Non-Integrated Hot-Reservoir Variable Conductance Heat Pipe Tested on Peregrine Lander

Calin Tarau, Jeff Diebold
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

William Johnson
NASA Marshall Space Flight Center

Jason Carter and Eric Conaway
Astrobotic Technology

As NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architecture will be impacted by unprecedented power requirements and extreme thermal environments. In these conditions, thermal management systems need to reject large heat loads into hot environments and have high heat rejection turn-down ratios to minimize vehicle power needs during periods of cold darkness, such as the 14-day lunar night. Variable conductance heat pipes (VCHP) are capable of passively transporting large quantities of heat and provide high thermal turndown ratios that are ideal for surviving extremely cold environments. As shown in a previous paper [1] a non-integrated Hot Reservoir the VCHP was developed as flight hardware designed to fly onboard Astrobotic Technology's lunar lander Peregrine and operate (as experimental hardware) both during transit and on the lunar surface utilizing a hybrid wick. The evaporator wick was 3D printed while the adiabatic and condenser sections utilized grooved wicks with high permeability optimum for operation in a microgravity environment. Three sets of tests were performed on this VCHP: testing on ground in ambient at ACT facilities (the results were presented at ICES 2022), pre-flight testing on ground in vacuum at NASA MSFC and testing during flight in microgravity on Peregrine Lander. In this paper, the development of the non-integrated HR-VCHP and the results obtained during the three sets of tests are discussed. All the successful evaluation, characterization and testing of the device both on ground and in space in microgravity led to its TRL increase to 8.

Nomenclature

ACT	=	Advanced Cooling Technologies
CCHP	=	Constant Conductance Heat Pipes
CDAQ	=	Compact Data Acquisition
HR-VCHP	=	Hot Reservoir Variable Conductance Heat Pipe
MSFC	=	Marshall Space Flight Center
NCG	=	Non-Condensable Gas
TC	=	Thermocouple
TDU	=	Technology Demonstration Unit
TRL	=	Technology Readiness Level
TVAC	=	Thermal Vacuum Chamber
VCHP	=	Variable Conductance Heat Pipe

I. Introduction

Under a Phase III SBIR program ACT developed an aluminum-ammonia non-integrated hot-reservoir variable conductance heat pipe (HR-VCHP) with a hybrid wick as flight hardware to be integrated on the Astrobotic's Peregrine I Lunar Lander for testing and operation as a stand-alone technology demonstration unit onboard the lander in microgravity and on the lunar surface in a gravity-aided orientation. The development of this VCHP, that eventually led to TRL 8, consisted of four distinct phases:

1. Design, fabrication and ground testing in ambient at ACT facilities
2. Pre-flight benchtop, vibration and thermal vacuum ground testing at NASA MSFC
3. Instrumentation and integration on the Peregrine 1 at Astrobotic facilities
4. Flight testing in microgravity

This paper briefs all four phases. However, since the details of the first phase, the development at ACT facilities, were already documented in [1] and presented at ICES 2022, this paper will only present design and testing results for completeness.

II. Background

Variable Conductance Heat Pipes

A VCHP is similar to a conventional heat pipe but has a reservoir containing a controlled amount of non-condensable gas (NCG). The VCHP works by passively varying the amount of condenser available to the working fluid, see Figure 1, in response to changes in vapor pressure which is a function of vapor temperature. A decrease in either sink temperature or power input will cause the vapor temperature and pressure to decrease. This allows the NCG to expand and block a portion of the condenser. The passive increase in thermal resistance limits the decrease in vapor and heat source temperature. Figure 1 illustrates a cold-reservoir VCHP where the temperature of the NCG reservoir follows the sink temperature. As the sink temperature decreases, the NCG temperature within the reservoir will also decrease, limiting the ability of the NCG to expand and block the condenser. During applications in extreme cold environments, such as the long lunar night (100K), the NCG must expand to fully block the condenser and adiabatic section to minimize heat leaks from the evaporator to the condenser. For a cold-biased reservoir VCHP, this typically requires electrical heating of the reservoir with 1-2W of thermal control power (to avoid confusion, this is not survival power or heat leaks) for the entire 14-day long lunar night, to push the NCG front into the adiabatic section as close as possible to the evaporator.

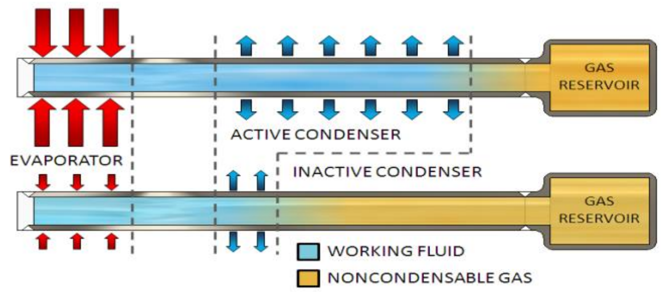


Figure 1. Operation of a cold-reservoir VCHP.

A hot-reservoir VCHP, illustrated in both Figure 2a and Figure 2b, utilizes an NCG reservoir close to the evaporator which thermally follows the heat source temperature. An internal tube passes through the heat pipe envelope to connect the NCG reservoir to the condenser. The hot-reservoir VCHP operates in the same manner as the cold-reservoir VCHP; a decrease in vapor temperature allows NCG to expand and block the condenser, but the elevated temperature of the reservoir results in superior passive temperature control and eliminates the need for electrical reservoir heating during survival mode [1,2 3,4]. For comparison, heating the reservoir of a cold-reservoir VCHP is necessary to shut down the condenser and potentially push the front further into the adiabatic section, as close as possible to the evaporator, to minimize the conductance. Again, this heating (with control power) would compensate for the lack of sensitivity that the cold-reservoir VCHP has. In a cold-reservoir VCHP, the reservoir experiences lower temperatures (without heating) so the NCG contracts more than in a hot-reservoir VCHP, generating a lower opposition to the vapor pressure in the evaporator. In addition, the reservoir also contains working fluid vapor at a partial pressure equal to the vapor pressure at the reservoir temperature. This component has two negative contributions to the lack of sensitivity: a) It allows less NCG charge for the same reservoir volume and b) When reservoir temperature decreases, the pressure component corresponding to the vapor, decreases making more "room" for the already contracting NCG. In a HR-VCHP, the reservoir contains mostly NCG. Moreover, its temperature doesn't follow the sink but it follows the source. When sink temperature decreases, NCG pressure decreases much less than in the cold-reservoir VCHP case, generating a stronger opposition to the vapor pressure in the pipe, and, therefore expanding "faster" through the condenser and adiabatic section towards the evaporator. The performance of both cold and hot-reservoir VCHPs are analytically modeled using the flat-front theory and they are discussed in [4]. This model assumes a flat, infinitely thin boundary that separates working fluid vapor and NCG.

