Mars Science Laboratory Launch Pad Thermal Control

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NASA is planning to send a large (>850 kg) rover as part of the Mars Science Laboratory (MSL) mission to Mars in 2011. The rover is powered by a Multi-mission Radioisotope Thermoelectric Generator (MMRTG), which generates about 2000 W of heat that is converted to about 110 W of electrical power for use by the rover electronics and science payload. The presence of the high thermal power MMRTG in the descent stage leads to difficult and interesting thermal problems in terms of maintaining the temperatures of the sensitive rover electronics, payload and the descent stage propulsion components within their allowable flight limits. A mechanically pumped single phase heat rejection system (HRS) using CFC-11 as the working fluid is employed to maintain the MMRTG temperature within reasonable levels by picking up its waste heat and rejecting it to the HRS radiators in the cruise stage. These radiators are cooled by the launch vehicle fairing air conditioning (A/C) system. This paper will describe the challenges faced in accommodating the warm MMRTG during the pre-launch phases of integration, launch pad operations as well as during launch. Predictions of temperatures during these phases will be presented when all the cooling systems (HRS and A/C) are operational. In-air tests conducted on the spacecraft in December 2008 to simulate the launch conditions were very successful and showed that all components would be within their allowable limits during these phases. Results of these tests will be shared in this paper.

Nomenclature

AFT = *Allowable Flight Temperature*
BOL = *Beginning of Life*
CFC-11 = *Trichloromonofluoromethane (Refrigerant 11)*
CIPA = *Cruise Integrated Pump Assembly*
CHRS = *Cruise Heat Rejection System*
GSE = *Ground Support Equipment*
HRS = *Heat Rejection System*
JPL = *Jet Propulsion Laboratory*
MER = *Mars Exploration Rover*
MMRTG = *Multi Mission Radioisotope Thermoelectric Generator*
MPF = *Mars Pathfinder*
MPFL = *Mechanically Pumped Fluid Loop*
MSL = *Mars Science Laboratory*
MSLFT = *MSL Focused Technology Program*
NASA = *National Aeronautics and Space Administration*
PDT = *Pacific Design Technologies*
RAMP = *Rover Avionics Mounting Plate*
RIPA = *Rover Integrated Pump Assembly*
RHRS = *Rover Heat Rejection System*
WCC = *Worst Case Cold*
WCH = *Worst Case Hot*

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I. Introduction

THE mission 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 will feature a rover enclosed in an aero-shell for protection during entry and descent onto the planet's surface. A cruise stage will carry the lander and aero-shell enclosure from Earth to Mars and will separate 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.

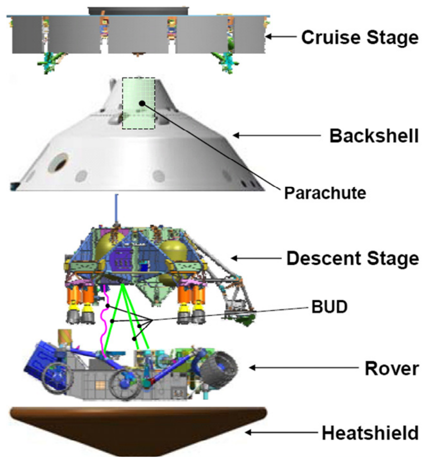

Figure 1. MSL Spacecraft.

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

Overall MSL Thermal Architecture

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 chloroflurocarbon-11 (CFC-11) as the working fluid. Figures 2 and 3 show the overall thermal architecture.

