

Advanced Passive Thermal eXperiment (APT_x) for Warm-Reservoir Hybrid-Wick Variable Conductance Heat Pipes on the International Space Station (ISS)

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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 impacted by unprecedented power requirements and 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 power needs during periods of darkness, such as the 14-day-long lunar night. Therefore, future exploration activities will have the need of thermal management systems that can provide higher reliability and performance. Several novel new passive thermal technologies have been selected and tested on the board of the International Space Station (ISS) during the Advanced Passive Thermal eXperiment (APT_x) project.

A hybrid-wick copper-Monel-water Variable Conductance Heat Pipe (VCHP) with warm reservoir design that consists of a copper evaporator (with sintered wick), a monel adiabatic section and a condenser both with grooved wick inside was developed and tested successfully on ground. The VCHP worked on-board ISS, but at higher temperatures than expected. The different behavior in microgravity are primarily due to the absence of natural convection. A new flight warm reservoir VCHP design is developed to mitigate these shortcomings, and has been tested successfully on the ground.

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
APT _x	=	Advanced Passive Thermal experiment
CCHPs	=	Constant Conductance Heat Pipes
ISS	=	International Space Station
LHPs	=	Loop Heat Pipes
NASA	=	the National Aeronautics and Space Administration
NCG	=	Non Condensable Gas
VCHPs	=	Variable Conductance Heat Pipes

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WEB = Warm Electronics Box

I. Introduction

The Advanced Passive Thermal Experiment (APT_x), is a collaboration between the Johnson Space Center (JSC), Marshall Space Flight Center (MSFC), the University of Texas, and Advanced Cooling Technologies, Inc. (ACT), to address the current technical gaps in thermal management systems. Three new technologies were selected for testing on board the International Space Station (ISS): (1) a new hybrid wick, warm biased integrated reservoir, variable conductance heat pipe (VCHP) developed that can passively adjust to changing thermal conditions allowing efficient energy transport in warm conditions and power conservation in cold conditions in both microgravity and planetary gravity environments; (2) a high conductivity plate (HiK™) for heat acquisition and heat sharing; and (3) an early concept of an electro-wetting heat pipe that may ultimately have the potential to increase heat transport by orders of magnitude over existing heat pipes completely gravity independent. The testing of these devices in a relevant extended micro-gravity environment will add essential information to on-going ground testing to help improve performance and understanding of these devices and will increase the Technology Readiness Level (TRL) in preparation for use in deep space missions, Lunar/Mars landers and rovers and other future spacecraft architectures. The use of these technologies is aimed at reduction in space system mass and power, enhanced heat transport and thermal switching in diverse, extreme thermal environments, and the passive nature of these devices has the potential to increase the reliability of thermal management systems for extended space missions compared to traditional passive and active (mechanically pumped) systems¹.

In this paper, warm-reservoir hybrid-wick VCHPs will be discussed; the HiK™ plate testing is discussed in another paper². Basically, 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 are among the near-term NASA applications. A hybrid 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 keep 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. In order to ensure the successful operation of the warm reservoir hybrid VCHP in space, there is a need to test in micro-gravity environment on the ISS^{3,4}.

The ISS as shown in Figure 1 is the only long-duration platform that can be used to validate operations, concepts and advanced technologies in space relevant conditions. 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, 2013⁵). The successful test in microgravity on the ISS for the warm reservoir hybrid VCHP will raise the TRL to 7.



Figure 1. The International Space Station (ISS) in low Earth orbit (Credit: NASA).

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 are 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.

