Performance Of The Mechanically Pumped Fluid Loop Rover Heat Rejection System Used For Thermal Control Of The Mars Science Laboratory Curiosity Rover On The Surface Of Mars

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The challenging range of landing sites for which the Mars Science Laboratory Rover was designed, required a rover thermal management system that is capable of keeping temperatures controlled across a wide variety of environmental conditions. On the Martian surface where temperatures can be as cold as -123°C and as warm as 38°C, the Rover relies upon a Mechanically Pumped Fluid Loop (MPFL) Rover Heat Rejection System (RHRS) and external radiators to maintain the temperature of sensitive electronics and science instruments within a -40°C to +50°C range. The RHRS harnesses some of the waste heat generated from the Rover power source, known as the Multi Mission Radioisotope Thermoelectric Generator (MMRTG), for use as survival heat for the rover during cold conditions. The MMRTG produces 110 Watts of electrical power while generating waste heat equivalent to approximately 2000 Watts. Heat exchanger plates (hot plates) positioned close to the MMRTG pick up this survival heat from it by radiative heat transfer and supply it to the rover. This design is the first instance of use of a RHRS for thermal control of a rover or lander on the surface of a planet. After an extremely successful landing on Mars (August 5), the rover and the RHRS have performed flawlessly for close to an earth year (half the nominal mission life). This paper will share the performance of the RHRS on the Martian surface as well as compare it to its predictions.

Nomenclature

AFT	=	Allowable Flight Temperature
BOL	=	Beginning of Life
CFC-11	=	Trichloromonofluoromethane (Refrigerant 11)
CFD	=	Computational Fluid Dynamics
CIPA	=	Cruise Integrated Pump Assembly
CPA	=	Cruise Power Assembly
CPAM	=	Cruise Power Analog Module
CHRS	=	Cruise Heat Rejection System
DPA	=	Descent Power Assembly
DPAM	=	Descent Power Analog Module
EDL	=	Entry, Descent and Landing
HRS	=	Heat Rejection System
HXCH	=	Heat Exchanger
JPL	=	Jet Propulsion Laboratory
MMRTG	=	Multi-Mission Radioisotope Thermoelectric Generator
MPFL	=	Mechanically Pumped Fluid Loop
MER	=	Mars Exploration Rovers
MPF	=	Mars Pathfinder

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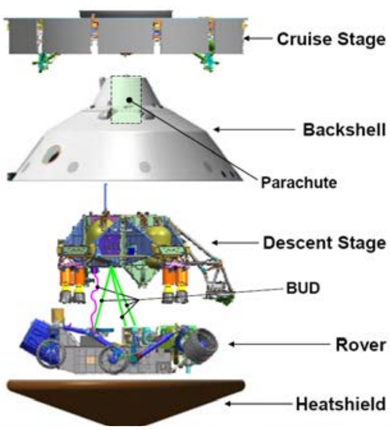
MSL	=	Mars Science Laboratory
NASA	=	National Aeronautics and Space Administration
RAMP	=	Rover Avionics Mounting Plate
RIPA	=	Rover Integrated Pump Assembly
RHRS	=	Rover Heat Rejection System
SDST	=	Small Deep Space Transponder
SSPA	=	Solid State Power Amplifier
STT	=	Solar Thermal Test
TWTA	=	Traveling Wave Power Amplifier
WCC	=	Worst Case Cold
WCH	=	Worst Case Hot
V&V	=	Verification and Validation

I. Introduction

THE MSL mission, with its Curiosity rover currently on Mars, follows the general design paradigm of the previous JPL rover missions to Mars (Mars Pathfinder, MPF[1,2,3,4,5] and Mars Exploration Rovers, MER[6,7]). The external configuration of the MSL spacecraft looks similar to that of MPF and MER. At 4.5 meters, the diameter of the MSL[8] spacecraft is almost twice that of the MPF and MER spacecraft (2.6 m). MSL features a rover enclosed in an aero-shell for protection during entry and descent onto the planet's surface. A Cruise Stage carries the lander and aero-shell enclosure from Earth to Mars and separates from the Lander, just prior to Entry, Descent and Landing (EDL). Figure 1 shows a rendering of the rover packed into the aero-shell enclosure with the Cruise Stage attached at the top. MSL landed on Mars on Aug 5th, 2012 and has operated successfully since then.