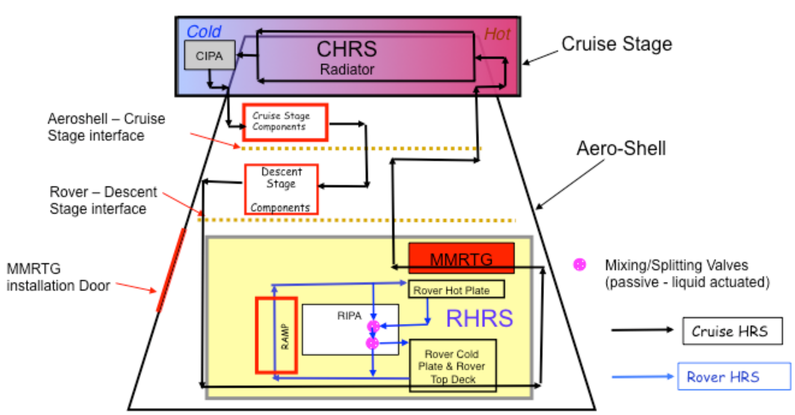

Figure 2. Schematic of Two HRS Fluid Loops.

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°C). It also picks up dissipated heat from the equipment on the rover and on the Cruise/Descent Stages of the MSL spacecraft.

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.

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.

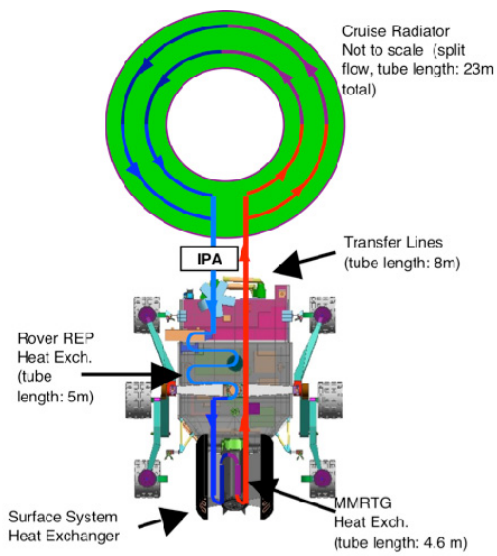

Figure 3. CHRS Fluid Loop Architecture.

The references[8 to 12] provide a brief history of HRS loops, particularly from JPL's experience in using them for Mars missions

Launch Pad Thermal Control

Similar to the requirements during cruise, the main driver of thermal control during pre-launch and launch is the removal of the 2000 W of heat dissipated from the MMRTG and the rejection of this heat to the cold airflow around the spacecraft, while maintaining the RTG at a reasonable temperature. Even though the maximum qualification temperature of the RTG is 200°C, the more important constraint for the safe removal of the MMRTG's heat is to ensure that all the components that are in the vicinity of the hot RTG do not overheat because their maximum allowable limits (typically 50°C) are much lower than the MMRTG's limits. In particular, the propulsion system, which not only has a maximum allowable limit of 50°C, it also has safety implications in terms of robustness of tanks to excessive temperatures and pressures.

The total power dissipated from the rest of the components in the spacecraft and rover is ~ 500 W. This enormous amount of power dissipated by the RTG and the rest of the spacecraft/rover also necessitated the usage of the CHRS for cooling these components during launch. The basic approach during launch and prelaunch phases is for the CHRS to pick up heat from these components and direct it to the CHRS radiators.

Three types of air flows are employed to cool the spacecraft during launch and pre-launch activities and these are shown in Figure 4.

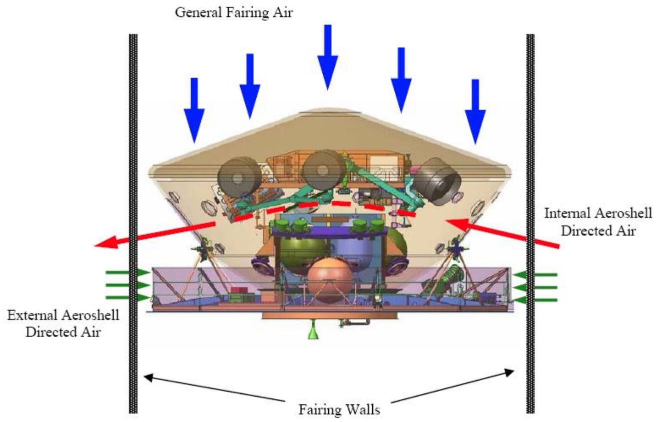

Figure 4. Cooling Air Flows on MSL Spacecraft During Launch (before aeroshell doors are closed).

