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From Concept to Flight: An Active Fluid Loop Based Thermal Control System for Mars Science Laboratory Rover

Gajanana C. Birur[1], Pradeep Bhandari[2], David Bame[3], Paul Karlmann[4], AJ. Mastropietro[4], Yuanming Liu[5], Jennifer Miller[3], Michael Pauken[4], and Jacqueline Lyra[6]
Jet Propulsion Laboratory, California Institute of Technology, M/S 125-123, Pasadena, CA, 91109-8099

The Mars Science Laboratory (MSL) rover, Curiosity, which was launched on November 26, 2011, incorporates a novel active thermal control system to keep the sensitive electronics and science instruments at safe operating and survival temperatures. While the diurnal temperature variations on the Mars surface range from -120 C to +30 C, the sensitive equipment are kept within -40 C to +50 C. The active thermal control system is based on a single-phase mechanically pumped fluid loop (MPFL) system which removes or recovers excess waste heat and manages it to maintain the sensitive equipment inside the rover at safe temperatures. This paper will describe the entire process of developing this active thermal control system for the MSL rover from concept to flight implementation. The development of the rover thermal control system during its architecture, design, fabrication, integration, testing, and launch is described.

Nomenclature

A-N	=	Army-Navy Mechanical Fittings
CAP	=	Cruise Auxilliary Pump
CFC-11	=	Trichlorofluoromethane
CHRS	=	Cruise Heat Rejection System
CIPA	=	Cruise Integrated Pump Assembly
CP	=	Cold Plate
CS	=	Cruise Stage
DS	=	Descent Stage
EDL	=	Entry, Descent, and Landing
HP	=	Hot Plate
HRS	=	Heat Rejection System
IPA	=	Integrated Pump Assembly
JPL	=	Jet Propulsion Laboaratory
KSC	=	Kennedy Space Center
MER	=	Mars Exploration Rover
MLI	=	Multi-layer Insulation
MMRTG	=	Multi Mission Radioisotope Thermal Generator
MPF	=	Mars Pathfinder
MPFL	=	Mechanically Pumped Fluid Loop
MSL	=	Mars Science Laboratory
NASA	=	National Aeronautics and Space Administration
PHSF	=	Payload Handling Systems Facility
RAMP	=	Rover Avionics Mounting Plate
RIPA	=	Rover Integrated Pump Assembly

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[1] Principal Thermal Engineer, Propulsion, Thermal, and Material Section
[2] Principal Thermal Engineer, Thermal and Fluid Systems Engineering Group
[3] Thermal Engineer, Thermal and Fluid Systems Engineering Group
[4] Senior Thermal Engineer, Thermal and Fluid Systems Engineering Group
[5] Senior Thermal Engineer, Applied Low Temperature Group
[6] Product Delivery Manager, Mars Science Laboratory Rover, Propulsion, Thermal, and Material Section

RHRS = Rover Heat Rejection System
RPS = Radioisotope Power System
RTG = Radioisotope Thermal Generator
SAF = Spacecraft Assembly Facility at JPL
STT = System Thermal Test
STV = System Thermal Vacuum
VIF = Vertical Integration Facility at KSC

I. Introduction

THE successful performance of Mars rover, lander, and orbiter missions in the last fifteen years along with their valuable science data was one of the reasons for NASA to embark on the development of the Mars Science Laboratory rover mission in 2005. The two Mars Exploration Rovers launched in 2003 provided extensive proof on the past presence of water from the rock samples analyzed. Further, the Mars polar lander, Phoenix, showed the presence of water ice on the surface. As a next step in its search for the existence of life on Mars, past or present, NASA needed to send a rover capable of conducting more complex physical and chemical analysis of surface samples. The MSL rover was conceived to carry enough scientific instruments to prove that Mars has or had an environment essential for the existence of biological life

The top level mission requirements for the MSL rover include a landing site in a wide latitude range and duration of operation (one full Martian year). The other requirements concerned the distance travelled (~20 km) and number of samples collected for onsite testing (~70). An MSL rover configuration was developed based on these requirements. A Radioisotope Power System was selected as the power source for the MSL rover for the Mars surface operations. The RPS developed for the MSL mission was of a new design and is called the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG).

