Development of a Passive Thermal Control Valve for 3D-Printed Loop Heat Pipes

Sean H. Hoenig[1], Nathan van Velson[2], Michael C. Ellis[3], William G. Anderson[4]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

As the capabilities of extended-duration science payloads on the Lunar surface increase, so do the thermal control requirements. The primary power source for near-term Lunar surface science missions is a combination of solar photovoltaic arrays and batteries. A thermal control system that rejects daytime heat efficiently and conserves energy through the night is essential to keep the payloads, batteries, and other critical components at suitable temperatures. Conventional loop heat pipes (LHPs) provide very efficient heat transfer between electronics and spacecraft radiators when necessary but require 2-3 W of power continuously to shut down and minimize heat transfer through the night. This can increase battery mass substantially if applied for the entire Lunar night. The focus of this work is the development of a passive thermal control valve (TCV) integrated with the design of a 3D-Printed LHP evaporator. In this study, it was demonstrated that an on/off TCV is sufficient to shut down an LHP quickly and is much less expensive than currently used proportional valves. Three different designs are demonstrated for the TCV: "open when cold", "closed when cold", and a 3D-printed integral (also "open when cold"). Benchtop testing demonstrated the functionality and feasibility of using an on/off TCV in an LHP system. Results for the two subtractive manufactured TCV designs, tested with an additively manufactured capillary pump, show that it is feasible to maintain a tight seal and passively shut down the LHP at a cold temperature setpoint. Additional progress is required to refine the additively manufactured TCV design to create a sufficiently tight seal.

Nomenclature

A_c	=	cross-sectional area
b	=	damping coefficient
CC	=	compensation chamber
CWC	=	close when cold
F	=	applied force
k	=	spring constant
LHP	=	loop heat pipe
M	=	effective mass
NCG	=	non-condensable gas
OWC	=	open when cold
P_{sat}	=	saturation pressure
T	=	temperature
TCV	=	thermal control valve
y	=	displacement

Subscripts

p	=	plug
s	=	stem
t	=	top of component inside bellows
wf	=	working fluid

---

[1] R&D Engineer III, R&D, 1046 New Holland Ave.
[2] R&D Engineer III, R&D, 1046 New Holland Ave.
[3] Senior Engineer, R&D, 1046 New Holland Ave.
[4] Chief Engineer, R&D, 1046 New Holland Ave.

I. Introduction

Loop heat pipes are a critical thermal management device for the efficient operation of planetary habitats, landers, rovers, and SmallSats/CubeSats. The recent Survive & Operate through the Lunar Night Workshop, sponsored by the Lunar Exploration Analysis Group (LEAG), identified a clear need for advanced thermal control solutions that can support extended-duration science payloads on the Lunar surface [1]. As the capabilities of extended-duration science payloads on the Lunar surface increase, so do the thermal control requirements. The primary power source for near-term Lunar surface science missions is a combination of solar photovoltaic arrays and batteries. A thermal control system that rejects daytime heat efficiently and conserves energy through the night is essential to keep the payloads, batteries, and other critical components at suitable temperatures. Conventional loop heat pipes (LHPs) provide very efficient heat transfer between electronics and spacecraft radiators when necessary, but require 2-3 W of power continuously to shut down and minimize heat transfer through the night. This can increase battery mass substantially if applied for the entire Lunar night. The temperature of the compensation chamber (CC) sets the operating temperature. In conventional LHPs, the CC is cold biased, so it will operate at a lower operating temperature than desired when not electrically heated. Electric heat is added to warm the CC up to the desired operating temperature. To shut down a conventional LHP, the temperature of the CC is increased until it is higher than the evaporator vapor temperature. Since the fluid is saturated, the pressure in the CC is slightly higher than the pressure in the evaporator, so heat is not transferred from the evaporator to the condenser. A passive system is more desirable since 1 W of electric heat over the 14-day-long Lunar night requires 5 kg of batteries [2].

A thermal control valve (TCV) provides a variable thermal link and requires no electrical power, passively shutting down the LHP and minimizing power needs and heat losses at night. At high temperatures, the TCV directs all of the vapor exiting the LHP to the radiator. At low temperatures, the TCV directs all of the vapor to the CC, short-circuiting the LHP. In past work, a proportional TCV was used since it is proven to work [3,4], installed within the LHP vapor line at the exit of the evaporator [5,6] (see Figure 1). The TCV split the vapor flow in a specific proportion to either the radiator for heat rejection or to the liquid return line for radiator bypass. During the long Lunar day, the thermal management system must be capable of removing the waste heat from the electronics/batteries and ensuring that they do not get too warm. Saturated vapor exits the evaporator and enters the TCV. The ratio of the two outlet vapor streams from the valve will change in response to the inlet temperature [7] and adjust the valve spool accordingly resulting in more flow directed to the radiator as the temperature increased. It is desired to maximize the amount of vapor to the radiator, for efficient heat rejection, and minimize vapor through the bypass line. Any vapor entering the bypass line will re-combine with the sub-cooled liquid exiting the radiator and increase the liquid return temperature depending upon the amount of bypass heat leak. In this example, 95% of the vapor flows through the radiator and 5% flows through the bypass line. If the radiator is oversized, the resultant change in sub-cooled liquid may be negligible and result in a small increase in the overall loop temperature. If the radiator is not oversized, the heat leak from the bypass vapor stream may result in excessive temperature increases, or cancel the pressure differential required for loop circulation causing shut down.

In contrast to the Lunar day, the thermal link must be as isolating (by minimizing heat transport) as possible during the Lunar night. This will keep the electronics and battery warm with minimal heater power, even with a very low-temperature heat sink. Heat may be shared between the electronics and battery, to keep the battery warm. De-coupling the LHP evaporator from the Lunar night sink will maintain the electronics/batteries within acceptable limits. As the sink temperature decreases, the ratio of the two outlet vapor streams from the TCV will change in response to the drop in the inlet temperature [7], and adjust the valve spool accordingly resulting in more flow directed away from the radiator and through the bypass line. In this case, it is desired to minimize the amount of vapor to the radiator, to de-couple the radiator and limit heat rejection, and maximize vapor through the bypass line. In this scenario, 5% of the vapor flows through the radiator and 95% flows through the bypass line. The hot vapor will flow through the bypass line and enter the CC. The increase in temperature and the associated saturation pressure in the CC will stop the LHP circulation. The potential exists for a small portion of the vapor to enter the radiator, depending upon the degree of the valve closure. In this case, the vapor will condense and the condensate will subsequently become sub-cooled and possibly frozen in the lines at the low sink temperature conditions. The result is that the vapor will bypass the radiator, resulting in minimal heat dissipation (loss) and achieving the purpose of maintaining the warm electronics box (WEB)/battery temperature.