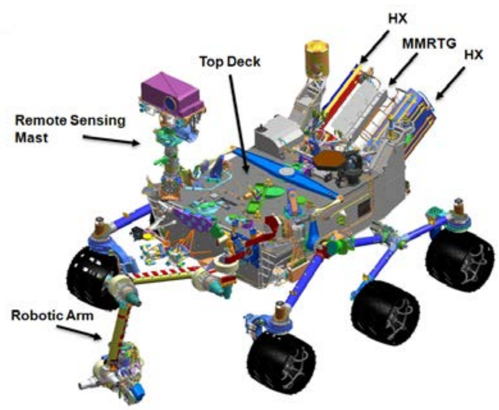


Figure 1. MSL Spacecraft and Deployed Rover.

The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is structurally attached to the rover and dissipates 2000 W of waste heat and weighs about 40 kg. The descent stage, containing the descent propulsion system and avionics, is adjacent to the stowed rover. The cruise stage contains the avionics, cruise propulsion system and the pumped loop radiators.

II. Overall MSL Architecture Which Utilizes Heat Rejection Systems for Thermal Control

The MSL spacecraft and the rover utilize mechanically pumped single phase fluid loop heat rejection systems (HRS) to create the backbone for thermal control of both systems: the Cruise Heat Rejection System (CHRS) and Rover Heat Rejection System (RHRS). Both fluid loops use Refrigerant-11 (CFC-11) as the working fluid. Figures 2 and 3 show the overall thermal architecture.

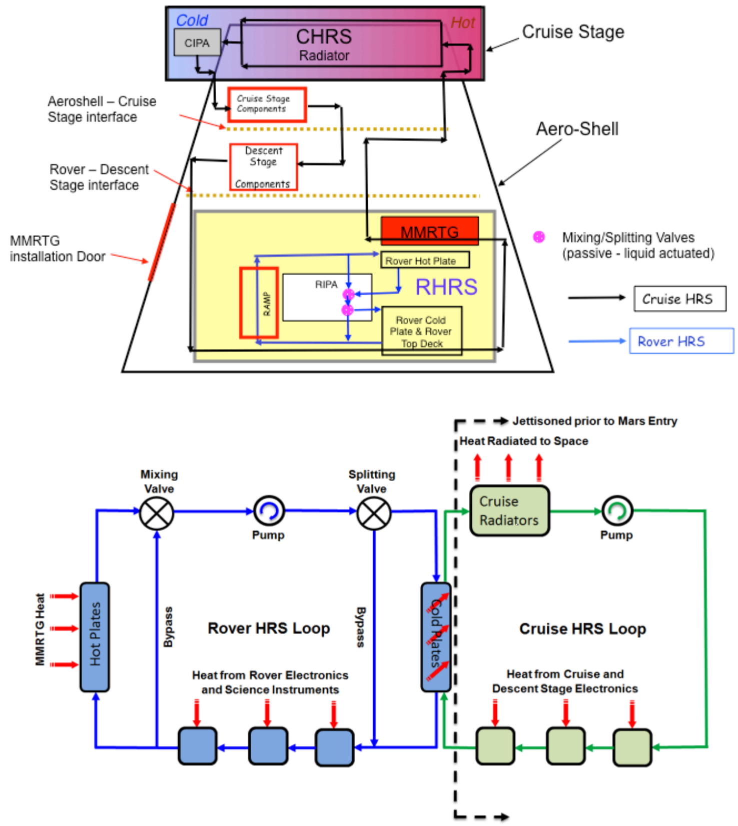


Figure 2. Schematics of Two HRS Fluid Loops.

The CHRS operates during the cruise portion of the MSL mission, from pre-launch to about an hour prior to the entry into the Mars environment. Its main function is to remove the waste heat from the MMRTG while maintaining its temperatures in a benign range (~100 to 180^{o}C). It also picks up dissipated heat from the equipment on the rover and on the Cruise/Descent Stages of the MSL spacecraft. Aluminum tubing is primarily employed in the loop, with a fraction being stainless steel.

Just prior to EDL, the working fluid in the CHRS loop is vented and the cruise stage containing the CHRS pumps is separated from the lander. Since EDL is short-lived (20 minutes) the thermal mass of the MMRTG prevents it from overheating, in spite of the lack of cooling of the MMRTG during this phase.

