Variable Conductance Heat Pipes for Variable Thermal Links

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Variable Conductance Heat Pipes (VCHPs) for spacecraft thermal control typically have a cold-biased reservoir for the Non-Condensable Gas (NCG) at the end of the condenser. During operation, electrical heat is supplied to the reservoir to provide ±1-2°C temperature control over widely varying powers and sink temperatures. A second application for VCHPs is as a variable thermal link. Applications that can benefit from using VCHPs as variable thermal links include Lunar and Martian Landers and Rovers, Research Balloons, and Lunar and Space Fission Reactors. The applications that can benefit from variable thermal links normally have: 1. Variable system loads resulting from intermittent use, 2. Large variations in the sink temperature, and 3. Limited electrical power. Since the lowest sink temperature can be below the freezing point of the working fluid, many applications with variable thermal links also need to consider freeze/thaw and start-up from a frozen state. Fortunately, the NCG in the heat pipe also helps when the pipe is frozen, and during start-up. An aluminum/ammonia VCHP was developed to act as a variable thermal link for lunar landers and rovers, passively minimizing heat losses during the lunar night, without requiring electric power to shut off. The reservoir was located near the evaporator, rather than near the condenser, to prevent the reservoir temperature from dropping during the lunar night, without requiring electrical heaters. Variable thermal links were also developed for high altitude, research balloons. Two VCHP configurations (hot and cold reservoir) were designed, fabricated and successfully tested, with methanol, toluene, and pentane as the working fluids. Both configurations provide a variable thermal link without electrical power. The warm reservoir VCHP has a 4.8ºC temperature control band, while the cold reservoir control band is larger, at 21ºC

I. Introduction

A typical Variable Conductance Heat Pipe (VCHP), shown in Figure 1, has an evaporator, a single condenser, and an electrically heated reservoir at the end of the condenser. This system is commonly used in spacecraft thermal control to provide ±1-2°C temperature control over widely varying powers and sink temperatures. While the standard VCHP is used for tight temperature control, this paper will discuss VCHP and gas-loaded heat pipe applications where a variable thermal link is desired instead. A gas–loaded heat pipe is similar to a VCHP, but "reservoir" is an extension of the condenser.

The objective of a variable thermal link is to maintain the evaporator temperature range in a fairly broad temperatures range, when subjected to changes in power, and very large variations in sink temperature. The variable thermal link should transmit heat readily during hot sink conditions, but minimize heat transmission during cold sink conditions. Applications that can benefit from using VCHPs as variable thermal links include:

- Lunar and Martian Landers and Rovers
- Research Balloons

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- Lunar and Space Fission Reactors

The above applications can allow relatively wide temperature swings, but need to minimize or eliminate electrical heater power.

Figure 1. A typical VCHP with an evaporator, a single condenser, and an electrically heated reservoir at the end of the condenser.

Applications that require variable thermal links generally have the following factors:

- Variable system loads resulting from intermittent use
  - Desire to power down systems between missions
  - Results in large turn down ratios, on the order of 10:1 or higher
- Large changes in environment temperature
  - Lunar surface temperature range: -140 °C to 120 °C
  - Mars equatorial, near-surface temperature range: -100 °C to 0 °C
  - Research balloons: air temperatures ranging from -90 °C to +40 °C
- Limited electrical power
  - Lunar applications must survive the 14-day-long Lunar night
  - 1 W = 5 kg of energy storage (batteries) and generation
  - Research balloons have similar constraints, since they often fly near the North and South Poles in the winter

Since the lowest sink temperature can be below the freezing point of the working fluid, many applications with variable thermal links also need to consider freeze/thaw and start-up from a frozen state. Fortunately, the Non-Condensable Gas (NCG) in the heat pipe also helps when the pipe is frozen, and during start-up. First, the NCG in the heat pipe suppresses fluid movement when a portion of, or the entire pipe is frozen. With a warm evaporator, the NCG prevents vapor from freezing in the condenser, starving the evaporator of working fluid. For water heat pipes and thermosyphons, the NCG minimizes sublimation of the water from the evaporator to the condenser when the entire pipe is frozen

Second, the NCG also aids start-up from the frozen state by providing a back pressure in the heat pipe condenser during start-up. This gives a short effective condenser length during startup, and is a commonly used method for rapidly starting up alkali metal heat pipes.

II. VCHP Design for Lunar Landers and Rovers

The lunar environment presents a number of challenges to the design and operation of thermal management systems. The heat rejection sink can be 60°C (330 K) during daytime and can drop down to -220°C (50 K) at night or in dark craters (Swanson and Butler, 2006). 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.

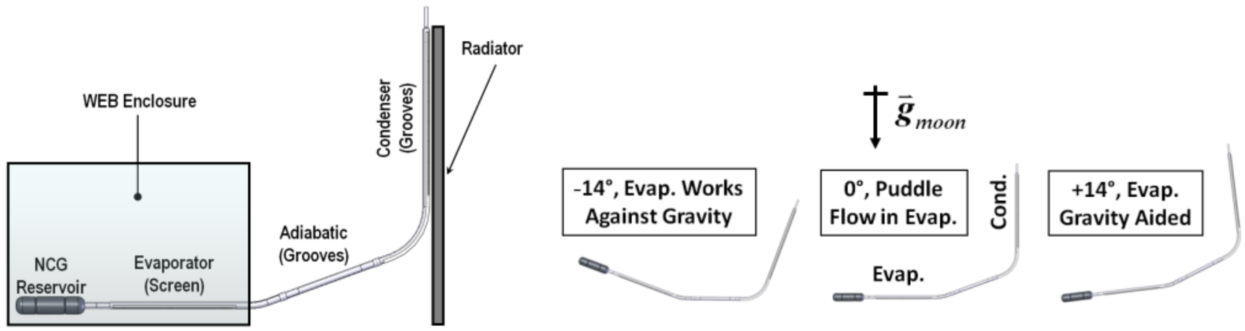
Due to the wide temperature swings, future lunar landers and rovers will require a variable conductance thermal link that can reject heat during the day and passively shut off during the lunar night without requiring any electrical power. During the long lunar day, the thermal management system must remove waste heat from the electronics and batteries to prevent overheating. During the long lunar night, the variable thermal link must passively limit the amount of heat removed from the electronics and radiated to space since little to no power is available for temperature regulation. For solar powered systems, the variable link design is complicated by the heavy mass penalties associated with providing continuous power throughout the 14-day-long lunar night: It is estimated that 5 kg of batteries, solar cells, etc., are required to supply 1 W of electricity. Therefore, designs that operate without electrical power are highly desirable. The Lunar Anchor Node design targets are shown in Table 1.

