Loop Heat Pipe with Passive Shut off for Lunar Night Survival

Michael Ellis, Ion Nicolaescu and Max Demydovych

August 16, 2024

53rd International Conference on Environmental Systems
21-25 July 2024, Louisville, Kentucky

ICES-2024-436

Loop Heat Pipe with Passive Shut Off for Lunar Night Survival

Michael C. Ellis[1], Ion Nicolaescu[2], and Maksym Demydovych[3]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

The lunar environment poses significant challenges for heat rejection. As the atmospheric density is negligible, thermal radiation is primarily used for this task. During lunar day, the radiative sink temperature can reach 380 K at the equator while dropping to 40 K at night or in polar craters. While the maximum temperature can be mitigated by radiator design and location, any long-term exploration system must survive the lunar night. Loop Heat Pipes (LHPs) are good choices for low gravity environments because they can passively transport kilowatts of thermal energy over several meters. However, the standard LHP has no way to stop flow during normal operation. As a result, for low sink temperatures, there is a risk that an LHP could bring component temperatures below their minimum survival temperature. An option to mitigate these low temperatures is to include electric heaters that rely on batteries for power. But considering the length and low temperatures of the lunar night, even a well-insulated system will require significant battery mass to prevent damage to sensitive components. To overcome this challenge, Advanced Cooling Technologies, Inc. (ACT) is developing a low cost, mass, and volume Thermal Control Valve (TCV) to passively shut down heat rejection from a LHP once the evaporator temperature reaches a user-specified value. As part of a NASA SBIR Sequential Phase 2 project, ACT has developed multiple TCV prototypes and tested them as part of a full-scale LHP system in both laboratory and vacuum environments. The work discussed here focuses on the TCV concepts, LHP vacuum chamber test data, and potential applications.

I. Introduction

As mankind prepares to expand our exploration of the solar system, long term missions are becoming a necessity. A natural stepping stone for these missions is our closest neighbor, Luna, more commonly referred to as Earth's moon. The largest orbital body relative to the size of the primary body and fifth largest moon in our solar system, our moon provides an excellent opportunity for rekindling mankind's exploration of space by providing a proving ground for the tools necessary for the successful, safe, and beneficial exploration of our solar system[1].

Lunar exploration presents numerous challenges such as low gravity, dust mitigation, solar radiation, and extreme temperature swings. The challenge that the innovation presented here targets is surviving the lunar night using a passive thermal control system capable of unlinking sensitive exploration systems, and potentially explorers, from adverse thermal environments. Depending on location, the lunar night can last approximately 15 days and reach temperatures as low as 40 K[1]. The sink temperature of a radiator, which provides the ultimate sink for a thermal management system, varies significantly based on location and orientation[2]. In this work, we consider a sink temperature of 193 K to 173 K. This range was found to be achievable by our vacuum chamber while also providing a sufficiently low temperature to demonstrate the Thermal Control Valve (TCV) as part of a Loop Heat Pipe (LHP) thermal management system. As our minimum control target was 273 K, these sink temperatures were more than sufficient to drive the thermal control system below this temperature should the TCV fail.

LHPs are good choices for low gravity environments because they can passively transport kilowatts of thermal energy over several meters[3]. However, the standard LHP has no way to stop flow during normal operation. As a

---

[1] Senior Engineer, R&D, 1046 New Holland Avenue, Lancaster, PA 17601.
[2] Senior Engineer, R&D, 1046 New Holland Avenue, Lancaster, PA 17601.
[3] Lead Technician, R&D, 1046 New Holland Avenue, Lancaster, PA 17601.

result, for low sink temperatures, there is a risk that an LHP could bring component temperatures below their minimum survival temperature. The TCV seeks to eliminate this risk by providing a minimum set point below which the LHP ceases to reject thermal energy.

II. Thermal Management System Concept

The LHP is a passive heat transport device that relies on a wicked evaporator, the latent heat of vaporization of a working fluid, and vapor pressure generated during evaporation to move thermal energy over long distances from a heat source to a heat sink. The evaporator serves as both a heat exchanger and capillary pump. The key to LHP operation is the wick located within the evaporator, which is typically a cylindrical shell containing the primary and secondary wicks. As heat is applied to the evaporator, liquid residing in the wick evaporates, accepting thermal energy as latent heat. As vapor pressure builds, this phase moves through grooves located near the evaporator wall and exits into a vapor outlet, which is typically a small diameter tube. Vapor pressure continues to drive fluid into the condenser, which is typically attached to a radiator where heat is rejected. Here the fluid changes phase and releases the latent heat gained in the evaporator. Vapor moving into the condenser drives condensed liquid back to the compensation chamber, which acts as an accumulator to handle volume transients resulting from changes in heat load. The secondary wick pulls liquid back to the primary wick. As the compensation chamber and evaporator exist at different saturation states, and therefore pressures, the primary wick must have sufficient capillary pumping capacity to return liquid to the evaporation surface. This completes the cycle of this passive heat transport device[4]. Figure 1 illustrates this concept.

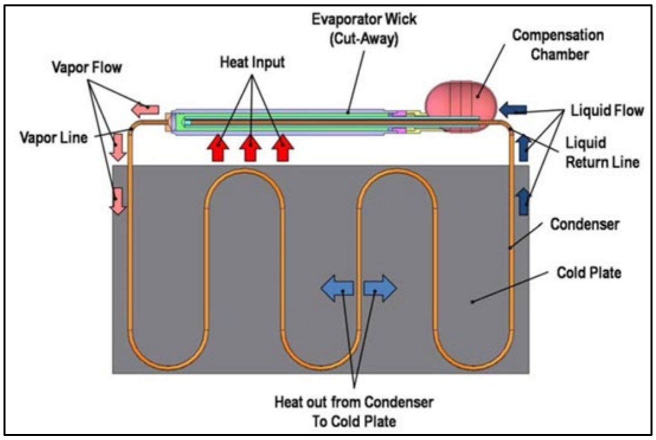

Figure 1. Diagram of Loop Heat Pipe Operation[4].

This device is typically designed to operate in a constant conductance mode. In this mode, the LHP evaporator follows the sink temperature within a specific temperature difference. In applications that could be exposed to large temperature swings, such as a lunar lander, this can result in cooling the heat source below survival limits. Batteries, for instance, can be damaged at low temperatures. In extreme cases, the working fluid can freeze and damage the LHP, rendering the entire system inoperable.

To combat this, ACT began investigating the integration of TCVs with LHPs[5]. In the referenced work, a proportional control valve produced by Pacific Design Technologies (PDT) that provided flow control for the Martian rovers was integrated with a prototype LHP. The valve functioned very well but did not provide the complete on/off function that was needed to protect the electronics and associated thermal management system from damage. For this reason, ACT sought to develop a TCV that allowed the sink to be completely decoupled from the source.

As part of a NASA Small Business Innovative Research (SBIR) Sequential Phase II project, ACT completed the design, fabrication, and testing of a TCV that provides a means to passively stop coolant flow to a radiator based on a user-defined set point. This valve is placed after the pumping mechanism of the coolant loop, such as the evaporator of a LHP. ACT has developed two styles of valve with each style named after their reaction to the set point temperature[6].

A Closed-When-Cold (CWC) valve stops the flow of coolant to the radiator when the coolant temperature drops below a specific set point. As the coolant temperature increases above this set point, the valve allows the flow of coolant to the radiator to resume. An Open-When-Cold (OWC) valve does not directly control coolant flow to the radiator but instead opens a bypass between the inlet and outlet to the coolant pump. Since the pressure drop through the radiator is much higher than the bypass, opening the bypass effectively stops coolant flow to the radiator. These valve types can be used separately or together, depending on the needs of the application.