For the rover, the overall system approach is to utilize a single phase mechanically pumped fluid loop based HRS for the majority of the thermal control of the rover during Mars surface operations. The main impetus behind this is to utilize, as much as possible, the waste heat from the MMRTG to provide heat to the rover for cold conditions as well to use the RHRS to reject heat from the rover to external radiators during hot conditions.

The combination of the MMRTG waste heat and the fluid loop greatly simplifies the rover thermal design in terms of the level of thermal isolation required to maintain the rover and payload at allowable temperatures during cold conditions. It also greatly improves the robustness of the design, decouples the mechanical design and configuration from the thermal design and reduces the level of testing required. The references[8,9,10,11,12,13,15] provide a brief history of HRS loops, particularly from JPL's experience in using them for Mars missions.

Both the Rover Integrated Pump Assembly (RIPA) as well as the Cruise Integrated Pump Assembly (CIPA) have two pumps each for the sake of redundancy. However, only one pump is powered at any time. There is also a metal bellows accumulator to accommodate volume changes due to temperature changes and small leaks in the system during the mission. Figure 3 has the schematic of the fluid loop of the RHRS with a simplified schematic of the RIPA. Each of the two pumps has its own electronics to power it independently. The input power for RIPA (including the electronics) is 10 W. Each pump and thermal control valve[16] (also referred to as "thermal valve") subassembly has check valves upstream and downstream of them to ensure no recirculation flow occurs when one pump is idle and the other is running. Two types of thermal control valves are employed: "Mixer Valve" to mix the flow and "Splitter Valve" to split the flow. The filters protect the pump bearings from particles in the flow stream. Each filter has a check valve in parallel to allow the flow to continue (although without providing protection for the pumps) in the event of a filter saturating or clogging. More detailed description of the two HRSs can be found in references 8-14.

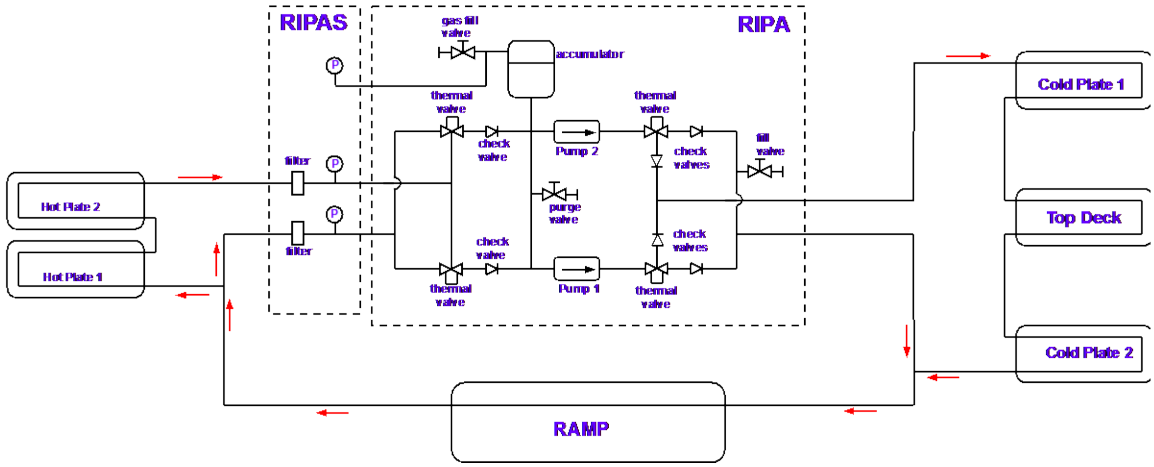


Figure 3. RHRS Schematic.

III. RHRS Heat Exchangers for Heat Pick Up and Rejection

The CHRS interface with the Rover occurs on the two MMRTG Heat Exchanger plates[14] (Figs. 5&6), which flank the sides of the MMRTG. Each of the two heat exchanger plates are composed of a hot plate and a cold plate pair that have the HRS tubing epoxied on them. The purpose of these hot plates (inside surface of heat exchanger plates) is to capture radiative waste heat from the MMRTG during the surface phase of the mission and use it to warm the Rover internals with the help of the HRS fluid flow. The cold plates (outside surfaces of the heat exchanger plates) in conjunction with RHRS tubing mounted on the rover chassis top deck, serve as the radiator system for dissipating the heat from the rover electronics/instruments as well as any unnecessary heat picked up from the MMRTG. The hot and cold plates are mechanically attached to each other via a honeycomb composite structure that minimizes the thermal coupling between the two to reduce the crosstalk between their totally different functions.

