Variable Thermal Conductance Link for Lunar Landers and Rovers

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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. Three different variable thermal links were identified that could perform this function: 1. A mini-loop heat pipe (LHP), 2. A mini-LHP with a bypass valve, or 3. A Variable Conductance Heat Pipe (VCHP) with a hybrid wick. The paper discusses the advantages and disadvantages of each link. The 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. The mini-LHP with bypass valve and the hybrid loop VCHP require more development, but will require no electrical power for shut-down.

Nomenclature

CC = Compensation Chamber
CCHP = Constant conductance Heat Pipe
ILN = International Lunar Network
NCG = Non-Condensable Gas
LHP = Loop Heat Pipe
VCHP = Variable Conductance Heat Pipe
WEB = Warm Electronics Box

I. Introduction

NASA Marshall and the Johns Hopkins Applied Physics Lab (APL) are preparing a conceptual design for the Anchor Node Mission for the International Lunar Network (ILN). The anchor nodes are small landers that include a seismometer, a laser reflector, and a probe for measuring heat flow from the Moon's interior. To accurately locate moonquakes, several seismometers on separate anchor nodes must operate simultaneously.

The anchor node network has a Warm Electronics Box (WEB) and a battery, both of which must be maintained in a fairly narrow temperature range. A variable thermal link between the WEB and radiator is required. During the day, the thermal link must transfer heat from the WEB electronics to the radiator as efficiently as possible, to minimize the radiator size. On the other hand, the thermal link must be as ineffective as possible during the Lunar night. This will keep the electronics and battery warm with minimal power, even with the very low temperature (100 K) heat sink. At this time, heat must be shared between the electronics and battery, to keep the battery warm. There are three basic elements to the thermal control system for the WEB:

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1. A method to isothermalize the electronics and battery during the lunar night, and to remove heat to a second, variable conductance thermal link during the day.
2. A variable thermal link between the WEB and the Radiator.
3. A radiator, to reject heat.

II. Design Targets

Table 1. Design Targets for the WEB.

Minimum Electronics Temperature	-10°C (263 K)
Maximum Electronics Temperature	30°C (303 K) May increase to 50°C (323 K)
Power During Lunar Day – Stirling	52 W
Power During Lunar Night – Stirling	52 W
Power During Lunar Day – Solar	60 W
Power During Lunar Night – Solar	20 to 22 W
Power During Transit	Assume Full Power
Trip Length	5 Days, or Several Months
Duration	~ 6 years
Warm Electronics Box Geometry (Will be Larger for Solar Option)	21.5” x 13” x 15” height
Radiator Dimensions	21” (tall) x 25” (wide)
Maximum Tilt	20° (10° slope, 10° hole) Reduced from 30° (15°/15°)
Radiator Emissivity	0.7
Maximum Radiator Sink Temperature (Landing)	263 K
Minimum Radiator Temperature	141 K
Minimum Soil Temperature	-173°C (100 K)
Maximum Soil Temperature	116°C (390 K)

Figure 1 shows a schematic of the notional Anchor Node with the WEB located in the middle. Table 1 gives the preliminary design targets for the WEB. The anchor node network has a Warm Electronics Box (WEB) and a battery, both of which must be maintained in a fairly narrow temperature range. The tentative locations for the WEB and the battery are near the middle of the Anchor Node, as shown in Figure 1. The battery size depends on the power system selected. One option is the Small RPS (Radioisotope Power Source), which uses a small Stirling convertor powered by a General Purpose Heat Source (GPHS). In this case, the battery is fairly small. Another power option uses solar cells. In this case, the battery is much larger, since it needs to supply power for the 14 earth-day-long lunar night.

The WEB thermal design is heavily influenced by two things. The first is the maximum tilt of the Anchor Node. When the Anchor Node lands on the surface, the surface could be sloped. In addition, the node could land partially on a rock, or in a hole. The design tilt for the anchor node is 20°, 10° for a slope and 10° for a hole (or rock). The second is the requirement for shut-down power, especially for a solar-powered system. As a rough rule of thumb, supplying 1 W of power through the 354 hour (14.75) day Lunar night requires roughly 5 kg of mass for batteries, solar cells, etc.

