Passive Control of a Loop Heat Pipe with Thermal Control Valve for Lunar Lander Application

John R. Hartenstine[1], Kara L. Walker[2], and William G. Anderson[3]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601, U.S.A.

It is often desirable to partially or completely shut down a Loop Heat Pipe (LHP), for example, to maintain the temperature of electronics connected to the LHP on a satellite during an eclipse. The standard way to control the LHP is to apply electric power to heat the compensation chamber. The amount of electrical power to shut down an LHP during an eclipse on orbit is generally reasonable. On the other hand, for LHPs on Lunar and Martian Landers and Rovers, the electrical power requirements can be excessive. For example, the Anchor Node Mission for the International Lunar Network (ILN) has a Warm Electronics Box (WEB) and a battery, both of which must be maintained in a fairly narrow temperature range using a variable thermal conductance link. During the Lunar day, heat must be transferred from the WEB to a radiator as efficiently as possible. During the night, heat transfer from the WEB must be minimized to keep the electronics and batteries warm with minimal power, even with a very low (100 K) heat sink. A mini-LHP has the highest Technology Readiness Level, but requires electrical power to shut-down during the 14-day lunar night, with a significant penalty in battery mass: 1 watt of electrical power translates into 5kg of battery mass. A mini-LHP with a Thermal Control Valve (TCV) was developed to shut down without electrical power. An aluminum/ammonia LHP which included a TCV in the vapor exit line from the evaporator was designed, fabricated and tested. The TCV could route vapor to the condenser, or bypass the condenser and route back to the compensation chamber, depending upon the temperature conditions. During test, the LHP condenser was cycled from approximately 30°C to -60°C and the power was kept constant; the evaporator remained above 19°C.

I. Introduction

Future Lunar Landers and Rovers will require a variable thermal link that can reject heat during the day and passively shut-off during the lunar night without requiring any electrical power. During the long lunar day, the thermal management system must remove waste heat from the electronics and batteries to prevent overheating. Since the heater power availability is restricted, a variable thermal link is required to limit the amount of heat that is removed from the electronics and radiated to space during the long lunar night.

Conventional Loop Heat Pipes (LHPs) can provide the required variable thermal conductance needed to maintain the WEB/battery temperatures. During the lunar day, the LHP will transfer the thermal load to the radiator for heat rejection. During the fourteen-day-long lunar night, the sink temperature will drop, potentially lowering the LHP and the WEB/battery temperatures. Without some type of control, the LHP will continue to operate during the lunar night, cooling the electronics and batteries to unacceptably low temperatures. In spacecraft, a small heater is typically attached to the LHP compensation chamber to prevent the LHP from lowering the electronics and battery temperatures below required conditions. The heater alters the thermodynamic balance between the sub-cooled liquid returning from the condenser and the thermal energy exchanged between the evaporator and compensation chamber, which is referred to as heat leak. The heater artificially reduces the sub-cooling provided by the condenser and the LHP compensates by operating at a higher saturation temperature. This behavior prevents the LHP from reaching temperatures below those desired. The penalty for this control is the additional power required to operate the heater, which is estimated to be about 1 W for a 50 to 100 W LHP. While this may seem to be an insignificant amount of power, it is estimated that 1 watt of power to effectively shut-off the LHP through the 14 day lunar night

---

[1] Manager, Aerospace Products, AIAA Member
[2] Research Engineer, Aerospace Products
[3] Chief Engineer, AIAA Member, Bill.Anderson@1-act.com

translates into an additional 5kg of mass for batteries and solar panels. This is an extremely large mass penalty and must be avoided if at all possible.

II. Background

The lunar environment presents a number of challenges to the design and operation of the radiator panels. The heat rejection sink can be 330 K during daytime and can drop down to 50 K at night or in dark craters (Swanson and Butler, 2006). The Apollo landings were timed for lunar morning, so the environment was relatively benign. In contrast, future missions will need to operate over the entire temperature range. Typical lunar surface temperatures are shown in Figure 1. Instruments and equipment, such as batteries, will need to be maintained within -20ºC to 40ºC throughout the large diurnal temperature swings (Birur and Tsuyuki, 2009). In addition, depending upon the mission, the thermal system will be required to work both on the Lunar surface after deployment and during the transit time from the Earth to the Moon.

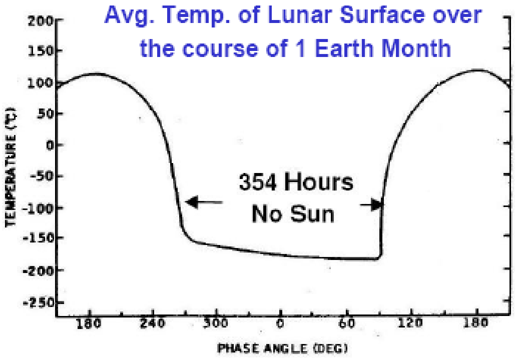


Figure 1. Typical Lunar Surface Temperatures (Swanson and Butler, 2006).

A. Loop Heat Pipes and Pumped Loops with Control Valves for Planetary Surfaces

All LHPs used in space to date have operated in zero gravity. NASA JPL developed and tested a mini-LHP for the Mars Rover program (Pauken, Birur, and Novak. 2002). This system was similar in size and power as the Anchor Node. The JPL mini-LHP design used a single evaporator and a single condenser; however, other designs were also examined. The system used an ammonia/aluminum evaporator with a half inch diameter sintered nickel wick that was 6 inches long. The transport lines and condenser were constructed of stainless steel. The total weight was roughly 0.3 kg. The mini-LHP had a start-up heater on the evaporator. Roughly 5 W was required for several minutes to start the LHP. A shutdown heater was used to turn the LHP off at night. This used approximately 1 W. Thermal tests demonstrated:

- Reliable start-up and shut-down
- Steady state heat transport
- Transient response to varying evaporator power and varying condenser sink temperatures

Mechanical testing included:

- Proof pressure
- Landing loads on Mars
- Random vibration
- Vapor and liquid transport-line flexibility
- Ammonia leakage

The JPL design used ammonia, and allowed the ammonia to freeze during the simulated Martian night. Thick stainless steel vapor and liquid transport lines were used to withstand the pressure when the ammonia thawed (the radiator thawed before the transport lines). Qualification testing showed that the LHP system could accommodate ammonia freeze/thaw in the condenser. The system successfully underwent 100 freeze/thaw cycles in the condenser. While the JPL mini-LHP has not flown, it has had all of the testing that would be conducted before a test in space.

