Loop Heat Pipe with Thermal Control Valve for Variable Thermal Conductance Link of Lunar Landers and Rovers

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A number of proposed Lunar landers and rovers have 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 and solar cell 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 vapor directly back to the compensation chamber, depending upon the temperature conditions. During testing, the LHP condenser temperature was decreased to -60°C and the power input was decreased to near zero power: the evaporator remained above 0°C. This paper will describe the LHP and TCV design, fabrication and testing details.

Nomenclature

LHP = Loop Heat Pipe
TCV = Thermal Control Valve
CC   = Compensation Chamber

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 therefore 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 and battery temperatures. During the lunar day, the LHP will transfer the thermal load to the

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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 remove power 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 WEB/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 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[1]. 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[2]. 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.
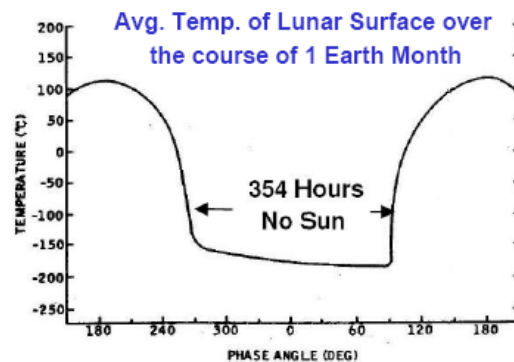

**Figure 1. Typical Lunar Surface Temperatures (Swanson and Butler, 2006).**

A. Loop Heat Pipes

LHPs are high thermal conductance devices that are self-contained and passive. Figure 2 shows a schematic of a LHP. Note that the figure is not to scale; the vapor and liquid lines can be made much longer. Figure 3 shows the LHP evaporator in more detail. Heat enters the evaporator and vaporizes the working fluid at the wick outer surface. The vapor is collected by a system of grooves and headers. The vapor flows down the vapor line to the condenser where it condenses as heat is removed by the cold plate (or radiator in this case). Most of the condenser is filled with a two-phase mixture. A small section at the end of the condenser provides a small amount of sub-cooling.

The heart of the LHP is the evaporator and compensation chamber assembly, which contain the primary and secondary wicks. The Compensation Chamber (CC), or reservoir, at the end of the evaporator is designed to operate at a lower temperature than the evaporator (and the condenser). Since the temperature is lower, the pressure of the saturated fluid in the compensation chamber is also lower. This lower pressure allows the condensate to flow from the condenser through the liquid return line to the compensation chamber. The fluid then flows into a central bayonet where it feeds the wick. A secondary wick in the evaporator and compensation chamber allows the liquid in the compensation chamber to feed the evaporator wick to make up for the heat leak caused fluid mass transfer from the evaporator to the compensation chamber.

The liquid in the compensation chamber and the interior of the wick must be returned to the exterior surface of the wick to close the cycle. Capillary forces accomplish this passively, drawing liquid back to the surface.

Loop heat pipes are made self-priming by carefully controlling the volumes of the compensation chamber and other components in the LHP so that liquid is always available to the wick. The compensation chamber and fluid charge are set so that there is always fluid in the compensation chamber even if all the other components in the LHP are completely filled with liquid. The LHP is thus inherently self-priming. Launay, Sartre, and Bonjour [3] presented a survey of the parameters affecting the LHP design.
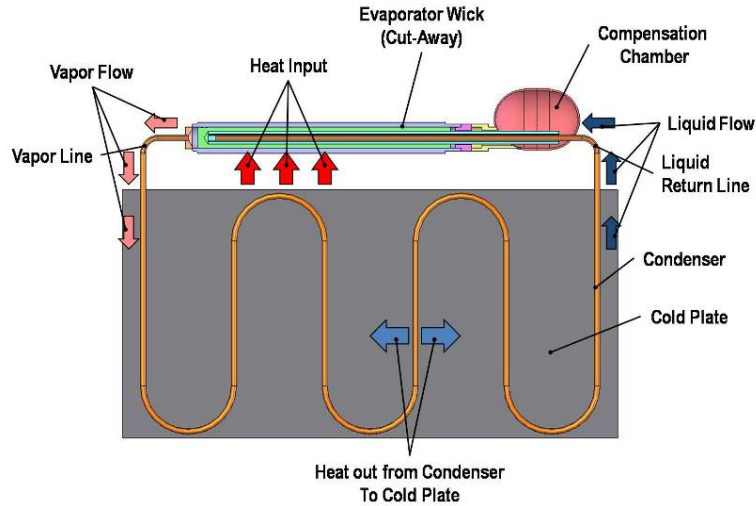
Figure 2. Loop Heat Pipe Schematic (Not to scale). For example, the vapor and liquid return lines can be much longer.
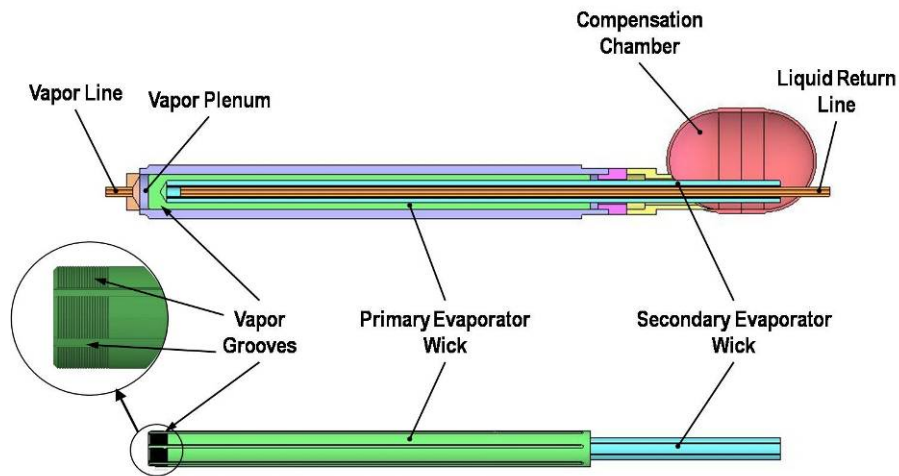
Figure 3. Loop Heat Pipe Evaporator.

