

# 3D-printed Loop Heat Pipes for CubeSat, SmallSat, and Lunar Habitat Applications

Lawrence N. Bradley III<sup>1</sup>, Ion Nicolaescu<sup>2</sup>, Philip Graybill<sup>3</sup>, Jimmy Hughes<sup>4</sup>, Adam Shreve<sup>5</sup>, Chien-Hua Chen<sup>6</sup>,  
William G. Anderson<sup>7</sup>

*Advanced Cooling Technologies, Lancaster, PA 17402, United States*

Advanced Cooling Technologies, Inc. has developed low-cost and rapidly deployable 3D Printed Loop Heat Pipes (3DP-LHPs) to enable high-performance SmallSats, CubeSats, and Lunar Habitats. The 3DP-LHP features a 3D printed evaporator, with the unique feature being the additively manufactured primary wick structure. The evaporator is printed as a single component using the laser powder bed fusion (LPBF) process and is constructed from stainless steel. By using additive manufacturing, the cost and lead time for LHPs are significantly reduced, enabling their usage in SmallSat and CubeSat applications, where traditional LHPs would be cost-prohibitive. The current paper discusses the development and fabrication of four LHPs. Two LHPs are for CubeSat applications (3U and 12U), one of which will fly as part of NASA's CubeSat Launch Initiative (CSLI). The third LHP is for SmallSat (ESPA-class) applications and includes a deployable radiator capable of 250 W of heat rejection. The fourth LHP is a heat exchanger built to reject 1 kW from single-phase loops inside future lunar habitats. The discussion includes details such as radiator panel sizing, evaporator-compensation chamber design, condenser layout, and hinge line design. Additionally, the paper discusses the fabrication and testing of the flight demonstration LHPs.

## Nomenclature

|            |   |                        |
|------------|---|------------------------|
| $Q_{EVAP}$ | = | Evaporator power       |
| $T_{SINK}$ | = | Sink temperature       |
| $q_{SUN}$  | = | Heat flux from the sun |

## I. Introduction

The SmallSat market has seen rapid growth in recent years, from tiny CubeSats to the larger ESPA-class SmallSats. With this new growth has come the demand for higher power payloads, necessitating improved thermal management systems. One promising thermal management device is the Loop Heat Pipe (LHP), which is a passive thermal management device capable of transporting heat across large distances. The LHP is a passive two-phase heat transfer device that utilizes a pressure difference between the evaporator and fluid reservoir to transport heat efficiently over long distances. It consists of a wicked evaporator, a fluid reservoir (compensation chamber), a condenser, and liquid and vapor transport lines. The primary wick inside of the evaporator uses capillary action to move liquid through the wick structure, and when heat is applied to the evaporator, the working fluid absorbs energy and vaporizes. The saturation point difference between the vapor grooves and the compensation chamber drives the vapor through the transport lines, where the fluid condenses. Upon condensation, the liquid returns to the evaporator through capillary action within the wick, enabling continuous operation. LHPs offer high reliability, operate in various orientations, and are widely used in spacecraft thermal control, electronics cooling, and other advanced heat management applications. Their passive nature makes LHPs attractive for satellite applications, where high reliability is required. The 3D-printed LHP promises to reduce cost and lead time for LHPs by eliminating expensive components such as the Knife Edge Seal (KES), a component used to seal the primary wick from the compensation chamber in traditional sintered wick LHPs. By reducing the cost and lead time, 3D-printed LHPs are particularly attractive for SmallSat and CubeSat

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<sup>1</sup> R&D Engineer, Research and Development, 1046 New Holland Ave, Lancaster, PA 17601

<sup>2</sup> Senior R&D Engineer, Research and Development, 1046 New Holland Ave, Lancaster, PA 17601

<sup>3</sup> PD Engineer, Product Development, 1046 New Holland Ave, Lancaster, PA 17601

<sup>4</sup> PD Manager, Product Development, 1046 New Holland Ave, Lancaster, PA 17601

<sup>5</sup> R&D Technician, Research and Development, 1046 New Holland Ave, Lancaster, PA 17601

<sup>6</sup> Director of R&D, Research and Development, 1046 New Holland Ave, Lancaster, PA 17601

<sup>7</sup> Chief Engineer, Research and Development, 1046 New Holland Ave, Lancaster, PA 17601

applications, where SWaP-C requirements necessitate economical thermal management systems. ACT has previously focused on the development of the 3D-printed evaporator primary wick<sup>1</sup> and fixed-body radiator applications<sup>2</sup>. More recently, ACT has developed the 3D-printed LHP for deployable applications, where a flexible thermal link is used to connect the 3D-printed evaporator to a Deployable Radiator Panel (DRP)<sup>3</sup>.