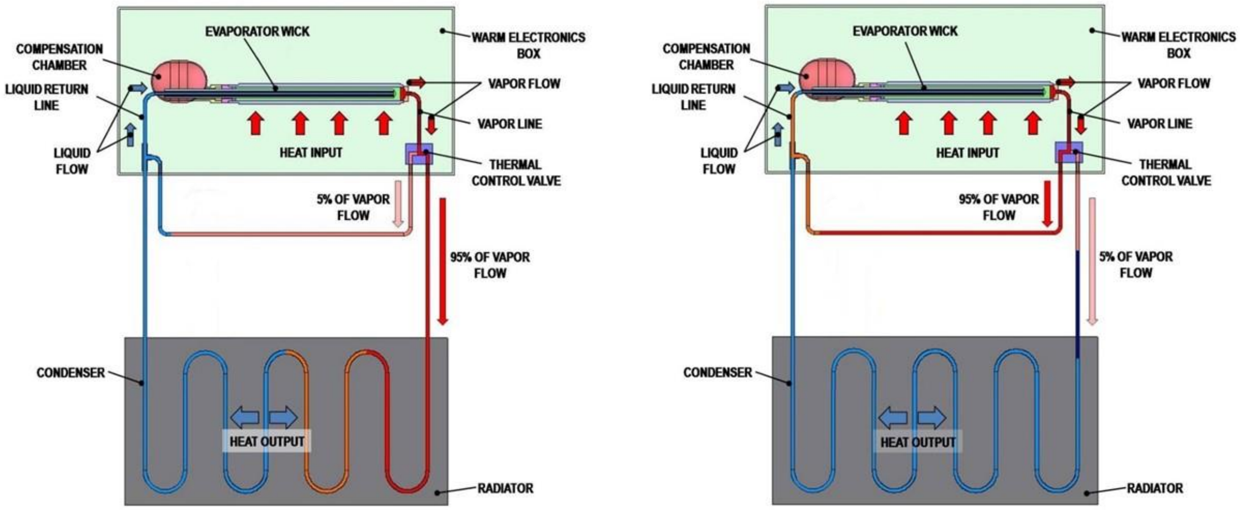

Figure 1. A variable conductance loop heat pipe with a proportional TCV. (Left) Lunar day, where most of the vapor flows through the radiator (95%). (Right) Lunar night, where most of the vapor flows through the bypass (95%).

An on/off valve can similarly achieve this effect during the Lunar day and night without excess flow diverted to the bypass or radiator, respectively. The on/off configuration also responds faster than a proportional valve. The two designed configurations are shown in a section of an LHP testbed in Figure 2. The Open When Cold ("OWC") TCV is shown in Figure 2 (1a to 2a). As the temperature drops, the vapor pressure reduces until the pressure in the gas-charged chamber is higher than the working fluid vapor pressure. This pushes the valve away from the seat, and the valve opens, equalizing the CC and evaporator pressures and shutting down the LHP. When the valve opens, it short circuits the vapor flow from the evaporator directly to the CC. The Close When Cold ("CWC") TCV is shown in Figure 2 (1b to 2b). As the temperature drops, the vapor pressure reduces until the pressure in the gas-charged chamber is higher than the working fluid vapor pressure. This pushes the valve against the seat, and the valve closes, shutting down the LHP. This prevents any vapor from getting to the condenser. This configuration is similar to the LHP design used by Mishkinis et al. [8]. These TCV designs are located at some distance from the evaporator, making it necessary to thermally link the TCV and evaporator. One benefit of the on/off valves is that they are smaller and can be located closer to the evaporator. An additional design configuration is an Integral (also "OWC") TCV. This design is 3D-printed and integrated directly with a 3D-printed LHP evaporator [9]. A benefit of this design is that the TCV temperature will be the same as the CC temperature, which more closely emulates the shutdown operation of LHPs. A second benefit is the compact design.

In this paper, the designs of the "OWC", "CWC", and Integral (also "OWC") TCV are described. A feasibility study was completed to determine the capability of an on/off TCV to shutdown a 3D-printed LHP during simulated Lunar night conditions. Initial experimental results demonstrated the capabilities of the TCVs to maintain a tight seal and uniform temperature vapor line during LHP operation and passive shutdown of the LHP at the specified setpoint temperature. A uniform temperature startup condition was observed for the "OWC" TCV. Methanol was used as the working fluid for ease of use. The proposed TCVs have comparable leak rates to traditional bellows-sealed valves and maintain a reduced per-unit mass (3.5x lower) with substantial flight hardware cost savings (5 – 16x smaller) compared with a competitor passive proportional valve product. The 3D-printed Integral (also "OWC") TCV demonstrated a sealing issue of the valve seat due to the porous nature of additively manufactured components. The valve plug and seat were 3D-printed in this design, which is dissimilar to the machine-finished parts of the original TCV designs. This issue can be alleviated with a machine finish of the components in future work to ensure the valve plug and seat create a tight seal to prevent working fluid leakage while the TCV is in the closed state.