## 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, Variable Conductance Heat Pipes (VCHPs) and LHPs. This work is discussed in Anderson, Walker, Hartenstine, and Farmer[4]. The thermal switch was dropped due to poor thermal conductance, less than ten times 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. However, this effort focused on the development of a 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.

Previous works in this area have been conducted by researchers at the NASA Jet Propulsion Laboratory (JPL) and Carlo Gavazzi Space, Milano, Italy [5][6][7]. In both cases a pressure actuated control valve was installed in the LHP to decouple the electronics during cold mission durations specifically for a United States and European Mars Rover application, respective to the research institute. The pressure actuated valves were successful in both cases in operation as a heat switch during terrestrial testing. Heat rejection systems using a mechanically pumped single-phase fluid loop (MPSL) system were also developed by JPL for the Mars Science Laboratory (MSL) rover [7]. In this case a passively actuated Thermal Control Valve (TCV) was used for flow control to manage the varying heat loads on the rover. Bench top performance testing using the TCV was successful: flight hardware testing was projected to start in early 2009 [7].

In this project, a near-flight-qualified TCV was used to passively control the LHP operation, providing the variable thermal link as required. 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. A splitter valve design was used for the LHP demonstration unit.

C. Thermal Control Valve

A schematic of the Thermal Control Valve configuration for the Mars Science is shown in Figure 4, as well as a photograph of two valves that are similar to the one used on this project: mixing valve and a splitter valve. 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. The valve was similar to the valve in Figure 4, except the inlet port was located opposite the two outlet ports, straddling the two outlet ports. The temperature-sensing portion of the valve was located opposite the port-end of the valve (adjacent to the nameplates in the above photo). The valve was configured to actuate based on the ambient temperature inside the WEB. As the internal actuator extends or contracts based on the WEB ambient 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 ports.
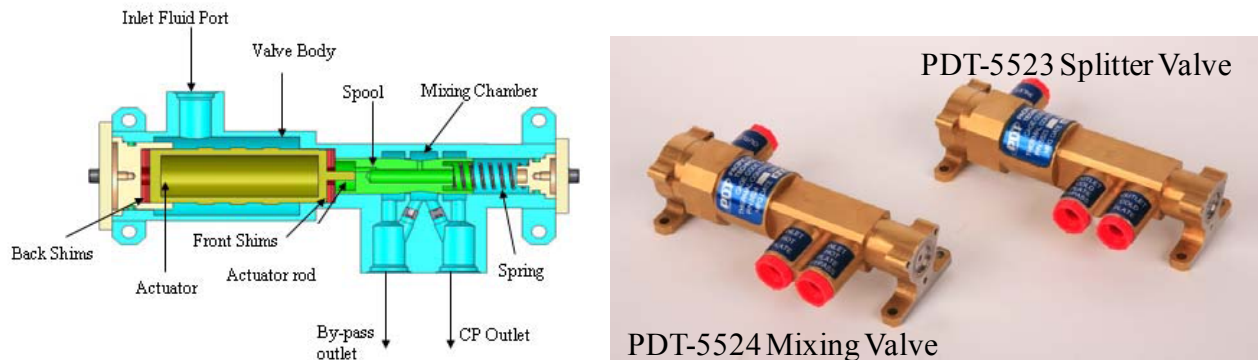
Figure 4. Thermal Control Valve Configuration for Mars Science Laboratory[7]. PDT-5524 Mixing Valve and PDT-5523 Splitter Valve.

III. Loop Heat Pipe with Thermal Control Valve Operation

The LHP TCV will be located within the WEB. 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 5. Within the TCV, the vapor line splits, routing vapor to either the radiator for heat rejection or to the liquid return line for radiator bypass. Operational scenarios during the variable lunar day and night temperature fluctuations are described in the next section.