The function of the RHRS is to transfer heat from the rover to the radiators or to pick up waste heat (radiatively) from the hot MMRTG and transfer it to the rover. All the thermally controlled components that required a narrow allowable temperature range were mounted on a Rover Avionics Mounting Plate (RAMP) and this is where the RHRS tubing is attached to supply or remove heat from these components. During the cruise phase of the mission, the RHRS loop moves waste heat from the inside of the Rover (RAMP) to these radiators. A tube-to-tube counter flow heat exchanger between the cruise and rover HRS is attached to the cold plates of the MMRTG heat exchanger and serves to pick up heat from the rover HRS and transfer it to the cruise HRS.

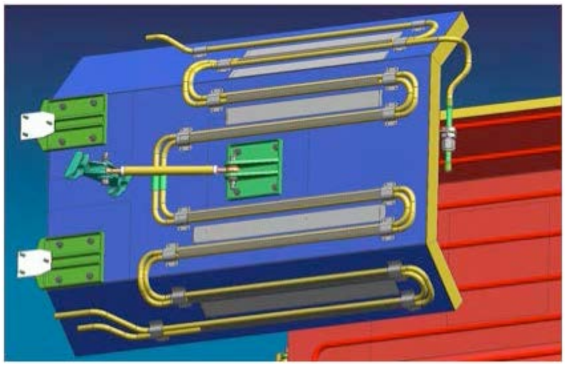


Figure 5: Rover Heat Exchanger Cold Plate

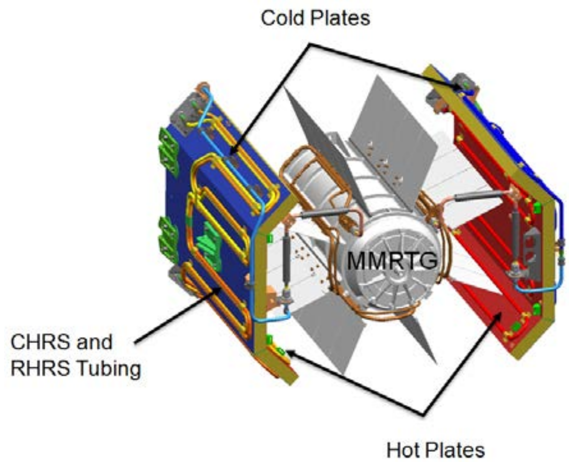


Figure 6. RHRS Heat Exchanger Assemblies, Red Face sheets-Hot Plates, Blue Face sheets-Cold Plates

The size of the HXCH plates is determined by the tradeoff between the hot and cold cases – make them too large and then they would pick up too much heat from the MMRTG (also the MMRTG would be warmer due to their view blockage). This would be a problem in the hot case because this unneeded excess collected heat would then have to be rejected by the real estate starved RHRS radiators (HXCH cold plates and rover top deck). Similarly for the cold case, these HXCH plates need to be large enough to pick up the required rover survival heat. So the HXCH is optimized to be able to meet both the hottest and coldest operating conditions. Martian atmospheric wind is always colder than the MMRTG and in most cases colder than the HXCH hot plates. The wind would tend to remove some of the waste heat available from the MMRTG as well as from the hot plates, so for a given geometric configuration of HXCH and MMRTG, they would both be colder in the presence of wind. Since one of the primary jobs of the RHRS is to pick up waste heat from the MMRTG in the cold conditions, this heat removed by the wind would make less of the waste heat available from the MMRTG to be used in the rover thermal control. Hence an accurate accounting of the thermal effect of the wind is very important to understand and design the RHRS to ascertain its adequacy in the coldest conditions. Wind speeds of 15 m/s were used to design the windbreaker. These speeds represent the 90-percentile range of speeds observed by the Viking lander on Mars.

Since Martian wind can impinge on the MMRTG and its HXCH from any direction, lacking a windbreaker, the direction of the wind along the MMRTG axis would clearly have the most deleterious effect, as seen in Fig. 7. Wind in other directions would encounter natural windbreakers in the form of the rover chassis itself (for wind along the MMRTG axis but coming from the opposite direction) and the HXCH plates (for wind in direction perpendicular to the MMRTG axis). So the most obvious windbreaker location is as shown in Fig. 7 where it bridges the HXCH plates on the anti-rover side of the MMRTG.