The International Lunar Network (ILN) Anchor Node VCHP design is shown in Figure 2.   The VCHP evaporator is nominally horizontal, and the condenser is nominally vertical during operation on the Lunar Surface. An important design target consideration for Lunar Landers and Rovers is that the VCHP must work both in space and in a gravity-aided mode on the lunar surface. For the Lunar Anchor Node, the VCHP needs to operate against a maximum slope. For the Anchor Node, it is ±14° (due both to the general tilt of the terrain, as well as any local rock or depression). The maximum slope for rovers can be as high as ±45°. The basic VCHP layout is shown in Figure 2 (a). The VCHP evaporator sits on the Warm Electronics Box (WEB) enclosure base plate. The adiabatic section is tilted so that it is always gravity aided on the moon.

Table 1. Anchor Node Design Targets.

Minimum Electronics Temperature	-10°C (263 K)
Maximum Electronics Temperature	50 °C (323 K)
Maximum Radiator Load (Moon)	73 W at lunar noon (30 % margin: 94.9 W)
Power During Transit (Space)	90 W during cruise (30 % margin: 117 W)
Mission Length	~ 6 years
Warm Electronics Box Geometry	24” x 41” x 14” (height)
Distance from WEB to Radiator	14” to side mounted vertical radiator
Minimum Radiator Sink Temperature (Moon)	-177°C (96 K)
Maximum Radiator Sink Temperature (Moon)	-4°C (269 K)
Maximum Tilt	±14° (8° slope, 6° obstruction)

Due to the ±14° slope, the conventional spacecraft all-grooved wick is not suitable in the evaporator section. Typically, grooved heat pipes are tested on earth with an adverse tilt (evaporator above condenser) of 0.1 inch (2.54 mm). As shown in Figure 2 (b), the lander evaporator can have an adverse tilt of several cm. To accommodate this high adverse elevation, a hybrid wick was developed. All of the condenser and most of the adiabatic section employ axial grooves for liquid return. A small portion of the adiabatic section and all of the evaporator use wrapped screen mesh as the wicking structure. The screen mesh wick, which has higher capillary pumping pressure than grooves, enables the evaporator to operate against the tilt caused by the uneven lunar surface.



(a) (b)

Figure 2. a. Schematic of the VCHP layout from the WEB to the radiator. b. Depending on the terrain, the evaporator can have a ±14° tilt relative to horizontal. In some cases, the evaporator wick must work against gravity on the lunar surface, which is not possible with a conventional grooved wick.

A schematic of the VCHP is shown in Figure 3. The VCHP incorporates three novel features in order to achieve the design targets of the ILN program:

1. Hybrid-Wick, discussed above.
2. Reservoir near Evaporator, to prevent the reservoir temperature from dropping during the lunar night.
3. Bimetallic Adiabatic Section, to minimize heat losses via conduction during the lunar night.

A stainless steel heat pipe section of 12.7 cm (5 inches), which replaces the original aluminum portion in the adiabatic section, acts as a thermal dam, and minimizes axial heat leak to the cold radiator during shutdown.

The heat pipe uses anhydrous ammonia as the working fluid, since it is the best working fluid when the heat pipe is operational, since it has the highest Merit number. The Non-Condensable Gas (NCG) has two purposes: 1. Provides a variable thermal link that turns off the condenser as the evaporator temperature drops, and 2. Suppresses the freezing of ammonia in the condenser during the lunar night. The freezing point of ammonia is -78°C (195 K), while the radiator could conceivably cool down to -177°C (96 K). In a CCHP, ammonia would tend to freeze in the condenser. However, in a VCHP, the gas in the adiabatic and condenser sections blocks the flow of ammonia from the evaporator to the condenser. Ammonia can only slowly diffuse through the gas. The gas also aids in starting up the heat pipe after sunrise (Ellis and Anderson, 2009).

VCHPs typically use argon as the NCG. Due to the low temperatures, neon was selected for this VCHP instead. The reason is that the critical temperature of Argon is -122°C (151 K), so the argon would not be a perfect gas during the lunar night, and could actually condense. Neon, with a critical temperature of -229°C (44 K), will behave like a perfect gas.

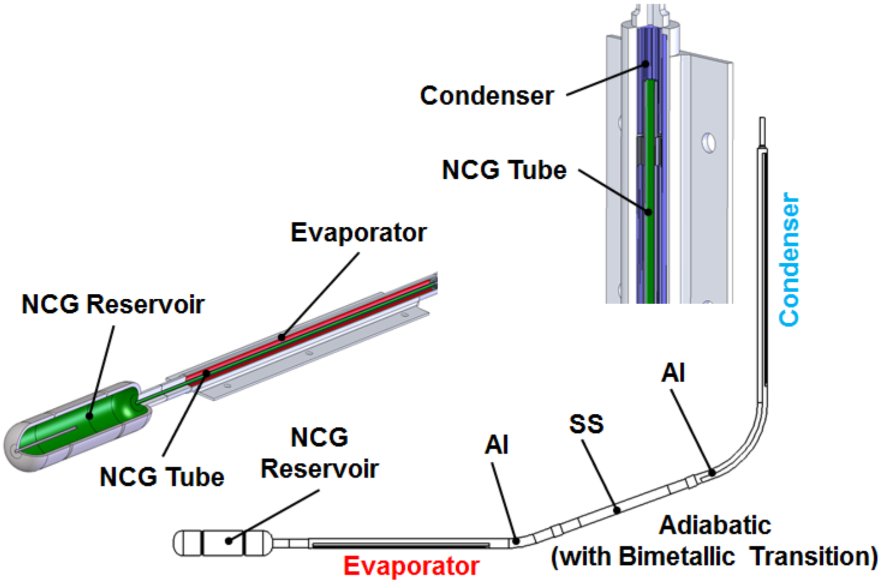


Figure 3. Schematic of the VCHP with a hybrid wick, to allow operation at different tilts. Placing the reservoir near the evaporator keeps the reservoir warm, minimizing the required reservoir size. Also, part of the adiabatic section is stainless steel, which minimizes heat leaks when the VCHP is turned off.

A. Reservoir Location

Placing the NCG reservoir near the evaporator, as opposed to the traditional location near the condenser, keeps the gas reservoir warm and minimizes the reservoir size. A conventional VCHP, shown in Figure 1, has the reservoir located next to the condenser. The VCHP reservoir temperature is controlled by tying it thermally to another portion of the spacecraft to cold bias the VCHP, then adding heaters on the reservoir to control power.

In contrast, no electrical heating is available to control the VCHP temperature in a lunar lander or rover. If the VCHP reservoir was located at the top of the condenser in Figure 2 (a), then the VCHP reservoir would operate near the sink temperature of -177°C (96 K) during the lunar night. Anderson, Ellis, and Walker (2009) developed the equations to size this type of radiator, and showed that with a wide variation in sink temperature, there is a minimum ΔT_{VCHP}, even with an infinite reservoir.

