

QUALIFICATION TESTING OF 3D-PRINTED LOOP HEAT PIPE WITH DEPLOYABLE RADIATOR

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ABSTRACT

Advanced Cooling Technologies, Inc. has developed low-cost and rapidly deployable additively manufactured Loop Heat Pipes (3DP-LHPs), enabling high-performance SmallSats. The 3DP-LHP features a primary wick and evaporator envelope 3D printed as a single component using the laser powder bed fusion process. The evaporator, made from 316L SS, reduces the cost and lead time of LHPs by eliminating several high-risk manufacturing processes used in traditional sintered wick evaporators. This paper discusses the development of an ammonia 3DP-LHP that is coupled to a Deployable Radiator Panel (DRP), to increase the heat rejection capabilities on an ESPA-Sat by 2-3x over the current state-of-the-art. The 3DP LHP and DRP are designed to provide up to 250W of additional heat rejection. The discussion in this paper includes two sets of qualification testing. Testing of the 3DP-LHP and DRP in ambient and thermal vacuum conditions is discussed, with the system achieving a maximum conductance of 12.8 W/°C.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

LHP Loop Heat Pipe

DRP Deployable Radiator Panel

TVAC Thermal Vacuum

INTRODUCTION

The ever-decreasing cost of SmallSats has increased the demand for higher-performance payloads in a SmallSat form factor. One challenge in deploying high-performance SmallSats is thermal management, specifically rejecting enough heat from the limited surface area on the payload. A common solution is to use a deployable radiator panel (DRP), which is generally coupled to the payload with a conductive strap, commonly known as a thermal strap. This solution is limited by an inherently high thermal resistance, failing to provide an adequate thermal management solution to the problem. Addressing these challenges requires an innovative solution.

One solution to this problem is to use a passive two-phase thermal management technology, which increases the overall system conductance compared to conduction-only solutions. One example of an advanced thermal management system is the Loop Heat Pipe (LHP). LHPs are

highly sophisticated devices designed to efficiently transfer heat over long distances by utilizing natural capillary action and phase transitions, eliminating the need for mechanical pumps. This passive mechanism ensures high reliability, making LHPs ideal for applications where maintenance is difficult, such as in SmallSat systems. Their ability to manage heat with minimal temperature fluctuations and adapt to varying thermal needs makes them a top choice for heat rejection in space environments. Traditional LHPs utilize sintered wicks, which can be cost-prohibitive due to several high-risk steps in the manufacturing process. The LHPs discussed in this paper are produced with additive manufacturing, crucially reducing cost and lead-time for low-cost SmallSat applications. Advanced Cooling Technologies, Inc. is advancing the development of cost-effective, quickly deployable 3D Printed Loop Heat Pipes (3DP-LHP) featuring a DRP.

Previous efforts have focused on the development of the 3D-printed primary wick^{1,2} and the design of the 3DP LHP with DRP³. This paper discusses the qualification of the 3DP LHP and DRP as a part of an Air Force Direct to Phase II SBIR program, which aims to reject an additional 250W from an ESPA-Sat with a single LHP and DRP. Qualification for the LHP involves constructing the LHP and demonstrating reliable start, stop, and steady-state operation in ambient conditions. Further qualification of the LHP and DRP takes place in a thermal vacuum chamber, where start, stop, and steady-state operations are demonstrated in a thermal vacuum. The thermal vacuum testing also validates that the DRP can reject the required 250W of heat, as was demonstrated by multi-physics models.

RESULTS

Ambient Condition Testing

The qualification process for the 3D-printed Loop Heat Pipe starts with conducting tests under ambient air conditions. This initial phase is crucial for verifying the loop's ability to reliably start, stop, and maintain steady-state operation. The procedure involves incrementally applying power to the loop to identify the threshold at which it begins to operate. Power is progressively increased in small steps to assess the system's steady-state performance across varying power levels. The process continues until dry-out is observed in the evaporator, indicating the maximum heat rejection capacity of the pump body has been reached.

Testing in ambient conditions requires a reliable way of rejecting the heat from the condenser. For this purpose, a liquid nitrogen cold plate is placed on top of the radiator panel. To apply heat to the system, cartridge heaters are placed inside the saddle in contact with the evaporator. The evaporator, compensation chamber, and liquid/vapor lines are insulated to avoid heat leak into the environment. Insulation is also placed around the radiator panel and cold plate. A PLC is used to monitor the data from 53 thermocouples. This testing setup can be seen in Figure 1.

