13th International Heat Pipe Conference
September 21-25, 2004
Shanghai, China

June 1, 2004

A Comparative Analysis of Loop Heat Pipe Based Thermal Architectures for Spacecraft Thermal Control

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Abstract

Loop Heat Pipes (LHP) have gained acceptance as a viable means of heat transport in many spacecraft in recent years. However, applications using LHP technology tend to only remove waste heat from a single component to an external radiator. Removing heat from multiple components has been done by using multiple LHPs. This paper discusses the development and implementation of a Loop Heat Pipe based thermal architecture for spacecraft. In this architecture, a Loop Heat Pipe with multiple evaporators and condensers is described in which heat load sharing and thermal control of multiple components can be achieved. A key element in using a LHP thermal architecture is defining the need for such an architecture early in the spacecraft design process. This paper describes an example in which a LHP based thermal architecture can be used and how such a system can have advantages in weight, cost and reliability over other kinds of distributed thermal control systems. The example used in this paper focuses on a Mars Rover Thermal Architecture. However, the principles described here are applicable to Earth orbiting spacecraft as well.

Introduction: Mission Description

The example mission considered in this study consists of a Mars rover, larger than the Mars Exploration Rover (MER), based on a Mega Rover design. The thermal design of the MER described in reference [1] is the basis for many of the requirements used in the development of the following analysis. The LHP thermal architecture for this study is also based upon the thermal hardware developed for MER as discussed in reference [2]. The surface mission duration is 250 Sols at a latitude around 15 degrees south with a landing occurring in mid Spring locally. For this rover, solar panels provide the power source with secondary batteries used for energy storage. The maximum energy used on a typical day is up to 1650 Watt-hrs, while the minimum energy dissipation is about 1400 watt-hrs. At any one time, the maximum available power dissipation is 200 Watts. The rover contains two bays for electronics, each with a mass allocation of about 66 kg. The conventional thermal architecture uses a pumped fluid loop based on the Mars Pathfinder and MER design. These designs are described in detail in references [3 and 4]. In this design, the pump assembly is on board the rover instead of on the cruise stage as in Pathfinder and MER. This permits using the same pump assembly for both the cruise and surface operation phases of the mission. The proposed ST8 thermal architecture incorporates a dual evaporator, dual condenser heat removal system with Thermoelectric Coolers (TECs) attached to the evaporator-compensation chamber assembly and a Variable Emittance Coated (VEC) radiator system. The TECs are used primarily for start up rather than temperature control within a tight band. The VECs are used for freeze protection more so than for heat transfer modulation.

Conventional Thermal Architecture

There are three primary mission phases that require the successful functionality of the thermal system after launch has occurred. These include: (1) Interplanetary Cruise, (2) Entry, Descent and Landing, and (3) Surface Operations. A brief description of how the conventional thermal architecture operates in all three phases is given below.

Interplanetary Cruise Configuration:

The electronics for the spacecraft (S/C) reside within the rover as shown in Figure 1. Heat generated by the electronics must be removed and dissipated at the radiators located on the cruise stage. The electronics are mounted to a temperature controlled interface plate that has a fluid line embedded within it to cool the electronics as required. The fluid used in the system is refrigerant R-11. Thermal analysis shows that about 25% of the electronics waste heat is lost through the rover into the lander and then through the aeroshell by conduction and radiation. The fluid lines are integral components of the three major S/C subassemblies: The Rover, The Lander and The Cruise Stage. The lander fluid line contains a flexible joint across the base petal and the side petal interface. The fluid lines of each subassembly are connected together using field joints during S/C assembly. A three-way pyro valve is located within the pump assembly to direct fluid to either the cruise stage radiators or to bypass the cruise stage branch for surface operations. Fluid flows through the rover radiators during cruise phase at all times. Pyro tube cutters are located at the cruise stage to lander interface and at the lander to rover interface to permit separation of these subassemblies. A pyro vent valve is located on the cruise stage to remove fluid from the cruise stage and lander fluid lines prior to Entry, Descent and Landing.

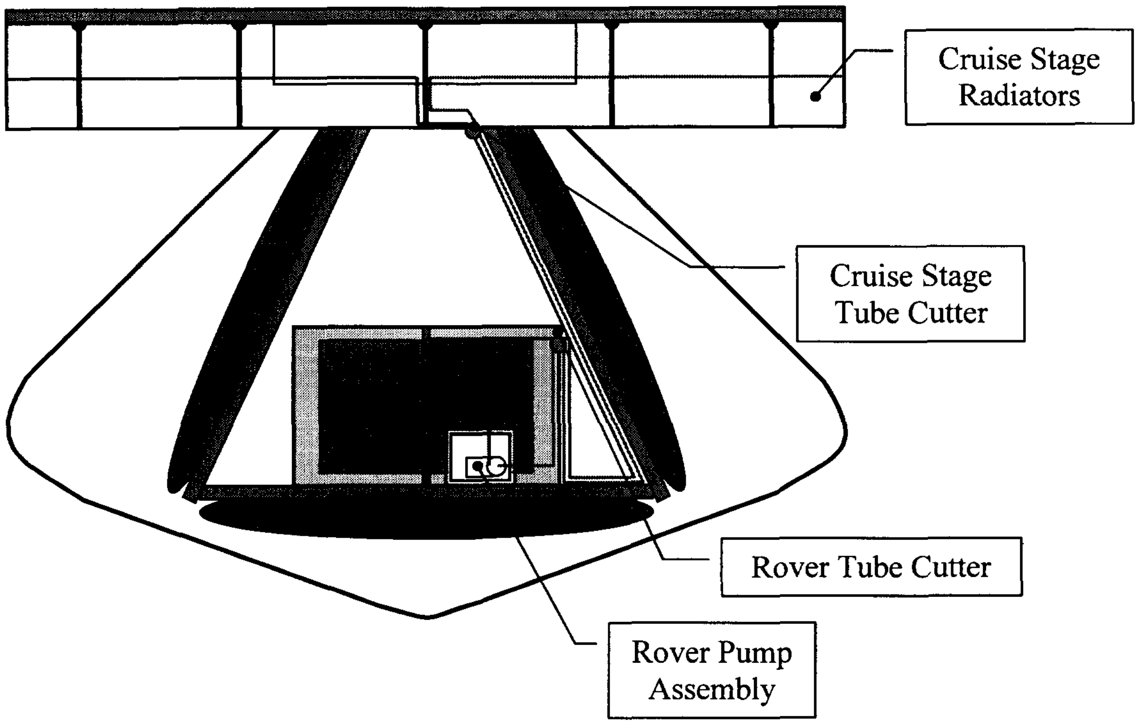

Figure 1. Pumped Fluid Loop Heat Rejection System from Rover to Cruise Stage During Interplanetary Cruise.