The valves actuate as a result of the force balance between two opposing pressures: the saturation pressure of the coolant and the set point pressure. As the set point pressure is adjusted, a different saturation pressure is required to open or close the valve. This effectively changes the set point temperature for valve actuation. This effect can be seen in Figure 2. During this test of an OWC valve, the radiator temperature was maintained at a low temperature so that valve opened and a minimum coolant temperature was reached. The set point pressure was then increased, which resulted in an increase in the minimum coolant temperature.

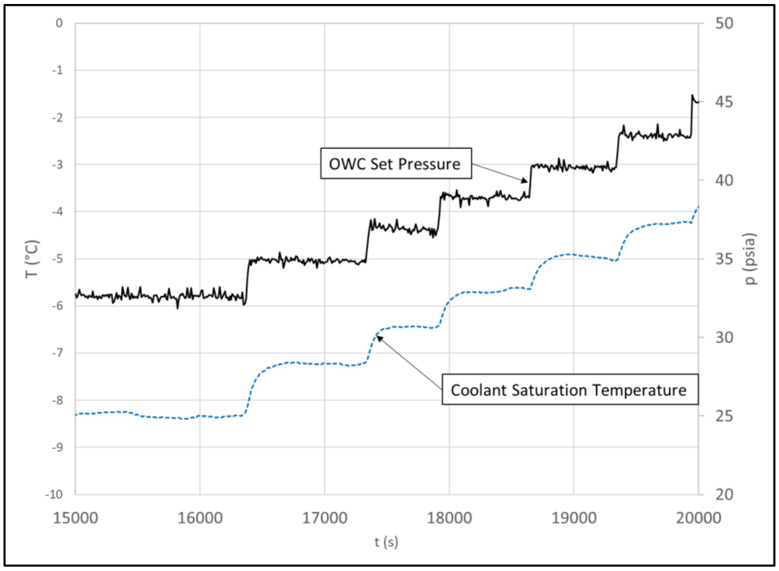

Figure 2. Test data showing the effect of the set point pressure on the saturation temperature of a LHP.

In a test of the CWC valve, the radiator temperature was varied across a 70 K range. Data from this test are shown in Figure 3. The valve was set to actuate at approximately 10 °C. There is an initial coolant temperature spike during LHP start up as the vapor channels are cleared of liquid[3]. After that, the coolant temperature drops until the set point temperature is reached and the valve closes. As the radiator temperature increases, the valve opens and the coolant temperature increases as the LHP operates again.

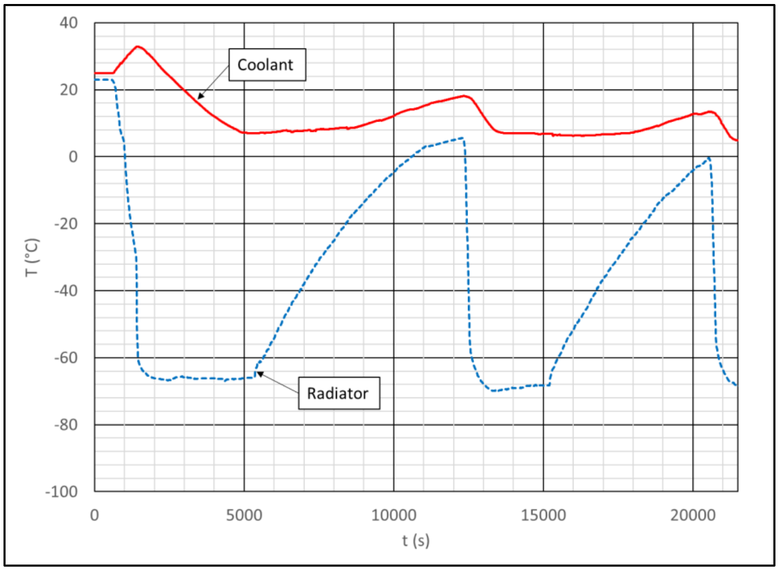

Figure 3. Temperature data obtained during testing of a LHP with a CWC valve and varying sink temperature.

III. Test Set Up

In October, assembly of the LHP was completed. This included integration of the LHP, TCV, radiator, and heat spreader plate. For reference, a labeled CAD model of the design is shown in Figure 4. During each assembly stage, all welds were inspected by a certified third party according to NASA-STD-5006A, Class C. The completed LHP is shown in Figure 5. A close up of the LHP evaporator and TCV is shown in Figure 6. Figure 7 shows the instrumented LHP. Thermocouples were attached using aluminum tape. After all thermocouples were attached, exposed tape on the radiator panel was painted. A thermocouple map is shown for reference in Figure 8.