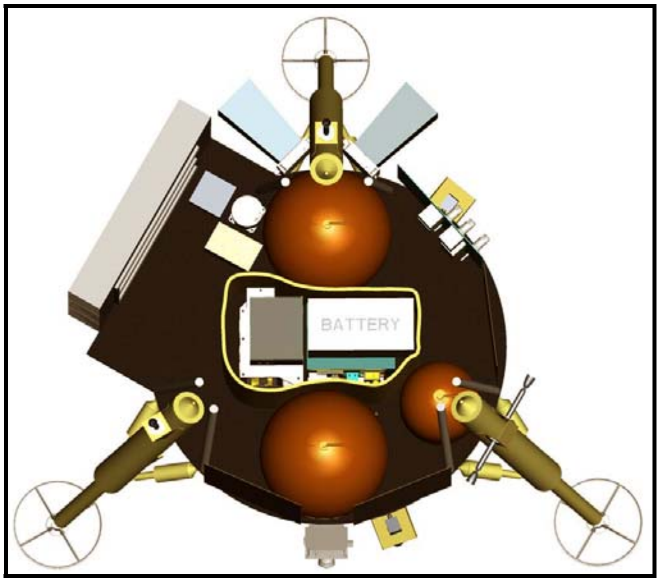

Figure 1. Anchor Node with WEB Located in Middle.

Table 2. Comparison of Potential Thermal Links (Partially based on Pauken, Birur, and Novak, 2002).

Technology Attributes	Mechanical Heat Switch	VCHP	Mini Loop Heat Pipe	Mechanically Pumped Coolant Loop
Heat Transfer Capacity Range, W	1 to 20	1 to over 100	10 to over 100	25 to over 500
Active/Passive System	Passive	Passive	Passive	Active
Configuration Flexibility	Inflexible, needs to be located close to the heat sink	Flexible	Very flexible, can easily transfer heat over large distances, over a meter	Very Flexible, can transfer heat over very long distances
Heat Collection Flexibility (at source)	Constrained to small foot print	Constrained to small foot print	Constrained to small foot print	No constraint on foot print
Heat Rejection Flexibility (at sink)	Constrained to small foot print	Constrained to small foot print	No constraint on foot print	No constraint on foot print
Typical mass, kg	0.10 to 0.12	0.3 to 0.5	0.3 to 0.5	4 to 20
Conductance, W/K On	0.4 to 0.5	20	10 to 15	5 to 10
Conductance, W/K Off	0.02 to 0.025	0.01 to 0.04	0.01 to 0.03	0.03 to 0.05
Electric Power, W	None	1-2 for tight thermal control	1 for "off condition" 5 for start up (a few min.)	3 to 10 for "on condition" (including electronics)
Heritage	Excellent (test on Mars)	Excellent for grooved wicks	Excellent for Space	Excellent for Space

III. Thermal Links

A conceptual level trade study was conducted to examine the viability/suitability of a number of potential concepts to address the variable heat transfer function required for extended lunar surface operation through both lunar day and night for the International Lunar Network (ILN) Anchor Node mission. The trade study examined four different concepts for the variable thermal link:

1. Thermal Switch
2. Variable Conductance Heat Pipe (VCHP)
3. Loop Heat Pipe (LHP)
4. LHP with a Bypass Valve

Table 2 compares the parameters of the different thermal links. Mechanically pumped loops were not considered, since they are not passive.

IV. Thermal Switches

A thermal switch is a device used to change the thermal conductance according to the thermal environment. When the WEB is hotter than desired, the thermal switch turns on, and transfers heat to the radiator. When the WEB is colder than desired (lunar night), the thermal switch turns off, and minimizes heat transfer to the radiator. Molina et al. (2008) examined a number of different thermal switches for a Mars rover, which has similar requirements as the Anchor Node targets. These switches and their principal of operation were:

- *Paraffin thermal switch*: increase in volume during phase change used to establish a mechanical and thermal joint.
- *Differential thermal expansion heat switches*: bimetallic link used to mechanically close a thermal connection. Not suitable due to limited heat transport capability, large transition temperature range.
- *Shape memory heat switch*: shape memory alloy mechanically closes a thermal connection. Not suitable due to low on conductance values, and poor heat transport capability.
- *MEMS thermal switch*: carbon nanotubes are moved to open/close thermal link. Requires controller with sensing and actuating capabilities.