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

D. Lunar Day Operation

During the long lunar day, the thermal management system must be capable of removing the waste heat from the WEB to prevent overheating. This removal will be accomplished by a LHP, which will transport thermal energy via latent heat from the evaporator, which will interface with the WEB electronics, to the condenser, which will interface with the radiator. During LHP operation, vapor is generated in the evaporator. This vapor leaves the evaporator and enters the inlet port of 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. Increasing fluid temperature will result in more flow directed to the radiator. Decreasing fluid temperature will result in more bypass flow.

During heat rejection mode, maximum vapor flow to the radiator is desired for efficient operation. Any vapor entering the bypass line will re-combine with the sub-cooled liquid exiting the radiator and increase the liquid return temperature. This represents additional heat leak and will increase LHP operating temperature. In the example shown, 95% of the vapor flows though the radiator and 5% flows though 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 increase, or cancel the pressure differential required for loop circulation and result in shut down.

To solve this potential problem, the bypass line was routed through a portion of the exiting radiator line, shown in Figure 5, to sub-cool the vapor before it re-combines with the bulk sub-cooled liquid from the radiator. This is one area for further examination in future development work to evaluate the LHP sub-cooling requirements and how they interact with the bypass valve, radiator design and compensation chamber.

As stated above, the compensation chamber must operate at a lower pressure and temperature than the evaporator, so that the fluid can flow from the evaporator to the compensation chamber. The operating temperature of the LHP is set by 4 heat flows, see Figure 6:

1. Heat leak from the evaporator to the compensation chamber, which must be balanced by sub-cooling in the condenser at steady state.
2. Heat leak from the environment, which must also be balanced by sub-cooling in the condenser.
3. Heating or cooling from a heater or thermoelectric system which requires power, and can raise or lower the system saturation state by altering the balance between sub-cooling and heat leak (optional).
4. Sub-cooling from the liquid returning to the compensation chamber at a temperature below the saturation temperature, which, along with LHP pressure drop, determines the saturation temperatures of the evaporator and compensation chamber.

The radiator must be designed to supply sufficient sub-cooling to the compensation chamber. Note that, from a heat transfer standpoint, the sub-cooling section of the radiator is considerably less efficient than the two-phase portion of the radiator. This is due to the high heat transfer coefficients associated with convective condensation in the two-phase region, in addition to the isothermal nature of two-phase heat transfer.
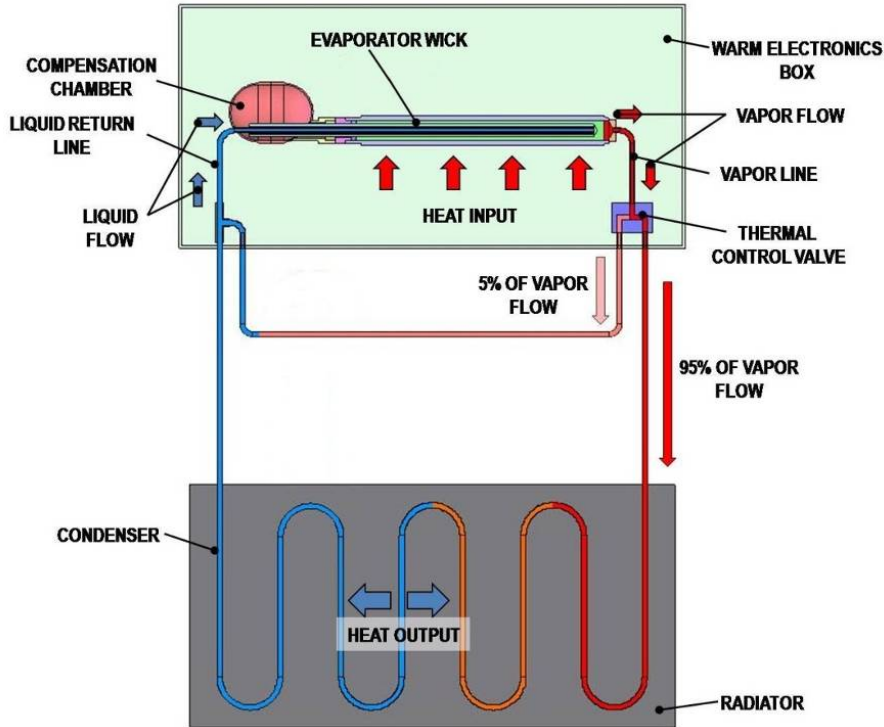
Figure 5. Variable Conductance Loop Heat Pipe schematic during the Lunar day. Most of the vapor flows through the Radiator. The 5% and 95% flow rates are representative.
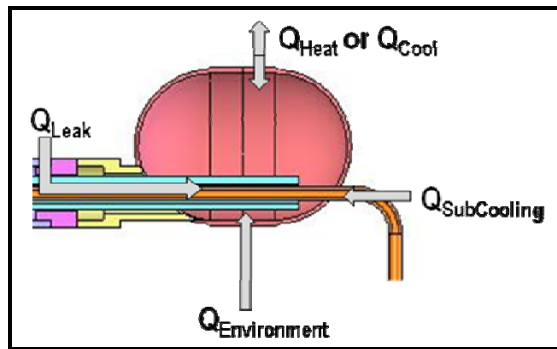

**Figure 6. Energy Balance of a Loop Heat Pipe Compensation chamber.**

E. Lunar Night Operation

In contrast to the Lunar day, the thermal link must be as ineffective as possible during the Lunar night; see Figure 7. This will keep the electronics and battery warm with minimal power, even with the very low temperature heat sink. To improve system efficiency, heat may be shared between the electronics and battery, although this is not required.

