# Multiple Loop Heat Pipe Radiator for Variable Heat Rejection in Future Spacecraft

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**As NASA refocuses its human mission ambitions to colder areas of exploration beyond Low Earth Orbit, the need for improved variable heat rejection thermal control systems increases. To account for large variations in heat loads and environment temperatures, a thermal control system with a large turndown ratio is required. This paper presents a variable heat rejection system that uses multiple Loop Heat Pipes (LHPs) to reject large heat loads from a single-phase pumped loop, with high turndown ratios. A novel method of LHP control through local flow rate modulation of the single-phase fluid is developed and demonstrated. Systematic Thermal Desktop modeling of multiple LHP systems was performed to demonstrate the potential of this method. A modeled 2.5 kW three LHP system was shown to have a turndown ratio of 10:1 at a sink temperature of -41°C K and a turndown of 1.5:1 at a sink temperature of -269°C. Finally, an experimental study of a two-LHP system was performed to support the conclusions of the modeling effort.**

## I. Introduction

From the simplest satellite to the most complicated human controlled vehicle, all spacecraft require some form of thermal control and management. A spacecraft's thermal control system can be separated into three main functions: heat acquisition, heat transport, and heat rejection. In manned spacecraft, heat acquisition can be accomplished through heat exchangers and cold plates utilizing a single-phase fluid. Heat transport may be carried out using a pumped fluid loop, constant conductance heat pipes, or loop heat pipes (LHPs). Heat rejection is then accomplished by a radiator, which radiates the waste heat to the cold of space. These thermal control functions are critical to the successful operation of any space flight mission.

Thermal control systems are typically sized to reject the maximum heat load in the warmest continuous environmental conditions. The resultant radiator surface area is larger than is needed for the portions of the mission when the heat load is lower and/or the environment is colder. To account for these variations in operating conditions, the spacecraft thermal control system must be capable of variable heat rejection and have a large enough turndown ratio to meet the requirements of the entire mission. The turndown of a heat rejection system is defined as the maximum heat load rejected that the system is sized for, divided by the minimum heat load the system is capable of rejecting while still maintaining required heat source temperatures.

Pumped single-phase fluid loops have in the past been used for heat rejection. A single-phase fluid can be pumped through a radiator panel, with variable heat rejection accomplished by controlling the flow rate of the fluid. However, because of the low temperatures encountered in the radiator, exotic and expensive fluids must be used to prevent freezing in the radiator. LHPs on the other hand, use commonly available working fluids and are more isothermal, so freezing in the radiator is only an issue when the LHP is inactive. Additionally, single-phase loops require additional spacecraft mass and power to provide the necessary pumping. The use of LHPs removes the need for additional pumps, as they operate passively and require only a small amount of power for control.

Loop heat pipes have been successfully used for the thermal control of many NASA and non-NASA spacecraft. LHPs passively provide variable thermal transport in variable heat rejection thermal management systems. However, there is a practical limit to the amount of heat a single LHP can carry. For this reason, a multiple LHP system has been developed for variable rejection of large heat loads. This paper presents a preliminary design of a multiple LHP system for rejecting heat from a single-phase pumped loop used to cool a crewed cabin on a future manned spacecraft. A

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novel method of LHP control through local flow rate modulation of the single-phase fluid is presented. An experimental study of a two-LHP system is performed to demonstrate the LHP control methodology.

## II. Background

Future manned spacecraft will encounter a wide range of environmental conditions. In addition to the transit through the cold of deep space, astronauts may also encounter warmer transient environments such as low planetary or lunar orbits. Additionally, different portions of the spacecrafts' mission will require varying levels of waste heat to be rejected.

### A. Loop Heat Pipes

The loop heat pipe (LHP) is a very versatile heat transfer device which can transport a large heat load over a long distance with a small temperature difference. A typical LHP consists of an evaporator with integral compensation chamber (CC, also known as a reservoir), a condenser, a vapor line, and a liquid line. Figure 1 shows a schematic of a LHP. Note that the figure is not to scale; the vapor and liquid lines can be made much longer. Figure 2 shows the LHP evaporator in more detail. Heat is applied to the evaporator, which evaporates liquid working fluid from the outer surface of the primary wick. This vapor is collected in a system of grooves and channels and flows to the condenser through the vapor line. Heat is removed from the condenser, and the vapor condenses back to liquid. Most of the condenser is filled with a two-phase mixture, while a small section provides a small amount of sub-cooling. The liquid then travels through the liquid line to the CC.

The CC is designed to operate at a lower temperature, and thus a lower pressure, than the evaporator. It is this pressure difference which allows the condensate to flow from the condenser back to the CC. The liquid is then fed into the primary wick through a central bayonet. The secondary wick between the evaporator and CC allows the CC to supply liquid to supplement the liquid return to ensure that the primary wick is always saturated. This is accomplished through the design of the CC volume and other components. The cycle is completed as liquid is pumped by capillary action to the outer surface of the wick, where the vaporization occurs. A more detailed description of the operating principles of the LHP (Ku, 1999), and a survey of parameters considered in LHP design (Launay et al., 2007), exist in the literature.