Molina et al. decided that the best thermal switch was the paraffin-activated thermal switch, so this was examined during the current trade study, partially because they have already been used on Mars to regulate the temperature of the batteries. These thermal switches used a seal boot containing paraffin wax with a selected melting temperature for mechanical actuation. The design consisted of two cylinders with a paraffin wax in the middle. As the temperature increases, the wax melts and expands which draws the two cylinders together, creating a contact and allowing the thermal load to transfer from one side to the other. As the temperature decreases, the wax cools causing the two cylinders to pull away from each other and removing the path of conduction.

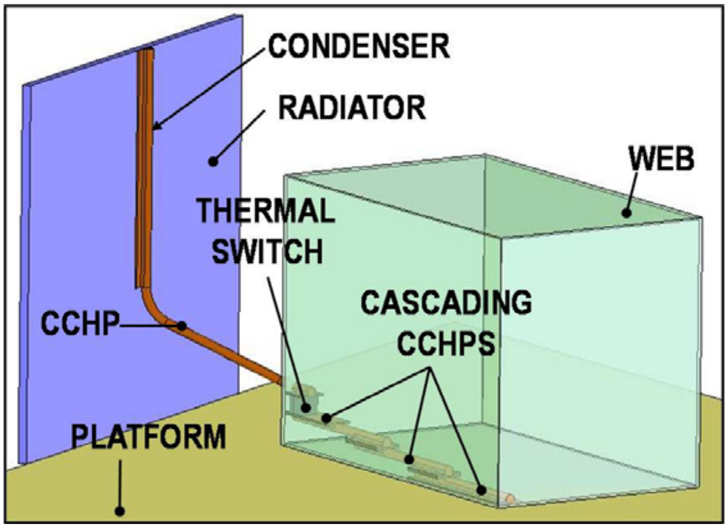

Figure 2. Thermal Switch Concept with Cascading CCHPs

A concept for a thermal switch system for the ILN network can be seen in Figure 2. This concept actually has 4 parts:

1. A series of Constant Conductance Heat Pipes (CCHPs) to isothermalize the electronics and battery during the lunar night, and to remove heat to a second, variable conductance thermal link during the day. These CCHPs are discussed in the VCHP section below.

2. A thermal switch, which is the variable thermal link between the WEB and the Radiator
3. A CCHP to carry heat from the switch to the radiator. The reasons for sloping the CCHP are discussed in the VCHP section below.
4. A radiator, to reject heat

According to data provided by JPL in regards to the Mars Rover thermal switches, the thermal conductivity of the switch can range from 0.018 W/K (closed) to 0.45 W/K (open), with a maximum capacity of about 20 W; see Table 2. Roughly 20 thermal switches would be needed to provide the same thermal conductivity as a VCHP or loop heat pipe (LHP). Due to their small size, thermal switches have a limited footprint in both heat input as well as heat rejection. The thermal switches proved to be very effective for the Mars Rover applications; however, they will not work as well for the WEB. For this reason, they were dropped from further consideration.

V. Variable Conductance Heat Pipes

The VCHP design utilizes multiple CCHPs and one VCHP that extends from the WEB to the radiator; see Figure 3. This design will use cascading CCHPs similar to those used in Figure 2. The VCHP will be bent at an angle 20° from horizontal in the adiabatic section to ensure that regardless of anchor node orientation, the condenser and adiabatic sections are always gravity aided. Unlike a conventional VCHP, the reservoir is located at the evaporator end. The reason for this is discussed below.

The VCHP will require the development of a hybrid wick system; see Figure 4. The condenser and adiabatic sections can be a standard grooved tube; however, this is not suitable for the evaporator wick. Grooved wicks typically are tested with an adverse elevation of 0.01 inch. As shown in Figure 5, it is necessary for the evaporator to work a significant height against gravity. The evaporator wick would be a screen wick, joined to the grooved wick. Another requirement for the VCHP, is a stainless steel portion of the adiabatic section to minimize the heat leak when the VCHP is shut off.