Placing the NCG reservoir near the condenser would necessitate a very large reservoir that can only provide coarse temperature control ($\Delta T_{VCHP} \geq 30$ °C). ΔT_{VCHP} is defined as the difference between the operating and shutdown temperatures of the evaporator ($\Delta T_{VCHP} = T_{On} - T_{Off}$). A very precisely controlled VCHP would have a small, but finite ΔT_{VCHP}. Such temperature control is only possible with a reservoir near the evaporator. Figure 4 illustrates these principles.

In Figure 4, items colored red correspond to a warm reservoir placed near the evaporator and items colored in blue correspond to a cold reservoir located near the condenser. The two dashed vertical lines represent the asymptotes for either the warm or cold reservoir. In both reservoir types, the mass of the system trends exponentially towards infinity as the degree of control increases and ΔT_{VCHP} decreases. Observe that an infinitely large cold reservoir provides $\Delta T_{VCHP} \approx 30$ °C and an infinitely large warm reservoir provides $\Delta T_{VCHP} = 0$ °C. For this reason, the reservoir is located in the WEB, next to the evaporator, where it can be kept warm by the heat pipes used to transfer heat in the WEB. A small NCG tube passes through the entire length of the heat pipe to pneumatically connect the NCG reservoir to the condenser (see Figure 3). This NCG tube allows the NCG reservoir to be located near the evaporator rather than the condenser. While this heat pipe design has been theoretically discussed as far back as Marcus (1971), to the best of our knowledge this is the first time that this type of VCHP has been fabricated.

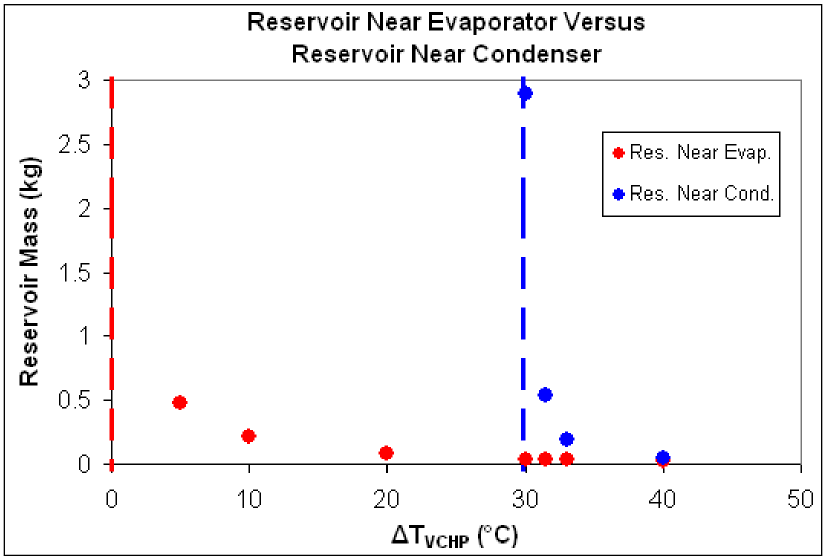


Figure 4. Comparison between NCG Reservoir Locations.

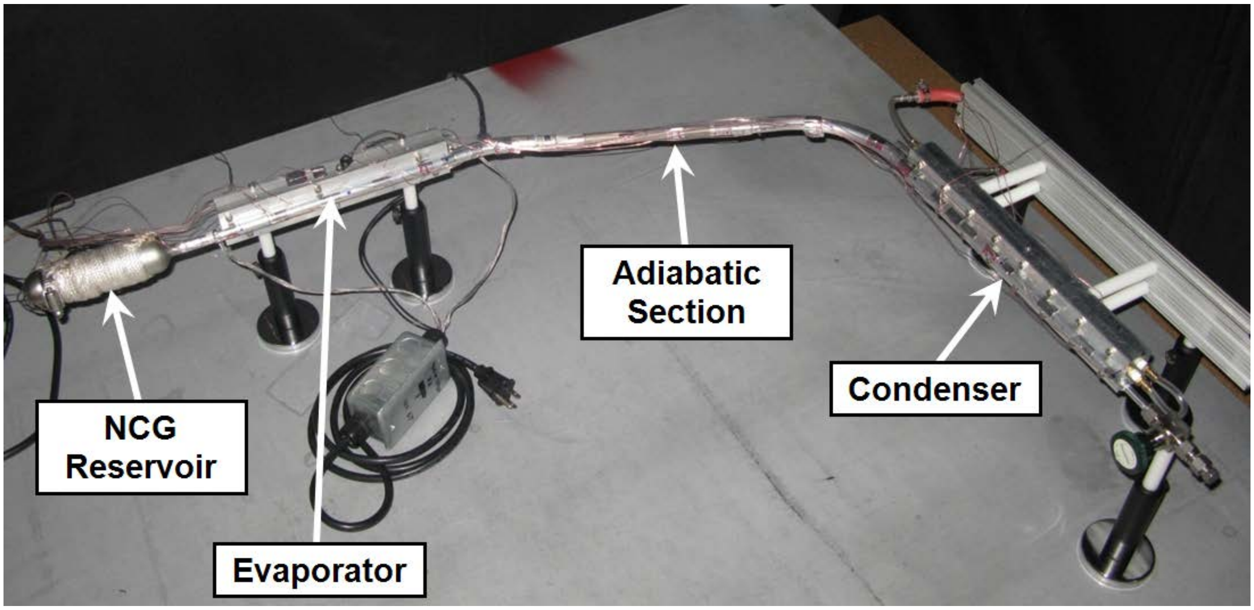


Figure 5. Hybrid wick VCHP with reservoir adjacent to the evaporator.

B. VCHP Fabrication and Test Setup

The VCHP had the following specifications:

- 30.5 cm (12 inch) Condenser / ≈ 48.3 cm (19 inch) Adiabatic Section – Grooved aluminum extrusion (6063-T6 Al)
    - Bimetallic Transition – 1.25 inch 6061-T6 Al × 5 inch 304 SS × 1.25 inch 6061-T6 Al
- 22.9 cm (9 inch) Evaporator – Nickel 200 50×50 screen mesh
- NCG Tube (304 SS) – 0.32 cm (0.125 inch) outer diameter
- NCG Reservoir (304 SS) – 73.7 cm^3 (4.5 $inch^3$) internal volume
- Working Fluid (Ammonia) – 20.8 grams
- Non-Condensable Gas (Neon) – ≈0.65 grams

The completed hybrid wick VCHP is shown in Figure 5, while the thermocouple locations are shown in Figure 6. Heat was supplied to the evaporator with electric cartridge heaters embedded in an aluminum block. Heat was removed from the condenser with a cold plate, cooled with liquid nitrogen to a fixed temperature.

