chiller unit to provide sink temperatures between -10 °C to 50 °C. The propylene glycol and water (PGW) flow to the condenser from the chiller unit is adjusted via a temperature controller, based on the required sink temperature. The pipes were instrumented with type T thermocouples (See Figure 11).

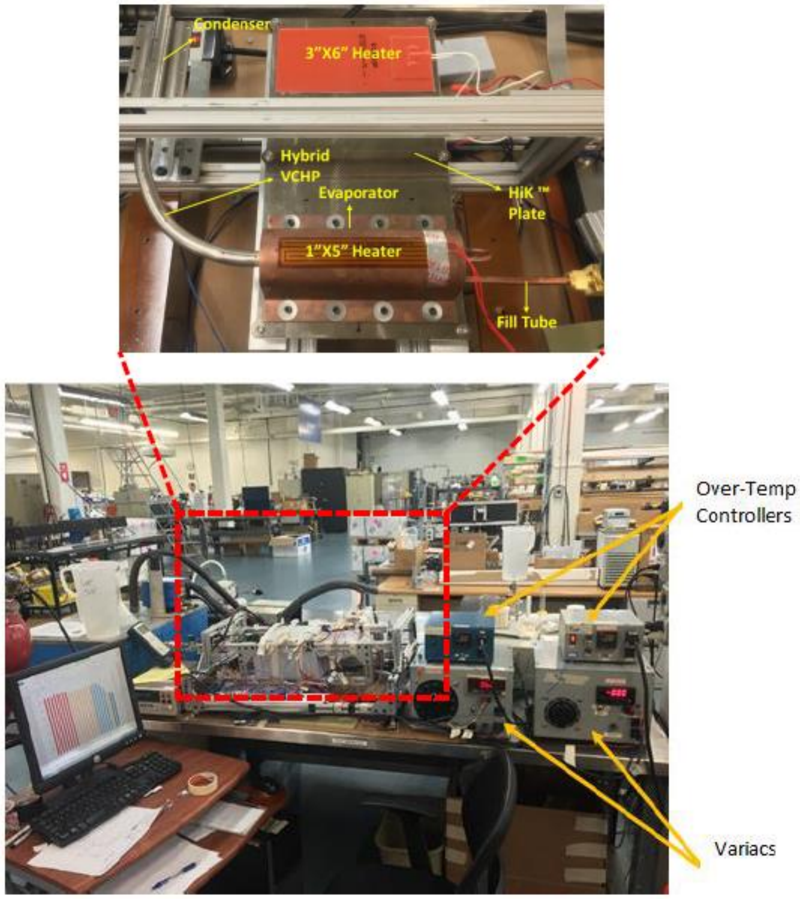


Figure 11. Testing setup for payload 1 (i.e. the hybrid VCHP and the HiK™ plate).

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 67W.
- 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. To ensure that the charge amount is correct, the NCG is dynamically adjusted while the VCHP is being tested, in order to obtain the ideal VCHP temperature profile.

<u>Testing Results:</u>

Figure 12 shows the thermal control testing results for the hybrid VCHP in horizontal orientation. The "standard" condition of rejecting 50 W into a 50 °C sink with vapor at ~ 70°C is shown in Figure 12. The power was maintained constant at 67W 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). Figure 13 shows instantaneous temperature profiles along the VCHP with a warm reservoir after and during cold sink conditions. Note that even though the evaporator (payload) temperature only varies from **69ºC to 67ºC** 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.