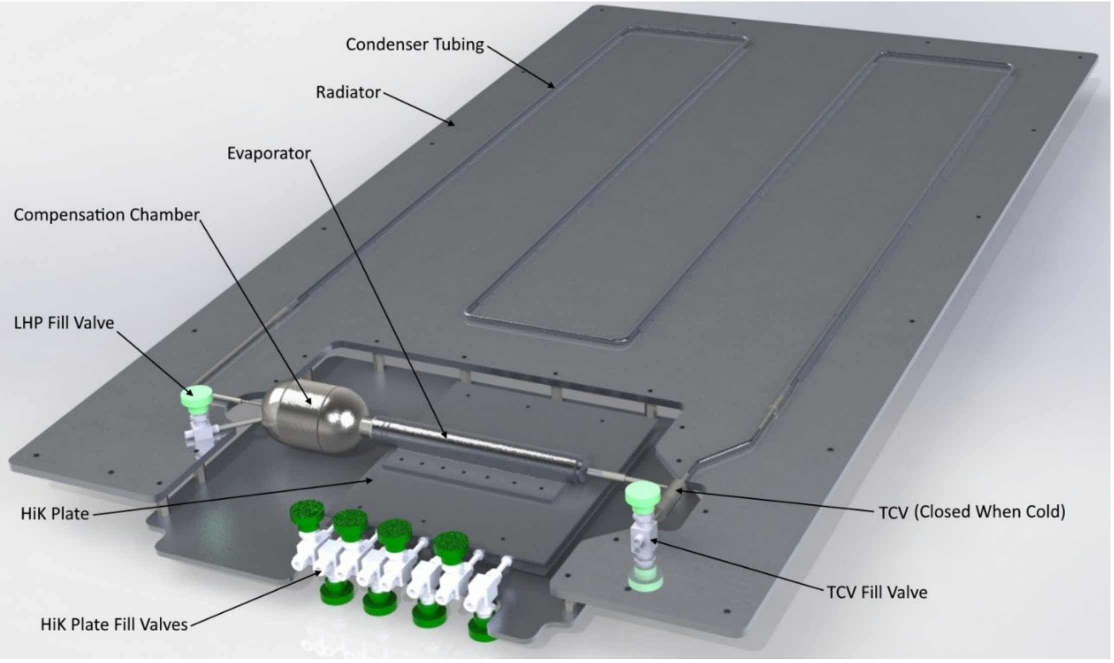

Figure 4. CAD Model of the LHP

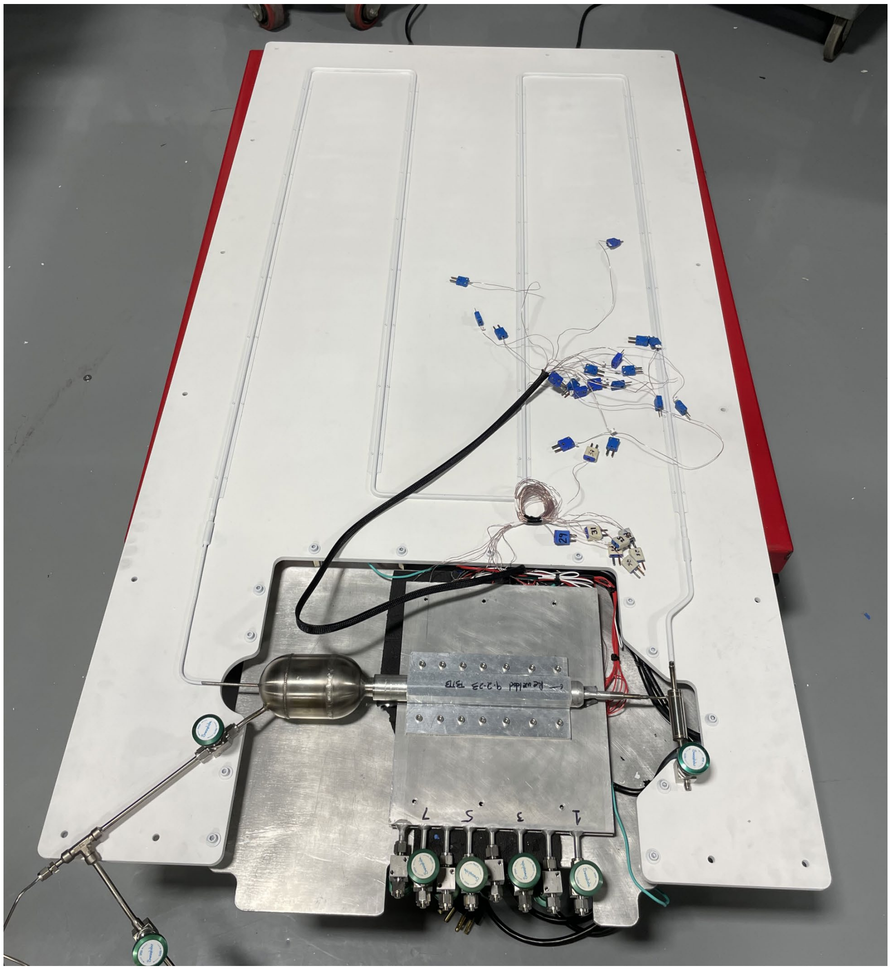

Figure 5. Assembled LHP

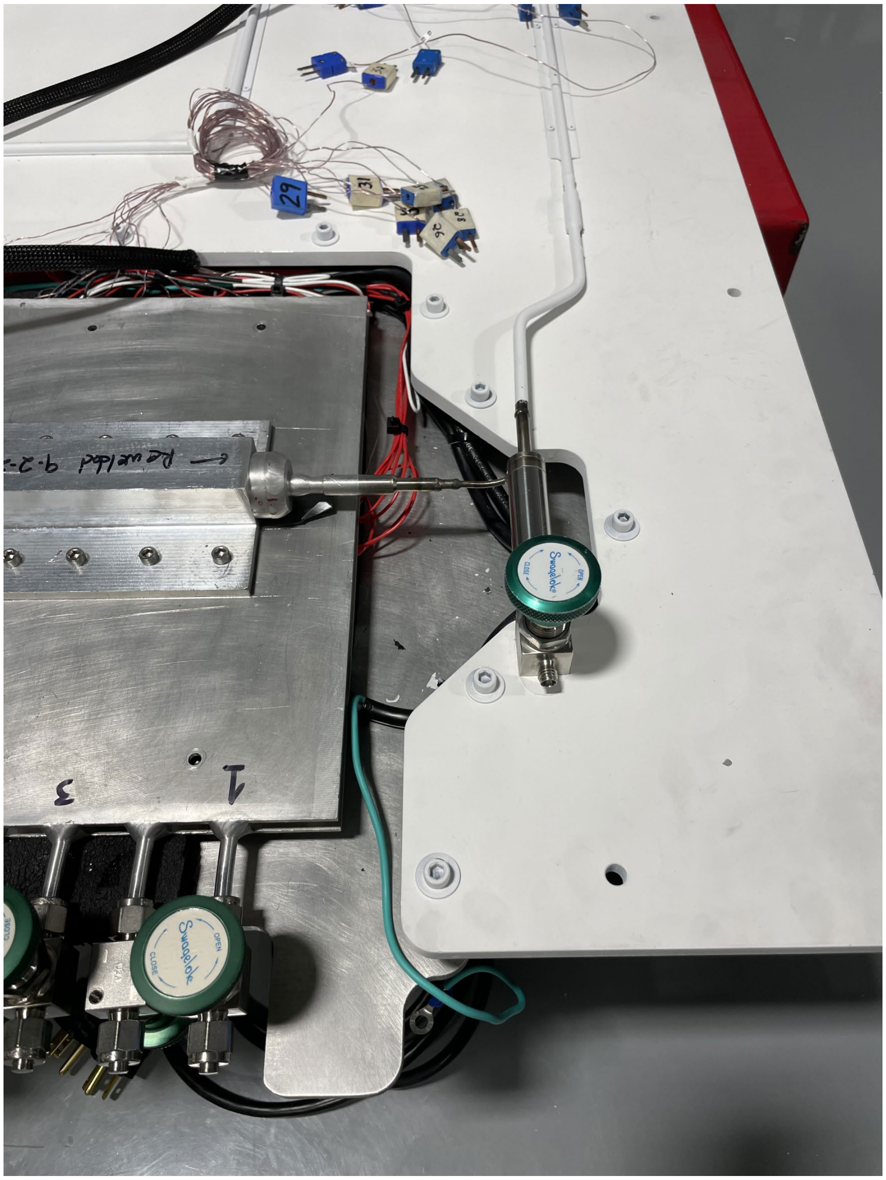

Figure 6. Close Up of LHP Evaporator and TCV

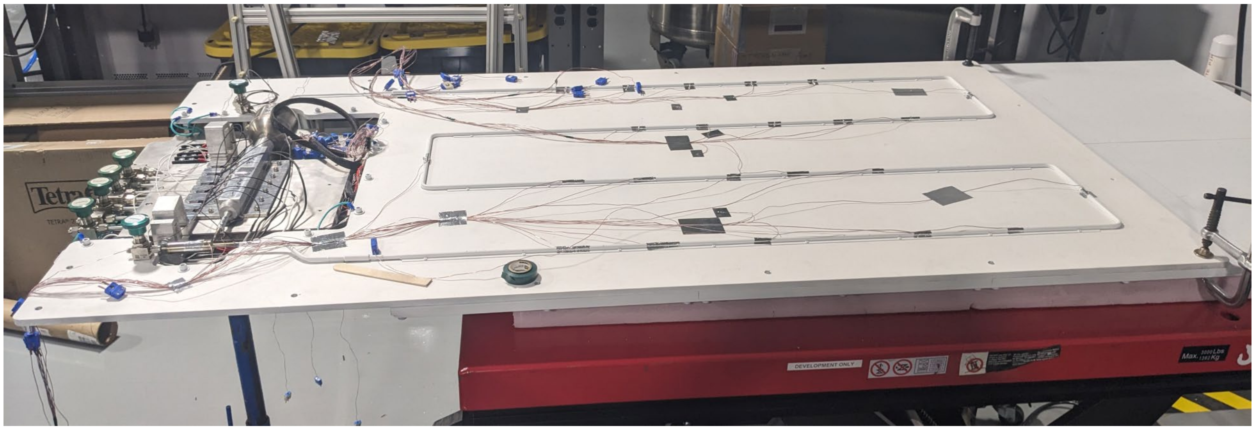

Figure 7. Instrumented LHP Prior to Final Painting

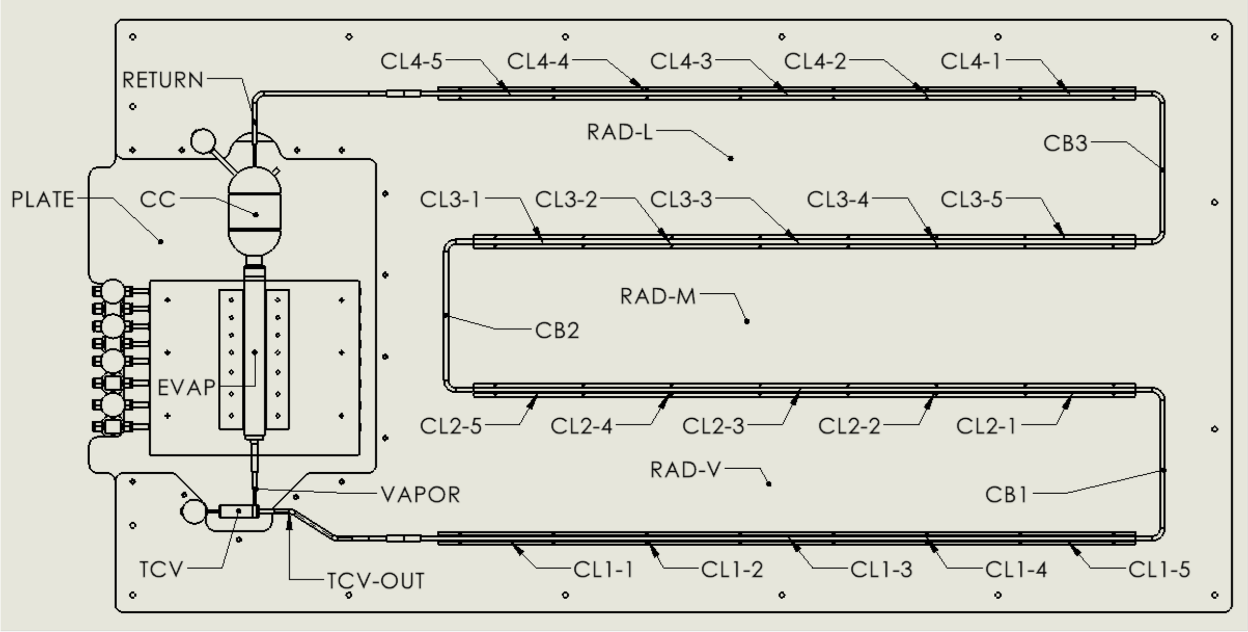

Figure 8. Thermocouple Map

The LHP and shroud were installed in our vacuum chamber as shown in Figure 9 and Figure 10. The shroud temperature is set and maintained by a Proportional-Integral-Derivative (PID) controller located outside the chamber. To prevent unwanted radiation between the LHP body and the shroud, the LHP evaporator, compensation chamber, HiK™ plate, and TCV were insulated using Multi-Layer Insulation (MLI), specifically AstraWrap™ 103460-1 perforated double side aluminized polyester film with B4A polyester netting spacer. The entire assembly was then insulated using MLI to mitigate heat losses from the shroud and radiator, as shown in Figure 11.