De-coupling the LHP radiator from the lunar sink during the night will maintain WEB/batteries to 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 inlet temperature[7] and adjust the valve spool accordingly. This adjustment will result 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, in order completely to de-couple the radiator and limit heat rejection, and maximize vapor through the bypass line. In the example shown, 5% of the vapor flows though the radiator and 95% flows though the bypass line. The hot vapor will flow though the bypass line, be slightly sub-cooled and enter the CC. Since the sub-cooling amount will be considerably less than that achieved when flow circulated through the

condenser, the LHP saturation state will settle on a higher temperature when the majority of the flow is bypassed. 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 end result is that the vapor will bypass the radiator, resulting in minimal heat dissipation (loss) and achieving the purpose of maintaining the WEB/battery temperature.

Working fluid selection is important to meet thermal transport and freezing requirements. Ammonia will freeze in the radiator lines at sink temperatures below 195K, while propylene freezes at 88K. In a previous work, JPL used ammonia as the working fluid for a mini LHP, 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). The system successfully underwent 100 freeze/thaw cycles in the condenser[4]. Propylene may also be used as the working fluid and may be easier to thaw compared to ammonia.
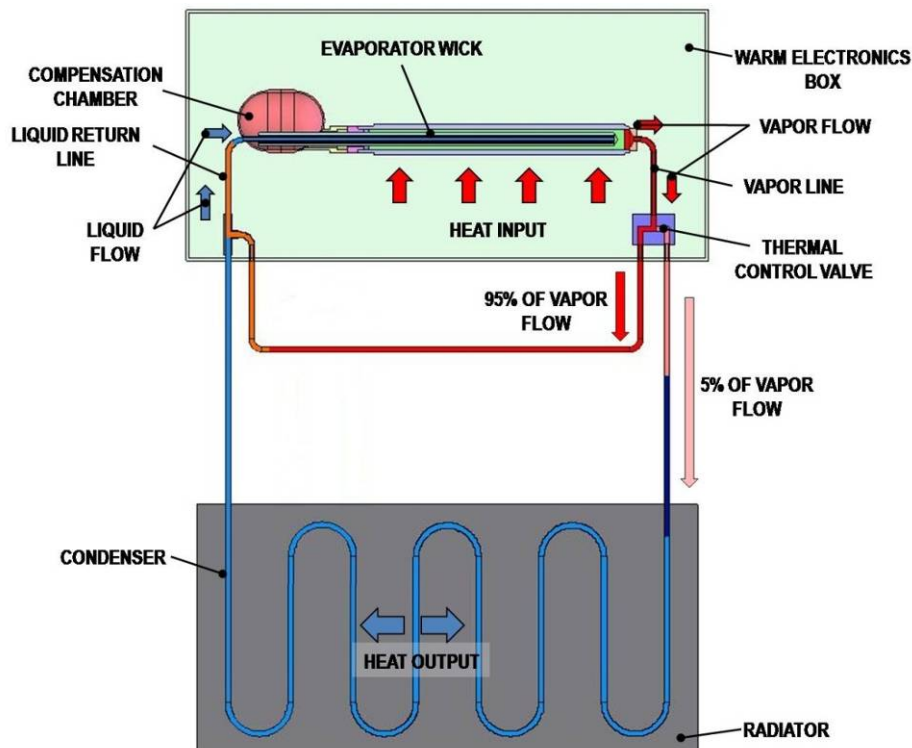
Figure 7. Variable Conductance Loop Heat Pipe schematic during the Lunar night. Most of the vapor flows through the Radiator. The 95% and 5% flow rates are representative.

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 8.