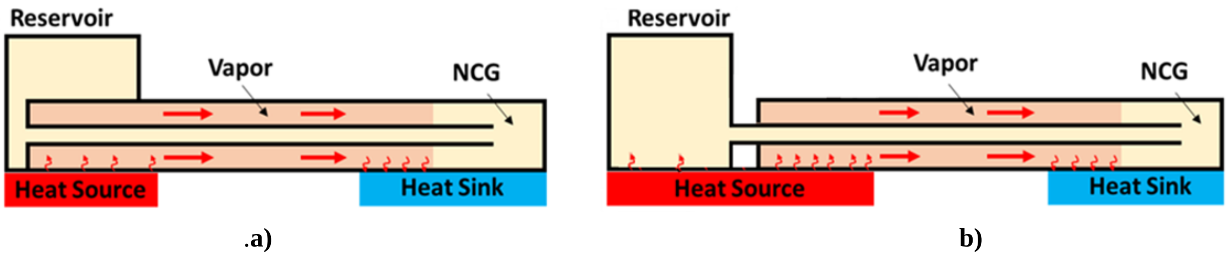


Figure 2. HR-VCHP a) *Integrated reservoir configuration*: the reservoir is physically and thermally connected to the evaporator b) *Non-integrated reservoir configuration*: the reservoir is physically and thermally connected only to the heat source, upstream the evaporator

While hot-reservoir VCHPs offer superior passive thermal control compared to cold-reservoir VCHPs, over time their performance can be degraded due to the migration of working fluid into the reservoir [5]. The partial pressure of superheated vapor into the hot reservoir displaces NCG from the reservoir resulting in a higher nominal operating temperature for the heat pipe. This challenge was experimentally observed by ACT during microgravity testing of a hot-reservoir VCHP onboard the International Space Station (ISS), indicating the need for advanced fluid control [5]. In the illustration of Figure 2a, representative of the VCHP tested onboard the International Space Station, the NCG reservoir was integrated with the evaporator. If the reservoir is not integrated as in Figure 2b, where the reservoir is separated from the evaporator, then during periods of non-operation an independent heater can be applied to the reservoir in order to purge the working fluid from the reservoir and restore normal operation. This is critical to ensure long-term reliability of the hot-reservoir VCHP. The reservoir purge process is experimentally demonstrated during ground testing [1] and also in microgravity on Peregrine as shown later in this paper. It was concluded that the non-integrated hot-reservoir (Figure 2b) and the hybrid wick designs are ideal for lunar and planetary surface applications and provide the following advantages:

- The hot-reservoir provides superior passive thermal control compared to a cold-reservoir VCHP [2].
- The non-integrated reservoir improves control over the distribution of working fluid and NCG during periods of non-operation.
- The hybrid wick allows the VCHP to operate effectively in both microgravity (transit) and on the surface in a gravity aided orientation [5,6].

III. VCHP Design and Ground Testing in Ambient at ACT

Non-Integrated HR-VCHP Design

The designing process of the non-integrated HR-VCHP was mainly driven by the requirements resulted from Peregrine 1 testing capabilities, their availability and mission profile. As mentioned, the HR-VCHP was going to operate as a stand-alone technology demonstration unit onboard the lander in microgravity and on the lunar surface in a gravity-aided orientation. The VCHP was going to be mounted on the enclosure panel alongside electronic components, but the heat transported by the VCHP will be supplied by dedicated heaters. Early in the design process, Astrobotic provided the limitation that the VCHP heaters could deliver a maximum of 40W each. The hybrid wick HR-VCHP was originally intended to utilize a grooved wick in the condenser and adiabatic section and a sintered powder wick in the evaporator. Due to scheduling constraints and the time required to manufacture sinter powdered wicks, ACT elected to design a 3D-printed evaporator that contained a 3D-printed porous wick (see [1]). Figure 3 shows an image of the completed aluminum-ammonia non-integrated hot-reservoir VCHP with hybrid wick for Astrobotic's Lunar Lander Peregrine I on a test stand at ACT. As seen in Figure 3, the evaporator and reservoir were mounted to the same aluminum plate that will be offset from the enclosure panel of the lander by legs manufactured from Ultem-1000, a low thermal conductivity material. After the evaporator, the grooved extrusion was bent so that the condenser could be mounted directly to the enclosure panel. The lengths of the evaporator, adiabatic and condenser sections were 10.2 cm, 10.2 cm and 17.8 cm, respectively. The NCG reservoir was sized based on flat front theory assumptions. Argon was used as the NCG. The total mass of the non-integrated HR-VCHP with hybrid wick, including the aluminum plate and low thermal conductivity legs, was 0.347 kg. The numbered boxes in Figure 3 indicate the locations of TCs for the experiments at ACT.

A strip heater was placed on the backside of the aluminum plate shared by the reservoir and evaporator as indicated in Figure 3. The heater was placed so that the reservoir operated at a higher temperature than the evaporator. Figure 3 also shows that a separate heater was placed on the reservoir. The purpose of this heater was to demonstrate the ability of the non-integrated HR-VCHP to purge working fluid from the reservoir via heating. The reservoir heater was only used during the purging process discussed below. During normal operation, the dedicated reservoir heater was off.

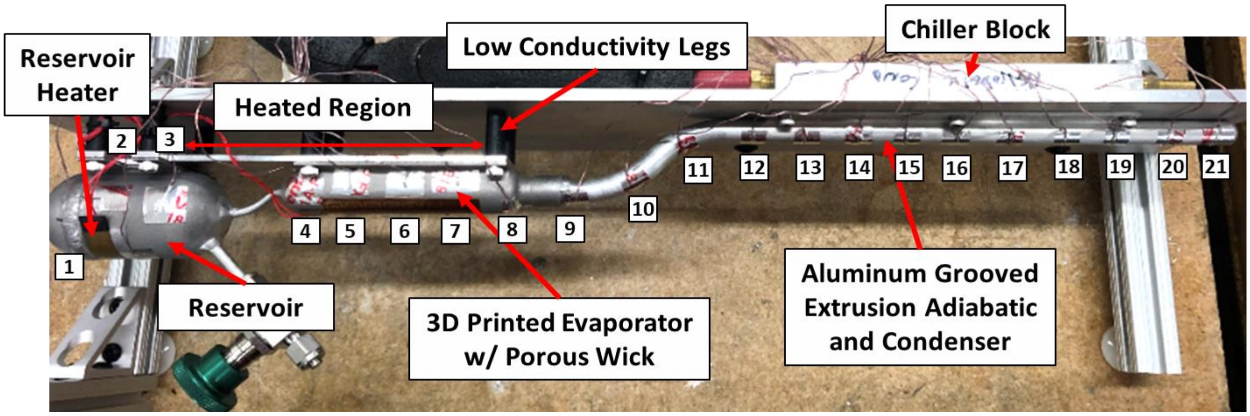


Figure 3. Image of the completed aluminum-ammonia non-integrated HR-VCHP with hybrid wick for Astrobotic's Lunar Lander Peregrine I. Locations of numbered TCs are indicated.

HR-VCHP Ground Testing in Ambient at ACT

The experimental procedures at ACT included a startup test, a thermal control test and a VCHP re-conditioning by purging test. Figure 4 shows experimental data of the startup process of the Astrobotic hot-reservoir VCHP in the vertical orientation with 40W applied to the evaporator and a chiller block setpoint of 40°C. A smooth startup was observed indicating that the hybrid wick successfully prevented temperature spikes associated with the working fluid pooling in the evaporator. The steady-state temperatures of the evaporator and reservoir were 53.6°C and 61.8°C, respectively. Again, the HR-VCHP was intentionally designed so the reservoir would be warmer than the evaporator to prevent working fluid from diffusing and condensing in the reservoir.

Note that the HT-VCHP was intended to operate in both microgravity and on the lunar surface. While the experimental results presented here were acquired in the vertical orientation, the HR-VCHP was also tested with a slight adverse elevation (evaporator above the condenser by 2.54mm). Testing at a slight adverse elevation is standard practice to ensure the heat pipe can operate in microgravity. The intended operating condition of 40W is significantly lower than the predicted maximum power of the heat pipe (~200W based on the capillary limit). As a result, the orientation of the HR-VCHP had negligible effect on performance at the design condition.