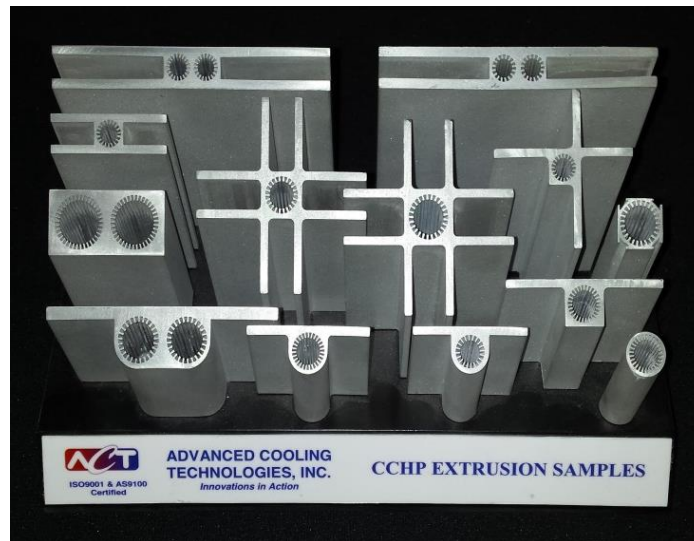


Figure 2. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow long heat pipes for spacecraft applications, but only work about 0.10 inch (0.00254m) against gravity for earth-based testing (ACT Inc., 2013⁶).

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 power³. 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 Kroliczek⁷, 1979), and (Marcus⁸, 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.

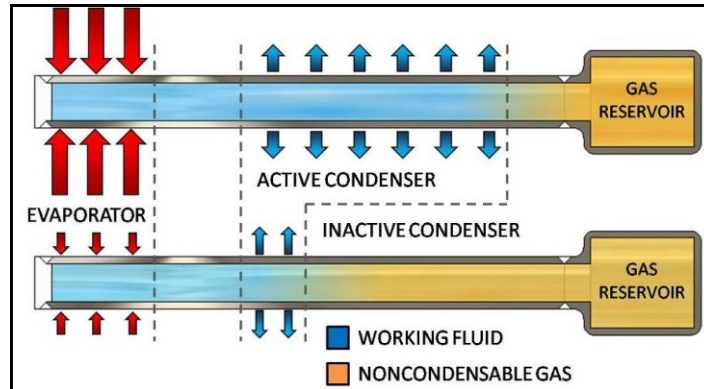


Figure 3. Operation of a VCHP. As heat load increases, the temperature dependent saturation pressure of the working fluid increases and the NCG is compressed into the reservoir (top). As heat input decreases, the working fluid saturation pressure decreases and the non-condensable gas is allowed to expand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

For the simple VCHP illustrated in Figure 3, the reservoir is cold-biased as in most spacecraft applications. Electric heaters on the reservoir are then used to control the temperature to within $\pm 2^\circ\text{C}$. 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) environment⁹. 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.

III. Heat Pipes Advanced Features

- **Hybrid wick heat pipes**

Heat flux limit in axial grooved heat pipe evaporators normally starts at 5-15 W/cm². In order to increase the heat flux limit to more than 50 W/cm², the concept as shown in Figure 4 is to develop heat pipes with a hybrid wick that contains screen mesh or sintered evaporator wicks for the evaporator region. 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.

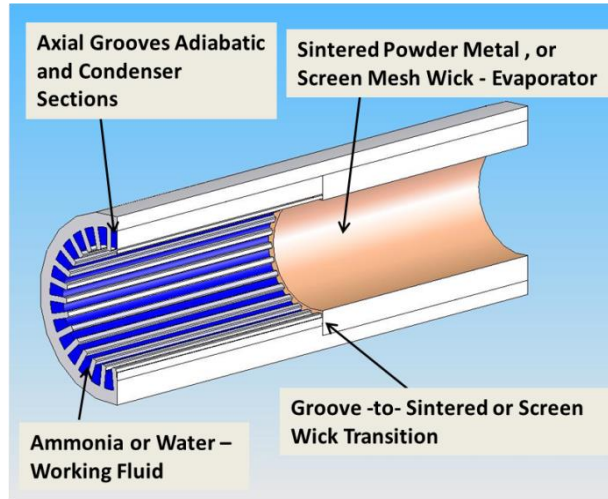


Figure 4. Hybrid CCHPs: axial grooved adiabatic and condenser sections - screen mesh or sintered evaporator wick.

The previous work² 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 transported against planetary gravity is 150 W or higher). Thus, the screen mesh wick was ruled out in the favor of sintered wick..

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 5 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).