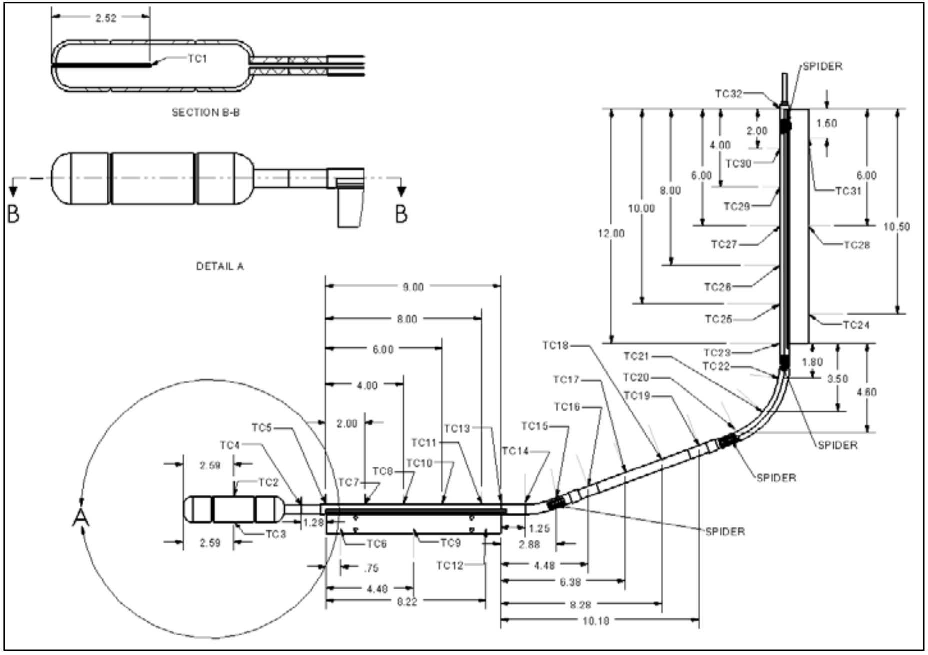


Figure 6. VCHP Thermocouple Placement.

III. Aluminum/Ammonia VCHP Testing

C.Test Objectives

The first major test objective was a simulated Lunar Freeze/Thaw test: Demonstrate the ability of the VCHP to act as a variable thermal link on the moon, and minimize the heat transfer as the condenser temperature dropped below the freezing point of ammonia. In addition, verify that the VCHP can operate for short periods with a cold condenser (which can occur in some lander and rover scenarios).

The second major test objective was to demonstrate that the VCHP will act as a diode in space, preventing heat from solar insolation from heating the WEB.

Table 2. Testing Procedure for Lunar Freeze/Thaw.

Inclination (°)	Evaporator Minimum Temperature (°C)	Condenser Temperature (°C)
-2.3	-10	-60
-2.3	-10	-177

D.Lunar Freeze/Thaw Results

For the simulated lunar tests, the VCHP was mounted in a test fixture on an optical table that set the condenser vertical and allowed the evaporator to be configured for gravity aided (+2.3°), gravity neutral (0°) and gravity adverse (-2.3°) inclinations (2.3° on earth is equivalent to a 14° inclination on the moon). Test conditions for the lunar freeze/thaw tests with the gravity adverse inclination are shown in Table 2.

Figure 7 plots VCHP temperatures as a function of time during the lunar freeze/thaw test. TC1 corresponds to the gas temperature in the NCG reservoir. TC10 measures the vapor temperature of the evaporator. TC23, TC26, TC27 and TC30 detect the vapor temperature of four locations within condenser, with TC23 at the entrance of the condenser and TC30 close to the tip of the condenser. The power curve shows the electrical power put into the heater block of the evaporator. For more information on the locations of these TCs, consult Figure 6.

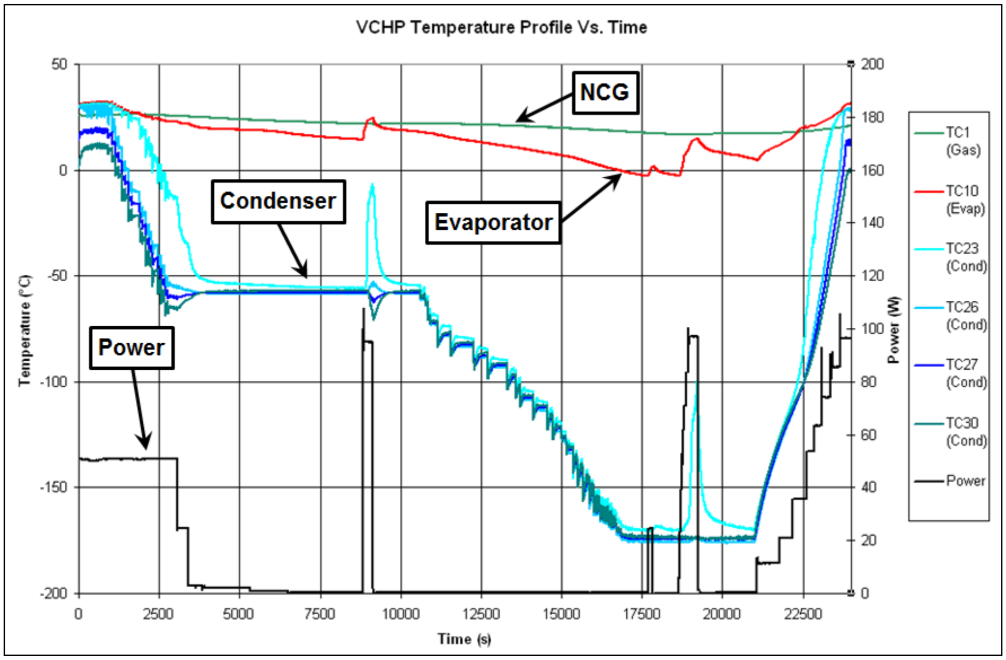


Figure 7. VCHP Temperature Profile as a Function of Time (-2.3° Orientation).

Initially, the pipe is operating at a nominal 25 °C and 50 W. At about 6000 seconds the pipe temperature and power input are reduced to -60 °C and 0.2 W, respectively. The purpose of 0.2 W of heat input was to maintain the evaporator above -10 °C. At around 9000 seconds, power is temporarily increased to the full 95 W, to simulate a brief period of activity during the lunar night. After this power increase, the pipe was returned to the -60 °C shutdown state. Next, the sink temperature is further reduced to -177 °C (96 K, ammonia freezes at 195 K). The pipe reaches a steady-state shutdown at -177 °C and 0.1 W. At approximately 17,500 seconds, the power is briefly increased to 25 W and the transient response of the frozen pipe was observed. With no indication of problems, the pipe is returned to -177 °C shutdown. Power is then increased to a full 95 W for a short duration. After the full power increase, the pipe is returned to a state of shutoff until around 21000 seconds when the power is gradually increased and heat pipe startup begins. Finally, the VCHP is brought to nominal steady-state operation at 95 W and 25 °C. Overall conductances for the heat pipe heat pipe during normal operation, and with -60 and -177°C sinks, given in Table 3, show that the heat pipe operates as a variable thermal link.