Entry, Descent and Landing Sequences:
Prior to Mars atmospheric entry, the fluid loop system is switched from the cruise configuration into the surface operations configuration in the following sequence:

1. The 3-way pyro valve is actuated, sealing off fluid flow to the cruise stage radiators. Fluid continues to circulate through the rover radiators.
2. The pyro vent valve is actuated, allowing all the fluid in the cruise stage and outside the rover to be vented to space
3. The cruise stage pyro tube cutter is fired, allowing the cruise stage to be separated from the aeroshell.
4. Other EDL sequences are executed such as cruise stage separation, parachute deployment, heat shield separation, etc.
5. After landing, the lander pyro tube cutter is fired allowing the rover to be separated from the lander.
6. The lander could possibly be a descent stage; the pyro tube cutter would then be actuated prior to separating the rover from the descent stage.
7. The fluid loop heat rejection system is now configured for surface operations.

Surface Operations:

The pumped fluid loop thermal control system within the rover is shown in Figure 2. The pump assembly contains a primary and a redundant pump connected in parallel to the fluid loop. Each pump requires about 10 watts of power for operation. Only one pump operates at a time. A filter is installed in series with the pumps to keep the fluid clean. A bypass is placed around the filter that can be activated if or when the filter becomes too dirty. The bypass line may or may not contain a redundant filter. The fluid loop is operated only during daytime hours when electronic components would otherwise overheat. Heat loss through the radiators at night is minimized by turning off the fluid pump. Temperature control of the fluid loop is maintained by two paraffin actuated bypass valves. One valve provides a bypass around the front radiator, the other valve bypasses the back radiator. The valves may be designed to actuate at any of a number of set points. This design established the set point at 18°C. When the valve outlet temperature falls below 18°C, it opens up the bypass line and closes off the radiator. Above 18°C, the valve closes off the bypass line and opens up the radiator branch. The pump assembly occupies a significant volume within the rover that could otherwise be occupied by a science electronic component. The radiators and thermal valves are configured to permit independent temperature control of the two electronic bays. Batteries and low power components could be on one side while the computer, communications and other high powered components could be on the other side for example.

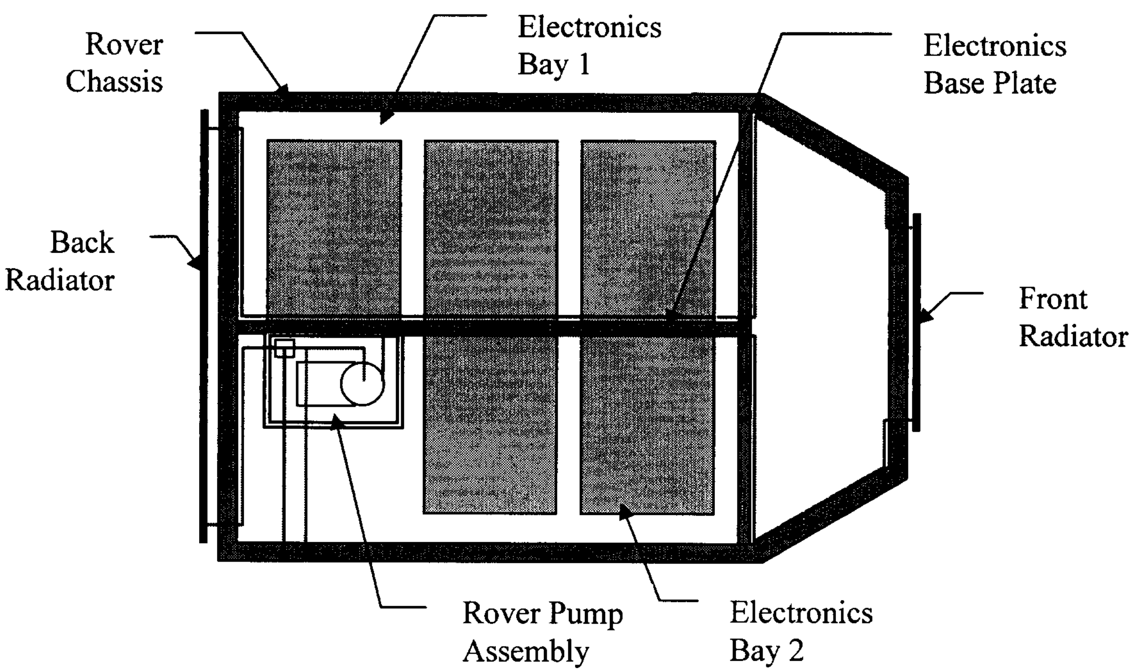

Figure 2. Pump Fluid Loop Architecture for a Mars Rover.

LHP Based Thermal Architecture

A brief description of how the LHP based thermal architecture operates in the three mission phases is given below.

Interplanetary Cruise Configuration:

The LHP based thermal architecture for the S/C is shown in Figure 3. The electronics for the S/C reside within the rover as in the previous architecture. Heat generated by the electronics must be removed and dissipated at the radiators located on the cruise stage. The LHP system within the rover has two evaporators, one located in each electronic bay. As in the conventional architecture, the electronics are mounted to a temperature controlled interface plate. However, for this architecture, the interface plate has constant conductance heat pipes embedded within it to gather waste heat from the electronics and move it to both LHP evaporators. The fluid used in the LHP system is ammonia. There are three separate LHP systems that are integral components of the three major S/C subassemblies: The Rover, The Lander and The Cruise Stage. Only the rover LHP is a dual evaporator, dual condenser. The other spacecraft subsystems have an ordinary single evaporator, single condenser design. The lander LHP contains a flexible joint across the base petal and the side petal interface. The LHPs of each subassembly are connected together using field joints during S/C assembly. Typically, the condenser of one LHP is attached to the evaporator of the next LHP. Pyro tube cutters are located at the cruise stage to lander interface and at the lander to rover interface to permit separation of these subassemblies by cutting through the liquid and vapor lines of each LHP. The cut ends of tube should be sealed by the cutter to prevent ammonia from venting.