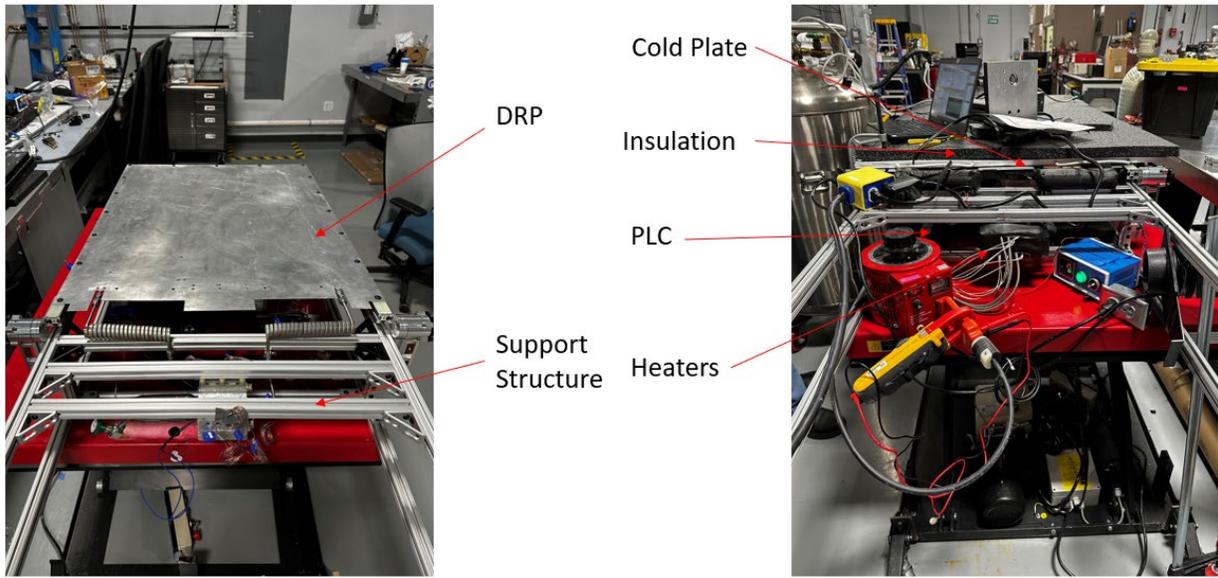


Figure 1: Testing set up for ambient condition testing of the 3DP LHP and DRP.

Figure 2 (left) shows the temperatures of the LHP and condenser outlet during these tests, with Figure 2 (right) showing where these measurements came from. As can be seen, the loop began operating once 25W of power was applied, which is indicated by the sudden drop in the liquid return line temperature. Note that the oscillations at start-up are common for LHPs operating at low power levels, with the oscillations smoothing out once 150W of power is applied to the system. Power was increased in increments of 50W until 500W of power was reached. After 500W was reached, the thermal control box (set to 45°C) tripped, ending the testing.

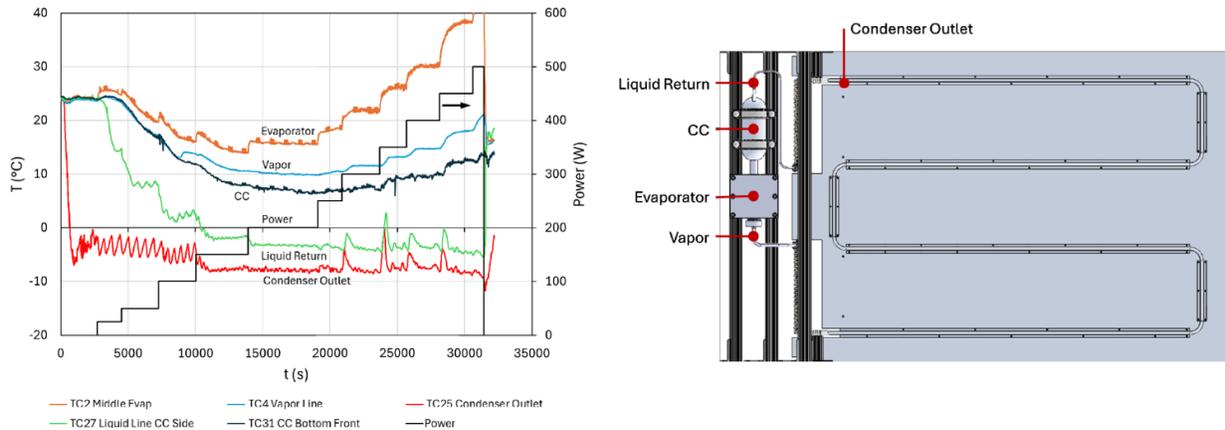


Figure 2: Thermocouple data from the 3DP LHP during ambient condition testing at various power levels.