Table 3. VCHP Overall Conductances for Lunar Freeze/Thaw.

Testing Condition	Overall Conductance (W/°C)	Power (W)
25 °C Operation	4.7	95
-60 °C Shutdown	0.0031	0.2
-177 °C Shutdown	0.00057	0.1

E. Space Thermal Diode Results

During transit, at some times the radiator will be hotter than the WEB due to solar insolation. During these times, it is desirable for the VCHP to act as a diode, preventing overheating of the WEB. A conventional VCHP would behave like a gas-loaded diode in this situation. Tests were conducted to verify that a VCHP with the reservoir near the evaporator would also act as a diode. During these tests, the ILN VCHP was kept in a horizontal orientation; however, the adverse elevation and heat input/output were reversed compared to the space thermal performance test. The goal of this test was to verify that the pipe inhibited heat transfer in the reverse direction; therefore, the test intentionally attempted to operate the heat pipe backwards. Heat was input into the condenser and rejected from the evaporator. Since the capillary flow would travel from the evaporator to the condenser, the adverse elevation was defined as the condenser being 0.1, 0.2, and 0.3 inch (2.54mm, 5.08mm and 7.62mm) above the evaporator.

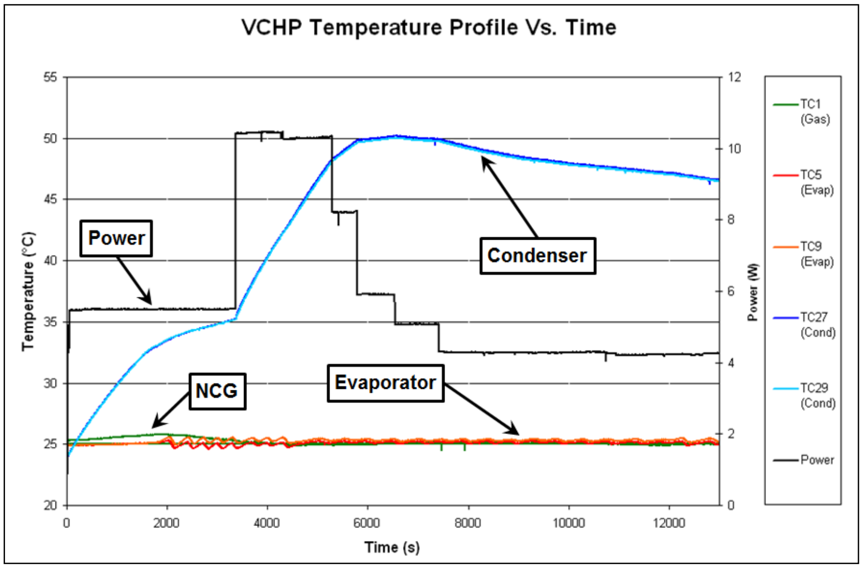


Figure 8. VCHP Temperature Profile as a Function of Time (Evaporator at 25 °C, 0.1 Inch).

Figure 8 illustrates the temperatures within the pipe as a function of time for the 0.1 inch adverse elevation trial. The plot shows that the input power was adjusted until a steady-state temperature difference of 20 °C was observed between the evaporator and condenser. Once this temperature difference was achieved, the input power was recorded as the reverse heat transfer rate. For this particular test, the reverse heat transfer rate was 4.3 W.

Table 4 lists the results of the thermal diode experiment. All of the reverse powers are low (less than 4 % of the 117 W target for space) and the conductances are minimal (two orders of magnitude less than the values of the space thermal performance test). The conductances are negative because the condenser is hotter than the evaporator, which is the opposite of normal operation.

Table 4. VCHP Results for Space Thermal Diode (Evaporator at 25 °C; Condenser at 45 °C).

Adverse Elevation (in)	Reverse Heat Transfer Rate (W)	Overall Conductance (W/°C)
0.1	4.3	-0.205
0.2	3.2	-0.165
0.2	3.2	-0.168
9 Inch Evaporator; 12 Inch Condenser		

IV. Variable Thermal Link Design for Research Balloons

Terrestrial high-altitude research balloons can also use VCHPs for a variable thermal link. As with the Lunar example above, the balloons have large swings in sink temperature, electronics with the ability to withstand fairly large temperature changes, and require minimal electrical power to operate. Balloons can reach altitudes above 36 kilometers, with suspended masses up to 3600 kilograms, and can stay afloat for several weeks. The payloads of terrestrial high altitude balloons need a thermal management system to reject their waste heat and to maintain a stable temperature as the air (sink) temperature swings from as cold as -90°C to as hot as +40°C. Currently, constant conductance, copper-methanol heat pipes are utilized on balloon payloads to effectively move the waste heat over significant distances. The problem with these devices is that the conductance cannot effectively be reduced under cold operating or cold survival environment conditions without expending significant energy in an active heater to maintain the condenser section warm.

Spacecraft VCHPs are axially-grooved aluminum-ammonia heat pipes, and require relatively thick, heavy walls to withstand the relatively high ammonia pressures. The high conductivity of the aluminum, in combination with the relatively thick walls would allow a relatively high heat leak when NCG gas blocks the condenser. Copper/water or copper/methanol heat pipes would have similar problems. Instead, as discussed below, VCHPs were developed based on smooth-bore, thin-wall stainless steel tubing, with methanol, pentane or toluene as working fluids. The thin wall will be much lighter and will provide much better temperature regulation due to its lower thermal conductivity.

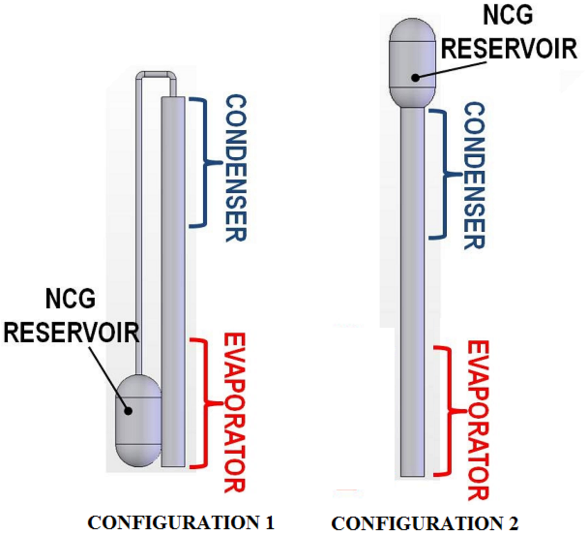


Figure 9. Potential VCHP configurations: Configuration 1 – reservoir attached to the evaporator (hot reservoir); Configuration 2 - reservoir attached to the condenser (cold reservoir).