Figure 1. Mars rover family – Sojourner (1996) in the foreground, MER rover (2003) on the left, and MSL rover (2011) on the right

The high level mission goals required the MSL rover to be more complex and much heavier than the previous two rovers shown in Figure 1 (MPF Sojourner in 1996 and MER Rover in 2003). The result of these MSL mission requirements and complexity of the MSL rover required a thermal control system that was robust and at the same time flexible. This led to development of a rover thermal control system based on an active fluid loop. This MPFL on the rover, called rover heat rejection system (RHRS), functioned as both a heat rejection and heat recovery system. For MPF and MER missions, the HRS consisted of a fluid loop only on the cruise stage [1-7] and the rover thermal control for surface operations was based on passive technologies such as heaters, aerogel insulation, and wax-actuated heat switches. This paper covers the active thermal control system on the cruise stage and the rover; however, emphasis is on the development of the rover fluid loop.

II. MSL Rover Description

The final design of the rover is a six wheeled vehicle weighing abround 900 kg, about the size of a compact car. It carries an MMRTG as its power source on Martian surface and a robotic arm that carries several equipment and science instruments for sample acquisition. A total of nine science instruments are carried by the rover.

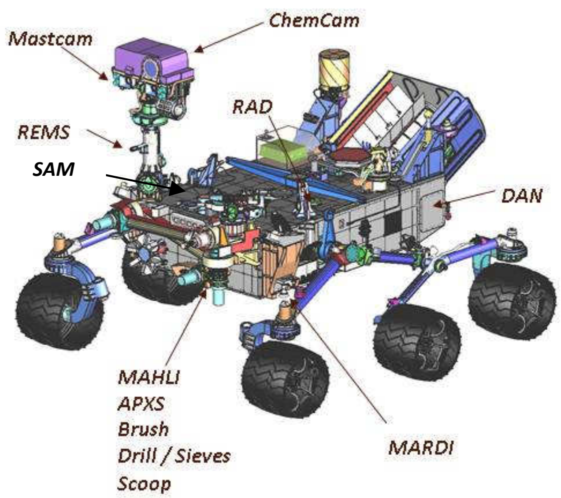

Figure 2. MSL rover with its science instruments

In terms of amount of science investigations and the extent of its operation on Mars, the MSL rover is the most complex of any rover built. It is larger by a half-order-magnitude compared to previous rovers in terms of many of the design parameters -- mass, volume, number of science instruments, mobility requirements, and rover's life on Mars. The science instruments on the rover are shown in Figure 2.

MSL's thermal control system is complex due to a large amount (2000 W) of waste heat generated by the MMRTG. The spacecraft configuration during pre-launch to Mars entry is shown in Figure 3. The waste heat management requires a special thermal control system right from pre-launch operations to end of rover operations on the Mars surface. MPFL is a major thermal control technology used for the thermal control architecture. Two independent MPFL's were designed for the thermal control of the rover: one on the cruise stage of the spacecraft and another inside the rover. The fluid loop inside the rover provides thermal control both during cruise and on the surface and was of new design and complexity whereas the fluid loop on the cruise stage was of heritage design except for the larger MMRTG heat load it had to handle. In addition, a separate ground based mechanically pumped fluid loop was used for the ground cooling of the MMRTG during its integration on the rover while the spacecraft was on the launch vehicle. This loop was not designed for operation during flight and was disconnected from the MMRTG prior to launch. The working fluid in both the flight loops is CFC-11, the ground based loop used Galden HT-170.

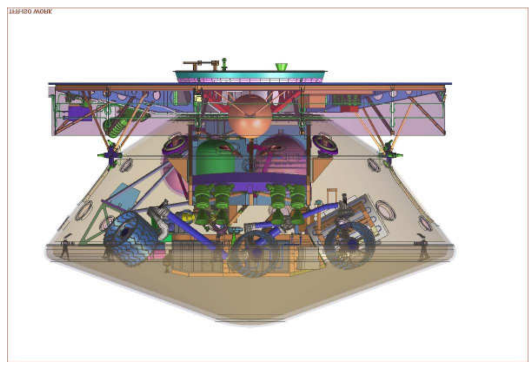

Figure 3. MSL rover cruise configuration

III. MSL Rover Thermal Challenges

The major thermal challenges of the MSL rover are: 1) protecting the sensitive electronics, battery, and science instruments from the extreme cold of Martian nights, especially during the winter months in high latitudes, 2) handling extremely limited electrical power available for the rover for surface operations, 3) rejecting a large amount of waste heat from the MMRTG and electronics residing inside the rover during the cruise phase when both the MMRTG and rover are inside the aeroshell, 4) rejecting waste heat from the rover inside electronics during surface operations in the hot conditions, and 5) accounting for extreme diurnal temperature variations of the surface environment.