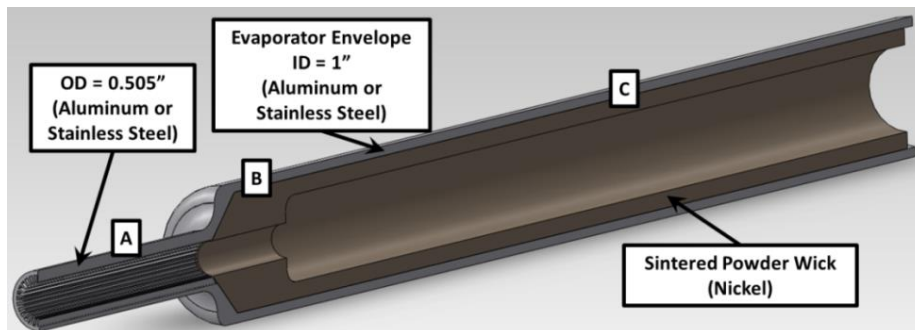


Figure 5. Planetary VCHP evaporator design (sintered wick after insertion into evaporator).

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 6 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.², 2015).

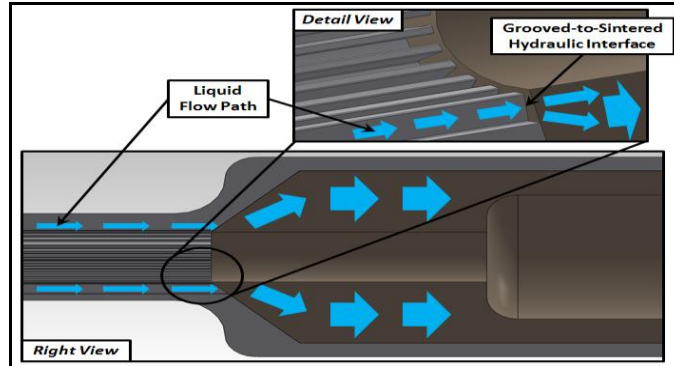


Figure 6. Planetary VCHP evaporator 45° conical interface (cross sectional right view and detail view).

- **Warm reservoir heat pipes**

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 7. In this case the warm reservoir mainly follows the payload (i.e. evaporator) temperature. Also the partial pressure of the NCG in the reservoir tends to be close to the total pressure of the system because of the absence of the working fluid liquid phase offering a stiffer behavior during temperature fluctuations. In addition, unlike in the cold reservoir case, sink temperature fluctuations do not influence significantly the gas in the reservoir and therefore, the gas provides a stiffer opposition to the vapor in the condenser, resulting in a more effective front location change. In conclusion, warm reservoir provides 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 supplying 1 W over the 14-day long Lunar night requires 5 kg of solar cells, batteries, etc. (Anderson et al., 2010⁹).

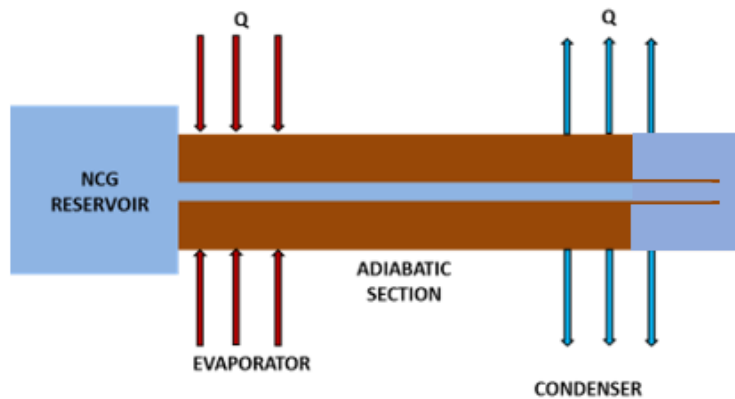


Figure 7. Schematic diagram of thermally coupled warm reservoir heat pipe.

