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Hybrid Thermal Control System for Extreme Thermal Environments

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NASA's return to the moon brings about many challenges, including issues with survival on the Lunar surface. Marshall Space Flight Center (MSFC) has been developing a hybrid thermal control system that can be utilized for various surface assets that must survive in extreme lunar environments. This scalable system is targeted for human-rated systems and utilizes a combination of a pumped fluid loop (PFL) and a loop heat pipe (LHP) with thermal control valve (TCV). Pumped fluid loops have a long history of use in human rated systems. They can collect large amounts of waste heat and transport it over long distances in rovers, habitats, and other systems. By utilizing a non-toxic working fluid in the habitable volume, the PFL is easily serviceable by the crew and does not pose a risk during any unexpected leaks or failures. The addition of a LHP for the exterior heat transport and rejection adds several benefits to the system for extreme environment survival. The quantity of LHPs can be tailored to optimize heat rejection for different systems and allows for large radiative surfaces. By utilizing a TCV in combination with the LHP, there can be high heat transfer during the daytime with minimal heat transfer during the night. The TCV passively controls the amount of heat transfer through the LHP based on the environmental temperature. A prototype system has been tested in benchtop and thermal vacuum conditions. Results are presented showing the feasibility of the system concept.

Nomenclature

ACT = Advanced Cooling Technologies
ATCS = Active Thermal Control System
CC = Compensation Chamber
cDAQ = Compact Data Aquisition System
COTS = Commercial Off the Shelf
CSM = Command Service Module
ECLSS = Environmental Control & Life Support System
ECS = Environmental Control System
HISET = High Intensity Solar Environment Test System
ISS = International Space Station
ITCS = Internal Thermal Control System
KPP = Key Performance Parameter
LHP = Loop Heat Pipe
LTL = Low Temperature Loop
MAX = Measurement and Automation Explorer
MMOD = Micro Meteoroid Orbital Debris
MTL = Moderate Temperature Loop
MSFC = Marshall Space Flight Center
NI = National Instruments
PDT = Pacific Design Technologies
PFL = Pumped Fluid Loop
PGW = Propylene Glycol Water
PSR = Permanently Shadowed Region
SBIR = Small Business Innovative Research
SEE = Space Environment Effects
STS = Space Transportation System
TCV = Thermal Control Valve
TCS = Thermal Control System
TIM = Thermal Interface Material
TRL = Technology Readiness Level

I. Introduction

NASA's return to the Moon brings about many challenges, including issues with survival on the Lunar surface. During the Apollo missions, astronauts only stayed on the Lunar surface for up to a few days. This allowed for the use of

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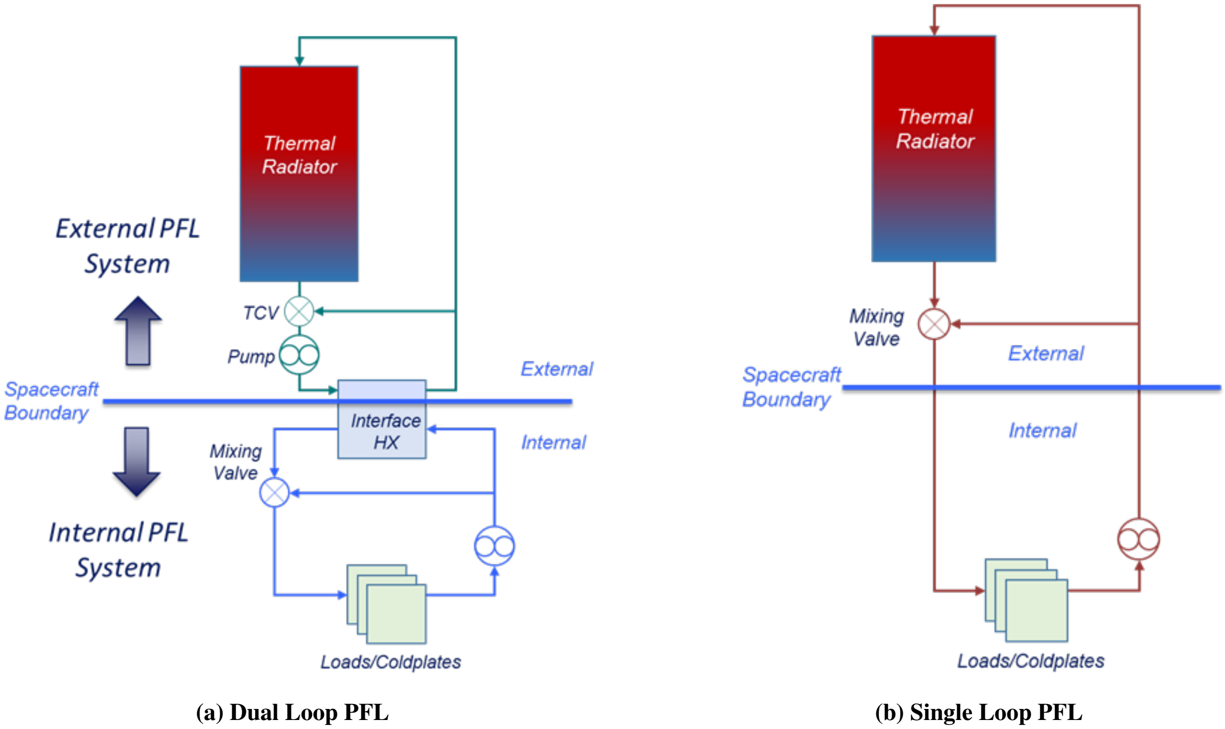
consumables in the Environmental Control and Life Support Systems (ECLSS) that kept the astronauts alive on the surface. The downside to this "flags and footprints" approach is a lack of sustainability – a necessary requirement for our planned return to the Moon, and someday Mars. By maintaining a sustainable approach to exploration, NASA will better ensure the success of extended human missions in extreme environments.

In order to be sustainable, assets such as landers, rovers, and habitats must be usable for more than a single mission. This can prove challenging during the design process of these surface assets. One of the key challenges with sustainability is designing adequate thermal control that allows for surface systems to survive both during the Lunar day and the Lunar night. Temperatures on the Lunar surface are extreme and vary greatly depending on location and time of day. At the equator the day time temperatures can reach 120°C; on the poles the nightly temperature can be as low as -200°C. In permanently shadowed regions (PSR) the temperature can approach a staggering -250°C. Robust, high-performance thermal control systems (TCS) will be required to survive these extreme environments. Since NASA's plan currently targets the Lunar south pole for the next crewed mission, the specific environment of concern is extremely low temperatures during the Lunar night and moderate temperatures during the day. This paper details a concept for a hybrid thermal control system that combines aspects of both active and passive TCSs for a versatile approach.