In the past, for Mars landed missions such as Mars Pathfinder and the MER rovers, the heat rejection during the cruise phase of the mission was accomplished by an HRS based on a mechanically pumped fluid loop. In the case of the MSL rover, the additional 2000 W of waste heat from the MMRTG required a much larger HRS with its working fluid operating at much higher temperature. This cruise stage HRS, called CHRS, operates only during the cruise phase of the mission and is jettisoned before Mars EDL. The challenges posed by this loop were not as severe as that of the rover fluid loop.

The thermal control architecture used in the past landers and rovers for surface operations was based on electrical heaters and passive thermal capacity of the rover to absorb the heat generated. However, in the case of the MSL rover, the severe extreme thermal environment combined with much larger heat leaks from the bigger rover along with the limited amount of available electrical power precluded the use of electrical heaters. The other options were to use RHU's or the MMRTG waste heat available on the surface and this became a thermal challenge on the MSL rover. Because the MMRTG was already on the rover, it was decided to use the MMRTG waste heat.

A Thermal Control Architectural Concepts

Several thermal control architectural concepts were considered for the spacecraft and rover that would meet the thermal control needs during cruise and surface phases. The propellant tanks and lines on Cruise stage and Descent Stage were of traditional design with heaters and MLI blankets on the tanks and lines. Early on, it was decided that the mission required two HRS fluid loops. During the cruise phase, the heat rejection needs were similar to the past Mars missions with a mechanically pumped fluid loop collecting the waste heat and rejecting to space through radiators on the cruise stage. However, the larger size of the heat rejection and also higher temperatures required some developmental effort. The use of MMRTG waste heat during the surface operation along with the need to reject heat during the surface hot conditions was a challenging task and required significant trades of various thermal control concepts and technologies.

Some of the concepts and technologies investigated for the rover surface operation included architectures based on loop heat pipes, high thermal conductivity material, thermal heat switches, phase change material thermal storage units, mechanically activating deployable flaps etc. After a thorough review of these concepts and tradeoffs, the final thermal control architecture selected for rover surface operation was a HRS based on mechanically pumped fluid loop. A key strength of the MPFL is that it allows the waste heat to be picked up from multiple locations and allows for the heat to be rejected at various locations. Its robustness and flexibility to accommodate late changes in rover configuration were the key capabilities that made it the selected option. A thorough description of the selected thermal control architecture is described in a paper[8] published in 2005.

B HRS Focused Technologies

The selected thermal architecture relied on fluid loops, one each for the cruise phase and the rover surface phase. Further, the long life needs and the additional complexities required in the MSL HRS necessitated developing the needed additional HRS technologies.

The development of several technologies under the focused technology program was conducted over five years (2002-2006). A detailed description of the advanced HRS technologies developed for the MSL rover is described in papers[9, 10] published in 2006 and 2008. The technology development for the MSL rover was done in the Thermal Technology Lab at JPL. The key HRS technologies required for the MSL mission included: 1) long life mechanical pumps, 2) a stable working fluid with good thermodynamic properties that is compatible with the materials used in the HRS plumbing, 3) mechanical field joints that are more leak tight and robust to mating/demating than the ones used on previous Mars rover missions, 4) thermal flow control valves that are more sensitive and have long life for operation of thousands of cycles, and 5) flexible lines to accommodate relative displacement of HRS tubing bonded to the body of the rover.

C JPL Thermal Technology Lab

. The JPL Thermal Technology Lab shown in Figure 4 was one of the key labs where life tests on pump motors and thermal control valves were conducted. The pumps are still being run at room and elevated temperatures in simulated rover fluid loop to ensure the performance does not degrade for at least three times its actual operating life (25,000 hours) during the MSL mission. Similarly, a thermal control flow valve was life cycle tested while its performance was monitored over 1,500 cycles which is three times its actual life on the Mars surface.