Figure 3 highlights the temperature across the condenser line during these tests. At 100 W, the two-phase flow forces the subcooled liquid downward past thermocouple 18, raising the temperature and bringing it closer to the saturation point. Most of the two-phase flow exhibits high vapor quality, with the flow pattern being either annular or stratified, resulting in a condenser temperature nearly equal to the vapor temperature. Oscillations can be seen, indicative of slug and bubble flow passing the thermocouple. As the power is increased, the development of the two-phase region can be visualized by the thermocouples as the temperature of the condenser line increases to that of the saturation temperature.

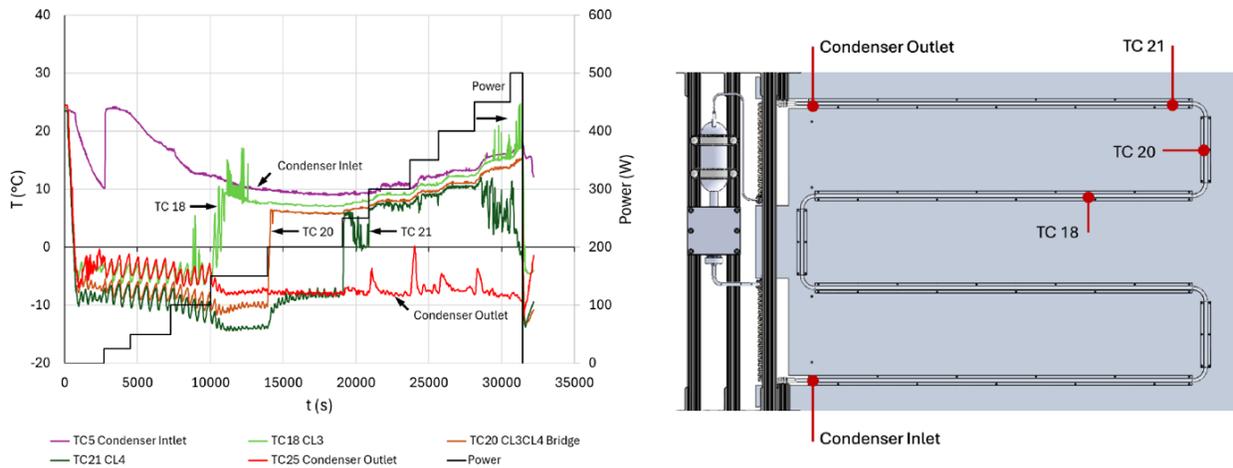


Figure 3: Thermocouple data from the DRP during ambient condition testing at various power levels.

Once the power is increased to 150W, the sharp increase in temperature and oscillations can be seen at thermocouple 20. The increase in temperature at thermocouple 20 results from the two-phase region being pushed further along the condenser line as the power increases. This phenomenon can be seen again at 250W, as the two-phase region extends to thermocouple 21. Beyond 250W, the temperature stabilizes, which hints that the condenser is oversized in this application. However, this is expected as the condenser plate is optimized for radiative heat transfer, not being cooled by the cold plate.

Thermal Vacuum Chamber Testing

After testing the LHP and DRP in ambient air conditions, the prototype was transferred to a thermal vacuum chamber on-site at ACT. Thermal vacuum testing is an important step in qualifying the LHP and DRP, as it validates that the system can reject the required 250W via radiation with acceptable system conductance. The radiator was placed inside the vacuum chamber along with a liquid nitrogen-cooled cold plate, as can be seen in Figure 4. The cold plate hangs above the radiator panel and rests on the sides of the vacuum chamber, effectively isolating the cold plate from the radiator. On the system, MLI is used to isolate components from radiating to the radiator panel. These components include the compensation chamber, the vapor and liquid lines, and the evaporator assembly. MLI is then draped from the cold plate

to the support structure for the radiator panel. The draped MLI ensures that the radiator panel is isolated from the walls of the vacuum chamber.