II. Human-Rated Thermal Control System Architectures for Exploration

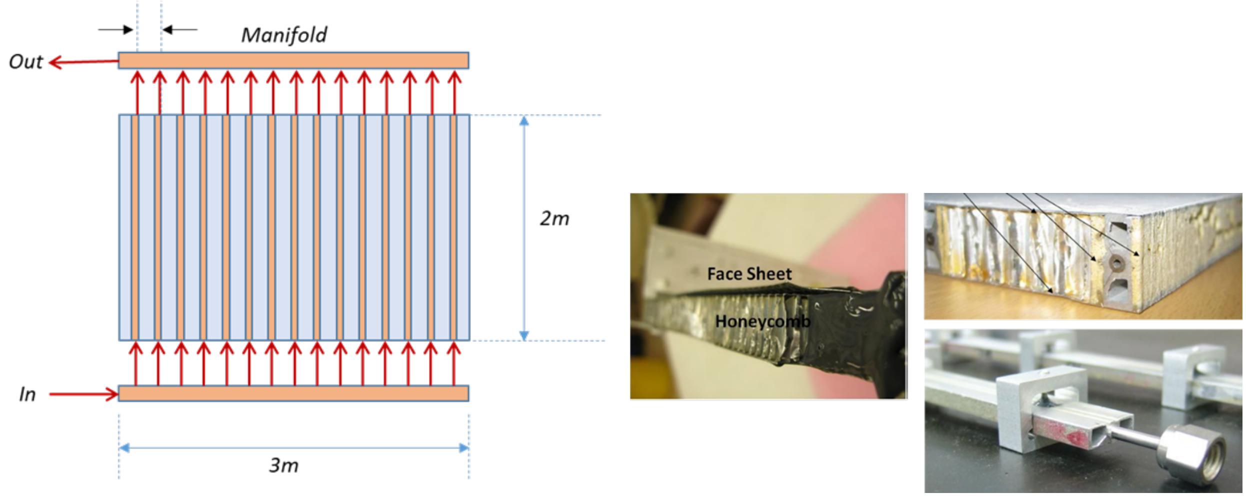
Single phase Pumped Fluid Loop (PFL) based Active Thermal Control System (ATCS) architectures have traditionally been utilized to provide acquisition, transport, and rejection of heat from crewed spacecraft. In a PFL TCS, coolant is circulated through internal cold-plates, heat exchangers, or other acquisition devices and transported via a pumped loop to thermal radiators outside the spacecraft to reject the heat. A common design approach for the International Space Station (ISS), Space Transportation System (STS), Orion and others has been to divide the TCS into two loops via a coupling through an interface heat exchanger as shown in the simplified schematic below (Figure 1a)[1,2]. The internal loop may utilize a crew friendly or non-toxic heat transfer fluid, such as water or a water/propylene glycol mixture, while the coolant for the external loop may be chosen for freezing point and heat transfer performance. Single loop systems (Figure 1b) have been utilized in crewed spacecraft as well, but a coolant must be chosen that is both satisfactory for potential crew exposure as well as transport and external heat rejection[3].



(a) Dual Loop PFL **(b) Single Loop PFL**

Fig. 1 Simplified Dual and Single Loop PFL TCS Architectures

PFL thermal radiators are characterized by multiple flow channels bonded to a radiating surface. The flow channels through a radiator panel may be equidistant (as shown in Figure 2a) or staggered to facilitate recovery from freezing or thawing. Inlet and outlet manifolds are utilized to distribute the flow through the radiator. Deployable radiators may utilize conductive face-sheets bonded to a honeycomb core for stiffness as shown in Figure 2b. The flow tubes are mounted in brackets as shown for the ISS example. Tube diameters must be sized to provide the desired heat transfer through the thermal boundary layer inside the tube. This can be a challenge for some fluids as reducing tube diameters to produce turbulent flow may also result in increased pressure drop. The tube spacing is also important to minimize fin effect losses through the radiator face-sheet between tubes.



(a) PFL Radiator Schematic **(b) Typical PFL Deployable Radiator**

Fig. 2 PFL Radiator Examples

The ISS external ATCS is shown in Figure 3 with ammonia circulating through the external loop and acquiring heat through multiple interface heat exchangers. The Heat Rejection System, comprised of three thermal radiator wings is shown on the far left with a bypass utilized to maintain the supply temperatures at approximately 37°F. Each interface heat exchanger represents a coupling to an Internal TCS (ITCS) loop for the respective element. Low and moderate temperature cooling loops are available on the ISS and, where appropriate, the Low Temperature Loop (LTL) interface heat exchanger is placed upstream of the Moderate Temperature Loop (MTL) interface heat exchanger to receive the coldest flow.

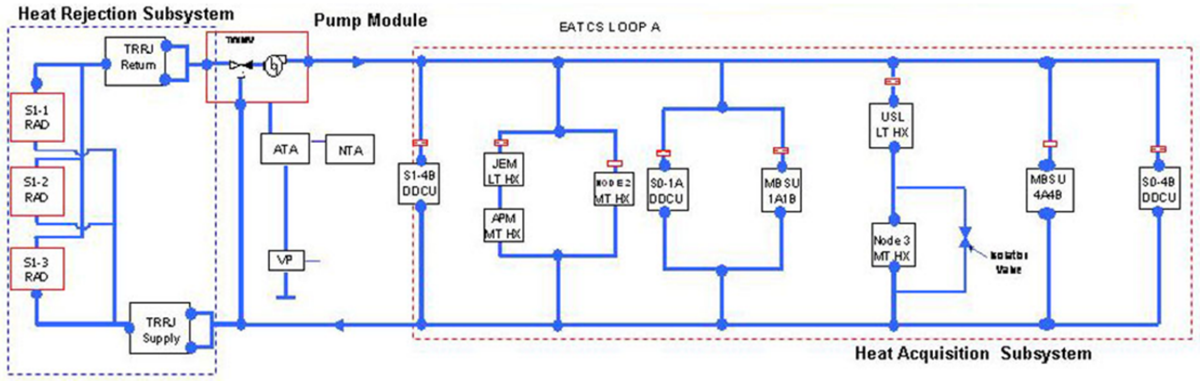


Fig. 3 ISS External ATCS

The STS external ATCS is shown in Figure 4 with Freon 21 circulating through the thermal radiators, various heat exchangers, an ammonia boiler, water flash evaporator, and external cold-plates[4]. The internal STS water loop interfaces with the external loop via the inter-changer heat exchanger shown in the lower left in the schematic.