The most significant cooling is done by cooled air flow from the launch pad ducting directed via several nozzles to the CHRS radiators which in turn cools the radiators to pick up the heat dissipated on them ("External Aero shell Directed Air").

In addition to the air flow directed perpendicular to the radiators' surfaces, additional air flow ("General Fairing Air") is directed along the axis of the spacecraft impinging on the heat shield (with the spacecraft oriented upside down in the launch configuration). This serves to provide general air conditioning to the spacecraft, in particular to cool off the heat shield. Any heat not picked up from the MMRTG via the CHRS fluid loop is parasitically lost from the MMRTG from its surface by radiation and natural convection, which is then inserted into the aero-shell's interior. This heat is then transferred from the aeroshell's interior to the launch vehicle fairing and picked up by the General Fairing Air.

Finally, an "Internal Aeroshell Directed Air" flow is employed as an additional means to augment cooling of the MMRTG when the aeroshell doors are open during spacecraft integration. This blows cold air from one door which goes past the interior of the aeroshell (rover + descent stage), over the MMRTG and then out of the second door. This air flow is obviously available only during the integration phase when the doors are still open. Once the doors are closed in preparation for launch the ducts providing this flow are detached from the spacecraft.

The key requirements of the three kinds of airflows are shown below (after MMRTG is installed in spacecraft):

- General Fairing Air
  - 150 lb/min (1.13 kg/s): nominal
  - 7-21°C
  - 30- 60% relative humidity

- External Aeroshell Directed Air

- 150 lb/min (1.13 kg/s): nominal
- 7-16°C
- 30- 60% relative humidity
- Provide >35 W/m^2/°C average heat transfer coefficient over >90% of CHRS Radiator area

- Internal Aeroshell Directed Air
  - 50 lb/min (0.38 kg/s): (nominal)
  - 12-20°C
  - 30- 60% relative humidity
  - Unavailable after Aeroshell doors closed

CHRS Design Description

Figure 5 shows an exposed view of the approximately 70 meters of Cruise HRS tubing on the MSL spacecraft. Since the amount of heat collected by the loop is quite large (>2000 W), large radiators (6 m^2) are employed to dissipate this heat to them while maintaining reasonable temperature levels in the MMRTG as well as other components served by the CHRS. A series of ten radiator panels—painted white and with double passes of tubing on the backside—ring the circumference of the Cruise Stage and provide an unobstructed view to deep space during cruise (and to cooling air flow during launch). The radiators are constructed of aluminum honeycomb with two face-sheets with the inner facesheet thermally and mechanically attached to the fluid tubing.

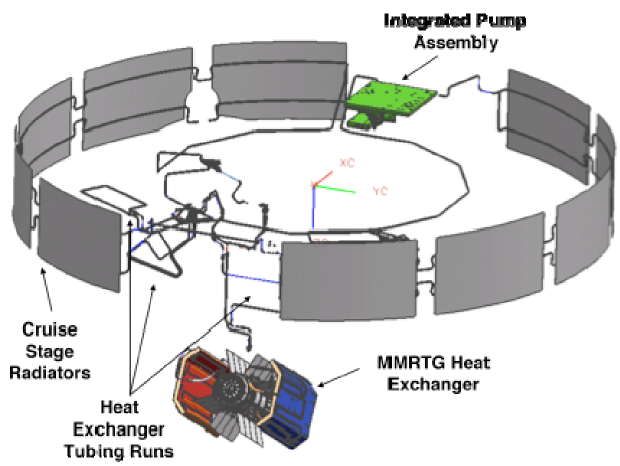

Figure 5. Cruise HRS Routing.

An integrated pump assembly is located on the Cruise Stage and produces a flow rate of up to 1.5 liters per minute within the loop. The cooled fluid exiting the last radiator is routed to a series of heat exchanger plates on the Cruise Stage, Descent Stage, and Rover to remove waste heat from components that are powered during the cruise phase of the mission[14].