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 current program; however, propylene will be evaluated in the future. 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 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 8 allow testing with either flow path.
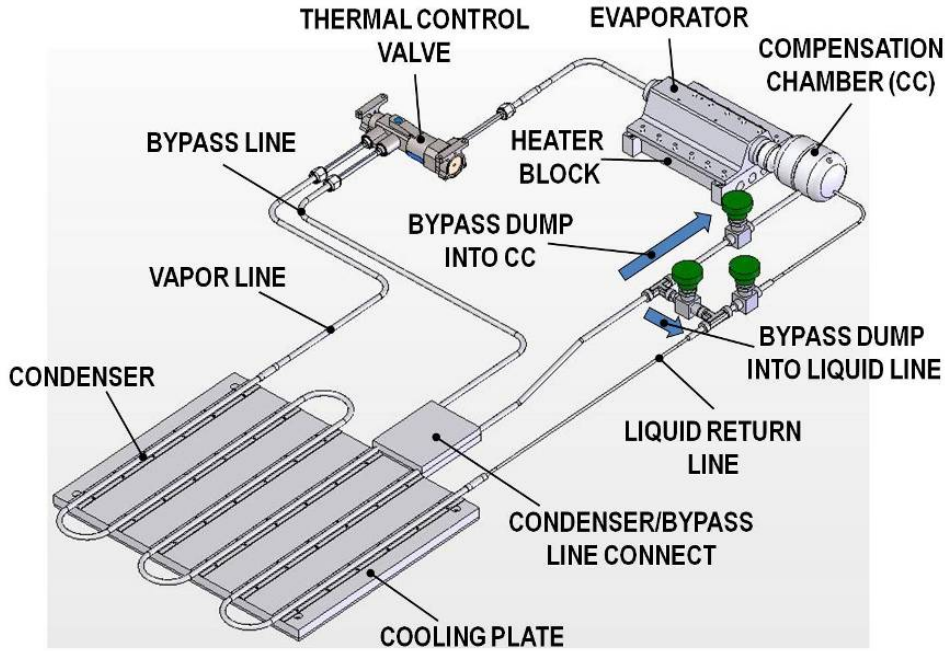
Figure 8. Loop Heat Pipe with Thermal Control Valve Design.

V. Loop Heat Pipe with Thermal Control Valve Manufacturing

The Thermal Control Valve 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 9. 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.
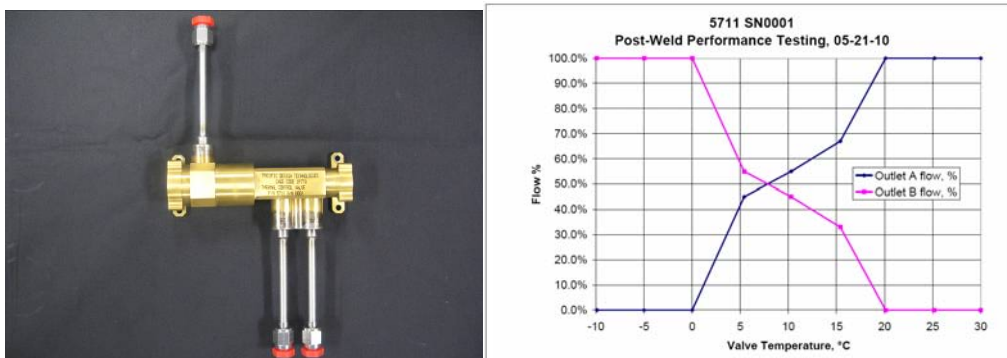

Figure 9. Photograph of the TCV for LHP with TCV Integration (left) and Post-Weld Performance Testing (right).

The loop heat pipe with a TCV was fabricated based on the design parameters outlined above. A photograph of the completed LHP is shown in Figure 10.
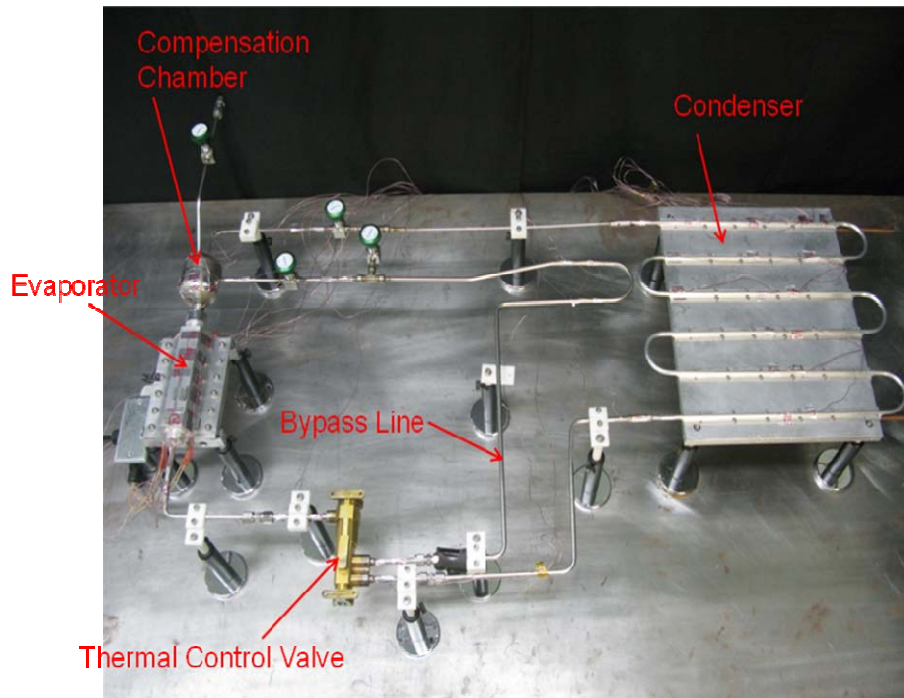
Figure 10. Final LHP with TCV Test Assembly.

