Variable Conductance Heat Pipe Performance after Extended Periods of Freezing

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Abstract. Radiators operating in lunar or Martian environments must be designed to reject the maximum heat load at the maximum sink temperature, while maintaining acceptable temperatures at lower powers or sink temperatures. Variable Conductance Heat Pipe (VCHP) radiators can passively adjust to these changing conditions. Due to the presence of non-condensable gas (NCG) within each VCHP, the active condensing section adjusts with changes in either thermal load or sink temperature. In a Constant Conductance Heat Pipe (CCHP) without NCG, it is possible for all of the water to freeze in the condenser, by either sublimation or vaporization. With a dry evaporator, startup is difficult or impossible. Several previous studies have shown that adding NCG suppresses evaporator dryout when the condenser is frozen. These tests have been for relatively short durations, with relatively short condensers. This paper describes freeze/thaw experiments involving a VCHP with similar dimensions to the current reactor and cavity cooling radiator heat pipe designs.

Keywords: Variable Conductance Heat Pipe, Lunar Radiator, Freeze
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INTRODUCTION

Long-term Lunar and Martian systems present challenges to thermal systems, including changes in thermal load, and large changes in the thermal environment between Lunar (or Martian) day and night. The Lunar VCHP Radiator will operate in an environment with effective sink temperatures ranging from 120 K (-153 °C) to 374 K (101 °C), depending on location and time of lunar day. During normal operation, the evaporator will remove thermal energy from a coolant line with temperatures ranging from 300 K (27 °C) to 550 K (277 °C). Mason, Poston, and Quails (2008) present a reference Fission Surface Power Design that operates between 370 K and 400 K. This is too hot for conventional aluminum/ammonia heat pipes, so a different heat pipe/working fluid combination is required. Anderson *et al*. (2006) have developed titanium/water heat pipe radiators that are suitable for this temperature range. While water has superior heat transfer properties, freezing must be considered.

The Lunar thermal environment typically includes long periods in extremely cold thermal environments. A Variable Conductance Heat Pipe (VCHP) radiator can passively accommodate the changing thermal load and environment. In a VCHP, a non-condensable gas is added that blocks a portion of the condenser. The gas charge blocks more of the condenser as the heat pipe evaporator temperature changes. This allows the heat pipe evaporators (and any attached heat exchanger) to remain at an almost constant temperature. In addition to passively controlling the thermal load, the gas allows the fluid in the heat pipe to freeze in a controlled fashion as the heat pipe is shut down, avoiding damage. In addition, the gas in the VCHP will help with start-up from a frozen condition.

This energy is rejected by the condenser to a sink temperature between 130 K (-143 °C) and 314 K (41 °C) (Dallas, Diaguila and Saltsman, 1971). As a result, water will exist at saturated conditions throughout the active portion of the heat pipe. However, in the non-condensable gas reservoir and inactive portions of the condenser, temperatures will drop below the freezing temperature of water. Furthermore, the radiator may experience periods of low or no power transfer. In this case, the entire VCHP may experience temperatures below the freezing point of water for extended periods of time.

This experiment determined the response of the VCHP working fluid during the approach to freezing, freezing, and operation after thaw out. In particular, the distribution of frozen water throughout the pipe during initial freezing and until thaw out is of interest. This distribution is important to restarting the VCHP after freezing. If frozen water is not present in the evaporator region, the heat pipe will remain dry and proper operation cannot be resumed. In addition, if frozen water bridges the heat pipe diameter, the condenser can be blocked, disrupting restart. An ice bridge could also deform the VCHP envelope.

VCHP FREEZING CHARACTERISTICS

Initially, the distribution of frozen water in the VCHP depends on the rate and uniformity of the cooling process. If freezing occurs quickly and uniformly, the working fluid will maintain the distribution experienced during normal operating conditions as freezing will occur in the condenser, evaporator, and adiabatic sections simultaneously. Since power is input at the evaporator region and removed from the condenser region, this type of freezing is unlikely to occur. Even if power transfer to the coolant is suddenly shut off, the VCHP radiator will continue to receive power from the coolant until thermal equilibrium is reached. During this period, the condenser will freeze first. Depending on coolant temperature at equilibrium, the evaporator may or may not freeze.