The fluid loop tubing is thermally and mechanically attached to the MMRTG fins to effectively pick up heat from it. The CIPA (Cruise Integrated Pump Assembly) contains a primary and two redundant pumps, with only one pump operated at any time. The flow in the radiator is split to minimize the pressure drop in the system since the total length of tubing in the entire system is about 70 m with the radiator accounting for more than 50% of the length. The fin efficiency of the radiator is about 80%. The tubing is 9.5 mm (3/8") O.D. with 0.7 mm (0.028") wall thickness in the loop, primarily constructed of Aluminum.

White paint (α= 0.15; ε= 0.9 at BOL) is utilized as the thermo-optical surface for the radiators to minimize the heat deposition on them from the sun. More detailed description of the CHRS can be found in references 8-14.

Pre-Cooling of MMRTG Prior to and During Integration with Spacecraft

The CHRS is charged with CFC-11 only after the MMRTG has been integrated with the rover (to complete the fluid loop). So without additional cooling, the MMRTG would be very hot on its own. Hence, prior to installation of the MMRTG in the aeroshell (integration with the rover), it is cooled by a ground cooling system (Ground Support Equipment, GSE, shown in Figure 6). This is required to ensure that the MMRTG is cooled enough so that during integration with the rover it does overheat the equipment within the aeroshell. The GSE contains a chiller and pump that flows Galden HT-170 working fluid through a secondary set of tubing attached to the MMRTG casing and fins. Due to the criticality of the pre-cooling of the MMRTG, redundant GSEs are employed.

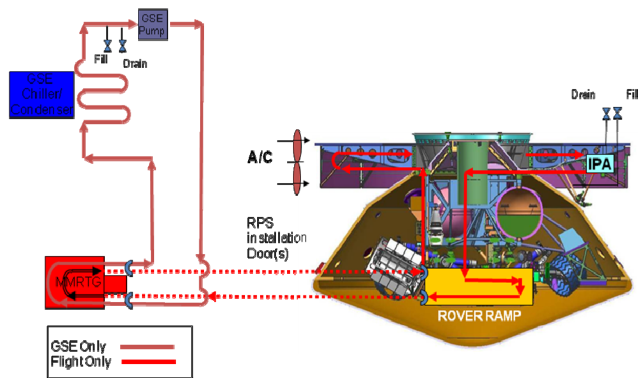

Figure 6. GSE for Pre-Cooling MMRTG.

The GSE keeps the RTG cooled enough from prior to the MMRTG's entry into the aeroshell all the way through the charging of the CHRS and its functional checkout. There is an overlap period of about ½ a day when both the GSE cooling loop as well as the CHRS are working simultaneously to cool the MMRTG.

Key Requirements for Components Served By CHRS

Component	Allowable Flight Temperatures (AFT)	Power Dissipation	Notes
MMRTG fin root	65/185°C	2000 W	• Pre-launch environment has GSE cooling available
<u>Propulsion Systems:</u> *Fuel Tanks/Lines, Pressurant Tanks, Valves, Filters, MLE Throttle Valves, RCS Thrusters/Lines*	[11.6]/50°C		• LV ICD under revision to change from 10C to 11.6C
Cruise Components	-40/50°C	134.7 W	
Descent Components (DPAM, DPA, DMCA)	-40/50°C	43.6 W	•Other Descent components with higher min. AFT
DS Thermal Batteries	-40/55°C		•Non-op
Rover RAMP	-40/50°C	130 W	
Rover Battery**	0/25°C		
Rover Heat Exchanger Plates	-100/[100]°C		

Table 1: Key Thermal Requirements during launch

Table 1 shows the key thermal requirements of components controlled by the launch pad cooling and the CHRS during launch.

Thermal Modeling of Launch Pad Cooling

Thermal models of the spacecraft in its launch configuration were constructed in three phases. The 1st one was a simple EXCEL based model with all the key components in the aeroshell represented as simple thermal mass models (MMRTG, radiators, air-conditioning boundary temperatures, CHRS, RHRS, rover, aeroshell, descent stage structure, propellant and pressurant tanks, etc.).