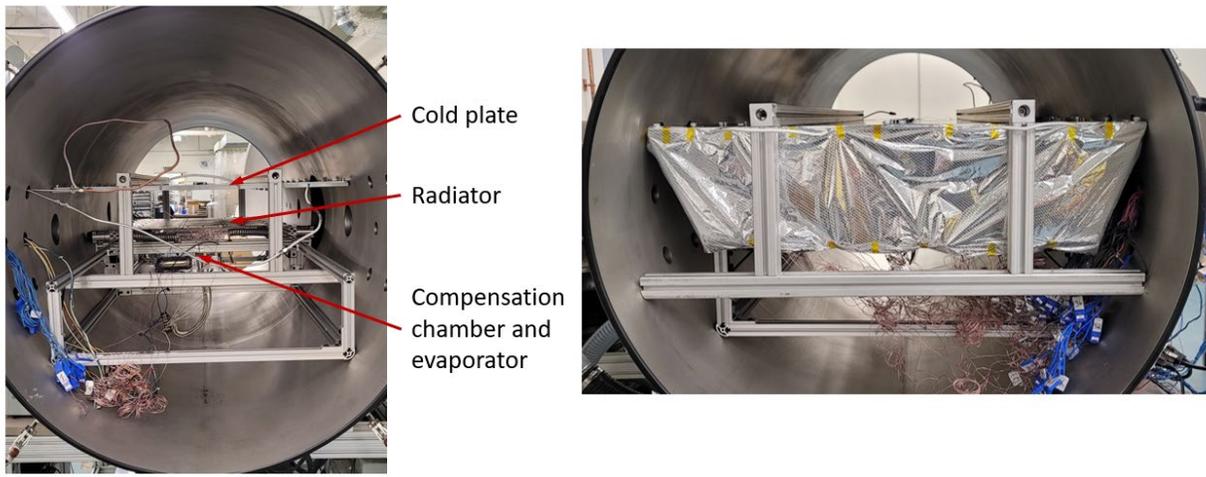


Figure 4: Testing setup for the 3DP LHP and DRP in the thermal vacuum chamber. On the left is the DRP, with the cold plate placed above. On the right is the same system with MLI.

53 thermocouples are used on the LHP and DRP to monitor temperature across them. The T-type thermocouples are mounted using aluminum tape. The thermocouples across the condenser line help visualize the two-phase region of the flow, and the thermocouples on the radiator record the bulk average surface temperature of the radiative surface. Similarly to testing in ambient conditions, power was slowly added to the LHP until startup was observed, with power then being increased in increments of 50W to demonstrate steady-state operation at different power levels. Figure 5 highlights the performance of the LHP and DRP during start-up operation with a -80°C cold sink. Oscillations can again be seen at start-up, which occurs at 25W. Once the power is increased to 50W, the oscillations smooth out.

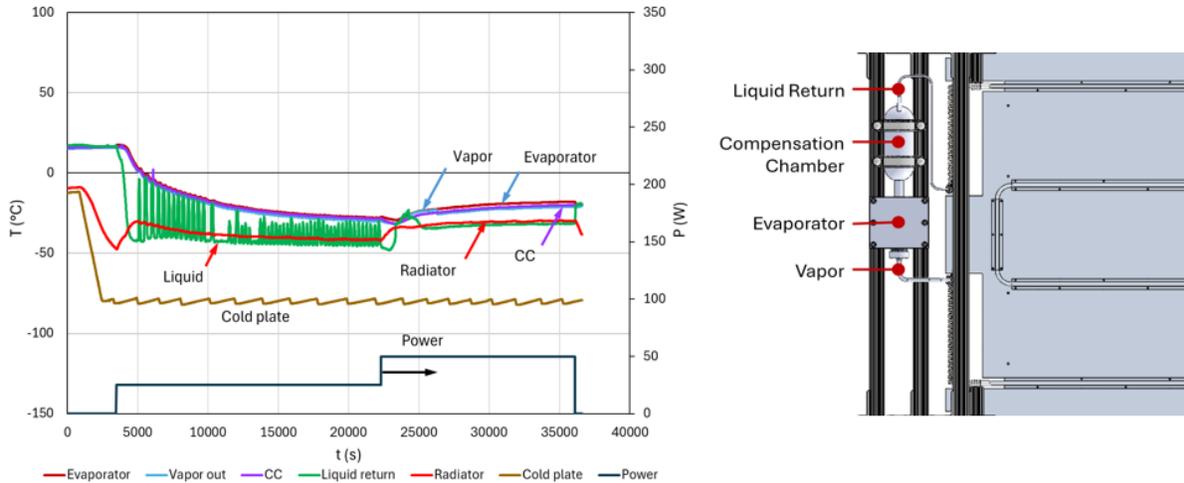


Figure 5: Thermocouple data from the 3DP LHP during startup.