This paper explores additional 3D-printed Loop Heat Pipes (LHPs) applications by developing four distinct thermal management systems for applications ranging from 15W to 1kW. The first two designs are for deployable systems, sized for a 12U CubeSat and an ESPA-class SmallSat. These CubeSat and SmallSat designs build upon ACT's previous SmallSat initiatives, incorporating the 3D-printed LHP into a higher fidelity deployable system. The third design focuses on developing and testing an LHP for a 15W application as part of NASA's CubeSat Launch Initiative (CSLI). This 15W LHP will be launched under the NASA CSLI program and integrated with a 3U payload. The fourth design involves scaling the 3D-printed evaporator for a 1kW application, where the LHP will be mounted to a fixed-body radiator to support lunar survival operations. Table 1 summarizes the requirements for the four LHPs.

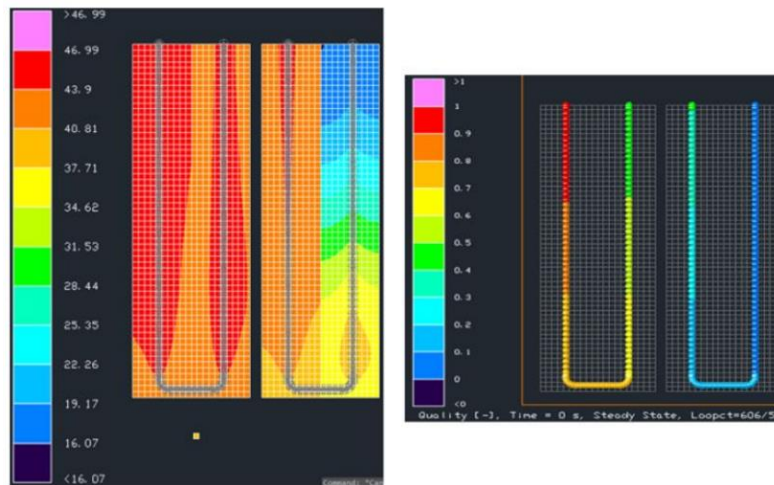
**Table 1: Outline of the four LHP designs.**

| Target Application      | Heat Load | Operating Fluid | Deployable Radiator Panel (DRP) | Thermal Control Valve (TCV) | Approx. Wick Size               | Approx. Radiator Size    |
|-------------------------|-----------|-----------------|---------------------------------|-----------------------------|---------------------------------|--------------------------|
| Tech Demo (CubeSat, 3U) | 15W       | Ammonia         | No                              | No                          | $\emptyset 5/8'' \times 1.25''$ | 0.04 m <sup>2</sup> (3U) |
| CubeSat (12U)           | 50W       | Ammonia         | Yes                             | No                          | $\emptyset 5/8'' \times 1.25''$ | 20 x 30cm                |
| SmallSat                | 300W      | Ammonia         | Yes                             | No                          | $\emptyset 1'' \times 4''$      | 0.7 m <sup>2</sup>       |
| Lunar TCS               | 1kW       | Propylene       | No                              | Yes                         | $\emptyset 1'' \times 10''$     | 2 m <sup>2</sup>         |