It assumes that the aeroshell doors are closed and no purge air is flowing. The air is modeled as lumped average temperature nodes with one node representing the outside of the heat shield exterior ("General Fairing Air"); while the other represents the directed air flow on the exterior of the CHRS radiator panels. The following model assumptions were used to make the initial assessments for launch:

- Heat Loads
  - MMRTG heat dissipation = 2000 W
  - RAMP heat dissipation = 131.2 W
  - Descent heat dissipation = 43.6 W
  - Cruise Stage heat dissipation = 134.7 W
- Cruise loop flow rate = 1.6 Lpm
  - Both pump strings on at launch
  - Split flow in CHRS Radiators
- Rover loop flow rate = 0.7 Lpm
  - 55% flow to hot plate
  - 45% flow to cold plate
- Convection
  - Aeroshell interior, heat shield exterior, CHRS radiator interior (h = 6 W/m^2-°C for all three; typical natural convection value for these items based on past experience and empirical correlations)
  - AC air on CHRS radiator panels (h = 35 W/m^2-°C, forced on CHRS radiator exterior face)
  - CHRS RTG tube (h = 1293 W/m^2-°C, forced)
  - CHRS Radiator tube (h = 670 W/m^2-°C, forced)
- Boundary Conditions
  - Air exterior to heat shield (T=20^{o}C)
  - AC air exterior to CHRS panels (T=12^{o}C)
  - Back shell (T=43^{o}C)
  - Rover (T=35^{o}C)

The air trapped in the MLI layers would represent a conductive air gap resistance to heat flow via the MLI. Hence, the interior Heat shield MLI blanket thickness was designed to be <1.27 cm (0.5") to minimize the resistance for heat flow from the interior of the aeroshell to the air-conditioned air via the heat shield and its MLI. The MLI was anchored to the heat shield with closely spaced buttons glue to the heat shield to minimize the sag in the MLI to allow for the trapped air gap in the MLI to meet its requirement.

The results of this simple model are shown in Figure 7. It is quite evident that the simple model shows that all the components should be within their allowable temperature limits during launch.

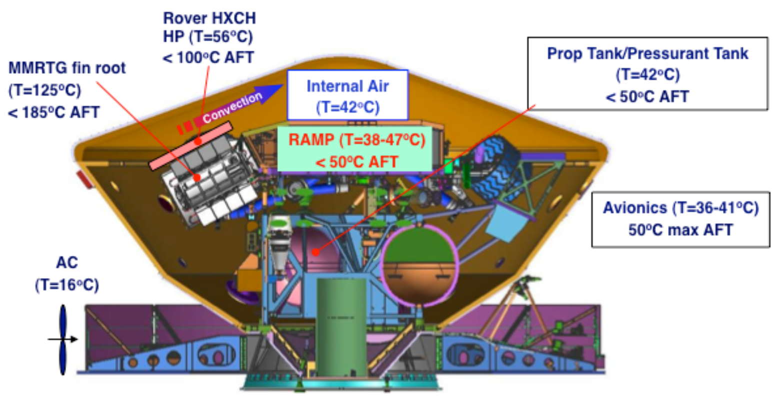

Figure 7. Steady state predictions from simple EXCEL model for launch.

Figure 8 shows the corresponding heat flow map from the same model to highlight the key heat flows from the MMRTG during launch.

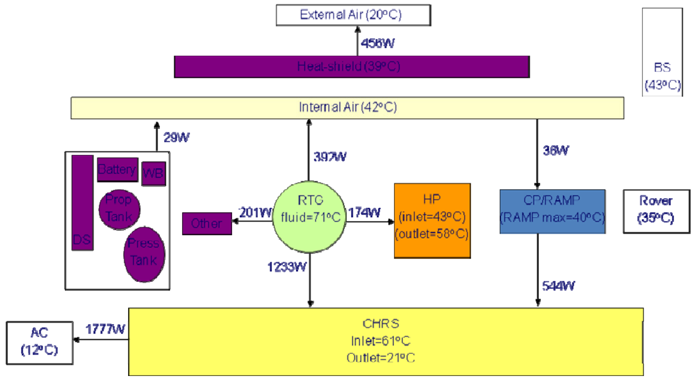

Figure 8. Heat flow map during launch from simple thermal model.