Heat rejection systems using a mechanically pumped single-phase fluid loop (MPSL) system were developed by JPL for the Mars Science Laboratory (MSL) rover (Birur et al., 2008). The Mars rover, named Curiosity, contains a MPSL called the Rover Integrated Pump Assembly (RIPA) that utilizes TCVs developed by Pacific Design Technologies (PDT) to control the heat path during different environmental scenarios. Like the Moon, Mars can experience long, cold nights as well as winters. This poses a potential problem for important instruments used in the rover that cannot drop below a certain temperature setpoint. The RIPA takes the waste heat generated by the radioisotope that is used to power the system and transfers it to either radiators for heat rejection during hot environmental conditions or to important instruments to keep them warm during cold environmental conditions. This choice of heat path is achieved through the integration of the passively actuated TCV developed by PDT. Bench top performance testing of the RIPA using TCVs was successful and flight hardware testing was performed in early 2009. The Mars Science Laboratory was launched on November 26th, 2011 and is projected to arrive on Mars on August 5th, 2012.

B. Previous Trade Studies and Research

A number of technologies have been evaluated for a variable thermal link, or “heat switch”, including mechanical thermal switches, pumped loops, Variable Conductance Heat Pipes (VCHPs) and LHPs. This work is discussed in Anderson, Walker, Hartenstine, and Farmer (2010). The thermal switch was dropped due to poor thermal conductance, less than one-tenth that of a VCHP or LHP, while the pumped loop system was dropped as a result of moving parts, a higher mass, and higher power requirements. Both the VCHP and the LHP have similar “on” and “off” thermal conductances, both have flown in space, and both have similar masses. The current effort focuses on the development of an LHP using a thermal control valve to establish the variable link. A stand-alone LHP does not require technology development and is commonly used for space thermal management: the main focus is the addition of the thermal control valve. A companion paper by Anderson et al. (2012) discusses the use of VCHPs for variable conductance links, for both space and terrestrial applications.

Goncharov et al. (2001, 2005) were the first to use an LHP with a Pressure Regulating Valve (PRV) for precise temperature control (±0.5°C). Vapor from the evaporator goes to a passive, two-way, pressure controlled valve; see Figure 2b. The valve contains a sealed bellows surrounded by argon. As the pressure, and subsequent temperature, of the vapor at the valve increase, more vapor is fed to the condenser, cooling the system. As the pressure and temperature of the vapor at the valve decrease, more vapor is fed back to the compensation chamber. Heat is applied to the argon surrounding the bellows to allow precise temperature control.

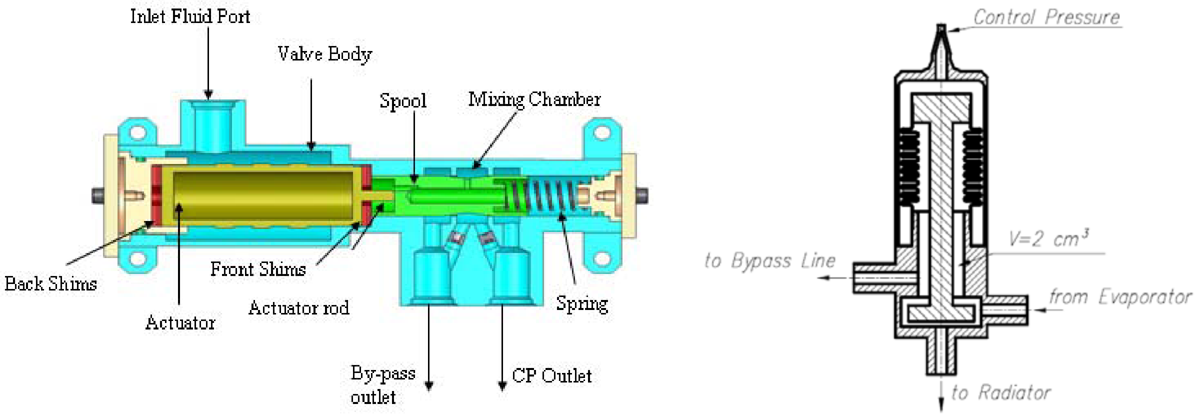
Researchers at Carlo Gavazzi Space, Milano, Italy (Molina et al, 2009, Franzoso et al., 2009) have used a similar TCV in an LHP for a Martian rover application. The aluminum/stainless LHP uses propylene as the working fluid, to avoid problems with freezing. The LHP thermal switch transports up to 40 W through 1.3 m long stainless steel vapor and liquid return lines. The 0.7 µm nickel wick is 11 mm diameter, and 120 mm long. As in the LHP developed by Goncharov et al., the ESA LHP thermal switch uses a bypass valve to provide the variable thermal link. The control temperature can be adjusted (before flight) by adjusting the argon pressure in the bellows. The difference here is that heat is not applied for precise temperature control.

More recently, Mishkinis and coworkers (Mishkinis *et al.*, 2011, Romera *et al.*, 2012) have developed a LHP with a two-way thermal control valve. The thermal control valve is located in the vapor line, and gradually reduces flow to the condenser as the TCV temperature is reduced. The valve uses a sealed bellows surrounded by Argon.

In the current project, a near-flight-qualified TCV was used to passively control the LHP operation, providing the variable thermal link as required. The TCV is based on the design developed by Pacific Design Technologies for the JPL RIPA (Birur et al., 2008). The TCV was selected due to its space flight quality, technology maturity and performance. Two TCV designs were evaluated, including splitter valve and mixing valve configurations. The difference between a mixing valve design and a splitter valve design is the internal porting. A splitter valve design was used for the LHP demonstration unit. Initial results with the loop, and a more thorough discussion of the loop operation can be found in Hartenstine, Walker, and Anderson (2011).

C. Thermal Control Valve

A schematic of the Thermal Control Valve (TCV) configuration for the Mars Science Laboratory is shown in Figure 4a. . The splitter valve used for the LHP with TCV was similar to the design in Figure 2a. The valve was configured to actuate based on the temperature of the vapor exiting the evaporator assembly and entering the TCV from the inlet port. As the internal actuator extends or contracts based on the vapor temperature, the valving is such that the inlet flow is ported to the radiator port, the radiator bypass port, or a combination of the two.