Spacecraft VCHPs normally have the gas reservoir at the end of the condenser, and maintain its temperature with electrical heaters. The aluminum/ammonia variable thermal link discussed above had a reservoir near the evaporator, with an internal connecting tube. Two other unheated reservoir designs were considered for the balloon application; see Figure 9. Configuration 1 shows a VCHP that has the reservoir attached to the evaporator. In this case it will be a warm reservoir since it will mainly follow the evaporator (payload) temperature. Configuration 2 shows a VCHP that has the reservoir attached to the condenser and, hence, it will be a cold reservoir since it will follow the condenser (or sink) temperature. Configuration 1, hot reservoir, will provide tighter temperature control then Configuration 2 although it is slightly more complicated. Specifications for the balloon variable thermal link are given in Table 5.

Table 5. High Altitude Research Balloon Variable Thermal Link Specifications.

Payload Power	Up to 1000 W
Subsystem Power	Up to 300 W
Flight Duration	2-3 weeks or longer
Electronics Temperature Range	-5°C to 50°C
Heat Sink Temperature Range	-90°C to 50°C
Envelope Material	Stainless Steel
Working Fluids	Methanol, pentane, toluene, propylene, or ammonia
Non Condensable Gas	Argon, Neon, Helium

F. Balloon VCHP Performance Predictions

A VCHP model based on flat front theory was used to predict the VCHP performance for the five potential working fluids. The VCHP performance (evaporator temperature control) is a function of the reservoir type (warm or cold), reservoir size, and working fluid. For a given reservoir size, Figure 10 shows the evaporator temperature variation as the sink temperature swings along the entire heat sink temperature range (-90…40ºC). As expected, Configuration 1 (reservoir attached to evaporator) provides better (tighter) temperature control than Configuration 2 (reservoir attached to condenser). From the working fluid point of view, methanol is the best fluid, very closely followed by toluene, then pentane. The vapor pressures are much lower than ammonia, allowing thinner walls, and lower parasitic heat loss when the VCHP is shut down. Based on these predictions, the three fluids selected were methanol, toluene, and pentane.

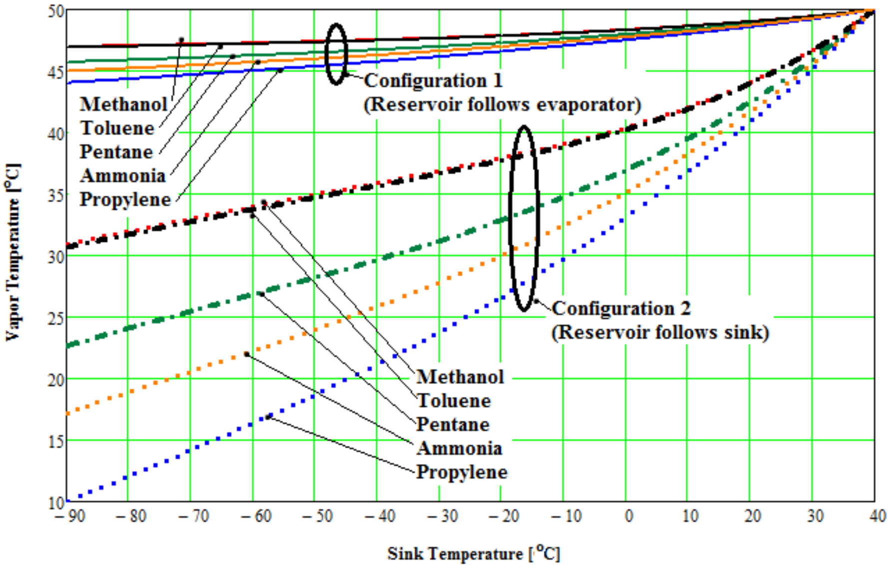


Figure 10. Evaporator temperatures variation as the sink temperature sweeps the entire HSTI (Heat Sink Temperature Interval).

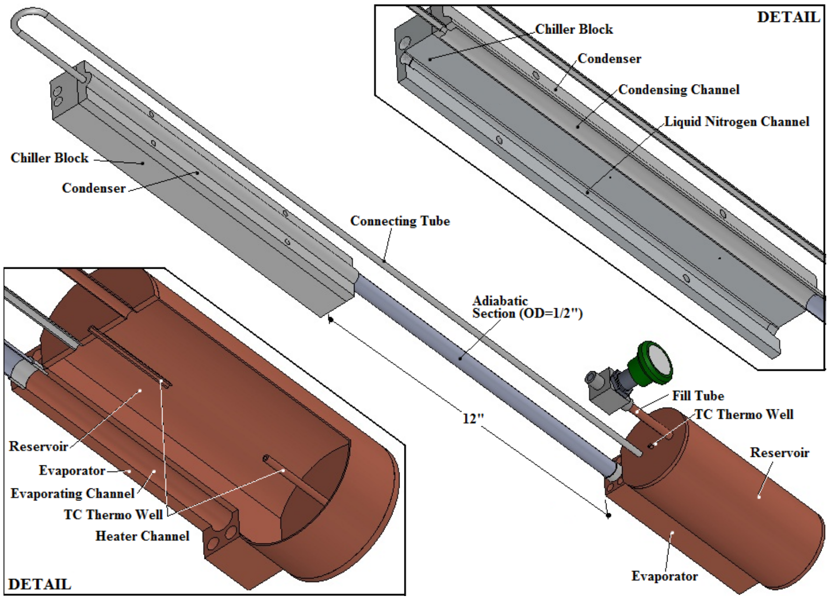


Figure 11. VCHP proof of concept test setup: configuration 1 reservoir attached to evaporator.

A.Balloon VCHP Design

Two VCHP configurations, one with the reservoir attached to the evaporator and one with the reservoir attached to the condenser, were designed and fabricated. The CAD models of the two proof of concept VCHPs are shown in Figure 11 and Figure 12. The geometrical parameters are shown in Table 6.

Table 6. VCHP geometry.