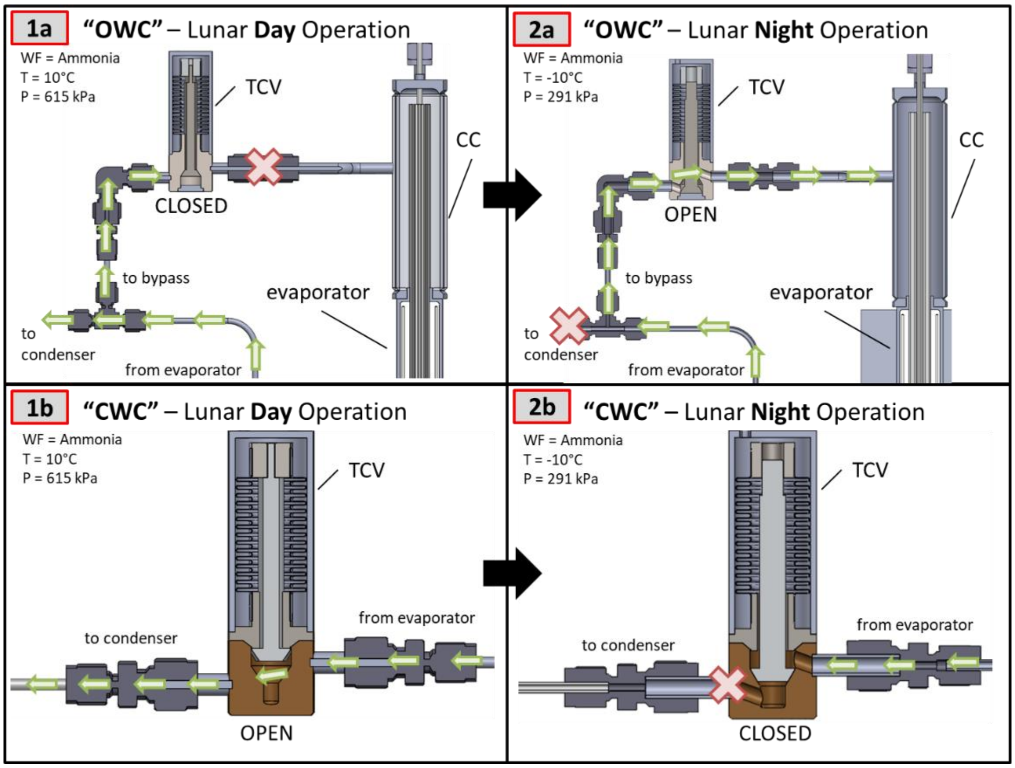

Figure 2. Storyboard of Thermal Control Valve (TCV) operation. The Open When Cold ("OWC") (top) design provides a thermal link between the evaporator and compensation chamber to open and shut down the loop heat pipe at cold vapor temperatures. The Close When Cold ("CWC") (bottom) design is in series with the vapor flow and closes at cold vapor temperatures to restrict vapor flow to the condenser to shut down a loop heat pipe or pumped two-phase loop. The 3D-printed Integral TCV operates similar to "OWC".

II. Prototype Designs for Close When Cold and Open When Cold TCVs

The design methodology of the TCVs is as follows. During normal LHP operation, the valve is designed such that the bellows are expanded ($F_{wf} > F_{NCG}$). The valve setpoint temperature is designed to be at a bellows displacement of 0 in. This can be tuned via the non-condensable gas (NCG) pressure depending on the displacement required to change from an extended to a compressed state. As the LHP gets colder than the setpoint, the bellows change over to a compressed state ($F_{NCG} > F_{wf}$). Now, the valve is actuated to either be open for "OWC" or closed for "CWC". The NCG chamber pressure also has to be charged to compensate for the reduction in gas pressure during compression of the bellows. This gas expansion follows the ideal gas law.

The static force balance calculation dictates the bellows compression and extension. In these calculations, compression of the bellows is considered a positive displacement, and extension of the bellows is considered a negative displacement. A mechanical model of the bellows fully describes the behavior of the TCVs. The bellows can be approximated as a mass-spring-damper system, with a bellows spring constant *k* and an effective mass *M*, primarily consisting of the mass of the bellows plug. The displacement *y* of the bellows can be found from the standard equation for a mass-spring system,

$$My'' + by' + ky = F(y). \tag{1}$$

As a first approximation, we can assume the damping coefficient *b* is zero. The forcing term *F(y)* is the balance of the internal and external pressures on the bellows stem and plug. This is a function of the saturated vapor temperature T_{sat} in the bellows and the pressure of the NCG in the bonnet. Specifically, the forcing term is given by Equation 2,

$$\sum F(y) = F_{NCG} + F_{cc} - F_{wf}. \tag{2}$$

The force of the bellows working fluid F_{wf} is determined from the saturation pressure P_{sat} as,

$$F_{wf} = P_{sat}(T)A_{c,p}, \tag{3}$$

where $A_{c,p}$ is the cross-sectional area of the plug. Similarly, the force of the NCG is determined by,

$$F_{NCG} = P_{NCG}A_{c,s}, \tag{4}$$

where $A_{c,s}$ is the cross-sectional area of the stem. The force of the fluid from the CC is accounted for in the "OWC" design, where the saturation pressure is reduced due to the pressure drop through the LHP. The saturated fluid in the CCwets the outer portion of the valve plug and the top of the valve stem inside the bellows. The force balance equation can be summarized in Equation 5,

$$\sum F(y) = P_{NCG}A_{c,s} + [P_{sat}(T) - \Delta P_{LHP}](A_{c,tp} - A_{c,ts}) - P_{sat}(T)A_{c,p} = ky. \tag{5}$$

A design tool in Microsoft Excel was generated to determine the compression and extension of the bellows for different saturation temperatures, working fluids, and NCG pressure. The designs used methanol as the working fluid at an elevated temperature due to ease of use and high saturated vapor pressure curve (compared to ammonia or propylene). The operating temperature of the LHP is set to 70 °C with a valve actuation setpoint at 50 °C. The "OWC" results are shown in Figure 3. The left image describes the bellows displacement (cm) as a function of NCG chamber pressure (kPa). For "OWC", a NCG chamber pressure of approximately 90 kPa would keep the bellows extended at the operating temperature and compressed at the actuation setpoint temperature. This NCG pressure charge is higher than the "CWC" design due to the competing force of the CC fluid acting against compression inside the bellows. As the LHP gets colder, there is a smaller working fluid force acting on the plug, which allows the plug to move to an open state at the setpoint temperature. Depending on the bellows compression achieved at a colder evaporator temperature, Figure 3 (right) is used to determine how to compensate for the NCG pressure reduction during compression. Knowing the nominal heat load for the LHP and cold evaporator temperatures during the Lunar night, the NCG can be pressurized accordingly to account for this pressure reduction due to ideal gas law. If a different setpoint is required, the NCG pressure can be simply altered to determine when compression will take place as the operating temperature gets colder. Choosing a smaller bellows spring constant would allow for a larger magnitude of displacement as a function of the NCG chamber pressure and vice-versa.

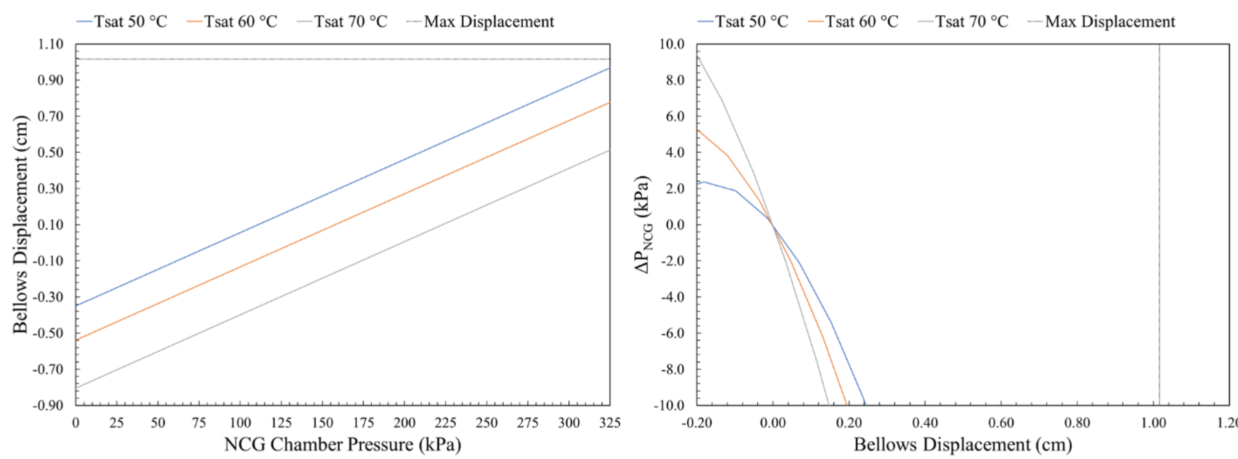

Figure 3. (left) "OWC" bellows displacement as a function of NCG chamber pressure for methanol at different saturation temperatures. The additional force of the working fluid acting against compression in the CC necessitates a larger NCG pressure to achieve compression at the same temperature setpoint. The NCG chamber pressure should be charged to approximately 90 kPa for the setpoint temperature of 50°C. (right) Results for the "OWC" TCV design for the change in NCG pressure as a function of bellows displacement due to the ideal gas law.