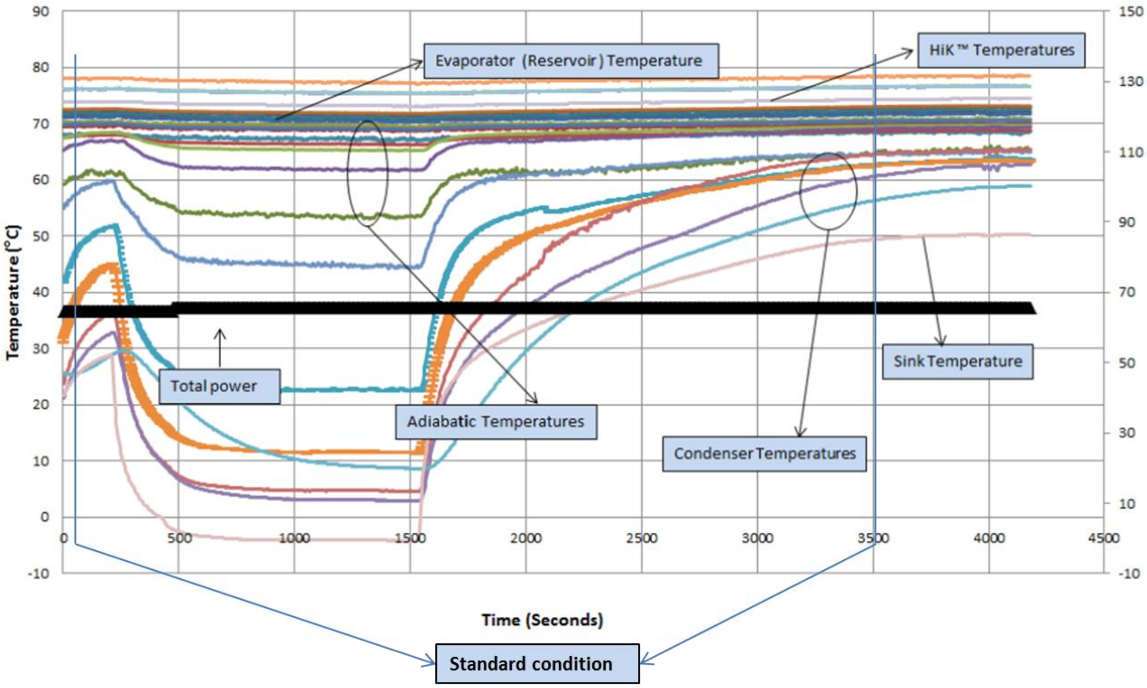


Figure 12. Thermal control testing for the hybrid flight VCHP.

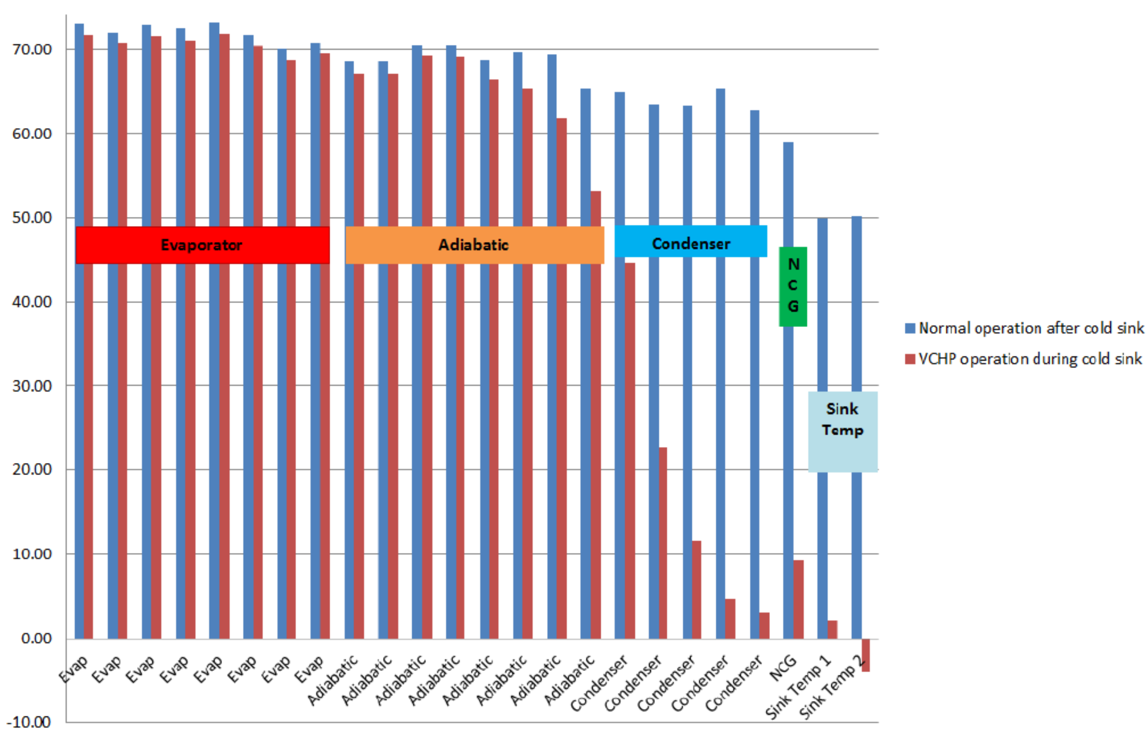


Figure 13. Instantaneous temperature profile within the hybrid VCHP during operation: (a) blue column - steady state during hot sink exposure (i.e. sink temperature = 50 °C) (b) red column – steady state at cold sink exposure (i.e. sink temperature = - 4 °C).