## II. CubeSat 50W

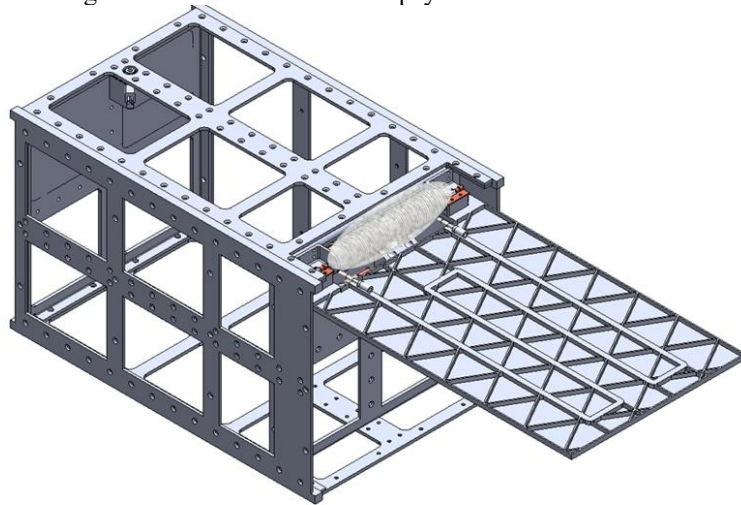
### A. LHP and DRP Design

The first of the four LHPs is for a deployable system to reject 50W of heat from a 12U CubeSat. The system comprises a deployable radiator panel (DRP) with an integrated 3D-printed stainless-steel LHP. The preliminary design of the CubeSat deployable system began with Thermal Desktop modeling to find the optimum condenser line spacing for the deployable radiator panel (DRP). The DRP, which occupies one face of the 12U CubeSat, is 20cm x 30cm in size. Using Thermal Desktop, ACT developed a CubeSat LHP model derived from CRtech's steady-state LHP model for system sizing. Input parameters for the model include elements such as  $Q_{EVAP}$ , set to 50W, representing the power going to the evaporator. The sink temperature,  $T_{SINK}$ , is assumed to be 3K, representing radiating to the background of space. The model also assumes zero backloading from the sun ( $q_{SUN}$ ). The model is used to find the ideal condenser spacing and validate LHP sizing for the proposed system. The model also outputs a plot showing the void fraction through the condenser line, ensuring sufficient subcooling of the working fluid. Figure 1 shows a temperature plot (left) and a void fraction plot (right) of the condenser from the Thermal Desktop model, demonstrating subcooling of the liquid before returning to the evaporator assembly.



**Figure 1: Temperature and void fraction plots of the DRP and condenser lines from the Thermal Desktop model.**

Joining the DRP to the LHP are flexible transport lines, which provide a flexible thermal coupling between the DRP and the payload. Made from stainless steel, the flexible transport lines allow for up to 180 degrees of deployment. The transport line's flexibility is dictated by the material and geometry of the line. Hinges connect the deployable Isogrid radiator panel to the payload body. The hinges allow for 180 degrees of deployment and contain torsion springs to deploy the radiator panel. The flexible transport lines aid the hinges in deployment by providing additional spring force. An aluminum saddle connects the evaporator to the payload. The evaporator is mated to the saddle, coupling the evaporator to the heat source. Figure 2 illustrates the CubeSat payload and associated thermal management system.



**Figure 2: CAD model of the LHP and DRP for the CubeSat.**

The evaporator assembly utilizes the 3D-printed evaporators developed by ACT over several SBIR efforts. The evaporator is printed as a single piece, reducing the number of parts and welds when compared to a traditional LHP evaporator. The evaporator is printed from stainless steel and is joined to a conventionally manufactured stainless steel compensation chamber. To join the stainless steel pump body assembly to the aluminum transport lines, bimetallic transitions are used. Figure 3 is a CAD model of the CubeSat evaporator body. Note that the vapor plenum is integrated into the print, reducing the number of welds on the pump body assembly. The evaporator is 3.8cm (1.5") in length and 1.7cm (0.675") in diameter, sized specifically for the small payload volume of a 12U CubeSat.



**Figure 3: CubeSat Evaporator (CAD). Note that the vapor plenum is integrated into the print.**

### **III. SmallSat 250W**

#### **B. LHP and DRP Design**

The second Loop Heat Pipe (LHP) design is for an ESPA-class Small Satellite, a system requiring a heat rejection capacity of 250W. The SmallSat system uses a 10.2 cm (4") long, 2.5cm (1") diameter evaporator, a significant increase from the CubeSat evaporator. Increasing the evaporator size is necessary to meet the required 250W heat rejection. This SmallSat evaporator draws upon a prior design established during an Air Force Direct-to-Phase II SBIR initiative. The current design efforts concentrate on enhancing the printability of the evaporator. In previous designs, including the CubeSat variant, the evaporator is produced as a singular component, whereas the compensation chamber and vapor plenum are welded to the evaporator assembly. Conversely, the improved SmallSat evaporator design

incorporates a portion of the compensation chamber and the entire vapor plenum into the print. By merging the evaporator, compensation chamber, and vapor plenum into a single component, the design has minimized the number of parts and the welds required for assembly. Figure 4 shows the printed evaporator, including the first hemisphere of the compensation chamber and the vapor plenum.



**Figure 4: 3D-printed SmallSat evaporator. Note that the vapor plenum and the first half of the compensation chamber are included in the print.**

The DRP design is similar to the CubeSat, utilizing aluminum condenser tubing and an isogrid panel. Though the CubeSat design began with Thermal Desktop simulations to drive the condenser layout, the SmallSat design uses a condenser layout from a previously developed system by ACT, so the same condenser layout is used for the model. Similar to the CubeSat unit, an Isogrid panel is used to balance performance and cost. The CubeSat hinges are also used for the SmallSat design; however, additional hinges are used to accommodate the additional mass of the panel. In addition to hinges, a locking mechanism is also included in this design, ensuring that the DRP does not move after deployment. Figure 5 shows the assembled DRP and LHP. Note that the flexible hoses that connect the pump body to the DRP are not pictured. The condenser line is embedded into the DRP and secured using epoxy. The DRP is painted with black paint to improve the optical properties of the panel for TVAC testing. Four hinges attach the DRP to the payload body, which is constructed from aluminum extrusions. The pump body is mounted horizontally, below the DRP. Cartridge heaters will be used to provide heat to the evaporator during testing.