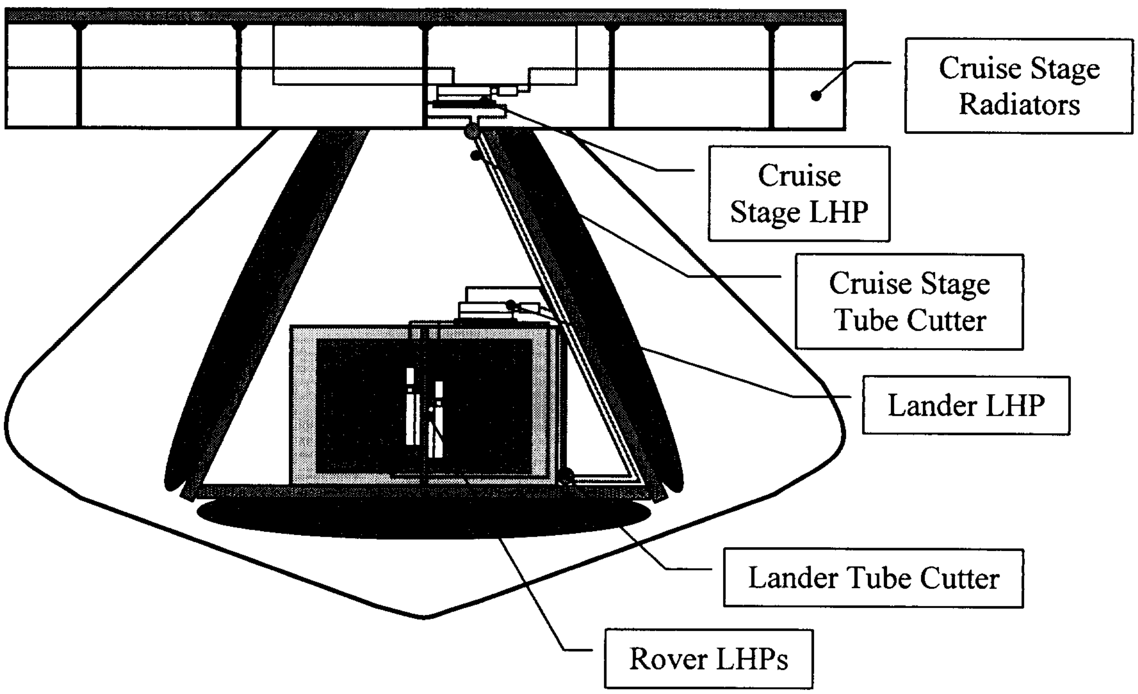

Figure 3. LHP Based Heat Rejection System from Rover to Cruise Stage During Interplanetary Cruise.

Entry, Descent and Landing Sequences:

Prior to Mars atmospheric entry, the LHP heat rejection system is converted from the cruise configuration into the surface operations configuration in the following sequence:

1. The cruise stage pyro tube cutter and the lander pyro tube cutter are fired, allowing the cruise stage to be separated from the aeroshell and the rover to be separated from the lander.
2. The lander could possibly be a descent stage; the pyro tube cutter would then be actuated prior to separating the rover from the descent stage.
3. Other EDL sequences are executed such as cruise stage separation, parachute deployment, heat shield separation, etc.
4. The LHP based heat rejection system is now configured for surface operations. Ammonia condenses in the radiators instead of the cruise phase condenser.

Surface Operations:

The LHP based thermal architecture for the rover is shown in Figure 4. The LHPs are operated only during daytime hours when electronic components would otherwise overheat. The LHPs can be shut off using the TEC or will turn themselves off when there is insufficient power dissipation to keep the fluid in the loop flowing. Heat loss through the radiators at night is minimized by turning the VEC to the lowest emissivity setting. This should also prevent ammonia from freezing in the radiators.

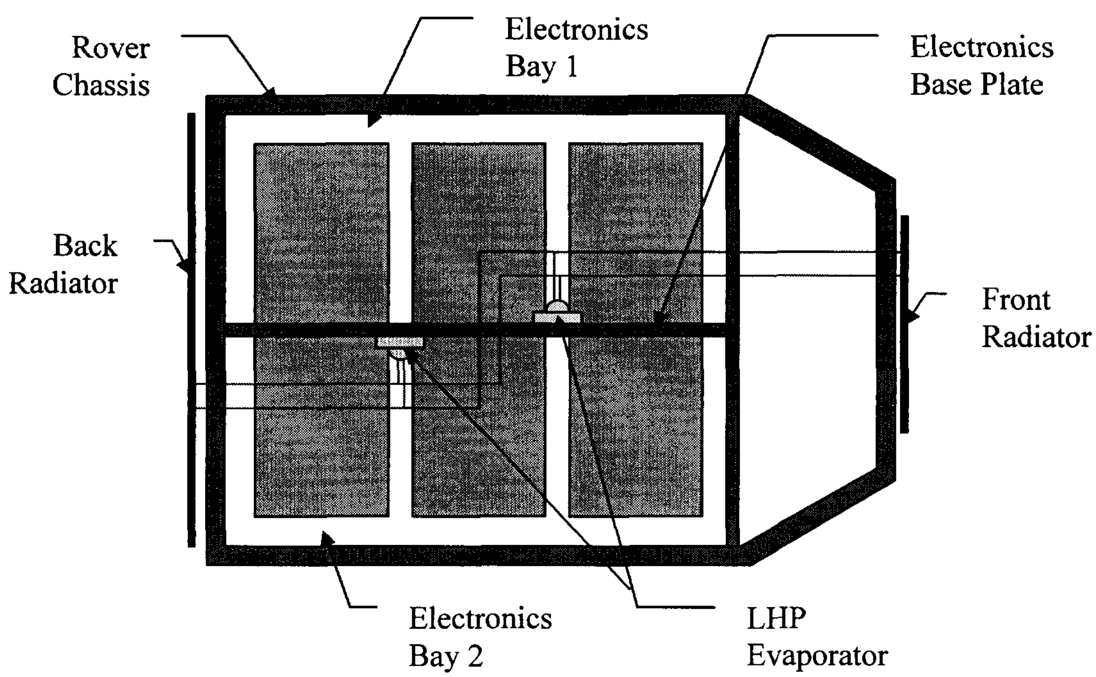

Figure 4. LHP Thermal Architecture for a Mars Rover

The LHP assemblies do not occupy a significant volume within the rover and may permit additional science electronic components over the pumped fluid loop system, depending on the size requirements of the TEC and the VEC electronics. The dual LHPs are configured to permit independent temperature control of the two electronic bays. Batteries and low power components could be on one side, computer and communication components could be on the other side for example. The joint LHP condenser used during cruise does not condense a significant amount of ammonia during surface operations since it has a small exposed area.

Thermal Analysis of Conventional Architecture

An analysis of the cruise phase of the mission study was not performed for the conventional architecture because the intent of this study was to focus on the surface operations since this is the more thermally demanding set of conditions. There were two cases analyzed bounding the mission between the hot case and the cold case. The boundary conditions for these cases are shown in Figures 5 and 6.

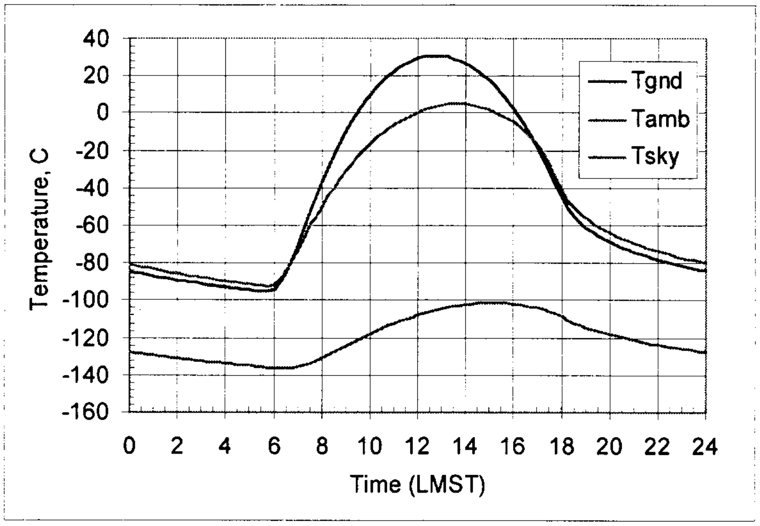

Figure 5. Hot Case Environmental Boundary Conditions.

