Ammonia and Propylene Loop Heat Pipes with Thermal Control Valves – Thermal/Vacuum and Freeze/Thaw Testing

Kara L. Walker[1], John R. Hartenstine[2], Calin Tarau[3], John Polak[4], and William G. Anderson[5]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

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, reducing the pressure differential across the system and decreasing LHP flow. The amount of electrical power to shut down an LHP during an eclipse on orbit is generally reasonable due to the short duration in the cold environment. On the other hand, for LHPs on lunar and Martian landers and rovers, the electrical power requirements can be excessive, since the Lunar night lasts for 14 days. 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, especially 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. Ammonia and propylene LHPs with Thermal Control Valves (TCVs) were developed to provide passive variable thermal conductance without electrical power. The TCV routes vapor to the condenser, or bypasses the condenser and routes the vapor back to the compensation chamber, depending upon the environmental temperature conditions. Thermal vacuum testing of both LHPs with thermal control valves demonstrated the ability of the TCV to passively maintain a warm evaporator during roughly 24 hours of operation at a 0W power input and a -60°C sink. For lunar applications, the sink temperature during the lunar night could reach as low as -223°C. It is possible for ammonia to freeze, potentially causing structural damage as the ammonia melts and expands. Freeze/thaw testing of a vertical condenser on an ammonia LHP with TCV was performed that showed negliglbe change in condenser dimensions after 9 freeze/thaw cycles.

I. Introduction

Future Lunar landers and rovers will require a variable thermal link that is capable of rejecting heat during the day and passively shutting down during the night without electrical power requirements. During the long lunar day, the thermal management system must reject waste heat from the electronics and batteries to prevent overheating. Thermal management systems are designed to reject the heat at the hottest operating conditions. If a fixed conductance system is used, a higher amount of waste heat will be rejected during the coldest operating conditions, when energy should be conserved to maintain the temperature of the batteries and electronics. 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.

[1] Mechanical Engineer II, Aerospace, 1046 New Holland Ave. Lancaster, PA 17601, AIAA member.
[2] Department Manager, Aerospace, 1046 New Holland Ave. Lancaster, PA 17601, AIAA member.
[3] Lead Engineer, Aerospace, 1046 New Holland Ave. Lancaster, PA 17601, AIAA member.
[4] Mechanical Engineer I, Aerospace, 1046 New Holland Ave. Lancaster, PA 17601.
[5] Chief Engineer, 1046 New Holland Ave. Lancaster, PA 17601, AIAA member.

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 temperatures out of their operational range. In spacecraft, a small heater is attached to the LHP Compensation Chamber (CC) to prevent the LHP from lowering the electronics and battery temperatures below the minimum allowable. The heater alters the thermodynamic balance between the sub-cooled liquid returning from the condenser and the thermal energy exchanged between the evaporator and CC, which is referred to as heat leak. The heater artificially reduces the sub-cooling provided by the condenser and the LHP compensates by increasing the operating temperature. This behavior maintains the LHP evaporator temperature. The penalty for this type of control is the additional power required to operate the heater, which is estimated to be about 1 W for a 50 to 100W LHP. While this may seem to be an insignificant amount of power, it is estimated that 1W 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 for some spacecraft systems 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 330K during the daytime and can drop down to 50K 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.

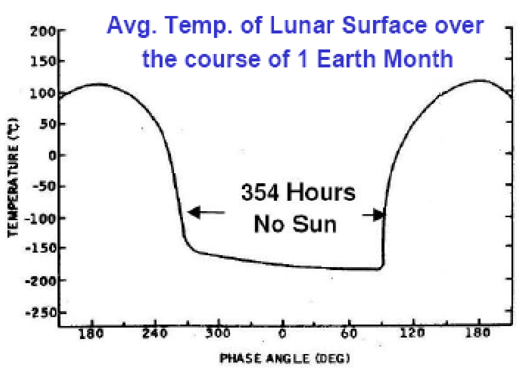

Figure 1. Typical Lunar Surface Temperatures (Swanson and Butler, 2006).

A. Loop Heat Pipes

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 outer surface of the wick. The vapor is collected by a system of grooves and channels. 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 CC assembly, which contain the primary and secondary wicks. The CC (also known as the reservoir) at the end of the evaporator is designed to operate at a lower temperature than the evaporator. Since the temperature is lower, the pressure of the saturated fluid in the CC is also lower. The lower pressure allows the condensate to flow from the condenser through the liquid return line to the CC. The fluid then flows into a central bayonet where it feeds the primary wick. A secondary wick in the evaporator and CC allows the liquid in the CC to supply liquid to supplement the liquid returned through the liquid return line.

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

LHPs are made self-priming by carefully controlling the volumes of the CC and other components so liquid is always available to the primary wick. The CC and fluid charge are set so that there is always some liquid in the CC 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 (2007) presented a survey of the parameters affecting LHP design.

B. Previous Trade Studies and Research

1. Loop Heat Pipes 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 primary wick that was 6 inches long. The transport lines and condenser were constructed of stainless steel. The total weight was roughly 0.3kg. The mini-LHP had a start-up heater on the evaporator. Roughly 5W was required for several minutes to start the LHP. A shutdown heater that used approximately 1W continuously was used to turn the LHP off at night.

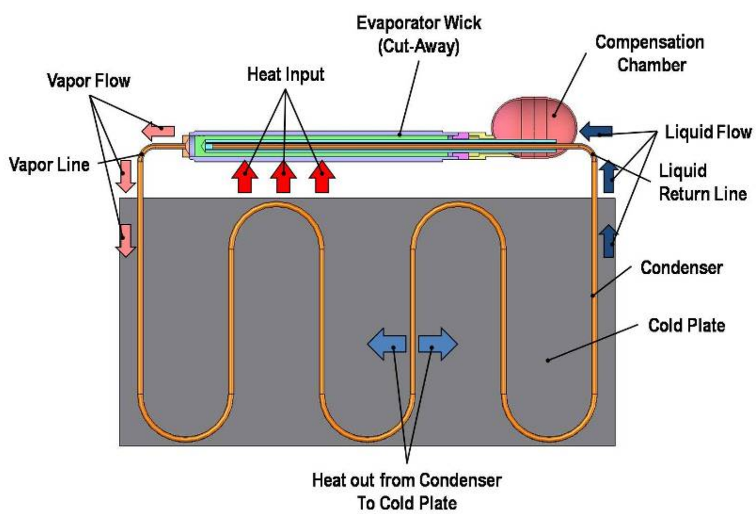

Figure 2. Loop Heat Pipe Schematic (Not to scale). For example, the vapor and liquid return lines can be much longer.

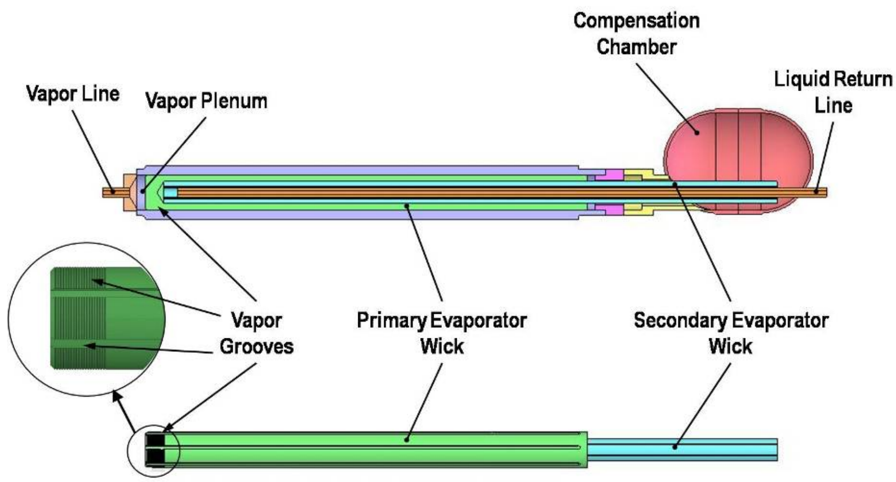

Figure 3. Loop Heat Pipe Evaporator.