VI.   Loop Heat Pipe with Thermal Control Valve Testing

F. 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 11. 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 nitrogen flow.
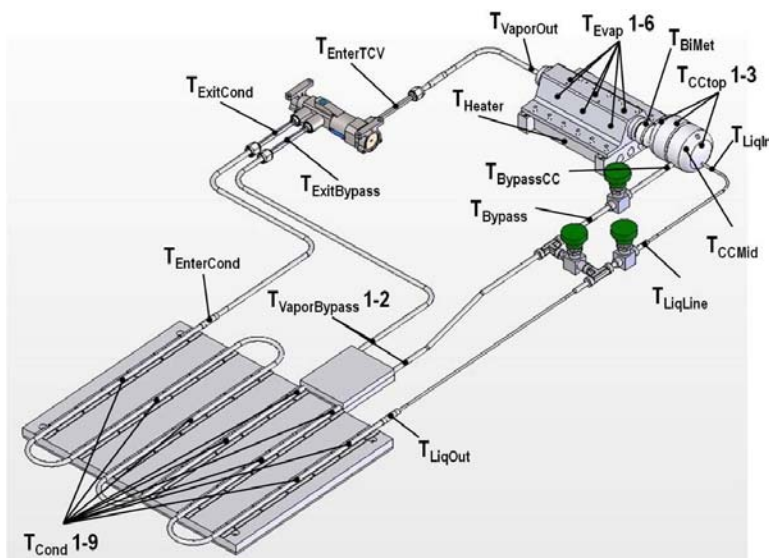

Figure 11. LHP with TCV Testing Thermocouple Locations.

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 lowered in stepwise increments.

The overall LHP test plan was established, as follows:

- A liquid nitrogen supply source was attached to the inlet of the condenser plate. The LN supply was attached through a solenoid valve that was controlled by a temperature controller. LN was delivered to the cold plate to maintain the temperature value set on the controller.
- 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 is reached.
- The condenser temperature was decreased using the LN temperature controller. The power input to the evaporator remained constant.
- The temperature profile across the LHP was measured and recorded until steady state is reached.
- The power was decreased in stepwise fashion, while maintaining the constant condenser temperature.
- The power was subsequently reduced from 110W to 25W, 5W and 0W.

The test plan described above was modified throughout the test based on LHP performance.

G. Test Results and Discussion

The test results for one test run are shown in Figure 12 and Figure 13. Figure 12 shows all data for the entire run profile. Figure 13 is a refinement of the data within a 4ºC to 20ºC temperature band to show specific details. In this test run the power input to the evaporator was set at 110W and the sink temperature decreased in stepwise increments to -60ºC. At -60ºC, the input power was decreased to 75W, 50W, 25W, 5W and 0W.

There are several observations that demonstrate the loop shut down using the TCV. Initially, the ΔT between the evaporator and CC is approximately 2-3ºC, demonstrating loop flow. During this time, the TCV is operating at approximately 19ºC: therefore a majority of the flow is through the condenser. The temperature of the vapor going through the bypass line is 18-19ºC near the valve inlet temperature, indicating that little to no vapor flows through the bypass line. The evaporator remains at 18-19ºC. When the power is decreased, the temperature of the vapor entering the TCV drops to 13ºC. The temperature of the vapor in the bypass lines (Bypass 1 and 2) increase temporarily to 19ºC as there may have been some fluid in the lines, but drops off in stepwise fashion to 5ºC. The temperature also drops at the exit of the TCV. These conditions indicate flow through the bypass line, where vapor is being transferred to the CC inlet. The ΔT between the evaporator and CC also decreases to <1ºC, indicating a drop in flow through the loop and loop shut down. In addition, the temperature of the liquid entering the CC increases well above the condenser temperature indicating the fluid is being bypass around the condenser. The evaporator drops to 5ºC and does not continue to drop to near the -60ºC sink temperature and actually starts to increase. Note that the evaporator temperature does not drop below 5ºC even when the evaporator power is reduced to 0 W. In fact, it is still increasing slightly, since the LHP had not completely reached steady state after each reduction in power.

Temperature and power measurements from a second test are plotted in Figure 14 and Figure 15. In this test, the condenser temperature was set to -10ºC. The transient temperature changes near 90 minutes occur because the power has been reduced abruptly, and the amount of cold liquid returning to the compensation chamber has changed. The ΔT between the Compensation Chamber midpoint and the evaporator drops off sharply when the power is turned back, but still maintains a 15ºC evaporator. It also shows the temperature of the vapor in the bypass line dropping off as the TCV temperature drops, indicating flow in the bypass line

By 200 minutes, the LHP has essentially reached steady state. With 25 W of evaporator power, the evaporator temperature stays near 15ºC, while the condenser is near -10ºC. The power was then reduced further to about 5 W, and the evaporator temperature was essentially unaffected. In this test, there were some temperature oscillations. We are not sure if this is the same phenomena reported by other researchers[8], or if this is caused by the way that the condenser temperature is set (the liquid nitrogen flow periodically cycles on and off).