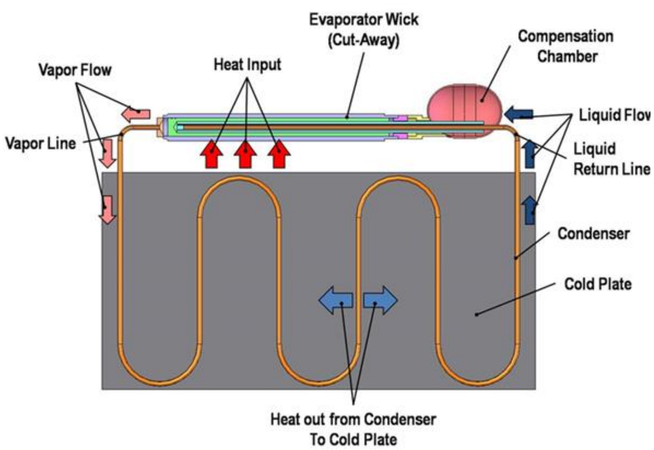


**Figure 1. Schematic of a typical LHP (not to scale)**

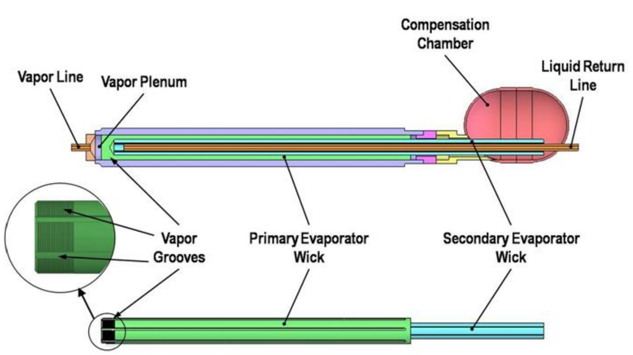


**Figure 2. Detailed view of LHP evaporator/compensation chamber assembly**

### B. LHP Temperature Control

The LHP operating temperature is governed by the saturation temperature in the CC, which varies with heat load and the condenser sink temperature. For most space applications, the LHP operating temperature must be controlled within a narrow range. The most commonly used method to control the CC saturation temperature at a desired set point is to cold bias the CC and use an electric heater. This method has been proven effective in controlling the operating temperature of the LHP within several Kelvin for many LHPs onboard orbiting spacecraft. One issue with cold-biasing of the CC is that the required control heater power can be very large when the condenser sink is very cold and there is a large amount of subcooling in the liquid line. This required heater power can translate to an unacceptably large mass penalty for some spacecraft systems. Therefore, minimizing the required control power is desired.

Several methods have been investigated to reduce the subcooling of the liquid and thus the control heater power requirements. Some of these methods include aluminum coupling blocks between the vapor and liquid lines, variable conductance heat pipes connecting the evaporator and the liquid line, and thermal control valves to provide a vapor by-pass and divert part of the vapor from the vapor line to the liquid line (Walker et al., 2013).

## III. Variable Heat Rejection Multi-LHP Radiator

A conceptual schematic of the multiple loop heat pipe system for variable heat rejection is shown in Figure 3. The evaporators of the LHPs are coupled in series to the single-phase pumped loop through a heat exchanger. Three LHPs are shown in the figure, but any number of LHPs could be used to meet the heat rejection and redundancy requirements. The temperature change of the single-phase fluid is measured between each LHP, with the goal of maintaining the set point temperature of the fluid returning to the crew cabin. As the heat rejection load or the sink temperature is reduced, the total thermal resistance of the LHPs can be changed by a variety of control methods to maintain this set point. An initial evaluation indicated the required CC control heater power to be large for this system, so a new control methodology was developed that does not require the application of control power.

As shown in Figure 3, a bypass loop can be added to the pumped single-phase loop, such that the local flow rate of the single-phase fluid traveling through the heat exchangers coupled to the LHPs can be varied, while the total flow rate returning to the cabin is maintained. This has the effect of changing the total thermal resistance of the LHPs in the following way. As the mass flow rate increases, the temperature drop in the single-phase fluid across each interface decreases, which has the effect of keeping the LHP radiator warmer, and thus increasing the heat rejection of the LHP. Similarly, decreasing the mass flow rate of the single-phase fluid will increase the temperature drop across each interface, such that downstream LHPs have a lower radiator temperature and will reject less power. The local flow rate can be modulated such that when the warmer fluid in the bypass is mixed with the cooled fluid that has gone through the LHP interface heat exchangers, the resultant temperature is the system set point temperature. Using this methodology, the total heat rejected by the system can be varied without the use of CC control heaters.