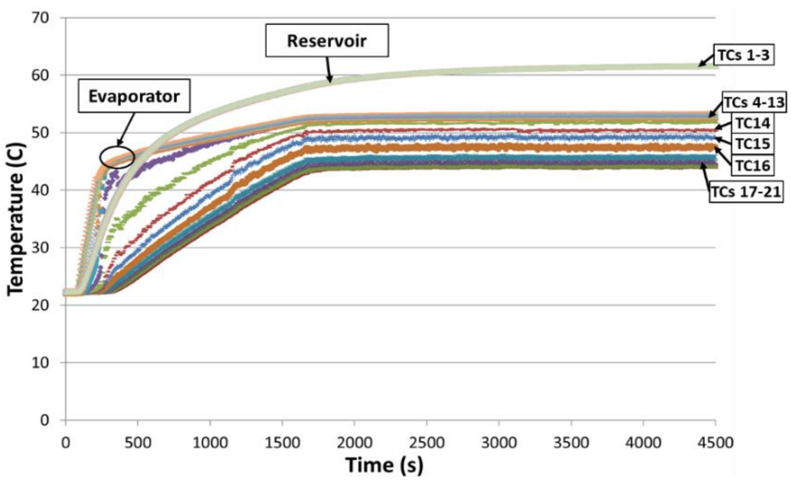


Figure 4. Startup of the HR-VCHP with hybrid-wick in the vertical orientation. Power = 40W. Chiller Block Setpoint temperature = 40°C. See Error! Reference source not found.**3 for TC numbers.**

Figure 5 shows a thermal control test of the HR-VCHP. The plot begins shortly after a startup period. The power was 40W and the chiller block setpoint was 40°C. The steady-state evaporator (TC 4) temperature was 53.6°C. After achieving the initial steady state, the chiller block setpoint temperature decreased in 20°C increments. The pipe remained at each new setpoint for a short period of time, approximately 15-20 minutes to allow the pipe to approach a new steady state condition and then the setpoint of the chiller block was further reduced. This process was carried out until the chiller block setpoint temperature was -100°C. While applying 40W to the HR-VCHP, reducing the setpoint temperature from 40°C to -100°C the evaporator temperature decreased from 53.6°C to 37.3°C, a reduction of only 16.3°C. Between approximately 8,000 and 10,000 seconds the power to the evaporator was reduced to 10W and then after 10,000 seconds the power was further reduced to only 1W. The pipe remained at 1W and a setpoint of -100C until a new steady state was reached, resulting in an evaporator temperature of -37.0°C. Many electronics have a survival temperature of approximately -40°C. In the current setup the HR-VCHP could maintain the minimum (survival) temperature of the "payload" with a sink temperature of -100°C by using only 1W of survival power.

It is noted that the freezing of the ammonia (as seen in Figure 5) in the grooves would not impact the thermal control or the performance of the VCHP as it occurs in the inactive part of the condenser.

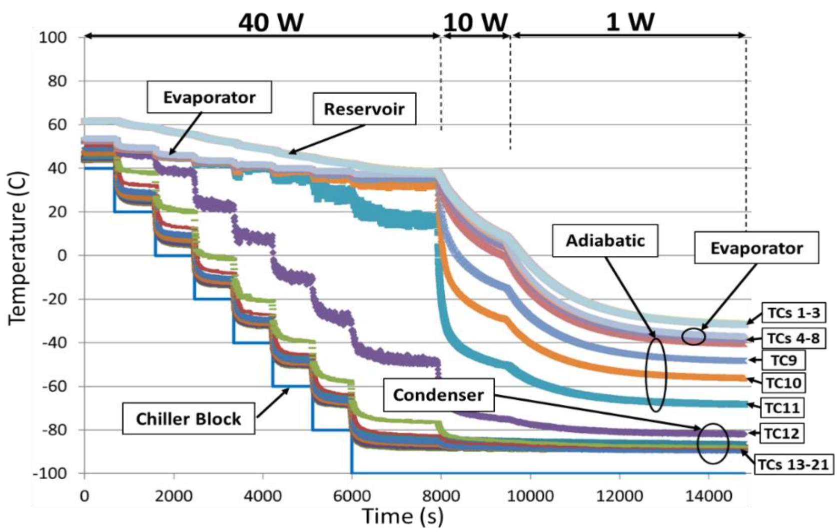


Figure 5. Thermal control test of the non-integrated HR-VCHP with hybrid-wick. Initial conditions: Power = 40W, Chiller Block Setpoint = 40°C, Evaporator Operating Temperature = 53.6°C. See Error! Reference source not found.**3 for TC numbers.**

The overall conductance of the HR-VCHP was estimated by using the applied power and the temperature difference between the evaporator flange and the chiller block. At the design operating condition (t=0s in Figure 5) the conductance was estimated to be 2.93 W/°C. At the low temperature/low power survival condition (t=14,500s in Figure 5) the conductance was estimated to be 0.0158 W/°C. The turndown ratio was defined as the ratio of these two conductance values. Based on these results, the estimated turndown ratio of the HR-VCHP was 185:1.

Figure 6 shows the variation in the HR-VCHP estimated conductance as a function of the chiller block temperature at a constant applied power of 40W. The conductance at the minimum sink and only 1W of applied power is also indicated. As the sink temperature was reduced, the decreasing vapor pressure allowed the NCG front to advance further into the condenser resulting in increased thermal resistance. It should be noted that due to time constraints it was not possible to test the HR-VCHP at high powers so the true maximum conductance of the pipe and therefore the true turndown ratio are probably higher than the values reported here.

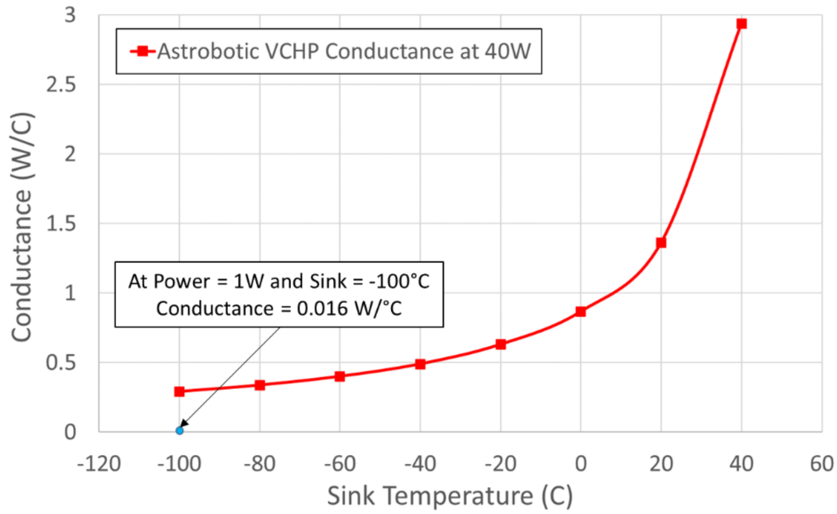


Figure 6. Variation in conductance of the HR-VCHP with sink temperature at a fixed power of 40W. The conductance at the minimum sink temperature and 1W applied power is also indicated.