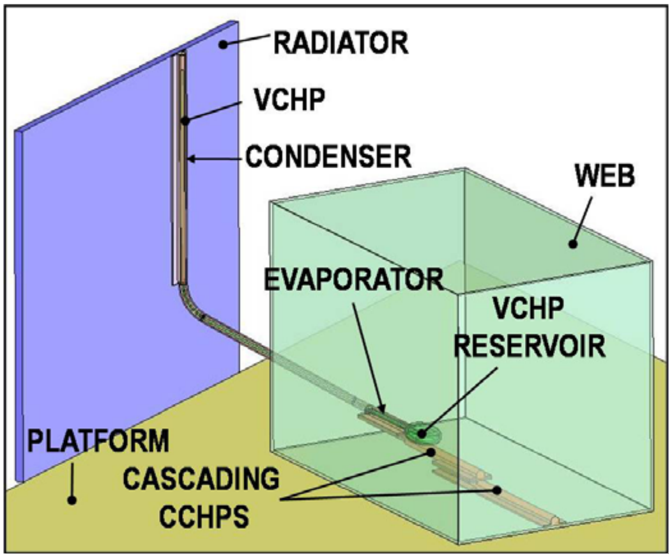

Figure 3. VCHP Concept #2 - Cascading CCHPs and VCHP with Internal Reservoir (at Evaporator End).

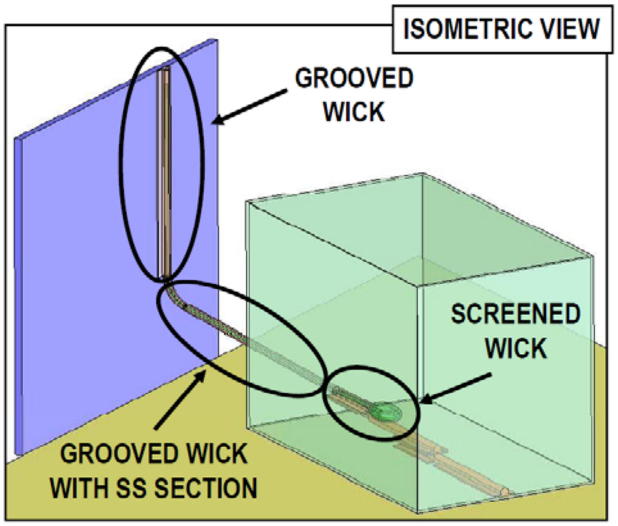

Figure 4. The VCHP requires a hybrid wick.

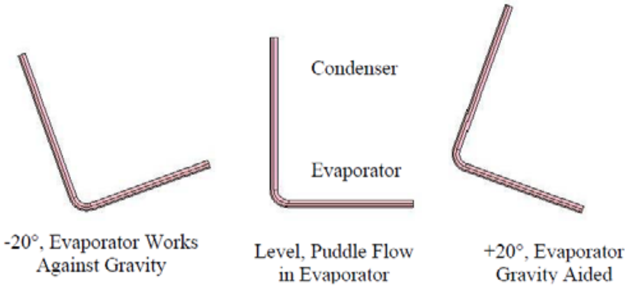

Figure 5. Unlike spacecraft heat pipes, the evaporator of the Anchor Node may be required to operate against gravity, depending on the spacecraft orientation.

A. Internal versus External VCHP Reservoir

Conventional VCHPs have the reservoir located at the end of the condenser, while the proposed design has the reservoir located next to the evaporator, in the WEB. The reason for this is to maintain the reservoir temperature near the WEB temperature, without using any electrical power. If the reservoir were external, it could be either heated or unheated. But a heated external reservoir uses too much electrical power to be feasible (recall that 1 W requires 5 kg of batteries, etc.). While an unheated reservoir is possible, the required size and mass is roughly five times that of an internal reservoir (Anderson, Ellis, and Walker, 2009).

Figure 6 is a schematic of the internal reservoir design. A small tube extends from the reservoir through the VCHP to deliver the Non-Condensable Gas (NCG) to the end of the condenser.