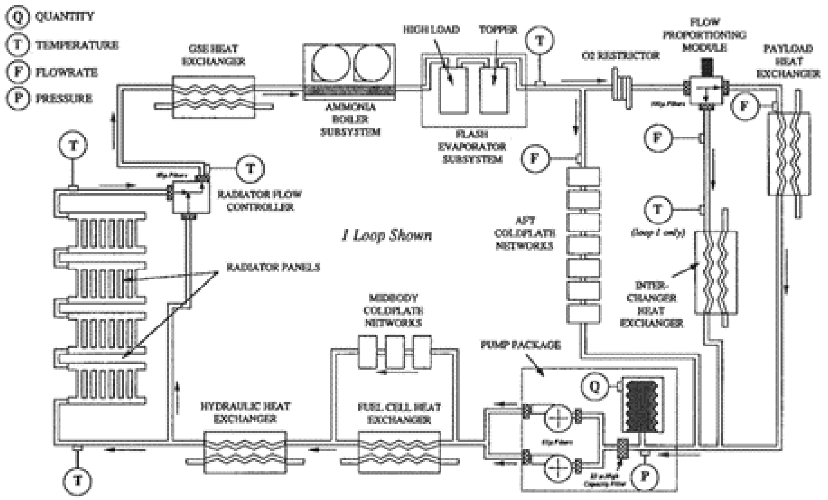
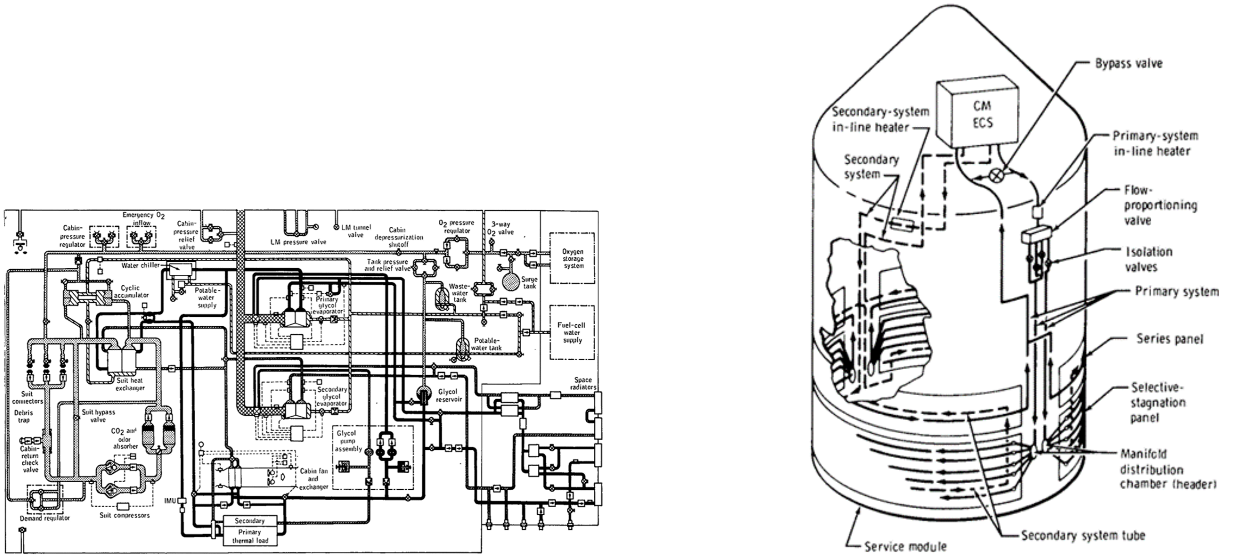


Fig. 4 STS External ATCS

Alternately, the Apollo Command and Service Module (CSM) utilized a single loop for heat rejection with a water-glycol mixture[5]. The Apollo CSM Environmental Control System (ECS) is shown in Figure 5a. The coolant circulated through the thermal radiators located on the Apollo service module (lower right) and provides cooling for the cabin fan and heat exchanger, suit loop heat exchanger, evaporators, and primary thermal loads. The Apollo CSM ECS radiators had a rejection capacity between 1100 and 1400 watts (depending on orbit about the Earth or Moon) with evaporators utilized to make up any difference relative to actual demand. The physical layout of the CSM ECS is shown in Figure 5b.



(a) Apollo CSM ECS

(b) Apollo ECS Layout

Fig. 5 Apollo ECS Schematics

III. Hybrid Thermal Control System Concept

Surface exploration on the moon presents many unique TCS challenges which include long eclipse periods, possibly exceeding 150 hours at optimum South Pole locations or 330 hours at lower latitudes or the equator, where surface temperatures may plummet well below 90K. High reliability and eliminating potential freeze/thaw cycles are primary considerations for the Lunar surface application. Loop Heat Pipe (LHP) radiators have been utilized at low heat dissipations for smaller spacecraft including Lunar landers and rovers. Being hermetically sealed with no moving parts, LHP radiators potentially offer significant reliability benefits over PFL radiators. LHP radiators can also utilize more exotic working fluids, but capillary pumping through the evaporator may limit overall dissipation. With the capability to interface and acquire many different types of thermal loads, internal PFL systems offer convenience, flexibility, and maintainability for crewed missions. If it is possible to scale up LHP heat rejection for human-rated applications, hybrid systems composed of LHP radiators coupled with an internal PFL could offer the benefits of both approaches.

Human rated and high heat rejection exploration TCS architectures typically employ separate internal and external PFL's to acquire, transport and reject heat with the internal fluid loop utilizing a non-toxic water-based coolant. In a conventional architecture, the external PFL coolant is isolated from the crew and is chosen for thermal performance (i.e., heat capacity, freezing point, etc.). An external Loop Heat Pipe (LHP) radiator may offer substantial improvements over an external PFL in reliability and performance for extreme thermal environments (i.e., Survive-the-Night) as well as providing potential resource savings. The goal of this effort was to demonstrate a hybrid TCS architecture utilizing a representative internal crew friendly PFL coupled with an external LHP thermal radiator, leveraging hardware from previous SBIRs.

A hybrid TCS schematic utilizing an external LHP Radiator coupled to an internal conventional PFL is shown in Figure 6. A propylene LHP, with a very low freezing point and high reliability, may mitigate issues associated with make-up heat during shadow periods as well as reliable operation during long dormant periods.

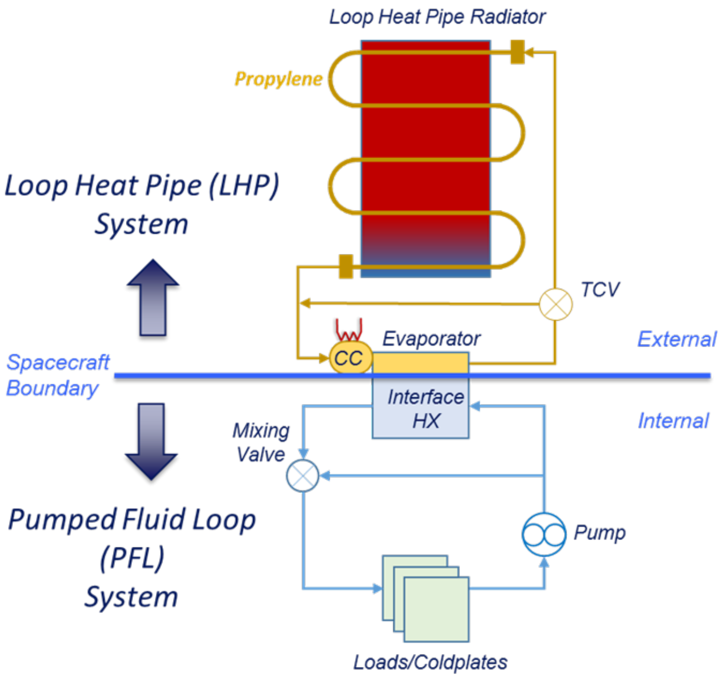


Fig. 6 Hybrid TCS Concept Schematic

A hybrid PFL/LHP TCS architecture has not been demonstrated in space for large scale heat rejection. The individual technologies are high TRL but not as an integrated system. This project aimed to provide a TRL 5 breadboard demonstration of the integrated hybrid technology against a projected starting TRL of 3. NASA's exploration missions necessitate high reliability for long term operations lasting up to 15 years (with dormancy). LHP TCS radiators have no moving parts with better Micro-Meteoroid Orbital Debris (MMOD) redundancy than similar PFL systems. LHP systems offer low freezing point fluids (propylene, -185°C) which are ideal for extreme the extreme temperature of the Lunar night.