(a) (b)

Figure 2. Thermal Control Valve Configurations. (a) PDT splitter valve for the Mars Science Laboratory has an actuator that does not depend on the working fluid pressure (Birur et al., 2008). (b) TCV design used by Goncharov et al. (2001, 2005) is dependent on the working fluid pressure to move the valve.

III. Loop Heat Pipe with Thermal Control Valve Operation

In the case of the Anchor Node application, the LHP TCV will be located within the WEB along with the evaporator and compensation chamber assemblies of the LHP. LHP thermal control valve operational conditions are detailed in Table 1. The table details the "on" and "off" temperature conditions for the loop heat pipe. The TCV was installed within the LHP vapor line at the exit of the evaporator; see Figure 3 and Figure 5. Within the TCV, the vapor line splits, routing vapor to either the radiator for heat rejection or to the liquid return line or compensation chamber for radiator bypass. Operational scenarios during the variable lunar day and night temperature fluctuations are described in detail in Hartenstine, Walker, and Anderson (2011).

Table 1. Example Thermal Control Valve Temperature Control Range.

Valve/Vapor Inlet Temperature (ºC)	Outlet A to Condenser (%)	Outlet B Bypass Condenser (%)
≤ 0ºC	Minimize	Maximize
0ºC to +20ºC	Increase in Flow to Condenser with Increasing Temperature	Decrease in Flow to Bypass with Increasing Temperature
≥ +20 ºC	Maximize	Minimize

IV. Loop Heat Pipe with Thermal Control Valve Design

The LHP model was completed for the lunar application that uses a thermal control valve as a passive thermal link during the lunar day and night operational conditions. A model of the final LHP with TCV integration can be seen in Figure 3.

The LHP consists of a 15.2cm (6 inch) long aluminum evaporator block with a sintered nickel primary wick. Ammonia was used as the working fluid for the Phase I program; however, propylene is currently being evaluated in the Phase II effort. Extruded aluminum tubing with integral flanges was used as the condenser. The tubing was mounted to an aluminum plate and attached through a mechanical joint. Grafoil was used as the interface material between the condenser tube and the aluminum plate. The TCV was installed in the vapor line of the LHP. Within the TCV, the vapor line splits, routing vapor to either the condenser for heat rejection, or to the liquid return line or directly to the compensation chamber for radiator bypass depending on the operational scenarios. Vapor entering the condenser will be sub-cooled and return back to the primary wick as a liquid though the liquid return line, or bayonet. Vapor entering the bypass line can re-combine with the liquid from the condenser, or be directed directly back into the compensation chamber. The LHP design was modified to allow for these options in testing by adding valves within the flow lines. Previous LHPs with a TCV have the bypass vapor flow directly mix with the liquid return line. In this arrangement, the vapor and liquid flows will interact with each other, possibly causing flow instabilities as the two streams come to thermodynamic equilibrium. Feeding the vapor back directly into the compensation chamber should minimize these effects by allowing mixing of the vapor and liquid flows in the relatively larger volume of the compensation chamber. The manual valves shown in Figure 3 allow testing with either flow path.

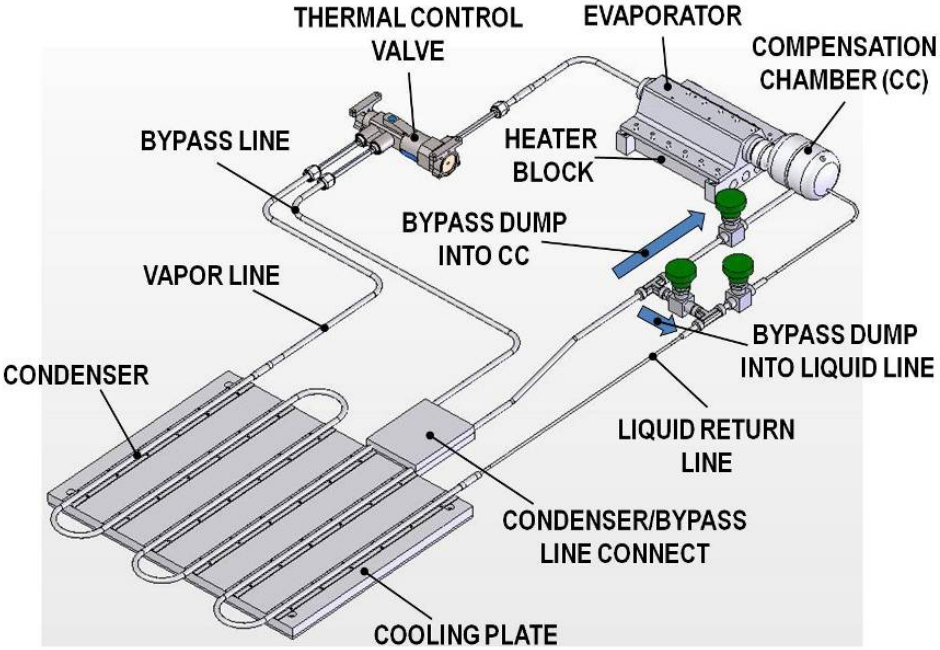


Figure 3. Loop Heat Pipe with Thermal Control Valve Design.

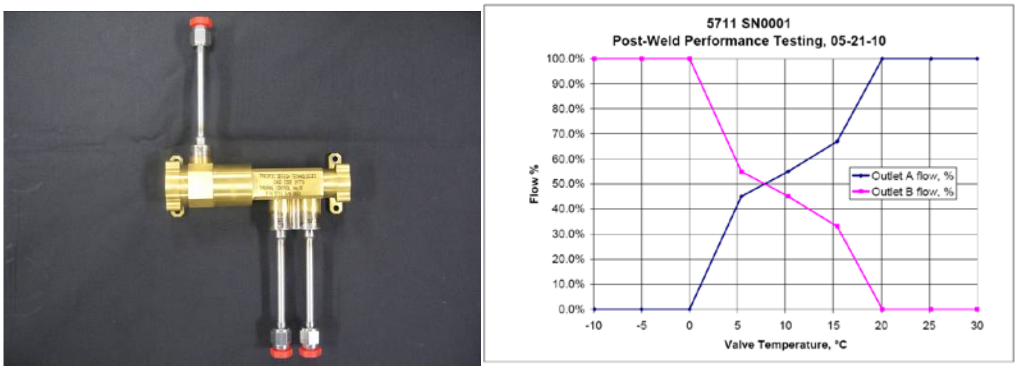


Figure 4. Photograph of the TCV for LHP with TCV Integration (left) and Post-Weld Performance Testing (right).