Figure 7 compares the instantaneous temperature distributions along the HR-VCHP at the design operating condition (40W and 40°C sink) and the survival operating condition (1W and -100°C sink). As is observable, at the design condition (Figure 7a) the reservoir operated approximately 8°C hotter than the evaporator. The elevated reservoir temperature was due to its placement relative to the heat source. The HR-VCHP was isothermal from TC4 in the evaporator to TC13 located within the condenser (see Figure 3 for TC locations). The temperature began decreasing after TC13 due to the presence of NCG. Note that based on this plot the HR-VCHP was overcharged with NCG for the operating condition of 40W and sink temperature of 40°C, the condenser was not being fully utilized at this condition. Unfortunately, there was insufficient time to fine-tune the NCG charge. At the low power/low temperature condition (Figure 7b) the condenser was at a relatively uniform temperature of approximately -90°C (partially frozen) while the evaporator was at approximately -38°C.

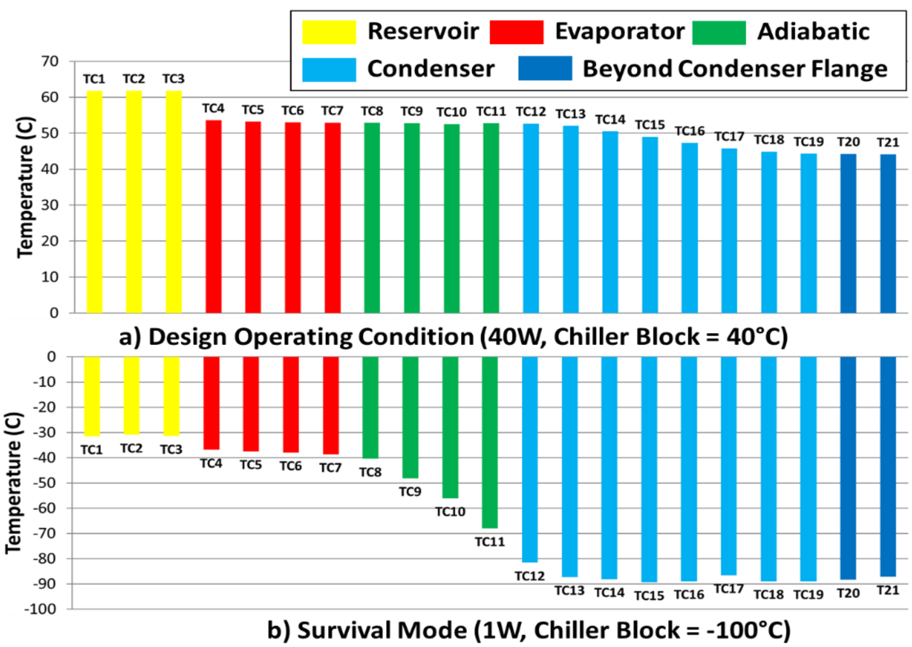


Figure 7. Comparison of instantaneous temperature distribution along the HR-VCHP during a) the design operating condition and b) the low temperature/low power survival condition. Ser Figure 3 for TC numbers.

A significant temperature gradient was observed throughout the adiabatic section indicating that the NCG front had exited the condenser and was approaching the evaporator. While the HR-VCHP was modeled using the flat-front theory, in reality, the boundary of vapor and NCG was diffuse, and it was further obscured by heat conduction through the aluminum envelope of the heat pipe.

During long periods of non-operation, working fluid can diffuse into the NCG reservoir increasing the humidity. This may occur during handling of the HR-VCHP, for example, during setup or shipping, can cause larger amounts of working fluid to end up in the reservoir. During operation, the partial pressure of the working fluid vapor within the reservoir will displace additional NCG into the condenser, increasing the thermal resistance of the VCHP and increasing the operating temperature. With a non-integrated reservoir, it is possible to independently heat the reservoir during periods of non-operation to purge working fluid from the reservoir.

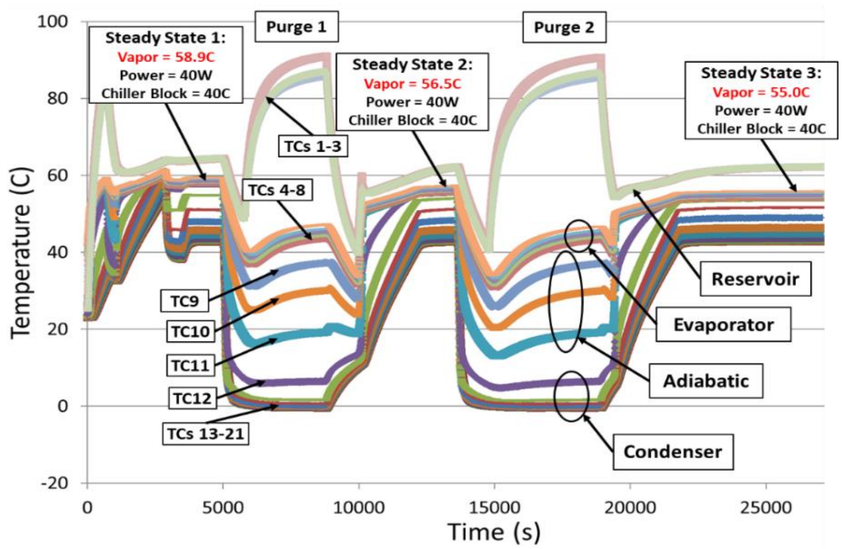


Figure 8. Example of two subsequent purge tests of the non-integrated HR-VCHP. Test was initiated after several days of non-operation allowing working fluid to diffuse into the NCG reservoir resulting in a higher steady-state operating temperature. During the purge tests, power to the evaporator was turned off and 12W of heater power was applied directly to the NCG reservoir using a dedicated heater. See Error! Reference source not found.**3 for TC numbers.**

Figure 8 shows example purge tests of the HR-VCHP. Prior to this test the HR-VCHP had been dormant for several days allowing the working fluid to diffuse into the NCG reservoir. The initial steady state condition, indicated at approximately 4,000 seconds, had a vapor temperature of 58.9°C for the nominal power of 40W and chiller block setpoint of 40°C. Note that this vapor temperature is 4-5°C higher than the results shown in Figure 4 and Figure 5 despite identical testing (power and sink temperature) conditions. At approximately 5,000 seconds the first purge test was initiated. During the purge test, power to the evaporator was shutoff, the chiller block setpoint was reduced to 0°C and 12W of heater power was applied to the heater mounted directly on the NCG reservoir, shown in Figure 3. This resulted in a significant increase in reservoir temperature.

The reservoir heater was shutoff and the evaporator heater was reapplied allowing the system to return to the nominal operating condition. After this initial purge the steady-state evaporator temperature was approximately 56.5°C, a reduction of 3.4°C indicating that some working fluid had left the reservoir. At approximately 13,000 seconds a second purge test was initiated. After the second purging, the steady-state evaporator temperature was 55.0°C a nearly 4°C decrease from prior to purging. These results indicate that reservoir heating is an acceptable method of removing working fluid from the reservoir (decrease humidity) and returning the VCHP to its nominal operating state.

IV. HR-VCHP Pre-Flight Testing Marshall Space Flight Center

After its testing at ACT, and before the integration on Astrobotic's Peregrine 1, the non-integrated HR-VCHP was ground tested at NASA Marshall Space Flight Center (MSFC). Both benchtop testing and thermal vacuum (TVAC) testing were performed. The benchtop testing was focused on gaining familiarity with the operation of the HR-VCHP.