In a Constant Conductance Heat Pipe (CCHP), vapor would continue to flow from the evaporator to the frozen condenser region. There the vapor would freeze, and eventually the evaporator region would dry out. A VCHP, however, benefits from the presence of non-condensable gas during the freezing process. As temperature drops and approaches the freezing temperature in the condenser, the vapor pressure within the VCHP decreases. The non-condensable gas expands to maintain pressure equilibrium at the vapor-gas interface, reducing the active condenser length in the process. This has the effect of both restricting the flow of vapor to the inactive portion of the condenser and maintaining the active condenser section at a higher temperature than an equivalent CCHP at the same power level. As the working fluid temperature reaches a limit specified by design, the entire condenser section is occupied by non-condensable gas. Further decrease in temperature beyond this shutoff point will result in the gas expanding into the adiabatic section. When freezing occurs, the working fluid is restricted to the evaporator and adiabatic regions.

Regardless of whether the evaporator freezes or not, working fluid vapor will continue to be present in the VCHP due to either evaporation or sublimation. While no pressure gradient exists to drive this vapor across the vapor-gas boundary, the concentration gradient across this boundary will result in diffusion of the vapor into the gas space and vice versa. As a result, vapor transport to the condenser region will continue, although at a significantly reduced rate compared to a CCHP. Eventually, the evaporator will dry out. A temperature gradient between the evaporator and condenser will accelerate this process.

Ochterbeck and Peterson (1993) found ice to form in the condenser as a concentrated deposit rather than evenly distributed along the condenser length. Over time, this deposit grew inward, in some cases blocking the condenser from the evaporator. These researchers found that for larger non-condensable gas charges, blockage did not occur. Furthermore, for heat pipes with a large condenser to evaporator ratio, such as those designed for the Lunar VCHP Radiator, blockage should not occur.

VCHP THAWING CHARACTERISTICS

Applying power to the evaporator will cause any frozen water present in this region to thaw. As a result, the vapor pressure will rise in the evaporator region, the non-condensable gas will contract, and the active portion of the condenser will increase. Water vapor will transport thermal energy to any ice in the condenser. If this energy is sufficient to overcome the cooling rate and latent heat of fusion, the condenser will thaw. If not, this vapor will freeze in the condenser and the evaporator will dry out. As water must be present in the evaporator region to resume operation of the VCHP, restart will fail. In this case, thawing could be accomplished with solar illumination, as demonstrated by research conducted at Glenn Research Center (GRC) (Jaworske, Sanzi and Siamidis, 2008).

Again, the VCHP has an advantage over a CCHP. At start up from frozen conditions, the non-condensable gas occupies a majority of the condenser section, significantly reducing the cooling rate of the condenser. This is not the case in a CCHP. As a result, the VCHP restarts by thawing a small section of the condenser and increasing this section length as more water, and therefore vapor pressure, becomes available to contract the non-condensable gas. This continues until the active length is appropriate for the power level.

Jang (1990) found that continued cooling of the condenser section resulted in an increase in the time required for a complete restart of a heat pipe. For the cases demonstrated in this researcher's study, cooling was discontinued at the condensing section until the heat pipe had begun to thaw. For the Lunar VCHP Radiator, such a condition would exist after lunar sunrise as sink temperatures can rise above freezing. This would only be applicable to locations of moderate lunar latitude.

Ochterbeck (1997) examined three restart regions. The first case involved a frozen heat pipe with a dry evaporator and blocked condenser channel. As expected, the researchers were unable to restart the heat pipe. The second case involved a frozen evaporator and partially blocked condenser channel. Start up again failed as there was not enough water present in the evaporator to overcome cooling in the condenser. As a result, the vapor generated in the evaporator froze in the condenser until dry out occurred. The final two cases involved higher non-condensable gas charges. In both cases, start up was successful as more of the condensing section was inactive during the initial thawing process. This study demonstrates the importance of non-condensable gas charge with respect to restarting a frozen VCHP.

EXPERIMENTAL VCHP

The experimental VCHP as fabricated is shown in Figure 1a. This VCHP is a full scale representation of the design developed for a lunar power system (Anderson, Ellis, and Walker, 2009), with a 15.2 cm (6 in.) evaporator section (the short leg), a 152 cm (60 in.) condenser section (the long leg), a 10.2 cm (4 in.) adiabatic section (the curved section), and an 21.6 cm (8.5 in.) gas reservoir, an extension of the condenser section. The outer diameter is 1.27 cm (0.5 in.) with a wall thickness of 0.165 cm (0.065 in.). The VCHP envelope is commercially pure, grade 2, (CP-2) titanium and the wick, present only in the evaporator, is a 50 mesh titanium screen. The working fluid is water and the non-condensable gas is argon.