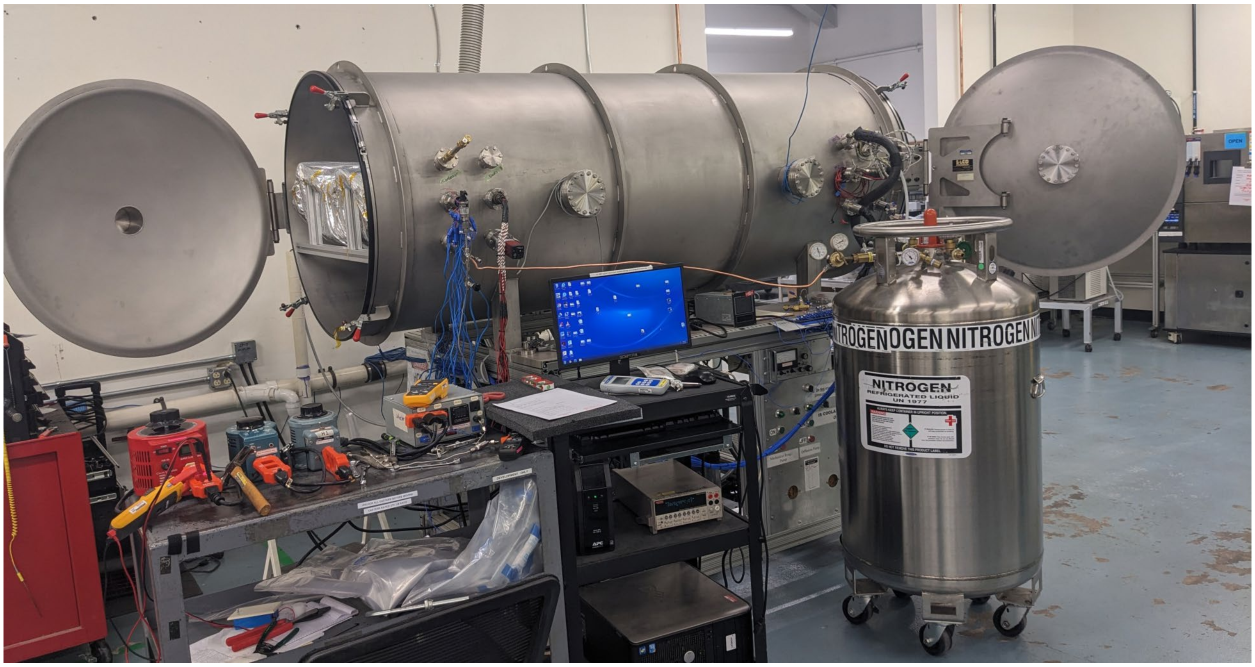

Figure 9. Vacuum Chamber

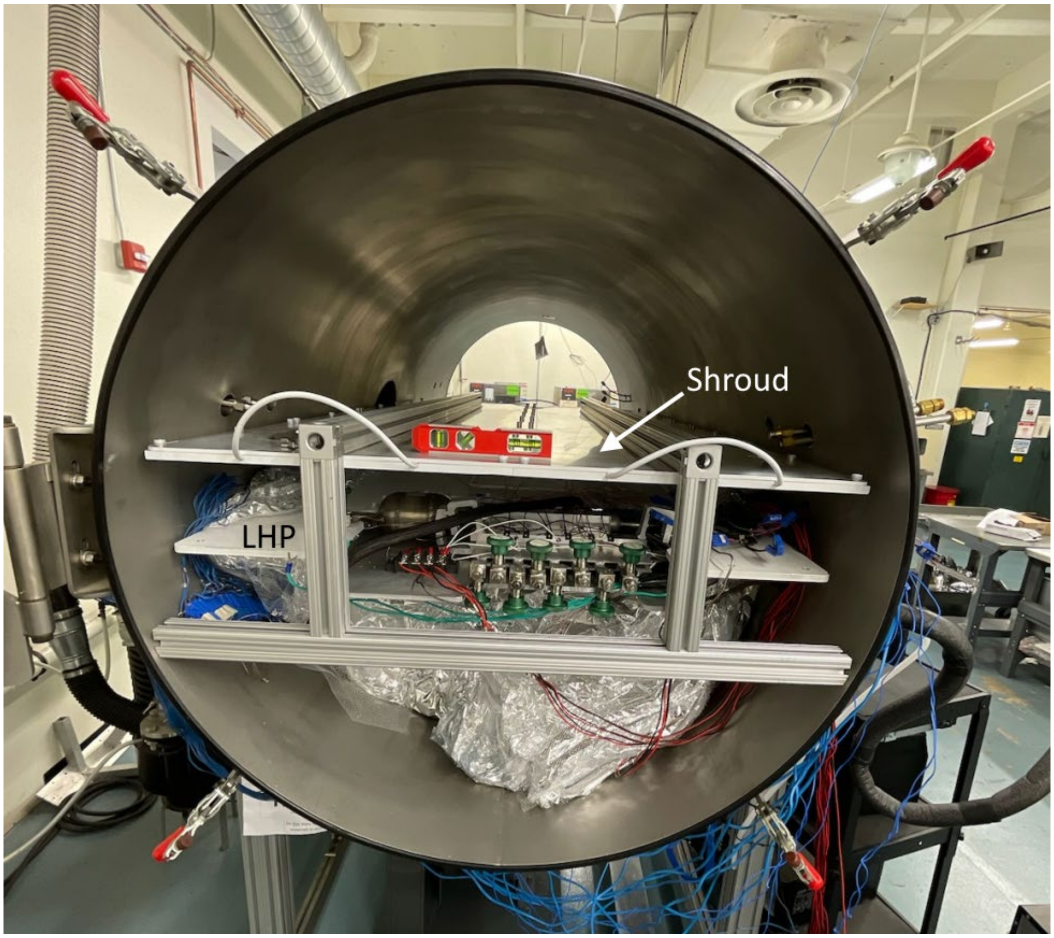

Figure 10. LHP and Shroud Installed into the Vacuum Chamber

Figure 11. Shroud and LHP Insulated with MLI

IV. Test Procedure

Testing began on January 23rd, 2024. Currently two sets of tests have been completed. These tests followed the following steps.

1. Vacuum was pulled to 10^{-7} Torr.
2. The shroud was cooled to -80 °C down to -100 °C depending on the temperature of the HiK plate. Since the plate contains ammonia, ACT set the temperature limit of the plate to 50 °C for safety reasons. If the plate approached this temperature, the sink was reduced by 20 °C.
3. Once the shroud reached steady state, power was applied in the following steps. Power was maintained until steady state was reached. Each test required a little less than 24 hours to reach steady state.
    a. 50 W
    b. 100 W
    c. 150 W
    d. 200 W
4. The first test involved a ramp up from 0-200 W. The second test involved a ramp down from 200-0 W.

V. Test Data

In February, the first set of test data for the ramp up test was analyzed. Figure 12 shows the initial test at 50 W, which was applied at approximately 10,000 seconds. As this test began from a no power condition, the vapor grooves were flooded with liquid. This causes the initial temperature spike as the vapor grooves are cleared and normal LHP operation commences. The LHP starts shortly after power is applied and this is evidenced by the temperature after the TCV ("TCV-OUT" in Figure 8) suddenly spiking while the evaporator temperature ("EVAP" in Figure 8) drops rapidly. In the liquid return line, temperature rapidly decreases as cold liquid is pushed out of the condenser by the vapor generated in the evaporator. At the same time, the radiator temperature ("RAD-M" in Figure 8) fluctuates as thermal energy is received from the working fluid moving through the condenser.

The mass flow rate of the LHP is relatively low, approximately 0.15 g/s at 50 W, owing to the highly efficient two-phase heat transport mechanism. As a result, the LHP takes 70,000 seconds, or 19.5 hours, to reach steady state. During this time period, the radiator temperature and liquid return can be seen to slowly decrease from their startup temperature of 20 °C to the steady state temperature of -17 °C. Without the TCV, the evaporator and compensation chamber would follow a similar trend and decrease along with the liquid return line.

The TCV was set to maintain the HiK plate to approximately 0 °C. At around 18,000 seconds, the evaporator temperature suddenly stops decreasing as the TCV closes. The condenser temperatures continue to drop and follow the radiator temperature. For clarity, only the liquid return temperature is shown here ("RETURN" in Figure 8) and represents the coldest temperature in the condenser section.

While the TCV is in this condition, the valve behaves like a back pressure regulator and controls the saturation pressure in the evaporator. As power is still applied, vapor is still produced. As pressure begins to increase, the valve opens momentarily and allows vapor to escape until saturation pressure is restored. The actuation mechanism allows for partial opening of the valve and is very sensitive to evaporator pressure. In addition to the low vapor flow rate, which is 6.8×10^{-6} m^3/s or 0.4 L/min at 50 W, these operating characteristics enable the valve to control temperature with no discernable oscillation in the test data.

When the valve closes, the compensation chamber is also affected. Vapor pressure no longer provides a driving force to move liquid into the compensation chamber. Since the evaporator and compensation chamber are thermally linked through the secondary wick, heat transfer between these two components, often referred to as heat leak, dominates the thermal balance. As a result, the compensation chamber temperature is also maintained.

Figure 13 shows operation at 100 W. Power is increased from 50 to 100 W at the start of the test. Unlike the previous test, the LHP is already operational and there is no temperature spike resulting from start up. Shortly after power is applied, the TCV re-opens and the evaporator temperature begins to increase. Vapor flow to the condenser is evidenced by the increase in temperature after the TCV. Temperatures increase until steady state is reached.

Figure 14 shows operation at 150 W. This test showed similar results as the previous test except the TCV was already open. For this reason, temperatures increase as soon as power is applied until steady state is reached.

Finally, Figure 15 shows performance at 200 W. This test began with a no power condition as the sink temperature was lowered to -100 °C to prevent reaching the temperature limit of the HiK plate. In addition, this test was conducted after the weekend so the shroud had to be cooled down from room temperature to this temperature at the start of the test. Like the first test, the initial spike occurs as the vapor grooves are cleared of liquid, then the temperatures decreases to steady state. In this case, the TCV is not triggered and remains open for the entire test.