Figure 6 illustrates that power was increased to 250W, which was the design objective for this LHP and DRP. At 250W, there are few oscillations in the liquid return line, as seen at lower power operation. The DRP is likely capable of rejecting additional heat in TVAC; however, once 250W was surpassed, the thermal fuses inside the evaporator tripped, ending testing.

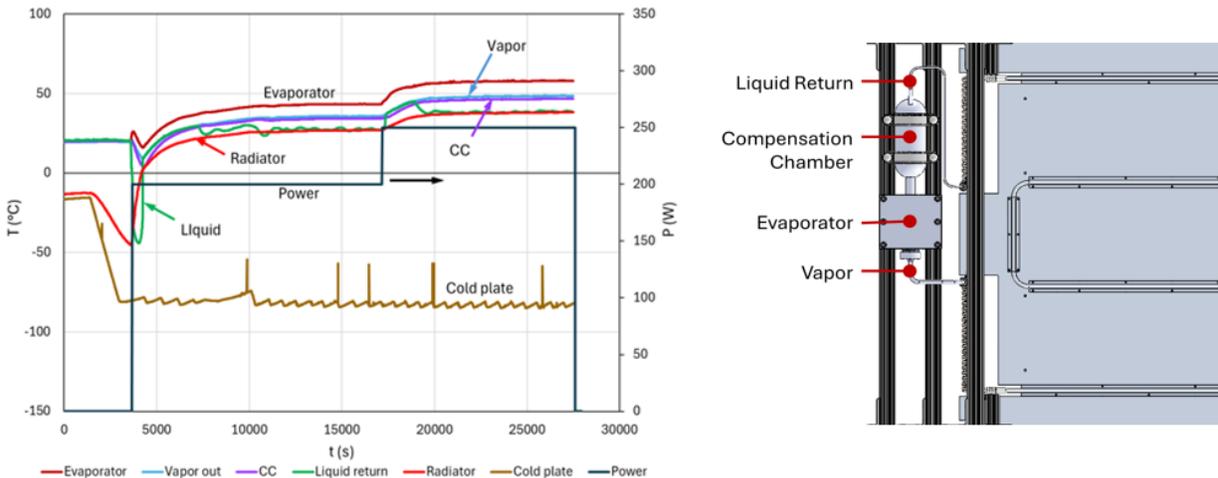


Figure 6: Thermocouple data from the 3DP LHP at 200 and 250W.

To reach the 300W, the cold plate temperature was lowered from -80°C to -140°C. This change helps to increase the heat rejection from the DRP, lowering the evaporator temperature and allowing the system to operate at higher powers. However, with the cold plate temperature being so low, it needed to be slowly brought down to temperature as power was slowly

increased into the evaporator. This was required to avoid freezing the ammonia inside the condenser line. As visualized in Figure 7, the system reaches a maximum of 300W with the lower cold plate temperature.

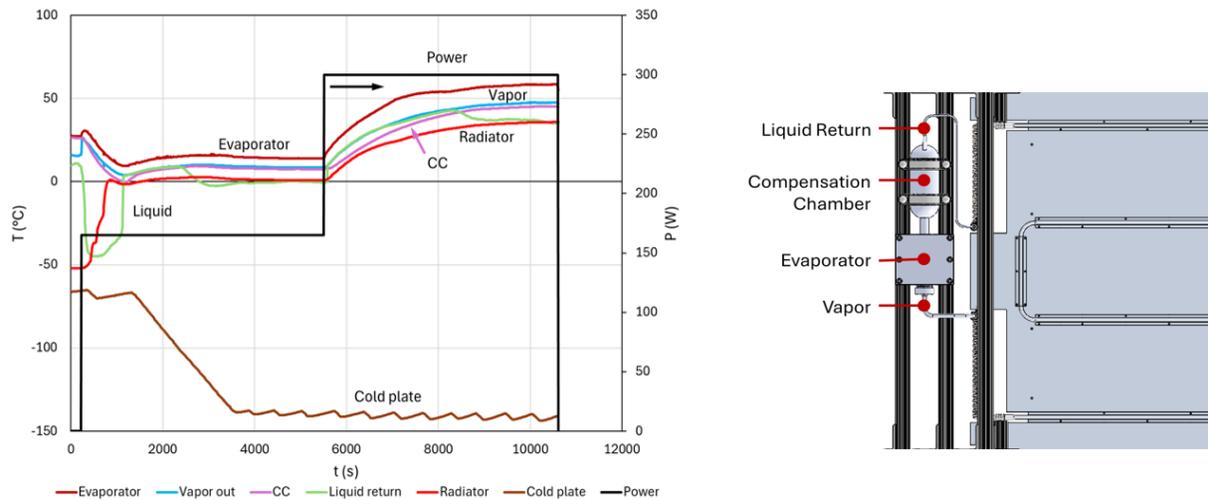


Figure 7: Thermocouple data from the 3DP LHP at 300W with a reduced cold plate temperature.