Thermal tests by JPL 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 of expanding liquid ammonia when it thawed (the radiator thawed before the transport lines). Qualification testing demonstrated that the LHP system could accommodate ammonia freeze/thaw in the condenser. The system successfully underwent 100 freeze/thaw cycles. While the JPL mini-LHP has not flown, it had all of the testing that would be conducted before a test in space.

2. Variable Thermal Links

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. However, this effort focused 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 (TCV).

Goncharov et al. (2001, 2005) were the first to use a 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 4. 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 CC. Heat is applied to the argon surrounding the bellows to allow precise temperature control.

More recently, researchers at Carlo Gavazzi Space, Milano, Italy (Molina et al, 2009, Franzoso et al., 2009) have used a similar TCV in a LHP for a Martian rover application. The aluminum/stainless LHP uses propylene as the working fluid, to avoid issues with freezing. The LHP thermal switch transports up to 40W through 1.3m long stainless steel vapor and liquid return lines. The 0.7μm nickel wick is 11mm diameter, and 120mm 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.

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 set point. 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 MSL was launched on November 26th, 2011 and has been successfully operating on Mars since August 6, 2012.

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. 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. The TCV was integrated and tested in an ammonia LHP.

C. Thermal Control Valve

A schematic of the TCV configuration for the MSL is shown in Figure 4a. Pacific Design Technologies provides two different types of TCVs; a 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 described in this paper. The valve used for the LHP with TCV was similar to the design in Figure 4a. 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.

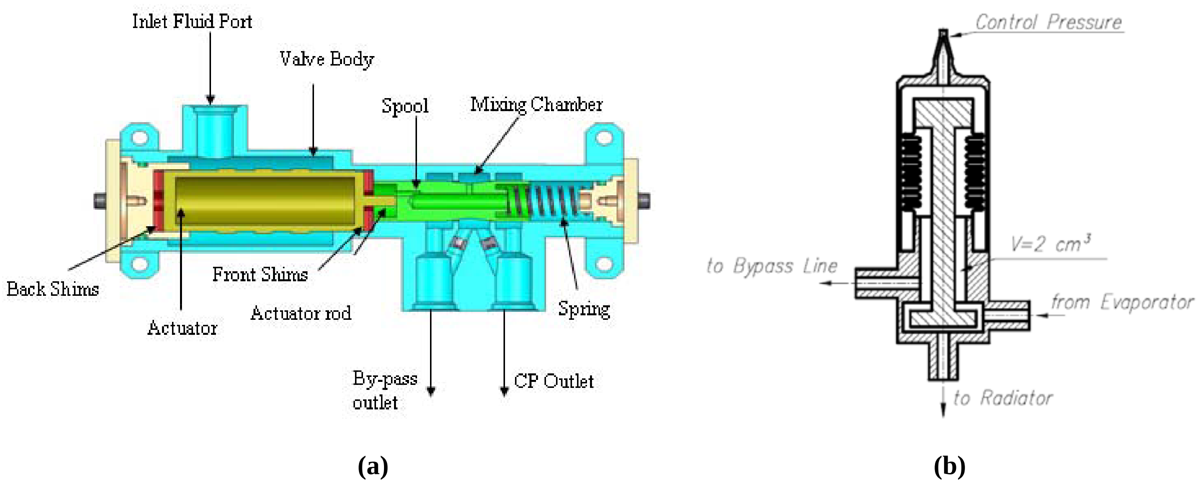

Figure 4. Thermal Control Valve Configurations. (a) PDT valve for the Mars Science Laboratory has an actuator that does not depend on the working fluid pressure (Birur et al., 2008). (b) TCV design used by Goncharov et al. (2001, 2005) is dependent on the working fluid pressure to move the valve.

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 Warm Electronics Box (WEB) along with the evaporator and compensation chamber assemblies of the LHP. LHP TCV 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. Within the TCV, the vapor line splits, routing vapor to either the radiator for heat rejection or to the CC 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 to Condenser (%)	Outlet to Bypass Condenser (%)
≤ +10ºC	Minimize	Maximize
+10ºC to +30ºC	Increase in Flow to Condenser with Increasing Temperature	Decrease in Flow to Bypass with Increasing Temperature
≥ +30 ºC	Maximize	Minimize

IV. Ammonia Loop Heat Pipe with Thermal Control Valve Design

An ammonia LHP with TCV was designed to be used as a potential thermal management system for the Anchor Node application. The LHP with TCV design can be seen in Figure 5. The system has been designed with a condenser that is capable of operating in a horizontal orientation as well as a vertical orientation. Flexible vapor and liquid lines were included in the design to allow the condenser to be rotated 90° relative to the evaporator assembly. The ammonia LHP has a 6.0in (15.24cm) long evaporator with a 1.0in (2.54cm) nickel primary wick. The ammonia LHP with TCV uses 0.25in (0.64cm) outer diameter tubing for the vapor, condenser, liquid and bypass lines. The ammonia LHP with TCV was designed to incorporate Differential Pressure Transducers (DPTs) across the TCV inlet and condenser outlet path as well as the TCV inlet and bypass outlet path to measure the pressure drop across the two fluid flow paths. Testing of the ammonia LHP with TCV showed that minimal pressure change happened during LHP with TCV operation across the two fluid flow paths and therefore, the results section will not include discussion regarding the pressure drop across the valve. The LHP with TCV has the ability to operate as a LHP with a TCV as well as operate as a standard LHP where the TCV is bypassed. This design decision was made to allow for additional comparative testing between LHP with TCV operation and standard LHP operation.

The ammonia LHP with TCV contains a TCV with a set point range of +10°C to +30°C. If incoming vapor flow to the TCV from the evaporator is above +30°C, 100% of that flow will be routed to the TCV condenser outlet for heat rejection. For vapor inlet temperatures between +10°C and +30°C, the flow will be split between the condenser outlet and the bypass outlet. For vapor inlet temperatures below +10°C, 100% of the flow will be routed to the bypass outlet and back to the CC.

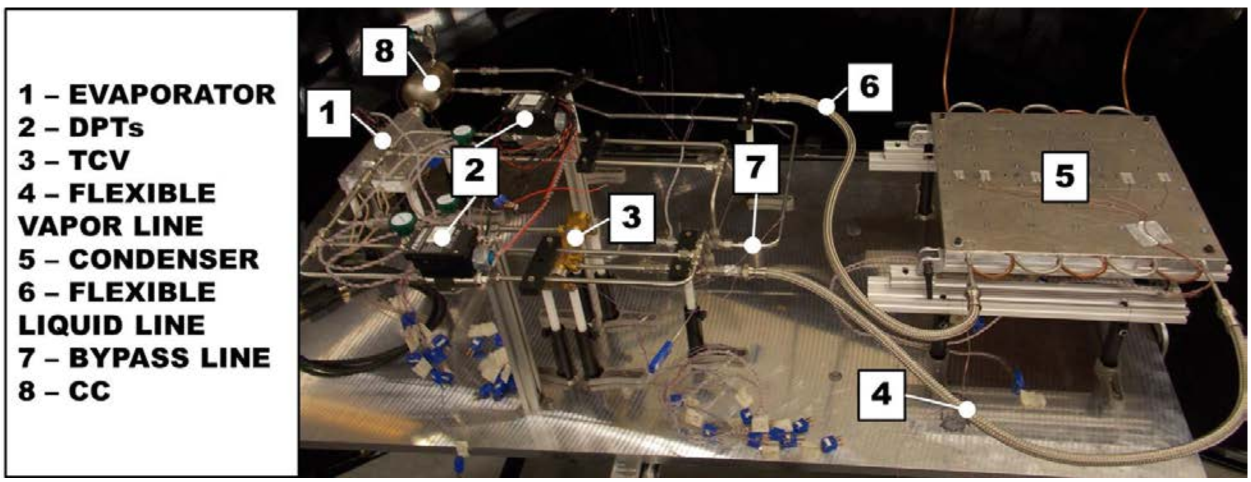

Figure 5. Ammonia LHP with TCV design.