V. Loop Heat Pipe with Thermal Control Valve Manufacturing

The Thermal Control Valve (TCV) was designed and manufactured for integration into the LHP. The TCV functions by adjusting the internal spool depending on the inlet fluid temperature. A specific range of 0ºC to +20ºC was set for the TCV that was used in the LHP; see Table 1. The TCV performance was tested prior to delivery using gaseous nitrogen. Testing was performed pre-weld and post-weld. Results from post-weld performance testing can be seen in Figure 4. Results from pre-weld and post-weld performance testing are as expected. As the temperature drops from 20ºC to 0°C, the ratio of flow switches so the flow transfers from outlet A to outlet B. This continues until approximately 20°C where outlet A now has nearly 100% of the flow and outlet B has nearly 0% of the flow.

The LHP with a TCV was fabricated based on the design parameters outlined above. A photograph of the completed LHP is shown in Figure 5.

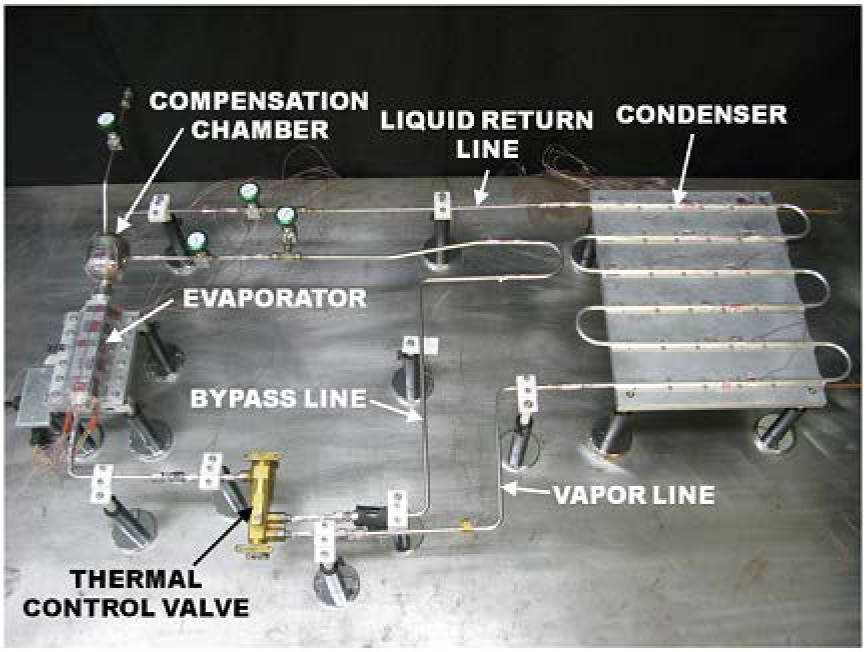


Figure 5. Final LHP with TCV Test Assembly.

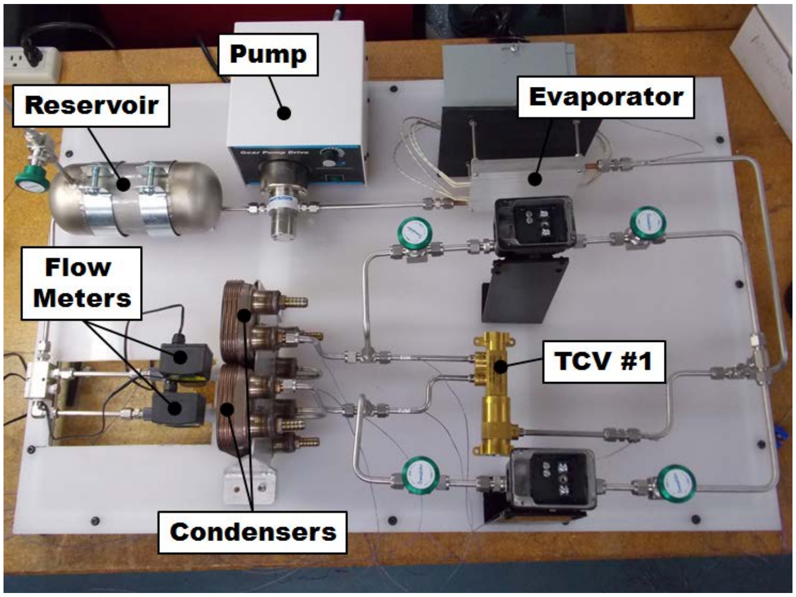


Figure 6. TCV qualification test system with TCV #1 installed.

VI. Thermal Control Valve Qualification Testing

Prior to delivery by PDT, the vapor flow split of each valve is measured as a function of valve body temperature; see Figure 4. These tests have no flow restriction on the outlet end. Birur (2011) has found that the flow split of these valves is dependent on the pressure restrictions in both legs downstream of the valve. A TCV qualification system has been designed and fabricated; see Figure 6. The qualification test system consists of an evaporator, the TCV, two condensers, a reservoir and a pump. The pump provides a mass flow rate that is similar to that of an actual LHP. Methanol was chosen as the working fluid for the TCV qualification test system because it is easier to handle then ammonia and it is capable of handling the temperature range the TCVs will be tested in. Differential pressure transducers are installed across the TCV inlet and condenser outlet as well as TCV inlet and bypass outlet to measure the pressure drops across the valve. Flow meters are installed after the condensers to measure the flow rates experienced in the system. Valves are used to restrict the flow from each leg of the TCV. The first valve is currently being tested. Once complete, the test results will be used in the Thermal Desktop model of the LHP.