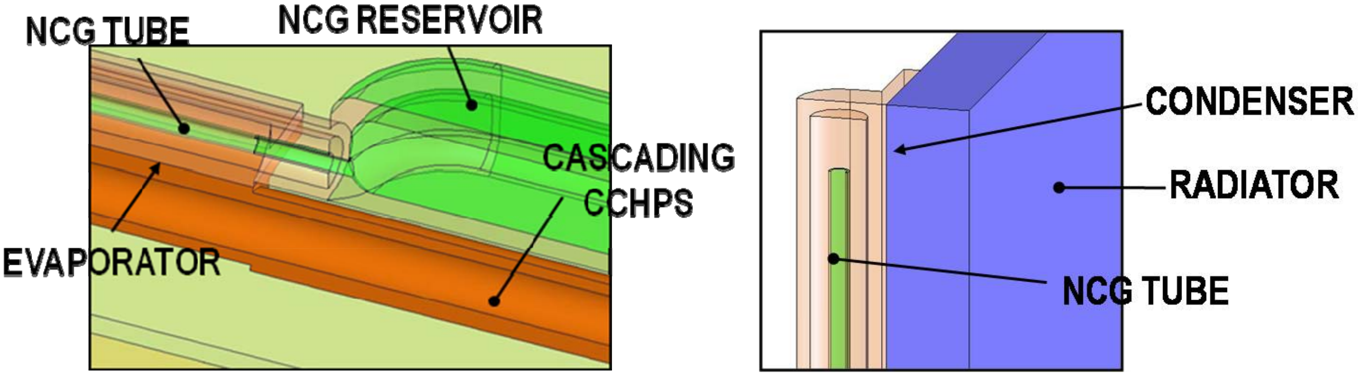

Figure 6. Design of VCHP with the Reservoir at the Evaporator.

VI. Loop Heat Pipes

The final variable thermal link that can be used is a mini-LHP. LHPs are very high thermal conductivity, self-contained, passive devices. A conventional LHP typically has a 1 inch diameter evaporator wick, 12 to 18 inches long. They can transfer up to ~ 1 kW over several meters in distance. In contrast, a mini-LHP has a 0.5 inch (or small) diameter evaporator wick, about 5 inches long. Mini-LHPs transfer 10 to 100 Watts over roughly 1 m.

A. NASA JPL Mini-LHP

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 1.27 cm (0.5 in.) diameter sintered nickel wick that was 15/2 cm (6 in.) 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 the following results:

- 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
- Simulated 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.

B. ILN Mini-LHP Concept

The ILN LHP concept uses a similar cascading CCHP design described in previous VCHP designs and a single LHP. This concept can be seen in Figure 7. The cascading CCHPs will carry the thermal load along the length of the WEB and transfer it to the LHP evaporator. The LHP will then carry the thermal load from the evaporator section to the radiator through the use of a long, thin vapor-liquid line. One of the benefits of the LHP design is that the condenser can cover the entire radiator, while a VCHP has a limited condenser area. LHPs are capable of carrying thermal loads across very long lengths, which allow the thermal load from the WEB to be spread across the entire face of the radiator preventing any hot spots from occurring.