D. Ammonia Loop Heat Pipe with Thermal Control Valve Test Setup

The ammonia LHP with TCV was instrumented with 34 Type T thermocouples. Three intrusive TCs were included in the instrumentation on the TCV inlet, TCV bypass outlet and TCV condenser outlet lines. The remaining thermocouples were taped to the exterior surface of the LHP with TCV. The ammonia LHP with TCV was instrumented with two Differential Pressure Transducers (DPTs) that were installed across the TCV inlet and TCV outlet flow paths. Heat input was provided through four cartridge heaters embedded in an aluminum heater block connected to the evaporator body. The condenser assembly was mounted to a test stand that allows for horizontal and vertical radiator operation. Stainless steel flexible lines were installed on the vapor and liquid sides of the condenser to allow versatility in radiator operation. Cooling for the condenser was provided using embedded copper tubing in the condenser assembly that is fed liquid nitrogen (LN).

A wide range of tests were performed on the ammonia LHP with TCV to determine its thermal performance capabilities. Testing was performed in a thermal vacuum chamber for the LHP assembly to reduce the heat leaks into the system experienced during testing in ambient. The entire ammonia LHP with TCV assembly was insulated with three wraps of aluminum foil prior to installation in the vacuum chamber. Testing was also performed with the condenser in horizontal and vertical orientations. Testing was also performed as a standard LHP where the TCV assembly was bypassed to compare operation between a LHP with TCV and a standard LHP. The following tests were performed on the LHP assembly:

1. -60°C constant sink condition with an incremental power decrease from 200W to 0W

2. Long duration operation at 0W power input with a constant sink of -60°C

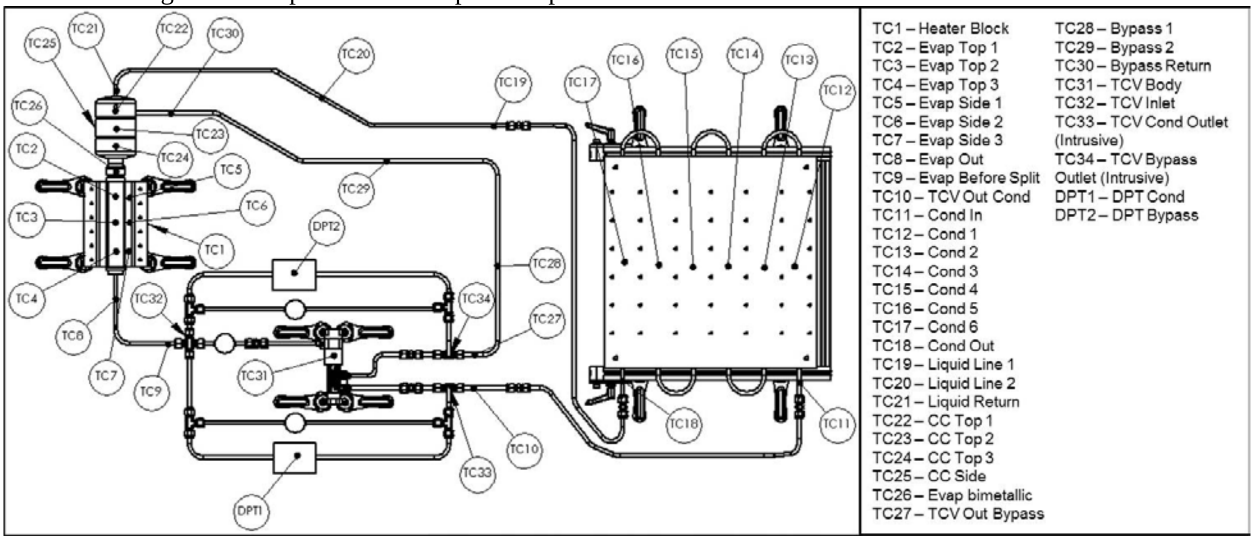

Figure 6. Ammonia LHP with TCV thermocouple map.

The two tests above were performed for both a horizontal condenser and a vertical condenser to provide a comparison on how the radiator orientation will effect LHP operation. The test plan for Test #1 is as follows:

- Set the power input to the evaporator to 200W and allow the evaporator temperature to reach a steady state.
- Decrease the condenser temperature in stepwise increments until a steady state of -60°C is achieved.
- Decrease the power input to the evaporator in the following stepwise increments: 150W, 100W, 75W, 50W, 25W, 0W, allowing the evaporator to reach a steady state condition at each increment

The test plan for Test #2 is as follows:

- Set the power input to the evaporator to 100W and allow the evaporator temperature to reach a steady state.
- Decrease the condenser temperature in stepwise increments until a steady state of -60°C is achieved.
- Decrease the power input to the evaporator to 0W and allow the evaporator to reach a steady state condition.

V. Ammonia Loop Heat Pipe with Thermal Control Valve Test Results

The results for vacuum chamber testing of the ammonia LHP with TCV can be seen in Figure 7 through Figure 10. Figure 7 and Figure 8 are the results for the horizontal condenser operation and Figure 9 and Figure 10 are the results for the vertical condenser operation. During an incremental power decrease and a constant -60°C sink, the evaporator of the ammonia LHP with TCV maintains an evaporator temperature of approximately 30°C. When power input is turned off to the LHP evaporator, the evaporator is maintained above 25°C. As seen in the figure, a steady state condition was not reached due to a lack of hours in the work day. Due to this, the long duration 0W power input test was performed. The LHP with TCV was operated at 0W power input for approximately 24 hours. The evaporator temperature for the long duration test was maintained at approximately 20°C. At approximately 13 hours, the TCV condenser outlet temperature begins to decrease at rate quicker than the rest of the temperatures in the evaporator and TCV assemblies. This indicates that the flow through the valve is decreasing enough that the conduction through the walls of the tubing from the condenser has an increased effect. The TCV is therefore, routing a majority of the vapor flow through the bypass line and back to the CC.

The ammonia LHP with TCV operated with a vertical condenser at an evaporator temperature of approximately 15°C during the power decrease test and experienced severe fluctuations in evaporator and TCV assembly temperatures. As seen in the results, the temperatures fluctuated between 20°C and 5°C. Attempts to reach steady state before moving onto the next power increment were attempted, but it was not achievable due to the unstable evaporator temperatures. A 0W power input was not achieved during the power reduction test due to time constraints. The LHP with the vertical condenser was operated at a 0W power input for approximately 45 hours during the long duration test. Severe fluctuations in the temperature of the evaporator and TCV assembly were experienced during the test. These fluctuations are believed to be due to condenser orientation and cold liquid slugs flowing back through the vapor line into the TCV assembly. The vertical condenser orientation contains an additional pressure drop during operation due to gravitational forces. During horizontal operation, the only pressure drop that drives the fluid through the loop is caused by the temperature difference between the evaporator and the CC. When the condenser is oriented vertically, the fluid experiences an additional pressure drop as gravity forces the fluid through the loops in the condenser (the condenser tubing is oriented perpendicular to the overall condenser) as well as through the flexible liquid and vapor lines. The liquid backflow through the flexible vapor line is indicated by a correlating sudden spike in condenser inlet temperature and sudden decrease in the temperatures at the TCV assembly. At these moments, it is believed that the vapor flowing from the TCV condenser outlet bypasses a liquid slug contained in the flexible vapor line causing the liquid slug to fall back to the TCV assembly and causes the sudden reduction in temperature. The results also demonstrate that the impact of liquid backflow decreases with time and it is assumed the evaporator will reach a steady state with additional time.

After LHP with TCV thermal performance testing was complete, the valving on the system was modified to operate as a standard LHP where the TCV assembly was bypassed. This shut off all flow through the bypass line and back to the compensation chamber and only allowed for flow to the condenser. This testing was also performed with the condenser in a vertical condition. A long duration, LHP shut down test was performed on this system in this configuration. The results of the test can be seen in Figure 11. The same test plan was followed as for the LHP with TCV operation where an initial power input of 100W was applied and the condenser temperature was decreased to -60°C. Once a steady state was reached in the evaporator, the power to the system was shut off. Under standard LHP operation, the evaporator temperature operated at approximately -40°C. After the power was shut off to the system, the evaporator temperature decreased further to approximately -50°C. Without the inclusion of the TCV in the LHP assembly, the evaporator temperature drops significantly, well below the established design requirements for the ILN Anchor Node application.