IV. ISS Flight Hardware

Future human exploration activities require thermal management systems to provide higher reliability, adaptability, mass and power reduction, and increased performance. The use of these technologies is aimed at reduction in space system mass and power, enhanced heat transport and thermal switching in extreme thermal environments. The passive nature of the thermal management components has the potential to increase the reliability

of thermal management systems for extended space missions compared to traditional passive and active systems. In an effort to start addressing the current technical gaps in thermal management systems, novel new passive thermal technologies have been selected and included as part of a suite of experiments tested on the board of the ISS, in 2017.

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 microgravity duration is much too short. The principal mechanism that has not been tested on the moon or Mars is the flooding limit. Our design used a lunar flooding limit for thermosyphons, validated by NASA Glenn with parabolic flights¹⁰. Consequently, ACT Inc., together with NASA Marshall Space Flight Center and NASA Johnson Space Center, worked together to test and validate hybrid wick VCHP with warm reservoir and HiK™ plates on the ISS under the Advanced Passive Thermal experiment (APT_x) 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 were:

- Demonstrate VCHP operation at the maximum temperature.
 - Show the gas front dynamics as a function of sink temperature and power fluctuations.
- 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).

The APT_x consists of two separate payloads that were 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. (HiK™ plate in Payload 2 will be discussed in a separate paper²)

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 APT_x had 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 was tested inside the ISS. Since water is not compatible with aluminum, the flight test VCHP had copper and Monel as the envelope.

The HiK™ plate in payload 1, which is assembled with 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 69°C to 67°C over widely varying sink temperatures between 50 and - 4°C. Furthermore, the VCHP can protect the payload against extremely low sink temperatures during survival (See ICES-2017-272: Ababneh et.al¹¹ for the full details).

NASA Ground Testing of Payload 1:

The fabricated VCHP was tested to demonstrate VCHP operation/shutdown and its thermal control capability. A chiller block and TEC assembly were attached to the VCHP condenser to provide a sink temperature that could be varied between -10 to 50°C. A 100W (3-in x 6-in) heater located directly below the evaporator was used and another reservoir heater was used as needed. The maximum applied power was approximately 50 W. Temperatures were monitored using type T thermocouples (TCs) attached to the VCHP. The condenser sink conditions were established using a TEC assembly. The assembly consisted of a Buna-N rubber sheet, a copper plate with embedded thermocouple probes to measure the sink temperature. TECs and an aluminum block connected to a fluid loop. The Propylene glycol and water (PGW) flow to the condenser was controlled by the Phase Change Heat Exchanger (PCHX), part of a testbed on ISS utilized for this project.

The testing profile for Payload 1 consisted of calibration, thermal control, shutdown, and startup. Calibration demonstrates the pipe is functional and that the vapor-gas front is in the correct location before beginning performance testing. Thermal control begins with maximum power, 50W, and maximum condenser sink temperature of 50°C. From this point, the sink temperature is ramped down to the minimum possible temperature

with full power, approximately 0°C, after which the power is ramped down while the TECs are fully activated until the system reaches shutdown condition. Thermal control demonstrates the ability of the VCHP to maintain a warm evaporator by passively changing conductivity of the pipe by the expansion of the NCG out of the reservoir, thereby changing the effective condenser length of the heat pipe. Shutdown occurs at the lowest power and sink temperature that causes the vapor-gas front to move into the adiabatic section of the VCHP, minimizing the effective length of the heat pipe and limiting the heat leak to the cold sink through only conductivity through the gas and pipe wall. Upon achieving shutdown, power is increased, shifting the location of the vapor-gas front out of the adiabatic and then out of the condenser part of the pipes and achieving maximum thermal conductivity again.

All of this test profile was demonstrated on the ground, however, not without a few anomalies. The first anomaly observed was that it was possible to put too much heat into the evaporator and drive the working fluid into the reservoir. Once this occurred, purging was required to transport the working fluid back into the pipe and restore the nominal functionality of the heat pipe. The second anomaly observed was that if the condenser was frozen before heat was applied to the evaporator, a slug of liquid could freeze inside the return tube to the reservoir. The working fluid on the backside of the slug would create enough pressure to melt and drive the slug into the reservoir. The presence of working fluid in the NCG reservoir impacted performance and was very difficult to remove. This condition occurred once on the ground and a second VCHP was sent to NASA in order to meet the delivery schedule. The new VCHP had less working fluid to try to mitigate the risk as the first VCHP had been slightly overcharged.