The thermal vacuum testing was built upon the benchtop testing to validate the thermal performance, while also qualifying the hardware to survive and operate in the expected operational environment. Additionally, the VCHP underwent vibration testing before TVAC to demonstrate its ability to survive launch loads. The ground test campaign was completed successfully to verify the thermal performance and qualify the VCHP for flight on Peregrine 1.

Benchtop Thermal Testing

The hardware is shown in Figure 9 attached to its ground-test support fixture. The support fixture consists of an aluminum plate the HR-VCHP is bolted to, which was then bolted to an extruded T-slot aluminum frame. The aluminum frame was built in such a manner that the VCHP could be tested in a gravity-neutral orientation (parallel with the ground) and a vertical orientation. Heating was provided by a thin-film heater attached to the aluminum plate bolted to the evaporator with a thermal interface material increasing conductance from the aluminum to the evaporator. A thin-film heater was also attached to the reservoir to provide troubleshooting and purging ability. Cooling for the condenser was provided in two ways depending on the desired temperature setpoint. For setpoints above 0°C a simple fluid recirculating chiller was used with deionized water. For setpoints below 0°C, a cold-gas nitrogen setup was used. Foam insulation was used to reduce convection during benchtop testing. Temperature measurement was performed using a National Instruments Compact Data Acquisition System (CDAQ) and Type T thermocouples.

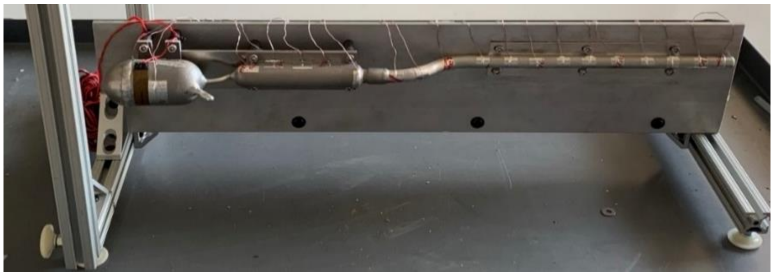


Figure 9. HR-VCHP before benchtop testing

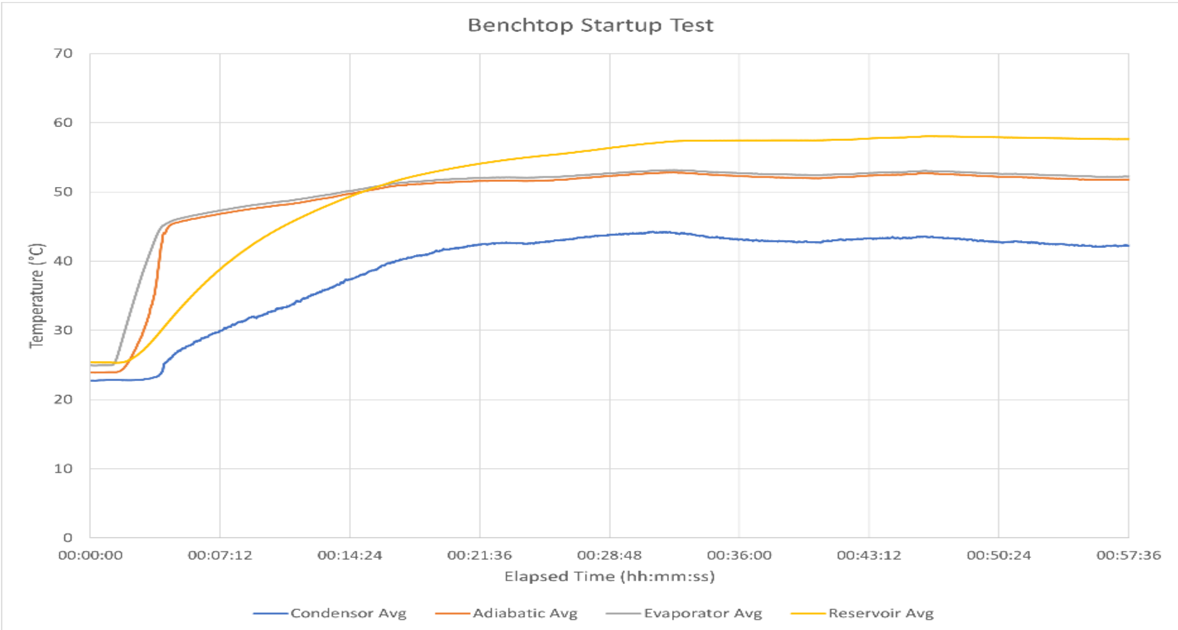


Figure 10. Benchtop startup testing

An example of benchtop test results is shown in Figure 10. This test was demonstrating HR-VCHP startup from room temperature. At an elapsed test time of 00:01:30 a heat load of 40 W was applied to the evaporator. A setpoint temperature of 40°C was maintained for the recirculating chiller that was removing the heat from the condenser. By a few minutes into the test the VCHP had started up, and approximately 30 minutes into the test a quasi-steady state was reached. The recirculating chiller had a slight oscillation around the 40°C setpoint which kept the temperatures from flatlining.

Vibration Testing

Prior to thermal vacuum testing, the HR-VCHP went through random and sine vibration testing. A dynamics analyst from MSFC worked with Astrobotic to define the necessary load conditions to impose on the HR-VCHP, as shown in Table 1. The HR-VCHP installed on the shaker table is shown in Figure 11.

Table 1. Vibration load cases

Random			Lateral Sine		Axial Sine	
Freq (Hz)	Limit (G^2/Hz)	Qual (G^2/Hz)	Freq (Hz)	Qual (g)	Freq (Hz)	Qual (g)
20	0.013	0.026	10.0	9.00	10.0	10.00
50	0.080	0.16	40.0	9.00	15.0	10.00
800	0.080	0.16	40.0	8.00	15.0	5.00
2,000	0.013	0.026	100.0	8.00	100.0	5.00
Grms	10.0	14.1				

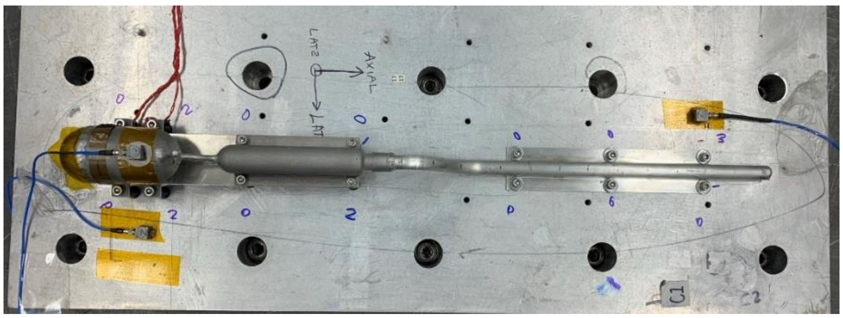


Figure 11. HR-VCHP on Shaker Table

A response accelerometer was placed on the HR-VCHP reservoir since that was predicted to be the location of maximum displacement. The test cycles were performed without any visible failures for the HR-VCHP. A benchtop functional thermal test verified that the thermal performance of the HR-VCHP was nominal post-vibe.

Thermal Vacuum Testing

To prepare for flight onboard Peregrine 1, the HR-VCHP underwent a thermal vacuum test campaign guided by the Goddard Environmental Verification Standard (GEVS). Since the unit under test was also the flight unit, a "protoflight" qualification plan was followed, which dictates test temperatures of 10°C above and below the allowable flight temperature (AFT) range.