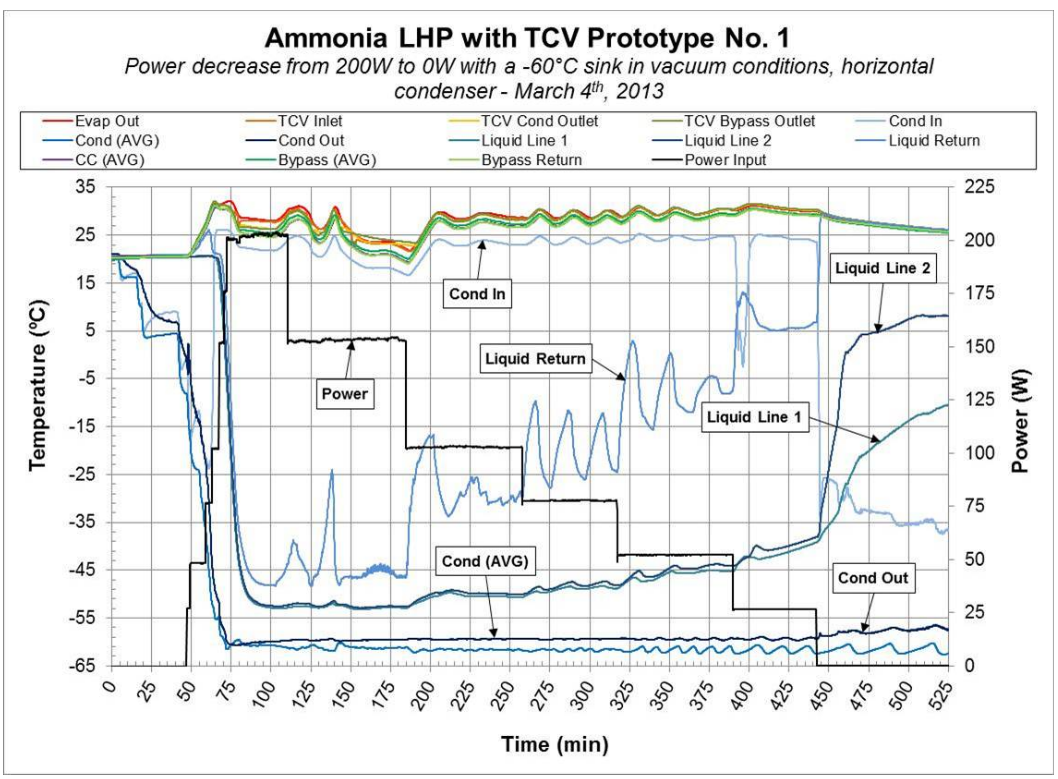

Figure 7. Ammonia LHP with TCV operating with a horizontal condenser in the thermal vacuum chamber, -60°C constant sink conditions with a power input decrease from 200W to 0W.

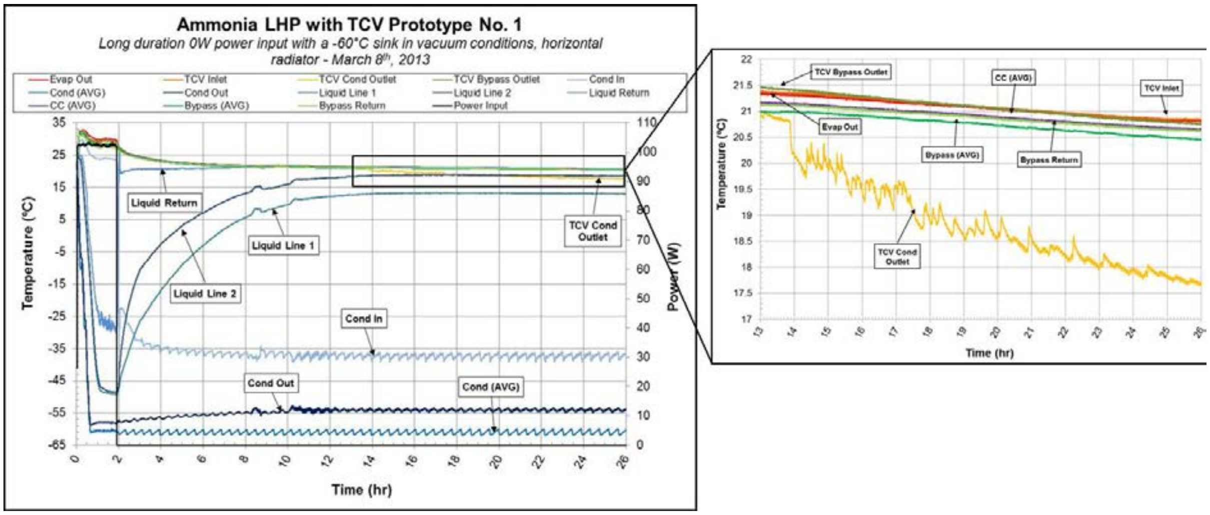

Figure 8. Ammonia LHP with TCV operating with a horizontal condenser in the thermal vacuum chamber, -60°C constant sink conditions with long duration 0W power input.

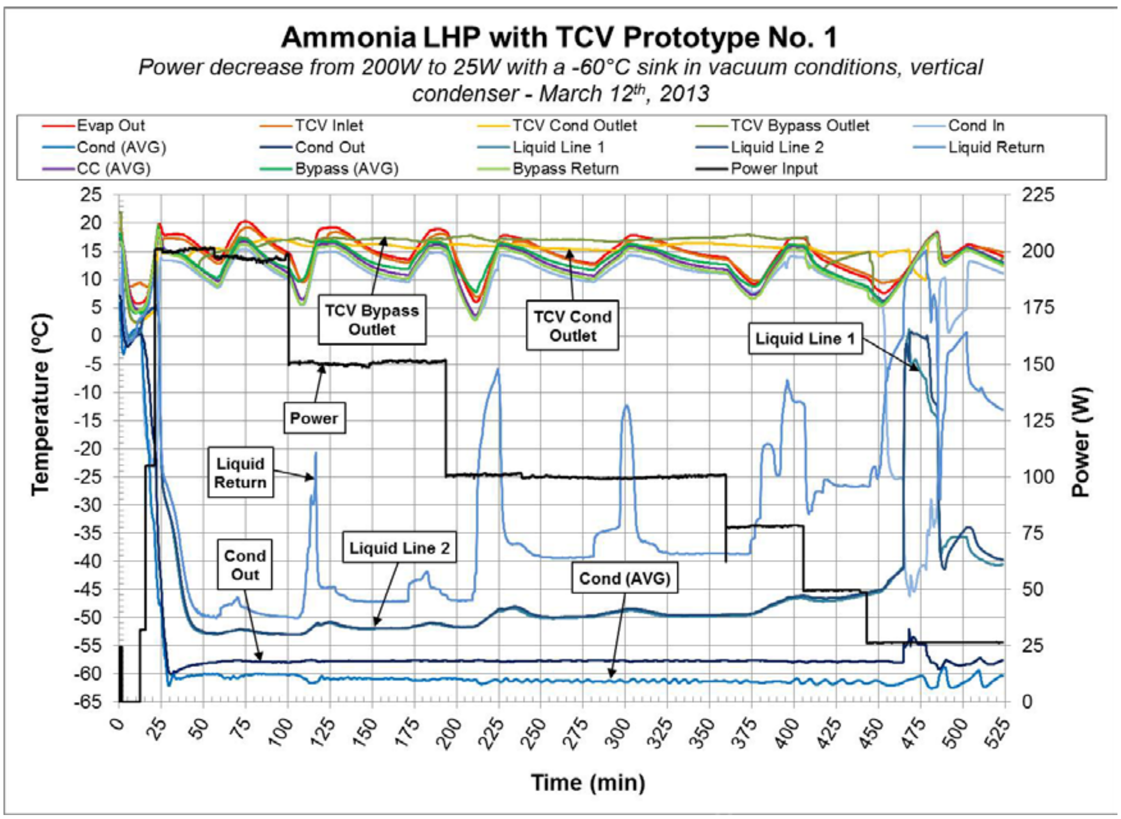

Figure 9. Ammonia LHP with TCV operating with a vertical condenser in the thermal vacuum chamber, -60°C constant sink conditions with a power input decrease from 200W to 0W.