Survival Testing:

During extreme survival times when heat sink temperature is very low, the NCGs block the condenser section and part of the adiabatic section, shutting down the heat pipe. consequently, the VCHP will keep the payload from experiencing low temperatures during survival periods. However, heat leaks still occur by conduction through heat pipe envelope in the adiabatic section. Assuming that no power is supplied to the instruments, the instrument temperatures will gradually, eventually drop below the lower limit of the STI (Survival Temperature Interval)[11].

Figure 14 shows testing results of the entire assembly in the following order of sequences:

A. 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.

B. 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).

C. 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.

D. 6300s-12000s, total power is incrementaly decreased to 15W while sink temperaturte 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.

E. 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.

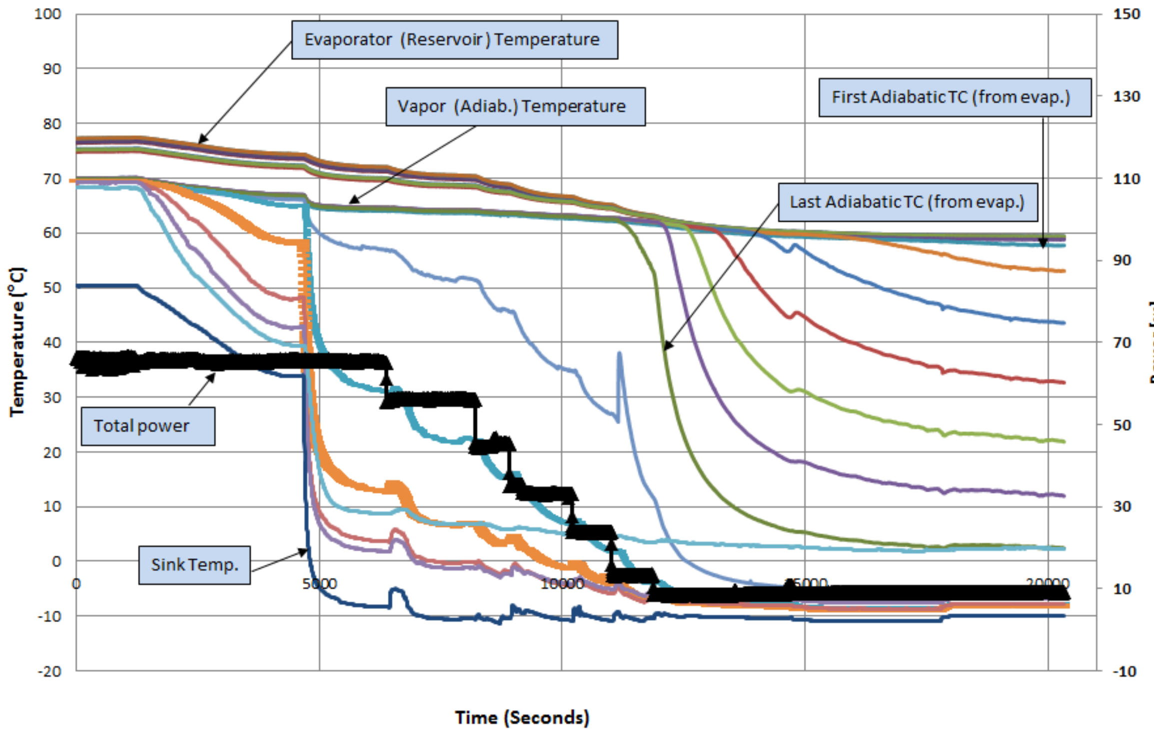


Figure 14. Thermal control survival testing results for the hybrid VCHP /HiK™ plate.

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. As mentioned above, 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.

After that, the functional hybrid VCHP was delivered to NASA for further testing and qualification and then will be tested on the ISS in the summer of 2017.

Payload 2:

The first step in fabricating a HiK™ plate is to determine the location of the high power components on the aluminum board, as well as the location of the cooling areas. The second step is to design the heat pipe by selecting the working fluid and its amount and the wick structure. Water is selected as the working fluid and screen copper wick is selected as the heat pipe's wick structure. Two HiK™ plates were designed, fabricated, tested, and shipped to NASA. Each HiK™ plate has 9 copper/water heat pipes. Figure 15 shows the expected performance for each heat pipe at 1 inch against gravity. Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit.