Figure 4. JPL Thermal Technology Lab

IV. Design of MSL Rover Thermal Control System based on an Active Fluid Loop

A key part of the thermal control system design for the MSL rover was the development of the RHRS fluid loop. This loop was integral to the rover thermal control as it connected the key science and engineering equipment of rover to the heat rejection/recovery system. RHRS not only connected the rover equipment to both heat rejection/recovery systems for the surface operations but also for heat rejection to the CHRS during cruise phase. The interface between CHRS and RHRS is shown in Figure 5.

A Rover HRS Design

Several concepts were investigated for the two HRS fluid loops. For the cruise stage HRS loop used for rejecting the MMRTG waste heat during the cruise phase of the mission, two concepts evaluated were heat rejection at high and room temperatures. An advantage of rejecting heat at higher temperatures is a significant reduction in the radiator area and the consequent mass reduction. After spending over a year investigating fluids that would be suitable for the MSL HRS, it was determined to go with the same CFC-11 fluid used earlier on MPF and MER. One of the constraints in using CFC-11 was keeping the maximum temperature of the fluid during cruise in this loop below 90 C. The other fluid investigated was water with corrosion inhibiters operating at 120 C. However, many of the uncertainties of using water were not resolved in time when the design and fabrication of the HRS needed to start.

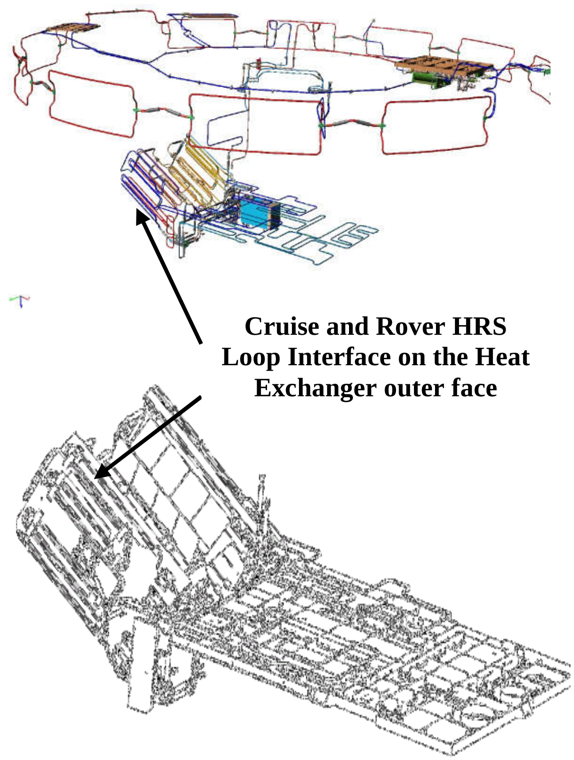

Figure 5. Cruise and rover HRS loop interface

In the case of the rover HRS loop, even though the same CFC-11 was used, more technology development was needed due to the fluid operating at temperatures as high as 90 C for 2 to 4 hours during the summer day time operation on the Mars surface. Further, the pump and the flow valves would operate as high as 70 C during these hours. The detailed design of the rover HRS is described in several papers[12-14] published earlier. The HRS design included developing an optimal configuration for the layout of the tube routing that met both thermal and mechanical requirements of the equipment and the science instruments. The key HRS assemblies that were designed and fabricated for the CHRS loop are: 1) CIPA, 2) CHRS tube assemblies, 3) Cruise radiators, 4) heat exchangers for cruise and DS electronics, 5) CFC-11 vent assembly, and 6) flex line assemblies. The assemblies for the RHRS loop included: 1) RIPA, 2) RHRS tube assemblies, 3) RAMP/HRS tube assembly, 4) CP/HP heat exchangers, 5) Top Deck tube assembly, and 6) flex line assemblies. The final routing of the CHRS loop is shown in a solid model of the rover configuration in Figure 5. The final RHRS tube routing is shown in Figure 6; the red color tubing in the figure is carrying the hot fluid to the cold plate on the heat exchanger and the top deck.