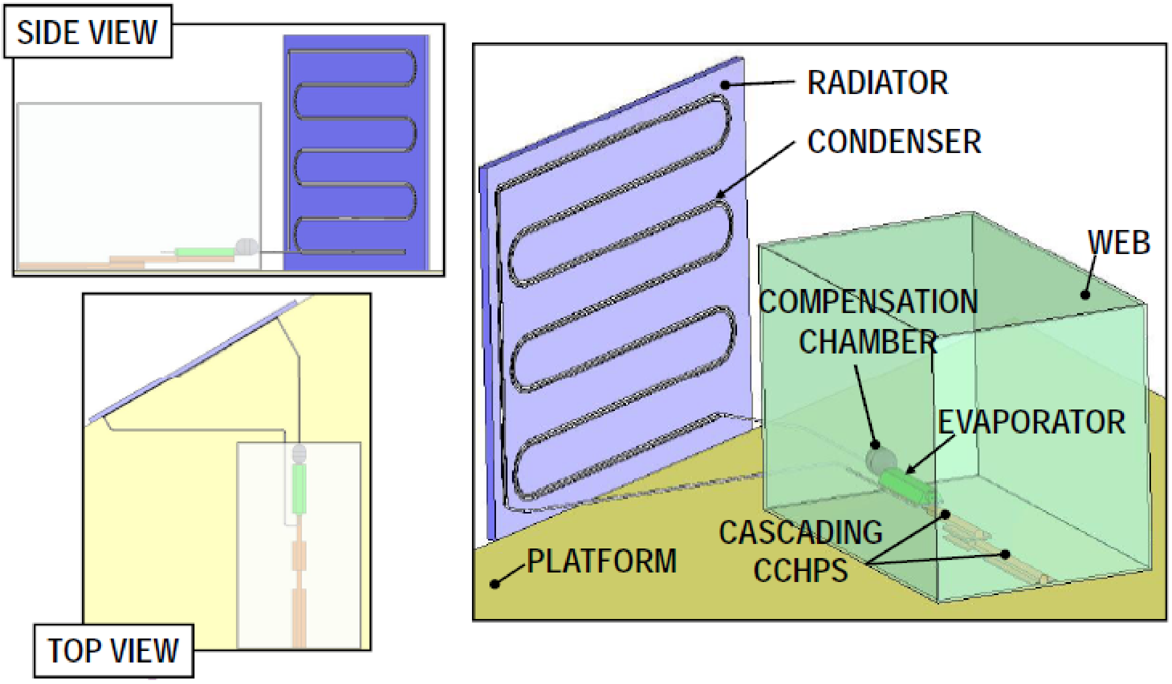

Figure 7. Loop Heat Pipe Concept Using a Single LHP and Cascading CCHPs.

C. LHP with Bypass Valve

Molina et al., 2008 have developed an LHP thermal switch 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. Unlike a conventional mini-LHP, the ESA LHP thermal switch uses a bypass valve to provide the variable thermal link; see Figure 8. Vapor from the evaporator goes to a passive, two-way valve. The valve contains a sealed bellows filled with argon. As the pressure and 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 (CC). At a low enough temperature, the valve opens enough to equalize the evaporator and CC pressures, turning the system off. The control temperature can be adjusted (before flight) by adjusting the argon pressure in the bellows. This device requires no control power to shut it off, however, this is done at the expense of moving parts.

The overall thermal conductance of the ESA device was 5 W/K. This is pessimistic, since it is based on the temperature difference from the LHP evaporator to the average radiator temperature, not a temperature associated with the LHP, as is usually done. The off conductance is 0.010 W/K. The system required 3.5 watts to start-up. A separate heater was not used, but the start-up was closely monitored. The basic LHP has a mass of 380 grams.

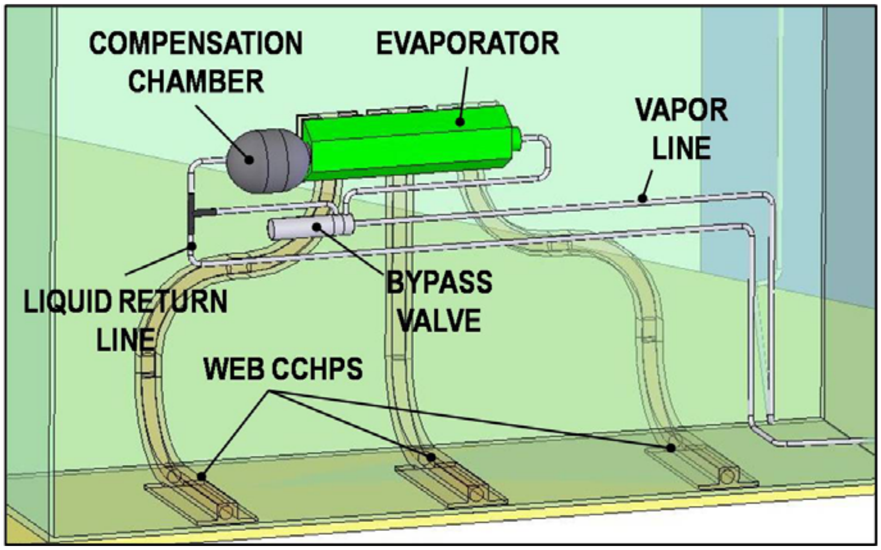

Figure 8. ILN LHP Thermal Switch Concept with Bypass Valve

D. LHP Conductances

The mini-LHP "on" thermal conductance is on the order of 15 W/K, based on the JPL mini-LHP tests. The ESA LHP reported lower thermal conductances, on the order of 5 W/K. However, this value is overly pessimistic, since it uses the temperature difference between the loop heat pipe evaporator and the average radiator temperature. Birur, Pauken, and Novak (2002) state that the average "off" thermal conductance for the mini-LHP is 0.01 to 0.03 W/K. The ESA thermal switch (Molina et al., 2008) had a measured "off" thermal conductance of 0.010 W/K.