The LHP is a two phase device which can utilize the waste heat acquired and transported via a PFL to vaporize a capillary pumped liquid. Through heat rejection, the vapor is condensed within the radiator and returned to a Compensation Chamber (CC) upstream of the evaporator based on pressure differential. Compensation Chamber heaters may be used to turn off the device by raising the temperature (and vapor pressure) of the sub-cooled liquid in the reservoir. The on-off operation of the LHP system may be explicitly controlled via a Thermal Control Valve (TCV) which closes below a defined temperature setpoint[6]. The LHP radiator differs from the PFL version in that a serpentine flow path is utilized to condense the fluid. Since the heat transfer is via condensation (i.e., latent) the heat transfer capacity of the vapor in the radiator is much greater (than the sensible heat transfer in a PFL), thus avoiding multiple flow paths and prioritizing adequate length to ensure condensation in the radiator. The serpentine flow path also provides adequate coverage to mitigate fin effect losses in the radiator.

The overall approach was to design, procure, and fabricate an integrated PFL/LHP breadboard TCS architecture for experimental evaluation inside of a thermal vacuum chamber. The breadboard test set-up with the LHP inside of a thermal vacuum chamber (to simulate the Lunar environment) integrated to a representative PFL is shown in Figure 10.

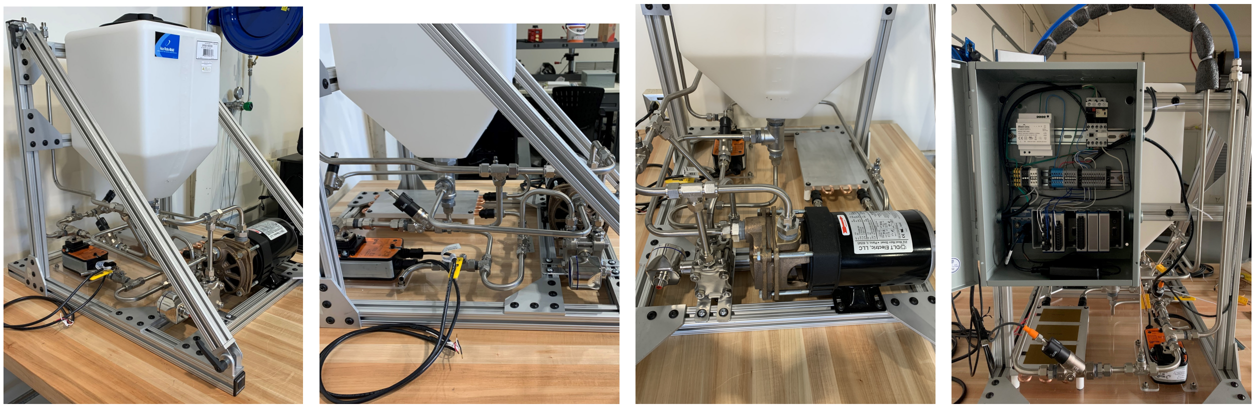
Evolution of this innovation would consider the development and test of more advanced systems with higher capacity LHP's and multiple LHP's to meet the temperature and high heat rejection demands of human rated systems in extreme thermal environments.

IV. Development of Representative Pumped Fluid Loop

In order to fully understand the performance of the concept, a representative pumped fluid loop (PFL) was built utilizing commercial off the shelf (COTS) components (Figure 7). While the system may not have the appearance of a traditional aerospace PFL due to the components used, it is functionally representative of such a system. The system was sized to provide up to 750 watts (W) of heat input, a nominal flow rate of 2 gallons per minute (GPM) (3.8 liters per minute), and a differential pressure between the pump inlet and outlet of around 50 pounds per square inch (PSI) (345 kPa). These specifications were chosen as an extensible representation of an aerospace PFL while remaining within the heat rejection capabilities of the loop heat pipe (LHP) that was developed. The PFL uses a 30% solution of propylene glycol to water (PGW), lowering the freezing point of the working fluid to around -14°C. A mixing valve is in the system to add further similarity to an aerospace system.

A preliminary component assessment was performed utilizing rubber tubing, barb fittings, and distilled water. The system was assembled to match the schematic; however, only one flow sensor, thermocouple, and pressure gauge were utilized for this early testing. All sensors were monitored using the National Instruments (NI) Measurement and Automation Explorer (MAX) since the control system would be built in LabVIEW. Once the PFL was assembled the pump was started and measurements showed that the pressure was hovering around 51 PSI as expected. The cumulative flow measurement, however, was a little high at around 3.5 GPM. This measurement was taken downstream of the mixing valve to ensure the total flow rate was captured.

The final assembly was built upon the lessons learned from the preliminary build. The rubber tubing was replaced with 0.5 inch (1.27 cm) diameter stainless steel. The second flow meter and the rest of the thermocouples were added to the system. Finally, a control box was built to integrate all of the electronics. The control box contained a distribution bus for 120VAC power for the cDAQ power supply, pump motor starter, and 24VDC power supply. The 24VDC power supply fed a second distribution bus for the low-voltage sensors. An input/output rail was installed to easily wire the sensors to power and the cDAQ current input module.