Even though the MMRTG is being cooled very effectively by the CHRS, which removes close to 80% of the 2000 W, it is still quite warm (around 120°C) and is passively dissipating about 400 W into the air within the aeroshell. This heat warms up the air in the aeroshell to about 40°C. The heat loss from the MMRTG and the subsequent heating of the air inside is a very complicated thermal-fluid problem, which cannot be analyzed by the simple model (the simple model assumes the air inside to be a single lumped thermal node).

To overcome this inadequacy a CFD model of the aeroshell's interior was undertaken to understand the temperature distribution within the aeroshell. A snapshot of the CFD output is shown in Figure 9. It is quite evident, and makes sense physically, that an air plume rises above the hot MMRTG and carries with it most of the heat towards the colder heat shield. This in turn conducts and convects it to the air conditioning flow outside the heat shield. The heat loss from aeroshell to the cooling airflow outside of it via the heat shield is very important to ensure that the air inside the aeroshell does not get excessively hot. That is why it is so important for the thickness of the air trapped within the MLI to be kept as practically small as possible.

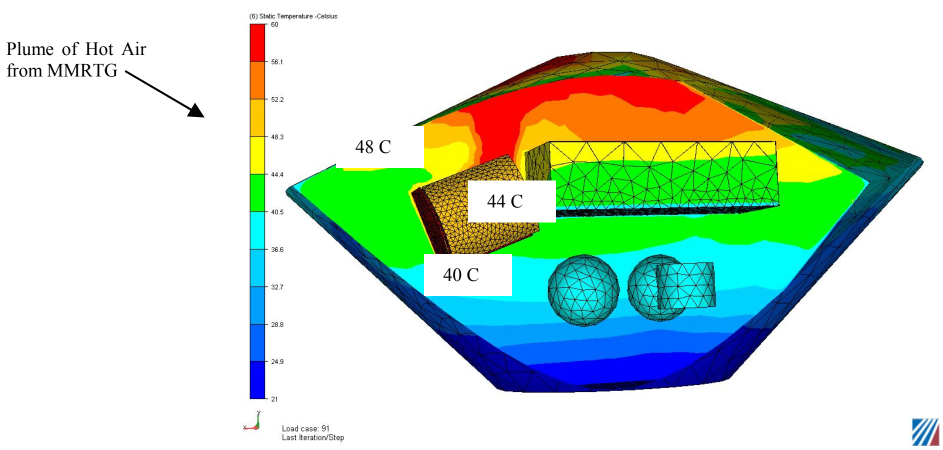

Figure 9. CFD model snapshot for temperature distribution within the aeroshell.

The CFD model shows the temperature of the air around the various key components, in particular the propulsion system tanks. The tanks need to be kept below their allowable maximum temperature limit of 50°C, and the CFD model shows that they would be well below that value (they simply follow the air temperature). The upside down launch configuration was very helpful in directing the hot plume emanating from the MMRTG towards the heat shield, and away from the descent stage (particularly the propulsion system tanks) and the sensitive components in the rover.

The simple model was then modified with an artificial offset from its single lumped node representation of the aeroshell air temperature to reflect temperatures of key passive components like the propulsion system tanks to arrive at a modified and well representative model of the launch phase that accounts for the more complicated temperature distribution within the aeroshell.