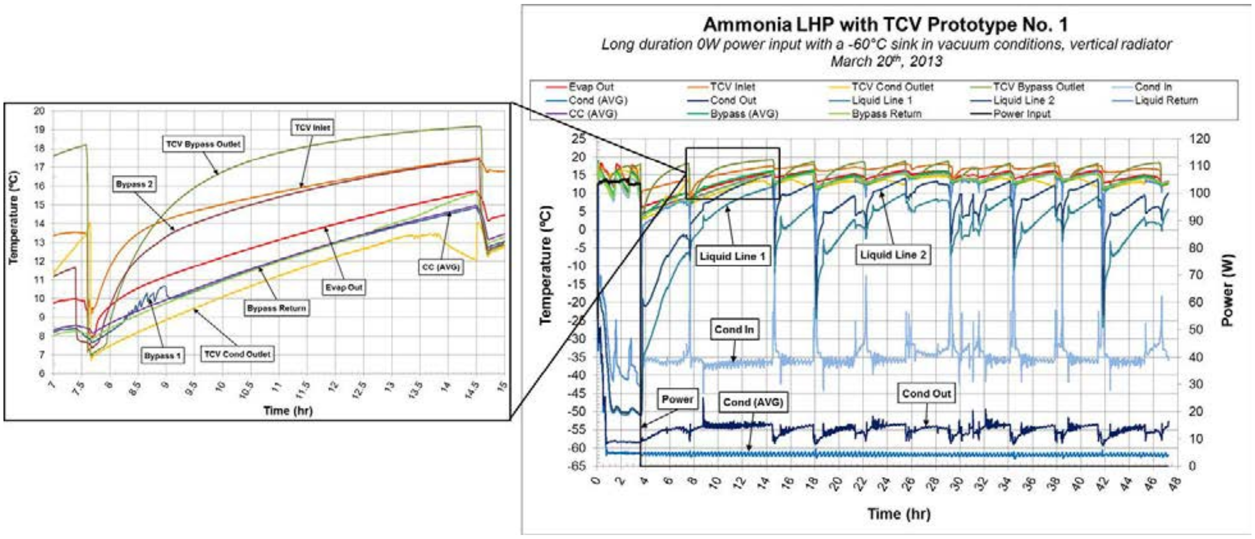

Figure 10. Ammonia LHP with TCV operating with a vertical condenser in the thermal vacuum chamber, -60°C constant sink conditions with long duration 0W power input.

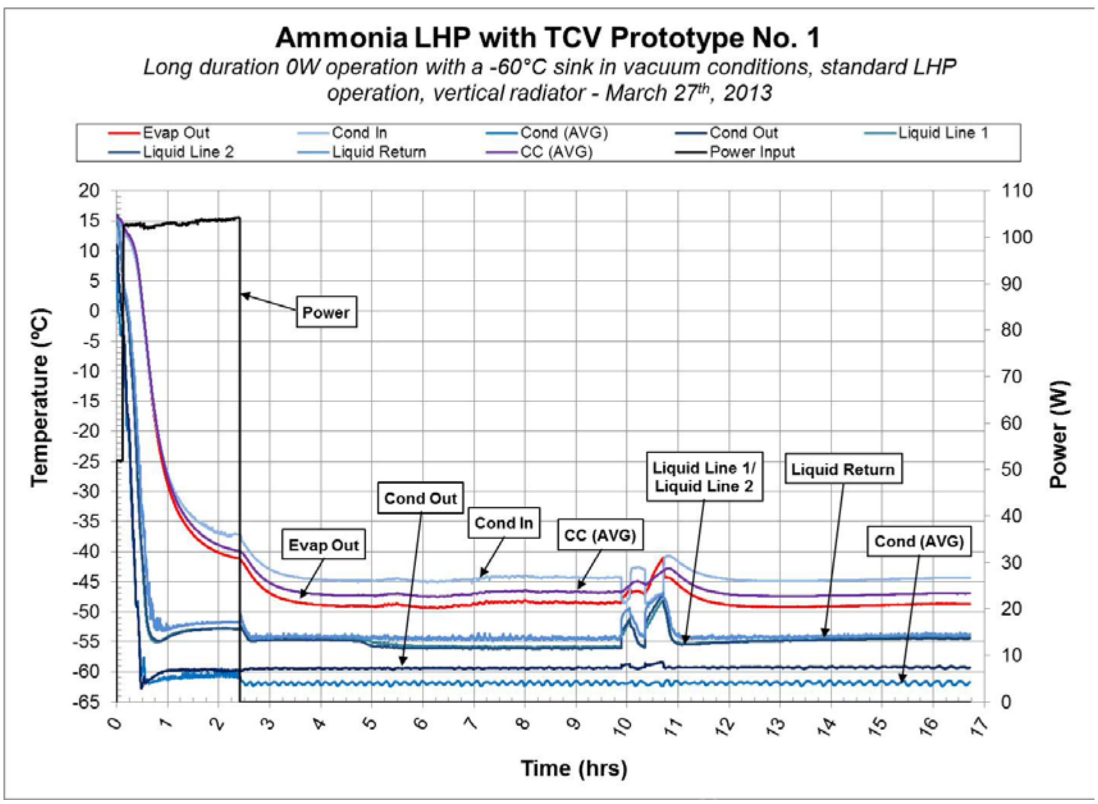

Figure 11. Ammonia standard LHP (flow is bypassed around the TCV) operating with a vertical condenser in the thermal vacuum chamber, -60°C constant sink conditions with long duration 0W power input.

VI. Ammonia Loop Heat Pipe with Thermal Control Valve Freeze/Thaw Experiments

An ammonia LHP with TCV that was previously designed, fabricated and tested on a Phase I NASA SBIR program was modified to perform freeze/thaw testing. The existing vapor and liquid lines were cut and the previous condenser assembly was removed. A new condenser assembly was fabricated that utilized stainless steel condenser tubing instead of the standard aluminum tubing. Stainless steel tubing was used for this particular test due to its superior strength when compared to aluminum. It was also chosen during the previous freeze/thaw tests by Pauken, Birur, and Novak (2002). A new condenser cold plate was fabricated that used embedded copper tubing connected to an LN Dewar to control the temperature. The stainless steel tubing was embedded halfway into the cold plate and was secured in place using a series of stainless steel straps. The traditional cover plate that is used for LHP condenser cold plates was not installed in this system to allow for the stainless steel tube deformation to occur if the expansion forces caused by the thawing ammonia were too severe. External geometric measurements were taken of the condenser tubing at 67 locations over the overall length prior to testing. Measurements at the same locations were taken after every test that was performed and the change in geometry was compared to determine if deformation was occurring. Figure 12 is a photograph of the ammonia LHP with TCV freeze/thaw test assembly.

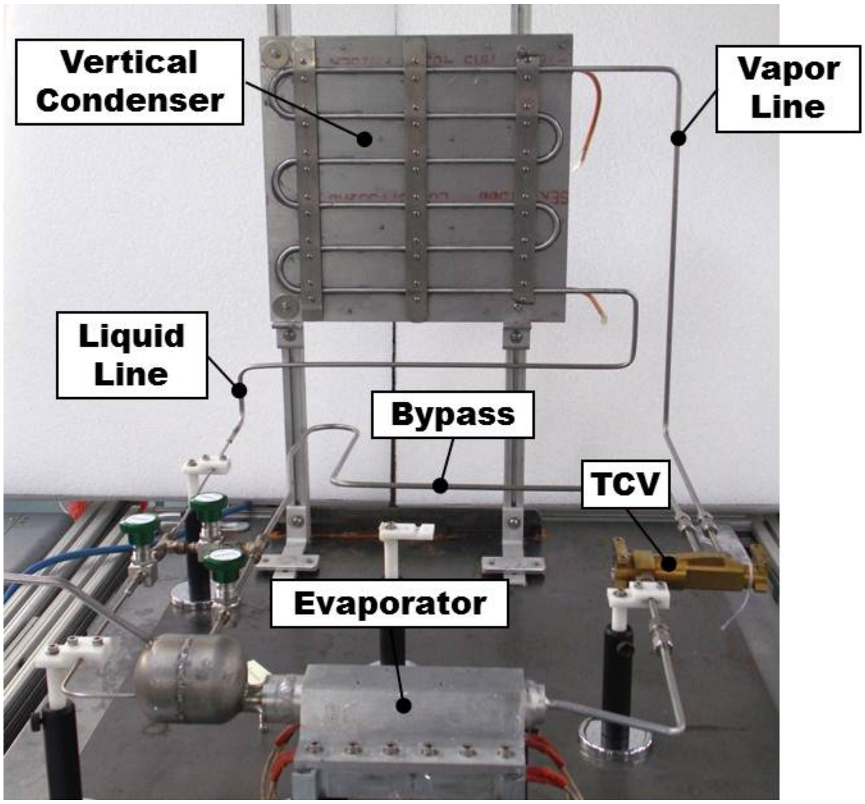

Figure 12. Ammonia LHP with TCV freeze and thaw test assembly.