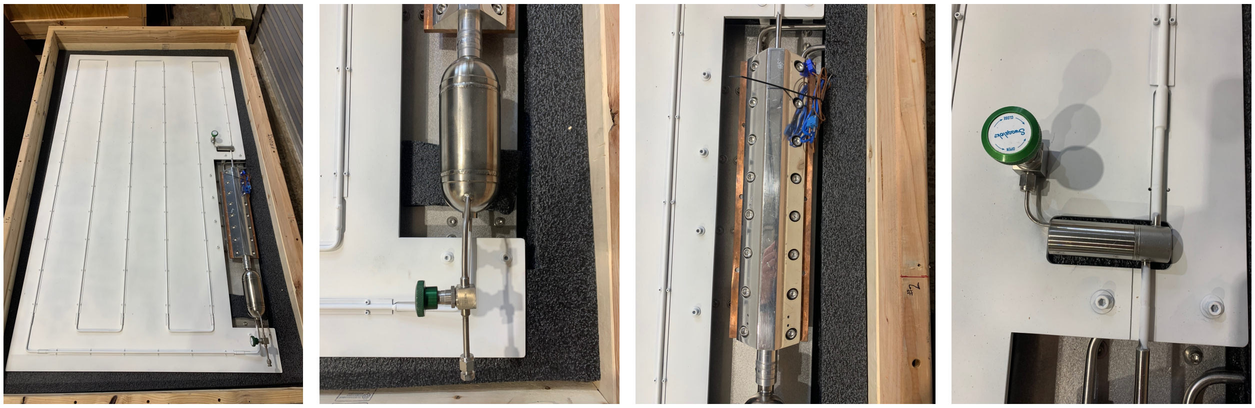


(a) PFL Isometric View **(b) PFL Side View** **(c) PFL Front View** **(d) PFL Control Panel**

Fig. 7 Representative Pumped Fluid Loop

V. Loop Heat Pipe with Thermal Control Valve

A loop heat pipe (LHP) is a two-phase thermal control device that can transport large amounts of heat over moderate distances. The design of an LHP allows for it to even be made with flexible transport lines, making it ideal for use with integrated radiators. The LHP for this effort was fabricated by Advanced Cooling Technologies (ACT) in Lancaster, Pennsylvania (Figured 8). Due to cost limitations, a previously developed evaporator prototype was incorporated into the LHP. The evaporator was integrated with a thermal control valve (TCV) and a radiator with an effective area of $1.44m^2$ that was painted white to maximize emissivity. The system was sized to accommodate up to 1000W of heat rejection.



(a) LHP Radiator **(b) LHP Comp Chamber** **(c) LHP Evaporator** **(d) LHP TCV**

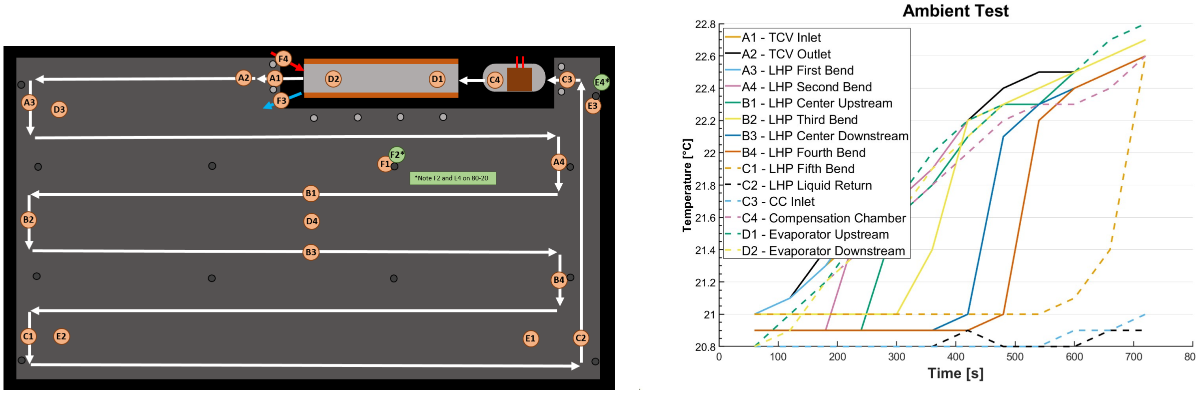
Fig. 8 Loop Heat Pipe Radiator with Thermal Control Valve

The key component to the LHP is the TCV which allows for passive shut down of the LHP at low temperatures. This passive shut down is important to protect systems that need to survive in the extreme thermal environments of the Lunar surface. In general, a TCV is designed to divert or restrict flow to the LHP condenser when the working fluid in the evaporator reaches a set minimum temperature. Previous TCVs from Pacific Design Technologies (PDT) have flown on several Mars rovers[7]; however, thermal vacuum testing of these valves for a Lunar rover application in 2021 showed a small amount of flow through the TCV at all times. This is not ideal for a survival application, so ACT has developed their own TCVs to mitigate this issue. The TCV can be charged with gaseous nitrogen at different pressures which correspond to the valve's set temperature. The gaseous nitrogen in the valve works against the evaporator's vapor pressure to fully close the valve. This TCV operates within a single flow path to restrict flow when the inlet temperature falls below the minimum temperature set point. When the working fluid temperature inside the LHP evaporator reaches the set temperature, the TCV closes to prevent vapor transport which prevents the LHP from rejecting heat unnecessarily during the lunar night.

A frame was built out of 80/20 T-slotted aluminum extrusions to support the radiator in the vacuum chamber. The frame was built to allow the angle of the LHP to be easily tilted without removing it from the vacuum chamber. Initial testing was performed with the LHP in a horizontal arrangement, which is conservative for a system that will be used in Lunar gravity. By tilting the frame approximately 10°with the evaporator on the low side (reflux mode), Lunar gravity can be simulated to better understand the maximum performance of the system.

VI. Ambient Testing

Ambient testing with the radiatively cooled LHP was a challenge, so limited observations were obtainable. While sitting in the vacuum chamber at ambient temperature and pressure, a brief test was conducted to demonstrate loop startup. This was performed to ensure the loop operated as expected before beginning to flow liquid nitrogen (LN_2) through the shroud. Cycling the chamber pressure to high vacuum (2×10^{-6} Torr) was a relatively quick endeavor (approximately one to two hours for high vacuum). On the other hand, cooling the cryo-shroud, took approximately 12 hours due to the large thermal mass of the stainless steel shroud. Thermocouple locations on the LHP are shown in Figure 9a and the ambient test results are shown to the right in Figure 9b.



(a) TC Diagram **(b) Ambient Test Results**

Fig. 9 Ambient Test Results

Not pictured in the ambient test results plot are the thermocouples for the PFL, which quickly approached 30°C with just the waste heat input from the pump. This level of base heat load from the pump was a persistent difficulty throughout testing. Over the approximately 10 minute duration of ambient testing, the LHP evaporator temperatures (TCs D1 and D2) continued to increase in temperature. The characteristic progressive temperature jumps throughout the condenser line (TCs A3 though C2) indicates the vapor front successfully moving through the two phase region of the LHP – demonstrating that the loop successfully started up upon the application of heat to the evaporator. Successful completion of this test allowed the team to proceed to reducing the chamber pressure to high vacuum and cooling down the cryo-shroud for more rigorous thermal vacuum testing.

VII. Thermal Vacuum Testing

Thermal vacuum testing of the combined system was performed in the Space Environmental Effects (SEE) lab at MSFC. The SEE team has the capabilities to simulate all aspects of the space environment in their facilities. In this case, their 4’ x 8’ High Intensity Solar Environment Test Capability (HISET) chamber was used due to the size of the LHP. The HISET chamber has a cryogenic liquid nitrogen shroud to set the sink temperature to around -170°C. It reaches a high vacuum level range of 1×10^{-7} Torr. Feedthroughs for 30 thermocouples, the PFL inlet and outlet fluid lines, and power for the compensation chamber heater were installed in the chamber. A schematic of the test setup for the combined hybrid system is shown in Figure 10.