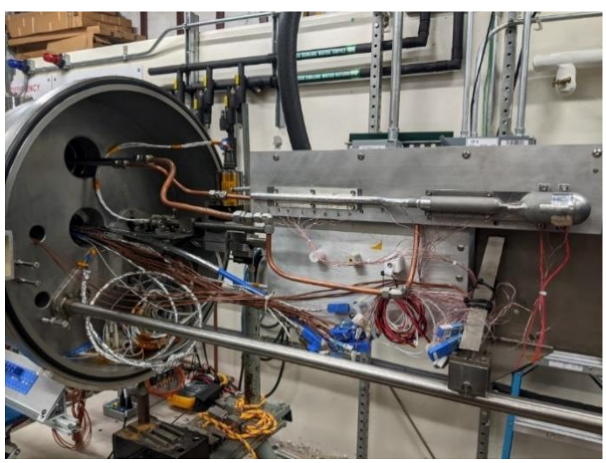


Figure 12. VCHP in TVAC

In coordination with ACT and Astrobotic, the AFT range was determined to be -22°C to 60°C, resulting in a test range of -32°C to 70°C. The test configuration is shown installed in the vacuum chamber in Figure 12. The vacuum pressure was always maintained below 10^{-5} Torr during the test.

A total of four test cycles were performed at each temperature extreme, with a four-hour dwell period at each setpoint. The first cycle is shown in Figure 13. Upon completion of the thermal cycling, a functional test was performed and verified that the HR-VCHP still operated as expected. Again, this test was performed by the Space Environmental Effects group at MSFC and completed the qualification program for the HR-VCHP.

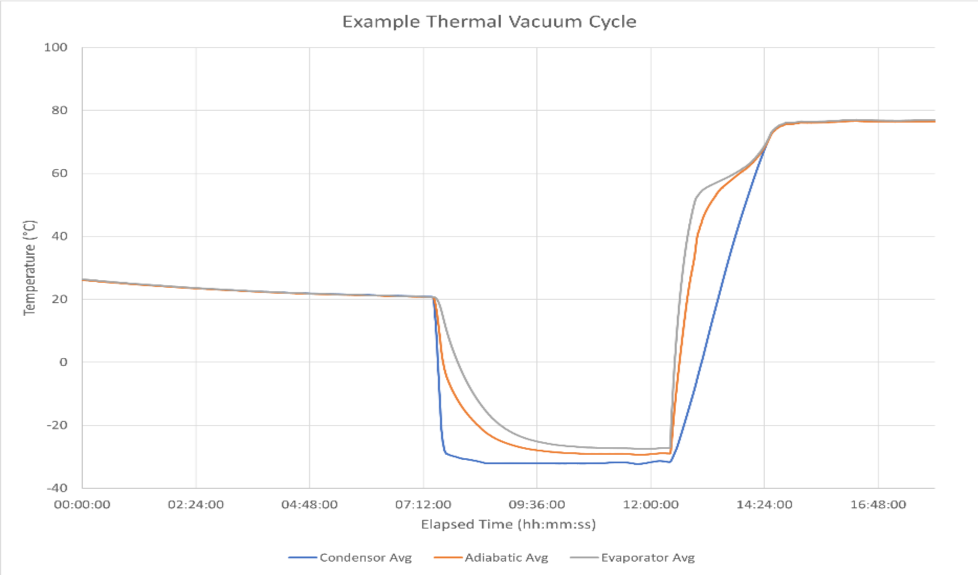


Figure 13. First TVAC cycle

V. VCHP Integration on Peregrine and Mission Details Testing in Microgravity

The main goal of the non-integrated HR-VCHP developmental effort was to increase its TRL to 8 by demonstrating its operation and reliability in microgravity for an extended period. As mentioned earlier, the prototype was installed on the Peregrine Lander for testing during its flight to the moon without other functional responsibilities.

Mission Details

Astrobotic's Peregrine Mission One (PM1) launched aboard the maiden flight of United Launch Alliance's Vulcan rocket at Cape Canaveral, FL on January 8, 2024, at 2:18 am ET. Approximately two hours after launch, during standard operational readiness procedures, Peregrine's propulsion system experienced an anomaly that prevented the mission from accomplishing its goal of a lunar landing, as described in the Peregrine Mission 1 Post-Mission Report [7]. After the propulsion anomaly occurred, the team stabilized the spacecraft and shifted mission priorities to gathering propulsion system data for a mission investigation, providing on-board payloads power and communications to capture science data, and obtaining performance data on the lander's subsystems to increase technology readiness levels for future missions.

Figure 14. Astrobotic Peregrine Mission 1 Lander (Enclosure Panel C1 hidden)

The collected flight data during these efforts resulted in other peer-reviewed publications [8]. After traveling more than 535,000 miles over the span of ten days, the mission team successfully conducted Peregrine's controlled re-entry into Earth's atmosphere over open water in the South Pacific on January 18, 2024, at 4:04 p.m. ET.

HR-VCHP Integration and Instrumentation

The ACT's HR-VCHP testing described herein began on January 9, 2024, at 5:01 am ET and concluded approximately seven hours later at 12:00 pm. The testing occurred during the initial transit of PM1 to cis-lunar orbit, prior to reaching apoapsis beyond the Moon's orbit and returning to Earth. During this phase of the mission, the environmental conditions on the spacecraft and Enclosure Panel C1 were constant, with the solar vector pointing consistently on the PM1 solar panel and no measurable contributions of infrared energy from the Earth or Moon.

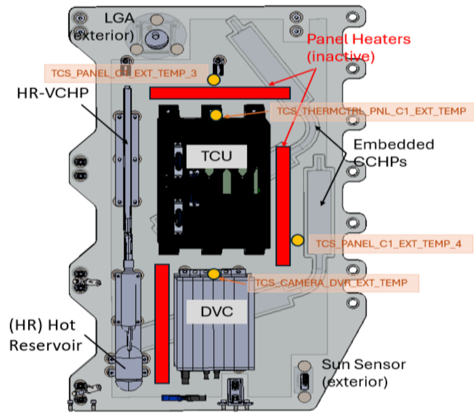


Figure 15. Enclosure Panel C1 viewed from enclosure interior

The Peregrine lander was designed with two open payload decks (named B and D) and two enclosures (A and C) to house critical avionics and computational systems, as shown in Figure 15. Each enclosure consisted of three panels, numbered from 1 to 3. The panels consisted of two aluminum face-sheets epoxied to and separated by an aluminum honeycomb core with embedded constant conduction heat pipes (CCHPs). The radiating and space-facing sides of the enclosure panels were covered with low-solar-absorptivity, high-infrared-emissivity silver fluorinated ethylene propylene (FEP) tape. The other sides of the enclosure interiors consisted of multi-layer insulation (MLI)-covered structural panels and the outer diameter of an oxidizer tank, also covered with MLI. The interiors of these enclosures had no view to deep space.