In spite of the obvious improvement of the heat pick up from the MMRTG due to the windbreaker, the actual effect of the wind is quite complicated due to the 3-D flow around the complex geometries of the MMRTG, HXCH plates, rover chassis and the windbreaker. Some finite residual wind speeds would be present past the windbreaker and the HXCH plates in the vicinity of the MMRTG. These residual winds would lead to heat transfer coefficients higher than for natural convection, and would lead to a heat loss increase from the MMRTG and the HXCH hot plates (when compared to no wind). A heat transfer coefficient map is thus required by fluid/thermal modeling to make a correct heat balance on these surfaces. The cold plates do not get affected to any significant degree due to the wind because the RHRS fluid flow essentially almost completely bypasses the cold plate radiators to conserve the collected heat. A CFD analysis, that was checked against simple bounding configurations found in heat transfer textbooks, was used to arrive at a heat transfer coefficient map around the MMRTG and its heat exchangers. The windbreaker was designed and built based on the results of this analysis and implemented at the launch facility after the MMRTG was installed on the rover a few days before launch.

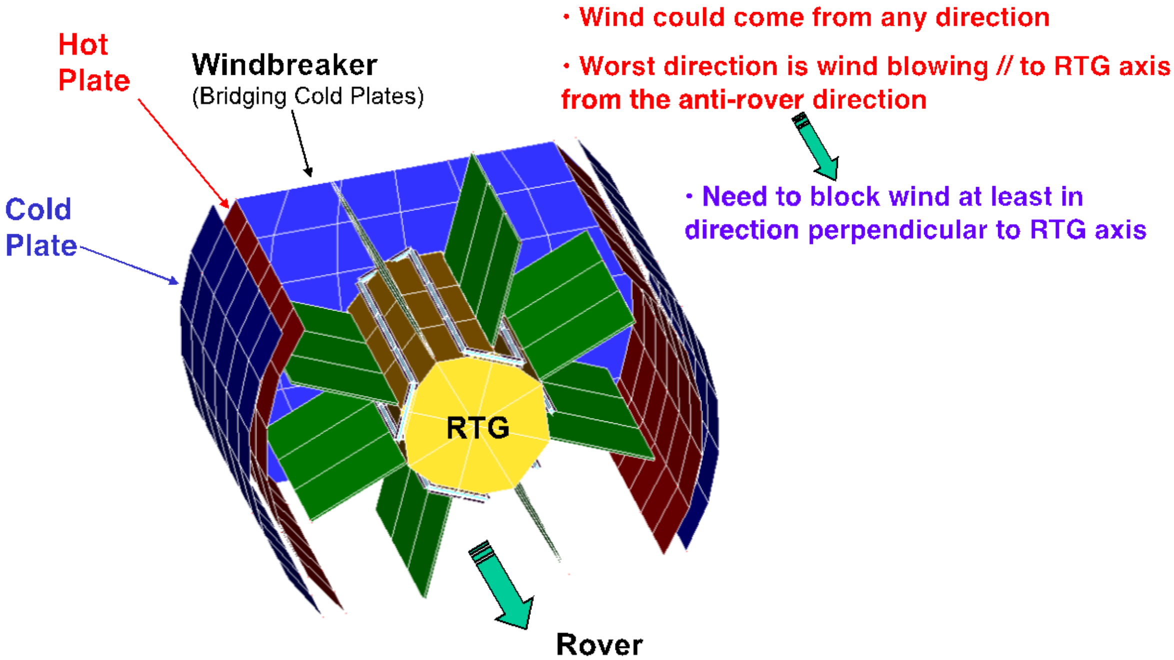


Figure 7: Windbreaker Functionality

IV. Key RHRS Requirements

The flight allowable temperature requirements of the key HRS controlled components on the RAMP are shown in Table 1. The instruments additionally have more detailed temperature and interface conductance requirements that pertain to day or night operation. This table also shows the key derived (flowed down) requirements for the HRS like the flow rates, pressure drops, pump input powers, etc. The components mounted external to the rover chassis typically had minimum non-operational allowable temperature limits (close to the Martian environment) except for few components that required survival heaters.