Also shown in Figure 1a are close-ups of the condenser end cap and fill tube in the upper left corner, with the evaporator end cap below that photo and the gas gap calorimeter mounting disc to the right. This disc supports the calorimeter during testing.

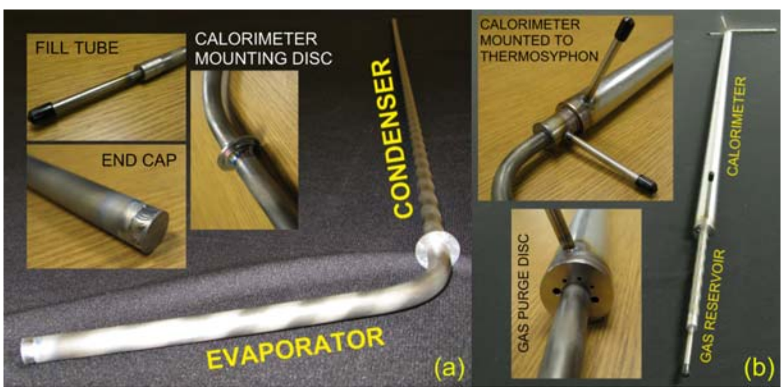

FIGURE 1. (a) Experimental VCHP and **(b)** Calorimeter Mounted to VCHP

The gas gap calorimeter is constructed from AISI 304 stainless steel and is shown mounted to the thermosyphon in Figure 1b. The calorimeter consists of an inner tube that contains a helium and argon gas mixture surrounded by an outer tube through which ethylene glycol flows. The helium and argon mixture can be adjusted to alter the thermal resistance of the calorimeter. The ethylene glycol provides a thermal energy sink below the freezing temperature of water.

In the upper left hand corner of Figure 1b, a portion of the inner tube can be seen protruding from the outer tube and resting on the calorimeter mounting disc. The ethylene glycol inlet is also shown here, pointing upwards from the outer tube, as well as the gas inlet, pointing to the right from the inner tube. In the lower left hand corner of Figure 1b, the ethylene glycol outlet is shown along with the perforated gas purge disc and gas reservoir section of the thermosyphon, pointing downward.

During steady state operation, the argon and helium gas mixture exists at a constant molar ratio, has negligible bulk flow velocity, and occupies the annular ("gas gap") region. Thermal energy is conducted from the thermosyphon condenser, through the gas gap, and into the ethylene glycol cooling jacket. The power removed from the condenser can be determined from the flow rate and temperature increase of the ethylene between the inlet and outlet. In this way, the power transferred through the thermosyphon is measured.

Between tests, as the power level is changed, the argon to helium mixture can be changed by purging the gas through the perforated disc at the top of the calorimeter and introducing a new mixture through the gas inlet at the bottom of the calorimeter. As helium is an order of magnitude more conductive than argon, this provides a manner to adjust the thermal resistance of the calorimeter and control the operating temperature of the thermosyphon. This temperature is set before each new power level and allowed to reach steady state before data collection begins.

The VCHP and calorimeter assembly was secured and oriented with the longest end, the condenser, in a vertical position. This is the orientation of the heat pipes in a lunar radiator (Mason, Poston and Qualls, 2008). The gas reservoir remained at the coldest system temperature to simulate exposure to the lunar sink. To accomplish this, copper tubing of 0.318 cm (0.125 in.) diameter was wrapped around the exposed gas reservoir and insulated. Ethylene glycol first passed through this tubing before entering the calorimeter cooling jacket.

The fluid charge of the thermosyphon depends on the liquid film developed along the condenser wall during operation. Calculation using both a Navier-Stokes approximation and Nusselt film theory indicate the film thickness is approximately a few thousandths of a centimeter at the maximum power level. This indicates a required fluid inventory of 5-10 mL. For the tests in which the evaporator remained warm, 10 mL was used. For the freezing tests, 5 mL was used. Non-condensable gas and working fluid parameters are shown in Table 1.

Table 1. Non-Condensable Gas and Working Fluid Parameters.