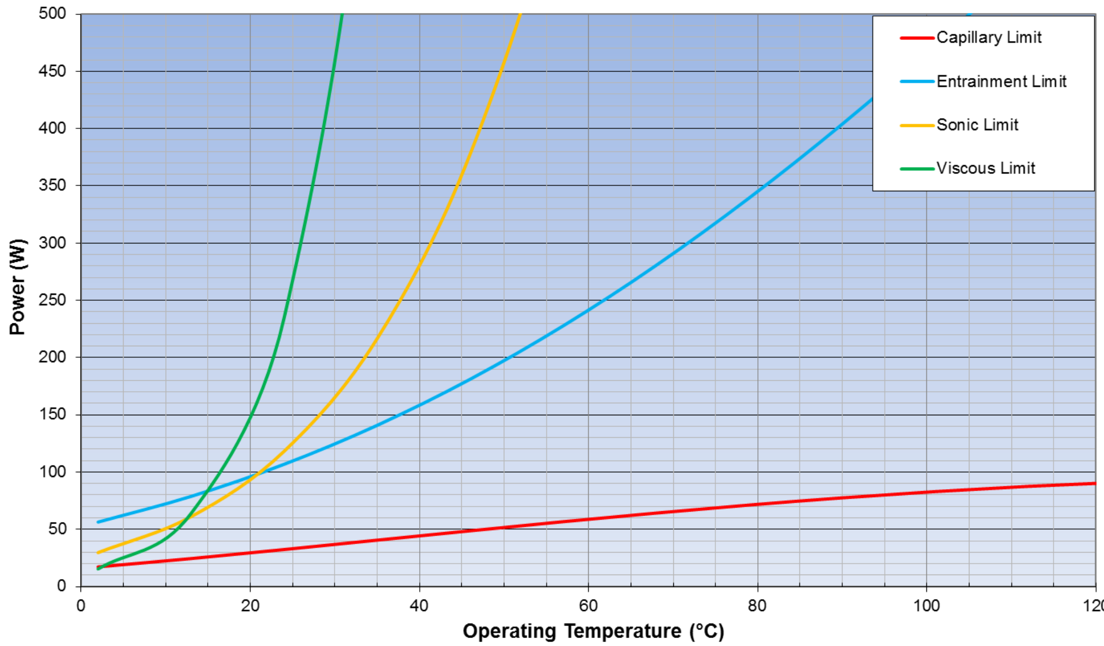
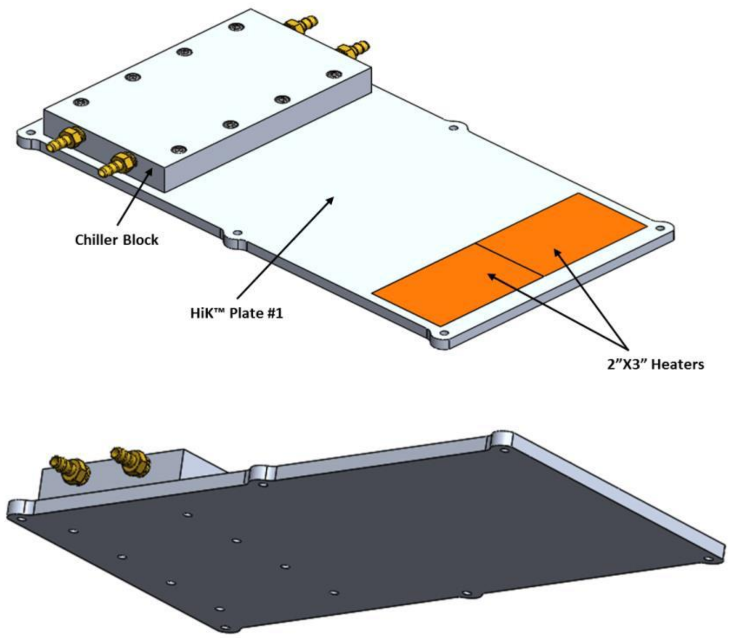
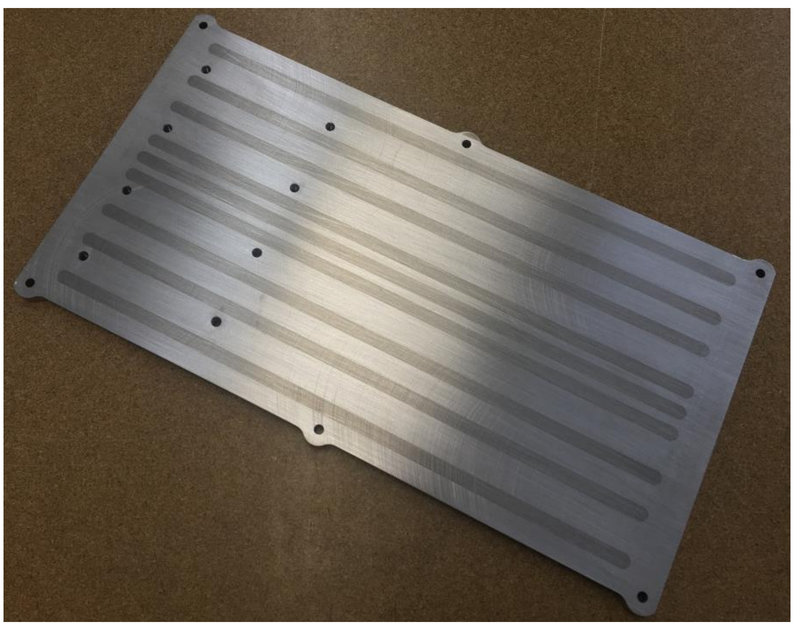