VCHP section	Length	Inner diameter	Volume	Wall thickness
Evaporator	L_{ev} = 15 cm	ID_{ev} = 1.2 cm	Vev = 14.2 cm^3	N/A
Adiabatic	L_c = 30 cm	ID_{ad} = 1.2 cm	Vad = 27.2cm^3	t_c = 0.05 cm
Condenser	L_c = 30 cm	ID_c = 1.2 cm	Vc = 32.6 cm^3	N/A
Condenser-Reservoir Tube	L_o = 81.3 cm (Config. 1) L_o = 7.5 cm(Config. 2)	ID_o =0.37 cm	Vo = 9.17 cm^3 Vo = 1.4 cm^3	t_{co} = 0.09 cm
Reservoir	H = 15 cm	ID_r = 6.17 cm	Vr = 455.5 cm^3	t_r = 0.081 cm

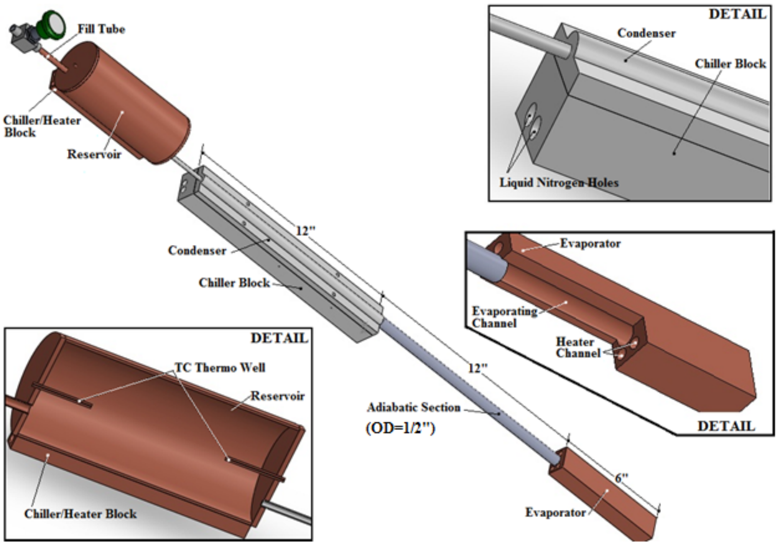


Figure 12. VCHP proof of concept test setup: configuration 2 reservoir attached to condenser.

Figure 13 shows the thermocouple arrangements on each VCHP configuration. This representation is useful in reading and understanding the results.

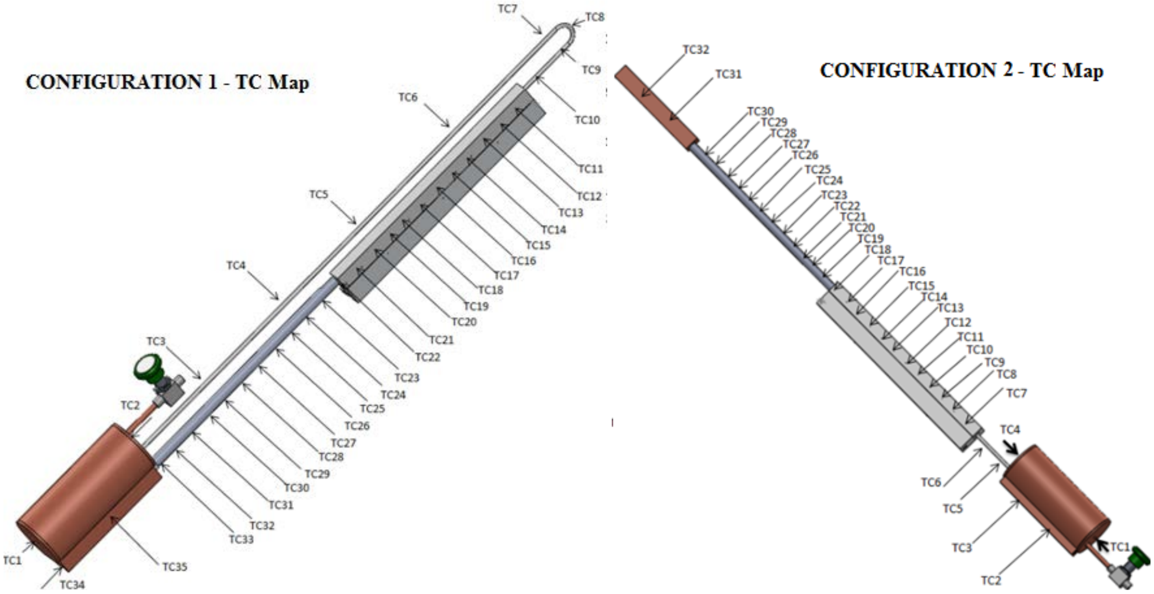


Figure 13. Thermocouple maps on the two experimental VCHPs.

B. Balloon VCHP Test Results

The two VCHP configurations were each tested with three different working fluids (methanol, toluene, and pentane), for a total of six combinations. The power was maintained constant at 100W while sink temperature was incrementally decreased along the entire interval. Figure 14 shows temperature profiles along the VCHP for methanol and a warm reservoir. Note that even though the evaporator (payload) temperature only varies from 50 ºC to 44ºC as the sink temperature swings between 40 and -90°C, demonstrating the ability of the VCHP to maintain the evaporator temperature over the entire sink temperature range.

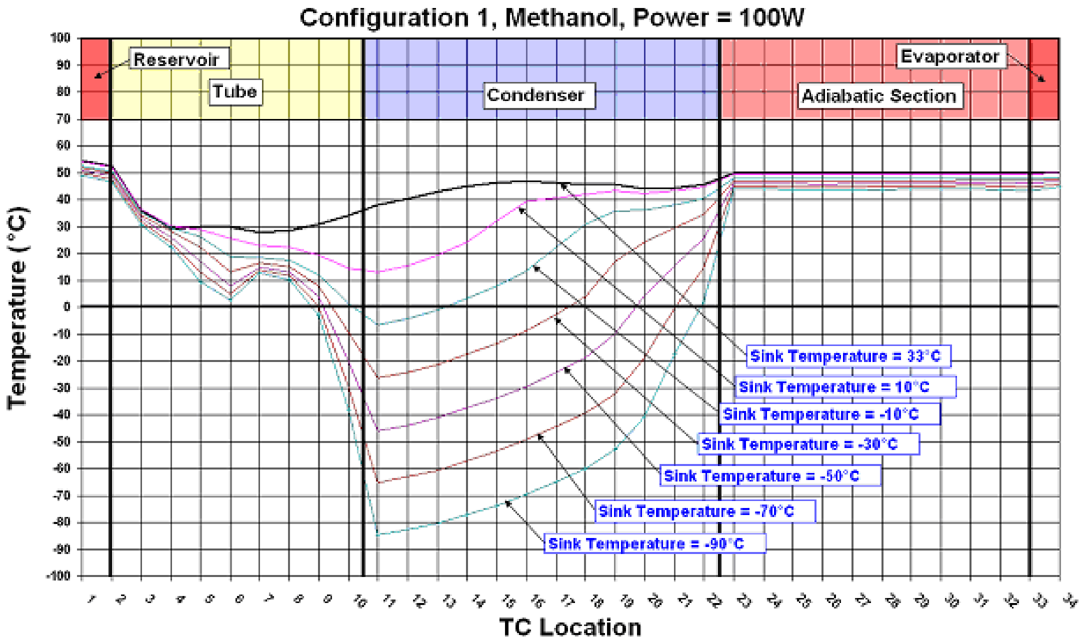


Figure 14. VCHP Configuration 1- methanol - steady state temperature profiles for several sink temperatures and a constant power of 100W.