Gas	Argon
Charge pressure at room temperature	6.7 kPa (50 Torr)
Reservoir length	21 cm (8.3 in)
Gas mass	2.9E-5 kg
Fluid	Water
Total Inventory	5 to 10 mL

FROZEN CONDENSER TESTING

Initially, only the condenser section was frozen. This case represents a low power operating condition with nearly the entire condensing section inactive. Vapor is still produced in the evaporator and travels to the gas-vapor interface. At this interface, vapor may travel to the condenser by diffusion and freeze there. Since the vapor pressure produced by a warm evaporator is considerably higher than that of a frozen evaporator, this case provides a considerably higher concentration of vapor at the interface than a completely frozen VCHP. As diffusion is a concentration driven process, operating with only the condenser frozen provides the greatest chance of evaporator dry out during the freeze period.

Three frozen condenser tests were conducted for 3, 6, and 15 days, respectively. For all tests, the VCHP was first brought up to power to fully activate the condenser. Once this condition was reached, the condenser was frozen quickly in an attempt to capture as much working fluid as possible in this region. Freezing fluid in the condenser is undesirable with regards to restart. A rapid freeze tests the ability of the VCHP design to prevent this event. Freezing was then maintained for the test period prior to the restart attempt.

Only the 15 day test is presented here and is represented by three charts. First, the initial start-up and freeze is shown. Second, the overall test period is displayed. Finally, the restart attempt is shown. Each chart shows the time from the beginning of the test on the abscissa, thermocouple temperature on the left ordinate, and power withdrawn from the calorimeter on the right coordinate. The evaporator thermocouple was located 5.1 cm (2 in) from the bottom of the evaporator and held against the evaporator wall using a plunger type thermocouple. The first condenser thermocouple is located at the beginning of the condenser. All condenser thermocouples were attached to the wall of the VCHP. The remaining condenser thermocouples were spaced 15.2 cm (6 in) apart up the length of the condenser. The final condenser thermocouple is located at the end of the condenser and beginning of the non-condensable gas reservoir. The non-condensable gas reservoir was maintained below freezing for all tests.

The relatively large temperature difference between the evaporator and condenser thermocouples is a result of conduction through the 0.165 cm (0.065 in) wall. This wall thickness was selected to reduce lead time. An actual radiator heat pipe would use a considerably thinner VCHP wall and reduce this temperature gradient.

In this test, the condenser was allowed to freeze for 15 days, which is a period longer than a lunar night. Again, the VCHP was brought up to power in order to fully activate the condenser. Once activated, the condenser was quickly cooled by introducing Helium gas to the calorimeter. The temperature and power removal profile during this start up and freeze is shown as Figure 2.

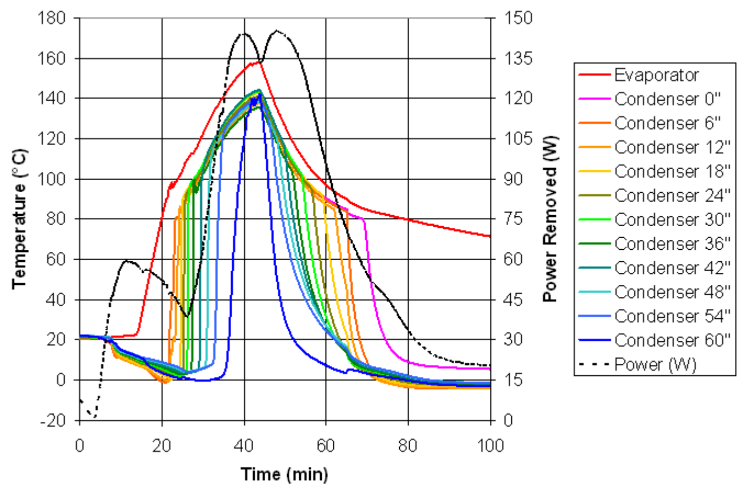

FIGURE 2. Power Up and Freeze for the 15 Day Test Period.

The condenser was then maintained below freezing for 15 days, shown as Figure 3. After day 8, insulation was added to several bends of the coolant tubing to reduce ice formation. This resulted in lowering the ethylene glycol and condenser freezing temperature. Power was adjusted to maintain the evaporator near 40 °C.