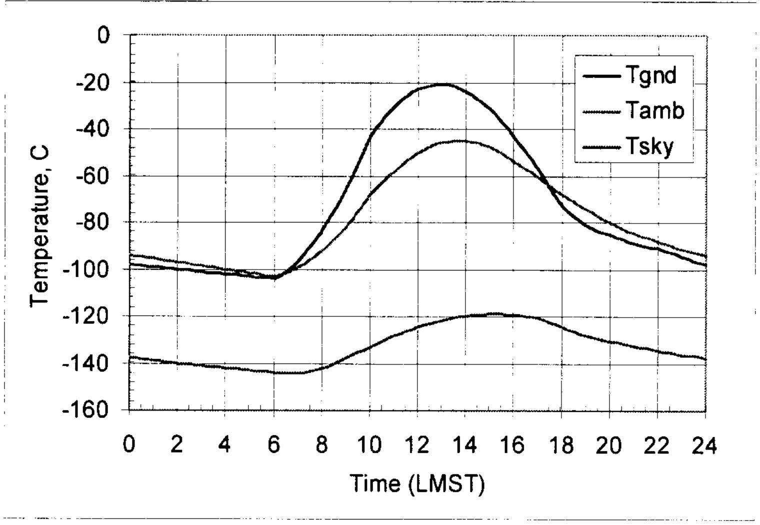

Figure 6. Cold Case Environmental Boundary Conditions.

In the rover surface thermal analysis, the rover was oriented locally such that the front radiator faced east and the back radiator faced west. The solar heat loads on the radiators were calculated for both the hot and cold cases as shown in Figures 7 and 8.

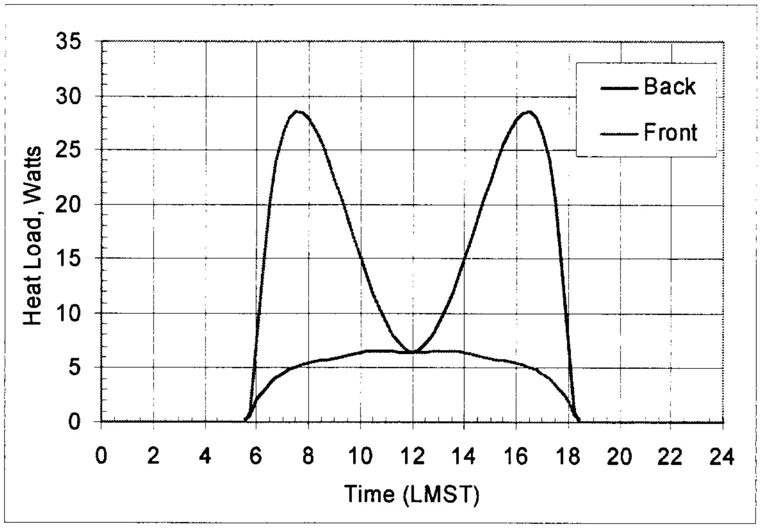

Figure 7. Hot Case Solar Heat Load on Rover Radiators for Pumped Fluid Loop.

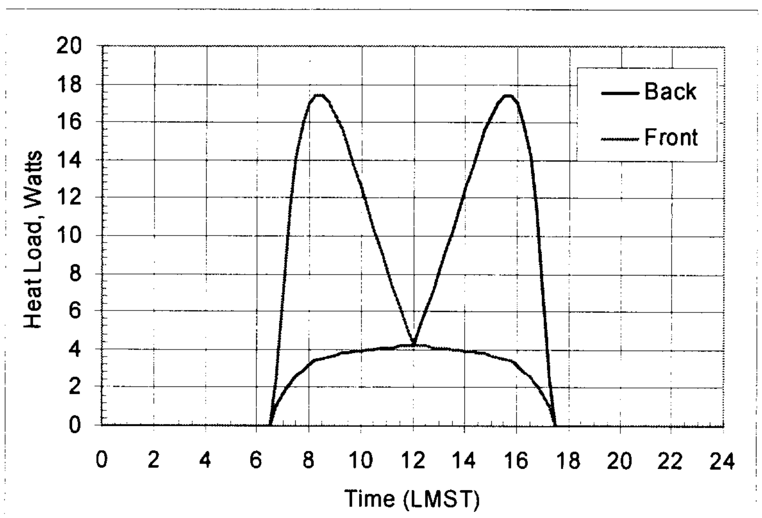

Figure 8. Cold Case Solar Heat Load on Rover Radiators.

Typical power profiles were used for electrical dissipation within the two electronic bays of the rover. The hot case profile used the maximum available power while the cold case used the minimum available power. These profiles are shown below in Figures 9 and 10.

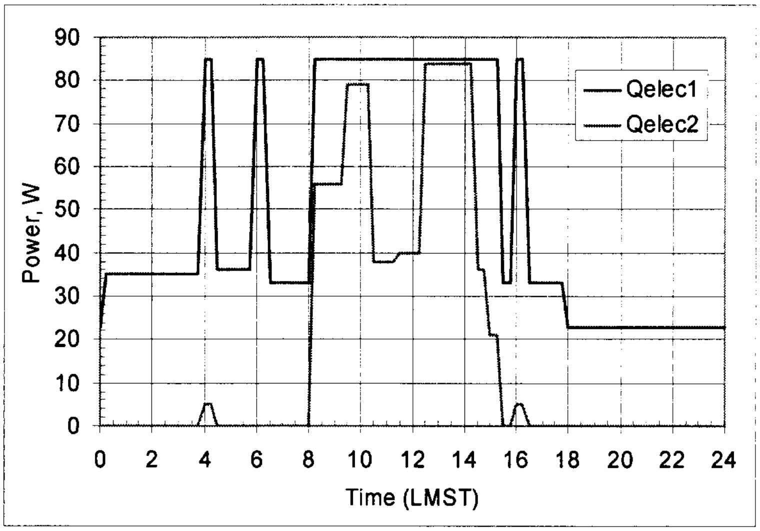

Figure 9. Hot Case Maximum Power Dissipation Profile.

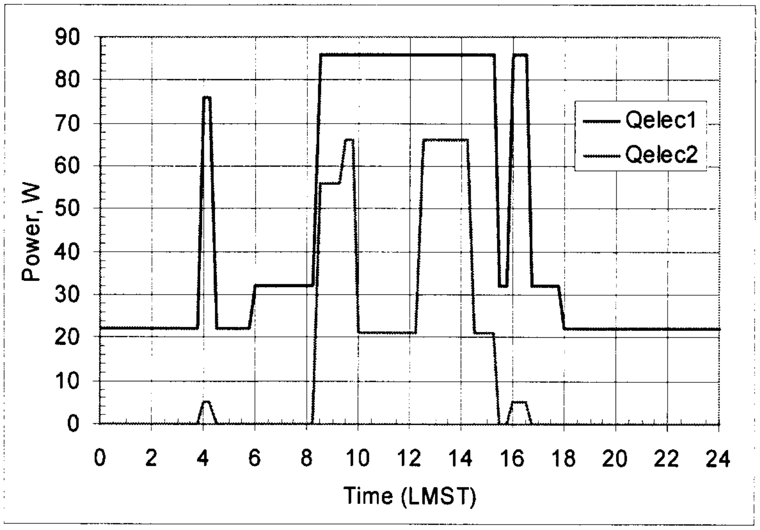

Figure 10. Cold Case Minimum Power Dissipation Profile.