VII. Loop Heat Pipe with Thermal Control Valve Testing

D. Instrumentation and Test Plan

The LHP was instrumented with 33 type T thermocouples. The assembly was insulated with a minimum of 3 inches of closed cell insulation to reduce the heat leak. A drawing showing the thermocouple locations is shown in Figure 7. The input power to the evaporator was provided by an aluminum heater block with integral cartridge heaters. Heat removal was provided by an aluminum cold plate. The cold plate includes a serpentine flow passage for liquid coolant flow. A liquid cooling loop containing Dynalene was used to control the temperature of the condenser plate (sink) during Phase II testing.

An initial test on this LHP is shown in Hartenstine, Walker, and Anderson (2011). These tests controlled the sink temperature with liquid nitrogen. Unfortunately, oscillation in the LHP temperatures occurred due to the on/off nature of the liquid nitrogen control system. Switching to a continuous Dynalene flow minimized the oscillations, except when the bypass flow fed into the liquid return line.

The previous tests demonstrated the ability of the LHP with TCV to maintain the evaporator temperature with minimal power, and very cold sink temperatures (Hartenstine et al., 2011). Two additional tests are discussed below:

1. Examine the difference in behavior when the vapor bypass is directed to the liquid line, versus the compensation chamber
2. Conduct tests at constant power, with varying sink temperature.

Tests were performed to evaluate the effectiveness of the TCV to bypass flow and maintain the evaporator temperature based on the inlet ammonia vapor temperature. To demonstrate the control valve operation, a constant power was applied to the evaporator and then the sink temperature was cycled from the high sink condition to the low sink condition and allowed to reach steady state at those two temperature setpoints for a designated period of time.

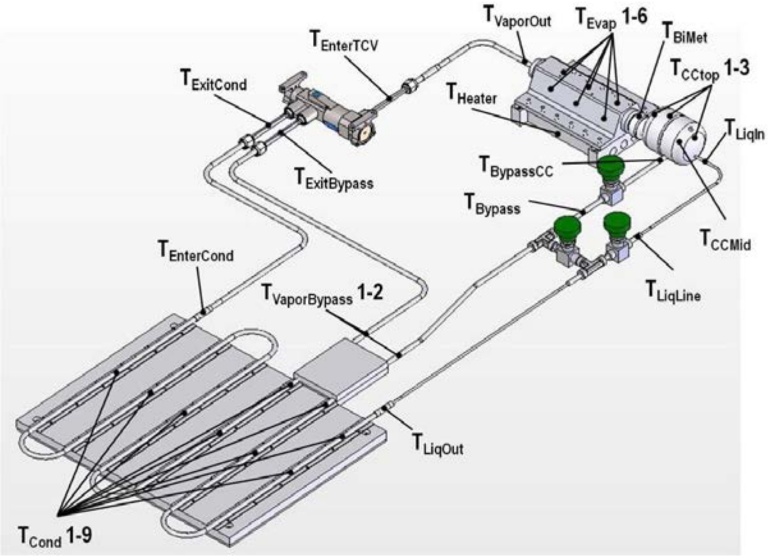


Figure 7. LHP with TCV Testing Thermocouple Locations.

E. Bypass to Liquid Line versus Bypass to Compensation Chamber

1. Bypass to Liquid Line versus Bypass to Compensation Chamber

There are two options for returning the bypass flow to the compensation chamber:
1. Bypass flow into the liquid return line
2. Bypass flow directly into the compensation chamber

Previous tests on LHPs with thermal control valves have typically returned the vapor through the liquid return line, and have often observed flow oscillations. We believe that one cause for these oscillations is that the vapor volumetric flow rate can be much larger than the liquid volume flow rate, which can sometimes impede the liquid flow rate. Returning the vapor directly to the compensation chamber will allow the liquid to be more easily supplied through the bayonet.

Tests were conducted to examine the effects of bypass location. Directing the bypass flow was achieved by opening and closing three valves, seen in Figure 7. Figure 8 shows the results of a test performed with bypass flow directly to the compensation chamber. At the beginning of the test the liquid return temperature is approximately -25ºC. As the power input is decreased the liquid return temperature begins to rise in temperature. This is due to the liquid return line picking up ambient heat gains as the power is decreased and the mass flow rate is slowed. At a power input of zero, the liquid return line is close to the temperature of the evaporator. The liquid return line temperature profile is similar to what would be seen in a standard LHP in this testing scenario.

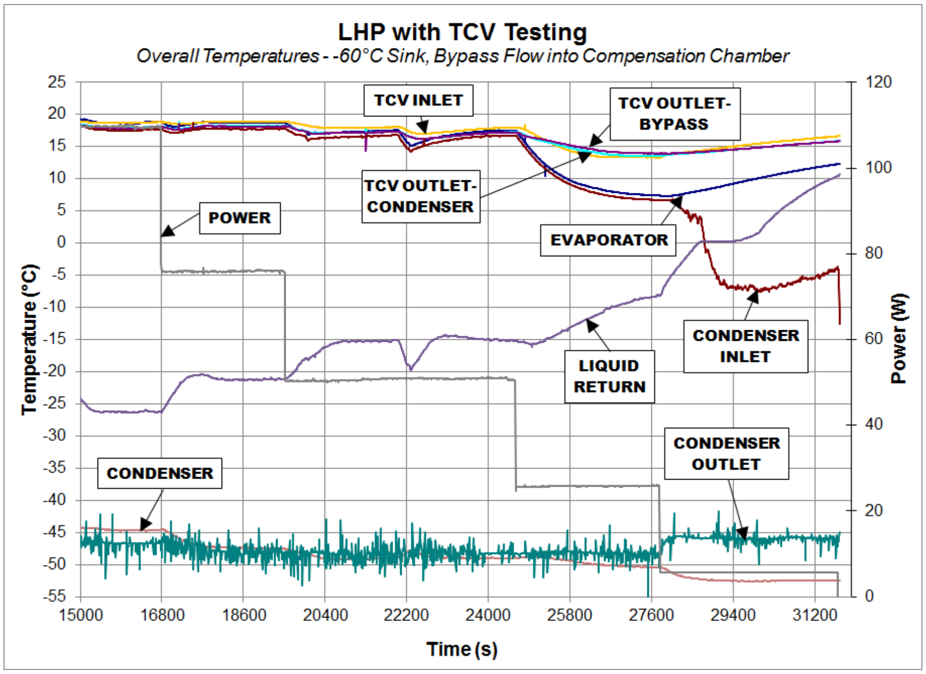


Figure 8. LHP with TCV testing with bypass flow directly into the compensation chamber.