Table 1: Key HRS Requirements

Component	Allowable Flight Temperature Limit, C (Operational)	
	During Cruise	On Mars Surface
Cruise Stage		
CIPA, CPAM	-40/50	N/A
CPA	-40/40	N/A
Descent Stage		
TWTA	-20/55	N/A
SDST	-35/50	N/A
DPAM, DPA	-40/50	N/A
Rover		
MMRTG Fin Root Average	100/185	100/185
RAMP Interfaces		
Avionics	-40/50	-40/50
Instruments*	-40/50	-40/50
Battery	-20/40	-20/30
SDST/Electralite	-35/50	-35/50
SSPA	-35/55	-35/55

- Recovers ~150 W of waste heat from MMRTG during Mars surface operations
- CFC-11 (working fluid): -100 to +100 C range
- Pumps & Valves: -40 to +100 C range
- Pump flow rate = 0.75 lpm
- Operating pressure < 200 psia
- Passive mixing/splitter types of thermal control valves (liquid based actuator)
- Pump input power = 10 W
- Three years operational life time

V. Predictions vs. Observed RHRS performance during tests and on the Martian surface

The thermal performance of the RHRS and the components controlled by it was predicted by a three-step process during the design maturation phase, which was then followed by the test phase. The initial preliminary architecture and design process employed simpler design tools that were EXCEL and ThermXL based. During this phase several design and concept trades were conducted to arrive at the final configuration and design. This design was then analyzed in great detail by using several software tools, e.g., IDEAS-TMG, NX, CFD and Thermal Desktop. Models used thousands of elements and nodes to digitize the entire rover geometry in great detail. This then led to the fine-tuning required to implementing the design that would fly to Mars.

During the implementation of this design, in parallel, several development tests were conducted. These tests were done at component or sub-subsystem levels to retire risks associated with any new or still in development technologies utilized in the RHRS. Examples of these were thermal conductances between the working fluid and components mounted on RAMP interfaces, heat transfer and pressure drops in fin tubing used in the RAMP, CO_2 gas gap effective thermal conductances, thermal control valves flow control performance validation, etc. Additionally a dynamic (transient) test that simulated thermal masses and coupling in the key components in the RHRS coupled with a pump and the two thermal control valves was conducted to verify that the valves actuate smoothly and do not have dynamic cross-talk or interference due to feedback between them while the RHRS and its controlled components undergo diurnal environmental cycles on Mars.

After the entire rover was fabricated and assembled along with the thermal control system (including the RHRS and a MMRTG simulator), a very extensive Solar Thermal Test[17] was conducted to observe the rover's thermal performance. The test was conducted in a GN_2 (8 Torr) atmosphere to simulate the Martian conditions (8 Torr CO_2) in a test chamber. To better anchor the thermal models, this test was additionally conducted in vacuum. Testing in vacuum eliminates the gaseous conduction and convection influence on the thermal behavior of the rover. This makes model correlations much easier by having fewer parameters (lacking those additional heat transfer modes).

Prior to the rover thermal test to simulate Martian environments, a Solar Thermal Vacuum Test[18] was conducted on the entire spacecraft (rover stowed inside of the entry vehicle along with the cruise stage). This tested the performance of the rover (and the whole spacecraft) during the cruise phase.

As is always done in every flight project, the predictions and tests are done for at least the two extreme bounding conditions that the rover would encounter during all phases: WCH (Worst Case Hot) & WCC (Worst Case Cold). The two extreme conditions for which the tests were conducted were to simulate WCC conditions in winter at a 27^{o}S latitude and the WCH conditions during summer at the same latitude. Table 2 shows comparisons of predictions and observed performance during rover STT for the RHRS mounted thermally controlled components as well as key elements of the RHRS. The rover HRS performed exceptionally well during Rover STT and the RAMP temperatures stayed within AFT limits (-40°C/+50°C) over the entire test. In general the RHRS performance observed in the test came out to be either better than predicted or close to predictions. In the WCC conditions the RAMP interfaces were 3^{o}C to 10^{o}C warmer than predicted, while they were within 0.2^{o}C of the WCH conditions for the hottest components (colder for other). This showed that the design was extremely robust and had positive margin for all conditions. Actual heat leaks from the rover boxes mounted to the RAMP and the RAMP were about 20% less than the cold-case conservative design model. The temperature drop from the inlet fluid to the exit fluid was less than predicted, indicating again that heat losses were smaller than expected. The early thermal design analyses used worst-case conservative (bounding) assumptions to ensure a robust design, whereas the actual performance was more realistic, which led to the smaller observed heat losses. Examples are more realistic thermal conductance of CO2 gas gaps, longer cable lengths (smaller heat leaks), additional radiation shielding from the RAMP mounted boxes to the rover chassis via cables, etc. when compared to the design models.