Microgravity Testing of Payload 1 on the ISS:

On orbit, the aforementioned four test cases were repeated— calibration, thermal control, survival, and startup. When the first calibration was performed, the heat pipe was functional and the vapor-gas front was in the proper location. The heat pipe was left with a constant power overnight with no change to the thermal profile of the heat pipe. The next day, calibration was performed again and the vapor-gas front had shifted into the condenser, designating migration of working fluid into the NCG reservoir. The heater was turned off and, after cooling, Calibration was performed for a third time and again the vapor-gas front had shifted further into the heat pipe, reducing the effective length and driving temperatures higher.

The explanation of the team that this behavior was due to a reduction in convective heat transfer within the gas of the NCG reservoir caused by the microgravity environment. This reduction of heat transfer caused the fluid in the evaporator to be warmer than the reservoir during transient heating, creating a pressure bias. The higher pressure of the working fluid in the heat pipe compared to the reservoir allows for migration of the working fluid into the reservoir, increasing overall temperatures within the pipe. During steady state, the vapor-gas front had reached equilibrium, and there was no noticeable migration of fluid into the reservoir. Due to this behavior, the heat pipe was left on continuously throughout testing on orbit and purging was attempted. Various methods of purging were attempted on orbit, including steady state, heater power oscillation, and condenser sink temperature oscillation. The most effective was a combination of 34W continuously applied to the reservoir heater and a sink temperature oscillating between -8°C and 15°C, holding for approximately 55 minutes at -8°C and 10 minutes at 15°C, with 1°C ramp up every 3 minutes.

Unfortunately, the payload had to be turned off due to loss of communication. From the understood phenomena of working fluid transport to the reservoir during transient heating, a discussion of startup methods concluded that low power startup while maintaining a frozen condenser (i.e. condenser TC temperatures at approximately -1°C) would be preferable. The intent was that as the front between Non-Condensable Gas, NCG, and vapor receded and the NCG moved towards the reservoir, vapor would condense and freeze in the condenser before it traveled to the reservoir, thus preventing migration of fluid to the reservoir. This was a similar test plan to the case occurring with the first VCHP that resulted in formation of an ice slug and forced fluid into the reservoir. As this pipe had less fluid, the possibility of this risk was decreased. In addition, the startup was attempted with low power instead of maximum power. With low power, the temperature of reservoir and evaporator should rise at a closer rate when compared to high powers and there would be a more favorable gradient between the two. The smaller gradient minimizes the potential of migration of fluid to the evaporator. Thus, a low power startup with a frozen condenser was attempted.

A similar behavior was noted in the on orbit heat pipe during this test to the first VCHP on the ground, reaffirming that power must be input before freezing the condenser. Ice formed in the condenser portion, including

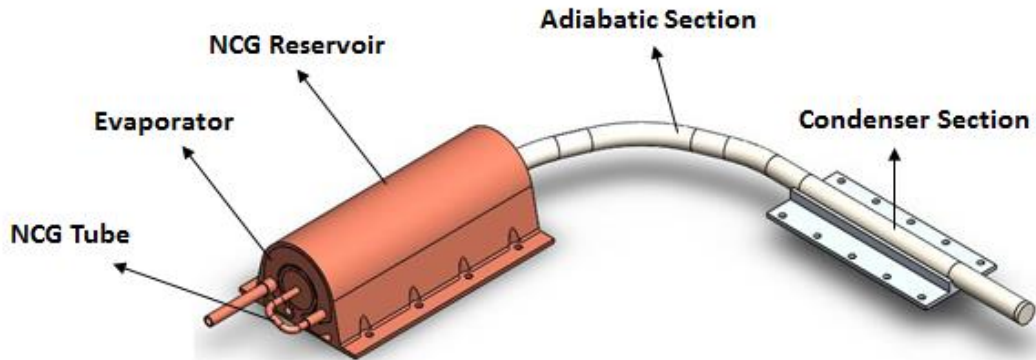
the NCG return tube, and caused a blockage between evaporator and reservoir, or vapor and NCG. The pressure rose until the vapor pressure dominated and dislodged the ice slug from the condenser region and it melted. This caused a pressure wave of vapor sweeping towards the reservoir, injecting fluid into the reservoir. The additional fluid mixed with the NCG and the pipe responded as if it was charged with less working fluid and more NCG, and the vapor front again shifted towards the evaporator. Due to this migration, temperatures in the pipe elevated such that only low powers could be used to maintain the heat pipe within temperature limits. At the low powers, the purge was less effective, as we had seen in earlier on orbit testing, and the pipe was unable to return to nominal functionality before it had to be uninstalled and returned to earth.