Figure 9 shows the results of a test where the bypass return flow was directed into the liquid return line. In this scenario, the liquid return temperature starts at approximately 5ºC, close to the evaporator temperature. After the first incremental decrease in power the liquid return temperature oscillates heavily. At the next decrease in power, the liquid return line drops significantly and then reaches a steady state at approximately -20ºC. At this time the evaporator temperature has also made a sudden decrease in temperature. At the third decrease in power the liquid return line increases in temperature as well as the evaporator. This indicates that the bypass line has opened in the TCV and is directing hot vapor into the liquid return line. This sudden increase in hot vapor also increases the evaporator temperature. The liquid return temperature continues to increase as the power input decreases. As seen in the results, the bypass flow into the liquid return line causes oscillations in temperature. When bypass flow is directed to the compensation chamber, the results are similar to that of a standard LHP and there are no oscillations.

Bypass flow into the compensation chamber is the chosen method for bypass return in all LHP with TCV systems going forward.

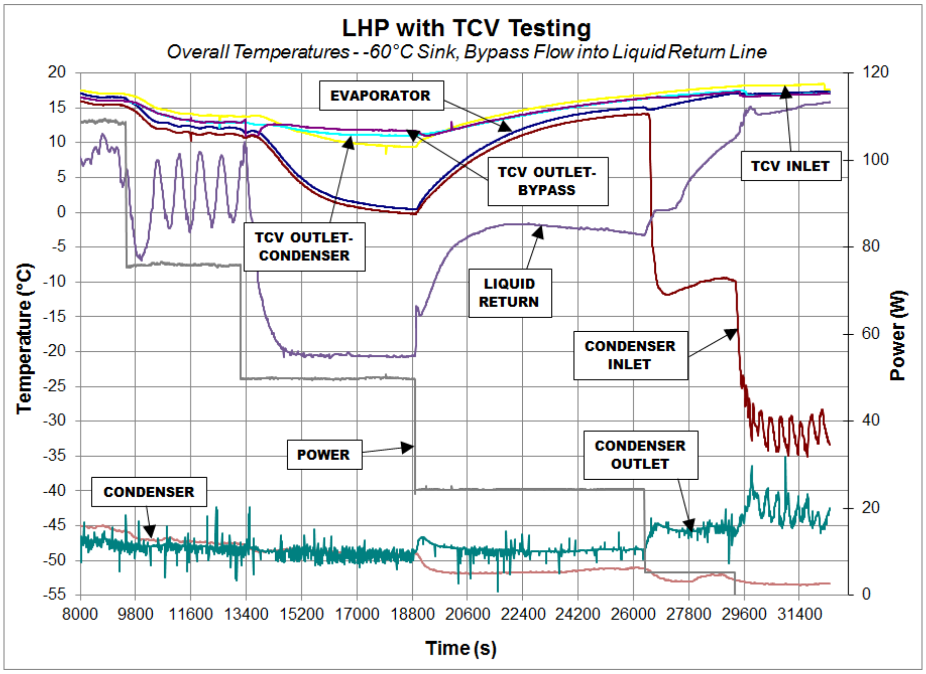


Figure 9. LHP with TCV with bypass flow into the liquid return line.

F. Constant Power Tests

Constant power tests were conducted with varying heat sink temperatures. The following procedure was used:

- A liquid cooling loop was attached to the inlet of the condenser plate. The cooling fluid supply was attached through a solenoid valve that was controlled by a temperature controller. Dynalene was delivered to the cold plate to maintain the temperature value set on the controller.
- A constant power was applied to the evaporator using the cartridge heaters in the evaporator block and a variable transformer.
  - The temperature profile across the LHP was measured and recorded until steady state was reached.
- The condenser temperature was decreased to the low sink condition using the liquid cooling loop temperature controller. The power input to the evaporator remained constant.
  - The temperature profile across the LHP was measured and recorded until steady state was reached.
- The condenser temperature was increased to the high sink condition using the liquid cooling loop temperature controller. The power input to the evaporator remained constant.
  - The temperature profile across the LHP was measured and recorded until steady state was reached.
- The condenser temperature was decreased to the low sink condition using the liquid cooling loop temperature controller. The power input to the evaporator remained constant.
  - The temperature profile across the LHP was measured and recorded until steady state was reached
- The condenser temperature was increased to the high sink condition using the liquid cooling loop temperature controller. The power input to the evaporator remained constant.

Test results for one test run at constant power are shown in Figure 10 through Figure 12. In this test, the bypass-vapor is fed directly into the compensation chamber. Figure 10 shows the condenser, evaporator, compensation chamber and power for the full test run. The majority of the test data has been removed to show a clear picture of the LHP with TCV operation. Figure 11 is a refinement of the data within a 17ºC to 32ºC temperature band to show specific details in operation. In this test run the power input was set to a constant 200W and the sink conditions were cycled from 28°C to -60°C. Figure 12 emphasizes the difference in the evaporator and compensation pressure as well as temperature. This data provides a clearer indication of the LHP shutting down.

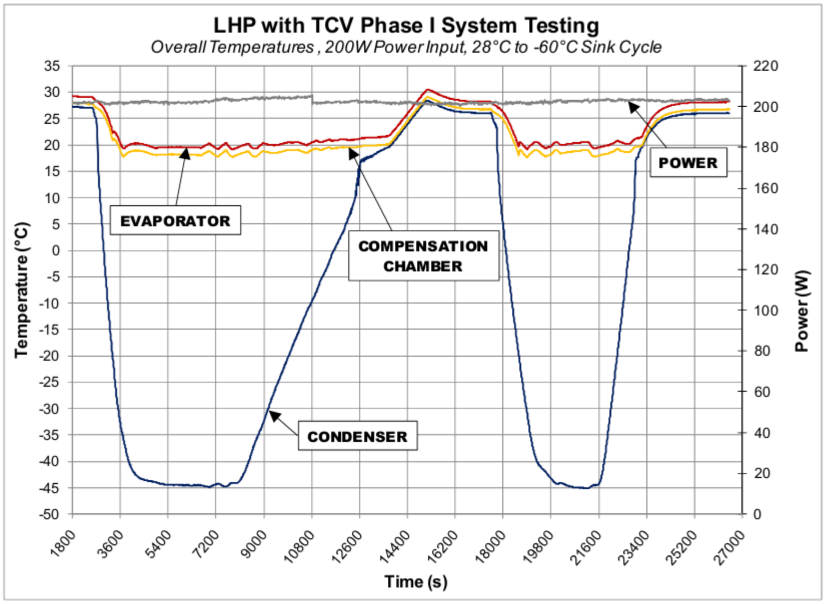


Figure 10. Loop Heat Pipe with TCV Thermal Performance Profile, 200 W constant power. The condenser temperature setpoint was reduced to -60°C.