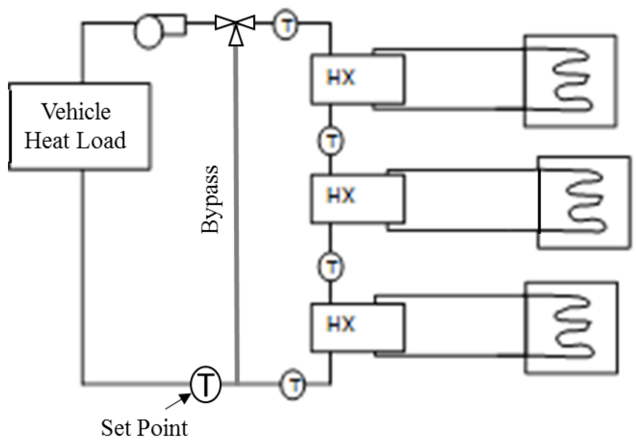


**Figure 3. Conceptual multi-LHP system architecture; 3 LHPs are shown**

## IV. Thermal Desktop Modeling of Multi-LHP System

An extensive modeling effort was performed using Thermal Desktop software to evaluate the new multiple-LHP system and control methodology. Thermal Desktop software, sold by C&R Technologies, is a graphical user interface for doing numerical fluid dynamics and heat transfer analysis based on SINDA/FLUINT. In this model, a 50/50 propylene-glycol/water mixture was used for the single-phase fluid, and its total mass flow rate was 0.1 kg/s. Three LHPs using propylene as the working fluid were coupled in series to the single-phase pumped loop. The system was sized to reject 2500 W in the warmest sink, and the set point temperature to be maintained was 8°C K.

The first case that was investigated was that of a constant power rejected to a variable sink temperature. Two iterations of this case were modeled. In the first, the LHP condenser lines share a common radiator panel, but have separate sections of that panel. In the second, the LHP condenser lines are overlapped and share a common radiator panel. Results for both configurations are shown in Figure 4, where the local mass flow of the single-phase fluid that is required to reject 2500 W (with a heat flux of 92.6 W/$m^2$ at the radiator) and maintain the set point is plotted against the sink temperature. Also shown are results for a similar three LHP model that used ammonia as the working fluid and had a higher total single-phase mass flow rate of 0.25 kg/s, rejecting 2500 W (with a heat flux of 188 W/m$^2$). Those results were similar, but were not able to be taken to lower temperatures due to freezing of the ammonia.

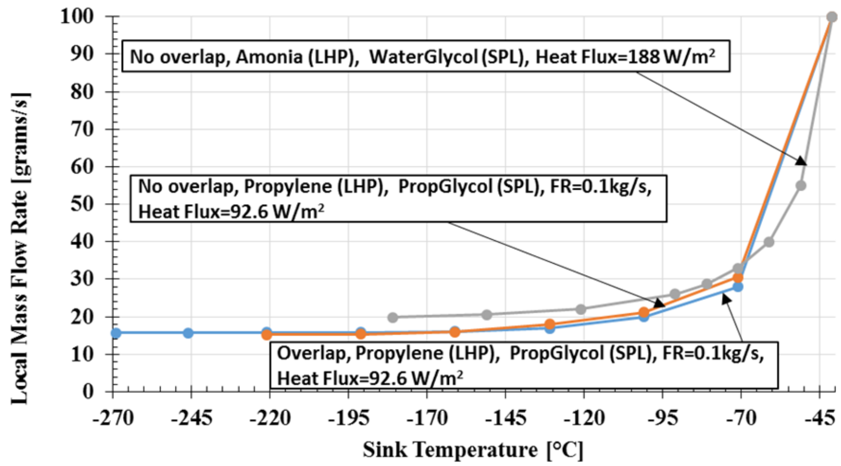


**Figure 4. Local mass flow rate required to maintain set point temperature while sink temperature changes for constant power (2500 W).**

The second case that was investigated was that of rejection a variable power with a constant sink temperature. In this investigation, only the non-overlapping radiator configuration was modeled. The rejected power was reduced from 2500 W down to lowest power that the LHPs would reject before the single-phase fluid in the local loop reached its freezing point. The results of this computation are shown below for sink temperatures ranging from -41°C down to -269°C . Figure 5 shows the local mass flow rate required to maintain the set point plotted against the rejected heat load.