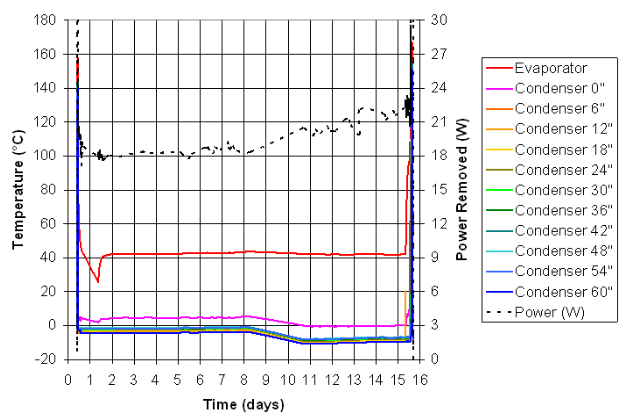

FIGURE 3. Complete 15 Day Freeze Period.

After 15 days, power was applied to the VCHP to attempt a restart. The resulting temperature and power removal profiles are shown in Figure 4. At about 280 minutes, the vapor-gas front moves into the condenser, raising the temperature of the thermocouple at this location to that of the vapor. Power is continually incremented from this point until the condenser is fully activated. After maintaining the condenser under freezing conditions for 15 days, the VCHP successfully restarts.

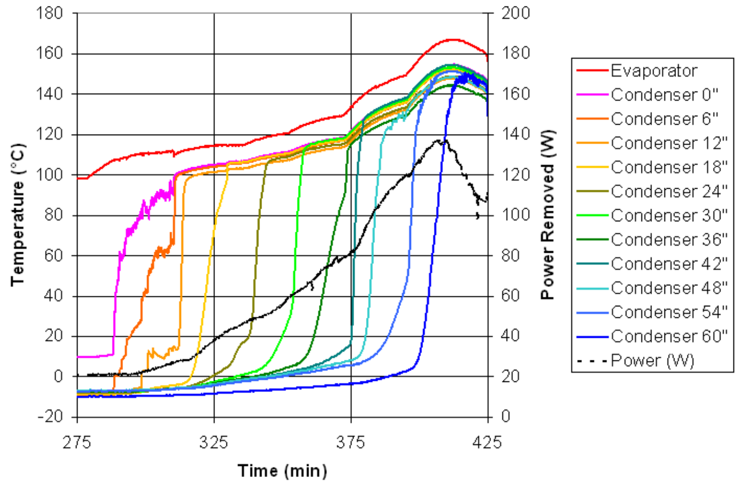

FIGURE 4. Restart after 15 day freezing period.

FULL VCHP FREEZE TESTING

The last test conducted involved freezing the entire VCHP to examine the effects, if any, on the titanium envelope. This test followed the previous approach. First, the VCHP was frozen. Unlike the previous tests, the evaporator was also frozen. The temperature and power removal profiles of this period are shown in Figure 5. Due to material temperature limits associated with the refrigeration unit used in these tests, coolant lines could only be run through the evaporator heat transfer block once sufficient heat was removed. For this reason, the VCHP is frozen from an ambient state, rather than the fully activated state as in previous tests.

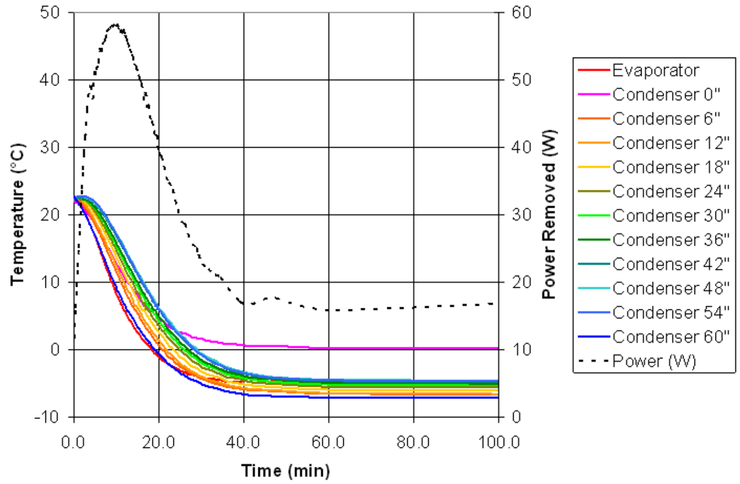

FIGURE 5. Temperature and Power Removal Profile for Full Freeze.