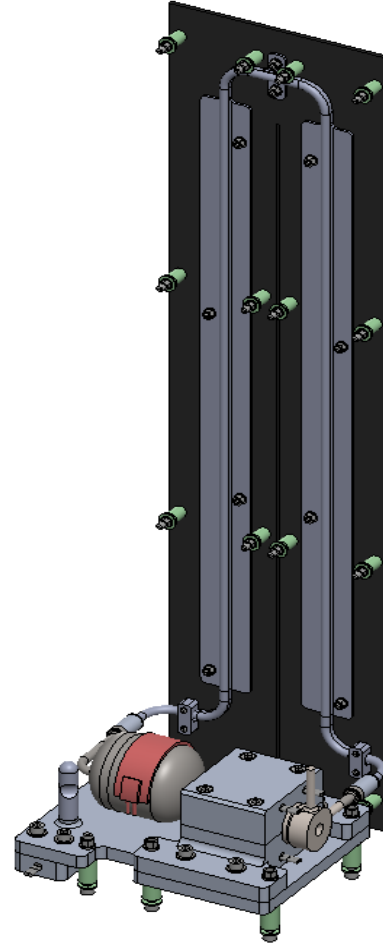


**Figure 5: The assembled SmallSat deployable radiator panel, along with the pump body.**



Advanced Cooling Technologies, Inc. and NASA are working towards a flight test of the 3D-printed LHP. ACT is developing a 3D-printed LHP for the flight demonstration unit to reject 15W from a fixed-body radiator panel on a 3U CubeSat. The small evaporator developed for the 12U CubeSat is used for this application. A CAD model of the proposed flight demonstration unit is shown in Figure 6. For flight operation, additional design elements needed to be considered. The CubeSat payload is power-negative, meaning the LHP will not be operational for most of the 6-month mission. To ensure proper shutdown and LHP control, a band heater is placed on the compensation chamber. The band heater raises the saturation point in the compensation chamber, effectively shutting down the LHP. For the flight demonstration unit, ammonia is used as the working fluid, which freezes at  $-77.7^{\circ}\text{C}$ , necessitating a heater placed on the condenser to eliminate the freezing risk of the working fluid. The heater only needs 2-3W to keep the condenser lines from freezing, less power than is required to operate the LHP. The condenser lines are made from 6061-T6 aluminum and are welded to the evaporator/compensation chamber assembly. Again, since the evaporator assembly is stainless steel, bimetallic joints are used to make the transition. A pulsating heat pipe (PHP) is also a part of the flight demonstration unit and is placed underneath of the LHP evaporator. The PHP has a heater on one end that will provide heat to the evaporator. If the PHP fails to perform as expected, cartridge heaters are also embedded in the LHP saddle so the LHP can be operated independently of the PHP.

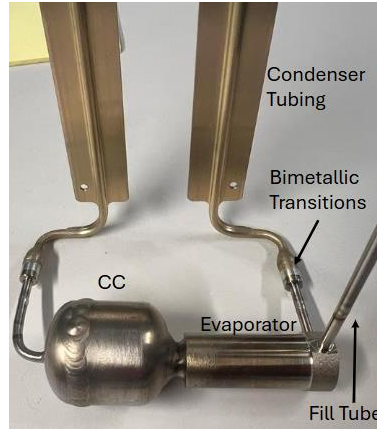
In preparation for the late Fall 2025 launch of the flight demonstration unit, fabrication has already begun on the LHP. The LHP evaporator, like the others presented in this paper, is 3D-printed. The driving parameters for the evaporator performance are the maximum pore radius and the permeability. The maximum pore radius sets the capillary pressure limit, and the permeability influences the pressure drop through the wick. The maximum pore radius is measured using a method called bubble point testing, which, in combination with the Young-Laplace correlation, allows for the measurement of the maximum pore radius in the wick<sup>4</sup>. Wick permeability is calculated using Darcy's Law<sup>5</sup>. Table 2 contains the calculated maximum pore radius and the permeability of the flight demonstration unit wick. Note that compared to some sintered wick evaporators, the 3D-printed has a larger pore radius, but an order of magnitude higher permeability. Figure 7 shows the assembled flight demonstration LHP. Though design elements such as the radiator panel, heaters, and saddle are not included, the LHP is fully welded and operational.