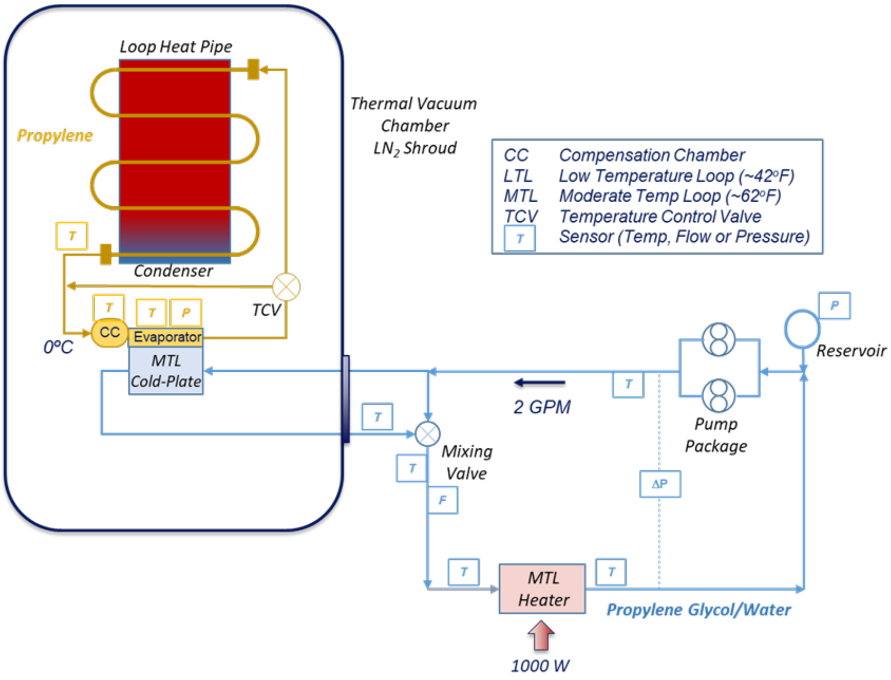


Fig. 10 Thermal Vacuum Test Schematics

The desired test plan sequence is shown in Figure 11 as an approximate representation of target temperatures. The ambient checkout ensures that the LHP starts as expected when the pump is turned on. Following this checkout, the chamber is pumped to high vacuum and the shroud is cooled to bring the LHP into a survive-the-night state to demonstrate the ability of the TCV to protect the PFL and keep the PGW mixture from freezing. The TCV is cycled on with a heat ramp and then brought back down to survive-the-night temperatures. Several thermal balance tests follow to demonstrate performance at various evaporator heat loads. This increase in power is driven until it is observed that the LHP no longer transports heat efficiently and begins to rise sharply in temperature. The second portion of the sequence tilts the radiator to simulate lunar gravity as described previously.

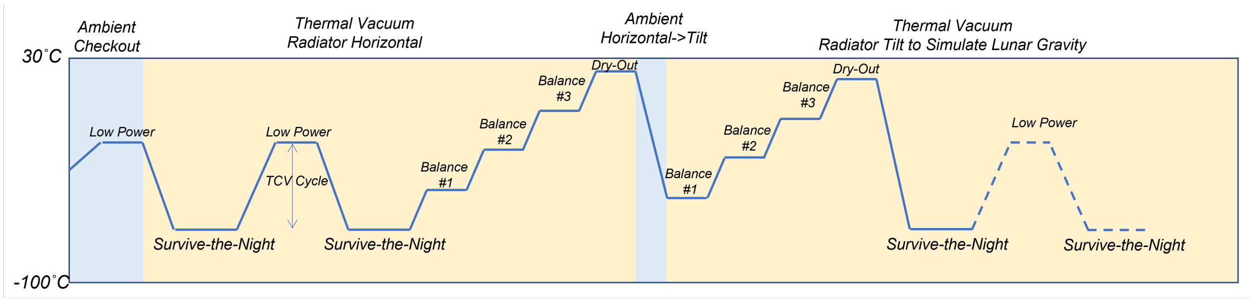


Fig. 11 Test Plan Sequence

Several challenges needed to be overcome during TVAC testing. After reaching a steady state with the actively cooled cryo-shroud and only the pump's base heat load, it was observed that the LHP was significantly colder than expected. The temperature difference between the PFL interfaces to the evaporator were also very large (delta T of 30°C), implying poor connections between the interfaces. The LHP also showed the typical operational temperature profile, with large temperature drops across the loop, at temperatures below the TCV setpoint which indicated the LHP had not shut off. In this case, the TCV was set to a pressure that was supposed to correspond to an evaporator temperature of 0°C; however, the evaporator reached a significantly colder temperature of -39°C by the end of the test. From this result, it became clear that the TCV was not operational; so the flow of LN2 to the shroud was turned off and the system was allowed to warm up to ambient temperature (an overnight process). Following the chamber venting the next morning,a pressure gauge was attached to the TCV which confirmed that there was no pressure inside the TCV. The TCV was recharged with gaseous nitrogen to 80 PSI (0°C evaporator set point). Additionally, the PFL interface was improved. The interface involves a copper spreader bar sandwiched between the evaporator and the PFL heat exchanger. It was confirmed that thermal interface material (TIM) was present at each interface, however the screws holding the PFL heat exchanger to the copper spreader bar had loosened almost completely with the dramatic temperature change of the test. This lack of clamping pressure under vacuum greatly increases the thermal resistance across the interface, explaining the large temperature difference observed between the PFL temperature and the evaporator temperature. Twelve additional screw holes were through-drilled in the copper and aluminum PFL heat exchanger to allow for screws to be added with locking nuts to ensure a consistent clamping pressure over the interface.

The chamber was pumped back down and the cryo-shroud was flooded with LN2 to reach its nominal -170°C temperature. Steady state results from this test trended in the expected direction, but were still showing the LHP in operation even during the survive the night phase of testing. After conferring with ACT, it was learned that the TCV was operating as designed, but not as the authors had expected. The authors were under the impression that below the set point the TCV would close and remain closed until additional heat was added to the system. In hindsight, and with clarification from ACT, the actual operation makes sense: with the constant base heat load from the PFL pump, the TCV operates in a pulsing manner to keep the evaporator at the set point temperature. This pulsing operation causes the loop to operate, instead of reaching the isothermal condition originally expected. This behavior is shown in Figure 12 by the TCV outlet (TC A2 from TC diagram in Figure 9a).