During this test the additional observation was that the RAMP temperatures were more uniform than predicted (7^{o}C gradient predicted vs. 2^{o}C in test). This showed that the actual heat spreading in the RAMP (due to the thick aluminum structure) was better than expected, which is also desirable to maximize temperature margins between all the components and the corresponding temperature limits since all the mounted components (except the rover battery) have identical allowable temperature limits. This minimal gradient in the RAMP in spite of significant differences in the power dissipations amongst the several components thermally controlled by the RAMP showed that the RHRS served as a true thermal bus on which a very diverse set of components were controlled to nearly identical temperatures.

Operating pressures in the HRS were maintained within the nominal expected range throughout the test. The minimum pressure recorded during STT was 67 psia (Min Yellow Alarm = 55 psia). The maximum system pressure recorded during STT was 153 psia (Max Yellow Alarm = 180 psia). No Freon leaks were observed. There was no evidence of accumulator bellows sticking; all gas-to-liquid pressure gradients inside the accumulator were less than 3 psid. All the thermal control valves functioned exactly as designed and tested with no malfunctions.

	Worst Case Cold, °C		On Mars, Gale Crater (Spring)		Allowable Min/Max Limit	Worst Case Hot, °C		On Mars, Gale Crater (Summer)	
Location	Pre-Test Prediction	Test Value	Flight Predict	Flight Value		Pre-Test Prediction	Test Value	Flight Predict	Flight Value
RHRS Fluid (RAMP In/Out)	-19/-30	-19/-21	21/26	27/24	-40/50	16/14	19/21	28/32	30/26
RAMP Mounted Components	-21/-28	-17/-24	31	31	-40/50	15/23	21/23	36	31
MMRTG (Fin root)	114	128	185	190	-40/50	170	171	186	192
RHRS Pressure (psia)		67	122	130	55/180		153	133	133