Finally, a 3D-printed LHP testbed was designed and fabricated to experimentally test the TCV designs in a simulated Lunar day to Lunar night condition. To save time and money in the Phase I program period and expedite testing of the TCVs, ACT re-used a previous 3D-printed evaporator and primary wick pieces from another NASA program [9, 10, 11]. The LHP testbed itself, with an "OWC" TCV in the bypass line, is shown in Figure 4. To make the testbed, a stainless-steel secondary wick was fabricated and inserted into the 3D-printed evaporator and primary wick structure. The LHP was charged with 52 mL of methanol as the working fluid. This corresponds to a void fraction of 35% in the CC at the hottest operating condition (100°C) and a compensation liquid fraction of 25% at startup (20°C), based on the internal volume of the LHP calculated from the CAD model and known wick properties [12]. This is considered the baseline LHP configuration without the TCVs installed.

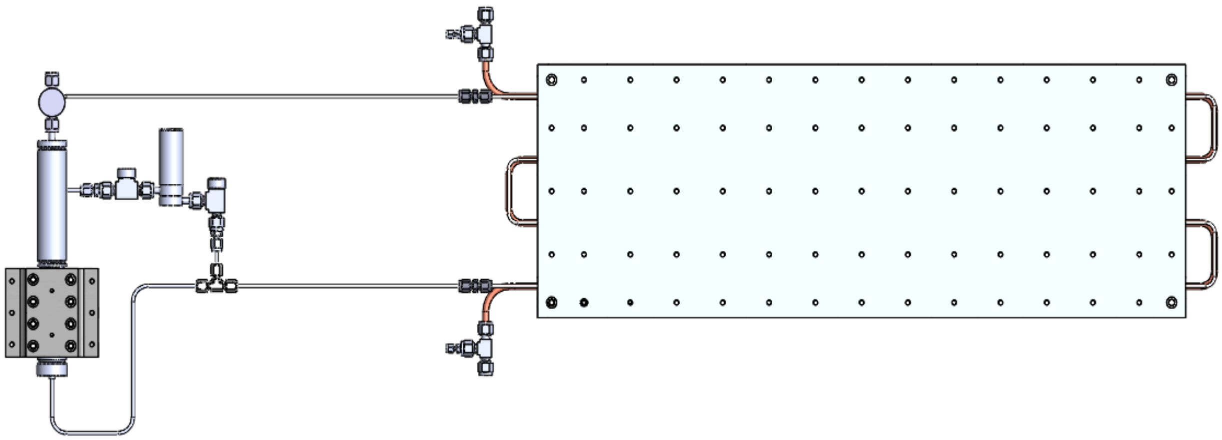

Figure 4. LHP testbed using a 3D-printed evaporator and "OWC" TCV design. This setup mimics the experimental setup from other previous LHP projects with NASA [9, 10, 11].

III. Experimental Results for Close When Cold and Open When Cold TCVs

A concise summary of the results for the leak rate, mass, and cost of the prototype TCVs compared to a traditional bellows-sealed valve and the proportional valve is shown in Table I. The leak rate of the TCV designs was measured using a helium mass spectrometer and measured between the inlet and outlet flow sections of the valve. The results demonstrated a comparable leak rate to a traditional bellows-sealed valve, which is significantly better than the 5% flow allowed by the proportional valves. The 10^{-6} to 10^{-9} scale leak rate measurement is insignificant to cause any heat leak issues. It is noted that the Integral (also "OWC") TCV design had a sealing issue due to 3D-printing imperfections, which is discussed later. The measured mass of the TCV designs is approximately 3.5x lower than the proportional valves, which is a significant reduction in payload on a satellite. The cost of the TCV prototypes was also compared to the cost of the proportional valves. Due to the proprietary nature of the proportional valve costs, the information was redacted and a comparison was made to the TCV prototype costs. An internal flight hardware quote was generated, leading to a 5 – 16x smaller cost per TCV unit compared to the proportional valve. The TCV prototypes are inexpensive enough to be stocked on the shelf.

Table I. Summary of TCV results

Valve	Leak Rate (std cc/s)	Mass (gm)	Cost ($USD)
SS-4H-TW (Swagelok Bellows-Sealed Valve)	4×10^{-9} std cc/s	130 gm	$146 (total)
Industry Proportional Valve	5% of flow	670 gm	redacted (proprietary)
"OWC" TCV Prototype	2.4×10^{-6} to 5.2×10^{-9} std cc/s	186 gm	8 – 15x cheaper than proportional valve
"CWC" TCV Prototype	4.2×10^{-6} to 9.1×10^{-10} std cc/s	196 gm	9 – 16x cheaper than proportional valve
Integral "OWC" TCV Prototype	-	Similar to "OWC"	5 – 10x cheaper than proportional valve

To confirm visual actuation of the valve, ACT used its Willick Engineering XPM-D1605-1 portable x-ray machine, typically used for investigating weld defects for space-qualified heat pipes. This device has a range of 60-160kV at a fixed 5mA, with a 0.8 x 0.8 mm focal point size and a 40° beam angle. The distance of exposure was approximately 72 inches, with an average cumulative exposure time of 10 minutes at 160kV. In Figure 5, the "CWC" and "OWC" prototypes are shown in a relaxed state with P_{NCG} = 0 psig and an expanded state at P_{NCG} = 50 psig. An arbitrarily large pressure was used to distinctly show the valve actuation. This visual evidence was critical before testing the TCV prototypes in the LHP to validate the actuation of the valve as the design intended.