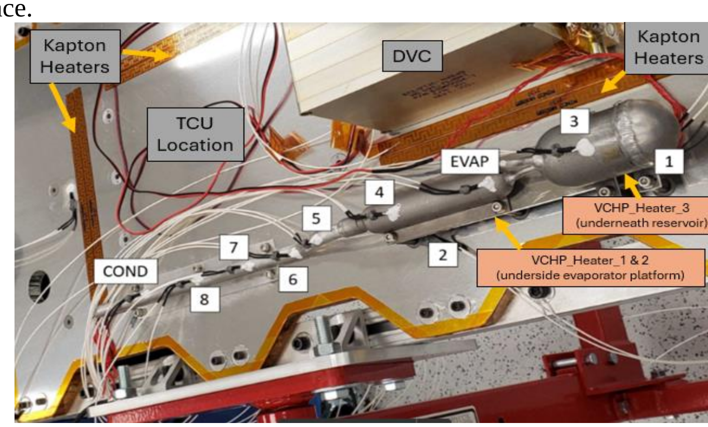


Figure 16. Enclosure Panel C1 in mid-assembly, showing HR-VCHP with temperature sensors installed

The non-integrated HR-VCHP was mounted on Enclosure Panel C1, next to the Digital Video Controller (DVC) and a Thermal Controller Unit (TCU) on the interior surface of the panel (Figure 15). Figure 16 shows the HR-VCHP mounted to Panel C1 (before panel integration onto the Peregrine lander), next to the DVC, but before the TCU was mounted. Locations of flight-monitored temperature sensors (thermistors) are noted in the white text boxes. Kapton heaters can also be seen mounted to the panel between and around the various components; these heaters were not operating during the HR-VCHP test.

The heaters, temperature sensors, and their locations along the HR-VCHP are shown in Figure 16. As seen, heaters VCHP_Heater 1 and 2 were installed on the underside of the evaporator platform while VCHP_Heater 3 was installed on the hemispherical end cap (opposite to the evaporator) of the reservoir. The first two heaters were used as payload power that could be varied only as 0, one heater (half power) or two heaters on (full power). The third heater (VCHP_Heater 3) was used only for pre-conditioning (purging) the reservoir before the actual testing. Ten temperature sensors (thermistors) were installed. T1 and T3 are on the reservoir with T1 being installed under the VCHP_Heater 3. T2 was installed on the underside of the evaporator platform, between the heater and the actual surface. TE and T4 were installed on the evaporator's "back", opposite the heat transfer interface. T5 was installed on the adiabatic section, typically to provide information about the actual vapor temperature (saturation point in the system). T6 through 8 were installed on the condenser to provide information about overall thermal resistance and NCG front location and TC was installed at the end of the condenser (as condenser temperature) and it will always be the closest to the Enclosure Panel C1 temperature that represented the heat sink for the HR-VCHP (the condenser is attached to it).

VI. Flight Test Results

Two main testing sessions were performed on the HR-VCHP during the flight on Peregrine: 1) thermal control test, to characterize the ability to achieve the nominal condition for operation by heating (purging) the reservoir, the startup, the operation as a heat pipe with hybrid wick, and finally the payload (evaporator) temperature response to heat sink and/or heat load changes; 2) reliability test, to observe the ability of the HR-VCHP to maintain nominal parameters (and very importantly the NCG humidity in the reservoir) steady boundary conditions for an extended period.

Thermal Control Test

The thermal control test was performed in three phases, which are all represented below in Figure 17. To be noted is that the temperatures sensed by T2 and T3 are not shown because of events that happened during the first phase (purging).

The ***first phase*** began by recording initial temperature conditions (ranging from -10 to -17 °C) and turning on the reservoir heater (VCHP_Heater_3, 30 W) for an hour (as seen in Figure 17). During this phase of testing, two thermistors (T1 and T3) exceeded their upper measurement limit due to the test procedure and a slightly oversized reservoir heater. T1 resumed function after cooling back down, but T3 was permanently damaged and did not return to service. The loss of this sensor did not affect the ability to perform the test or obtain useful data. During the first cooldown, signal was lost briefly (~5 minutes) as Peregrine transitioned between NASA DSN (Deep Space Network) communication stations. The purpose of this first phase was to condition the HR-VCHP in its preparation for operation. The HR_VCHP conditioning consists of purging by heating the reservoir alone to decrease its humidity that could have potentially increased after the long resting period since the last/previous test (at MSFC).

The ***second phase*** started after the first HR-VCHP cool down ended at ~5000 seconds (84 minutes). It is then when the first evaporator heater (VCHP_Heater_1, 30 W) was turned on for 2 hours and then allowed to cool down for 20 minutes. As seen in Figure 17, this 30 W represented half the total power. Temperatures reached a reasonable degree of steady state by the end of the phase showing that the HR-VCHP transfers the heat to the condenser and automatically meaning that the hybrid wick works as designed. This was a key positive conclusion. In terms of thermal control, obtaining a steady state also shows that NCG humidity in the reservoir is constant and no net accumulation of superheated vapor occurs. Reservoir temperature T1 is the highest (as expected) since the reservoir was located on the adiabatic side of the evaporator platform so it should have almost heater's temperature.

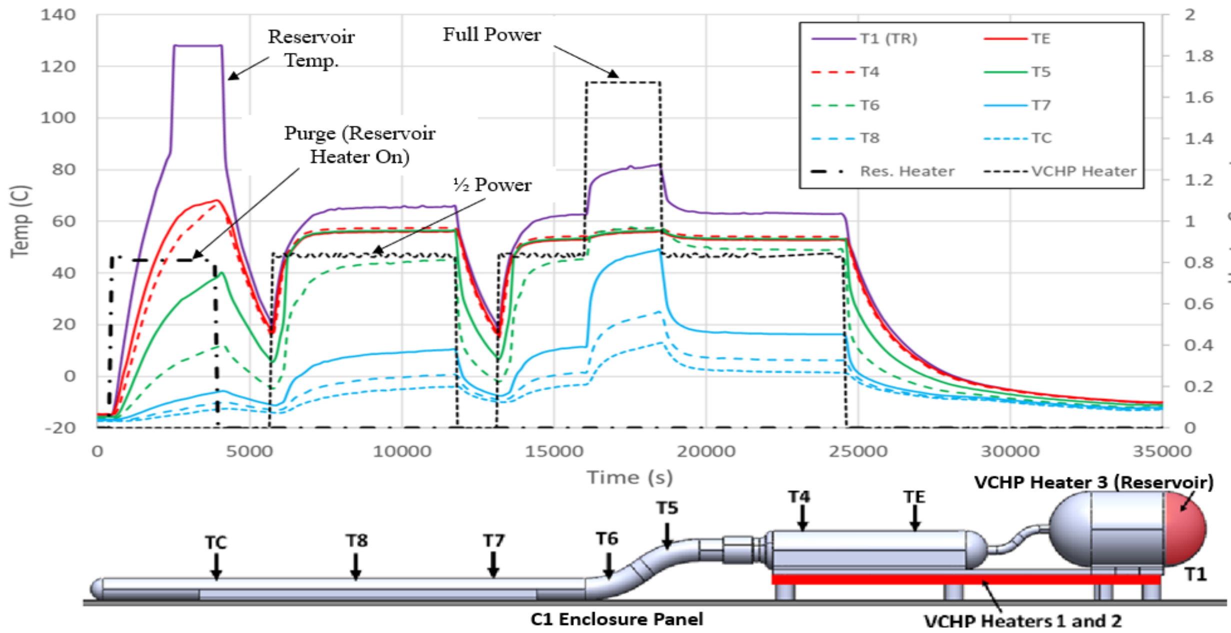
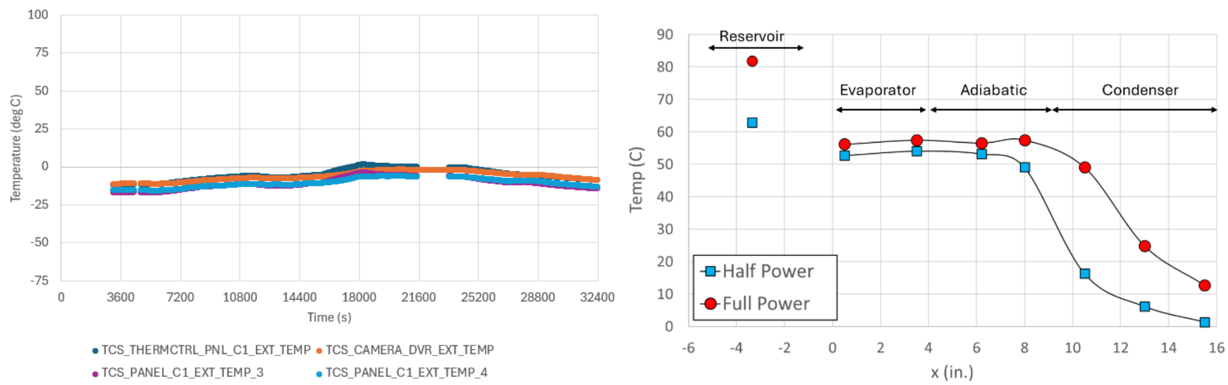