Figure 15. Heat pipe limit chart for the embedded copper/water heat pipes into the HiK™ plate for ISS APTx experiment.

Figure 16 shows the design of the HiK™ plate for the ISS experiment in payload 2. Two 53W (2"x3") 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, and about 30 TCs will be used to monitor the temperatures. Freeze/thaw testing was performed successfully for the shipped HiK™ plates as shown in Figure 17. Freeze/thaw test is conducted for both HiK™ plates from temperature ranging from -30 to +70°C for 15 cycles.



(a)



(b)

Figure 16. The HiK™ plate for the ISS experiment in payload 2: (a) The CAD model, (b) The fabricated HiK™ plate.

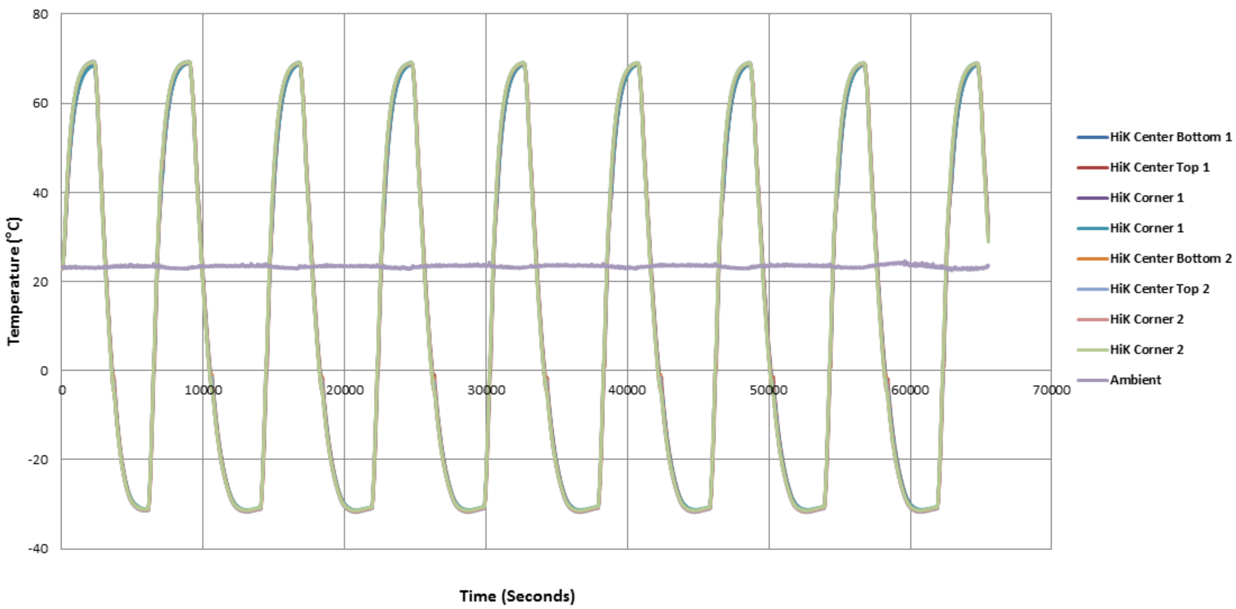


Figure 17. The temperature profile of HiK™ plates exposed to thermal cycling.

The flight article was delivered to NASA for testing and qualification. The flight package will be tested on the ISS in the summer of 2017.

V. 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 will verify the operation of the hybrid wick VCHP at the maximum and shutdown temperatures and 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. The thermal control test 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. Furthermore, 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 repectively, 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 in an unfavorable orientation (against gravity) of 1 inch. Also, freeze/thaw test is conducted successfully for both HiK™ plates from temperature ranging from -30 to +70°C for 15 cycles. The flight package will be tested in Low-Earth Orbit, aboard the ISS in the summer of 2017.

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