As shown in Figure 6, the VCHP was maintained below freezing temperatures for 15 days. Prior to restart, the refrigeration coolant flow was temporarily removed from the calorimeter. This again resulted in a sudden drop in power removal, followed by a brief peak in power removal. During the freeze period, the thermocouple between the condenser section and adiabatic section remained slightly higher than the other thermocouples. This thermocouple is directly above the tube bend which was experiencing some ambient gains and cooled only by conduction through the titanium pipe wall. The poor conductivity of titanium resulted in somewhat higher temperatures in this section. However, freezing temperatures were maintained.

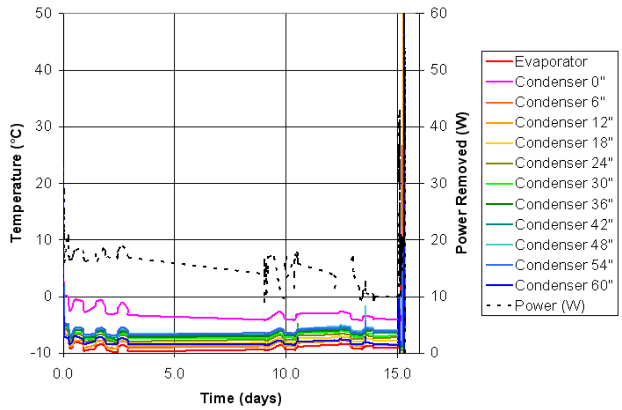

FIGURE 6. Temperature and Power Profiles for Full Test Period.

The VCHP was then restarted. The temperature and power profiles of the restart are shown in Figure 7. To fully reactivate the condenser, a higher operating power and fluid temperature was required. The envelope material, titanium, generates gas until the titanium is passivated. Typically, titanium heat pipes are operated well above operating temperature for a considerable amount of time to remove these gases. Due to time constraints of the Phase I project, this was not possible prior to operation. As a result, the envelope material is likely generating gases during operation, resulting in a higher quantity of NCG in the VCHP. As a result a higher vapor pressure and, therefore, fluid temperature is required to fully activate the condenser. Regardless, the VCHP was successfully restarted after a full freeze of 15 days. Measurements of the VCHP after testing showed no change in envelope diameter, which indicates no damage from freezing in the pipe.

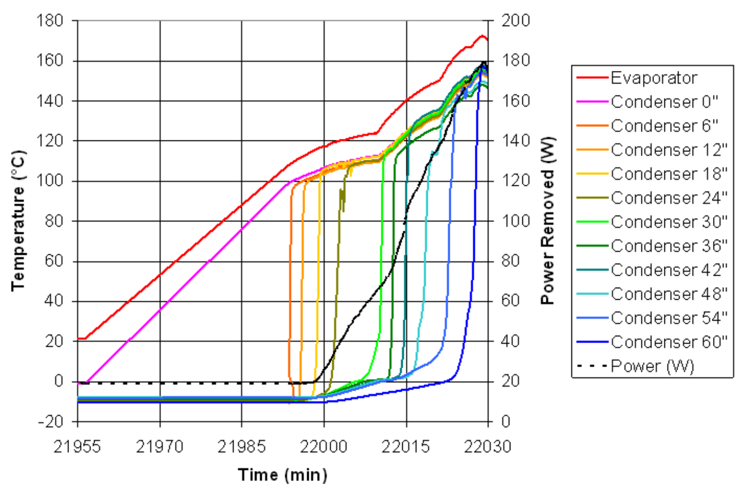

FIGURE 7. Temperature and Power Profiles for VCHP Thaw after Freezing.

CONCLUSION

The testing described in this paper demonstrated the ability of a titanium/water VCHP to restart after partial and complete freezing. The VCHP had similar dimensions to the heat pipes that would be used in a lunar surface power radiator. The partial freeze represents the most demanding operating state of the VCHP as high vapor pressure exists at the vapor-NCG interface, which presents greater opportunity for vapor to enter the condenser and freeze.

Complete freezing represents a material hazard as the envelope may rupture. Testing showed the VCHP operated reliably and without damage after 15 day partial and complete freezing periods. This period is longer than a lunar night and indicates a VCHP, water-titanium radiator would survive freezing if subjected to no or low power operation in lunar conditions.

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