Figure 17. Thermal control testing: non-integrated HR-VCHP temperature vs. time



a) b)

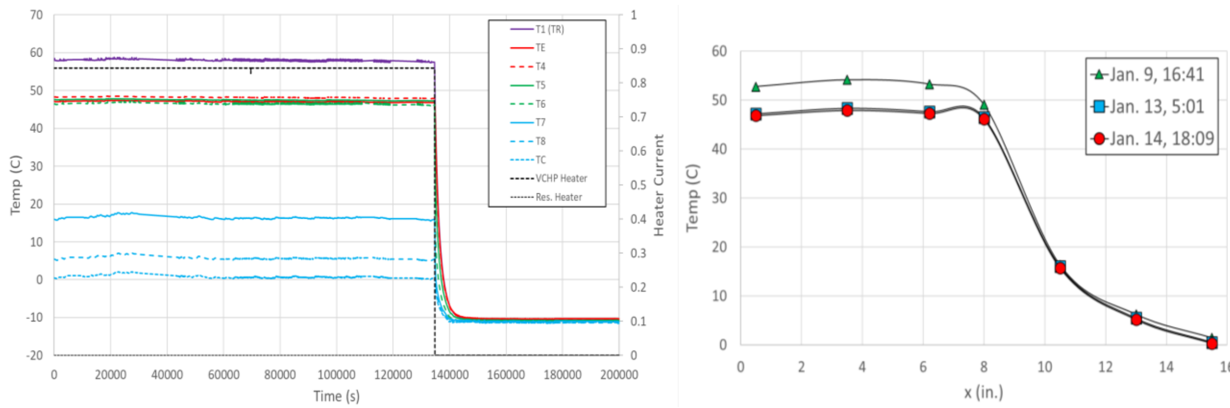
Figure 18. Thermal control testing: a) Enclosure Panel C1 (heat sink) temperatures b) Instantaneous temperature profiles along the HR-VCHP for half-power and full power sequences

The Enclosure Panel C1 to which the HR-VCHP was attached, represented the ultimate heat sink for the condenser. Figure 18a shows the panel temperatures captured from the sensors identified in Figure 15. As seen, the Enclosure Panel C1 (the heat sink) remained between -17 °C and +2 °C during the HR-VCHP thermal control testing. Figure 18b shows two instantaneous temperature profiles along the HR-VCHP that correspond to the full power sequence at ~ 18000 seconds (300 minutes), just before shutting down one of the heaters and to the half power sequence at ~ 24500 seconds (408 minutes) just before turning off the other heater. The reservoir temperature T1 is not included in the two profiles.

Reliability Test

The second testing session for the HR-VCHP during the Peregrine's flight was for reliability. A constant power (VCHP_Heater 1, 30W) corresponding to half power was applied to the evaporator for a duration of 138300 seconds (38 hours and 25 minutes). As observed in Figure 19a, all the temperatures were reasonably constant during the entire test including the reservoir temperature, T1, that was the highest to avoid diffusion and condensation in the reservoir. In Figure 19b, instantaneous temperature profiles along the HR-VCHP are presented (T1 – reservoir, is not included). The Jan. 9 profile is the end of the thermal control test session while Jan. 13 and 14 profiles are the beginning and the end of the actual reliability (38 hour) test. One observation would be that the most relevant temperatures (reservoir

T1, evaporator TE and T4 and vapor T5) were slightly lower than the ones recorded during the corresponding testing configuration (half power) from the thermal control testing session. This may be due to a potentially lower sink (Enclosure Panel C1) temperature during the reliability test. However, since the temperatures are constant and at low values shows that NCG humidity in the reservoir did not change for such an extended period.



a) b)

Figure 19. Reliability test results a) Temperature vs. time b) Instantaneous temperature profiles along the HR-VCHP

The results presented in Figure 19 are significantly important since they demonstrate the reliability of the non-integrated HR-VCHP, a feature that, despite the tight passive thermal control that the hot reservoir offers in general, it has been questionable since the integrated version of the HR-VCHP failed during the 2017 testing at ISS. Now, these testing results of the non-integrated Hot Reservoir VCHP on Peregrine 1 elevated its TRL to 8.

VII. Conclusion

This paper detailed the development that led to the TRL elevation to 8 of a non-integrated Hot Reservoir VCHP with hybrid wick that was designed and fabricated by Advanced Cooling Technologies, Inc. This HR-VCHP was fabricated with a 3D printed evaporator that included a 3D printed porous wick that was interfaced to the grooved wick of the adiabatic section of the heat pipe. This development consisted of actual design, fabrication, and ground testing at ACT (see [1]), pre-flight testing at NASA MSFC, instrumentation and integration on Peregrine Lander at Astrobotic and testing during the mission in microgravity. Thermal testing of the HR-VCHPs during all these developmental stages demonstrated several key features of the non-integrated hot-reservoir hybrid wick VCHP:

- The hybrid wick (screen or 3D printed porous structure in the evaporator and grooves or no wick in the adiabatic/condenser) prevented temperature spikes during startup in a gravity-aided orientation (during ground testing). The porous wick distributes the working fluid throughout the evaporator even when the pipe is not operating (shown in [1]).
- The non-integrated HR-VCHP, which maintains the NCG reservoir at a warmer temperature than the evaporator, exhibits excellent passive temperature control. Turndown ratios of 544:1 and 185:1 were estimated during ground tests at ACT (shown in 1)
- The non-integrated NCG reservoir allows for independent heating of the reservoir which can be effectively used to purge working fluid from the reservoir. As a result, it is possible to return the VCHP to nominal operating conditions even after long periods of non-operation, during which the working fluid may migrate into the reservoir.
- Microgravity testing results again showed that the thermal control capability of the non-integrated HR-VCHP is high and corresponds to the one that is characteristic to hot reservoir VCHP in general
- The reliability of the HR-VCHP was finally fixed and demonstrated by the non-integrated version that introduced independent purging (not significantly impacting evaporator temperature), allowing the reservoir to operate constantly at a higher temperature than the saturation point in the pipe. The conclusion is that as long as the reservoir is warmer than the saturation point in the HR-VCHP, no net accumulation of superheated vapor (increased humidity) occurs.

- The successful testing on Peregrine 1 in microgravity elevated the TRL of the non-integrated HR-VCHP to 8.

Acknowledgments

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