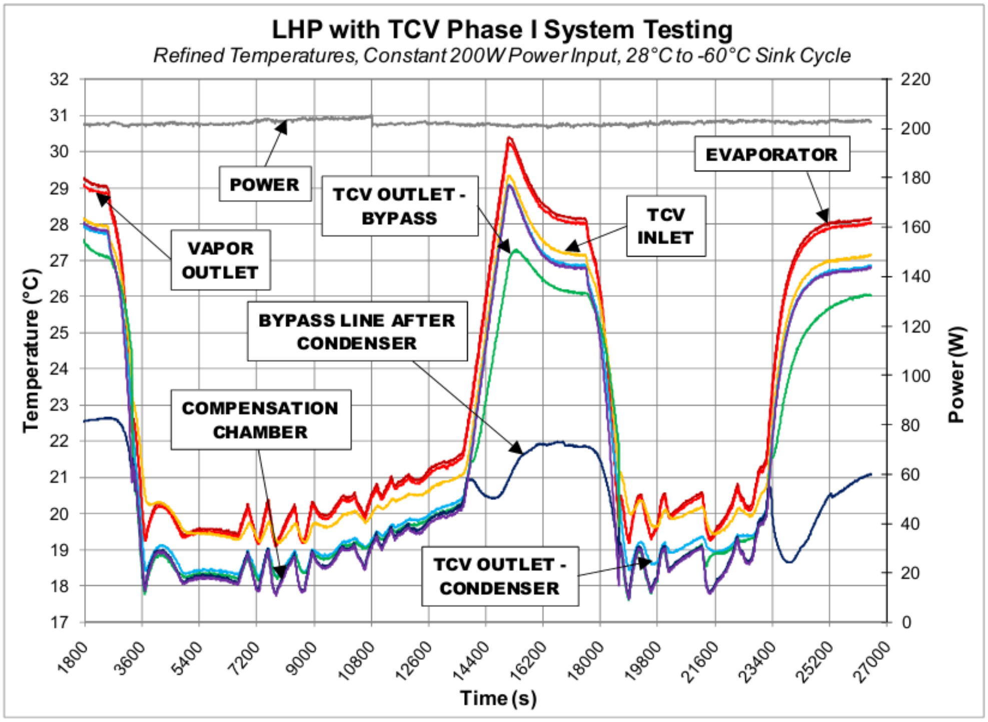


Figure 11. Loop Heat Pipe with TCV Thermal Performance Profile, same as the figure above except the data is refined to within a 17ºC to 32ºC temperature range.

The most important aspect of the LHP with TCV system is that it maintains the evaporator temperature and thus the batteries within the WEB at an acceptable temperature range. There are several observations that demonstrate the LHP with TCVs ability to achieve this goal. At the high sink condition, the TCV is operating at approximately 28°C; therefore all of the vapor flow is being directed to the condenser for heat rejection. When the low sink condition is introduced the evaporator assembly temperatures begin to drop with the sink, as expected. As the TCV inlet temperature reaches the 20°C high end temperature setpoint the temperatures in the evaporator stop their rapid decline and begin to achieve steady state. This indicates that the bypass line has opened and vapor is flowing through back into the compensation chamber. The sink is then increased to the hot sink condition and the evaporator temperature returns to approximately 30°C. The opening and closing of the bypass line can also be seen by the TC located on the bypass line after the condenser. During hot sink operation, the bypass line is maintained at a temperature close to ambient. When the TCV inlet temperature reaches approximately 20°C the bypass line temperature begins to drop, indicating that vapor is flowing through the line. Once the hot sink condition is applied, the bypass line returns to ambient temperatures, indicating that there is no vapor flow through the bypass line.

The difference between the evaporator and compensation chamber pressure and temperature can also be an indication of LHP shut down. The primary driving force of an LHP is the pressure differential between the evaporator and the compensation chamber. As the pressure difference decreases, the driving force also decreases eventually leading to a full shut down of the LHP. The curve of the pressure differential line follows closely to that of the evaporator and compensation lines in the refined data graph. As the sink temperature drops, the pressure difference between the evaporator and the compensation decreases indicating that the LHP is beginning to shut down and decrease its thermal transport capability.

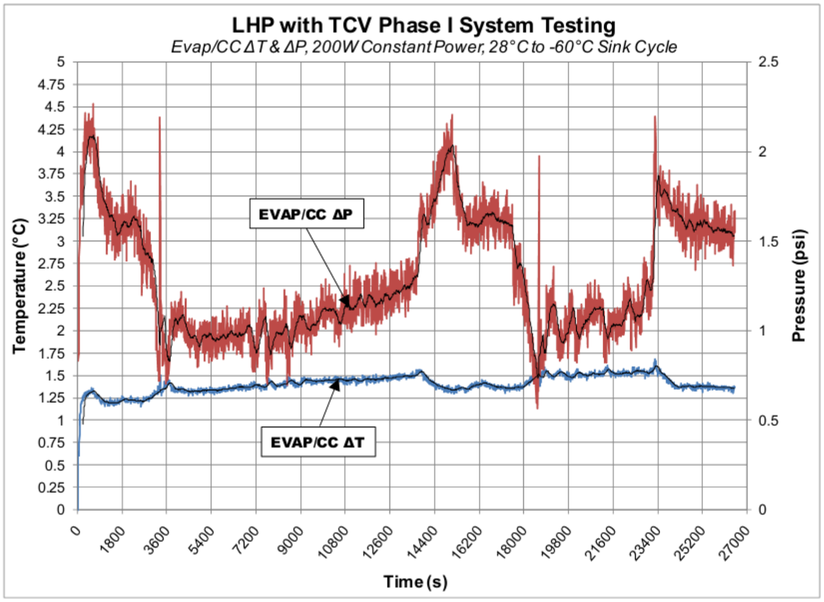


Figure 12. Evaporator and compensation chamber ΔP and ΔT for the 200W constant power, 28°C to -60°C sink cycle test.