**Figure 6: CAD of the flight demonstration unit.**

**Table 2: Wick parameters for the flight demonstration primary wick structure.**

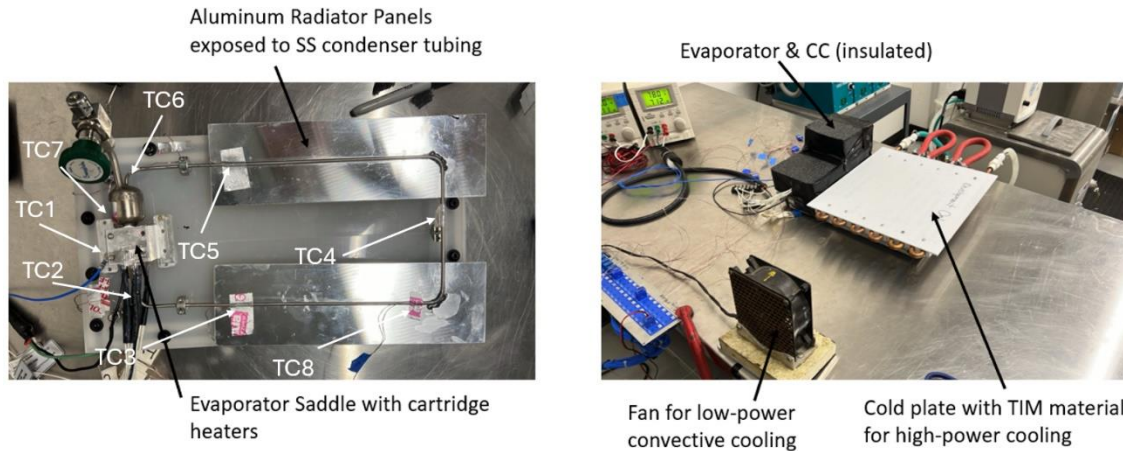
|                                               |          |
|-----------------------------------------------|----------|
| <b>Permeability (<math>\text{m}^2</math>)</b> | 4.30E-13 |
| <b>Pore Radius (<math>\mu\text{m}</math>)</b> | 5.756    |



**Figure 7: Fabricated flight demonstration unit LHP. Note that the vapor line connects perpendicularly to the evaporator, creating a compact design.**

### C. Testing

At the time of submission, the LHP for the flight demonstration unit still needs to pass through quality checks before ambient or thermal vacuum testing; however, testing was conducted on another LHP using the same size evaporator and compensation chamber assembly. Two tests of the evaporator were performed: one using natural convection to cool an aluminum radiator panel and another using a liquid-cooled cold plate. Figure 8 shows the two units (note that both use the same evaporator and compensation chamber assembly; only the condenser is different). The test LHP also uses stainless steel condenser lines, rather than the aluminum lines found on the flight LHP, eliminating the bimetallic joints. For cooling via natural convection, aluminum radiator panels were connected to the stainless steel condenser line. T-type thermocouples were utilized to monitor the temperature at seven locations on the evaporator, compensation chamber, and condenser. Both units were charged with ammonia. Cartridge heaters were embedded in the aluminum saddle, providing heat to the evaporator.

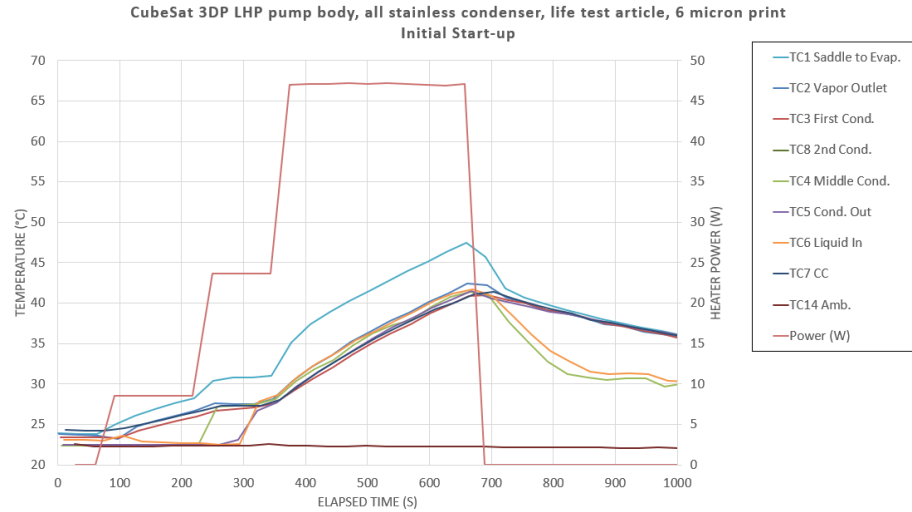


**Figure 8: The LHP during testing. Note that the same type of evaporator is used as the flight demonstration unit. The left figure shows the aluminum radiator panels for cooling via natural convection, and the right shows cooling with a liquid-cooled cold plate. Thermocouple locations are also shown on the left of the figure.**