Table 2: RHRS performance predictions vs. test

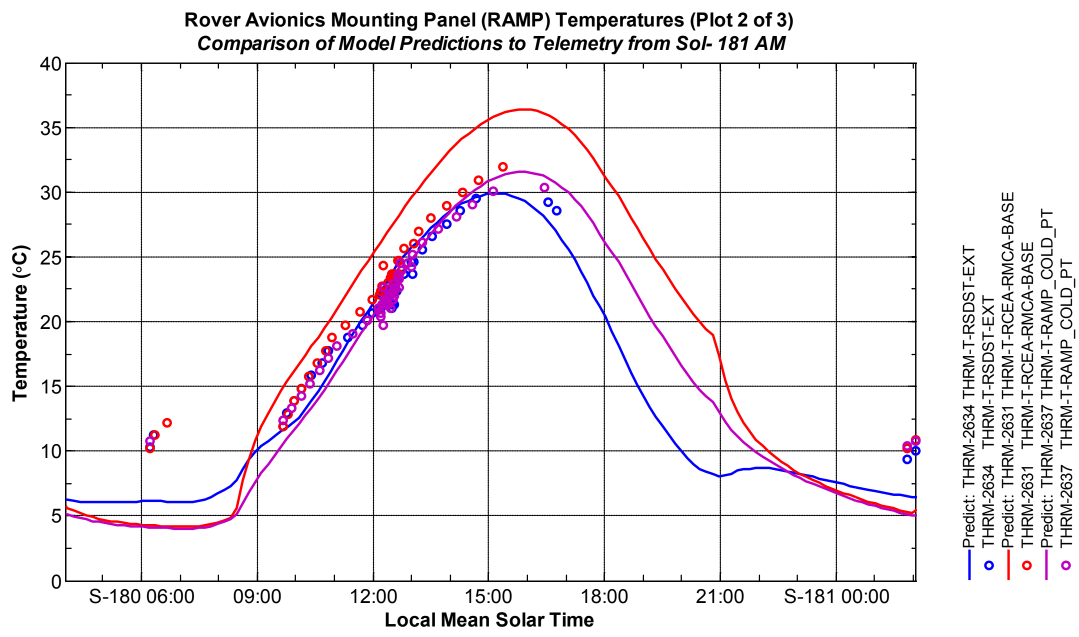


Figure 8: RAMP Mounted Component Flight Temperatures on Mars

The Curiosity rover has been on the surface of Mars for about 8 months since its very successful landing on August 5th, 2012. It landed in spring and is in the summer season at the Gale landing site. Its overall performance has been excellent. During EDL the RAMP components with a total mass of ~150 kg were very well thermally coupled via the RHRS and experienced very small temperature changes between the time the CHRS was vented to the time of landing on Mars (~20 minutes duration). Once on the surface of Mars, the rover thermal control (via the RHRS and passive thermal control valves) automatically responded to the change in the environment from cruise to that on the Martian surface to come to a new thermal equilibrium without any commands from the ground or the rover computers. The RHRS has performed very close to the predictions made by the post-test correlated thermal models. Table 2 also shows the comparison of the thermal predictions for the RHRS controlled components on the RAMP and the key RHRS components. It is evident from this table that the RHRS is performing very close to the predictions. Figure 8 shows a snapshot of some RAMP temperatures during early summer on Mars.

VI. Possible Improvements for Future RHRS designs

Even though it is quite evident that the RHRS has performed exceptionally well in flight, it's performance is very robust and predictable and functions as a very uniform temperature thermal bus, there are still possible ways to improve it further for future missions. Some of these possible improvements are delineated below:

a) The thermal design could be biased lower in desired temperatures by using lower thermal control valve control set points. This is feasible because the heat loss from the rover turned out to be lower than originally predicted and there is roughly a 10 C margin at the low end that could be utilized to create this bias. This would reduce the maximum temperatures for the WCH conditions, although not by an amount equal to the reduction in the WCC temperatures. This is because even though the start temperature (Figure 8) would be lowered by lowering the thermal control valve set points, the available area of the RHRS radiators is inadequate to maintain the RAMP temperatures is configurationally inadequate to maintain the RAMP temperatures in the control range. Hence in the hot conditions the RAMP thermal mass provides the thermal inertia to prevent excessive rise of its temperature while the environment is getting warmer and power is dissipated in the components on the RAMP. Hence the initial condition during the thermal mass dampened rise of RAMP temperatures would be lower but the max temperature at the peak in the afternoon would not be lowered by the same amount because the shape of the temperature curve at the peak shows that the system is approaching a quasi steady state heat balance near the peak.

b) The MMRTG fin root average temperatures were 5 to 10 C higher that predicted, but still within their allowable limits by a relatively small margin. Again some of the RAMP temperature margin observed in test & flight could be utilized to reduce the hot plate size (less heat pick up). That in turn would open up the view from the MMRTG and cool it off. But this is more in the category of fine-tuning the design rather than a very significant change.

c) An actuator-operated flap in the opening view of the MMRTG that could be opened or closed depending on the season or RAMP/MMRTG temperatures could be utilized to provide a more robust RHRS design because in the winter, with a closed flap, the MMRTG would have a more restricted view of the environment and warmer, whereas in the hot cases the open flap would bring the configuration back to being similar to the current one.

d) Qualification of alternative working fluids (instead of CFC-11, which is no longer produced but only available in a recycled form).

e) Lighter weight and lower power pump assemblies would benefit future missions.

VII. Conclusion

This paper presented an overview of the requirements, design and performance of the Mars Curiosity Rover (currently on Mars) that utilizes a mechanically pumped fluid loop for thermal control. This is the 5^{th} heat rejection system that utilized mechanically pumped fluid loops for thermal control of interplanetary missions (all JPL missions to Mars). Its flawless performance in all phases of flight allowed it to tightly and robustly control the temperatures of all sensitive components within their allowable limits. It was the first such system to harness waste heat from an MMRTG for the rover's thermal control allowing for all electrical power produced by the MMRTG to be used for mission operations (except for the 10 W required for the pump). Overcoming the extreme thermal and mechanical environments encountered by this mission during the various mission phases was a major challenge and an enormous achievement. Employment of these systems in the Curiosity rover has paved the way for their use in the thermal control of future interplanetary missions in their current or extrapolated forms.

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