E. LHP Power

There are two times when power may need to be supplied to an LHP:

1. Keep the LHP off during the lunar night
2. Start-up

A conventional LHP (or mini-LHP) heats the compensation chamber above the evaporator temperature to shut the LHP off. The fluid in an LHP flows from the evaporator through the condenser, and ends up in the vapor line. For this flow to occur, the Compensation Chamber must be at a lower pressure (and temperature, since the system is in a saturated state) than the evaporator. Heating the Compensation Chamber to a temperature above the evaporator stops the fluid in the LHP from circulating. This is a standard method that has been validated on aircraft. See Dussinger et al. (2009) for an example of an LHP shut-down test. The power to shut off the mini-LHP was roughly 1 W in the JPL tests. The ESA LHP thermal switch would not require this power, since it is passively activated by the fluid temperature.

The second time when power may need to be supplied to the LHP is during start-up. Problems can occur when the grooves in the LHP are completely filled with liquid. This is most likely to occur when the Compensation Chamber was previously heated to shutdown the LHP, driving fluid out of the CC into the evaporator wick. Without vapor in the grooves, heat can be conducted into the wick interior (CC), raising the entire LHP temperature, rather than forming vapor. The problem has been solved with a start-up heater. These heaters use electrical power to apply a high heat flux to a portion of the wick. This allows a vapor bubble to form and clear the evaporator grooves. This is now a standard method for starting spacecraft LHPs. The start-up power was about 5 W for the JPL mini-LHP (smaller powers were not tested). Ku et al (2006) reported a similar value. They used a thermoelectric device that pulled heat from the Compensation Chamber. This aided in start-up, because it simultaneously cooled the Compensation Chamber.

VII. Comparison of LHP and VCHP Variable Links

The variable thermal link could be:

1. LHP
2. LHP with bypass valve
3. VCHP with internal reservoir

Table 3 compares LHP and VCHP variable thermal links. Either the LHP or the VCHP could be used as the variable thermal link. Both have similar “on” and “off” thermal conductances, both have flown in space, and both have similar masses.

Table 3. Comparison of LHP and VCHP Variable Thermal Links.

	LHP	VCHP
Working Fluid	Propylene	Ammonia
Mass[1]	0.3 kg	0.45 kg
Shutdown Power	0 to 2 W	0 W
Start-Up Heater	5 W	0 W
Conductance - On	~ 15 W/K	~20 W/K
Conductance - Off	0.01 W/K	0.04 W/K (all Al) 0.008 (5 in. SS)
TRL Level - Conventional	9	9
Radiator Coverage by Condenser	Full	Partial, unless Raised
May require Radiator CCHPs	No	Yes

[1] VCHP requires more massive radiator. [2] 38 cm (15 in.) evap., 38 cm (15 in.) condenser

A mini-LHP has the highest TRL level. However, as already mentioned, supplying 1 W of power through the 14-day Lunar night requires roughly 5 kg of mass. A mini-LHP with a bypass valve requires more development and validation, but eliminates the electrical shut-down power. A VCHP with a hybrid wick requires the most development. The benefit is that it would be much less expensive to fabricate than a loop heat pipe.

VIII. Conclusion

Either the mini-LHP, the mini-LHP with bypass valve or the VCHP could be used as the variable thermal link. All have similar “on” and “off” thermal conductances, both have flown in space, and both have similar masses. The mini-LHP has the highest TRL level, since JPL performed all of the testing that would be conducted before a test in space. The primary disadvantage is the need for electrical power to shut-down the LHP during the 14-day Lunar night.

There has been significant development in Europe on the LHP with by-pass valve, but no work that we are aware of in the United States. The current design has had some problems with thermal oscillations. ACT is currently fabricating a mini-LHP valve with a different valve that may help prevent the oscillations.

Finally, an internal reservoir VCHP with a hybrid wick could also act as a variable thermal link. The VCHP would not require any electrical power for shut-down, and would be simpler in operation and less expensive than the loop heat pipes.

Acronyms

CC, Compensation Chamber
CCHP, Constant conductance Heat Pipe
ILN, International Lunar Network
NCG, Non-Condensable Gas
LHP, Loop Heat Pipe
VCHP, Variable Conductance Heat Pipe
WEB, Warm Electronics Box

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