The first test used natural convection to cool the aluminum radiator panels. This test aimed to demonstrate start-up and at least 15W of heat rejection from the evaporator. Figure 9 shows the data collected from the thermocouples placed along the LHP at several power levels. LHP start-up was demonstrated at 8W, sufficient for the flight demonstration unit, which is limited to 15W of power. The heater power was increased to 47W, concluding the testing. Conductance (W/K) of the LHP is defined by equation 1

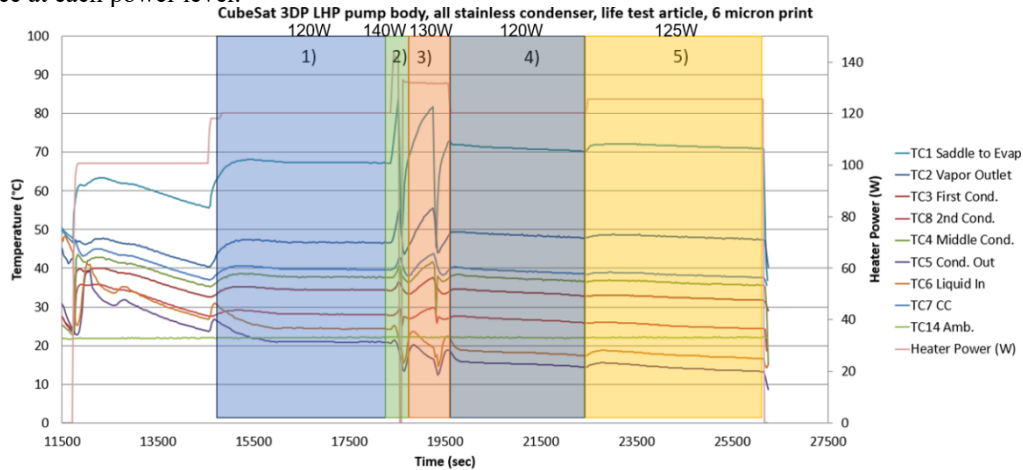
$$\text{Conductance} = \text{Heater Power}/(\text{TC1} - \text{TC6}) \quad (1)$$

where TC1 represents the temperature at the saddle, TC6 represents the temperature of the liquid return line, and Heater Power is the power applied to the cartridge heaters in Watts. For the natural convection case, the conductance of the LHP reaches a maximum of 5.1 W/K at a power of 25W, with a maximum power of 47W being achieved. Note that convergence was not reached at 47W due to limitations of the condenser cooling capacity.



**Figure 9: Flight demonstration unit LHP testing with natural convection cooled radiator. Red represents the power to the evaporator, and TC1 (light blue) and TC6 (orange) are used to calculate conductance.**

Following the tests with the natural convection-cooled radiator, a liquid-cooled cold plate was used to find the maximum heat transport capabilities of the CubeSat evaporator. Though the nominal power output for the CubeSat application is only 15W, the newly designed evaporator was tested further to understand maximum transport capabilities. The cold plate was cooled by a chiller using a 50/50 propylene-glycol water mixture. Testing began by starting up and increasing power to 120W (section 1, blue). Increasing to 140W, at which point dry-out conditions were observed, as the evaporator temperature dramatically increased relative to the condenser (section 2, green). Following the power reduction after dry out, power was increased to 130W, where dry out was again observed (section 3, orange). Note that in section 3, the high-temperature thermostat was triggered, resulting in a cutoff of power to the evaporator. Once the thermostat was reset, power was set to 120W (section 4, gray). Finally, power was increased to 125W, where dry-out conditions were not observed (section 5, yellow). Based on equation 1, the conductance at the maximum power was 2.4 W/K, partly driven by the large subcooling caused by the liquid-cooled cold plate. Future ambient testing will focus on modifying the cold plate to reduce the significant subcooling. Table 3 shows the conductance at each power level.