A series of nine tests were performed on the ammonia LHP with TCV freeze and thaw test assembly. All testing was performed under ambient conditions and the entire system was insulated with an inch of closed cell polyethylene insulation. An initial power input of 100W was provided for each test and the condenser temperature was decreased in a stepwise fashion to -70°C. The system was then operated at a 100W power input and a sink of -70°C for an hour. After an hour, the power was decreased in 25W increments until the system was completely shut off at 0W of power input. The system was then allowed to operate under these conditions for an hour. Four different freeze procedures were evaluated over the course of the nine tests. All tests were performed with a vertical condenser. The procedures are as follows:

- A rapid cool to -120°C where the condenser is decreased to -80°C, -100°C and -120°C in 20 to 30 minute steps and then held at -120°C for an hour.
- A rapid cool to -120°C where the condenser is decreased to -80°C, -100°C and -120°C in 20 to 30 minute steps and then held at -120°C for two hours.
- A slow cool to -120°C where the condenser is decreased in 5°C intervals every 30 minutes to -100°C and then decreased to -120°C and held for an hour.
- A slow cool to -120°C where the condenser is decreased in 1.25°C intervals every 5 minutes to -80°C, 5°C intervals every 5 minutes to -100°C and then decreased to -120°C and held for an hour.

After completion of each test the condenser was warmed to 20°C by shutting off the LN supply and allowing to warmup overnight. No additional heat input was provided. Measurements of the tube diameters were taken the morning after each test, prior to the start of the next test.

After nine successful freeze and thaw tests were performed, the largest change in geometry was approximately 0.18 mm (0.007 in.) in three of the 67 measurement locations. No other changes were recorded greater than 0.13 mm (0.005 in.). It was concluded that no significant deformation to the stainless steel condenser tubing occurred and that no damage had occurred to the tubing over the course of freeze/thaw testing. LHP startup testing was performed during the course of the freeze and thaw experimentation. The results of the LHP startup can be seen in Figure 13. The system was operated at 100W power input and a -70°C condenser for an hour and then the power was decreased to 0W. The condenser was then decreased to -120°C and the system was allowed to operate for two hours under these conditions. A power input of 50W was then applied to the evaporator and the condenser was increased to -60°C. The evaporator of the LHP with TCV assembly initially operates at approximately 0°C prior to the decrease to -120°C in the condenser. During -120°C condenser temperature conditions and 0W of power input, the evaporator gradually increases to approximately 15°C, due to the TCV routing vapor back to the compensation chamber. Upon the 50W power input and increase in condenser temperature to -60°C, the evaporator returns to its previous operating temperature indicating proper startup of the system from a frozen condition.

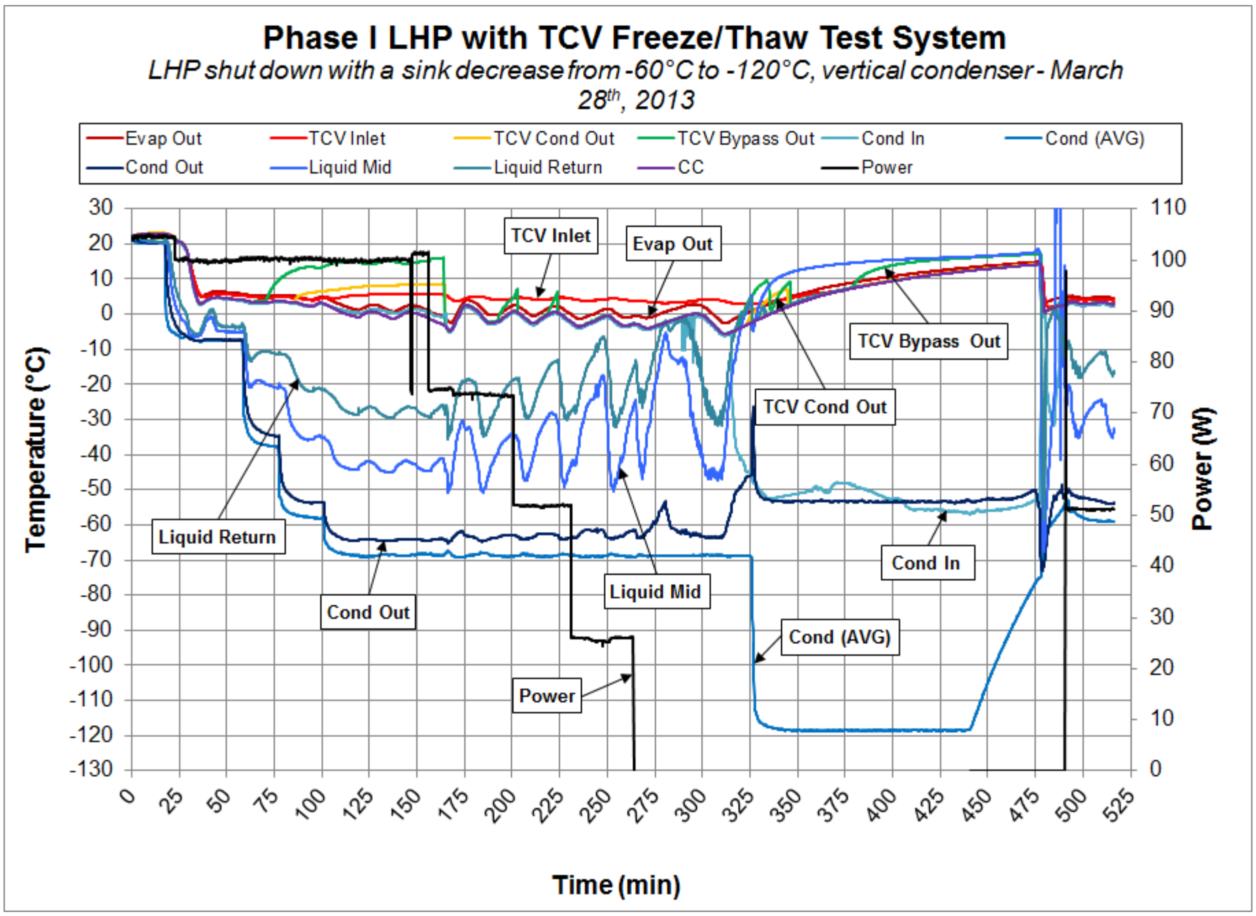

Figure 13. Ammonia LHP with TCV operation at -120°C sink during shut down with a restart of 50W.

VII. Propylene Loop Heat Pipe with Thermal Control Valve Design

Propylene is typically used in LHPs when ammonia could freeze. The LHP with TCV design can be seen in Figure 5. The system has been designed with a condenser that is capable of operating in a horizontal orientation as well as a vertical orientation. Flexible vapor and liquid lines were included in the design to allow the condenser to be rotated 90° relative to the evaporator assembly. The propylene LHP has a 6.0in (15.24cm) long evaporator with a 1.0in (2.54cm) nickel primary wick. It uses 0.25in (0.64cm) outer diameter tubing for the vapor, condenser, and bypass lines. The liquid return line uses a 0.125in (0.318cm) outer diameter tubing. The propylene LHP with TCV contains a TCV with a set point range of +10°C to +30°C.