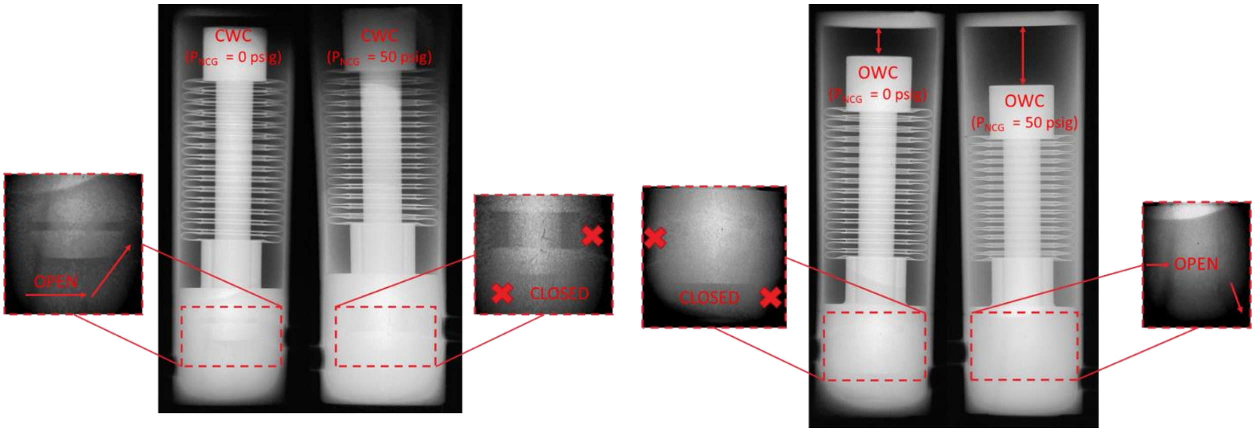

Figure 5. X-ray images of the "CWC" prototype (left) in an open state and closed state as well as the "OWC" prototype (right) in a closed state and open state, respectively.

The "CWC" test was completed to demonstrate the shutdown of the LHP. The "CWC" TCV was placed directly in the vapor line, as shown in Figure 6. For the experimental test (see Figure 7), the LHP startup was executed and the TCV was originally closed. Near the setpoint, the TCV actuated and opened, allowing the LHP to operate normally & reach a steady-state condition. To simulate the shutdown of the LHP, the pressure of the NCG was increased from 55 kPa to 552 kPa to ensure closure. The power was also decreased to a nominal heat load of 15W (from 50W) to simulate Lunar night conditions. A red background indicates the LHP is shut down or not functioning and a green background indicates the LHP is operational. When the LHP vapor temperature reaches its setpoint near 50°C, the valve opens and the LHP begins to function. The entire vapor line warms up at a different rate until a steady-state operation is achieved. After steady-state was reached, the NCG pressure was purposely altered to ensure closure of the valve, as a way to prove the actuation of the valve. The vapor line temperature immediately following the evaporator remains warm during this entire process, while the rest of the line cools down at different rates. This finding was specifically important since the seal of the "CWC" TCV was sufficient and kept the evaporator warm during a shutdown of the LHP.

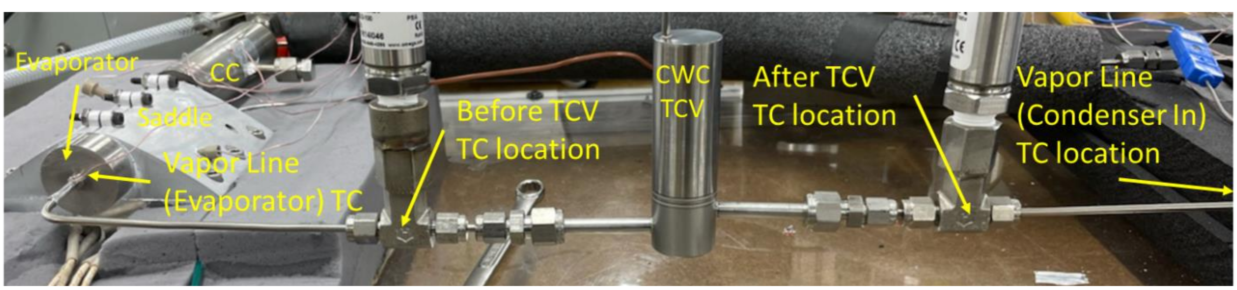

Figure 6. "CWC" TCV in the LHP test setup.

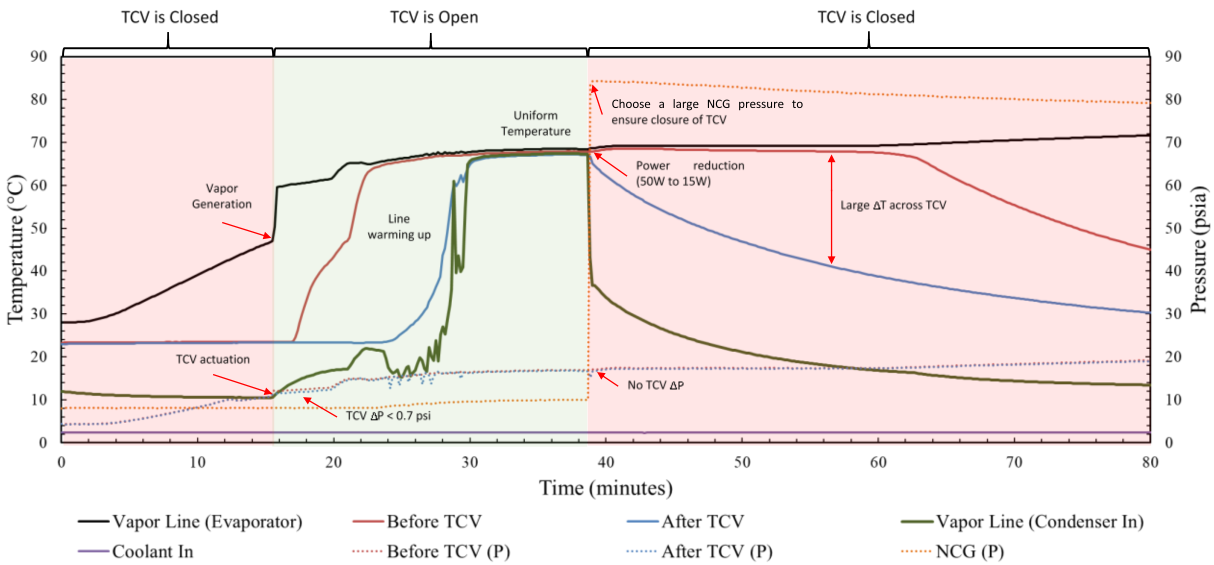

Figure 7. "CWC" TCV experimental results. The evaporator is kept warm during the shutdown of the LHP due to the TCV preventing condenser access for the vapor flow, meaning the seal was sufficient.