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. As shown the VCHP worked on ISS at higher temperatures than expected due to the evaporator's design that is therefore not appropriate for micro-g environment. Hence, a new design of the warm reservoir VCHP was developed.

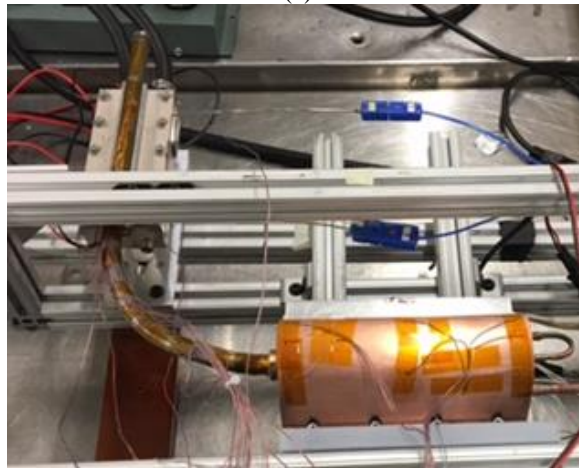
V. Redesigned Warm Reservoir VCHP

Ground Testing for the modified warm reservoir VCHP:

The hybrid-wick copper-Monel-water VCHP modified 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. Figure 8 shows the CAD model and the fabricated new hybrid wick VCHP.



(a)



(b)

Figure 8. The modified hybrid wick warm reservoir VCHP: (a) The CAD model, (b) The fabricated VCHP.

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 -20 to 50°C. A 100W (3"x 6") heater located directly below the evaporator is used and another reservoir heater is used as needed. The maximum applied power is ~ 66 W (assuming the power loss is ~ 16 W at 70°C vapor temperature). Temperatures are monitored using thermocouples (TCs) attached to the VCHP. The Ethylene glycol and water (EGW) flow to the condenser from the chiller unit is adjusted via a temperature controller, based on the required sink temperature. The NCG 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.

Testing Results:

Figure 9 shows the thermal control testing results for the modified 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 9. The power was maintained constant at 67W while the sink temperature was incrementally decreased at about 3000 seconds (the sink temperature was about 26 °C), and at about 7200 seconds (the sink temperature was about -20°C) then the sink temperature increased back again to 50°C at ~ 18000 seconds (i.e. steady state condition). Note that the evaporator (payload) temperature only varies from 70°C to 68°C as the sink temperature swings between 50 and -7°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 -7°C.