A diagram of the system used in the model is shown in Figure 11. The rover electronics interacted with the given power profiles and environmental boundary conditions according to the following summary of system parameters:

Radiation Properties:

- –Radiator solar absorptivity: 0.25
- –Radiator emissivity: 0.9
- –Radiator Area: 0.25 m^2 for both front and back
- –View factor to sky: 0.5
- –View factor to ground: 0.5

•Ambient convection coefficient: 0.4 W/m^2K
•Conductance from Electronics to Ambient temperature: 0.8 W/K
•Mass equivalent of Electronics in each bay: 66 kg of aluminum
•Required radioisotope heating: 20 watts in bay 1, 35 watts in bay 2.
•Pump power: 10 watts during the day, 0 watts at night. 3 cases studied:
  –Pump turns on at 8 am, turns off at 6 pm local Mars Solar time.
  –Pump turns on when temperature of electronics rises above 12°C and turns off when it falls below 15°C (built-in hysteresis)
    –Without bypass valves/lines
    –With bypass valves/line
•Bypass operating range:
  5% flow through radiator below radiator inlet temperature of 15°C,
  95% flow through radiator above radiator inlet temperature of 19°C.

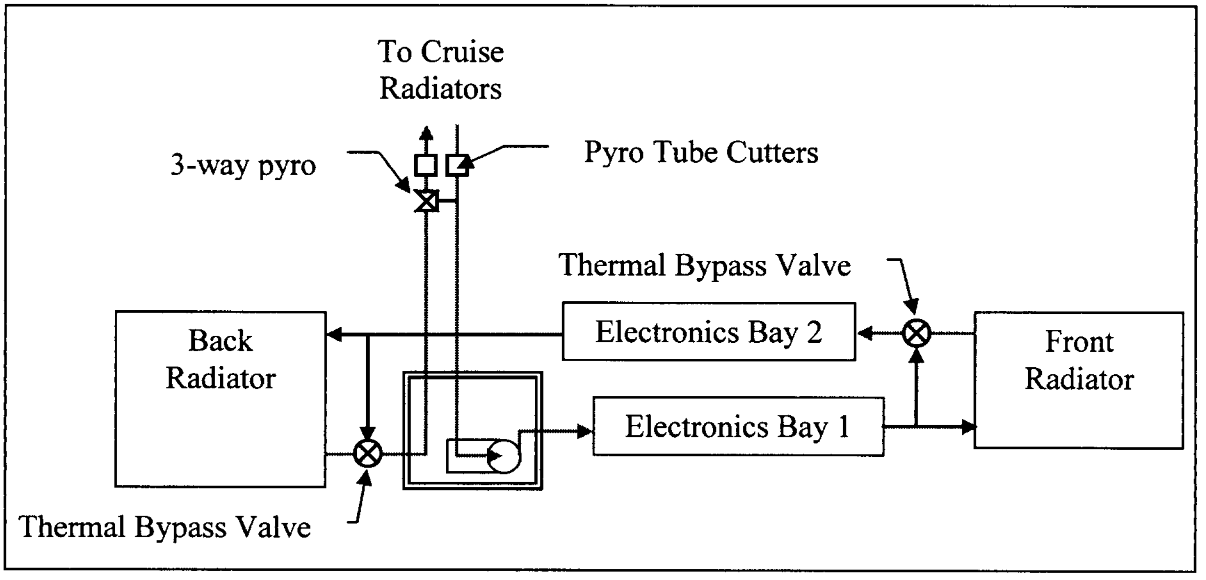

Figure 11. Pumped Fluid Loop Rover Thermal Architecture fluid flow diagram.

The results of the analysis shows that the case in which the pump turns on when the electronics temperature reaches 12°C with the bypass valves and lines gives the best thermal system performance for both the hot and cold cases. These are shown below in Figures 12 and 13. In the hot case the temperature of the electronics varies from -10°C to +30°C, while in the cold case, the variation is -27°C to +13°C. These are well within the allowable flight temperature limits for typical electronic hardware.

The primary conclusion from the pumped fluid loop analysis is that the bypass valve combined with the pump produced the minimum daily temperature variation of the electronics. The bypass allows heat load sharing between the two electronics bays. Without the bypass valve, all the heat from one electronics bay is dumped to the ambient sink before it can be used by the second electronics bay. It was observed that having the pump on a timed operation provides more heat load sharing than the temperature based pump operation scenario. This is because the pump circulates the fluid throughout the system even when the electronics temperatures aren't very high.

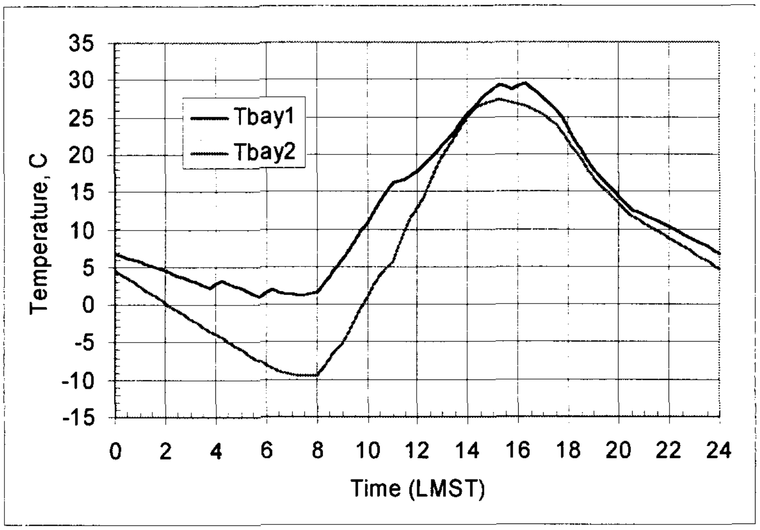

Figure 12. Hot Case Fluid Pumped Loop Electronics Bay Temperatures.