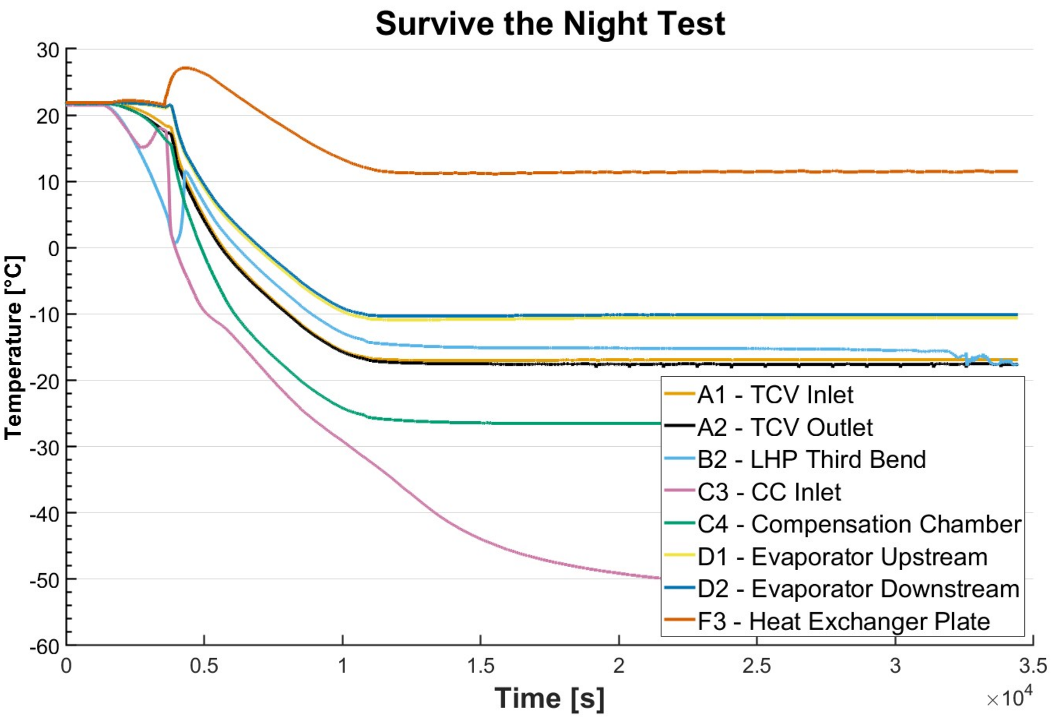


Fig. 12 Survive the Night Results

The periodic drops in temperature correspond to the release of pressure from the TCV. In other words, the vapor pressure inside the evaporator reaches a point where it overcomes the TCV pressure, which can be observed by the short temperature pulse. It can also be seen in Figure 12 that the evaporator temperatures, TC D1 and D2, are holding steady at -10°C. This demonstrates another unexpected response that was revealed from the testing, since the TCV was supposed to be set to an evaporator set point of 0°C. Upon further discussion with ACT, it was clarified that the relationship between TCV pressure and evaporator was derived by applying constant TCV pressure through a pressure regulator. In application, the TCV pressure will not be constant due to the environmental and internal LHP temperature changes. To mitigate this discrepency, the TCV was plumbed out of the vacuum chamber to a regulated K-bottle of high pressure GN2. Once the chamber was back to high-vacuum and the shroud was cold, a series of TCV set point tests were performed to verify that each constant pressure set point corresponded to the expected evaporator temperature set points.

An experiment to reduce the base heat load from the PFL pump was performed. This purpose of this experiment was to determine if enough heat could be removed such that the TCV would stay closed and keep the LHP in a shutdown state, since the minimum PFL pump heat load (200 W) was enough to cause the pulsing operation as described previously. Unfortunately, the pump could not simply be stopped, which would remove the heat load from the evaporator entirely, since the PGW would freeze inside the PFL interface. Shutting down the pump would also not be an extensible case to an operational system. In a full TCS, the pump power would be distributed through multiple LHPs, so an individual LHP would have a lower minimum heat load during survive-the-night operation. To simulate this case, a secondary recirculating chiller was introduced via a cold plate fastened to the PFL heater plate. These plates were identical model numbers so they matched exactly. A TIM was installed between them, and moderate clamping pressure was applied. The working fluid in the secondary chiller was pumped through the cold plate to pull heat out of the PFL. With the secondary chiller set to 0°C the temperature of the PGW with the pump operating was reduced from 22°C to 13°C. The observed result in the LHP was a decrease in TCV pulse frequency and a decrease in downstream condenser temperatures, showing that reducing the heat load on the evaporator did trend towards shutting the LHP down completely. Unfortunately, the secondary chiller was at its capacity for heat rejection and the PFL temperature did not decrease enough to completely shutdown the LHP. At this point the decision was made to accept the TCV operation as is with a -10°C evaporator set point and proceed to the test profile.

The survive-the-night test results shown in Figure 12 demonstrate that the combination of a PFL and a LHP with TCV can passively protect the PFL from freezing. Additionally, with a low heat load, it will maintain a roughly constant

PFL loop temperature for consistent heat rejection inside the crewed space. The thermal balance tests were performed at heater set points of 0 W (survive-the-night), 200 W, 400 W, and 600 W as shown in Figure 13. The increase of LHP temperature at selected points with increasing power is shown in Figure 14. It can be seen in Figure 13 that the evaporator temperature increased above -10°C upon the application of heat, implying the TCV remained open to reject as much heat as possible as expected. This behavior was consistent for every balance test. A steady state condition of $\frac{0.5°C}{hour}$ was imposed for these developmental level tests. Due to the base heat load of 200 W from the PFL pump, the maximum heat load tested was near 800 W. This fell short of the 1000 W goal, but the limitation was caused by PFL hardware temperature limits. Due to the still relatively poor interface between the PFL and LHP evaporator the PFL temperature was increasing drastically with the increased heater power. During the 600 W test the LHP temperatures were still very moderate, however the PFL temperature was approaching the maximum hardware limit of 50°C. Based on observations of LHP performance, the LHP would have easily supported 1 kW of heat rejection given adequate coupling to the PFL.