**Figure 10: Flight demonstration unit LHP testing with a liquid-cooled condenser. Five distinct power levels were tested, as shown by the highlighted sections.**

## IV. Lunar Habitat 1000W

### D. Evaporator Design

Unlike previous systems, the Lunar Habitat LHP is not designed for SmallSats, but for Lunar Survival in a potential lunar habitat. Lunar survival presents some unique challenges, with lunar night being a particularly difficult thermal challenge. Heat must be kept in the habitat for Lunar Night survival and then rejected during Lunar Day. The Lunar LHP system is designed to effectively dissipate energy from the habitat during the Lunar Day and conserve energy in the habitat during Lunar darkness conditions. Unlike typical LHP applications, where the evaporator is joined to a heat source with a saddle, the Lunar LHP must integrate with a single-phase liquid loop. The single-phase liquid loop is used for heat rejection inside the habitat and is then thermally coupled with the LHP evaporator outside the habitat. The evaporator for the Lunar design will use the same AM manufacturing process as the CubeSat and SmallSat evaporators. Figure 11 shows a CAD model of the lunar evaporator and the compensation chamber.

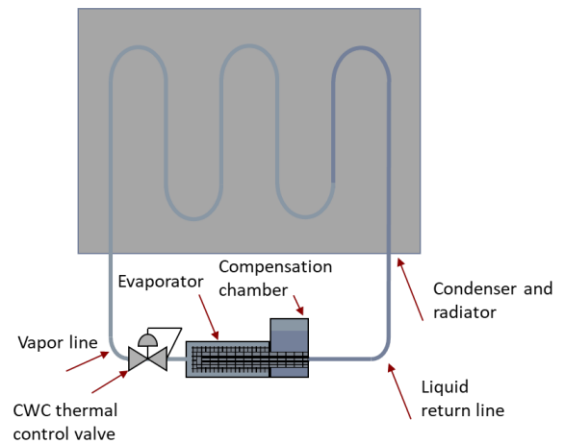


**Figure 11: CAD model of the Lunar evaporator and compensation chamber.**

### E. Thermal Control Valve

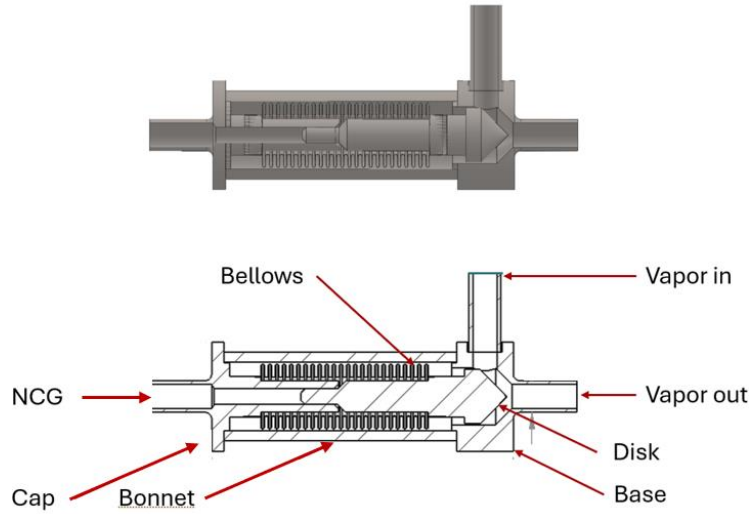
A Thermal Control Valve (TCV) is added to address the system's lunar survival aspect. During the long lunar night, the solar panels do not generate power, and the payload switches to survival mode, relying solely on batteries. Some functions are disabled or put into sleep mode. The generated heat is minimized, and the radiator must be isolated from the payload to maintain the minimum temperature required by the components. ACT designed the thermal control valve (TCV) to perform this function.

The variant is shown in Figure 12 is the Closed-When-Cold (CWC) type and is inserted into the loop heat pipe (LHP) between the evaporator and the condenser. It closes the vapor line when the vapor pressure of the working fluid decreases below a value corresponding to the desired minimum temperature, thus stopping the heat transfer to the radiator. The TCV cross-section is shown in Figure 13. The bellows between the valve cap and the disk rod separate the vapor-filled space from the volume filled by a non-condensable gas (NCG). The NCG amount sealed in the space behind the bellows remains at the payload temperature along with the evaporator with which the TCV is thermally connected. Its pressure varies within a limited range when the payload operates in the desired temperature range. If the temperature of the payload decreases below the desired minimum value the vapor temperature decreases more and its pressure falls below the NCG pressure, causing the bellows to expand and press the valve disk against the seat, therefore stopping the heat loss through the radiator.