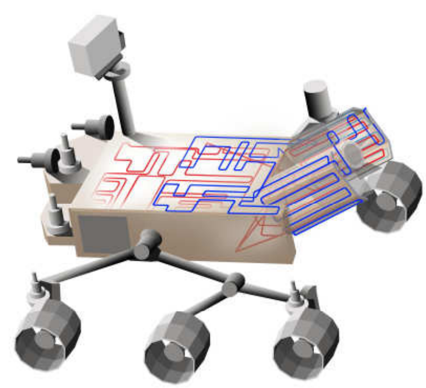

Figure 6. RHRS tube routing on the rover

B Major Changes Made after the HRS Design Phase

Design of the CHRS and RHRS loops started in 2005 and most of the detailed analysis was completed by 2007. Fabrication was started in 2006 with the procurement of the material for the fabrication of the tubes, radiators, and heat exchangers. At the same time the specification for the pump assembly was completed in 2006 and procurement was issued to Pacific Design Technologies in Goleta, California in October 2006.

The detailed design review of the MSL rover thermal control system was held in May 2007. Soon after, fabrication of the HRS flight assemblies started. As more data on the rover avionics and science instruments became available, the results from the thermal analyses showed some of the rover thermal design features needed to be changed in order to keep the equipment within allowable temperature limits. Some of the major changes made after the CDR design phase are listed below.

1. Changing RAMP tubing from a smooth interior surface to a finned interior surface

The thermal/fluid analysis of the RAMP HRS tubing showed the high heat flux from some of the equipment attached to RAMP caused them to exceed their upper temperature limit. Because of the constraints on routing of the RHRS tubing on RAMP, one way to enhance heat transfer into the fluid in the tube was using a finned interior. The interior fins were designed and incorporated into extruded aluminum tubes for use on RAMP.

2. Incorporating flex line assemblies in HRS tube routing

The RHRS and CHRS tubing run through various parts of the cruise stage, descent stage, and rover. A stress analysis of the tubing showed the relative displacement of the tubing between the major spacecraft assemblies during launch, EDL, and surface operations would lead to excessive tube stresses. Flex line tube assemblies were designed and incorporated whenever there was a jump from one major spacecraft subassembly to another.

3. Epoxy thermal conductivity was lower than published values

During a developmental test it was found that the actual thermal conductivity of the epoxy used for bonding the tubes to heat exchanger plates[15] to be almost an order-of-magnitude lower than the published values. This led to redesigning the HRS tube to plates bonding method for the rover heat exchangers.

4. Designing of additional tubing on the MMRTG for ground cooling purposes

During the detailed design phase of the thermal control system, it was found[16] that the hot MMRTG during its mechanical integration on the rover on the launch pad would lead the Descent Stage propellant tanks to exceed their upper limit. This led to the design and installation of a second set of tubing on the MMRTG to circulate cooling fluid to keep the MMRTG below maximum allowable temperatures. These tubes were installed next to the primary HRS tubes which were already designed.

C Detailed Analysis of Rover HRS

Several detailed analyses were performed in support of HRS design verification. These analyses include thermal modeling and analysis of the rover with the HRS fluid loops, internal fluid flow analysis for pressure drops in the system, finite-element structural analysis to verify the robustness of the tube design, and computational fluid dynamics analysis for HRS performance with fluid flow situations. A detailed description of these analyses is given in References 12 and 13.

D Integrated Pump Assembly

The two integrated pump assemblies, RIPA and CIPA, were designed and built by Pacific Design Technologies (PDT) in Goleta, California. PDT had built the pump assemblies for the previous Mars rovers in 2001-2003. Even though many parts of the MSL pump assemblies were similar to the MER IPA, there were significant changes in RIPA compared to the MER rover IPA. RIPA has two sets of flow control valves – two mixing valves and two splitter valves – whereas the MER IPA had only one set of splitter valves to control the heat rejected at the radiator. The cruise pump assembly, CIPA, is very similar to the MER IPA, except the pump flow rate is double that of the MER IPA and there is no thermal control valve to control the flow to the radiator. Figure 7 shows CIPAS ready to be installed on the spacecraft. CIPAS includes CIPA and a separate third pump called CAP operated to provide a two-fault tolerance system during launch phase. In addition CIPAS includes vent and pyro valve assemblies, a filter system, and pressure transducers.