Tests with the "OWC" TCV were then completed to demonstrate its functionality to passively shut down the LHP without intervention. The "OWC" TCV was inserted in the LHP testbed as shown in Figure 8. The "OWC" TCV thermally links the evaporator to the CC, functioning as a bypass valve in the system to equalize the pressures in the LHP and shut it down during the Lunar night. For the test, the LHP was started up with the TCV open. Near the setpoint, the TCV passively actuated and closed, allowing the LHP to fully start up and reach a steady-state operating condition. Following this, the power was ramped up to reach the operating temperature (70 °C) and subsequently, the condenser heat sink temperature was ramped down. At the end of the test, to decrease the vapor temperature, the power was ramped down to demonstrate the "OWC" TCV actuation at the setpoint to shut down the LHP. This simulates operation during the Lunar night. These results are shown in Figure 9 and Figure 10, where a red background indicates the LHP is shut down or not functioning and a green background indicates the LHP is operational. In the latter, the operating pressure of the LHP is demonstrated surpassing the NCG pressure before 40 minutes, and in the former, the temperature after the TCV drops off significantly after this occurrence. This indicates the valve changed from an open to a closed state. Another occurrence that was noticed was that a uniform temperature startup condition was achieved, which is dissimilar to a baseline LHP operation where only the evaporator warms up until vapor is generated to drive the loop. With the "OWC" TCV open during startup, the vapor lines around the bypass warm up uniformly. This can help reach steady-state operation faster than a conventional LHP operation.

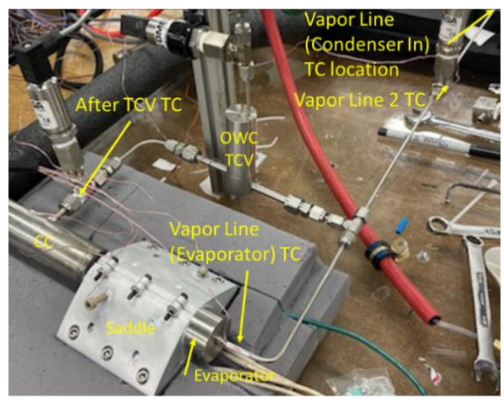

Figure 8. "OWC" TCV configuration in the LHP testbed. The TCV thermally links the evaporator to the CC, functioning as a bypass valve.

At the end of the test, the power was ramped down to allow the operating pressure of the LHP to decrease below the NCG pressure to demonstrate a passive shutdown of the LHP. This is similar to what would occur on a satellite during the Lunar night, as a nominal heat load is maintained to mitigate heat losses to the radiator. These results are shown in Figure 11, where a red background indicates the LHP is shut down or not functioning and a green background indicates the LHP is operational. When the setpoint is reached, the operating pressure of the LHP decreases below the NCG pressure, which allows the valve to passively actuate and open, short-circuiting vapor flow to the CC. The bypass line heats up subsequently to match the vapor line temperature, while the temperature before the condenser inlet cools down. Longer test results were not determined due to the test ending at the end of the workday.

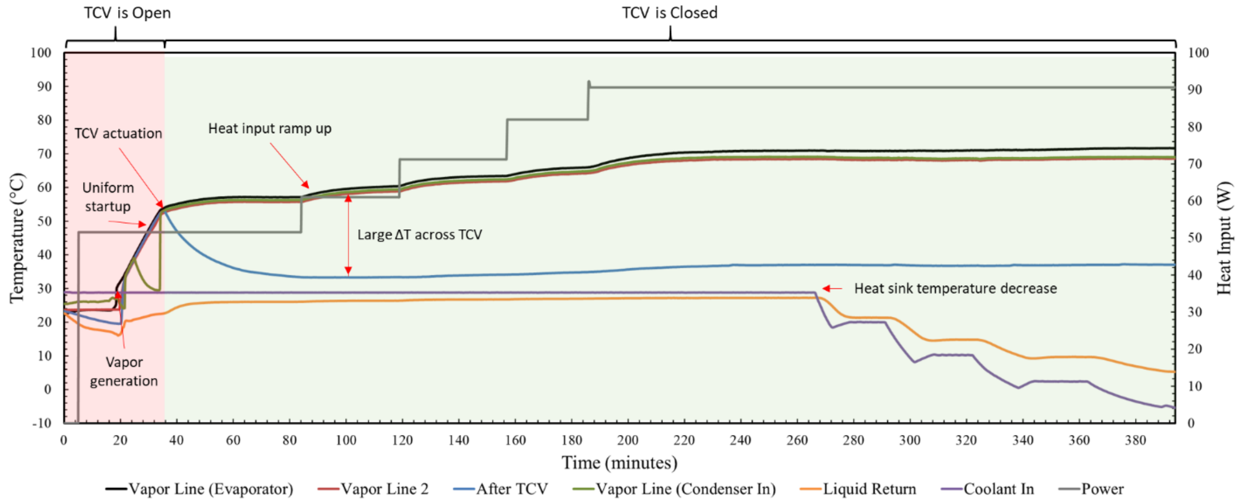

Figure 9. "OWC" TCV results during startup and steady-state conditions (temperature and heat input vs. time). The "OWC" TCV leads to a uniform temperature start-up condition and keeps the evaporator warm (tight seal), even as the heat sink temperature drops off.

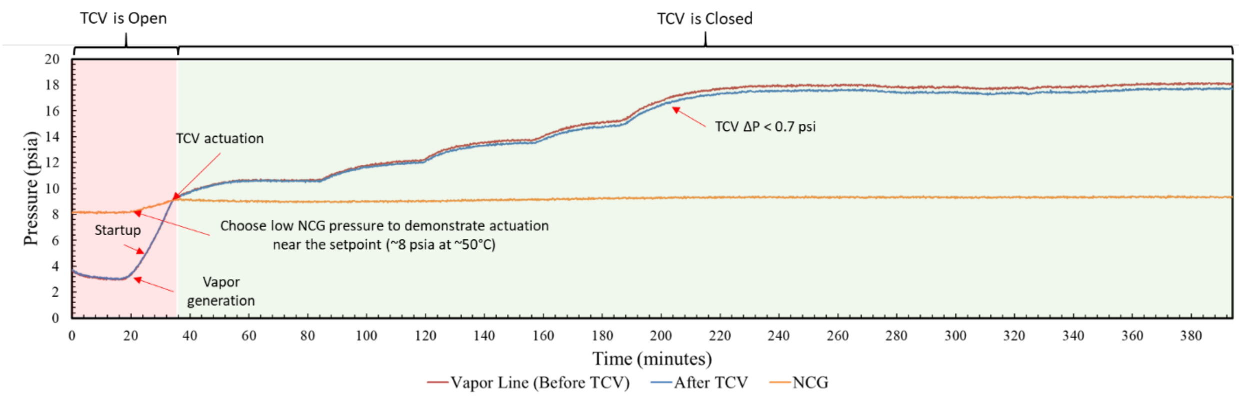

Figure 10. Pressure vs. time for the "OWC" test results.