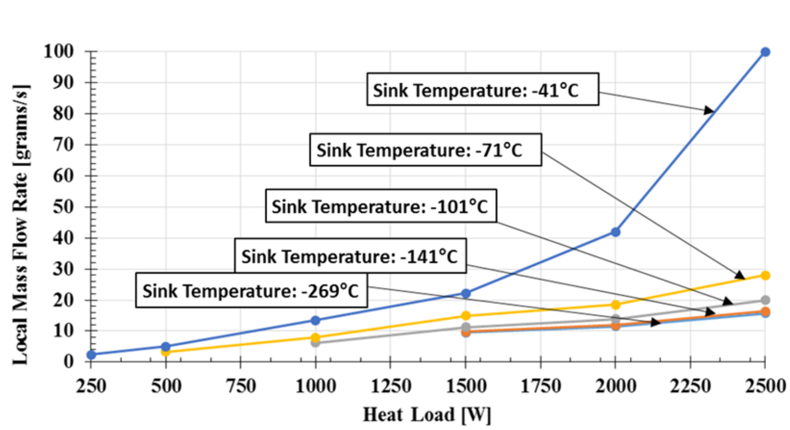


**Figure 5. Local mass flow rate required to maintain set point temperature as heat load changes for constant sink temperature.**

These results are further explored in Figure 6 and Figure 7. Figure 6 shows the temperature distribution along the length of the local single-phase fluid between the LHP interfaces for several heat loads at a sink temperature of -269°C . this is the coldest sink temperature that would ever be seen by a radiator in deep space, and can be considered the worst case scenario for turn down. A turn down of 1.5:1 is shown here without the need for CC heating or other control measures. Further turndown could not be achieved for these conditions without freezing the local single-phase fluid.

In Figure 7, the temperature distribution along the local single-phase fluid is shown for several powers at a sink temperature of -41°C K, which can be considered the warmest sink a radiator might see, and thus a worst case scenario for power rejection. For this sink, a turn down of 10:1 is shown without the need for CC heating. Note in Figure 7, that at low powers (higher turn down ratios), the single-phase fluid temperature experiences a reversed gradient across the last LHP. This is due to the fact that the third LHP is completely shut down in this case, and heat gained by the ambient causes the single-phase fluid to warm slightly. Ambient gains and losses are accounted for in the model for

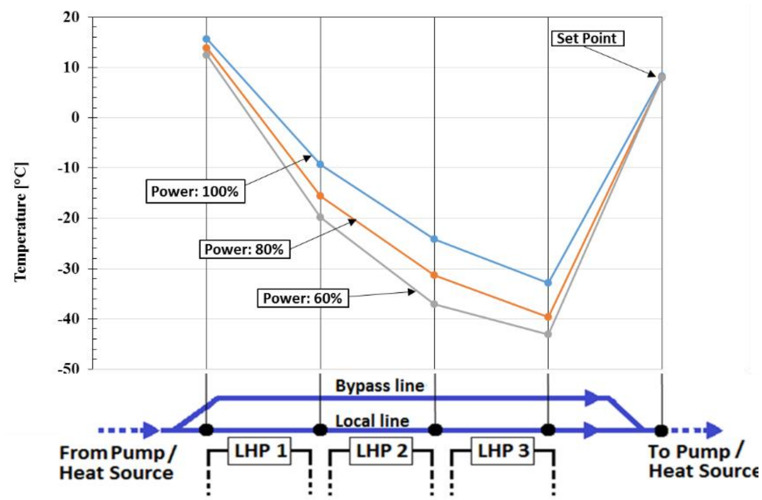


**Figure 6. Temperature distribution along local portion of single-phase loop as power changes for a sink temperature of -269°C.**

the vapor lines, liquid lines, evaporator bodies, and CCs, with the ambient temperature held at 11.5°C.

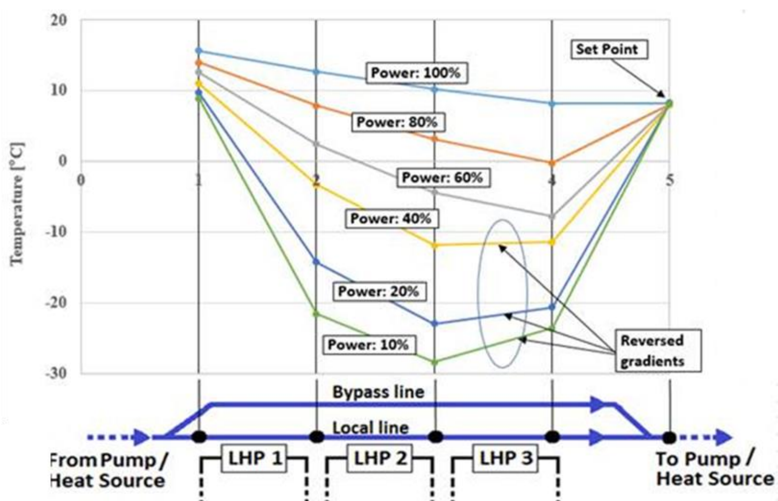


**Figure 7. Temperature distribution along local portion of single-phase loop as power changes for a sink temperature of -41°C.**

## V. Experimental Validation

An experimental study was performed to demonstrate the feasibility of variable heat rejection with multiple LHPs and thermal control using local flow rate modulation, and to validate the conclusion of the Thermal Desktop modeling effort. Two existing LHPs were incorporated into a test setup that was developed and fabricated to perform these experiments. A third LHP was originally included in the test setup, but it would not startup during initial testing, likely due to internal damage of the primary wick during handling and assembly of the test setup. The two remaining LHPs both consisted of 30.5 cm flanged evaporator bodies, with slightly different CC volumes. The liquid and vapor lines of each LHP were connected to a section of a common condenser plate. The condenser rejected heat through radiation and natural convection to a cold wall cooled by liquid nitrogen.