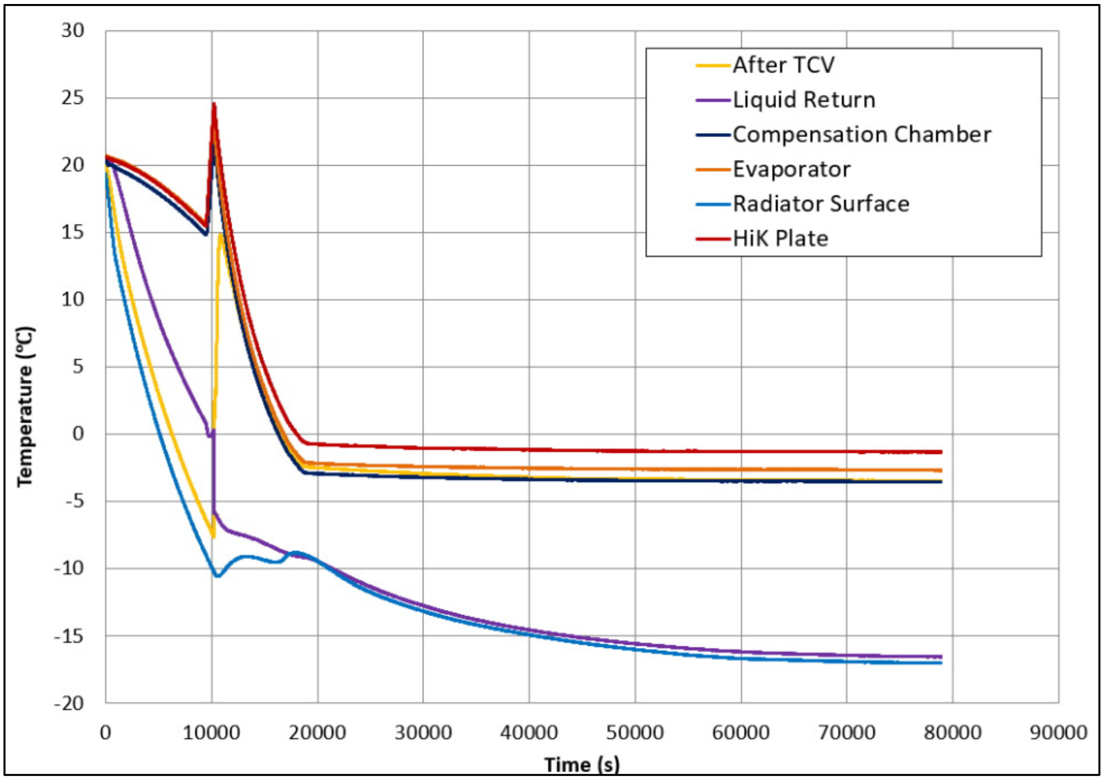

Figure 12. LHP Performance at 50 W

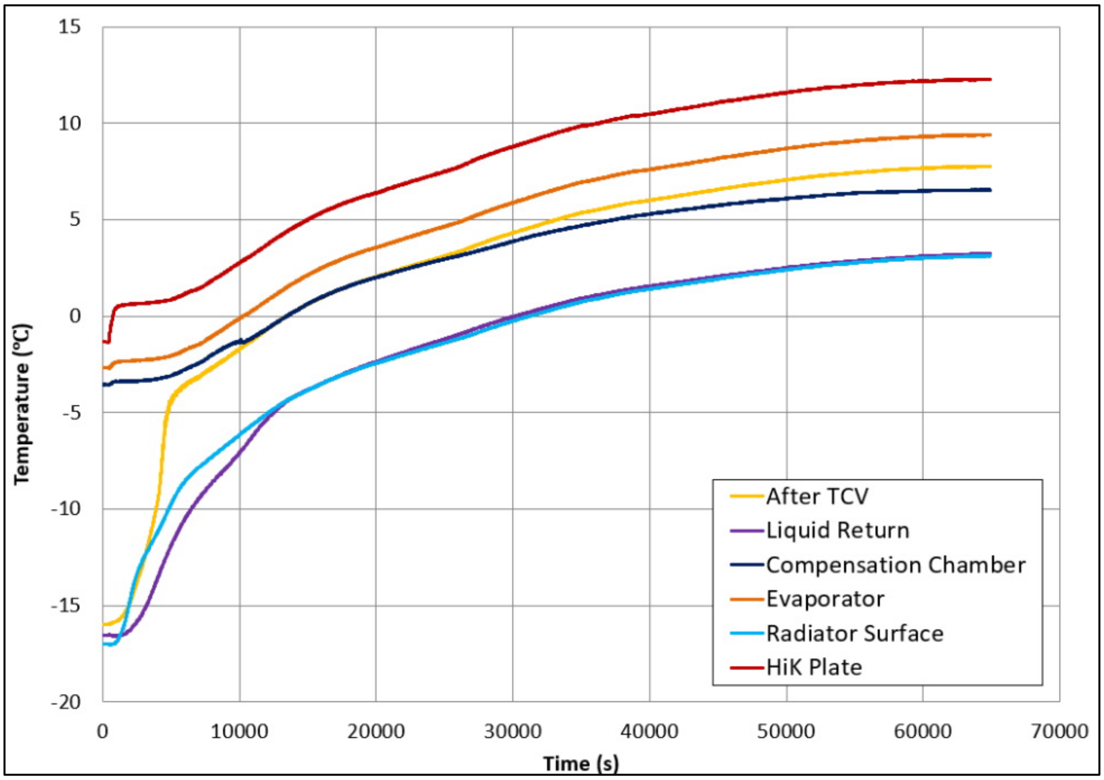

Figure 13. LHP Performance at 100 W

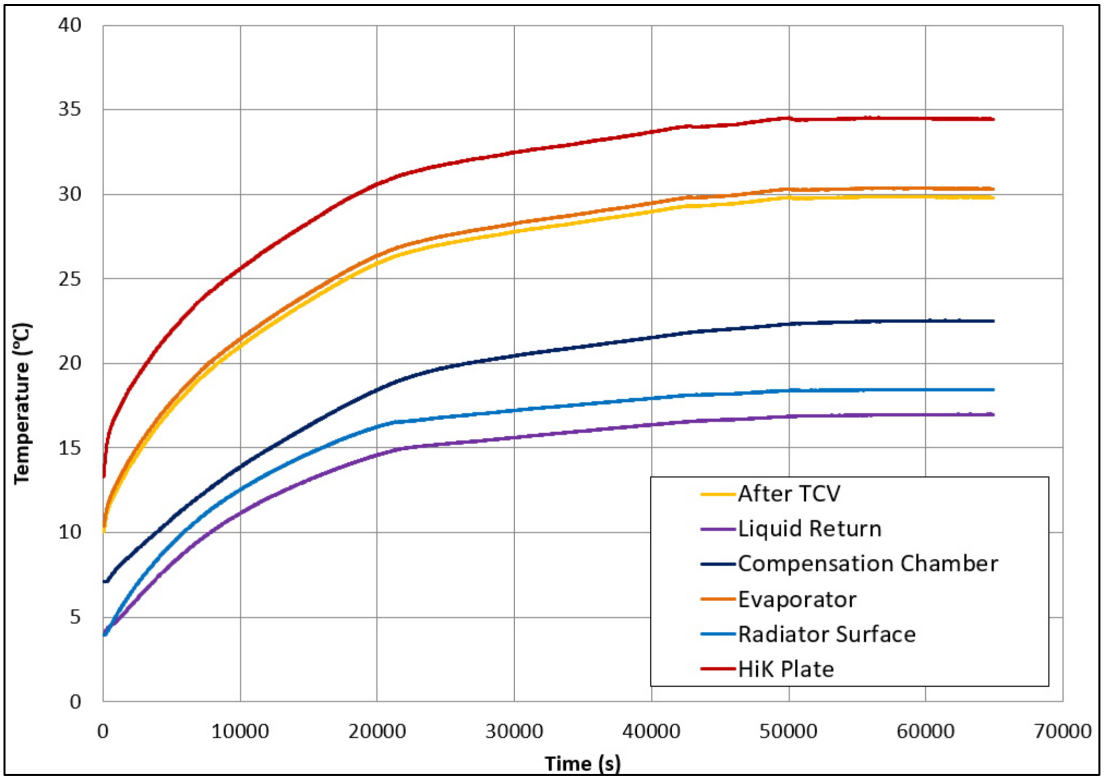

Figure 14. LHP Performance at 150 W

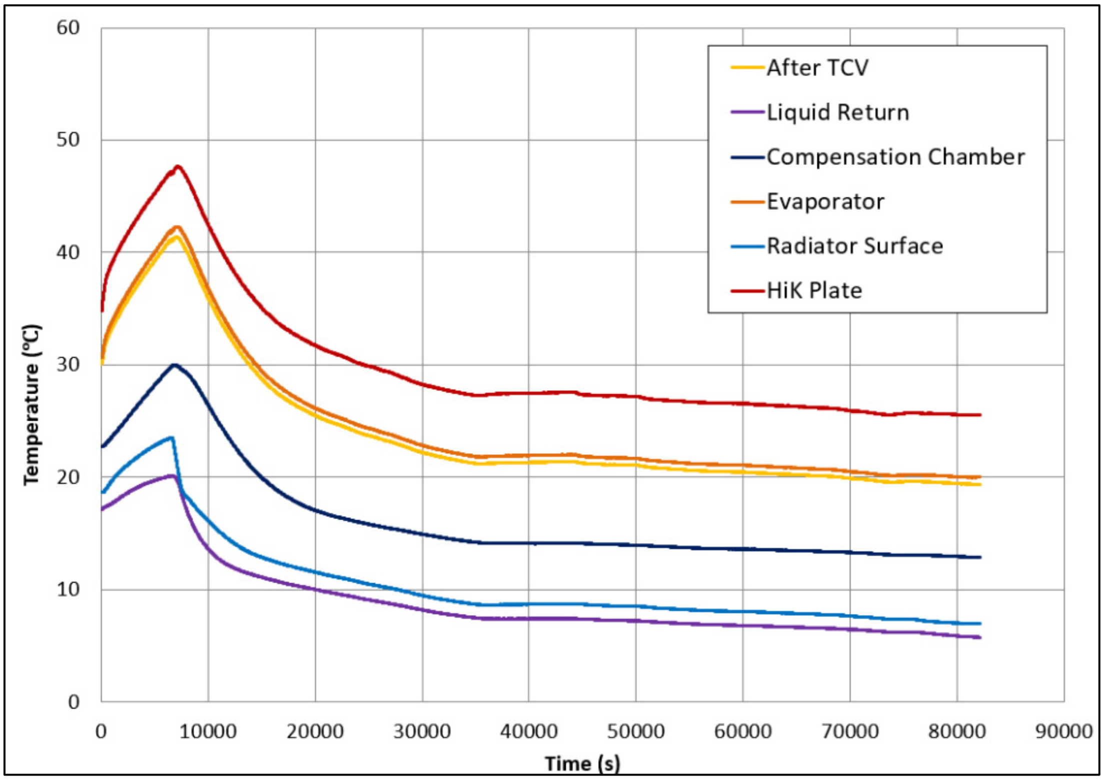

Figure 15. LHP Performance at 200 W

Figure 16 shows the HiK™ plate temperatures for the 200 W tests. They follow the evaporator temperature and maintain good temperature uniformity, approximately 6 °C, throughout the test, despite uneven heating of the surface. This is a result of the two-phase heat transfer occurring between the heat sources and heat pipes embedded in the plate. The heat pipes are arranged to produce a nearly isothermal heat spreading effect[7]. Similar results were seen for all other tests.

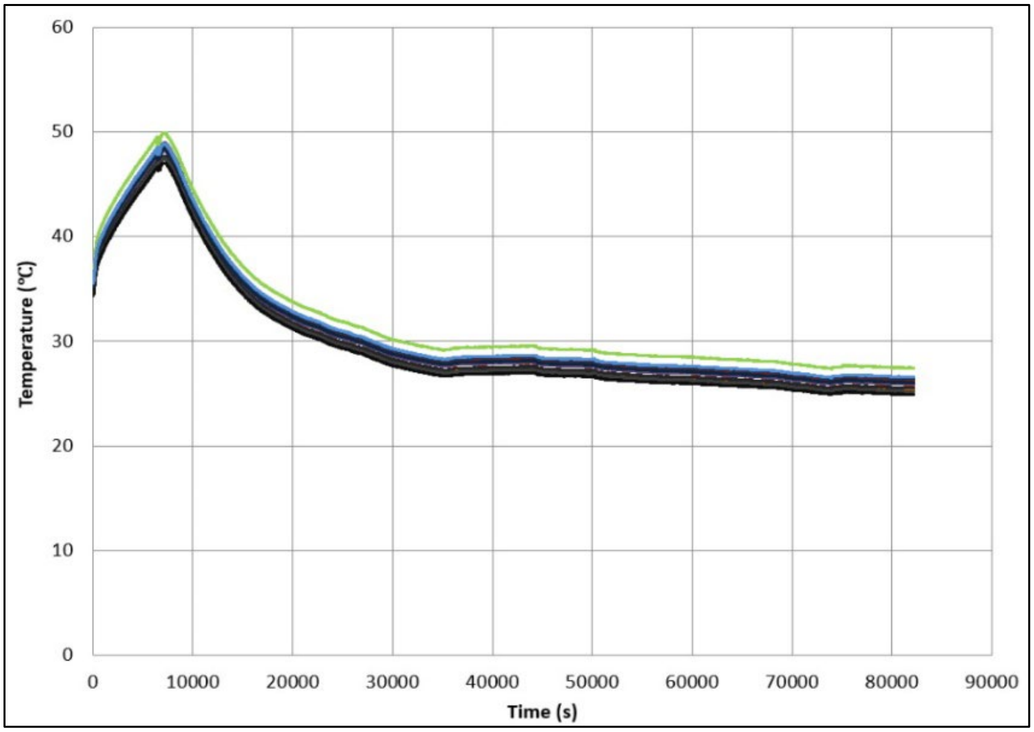

Figure 16. HiK Plate Temperatures at 200 W

Steady state temperatures across the tested power range are shown in Figure 17. Note that the final power of the ramp up test, 200 W, operated with a shroud temperature of 20 °C lower than the other tests in this series to prevent overheating the HiK plate. This sink temperature, -100 °C, was used for the entire ramp down test. For this reason, data is split between these sink temperatures.

For the -100 °C data, the LHP performs in the constant conductance range: temperatures increase with increasing power but the temperature difference between the evaporator and condenser is maintained. As the compensation chamber temperature depends on the pressure drop through the system, the increasing power and, therefore, flow rate, results in a decrease as power is increased. At 100 W, the TCV began to close and the 50 W case was not explored for this reason.

For the -80 °C data, the LHP also operates in constant conductance mode after 100 W. At 50 W, we can see the effect of the variable conductance produced by the TCV. When the TCV closes, the evaporator is uncoupled from the radiator. Here, conductance is defined as the ratio of the heat load to the temperature difference between the HiK™ plate surface and the radiator surface. Once the evaporator is uncoupled, conductance could be driven very low by reducing sink temperature. A lower sink temperature will also cause the TCV to actuate at higher heat loads. This will increase the range over which the LHP operates in variable conductance mode.

Once the TCV opens, the thermal conductance, shown in Figure 18, is relatively stable. The impact of the TCV is clearly shown in this figure. With the TCV closed, the thermal conductance decreases significantly. This can be seen at 50 W and at 100 W with a -100 °C sink temperature. With a -80 °C sink temperature, the valve remains open at 100 W and the conductance approaches that of the tests with higher heat loads. This variation in thermal conductance is a result of the TCV regulating flow. At the higher power, the valve remains open longer and the conductance is higher despite a lower sink temperature. As power decreases, conductance will also decrease. This is the purpose of the TCV and the key to surviving the long, cold lunar night: achieving very low conductance values at low heat load and low sink temperatures. Future tests will explore the minimum conductance achievable.