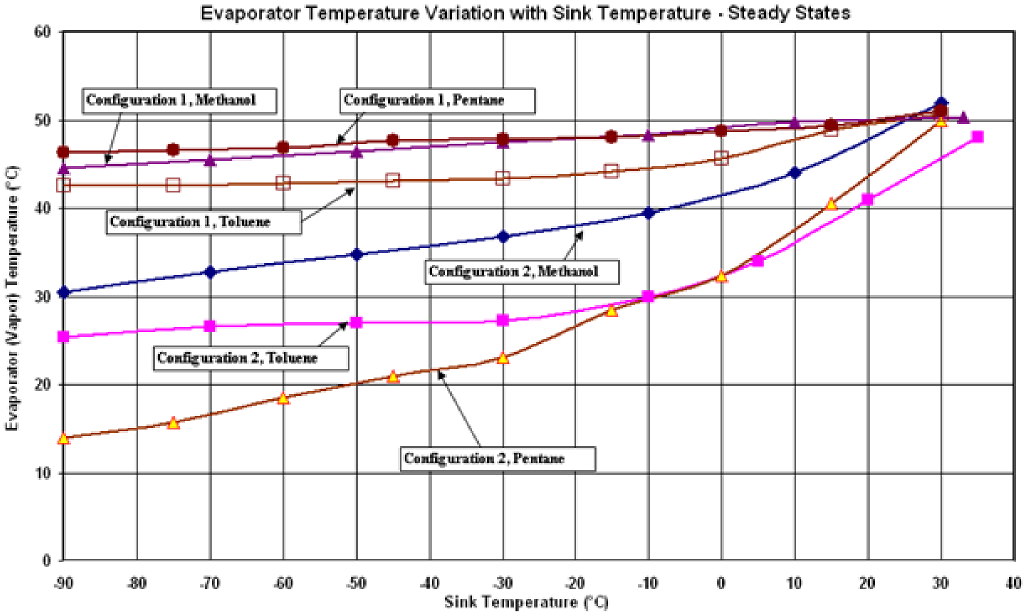


Figure 15. Steady state evaporator temperatures for both VCHP configurations and all three working fluids when sink temperature sweeps the entire HSTI.

Figure 15 shows the evaporator steady state temperatures as a function of heat sink temperature for all six configurations. It can be seen that Configuration 1 (warm reservoir) shows better temperature control than Configuration 2 (cold reservoir). However, both configurations with all three working fluids provide a variable thermal link with temperature control tight enough to satisfy the requirements. The tightest control was shown with pentane in VCHP Configuration 1 with only a 3.7ºC (46.3..50ºC) temperature swing. The loosest temperature control was seen using Configuration 2 with Pentane, which was only ~36ºC (14..50ºC), as the sink temperature varied by 130°C.

The ability of the different configurations to maintain the evaporator temperature in the desired range as the sink temperature drops is summarized in Table 7, and compared to the predicted range. In each case, the VCHP was supplied with constant power (100 W for methanol cases and 70 W for the toluene and pentane cases) while the heat sink temperature (liquid nitrogen controller set point) was varied systematically from 40ºC all the way to -90ºC (along the HSTI).

Table 7. Summary of the modeling and experimental evaporator temperature intervals as the heat sink sweeps the HSTI.

Working Fluid →	**Methanol**		**Toluene**		**Pentane**	
Configuration	Predicted	Measured	Predicted	Measured	Predicted	Measured
VCHP Configuration 1	47..50ºC	45.3..50ºC	46.9..50ºC	43..50ºC	45.2..50ºC	46.3..50ºC
VCHP Configuration 2	30.8..50ºC	30.4..50ºC	30.3..50ºC	26.2..50ºC	17.4..50ºC	14..50ºC

V. Conclusion

The objective of a variable thermal link is to maintain the evaporator temperature range in a fairly broad temperatures range, when subjected to changes in power, and very large variations in sink temperature. The variable thermal link should transmit heat readily during hot sink conditions, but minimize heat transmission during cold sink conditions. Applications that can benefit from using VCHPs as variable thermal links include Lunar and Martian Landers and Rovers, Research Balloons, and Lunar and Space Fission Reactors. The applications that can benefit from variable thermal links normally have 1. Variable system loads resulting from intermittent use, 2. Large variations in the sink temperature, and 3. Limited electrical power. Since the lowest sink temperature can be below the freezing point of the working fluid, many applications with variable thermal links also need to consider freeze/thaw and start-up from a frozen state. Fortunately, the NCG in the heat pipe also helps when the pipe is frozen, and during start-up. It suppresses fluid movement when a portion of, or the entire pipe is frozen, minimizes sublimation of water for a water heat pipe, and aids in start-up from the frozen state by providing a back pressure in the heat pipe condenser during start-up.

A VCHP was developed to act as a variable thermal link for lunar landers and rovers, passively minimizing heat losses during the lunar night, without requiring electric power to shut off. Differences from a conventional spacecraft VCHP include 1. A hybrid wick, to allow the evaporator to operate when tilted at adverse orientations of up to 14°. 2. The reservoir was located next to the evaporator, to minimize the reservoir size and mass, while using no electrical heaters, and 3. The addition of a bimetallic adiabatic section, with a length of grooved stainless steel to minimize heat leaks during the lunar night.

The simulated lunar performance testing demonstrated that the VCHP shut off as the condenser temperature was lowered, so the system acted as a variable thermal link. The VHCP was able to withstand multiple freeze/thaw cycles without performance degradation. Short-duration, full-power bursts were demonstrated during -60°C and -177°C cold shutdowns. Startup of the VCHP with a frozen condenser was also demonstrated. As expected, the VCHP behaves as a gas diode heat pipe when the condenser is heated in a simulated space environment.

Variable thermal links were also developed for high altitude, research balloons. Two VCHP configurations (hot and cold reservoir) were designed, fabricated and successfully tested, with methanol, toluene, and pentane working fluids. Both configurations provide a variable thermal link without electrical power. The warm reservoir VCHP has a 4.8ºC temperature control band, while the cold reservoir control band is larger, at 21ºC

Acronyms

CCHP	Constant Conductance Heat Pipe
ILN	International Lunar Network
NCG	Non-Condensable Gas
VCHP	Variable Conductance Heat Pipe

WEB	Warm Electronics Box

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