The LHP evaporators were coupled to a pumped single-phase loop through heat spreader plates fastened to the LHP evaporator flanges. The single-phase loop was configured with a bypass loop, so that the relative flow rate could be varied from 100% through the heat spreaders to 100% through the bypass. This was done by manually operating a valve to adjust the respective flow rates. The two streams were recombined and the temperature downstream of the junction was measured and defined as the set point to be maintained. Power was input to the single-phase loop through heaters embedded in a reservoir. The single-phase fluid used in the experiments was water. The temperature of each component of the LHPs, as well as the water temperature entering and exiting each heat spreader was recorded

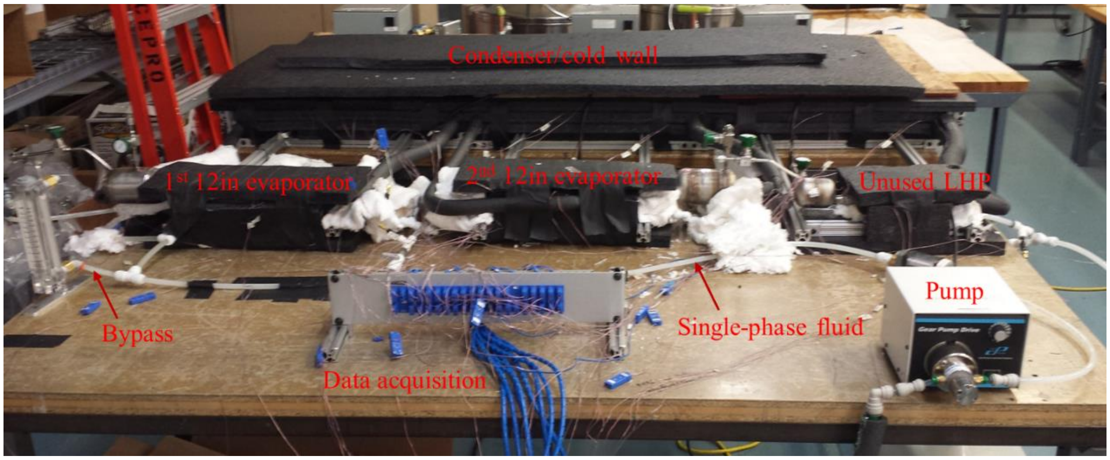


**Figure 8. Photograph of fully assembled and insulated multiple LHP variable heat rejection test setup.**

throughout the measurement. A picture of the test setup, fully insulated, is shown in Figure 8.

The first test demonstrated the ability to maintain the single-phase fluid loop set point temperature as the sink temperature dropped for a constant heat load. This was done by gradually reducing the flow rate through the heat spreaders and correspondingly increasing the flow through the bypass. To begin the test, a fixed power was applied to the water reservoir, and the LHPs were allowed to reach a steady state, with the full flow rate through the heat spreaders and the heat sinks at a temperature of 2°C. The set point temperature was measured to be 51.5°C. For the remainder of the test, the goal was to maintain this temperature. The sink temperature was gradually reduced to -18°C, at which point the LHPs were allowed to reach steady state again. Figure 9 gives the temperatures of the heat sink and various components of the LHPs, along with the local water flow rate. Figure 10 shows how the set point temperature was maintained at 51.5°C +/- 0.5°C through the whole range of sink temperatures. Finally, Figure 11 shows the total heat rejected and the heat rejected from each LHP, calculated from the flow rate and temperature change of the water loop. The power rejected by the system was fairly constant, between 400-500 W.