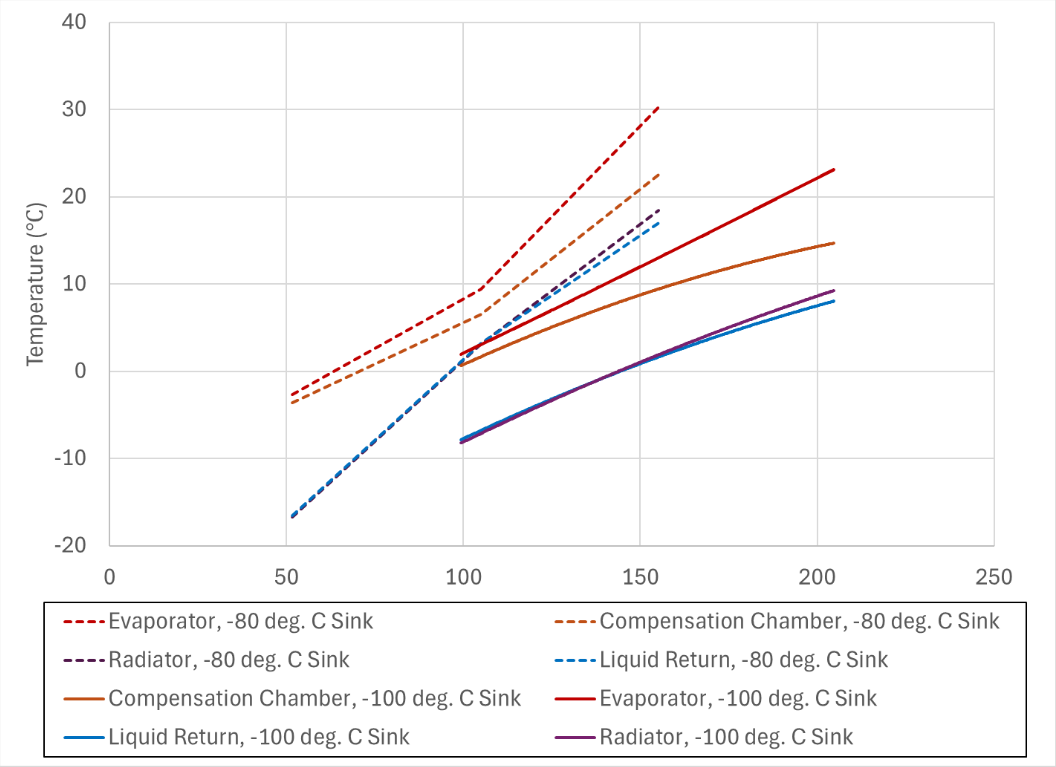

Figure 17. Steady State Temperatures across the Tested Power and Sink Temperature Range

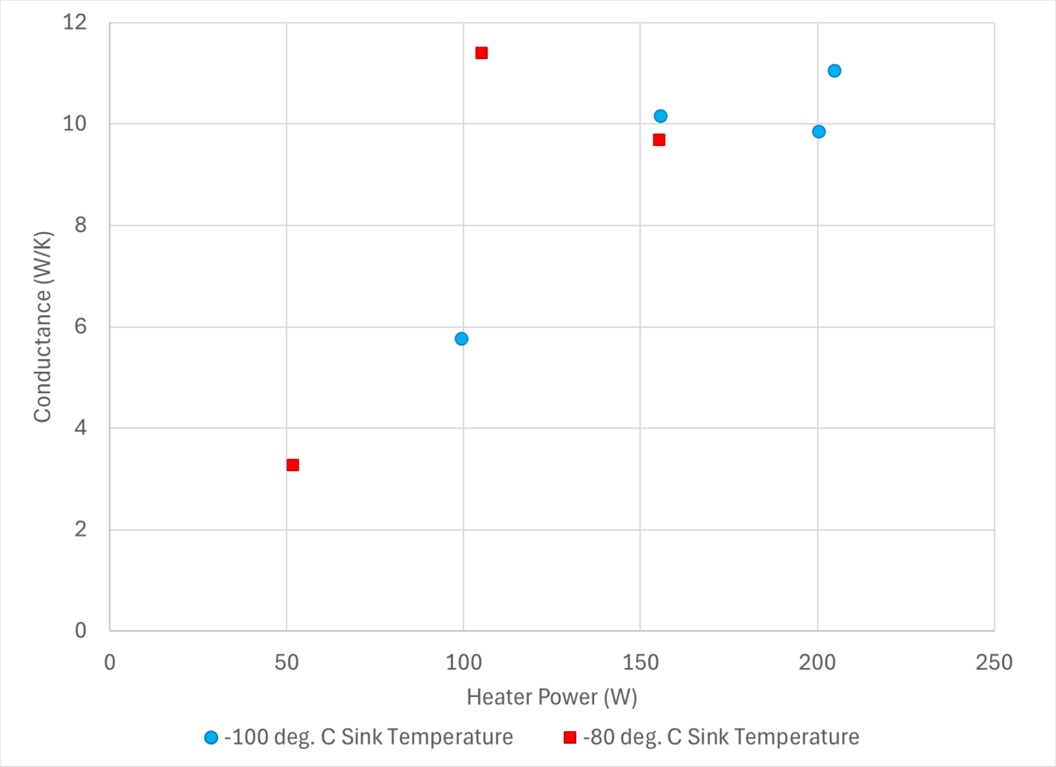

Figure 18. Thermal Conductance across the Tested Power and Sink Temperature Range

VI. Conclusion

While more testing is currently being conducted, initial results show that the TCV is capable of maintaining a LHP evaporator at a user-defined set point temperature by reducing the thermal conductance at low heat loads and low sink temperatures. This is extremely beneficial in environments with large temperature swings, such as the moon. The LHP can be designed to reject spacecraft or habitat waste heat during nominal conditions and uncouple from the heat sink during extreme conditions. And this uncoupling can be intermittent so that heat can still be rejected but at a lower conductance. While tested with a LHP, this technology could be applied to any two-phase system.

The data shown here is just a portion of the data that is being collected over the next several months. In addition to the power ramp down tests, ACT intends to simulate a long term, no power exposure to sink temperatures of 150 K, as well as response to a simulated avionics system operating at varying power levels. These data will be presented at the next ICES conference.

VII. Acknowledgments

The authors would like the acknowledge Jeff Farmer and William Johnson at Marshall Space Flight Center (MSFC) for giving us the opportunity to explore this technology. We also appreciate the assistance of Megan Gettle and Adam Shreve in the experimental work presented here.

VIII. References

[1] Jablonski, A.M and Ogden, K.A., "Technical Requirements for Lunar Structures," *Journal of Aerospace Engineering*, vol. 21, no. 2, pp. 72-90, 2008.

[2] Dallas, T., Diaguila, A.J. and Salisman, J.F., "Design Studies on the Effects of Orientation, Lunation, and Location on the Performance of Lunar Radiators," NASA TM X-1846, Washington, D.C., 1971.

[3] Ku, J. "Operating Characteristics of Loop Heat Pipes," *29th International Conference on Environmental Systems*, Denver, CO, 1999.

[4] Anderson, W.G., Dussinger, P.M., Garner, S.D., Hartenstine, J.R. and Sarraf, D.B., "Loop Heat Pipe Design, Manufacturing, and Testing - An Industrial Perspective," *Heat Transfer Summer Conference*, San Francisco, CA, 2009.

[5] Walker, K.L., Hartenstine, J.R., Tarau, C., Polak, J. and Anderson, W.G., "Ammonia and Propylene Loop Heat Pipes with Thermal Control Valves - Thermal/Vacuum and Freeze/Thaw Testing," *43rd International Conference on Environmental Systems*, Vail, CO, 2013.

[6] Nicolaescu, I., Ellis, M.C., Anderson, W.G. and Demydovych, M., "Thermal Control Valve for Lunar Night Survival," *53rd International Conference on Environmental Systems*, Louisville, KY, 2024.

[7] Ababneh, M.T., Tarau, C., Anderson, W.G., Farmer, J.T., Alvarez-Hernandez, A.R., and Ortega, S., "Advanced Passive Thermal Experiment for Hybrid Variable Conductance Heat Pipes and HiK™ Plates on the International Space Station," *47th International Conference on Environmental Systems*, Charleston, SC, 2017.