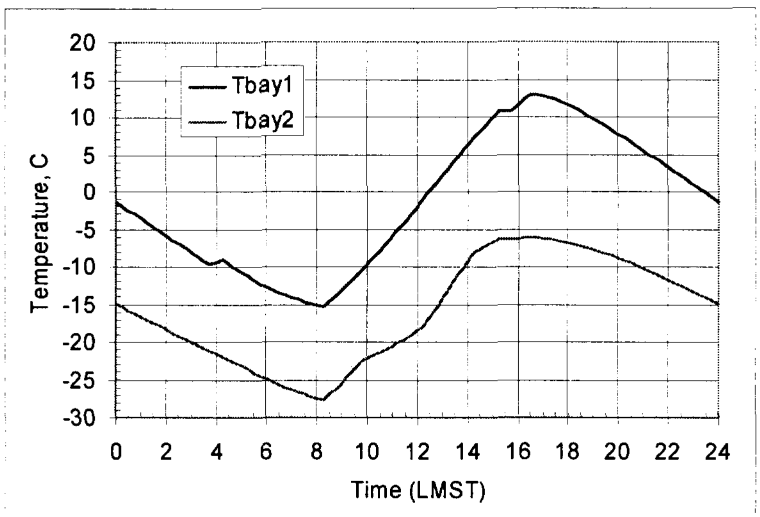

Figure 13. Cold Case Fluid Pumped Loop Electronics Bay Temperatures.

Thermal Analysis of LHP Based Architecture

The environmental boundary conditions, solar heat loads and power dissipation profiles for the LHP architecture were identical to those used for the pumped fluid loop analysis. The LHP thermal architecture incorporates many features that are similar to those used in the pumped fluid loop. The radiator sizes are the same as the conventional case each with an area of 0.25 m^2. However, the LHP radiators have a solar absorptivity of 0.4 using the VECs instead of the white paint value of 0.25. The emissivity of the VEC varies from 0.1 to 0.75 compared to the white paint value of 0.9. Since the optical properties of the VEC radiators differ from those of white paint, the solar loads are also different. The solar heat loads on the VEC radiators are shown in Figures 14 and 15 for the hot and cold cases respectively.

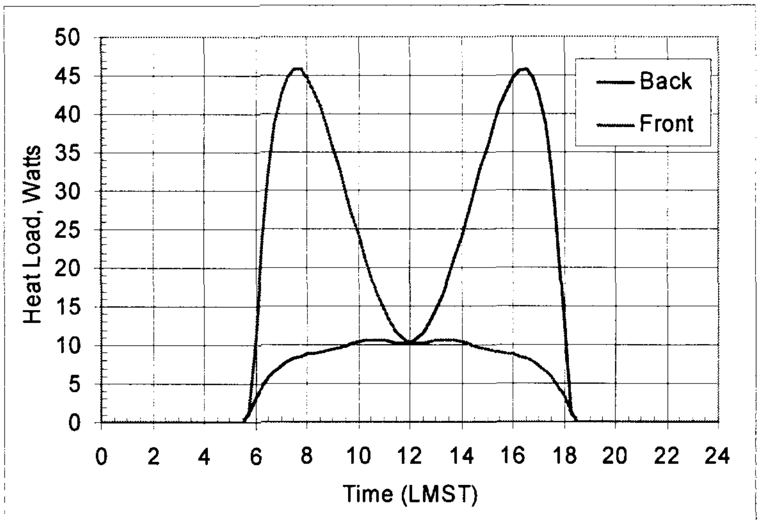

Figure 14. Hot Case Solar Heat Load on Rover Radiators with VEC Surface.

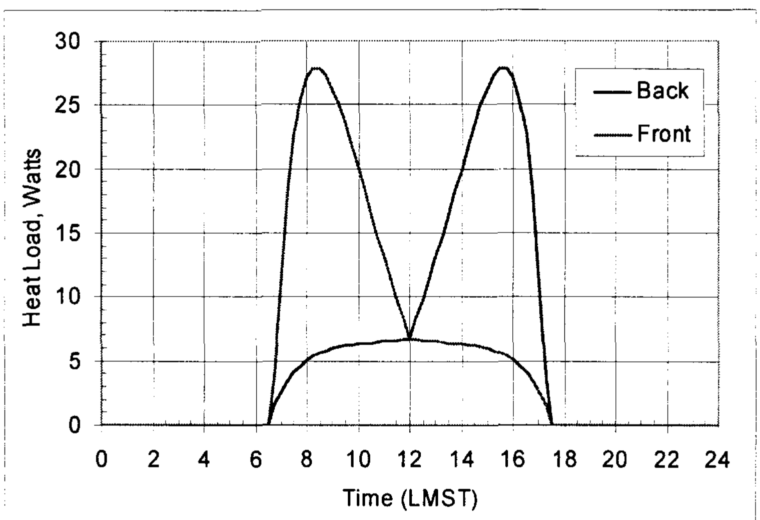

Figure 15. Cold Case Solar Heat Load on Rover Radiators with VEC Surface.

The VEC operational strategy was designed to activate or deactivate portions of the VEC surface as a function of radiator temperature. The logic used in this analysis simply set the VEC emissivity to 0.1 if the radiator temperature was below –40°C, then linearly raised the emissivity up to 0.75 until the radiator temperature reached –20°C and remained at the high state for all warmer temperatures. The resulting emissivity values from the hot and cold case analyses are shown in Figures 16 and 17 respectively.

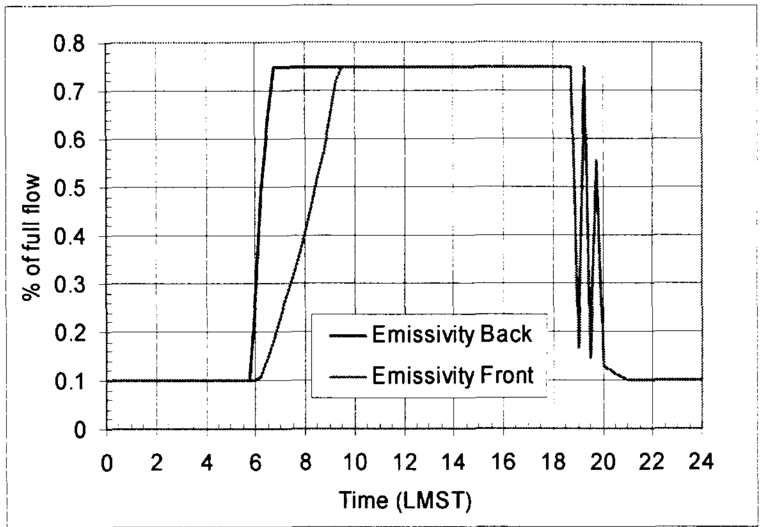

Figure 16. VEC Radiator Surface Emissivity values for the Hot Case.