In summary, testing shows the LHP with a TCV can effectively reduce and shut down LHP flow and maintain the evaporator temperature without the need for electrical power added to the compensation chamber.
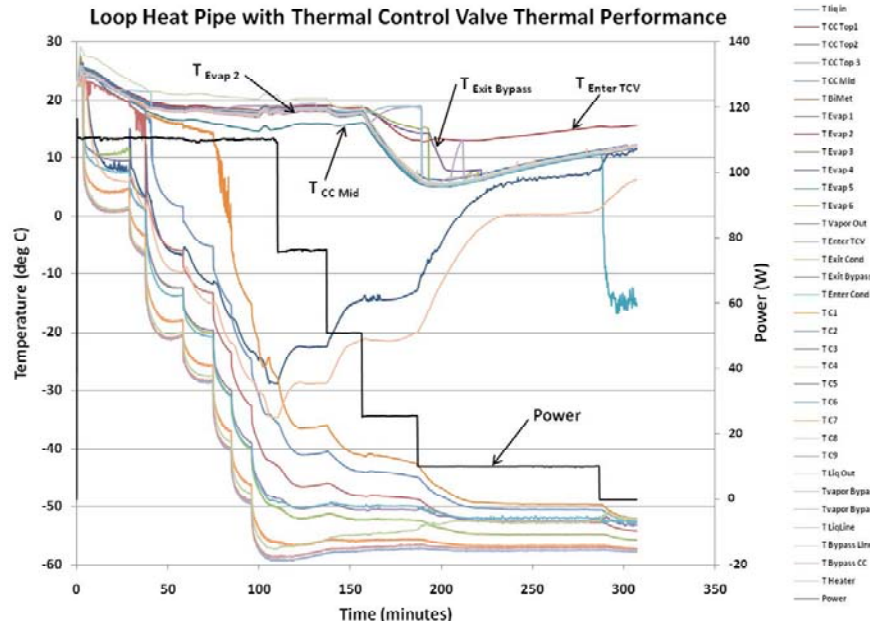
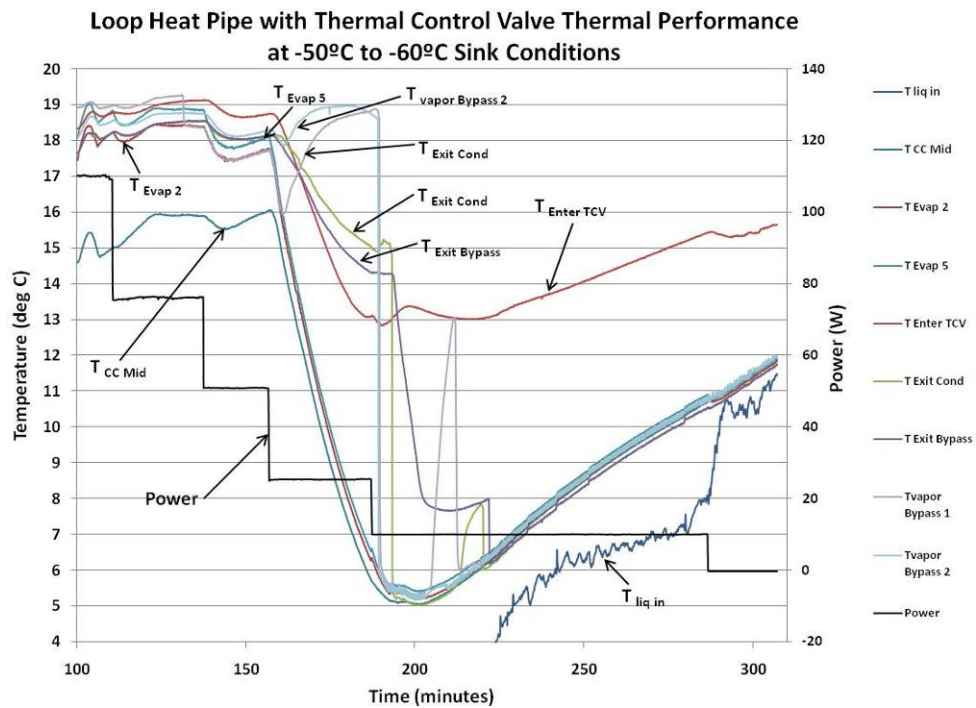**Figure 12. Loop Heat Pipe with TCV Thermal Performance Profile. The condenser temperature was reduced to below -50°C.**