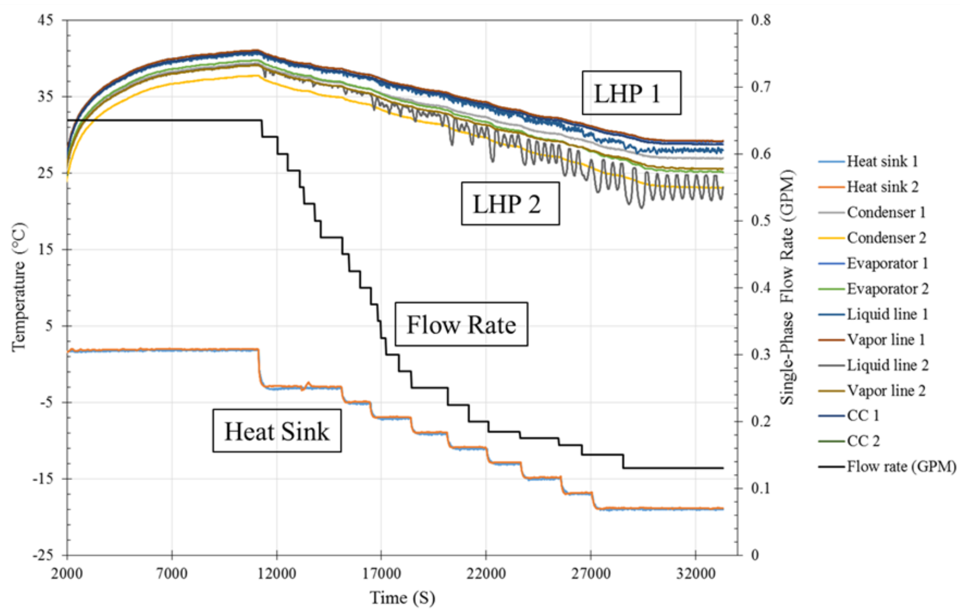


**Figure 9. LHP component temperatures recorded as heat sink temperature is reduced from 2°C to -18°C. Local water flow rate is also shown.**

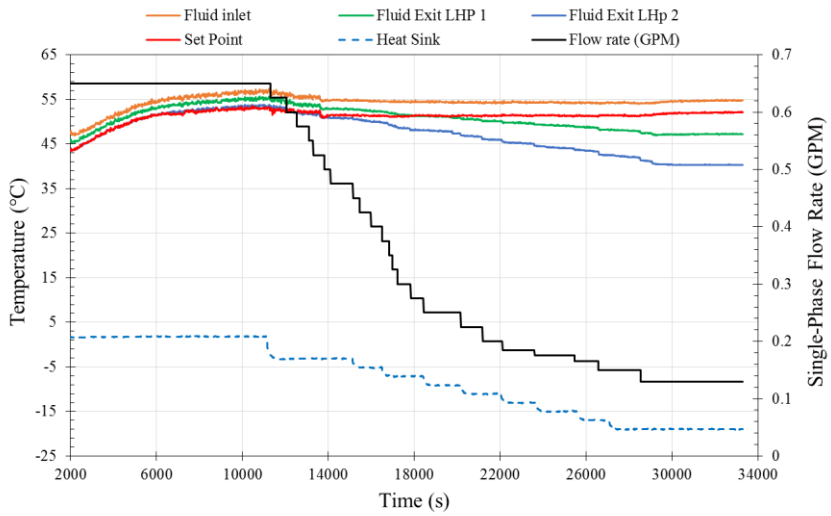


**Figure 11. Water temperature entering and exiting each LHP heat spreader, along with water flow rate. Note how the set point temperature is maintained as the sink temperature and local water flow rate are reduced.**

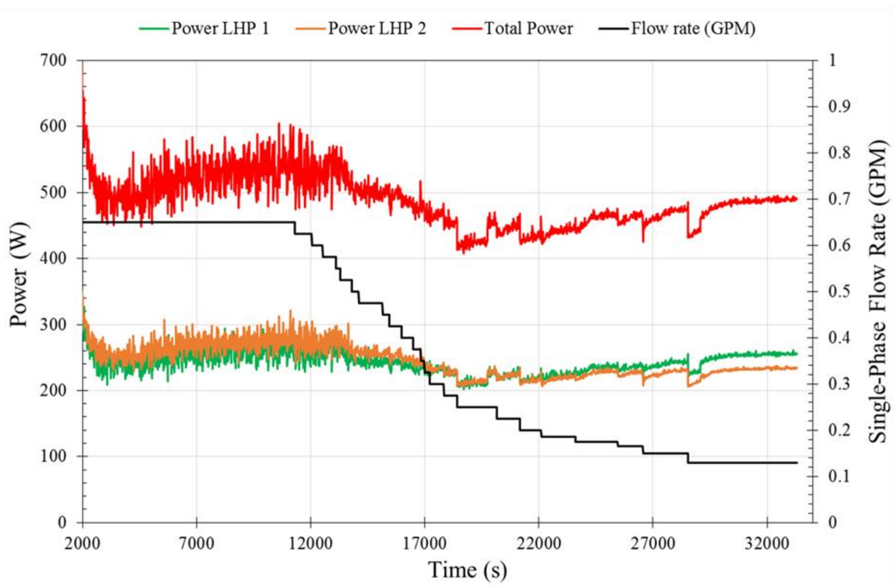


**Figure 10. Heat rejected by each LHP, along with local water flow rate. Note how total rejected power remains fairly constant as the local water flow rate is reduced.**

The second test demonstrated the ability to maintain the set point as the heat load was reduced for a constant sink temperature. The heat sink was set and held at a constant -29°C for the duration of the measurement. A fixed amount of power was applied to the water reservoir, and the LHPs were allowed to reach steady state with the full flow rate through the heat spreaders. The set point at this initial steady state was recorded as 48°C. For the remainder of the test, the goal was to maintain this set point temperature. The applied power was reduced, and the LHPs were allowed to reach a new steady state. The flow rate through the bypass was increased to maintain the set point as the temperature of the LHPs decreased. The temperatures of the various LHP components are shown in Figure 12, along with the local flow rate. Figure 13 shows how the set point was maintained throughout at 47.7°C +/- 0.5°C. Finally, Figure 14 shows the total heat rejected and the heat rejected by each LHP. It can be seen that the power rejected decreased from approximately 700 W to approximately 450 W, for a turndown ratio of around 1.5:1.