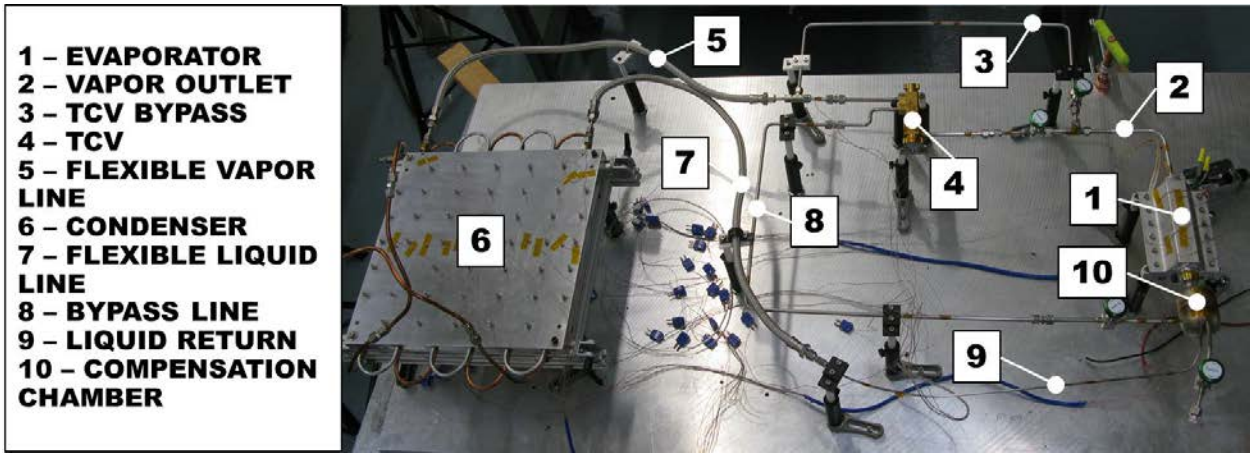

Figure 14. Propylene LHP with TCV assembly.

E. Propylene LHP Test Setup

The propylene LHP with TCV was instrumented with 30 thermocouples prior to experimental testing in the vacuum chamber. The location of these TCs can be seen in Figure 15. Intrusive TCs were installed at the TCV inlet, TCV bypass outlet and TCV condenser outlet. The remaining TCs were taped to the exterior surface at their designated location on the TC map. Heat input was provided by an aluminum heater block with embedded cartridge heaters. Cooling was provided by a condenser block with embedded serpentine copper tubing that is attached to an LN Dewar. All testing for the propylene LHP with TCV was performed in the vacuum chamber. The assembly was insulated with three wraps of aluminum foil prior to installation into the vacuum chamber.

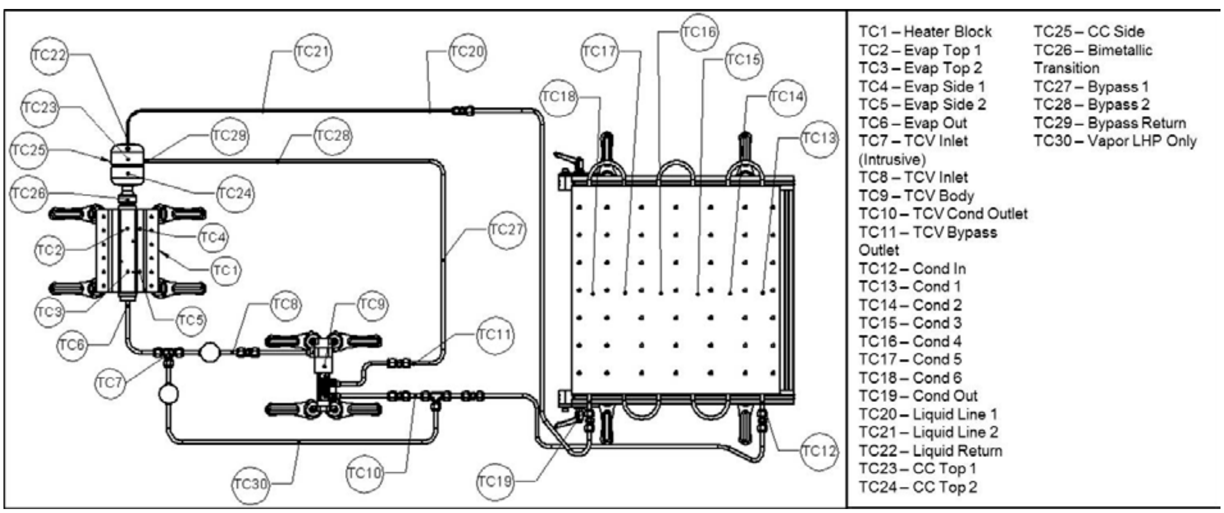

Figure 15. Propylene LHP with TCV Thermocouple map.

The test plan for the propylene LHP was similar to the plan for the ammonia LHP. The test plan for the long duration LHP shutdown is as follows:

- Set the power input to the evaporator to 200W and allow the evaporator temperature to reach a steady state with a -60°C condenser.
- Decrease the power input to the evaporator to 0W and allow the evaporator to reach a steady state condition.

The test plan for the power step-down is as follows:

- Set the power input to the evaporator to 125W and allow the evaporator temperature to reach a steady state with a -60°C condenser.
- Decrease the power input to the evaporator in the following stepwise increments: 125W, 100W, 75W, 50W, 25W, allowing the evaporator to reach a steady state condition at each increment.

VIII. Propylene Loop Heat Pipe with Thermal Control Valve Test Results

The propylene LHP with TCV was tested in a thermal vacuum chamber using procedures similar to the ammonia LHP; the results are shown in Figure 16 through Figure 17. The long duration LHP shut down test results can be seen in Figure 16. Once a steady state condition at 200W of power input was achieved, the power input to the LHP was turned off and the condenser was maintained at -60°C. A significant decrease in temperature was experienced in the evaporator and TCV assemblies after the initial shut off of power. The temperatures in the evaporator decreased to approximately -5°C, which is well below the low end set point range of +10°C of TCV #1. During this decrease in temperature, the TCV inlet temperature decreased to approximately 18°C. The steep decrease in temperature is reduced at this point as the evaporator temperatures begin to increase. At 18°C a majority of the vapor flow should be routed to the bypass outlet and back to the CC in the evaporator assembly. The sudden increase in temperature could be attributed to this increase in propylene vapor to the CC through the bypass line. The elevated temperatures in the TCV body could be attributed to the overall thermal mass of the body itself and its ability to hold the heat in for a longer period of time due to the large amount of stainless steel. The temperatures in the evaporator assembly continue to slowly increase over the duration of the LHP shut down test. The temperatures eventually reach the low end design requirement of 10°C after approximately 14 hours. The temperatures in the evaporator assembly eventually reach approximately 15°C after 17 hours of shut down.

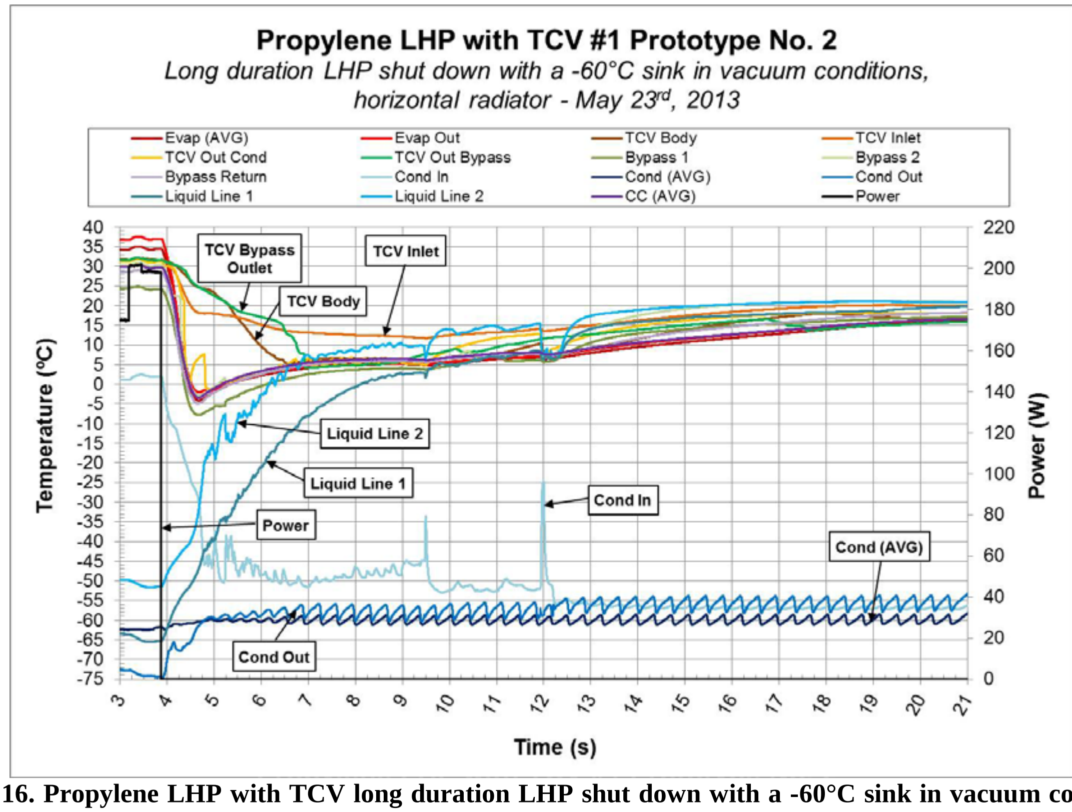

Figure 16. Propylene LHP with TCV long duration LHP shut down with a -60°C sink in vacuum conditions with a horizontal condenser.