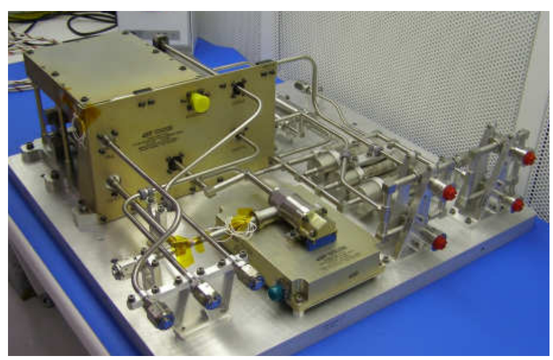

Figure 7. CIPAS ready to be installed on the spacecraft

A flow-path schematic of the RHRS fluid loop inside the rover is shown in Figure 8. The assembled RIPA is shown in Figure 9. One of the major modifications in RIPA was the development of the advanced thermal flow control valves. The actuator used in these valves was based on oil instead of a paraffin wax used in the MER IPA valves. This was a new technology specifically developed for the MSL RHRS. A detailed design description and testing of the valves is given in paper[11] published in 2008.

Several life test programs were implemented for the pump assembly components to ensure the reliability of the design and the build. The life testing of the first set of bellows for the accumulator showed the stiffness of the bellows made its life fall short of the MSL life requirements and required a redesign. The redesigned bellows were not as stiff, and during the final fabrication stage of the RIPA, it was found that the Teflon bellows guide could jam inside the accumulator housing if the interior surface finish were not highly polished. The bellows guide design was changed to ensure it would never jam for any tilt in the bellows during its motion. The completed RIPA as delivered to JPL is shown in Figure 9.

V. HRS Fabrication and Integration

The entire fabrication of the HRS flight hardware was done at JPL. Starting with raw stocks of aluminum and stainless steel tubing, sections of the HRS tube subassemblies were fabricated. These included radiators, heat exchangers, tubing assemblies consisting of aluminum and stainless steel tubing, and integrated pump assemblies with service valves and pyro valves.

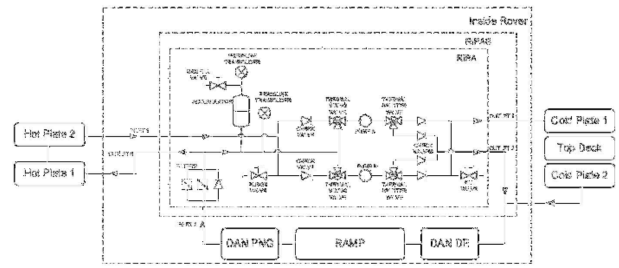

Figure 8. RHRS flow path in the rover

A Fabrication of HRS assemblies

The actual buildup of the HRS assemblies for MSL required setting up of specialized laboratories. A separate HRS laboratory (HRS lab) was set up in 2006 at JPL for flight fabrication of the HRS assemblies. The lab housed various tools and fixtures needed for fabrication. Some of the key equipment set up in the HRS lab were: a manual bench tube bender, orbital tube welding machines, a TiG set up for aluminum tube welds, a mass spectrometer Helium leak detector, a hydrocarbon dew point analyzer, chillers for providing 2000 W heat removal, a Class 100 laminar flow bench, dry scroll vacuum pumps, CFC-11 recovery carts, service carts for flight fill and circulation of CFC-11, and an electronic rack with instruments for monitoring the pump assembly during tests. A view of HRS lab during the peak fabrication period is shown in Figure 10.