In Air Test of Spacecraft to Simulate Launch Phase

The completely assembled MSL spacecraft was tested in an air-conditioned assembly facility to simulate its thermal performance similar to during launch, with the assembled spacecraft in an upside down configuration to simulate launch conditions. The test was performed in the Spacecraft Assembly Facility (SAF) at JPL, which has controlled air temperatures. The flight MMRTG was simulated by an electrically powered unit, and the entire spacecraft and the rover were fully functional in their launch power states. The primary emphasis of this test was to show that the propulsion system tanks (fuel/pressurant) do not overheat, and all the HRS controlled components are maintained within their allowable limits. Figure 10 shows the configuration, and some key results are shown in Table 2.

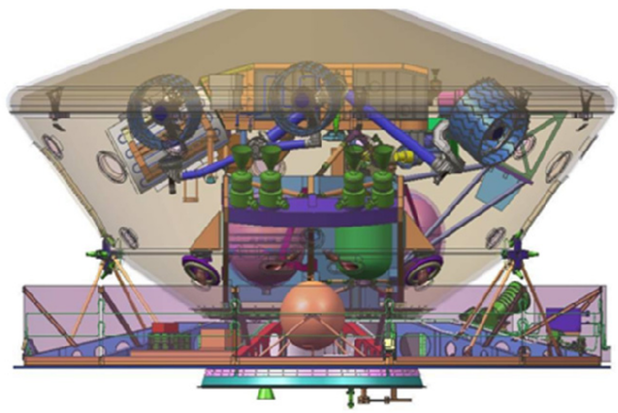

Figure 10. Launch pad cooling test.

Launch Pad Cooling Test Results					
Pradeep Bhandari, 2-2-09					
			Results		
		Full Battery Flow	Low battery Flow	No Battery Flow	
Parameter	Requirement		Test Condition/Result		Comment
RTG Dissipated Power	1900 W	2000 W	1900 W	1900 W	Net = 2000 W Diss. - 100 W Electr.
CS/DS Elec. total power	158 W	158 W	158 W	158 W	PEL
Rover RAMP Elec. total power	158 W	158 W	158 W	158 W	PEL
RTG average fin root temp.	<185 C	100 C	99 C	99 C	
Prop. Tank temp.	<50 C	28 C	29 C	30 C	at hottest location; fuel & pressurant tank
RCE RAMP interface temp.	<50 C	31 C	35 C	36 C	
Rover Battery temp.	<25 C	19 C	29 C	36 C	*Extrapolated for no flow test using RAMP as boundary*
Battery Cooling Flow Rate		6 lb/min	1.4 lb/min	0 lb/min	Current capability ~ 1.4 lb/min
Batt. Flow temp. at IFD		16 C	25 C	N/A	Capability with vortex cooler ~ 25 C

Table 2: Key results from Launch pad cooling test at JPL.

The test was inherently conservative in nature because there was no forced air convection simulated in the test (it was not feasible to implement such a scheme during this test due to the associated prohibitive costs and schedule). So only natural convection was present to cool the CHRS radiators, hence the spacecraft would be cooler during launch when forced convection would be employed to cool the radiators. Additionally due to SAF temperature constraints, an ambient temperature of 20°C was utilized in the test. Since the launch air-conditioning requirements have a maximum temperature of 16°C, this test would result in spacecraft temperatures that would be higher than during launch. From the thermal models it is estimated that this would result in a temperature conservatism of ~5°C.

The test was extremely successful and showed significant margin for all these components. For example the MMRTG was held to <100°C which is obviously much lower than its maximum allowable limit of 185°C. More importantly the propulsion tanks were held at <30°C which is well below the 50°C maximum allowable temperature. All the electronics within the spacecraft were also well within their allowable limits as shown in Table 2. Even though the battery temperature exceeded its original maximum allowable limit, this limit was later increased to be consistent with the test extrapolated data, based on a system level assessment of its implications on mission performance.

II. Conclusions

This paper presented an overview of the design, implementation and testing of the launch pad thermal control used for the Mars Science Laboratory. Design testing of the actual spacecraft in a thermal environment to simulate launch conditions demonstrated that this system is very robust and exhibits substantial margin in meeting its requirements. Employment of these systems for MSL have paved the way for their use in future interplanetary missions in their current or extrapolated forms.

Acknowledgments

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