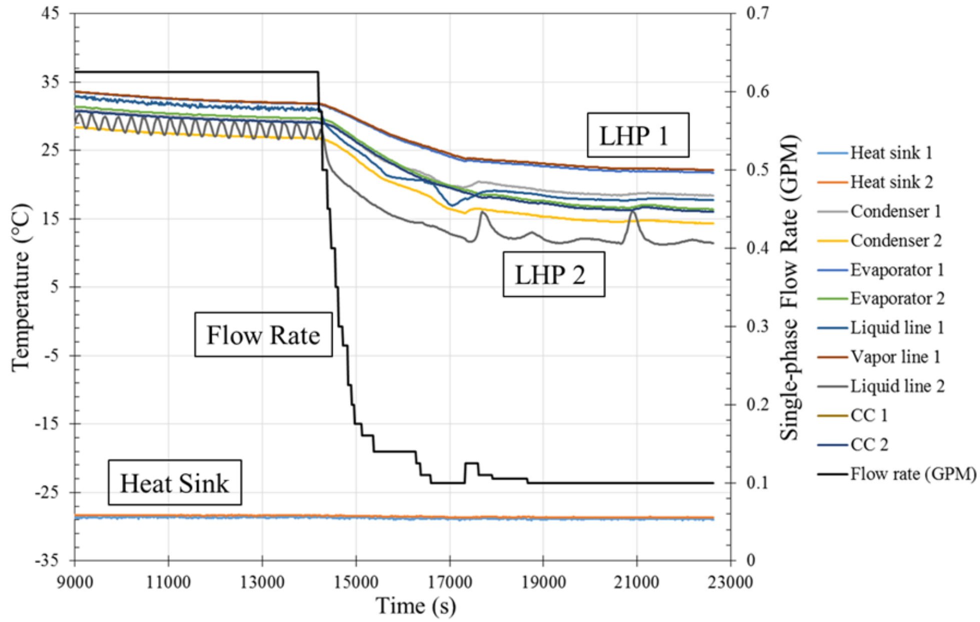


**Figure 12. LHP component temperatures recorded as heat load is reduced for a constant sink temperature. Local water flow rate is also shown.**

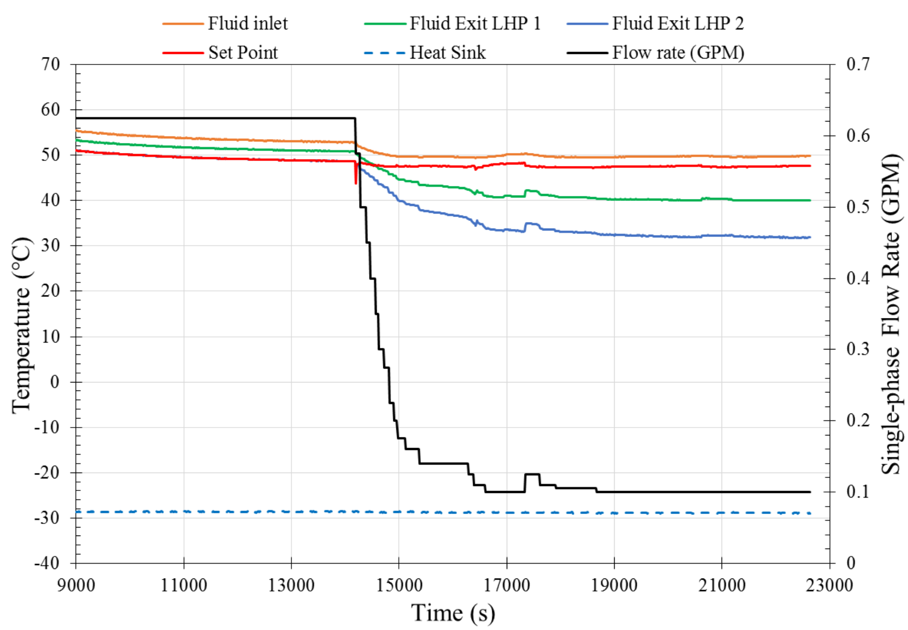


**Figure 13. Water temperature entering and exiting each LHP heat spreader, along with local water flow rate. Note how the temperature of the set point is maintained as the power applied and local water flow rate are reduced.**