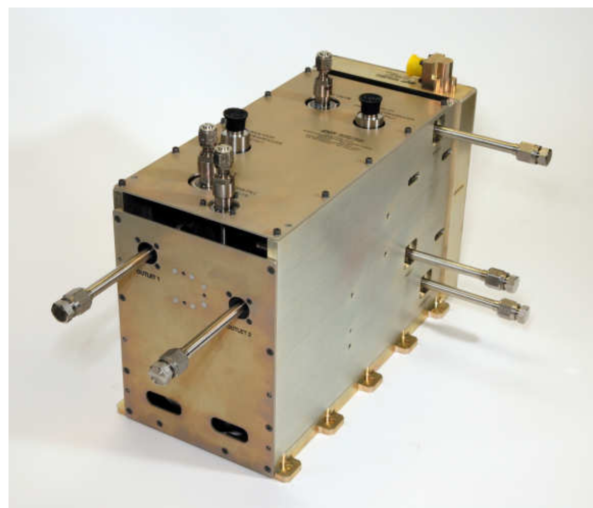

Figure 9. RIPA as delivered by PDT to JPL

Figure 10. MSL HRS flight fabrication lab

The actual integration of the HRS assemblies on the spacecraft took place in SAF at JPL. Some of the final HRS integration on the spacecraft and rover took place in PHSF at Kennedy Space Center in Florida. The final integration of the MMRTG on the rover and the completing of the CHRS fluid loop occurred on VIF at KSC. The major issues that needed special attention during fabrication were: TiG welding of aluminum tubes, installing of HRS tube assembly into RAMP, installing of flex line assemblies between the cruise radiator panels, and bonding of the tube assemblies on the rover heat exchangers.

B HRS Issues during STV and STT

The first System Thermal Vacuum (STV) testing[16] was conducted in January 2009 in JPL 25-Foot Spacecraft Simulator Facility. The test was for verifification of the thermal control design for the cruise phase of the mission. The spacecraft configuration included the full rover, Descent Stage and Cruise stage. One of the key objectives in this nine-day test was the characterization of the Cruise and Rover Heat Rejection System thermal design performance in extreme cold and near-extreme hot thermal cruise environments. The MSL spacecraft in the test configuration in the 25-foot chamber is shown in Figure 11.

The test results showed the Cruise and Surface Heat Rejection Systems design to be robust. The results from the test demonstrated that all the sensitive components controlled by both the HRS were provided with excellent thermal control during the cruise phase worst cold environment (Reference 16).

A System Thermal Test[17] was conducted in March 2011 to verify the thermal design of the rover for surface operations. In this 16-day test, thermal balance testing as well as rover functional tests were conducted. The HRS test objectives met during this test were the verification of Rover HRS thermal performance and the functionality of the rover bypass and mixing thermal valves. The Rover system-level analytical thermal model of RAMP/HRS predicted for the extreme worst-case cold (27°S Winter) environment at least 10°C of margin to the minimum AFT limit of -40°C. RAMP/HRS predicts in the extreme worst-case hot (27°S Summer) thermal environment showed 0°C of margin to the maximum AFT limit of 50°C. The rover configuration in JPL 25-foot thermal vacuum chamber during STT is shown in Figure 12.

Figure 11. MSL Spacecraft in JPL 25-foot thermal Vac chamber

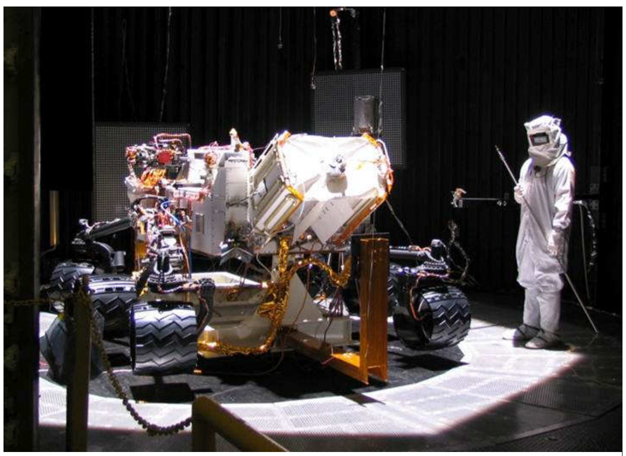

Figure 12. MSL rover in the JPL thermal vac chamber during System Thermal Test

C HRS Activities during ATLO in PHSF at KSC

The MSL spacecraft was disassembled into Cruise, Descent, and Rover stages and shipped to KSC after all the system level tests were completed at JPL. The spacecraft was reassembled at PHSF in KSC and further tests were performed before encasing the entire spacecraft in the rocket fairing. About two weeks before the launch date, the fairing with the spacecraft was hoisted onto atop the Atlas V rocket in VIF.