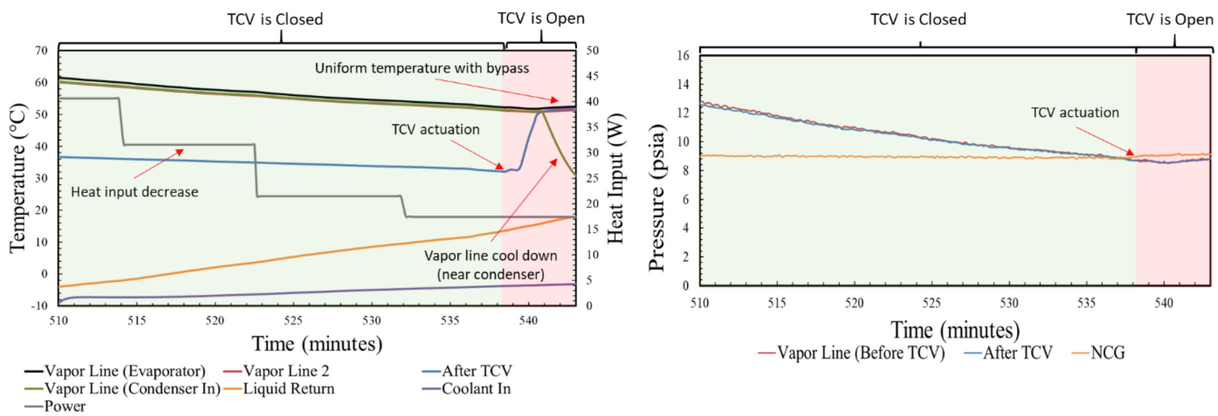

Figure 11. The passive shutdown of the LHP using the "OWC" TCV. After the setpoint temperature, the bypass line heats up and the vapor line near the condenser cools down (left), indicating the TCV opened. This is similarly shown with the operating pressure of the working fluid dropping below the NCG pressure (right).

IV. Prototype Design for 3D-Printed Integral (also Open When Cold) TCV

The final TCV design is an Integral (also "OWC") valve. This design directly integrates the valve body and components with the CC and vapor plenum to create a 3D-printed unit. The advantage of this design is that it functions in the same manner as "OWC" except the valve body is directly bonded to the CC via 3D-printing. This eliminates an additional bypass line where the "OWC" TCV would need to be placed in the LHP testbed, which also reduces heat leak concerns. The valve also follows the CC temperature directly, as opposed to any temperature drop through an external line. The other main advantage is that since the TCV is 3D-printed, it can be directly fabricated with an additively manufactured LHP evaporator and porous wick structure. ACT has been developing 3D-printed LHP evaporators and porous wick structures for NASA to provide a low-cost LHP fabrication alternative for CubeSats and SmallSats [9, 10, 11]. The design of an Integral (also "OWC") TCV, with an accompanying separated view of the designed components in Figure 12. For this design to function, a groove has to be made in the primary wick to connect the vapor plenum to the valve opening. Normally, the vapor plenum travels directly to the condenser. In this case, the vapor has to be thermally linked to the valve opening so that the TCV can operate passively with changes in vapor pressure of the working fluid.

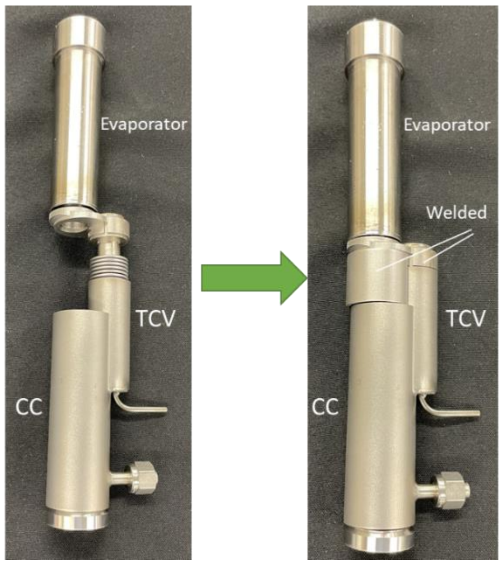

Figure 12. View of the fabricated TCV for the Integral (also "OWC") design. The components were 3D-printed except the internal valve components and were sent to a laser weld shop for fabrication of the internal valve body components (i.e. stem). 3D-printing of the valve body, adapters, and compensation chamber is easily integrated with a 3D-printed LHP evaporator, which ACT has separately developed for NASA.

V. Experimental Results for 3D-Printed Integral (also Open When Cold) TCV

A test of the Integral (also "OWC") TCV design was then set up. To demonstrate passive shutdown of the LHP, the plan was to ramp up the heat input from startup conditions, reach the operating temperature of the LHP, and ramp down the heat input to overcome the setpoint temperature (50 °C) and passively actuate.

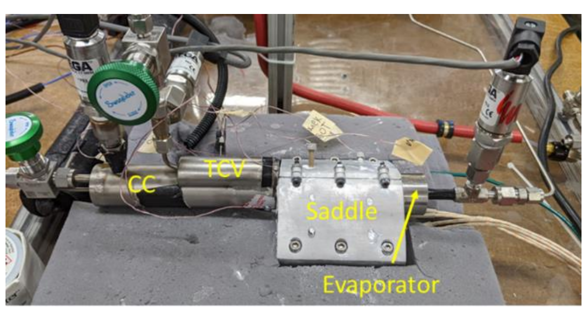

Figure 13. Integral (also "OWC") test setup in the LHP testbed.

The test results are shown in Figure 14. The LHP started up around 15 minutes, but the vapor flow to the condenser and after the TCV were identical. The operating pressure of the LHP exceeded the NCG pressure, but the TCV never shut. We believe this to be a sealing issue. The 3D-printed parts are porous and have imperfections. Due to the lack of time on the program, the valve seat was not able to be machine finished (milled) to create a smooth surface with the valve stem/plug. We attempted to hand polish the part, but it was not sufficient to seal the vapor flow. Images of these defects are shown in Figure 15. In future work, the part can be sent to a machine shop to be machine finished (milled) to create the same seal structure used in the “OWC” TCV prototype.