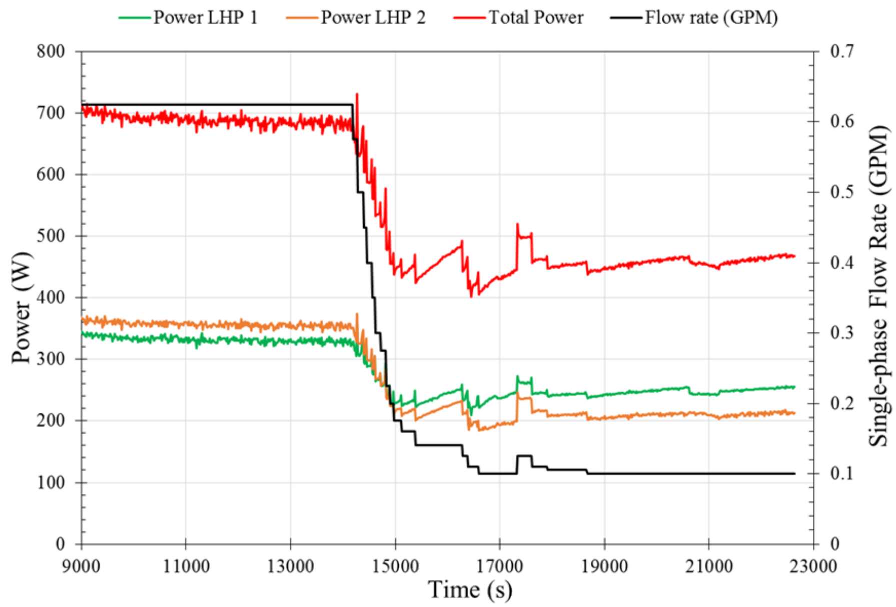


**Figure 14. Heat rejected by each LHP, along with local water flow rate. As the total power applied is reduced, the local water flow rate is reduced to maintain the outlet set point temperature (not shown).**

Due to the large number of parameters that affect the performanc of a LHP, and the complexity of the LHP Thermal Desktop model, an attempt to model the experimental system for a direct comparison was not made. However, the general conclusions of the modeling effort, that variable heat rejection from multiple LHPs coupled to a single phase fluid loop can be achieved by modulation of the local single phase fluid flow rate, were clearly demonstrated by the experimental effort. Therefore, as a proof-of-concept demonstration, the experimental data confirms the conclusions of the modeling effort.

## VI. Conclusion

Spacecraft thermal control systems are sized for the worst case conditions of maximum heat load in the warmest environment, resulting in a radiator that is oversized for much of the mission. To account for variations in operating conditions, a thermal management system with variable heat rejection and a large turndown is required. A conceptual design of a multiple loop heat pipe radiator system for variable heat rejection from a single-phase fluid used to cool a crewed cabin on a future manned spacecraft has been developed. A novel control methodology for modulating the power rejected by the LHPs through the modulation of the local single-phase fluid flow rate has been developed and demonstrated.

This multiple-LHP system and control methodology provides several benefits, including passive heat transfer, and the reduction of required electric power which must be supplied for either additional single phase fluid pumps or batteries to provide CC heater power. Additionally, the complexity of the control system is reduced. Instead of multiple feedback loops to adjust CC control heaters, a single parameter is adjusted: the local single phase flow rate. However, if additional turndown capability is required beyond what local flow rate modulation can provide, the system can still be integrated with other LHP control methodologies such as thermal links, thermal control valves, or small amounts of CC heating.

This control methodology was developed independently through Thermal Desktop numerical modeling and through experimental efforts. A 2.5 kW three propylene LHP system was modeled and shown to have a turndown ratio of 10:1 at a sink temperature of 232 K, solely through local flow rate modulation and without CC heating. The same model system was also shown to have a turndown ratio of 1.5:1 at a sink temperature of 4 K, again using only flow rate modulation. Significant turndown ratios have been theoretically demonstrated for a wide range of sink temperatures, and further turndown could be accomplished by the incorporation of complementary control technologies such as compensation chamber heating.

An experimental evaluation of an unoptimized two-LHP system was performed to validate the conclusions of the Thermal Desktop modeling. Two tests were performed. In the first, the set point was maintained within 1°C as the sink temperature was lowered by 20°C, while rejecting a constant heat load. In the second, a turndown ratio of 1.5:1 was shown, and the set point temperature maintained within 0.5°C, for a fixed heat sink temperature. While this is not a large turndown ratio, it was not expected to be. The test setup was not optimized and consisted of only a two LHP system. However, the concept of using flow rate variation to control the heat rejection of the LHPs was clearly demonstrated.

## Acknowledgments

This project was sponsored by NASA Johnson Space Flight Center under Purchase Order Number NNX14CJ24P. The technical monitor was Dr. Eugene Ungar.

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