Major HRS activities at VIF were precooling the MMRTG with GSE chillers. The precooling was to lower the MMRTG fin root average temperature down to 70 C at which time the MMRTG unit is ready for installation on the rover inside the aeroshell. A key MMRTG requirement on the rate cooling was that it should not exceed the limit of 18 C/ten minutes. According to the prelaunch plan, the secondary loop operates continuously after mating with the MMRTG until the complete integration of the MMRTG to the rover and completion of the CHRS loop connections and its steady state operation. The entire GSE operation was planned to last for one week starting with setting up the chillers to its final disconnection from the MMRTG.

The first step in the GSE cooling of the MMRTG was to connect the GSE lines to the GSE tubing on the MMRTG and start circulating the Galden HT-170 fluid through the GSE loop. Once the MMRTG fin root temperature dropped to a predetermined value, it was mechanically installed on the rover. The CHRS flight tube connections to the HRS tubing on the MMRTG was made next and load the entire CHRS loop with CFC-11 while GSE was still removing the waste heat from the MMRTG. A good description of these activities is given in Reference 18 and 19 while a description of the loading of the CHRS is given in Reference 20. At this time all the three pumps in the CHRS loop and the two pumps in the RHRS loop were operating and stayed operating until an hour after launch. Druing the cruise phase, only one pump in the each loop was operating.

D HRS operation during MSL rover flight to Mars

The two HRS fluid loops are smoothly operating on the spacecraft as it cruises through space to Mars. The operating pressures of the fluid loops are monitored regularly along with the accumulator gas side pressures and temperatures of the various components on the Cruise and rover stages. The performance of the MSL thermal control system during its cruise since November 26th 2011 is described in Reference 21. The pumps and the loops are performing well. The loop operating pressures are expected to come down as the spacecraft moves further away from the Sun. The flight performance so far is close to that expected based on the analysis.

VI. Lessons Learned

There were many lessons learned during the development of the MSL rover thermal control system. These were in the areas of architectural concepts, selection of appropriate thermal technologies, design and fabrication of the flight HRS hardware, and integration and testing of the HRS on the rover and spacecraft. Some of the lessons are:

1) While developing the RHRS architecture some additional features such as a deployable flap to cover the MMRTG during the winter season on the mars surface would have made the thermal control system design even more robust.
2) In the area of flight hardware and fabrication, the choice of OmniSafe mechanical fittings turned out to be an excellent choice as they were better than the A-N fittings in terms of leak rate and the number of times they could be safely mated and demated.
3) The use of short flex tube assemblies to take on relative displacement between major spacecraft parts through which HRS loop runs through made the HRS integration on the spacecraft easier.
4) The TiG welding of aluminum tubing was very sensitive to the workmanship and making it more automatic like orbital welding would have made the fabrication easier.
5) The experience with conductive epoxies showed that the actual performance of an epoxy bonded interface was far lower than that expected from the manufacturer’s data; it is better to test the epoxy before using it and not rely on vendor’s data.
6) In terms of the working fluids for the HRS loops, a more involved investigation should have been taken up to find an alternative fluid. The heritage fluid, CFC-11, needs to be operated at high pressures if the loop temperatures go above 100 C and further, it is no longer produced.
7) In the design of the pump assembly, keeping the working fluid outside the bellows in the accumulator makes charging the loop with fluid a lot easier and also this is the method used in the International Space Station fluid loop.

VII. Conclusions

The development of the active thermal control system for the MSL rover was a major technology, design, fabrication, and implementation effort. The thermal requirements and challenges posed by the MSL rover were significant and no traditional thermal control system architecture would have easily met them. In the development of the MPFL for MSL, several new technologies were developed, tested and implemented. These included passive thermal control flow valves with long cycling life, robust precision mechanical field joints lasting dozens of mate/demate cycles, long-life pumps lasting over six years, and flex line assemblies that can withstand hundreds of thousand small mechanical cycles. For the RHRS implementation, several fabrication techniques had to be developed to accommodate the tightly packed rover. The first time implementation of such a novel thermal control system resulted in many rework and design modifications during the MSL rover build; however, the whole system came through on time for launch. The two HRS loops have operated smoothly for the last seven months and the Mars landing is expected on August 5, 2012.

This active thermal control system could be easily implemented on future planetary landers, rovers, or any spacecraft with demanding thermal requirements and challenges.

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