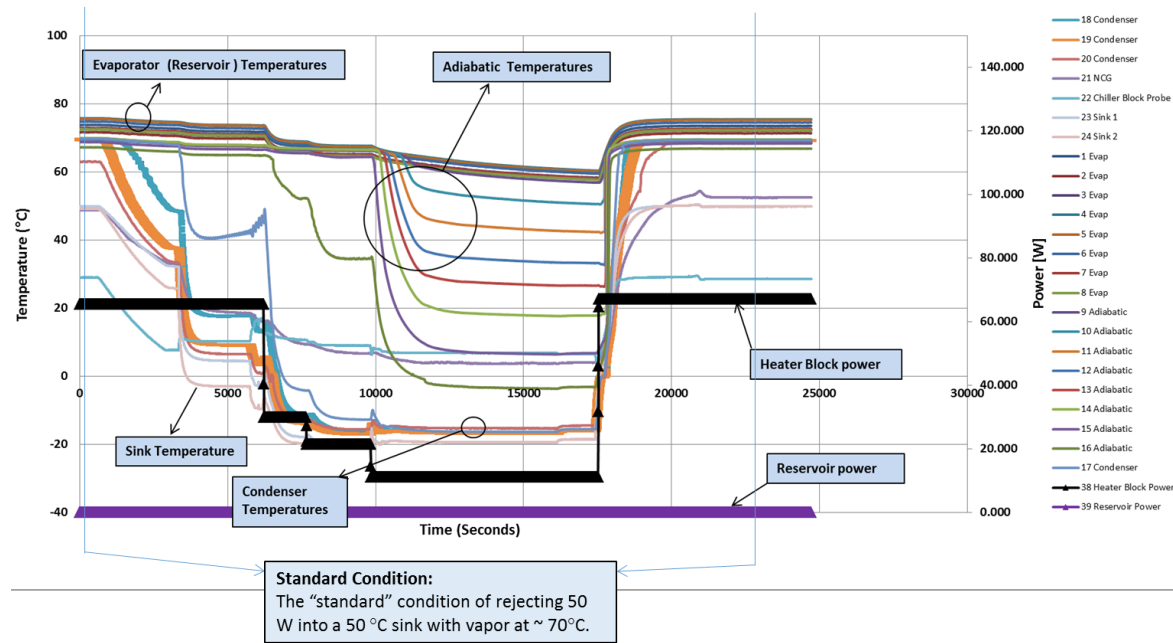


Figure 9. Thermal control testing for the hybrid flight VCHP.

Figure 9 shows testing results of the entire assembly in the following order of sequences:

- 0-1000s, steady state at standard condition where the total power is 67 W (50W nominal and a measured power loss to the ambient of 17W) with maximum sink temperature of 50°C and vapor temperature of ~70°C.
- 1000s-6200s, total power is constant (and maximum) while sink temperature is decreased to -7°C. As a result, vapor temperature decreased to ~68°C.
- 6200s-7200s, total power is incrementally decreased to 30W while sink temperature further decreased and stabilized at ~ -20°C. Slightly before the 7200s, 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.
- 7200s to the 17000s, the total power was further reduced to 11W 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 $\sim 58^{\circ}\text{C}$. The authors believe that the total applied power of 11W 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 11W of total power.

- E. 17000s-end, total power is increased to 67 W while sink temperature increased 50°C (i.e. reaching the standard condition again). The vapor temperature was back again to $\sim 70^{\circ}\text{C}$.

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 the heat pipe envelope in the adiabatic section. Assuming that no power is supplied to the instruments, the instrument temperatures will eventually drop below the lower limit of the STI (Survival Temperature Interval)¹².

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 $2.5\text{ W}/^{\circ}\text{C}$. 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 (-20°C). The result is $0.01282\text{ W}/^{\circ}\text{C}$ and the turndown ratio is ~ 195 .

VI. Conclusion

ACT Inc., NASA Marshall Space Flight Center and NASA Johnson Space Center, worked together to test and validate hybrid wick VCHP with warm reservoir and HiK™ plates on the ISS microgravity environment. The objective of the flight test is to 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 on ground and on board ISS. The HiK™ plates showed the expected performance. However, the VCHP worked at higher temperatures than expected during ground test due to the evaporator's design that was not appropriate for micro-g environment. The different behavior in microgravity are primarily due to the absence of natural convection. Hence, a new modified warm reservoir hybrid VCHP was developed. The thermal control ground test of the modified hybrid wick VCHP with warm reservoir shows that vapor temperature varies from 70°C to 68°C over widely varying sink temperatures between 50 and -7°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 $0.01282\text{ W}/^{\circ}\text{C}$ respectively. This shows the heat pipe can operate as a variable thermal link with large turn down ratio (i.e. 195). The modified warm reservoir hybrid VCHP will be tested in Low-Earth orbit, aboard the ISS tentatively in 2018.

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