Overall, the system reached a maximum conductance of 12.8 W/°C during TVAC testing. This conductance was achieved from 150W all the way to 300W, indicative of a large constant conductance zone for the LHP. Figure 8 shows these conductance values across various power levels and cold sink temperatures. Note that changing the sink temperature has a negligible effect on the overall system conductance. To calculate this conductance, the temperature of the evaporator wall and the average temperature of the radiator panel are used. Future efforts will focus on improving the evaporator design to allow for even higher conductance values.

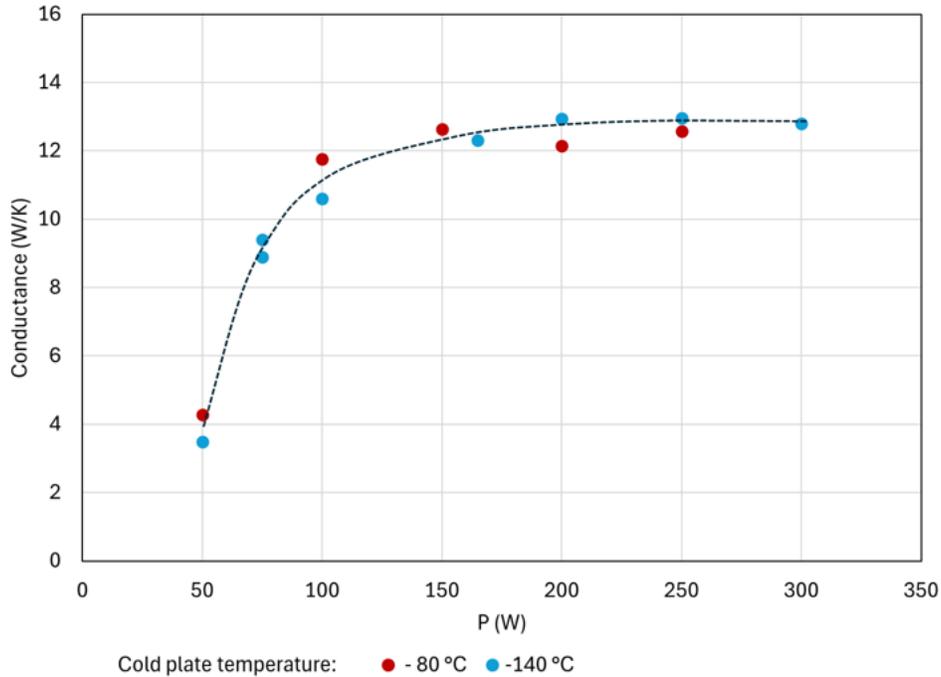


Figure 8: Overall system conductance during TVAC testing. Note that the conductance is calculated using the evaporator wall temperature and the average radiator surface temperature.

CONCLUSIONS

In the ever-growing world of high-performance SmallSats, the demand for improved thermal management systems has grown. Advanced Cooling Technologies, Inc. has addressed this challenge with an additively manufactured Loop Heat Pipe and a Deployable Radiator. The LHP and DRP were engineered to dissipate 250 W of heat from a deployable radiator panel (DRP) that fits within an ESPA-sized payload. The LHP incorporates a 3D-printed evaporator developed through a separate NASA SBIR-funded initiative. This 3D-printed LHP is designed to significantly boost the thermal performance of ESPA-sized and smaller satellites. In this paper, ACT demonstrates the ability of the prototype system to reject the 250W of heat in ambient and thermal vacuum testing conditions. Additionally, the system reached a maximum of 300W of heat dissipation in the thermal vacuum chamber. The maximum system conductance in the vacuum was 12.8 W/°C. This testing has evaluated the Technological Readiness Level (TRL) of the system to a TRL of 6. Future efforts will involve improving the evaporator wick structure for even higher system conductance. Additionally, the technology presented will be a part of a flight technology demonstration on a 3U CubeSat, which will establish flight heritage and further increase TRL.

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