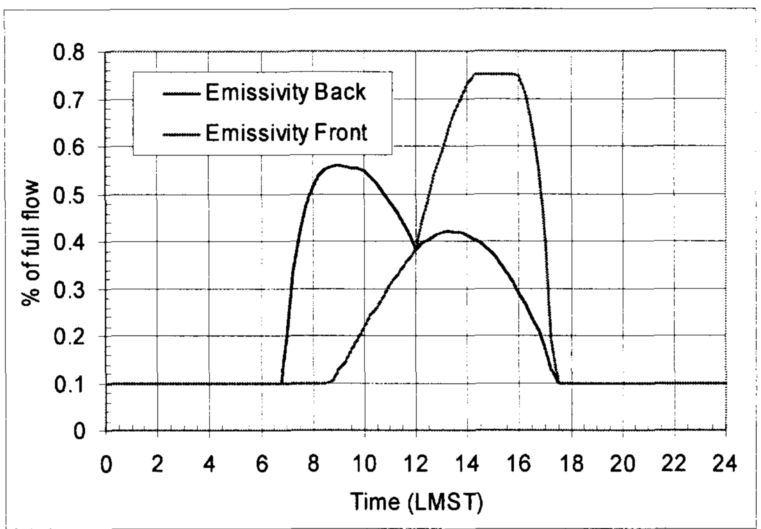

Figure 17. VEC Radiator Surface Emissivity values for the Cold Case.

A diagram of the heat flows with the LHP architecture is shown in Figure 18. Fixed conductance values between various components such as the electronics, LHP evaporators and the ambient environment are also shown in the figure. The LHP has variable conductance between the evaporators and the radiators over most of the operating conditions in this analysis.

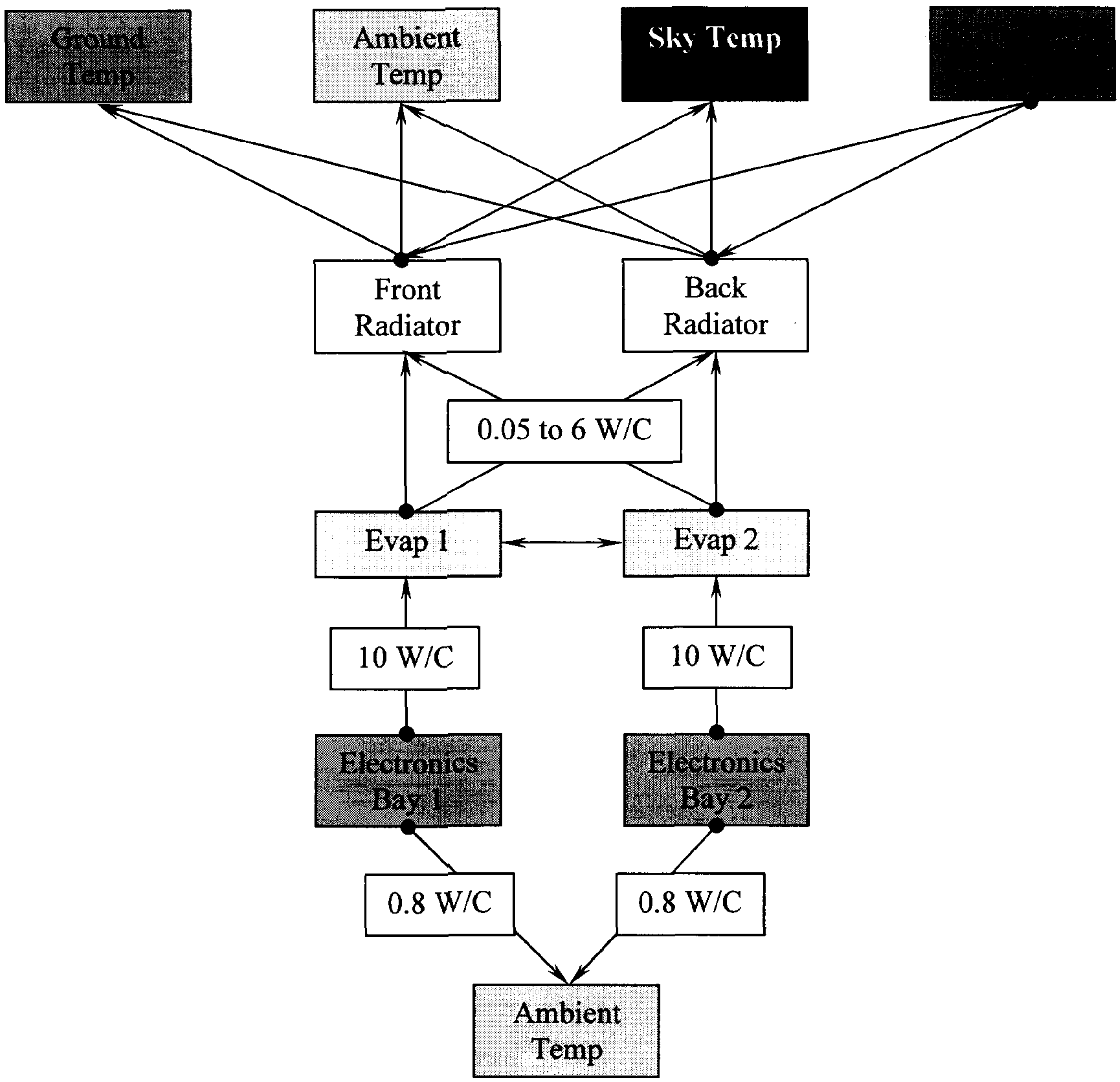

Figure 18. Heat Flow Diagram for a Mars Rover LHP thermal architecture.

The conductance values as a function of evaporator power and radiator temperature are shown in Figure 19 for a LHP similar to the unit described in this architecture. The LHP architecture analysis computed the conductance between each evaporator and each radiator based on the radiator temperature and the amount of heat dissipated from each evaporator by each radiator. Thus four conductance values were calculated for the system. The conductance between evaporators was taken to be one half of the average of the four evaporator to radiator conductance values. This results in a reasonably close approximation to observed conductance values (~2 W/°C) on the breadboard unit tested at GSFC. The variable conductance values computed for the hot case analysis are shown in Figure 20. In the cold case the LHP does not operate because the electronics temperatures remain cold and there is no need to remove waste heat to the radiators, hence the conductance values for this case are not shown.

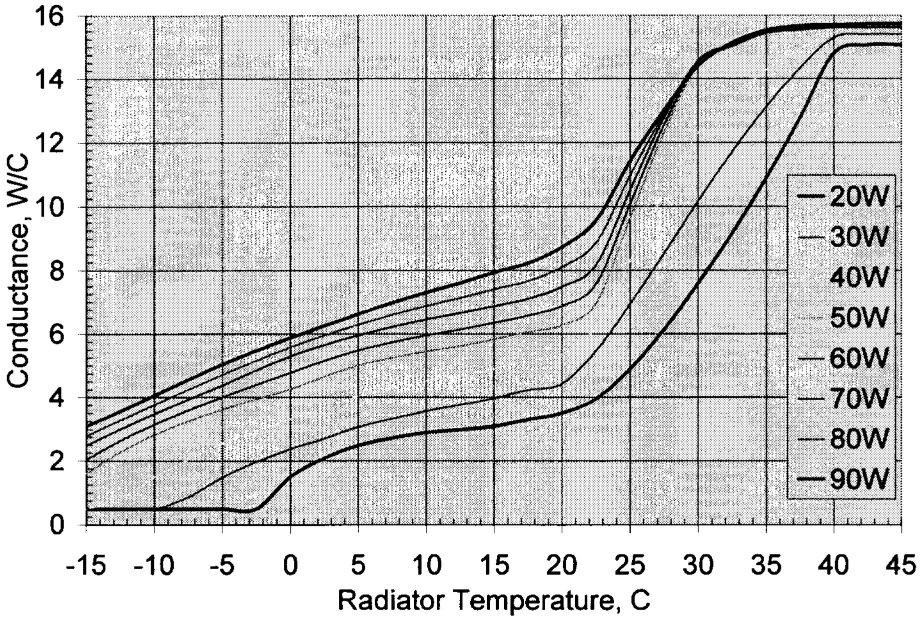

Figure 19. LHP Conductance map used for thermal analysis.