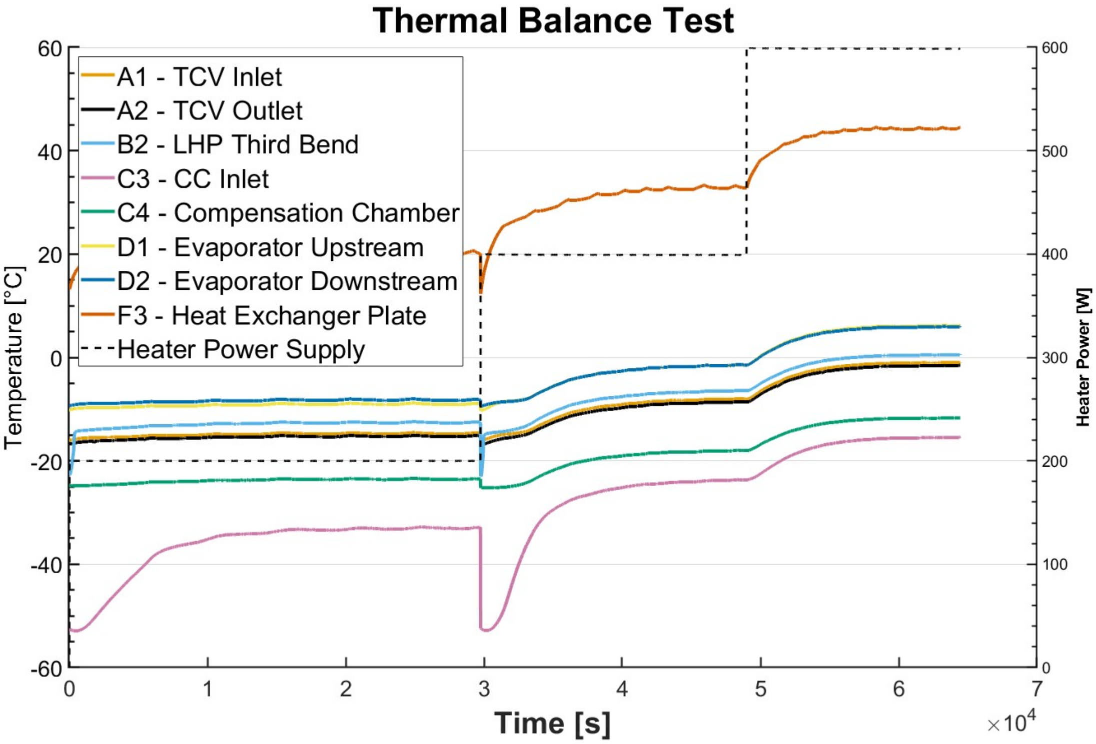


Fig. 13 Sample Thermal Balance Test

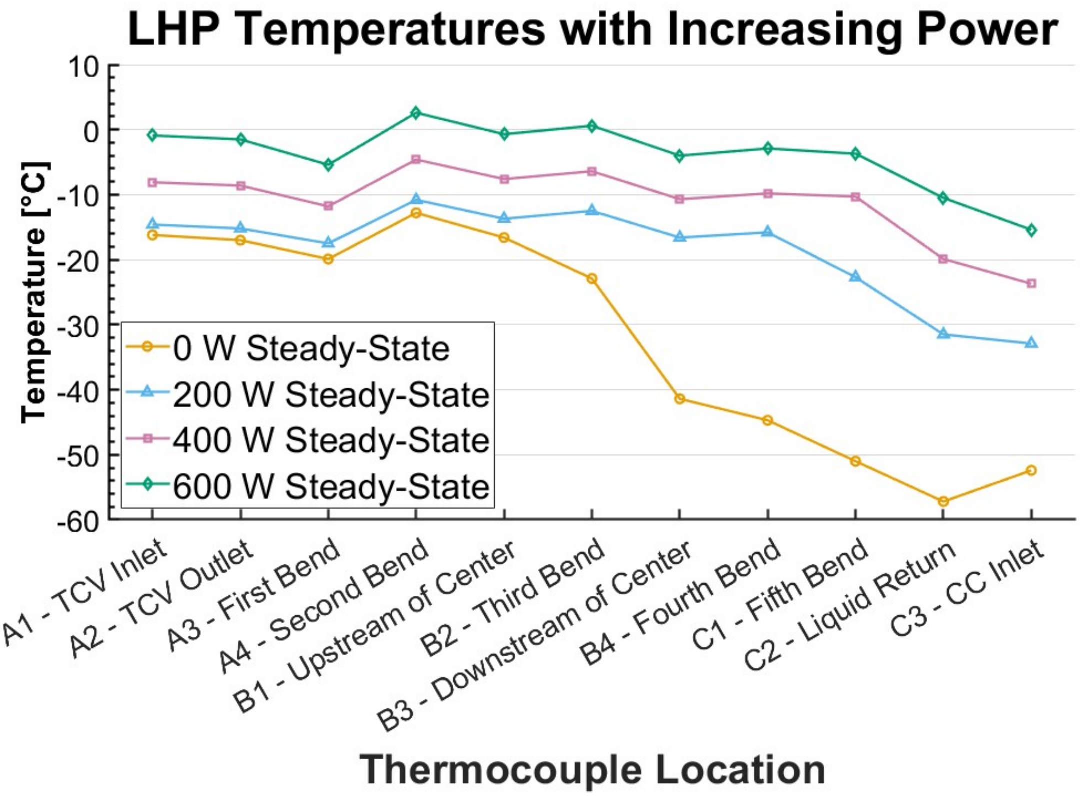


Fig. 14 Heat Pipe Temperature Increasing with Power

VIII. Future Testing

While the overall hybrid concept was demonstrated, several improvements are needed between the hardware and the test apparatus to draw quantitative conclusions compared to traditional systems. A significant pain point during testing was the large temperature difference (due to poor interface conductance) across the interface between the PFL and the LHP evaporator. Ideally, this temperature difference would be minimized to ensure the PFL working fluid is not increasing in temperature with added heat load. For future tests this interface will be optimized. Potential solutions include custom fabricating a heat exchanger that exactly matches the flange dimensions of the LHP evaporator, eliminating the copper spreader block used in this test. In turn, this reduces the number of mating surfaces down to a single interface. A more elaborate, but potentially more effective, option would be to fabricate the LHP evaporator with embedded fluid channels for the PFL. A trade study and cost-benefit analysis would need to be performed to determine the ideal option.

Another improvement required for future testing is to develop a TCV charging curve that more accurately captures the physics in operation. The TCV charge curve for this testing was created utilizing a constant pressure on the TCV, which neglects to take temperature change into account. A more accurate curve would establish pressure setpoints at operating temperatures.

The PFL also needs to be improved to more accurately represent operational systems. The current PFL was built entirely utilizing commercial and industrial-grade components. These components were suitable to demonstrate concept feasibility, but a more extensive test would benefit from utilizing aerospace-grade components.

Finally, additional two-phase heat transfer devices should be procured and integrated in future testing. A variable conductance heat pipe (VCHP) radiator concept is also viable in place of the LHP radiator and should be tested for comparison. The hybrid concept will rely on multiple radiators in application, so the next test campaign should include at least two radiators operating together. Implementing all of these improvements will allow for quantitative comparisons to traditional systems.

IX. Conclusion

A hybrid concept for exploration-class thermal control systems was demonstrated. The concept combined an active pumped fluid loop for waste heat collection inside a crewed volume, coupled with an exterior loop heat pipe radiator for rejection to space. Given the difficulties faced during testing, quantitative comparisons to a traditional TCS for exploration spacecraft are challenging. The fundamental concept was proven to work – heat was successfully rejected from a PFL via a LHP radiator. The passive nature of the TCV was shown, albeit in a different manner than originally anticipated. Heat rejection of up to 800 W was shown, with a feasible path to the 1 kW rejection goal. Future testing with improved interfaces between the LHP evaporator, and with increased PFL capabilities to reach lower and higher heat loads on the LHP, will continue to demonstrate the feasibility and extensibility of the hybrid TCS concept for exploration-class habitats and vehicles.

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