Figure 13. Loop Heat Pipe with TCV Thermal Performance Profile, same as the figure above except the data is refined to within a 4ºC to 20ºC temperature range.
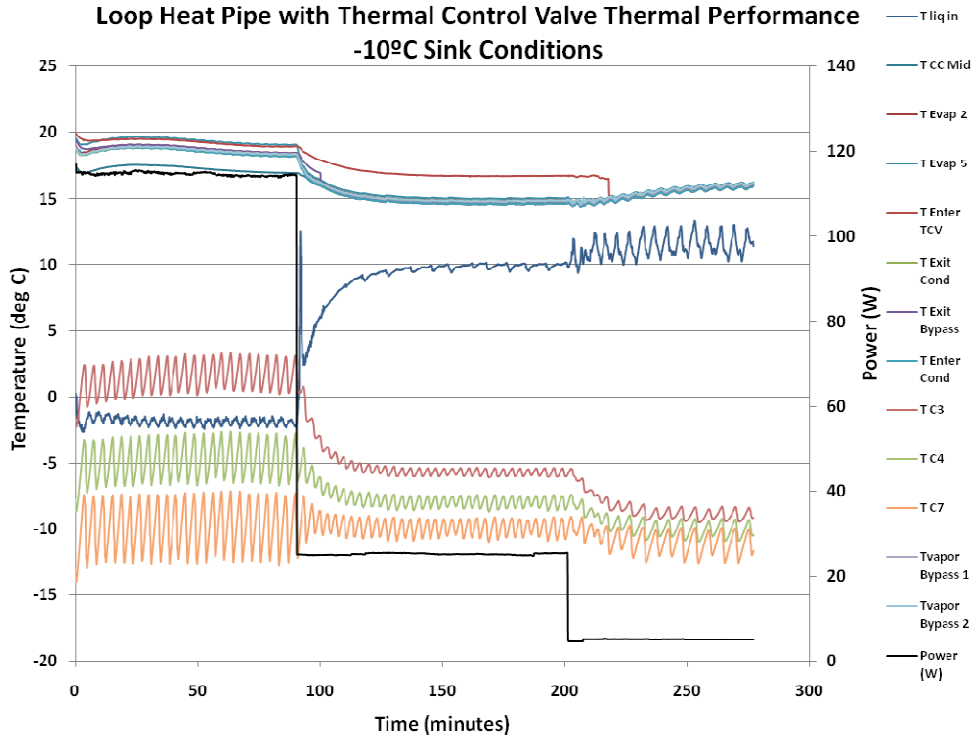
American Institute of Aeronautics and Astronautics

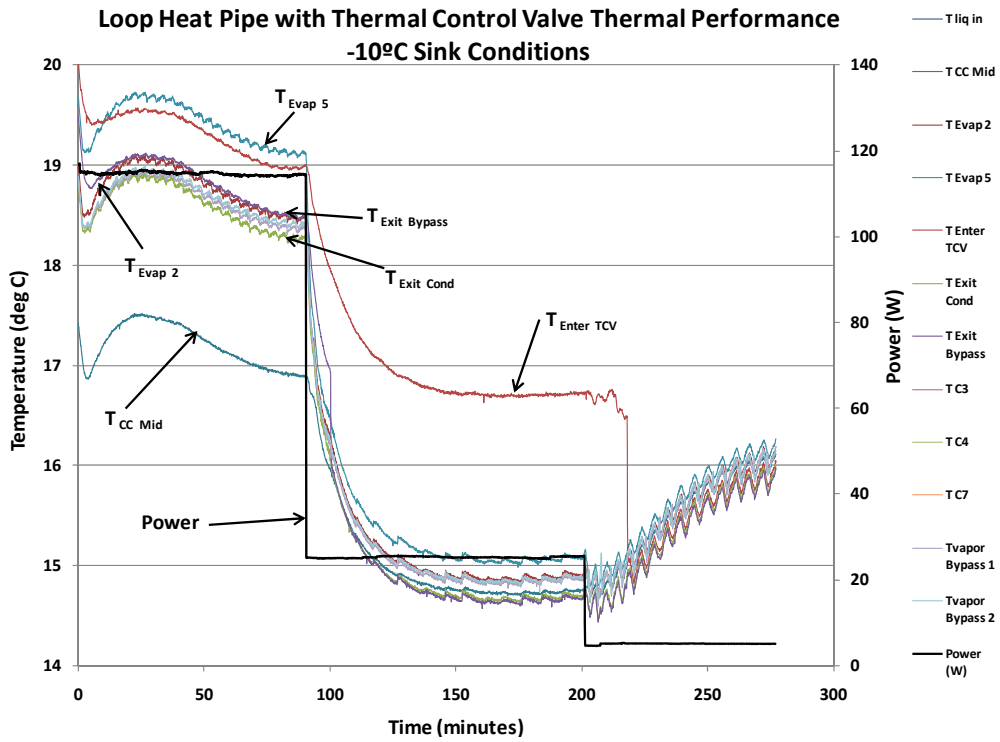**Figure 14. Loop Heat Pipe with TCV Thermal Performance Profile, with the condenser temperature reduced to -10°C.**

Figure 15. Loop Heat Pipe with TCV Thermal Performance Profile, with the condenser temperature reduced to -10°C. This figure is a detail from the previous figure.

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VII. 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 with a Thermal Control Valve was develleoped as a solution for this problem. A 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 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, a majority of the vapor was routed to the condenser. Between 0ºC and 20ºC, a portion of the flow was bypassed to the compensation chamber. Below 0ºC, a majority of the flow is bypassed. At low sink conditions and power input, -60ºC and 0-5W, respectively, thermal performance testing shows that the LHP with a TCV can effectively reduce and shut down LHP flow and maintain the evaporator temperature without the need for electric power.

Acknowledgments

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