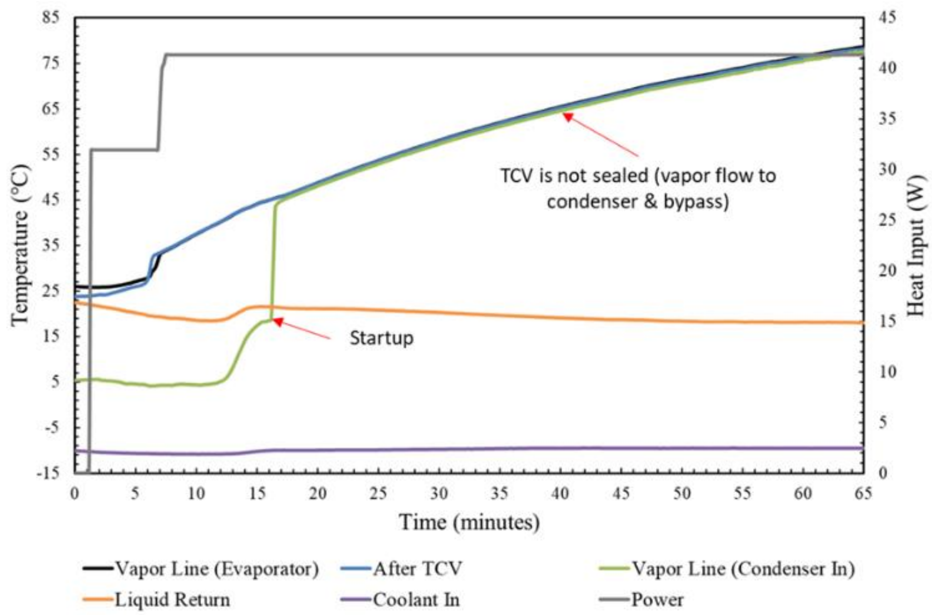

Figure 14. LHP operation with the Integral (also “OWC”) TCV. The vapor flow to the condenser and the bypass are identical, indicating a sealing issue with the 3D-printed valve seat component.

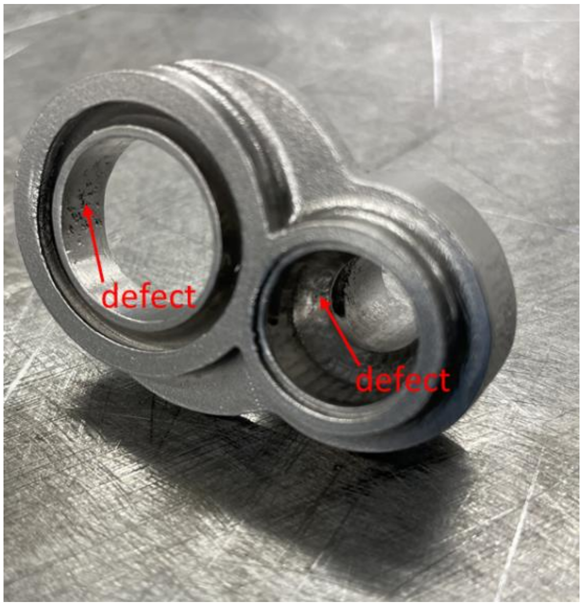

Figure 15. The 3D-printing defects were observed in the Integral (also “OWC”) TCV prototype. A machined finish (milling) would create a smooth surface for the valve seat to seal with the valve plug.

VI. Conclusion

Open When Cold, Close When Cold and 3D-Printed Integral (also "OWC") TCVs were designed, fabricated, and experimentally tested in a 3D-Printed LHP testbed. A feasibility study was completed to determine the capability of an on/off TCV to shutdown a 3D-printed LHP during simulated Lunar night conditions. Initial experimental results demonstrated the capabilities of the subtractive manufactured TCVs to maintain a tight seal and uniform temperature vapor line during LHP operation and passive shutdown of the LHP at the specified cold setpoint temperature. A uniform temperature startup condition was observed for the "OWC" TCV. The proposed TCVs have comparable leak rates to traditional bellows-sealed valves and maintain a reduced per-unit mass (3.5x lower) with substantial flight hardware cost savings (5 – 16x smaller) compared with a competitor passive proportional valve product. The additively manufactured Integral (also "OWC") TCV demonstrated a sealing issue of the valve seat due to the porous nature of 3D-printed components, which can be alleviated with a machine finish. With further development and qualification of the TCV designs, a passive on/off TCV can be implemented within an LHP system to shut down an LHP during the Lunar night and maintain efficient heat transfer during the Lunar day.

Acknowledgments

This project is funded by NASA Marshall Space Flight Center under an SBIR Phase I program (Contract No. 80NSSC20C0686). The technical monitor is Brian O'Connor. The authors would like to thank Max Demydovych and Larry Waltman for their exceptional design, fabrication, and testing support.

References

1. "Survive and Operate Through the Lunar Night Workshop," *The Lunar and Planetary Institute Meeting Planning Services*, USRA, 2018, https://www.hou.usra.edu/meetings/survivethenight2018/.
2. Anderson, W.G., M.C. Ellis, J.R. Hartenstine, C.J. Peters, C. Tarau, and K.L. Walker, "Variable Conductance Heat Pipes for Variable Thermal Links," 42nd International Conference on Environmental Systems (ICES), San Diego, California, July 15-19, 2012.
3. Goncharov, K., Schlitt, R., and Hildebrand, U., "Loop Heat Pipe for High-Precision Satellite Thermal Control," International Two-Phase Thermal Control Technology Workshop, El Segundo, CA, May 7-8, 2005.
4. Goncharov, K., Orlov, A., Tarabrin, A., Gottero, M., Perotto, V., Tavera, S., and Zoppo, G., "1500 W Deployable Radiator with Loop Heat Pipe," 31st International Conference on Environmental Systems, Orlando, FL, July 9-12, 2001.
5. Walker, K.L., et al., "Ammonia and Propylene Loop Heat Pipes with Thermal Control Valves – Thermal/Vacuum and Freeze/Thaw Testing," 43rd International Conference on Environmental Systems (ICES), Vail, CO, July 14-18, 2013.
6. Hartenstine, J.R., K.L. Walker, and W.G. Anderson, "Passive Control of a Loop Heat Pipe with Thermal Control Valve for Lunar Lander Application," 42nd International Conference on Environmental Systems (ICES), San Diego, California, July 15-19, 2012.
7. Birur, G., Prina, M., Bhandari, P., Karlmann, P. et al., "Development of Passively Actuated Thermal Control Valves for Passive Control of Mechanically Pumped Single-Phase Fluid Loops for Space Applications," *SAE Int. J. Aerosp.* 1(1):62-70, 2009, https://doi.org/10.4271/2008-01-2002.
8. D. Mishkinis, C. Gregori, D. Huidobro, and A. Torres, "Low Power and Low Temperature LHP for Thermal Control of Rovers," 41st International Conference on Environmental Systems, Portland, Oregon, July 17-21, 2011.
9. Richard, B., et al., "Development of a 3D Printed Loop Heat Pipe," 49th International Conference on Environmental Systems (ICES), Boston, Massachusetts, July 7-11 2019.
10. Richard, B., D. Pellicone, and W.G. Anderson, "Loop Heat Pipe Wick Fabrication via Additive Manufacturing," 47th International Conference on Environmental Systems (ICES), Charleston, South Carolina, July 16-20, 2017.
11. Richard, B., D. Pellicone, and W.G. Anderson, "Loop Heat Pipe Wick Fabrication via Additive Manufacturing," Joint 19th IHPC and 13th IHPS, Pisa, Italy, June 10-14, 2018.
12. J. Ku, "Operating Characteristics of Loop Heat Pipes," 29th International Conference on Environmental Systems (ICES), Denver, Colorado, July 12-15, 1999.