Conclusion

The lunar surface experiences a wide range of environmental thermal conditions from long, hot lunar days to long, cold lunar nights. Future lunar surface missions will require a variable thermal link for thermal management that is capable of removing the waste heat during the lunar days and limit the amount of heat removed during lunar nights. A Loop Heat Pipe (LHP) with a Thermal Control Valve (TCV) was developed as a solution for this problem. An LHP with a TCV is capable of rejecting excess heat during the lunar day by routing the hot vapor through the TCV and to the condenser for rejection as well as limiting by heat rejected during the lunar night by routing hot vapor through the TCV and through a bypass line directly into the compensation chamber.

An integrated LHP and TCV system was designed, fabricated and tested to operate as a variable thermal link. The TCV was installed within the LHP vapor line to allow vapor produced in the evaporator to be routed to the condenser or compensation chamber depending on the vapor temperature. Above the 20ºC maximum temperature set point, the vapor was routed to the condenser for heat rejection. As the temperature is reduced from 20ºC to 0ºC, an increasing amount of the fluid is bypassed to the compensation chamber, shutting down the loop and maintaining the evaporator temperature. Two sets of tests were conducted:

1. Tests examining the effects of having the diverted vapor from the TCV pass to the liquid line, or directly to the compensation chamber. It was shown that oscillations are reduced with the direct line to the compensation chamber.
2. Constant power tests where the sink temperature was reduced from 28°C to -60°C, with a constant 200 W power. The evaporator was maintained within the desired temperature range.

In addition, tests discussed in a previous paper (Hartenstine et al., 2011) showed that the LHP with TCV can effectively reduce and shut down LHP flow and maintain the evaporator temperature without the need for electric power.

Acronyms

CC	Compensation Chamber
ILN	International Lunar Network
LHP	Loop Heat Pipe
MSL	Mars Science Laboratory
MPSL	Mechanically Pumped Single-Phase Fluid Loop
RIPA	Rover Integrated Pump Assembly
PRV	Pressure Regulating Valve
TCV	Thermal Control Valve
VCHP	Variable Conductance Heat Pipe
WEB	Warm Electronics Box

Acknowledgments

This project was sponsored by NASA Marshall Space Flight Center under SBIR Purchase Order No. NNX11CB96C. We would like to thank the technical monitor, Jeffery Farmer of NASA Marshall, for many helpful technical discussions. Tim Wagner and James Bean were the laboratory technicians responsible for the fabrication and testing of the demonstration heat pipe and nickel wick analysis, and Mike Ellis performed the Loop Heat Pipe Model analysis. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

References

Anderson, W. G., Hartenstine, J. R., Walker, K. L., and Farmer, J. T., “Variable Thermal Conductance Link for Lunar Landers and Rovers,” 8th IECEC, Nashville, TN, July 25-28, 2010.

Anderson, W. G., Ellis, M.C., Hartenstine, J. R., Peters, C. J., Tarau, C., and Walker, K. L., “Variable Conductance Heat Pipes for Variable Thermal Links,” 42nd International Conference on Environmental Systems (ICES 2012), San Diego, CA, July 15-19, 2012.

Birur, G., Prina, M., Bhandari, P., Karlman, P., Hernandez, B., Kinter, B., Wilson, P., Bame, D., Ganapathi, G., “Development of Passively Actuated Thermal Control Valves for Passive Control of Mechanically Pumped Single-Phase Fluid Loops for Space Applications”, SAE International Journal of Aerospace, April 2008, 1:62-70.

Birur, G., Prina, M., Bhandari, P., Karlman, P., Hernandez, B., Kinter, B., Wilson, P., Bame, D., Ganapathi, G., “Development of Passively Actuated Thermal Control Valves for Passive Control of Mechanically Pumped Single-Phase Fluid Loops for Space Applications”, SAE International Journal of Aerospace, April 2009, 1:62-70.

Birur, G., Tsuyuki, G., “JPL Advanced Thermal Control Roadmap – 2009”, presented at the Spacecraft Thermal Control Workshop, March 10-12, 2009.

Birur, G., personal communication, March 9, 2011.

Franzoso, A., Molina, M., Fernandez, F.R., and Barbagallo, G., “Thermal Testing of a Heat Switch for European Mars Rover,” ICES 2009, Savannah, GA, July 12-16, 2009.

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.

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.

Hartenstine, J. R., Walker, K. L., and Anderson, W. G., “Loop Heat Pipe with Thermal Control Valve for Variable Thermal Conductance,” 41st International Conference on Environmental Systems (ICES 2011), Portland, OR, July 17-21, 2011

Mishkinis, D. Gregori, C., Huidobro, D., and Torres, A., “Low Power and Low Temperature LHP for Thermal Control of Rovers,” 41st International Conference on Environmental Systems (ICES 2011), Portland, OR, July 17-21, 2011.

Molina, M., Franzoso A., Bursi, A., Fernandez, F. R., and Barbagallo, B., “A Heat Switch for European Mars Rover,” 38th International Conference on Environmental Systems (ICES), San Francisco, CA, June 29 – July 2, 2008.

Pauken, M. T., Birur, G. C., and Novak, K. S., “A Mini Loop Heat Pipe Suitable for Mars Rovers,” 12th International Heat Pipe Conference, Moscow, Russia, 2002. http://trs-new.jpl.nasa.gov/dspace/handle/2014/11777

Romera., F., Mishkinis, D., Kulakov, A., and Torres, A., “Active Control of the Set Point of a 2-Way Pressure Regulating Valve in an LHP,” 16th International Heat Pipe Conference, Lyon, France, May 20-24, 2012.

Swanson, T., and Butler, D., “NASA/Goddard Thermal Control Technology Roadmap-2006”, 17th Aerospace Spacecraft Thermal Control Workshop, Los Angeles, CA, March 14-16, 2006.