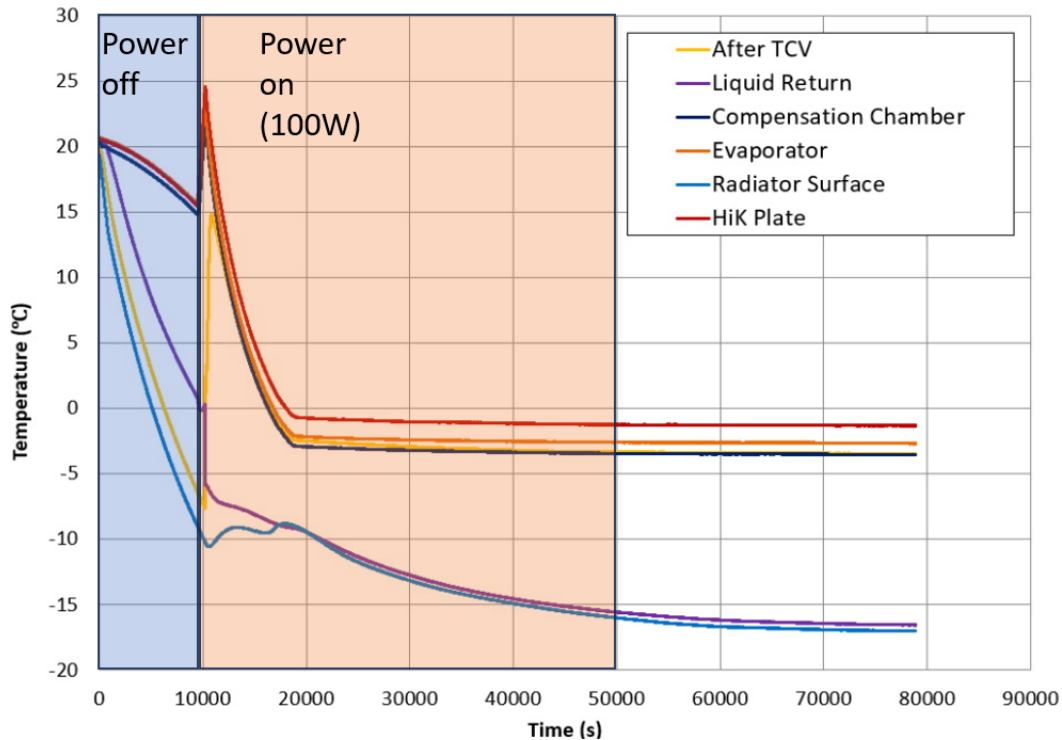
**Figure 12: Schematic of TCV operation.**





**Figure 13: Thermal Control Valve cross-section.**

Figure 14 shows the effect of the TCV during a vacuum chamber test of a smaller LHP with propylene as the working fluid, similar to the LHP that will be fabricated for the Lunar Habitat. The NCG in the TCV was adjusted to maintain approximately 0 °C, the minimal temperature of the load. The condenser radiated heat towards a cold plate maintained at liquid nitrogen temperature. The blue line represents the radiator temperature as the cold plate is cooling. The red line shows the temperature of the heat load represented by the HiK collecting plate. A 100 W heat load was applied at 10,000 s. One can see the surge in temperature, followed by the drop when the LHP started, as indicated by the colder liquid return (purple line). The temperatures of HiK, vapor, evaporator, and compensation chamber remained constant after the TCV closed, while the radiator temperature decreased. Though 100W is less than the nominal power of 1000W for the Lunar LHP, the test demonstrates proper function of the CWC TCV when paired with a LHP.



**Figure 14: Thermal Control Valve operation on a propylene-charged LHP.**

## V. Conclusion

Advanced Cooling Technologies, Inc. has applied the 3D-printed LHP to four systems. The first system is for a 12U CubeSat, where an LHP is coupled to a DRP for 50W of heat rejection. The second system is similar to the first; however, it is scaled to a 250W application for an ESPA-class satellite. Based on previous work by ACT, the SmallSat system focuses on improving the printability of the evaporator. The third system is an LHP sized for a 3U application. The 3U system is part of NASA's CSLI, a program enabling flight testing of the 3D-printed LHP. The flight unit focuses on demonstrating the reliable function of the 3D-printed LHP in a microgravity environment. The last system presented is for Lunar Survival applications, specifically for future lunar habitats. For the lunar system, an LHP is integrated with a single-phase liquid loop, which provides heat to the evaporator. The system is paired with a TCV to survive lunar darkness, enabling the LHP to bypass the habitat's radiator. With the design phase of each system near completion, future efforts will focus on the fabrication and testing of hardware. Each of the four systems will be fabricated and undergo thermal vacuum testing to demonstrate their capabilities.

## Acknowledgments

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