The power decrease tests results for the propylene LHP with TCV can be seen in Figure 17. The evaporator reaches a steady state condition at approximately 35°C for the 125 W power and the 100 W power. The TCV inlet and body temperatures are operating at a steady state condition of approximately 30°C for these two power inputs. At 75W power input the system temperatures begin a cyclical oscillation occurring every approximately 20 minutes.

The power was then decreased to 50W and once again the evaporator and TCV temperatures continue to increase and reach a peak temperature and then begin a steady decrease. The evaporator and CC temperatures reach a steady state at approximately -5°C, which is significantly below the low end set point of 10°C for the TCV. The temperatures in the TCV assembly operate significantly higher than those in the evaporator and CC assemblies. This could be attributed to the TCV assembly having a large thermal mass and therefore retaining heat. The TCV condenser outlet temperature operates higher than the TCV bypass outlet during the decrease in temperature at 50W of power input. Under these conditions the TCV inlet temperature drops below the mid-range set point of the TCV of 20°C, allowing a majority of the vapor to flow towards the TCV bypass outlet and back to the CC. The power input is further decreased to 25W and the evaporator and CC temperatures experience an initial decrease in temperature, but then begin to increase and reach a steady state condition at -6°C. The TCV assembly temperatures under these conditions operate between 10 and 15°C.

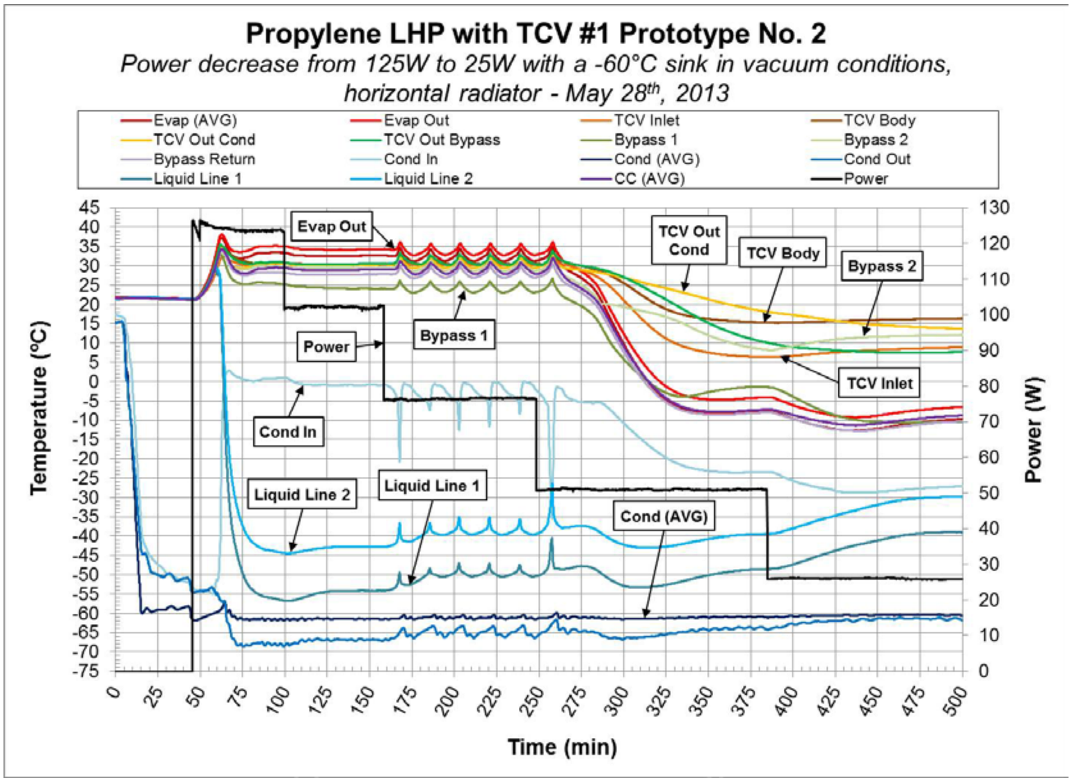

Figure 17. Propylene LHP with TCV power decrease from 125W to 25W with a -60°C sink in vacuum conditions with a horizontal condenser.

IX. Conclusion

Ammonia and propylene loop heat pipes with thermal control valves were developed to act as passive variable thermal links for Lunar and Martian landers and rovers. They are capable of rejecting heat from a WEB during hot sink conditions and maintaining the WEB in a safe operating temperature range during cold sink conditions. The thermal control valves had a set-point range from +10 to +30°C.

Ammonia was chosen because of its known performance capabilities in a LHP, however, the sink conditions on the Lunar and Martian surfaces will cause the ammonia to freeze in the LHP lines that are exposed to the cold sink conditions. Ammonia expands when it thaws and therefore the excessive stress that could be experienced in the lines during a thaw is cause for concern. An ammonia LHP with TCV was fabricated to perform freeze/thaw experimental testing to determine if expansion of ammonia during melting would be a concern. Test results showed that no significant amount of deformation of the stainless steel condenser tubing occurred through all tests performed. The LHP with TCV was also capable of startup after a freeze of the condenser was experienced.

A second ammonia LHP with TCV was designed, fabricated and tested in vacuum conditions with two condenser orientations; horizontal and vertical. The LHP has a 6.0in (15.24cm) long aluminum evaporator and a 1.0in (2.54cm) outer diameter nickel primary wick. Thermal performance testing of the ammonia LHP with TCV with a horizontal condenser demonstrated that the TCV prevented the evaporator temperature from dropping below 20°C during 24 hour operation at a 0W power input and a -60°C sink. Similar thermal performance testing of the same system with a vertical condenser demonstrated that the TCV maintained the evaporator at approximately 15°C over a 45 hour period, but the vertical orientation of the condenser caused significant fluctuations in the evaporator and TCV assemblies.

Propylene is typically used in LHPs when ammonia could freeze. A propylene LHP with TCV with a +10 to +30°C temperature range was fabricated and tested. The tests performed evaluated the overall performance of the propylene LHP with TCV during both a long duration LHP shut down and a decrease in power input. Overall, the propylene LHP with TCV performed well during all experimental testing; however, the TCV did not prevent the evaporator temperature from dropping below the required +10°C. The propylene LHP with TCV evaporator operated at a steady state temperature of 35°C for power inputs ranging from 200W to 100W with a -60°C constant sink. The TCV assembly operated at approximately 30°C for these same conditions. At 75W of power input with a constant -60°C, the temperatures in the test assembly experienced a cyclical oscillation every 20 minutes. This oscillation could be attributed to the TCV allowing some vapor flow through the bypass line back to the CC. At low power inputs of 50 and 25W, the evaporator assembly temperatures decreased to approximately -5°C, which is below the low end set point of the TCV as well as the temperature design requirements established in Task 1. During these conditions, however, the TCV assembly operates at a 10 to 15°C. During a long duration, LHP shut down the evaporator assembly temperatures reached approximately -5°C, but recovered to a steady state condition at 20°C after approximately 17 hours.

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