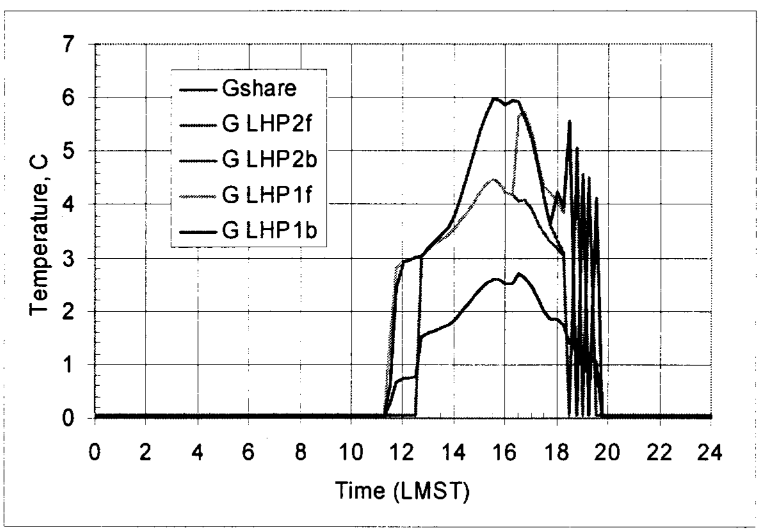

Figure 20. Conductance Values between Evaporators and Radiators for the Hot Case.

The temperatures of the electronic bays using the LHP architecture are similar to those observed in the pumped fluid loop architecture. The temperature of Bay 1 in the hot case is slightly higher for the LHP architecture because the VEC surfaces are not as efficient at rejecting heat to the ambient environment as the white painted radiators. These are shown below in Figures 21 and 22. In the hot case the temperature of the electronics varies from -6°C to +33°C, while in the cold case, the variation is -27°C to +7°C. These are well within the allowable flight temperature limits for typical electronic hardware.

The number of radioisotope heater units is the same for this architecture as in the conventional case. However, five of them were moved from Bay 1 to Bay 2 because the logic used in the analysis kept the LHPs turned off in the cold case in which the electronics temperature remained less than 10°C at all times. This brought the constant source heat load in Bay 1 down to 15 watts and raised the load in Bay 2 up to 40 watts.

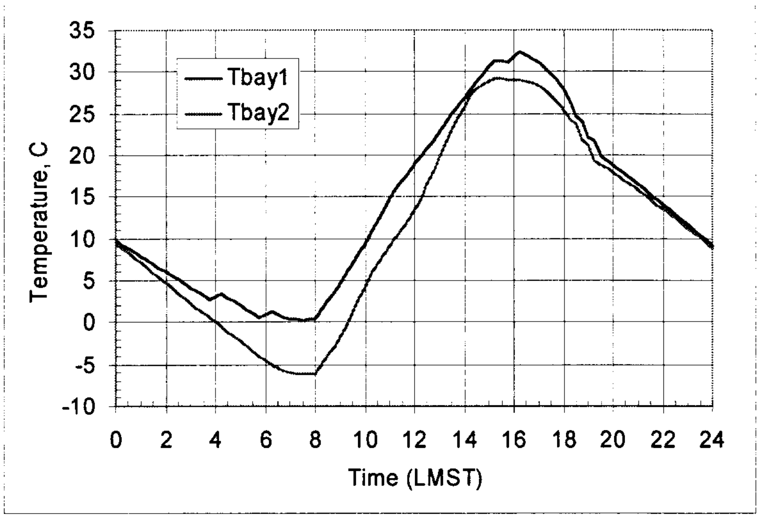

Figure 21. Hot Case LHP Architecture Electronics Bay Temperatures.

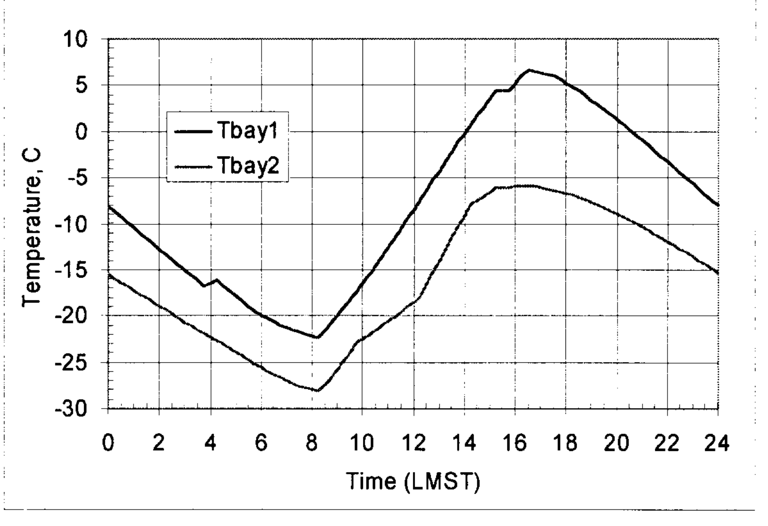

Figure 22. Cold Case LHP Architecture Electronics Bay Temperatures.

Conclusions to be made from the LHP thermal architecture analysis are that it delivers similar performance to the conventional pumped fluid loop architecture and that the design is robust enough to handle the hot and cold case extremes with adequate margins for typical electronic component allowable flight temperature limits. Additional comparisons between the two architectures for the rover are summarized in Table 1.

Table 1. Mass, Power, Cost, Volume and Complexity Comparison

Attributes	**Baseline TCS**	**LHP Based TCS**
Mass	Pump assembly ~10 kg, Radiators and tubing ~ 3 kg	LHPs and electronics ~3 kg Radiators and VECs ~3 kg
Power	10 W Power needed up to 60% on the surface	5 W for TEC. 5 W for VEC. Power needed less than 5% of the time
Cost	100% Baseline cost	30% of Baseline cost
Volume	0.020 m^3 not including piping and radiator	0.005 m^3 not including tubing and radiator
I & T Complexity	Medium: Needs field joints. Components can be installed individually. System is charged after S/C assembly. Disassembly and reassembly requires system recharging. Expensive GSE required for servicing.	Medium: No field joints but system must be installed or removed as a complete unit from evaporator to radiator. Charged by vendor once. No GSE required for servicing, some GSE may be needed for installation.

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