

Mars Science Laboratory Mechanically Pumped Fluid Loop for Thermal Control – Design, Implementation, and Testing

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ABSTRACT

The Mars Science Laboratory (MSL) mission to land a large rover on Mars is being prepared for Launch in 2011. A Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) on the rover provides an electrical power of 110 W for use in the rover and the science payload. Unlike the solar arrays, MMRTG provides a constant electrical power during both day and night for all seasons (year around) and latitudes. The MMRTG dissipates about 2000 W of waste heat to produce the desired electrical power.

One of the challenges for MSL Rover is the thermal management of the large amount of MMRTG waste heat. During operations on the surface of Mars this heat can be harnessed to maintain the rover and the science payload within their allowable limits during nights and winters without the use of electrical survival heaters. A mechanically pumped fluid loop heat rejection and recovery system (HRS) is used to pick up some of this waste heat and supply it to the rover and payload. During warm conditions, the same HRS works in reverse to pick up the heat dissipated by the rover electronics and payloads and reject it to the Martian environment via radiators. The large heat capacity of the flowing fluid in the HRS also serves to create a nearly isothermal interface temperature for the components controlled by the HRS. During cruise to Mars, the thermal management of the MMRTG waste heat is also a big challenge. A second mechanically pumped fluid loop is used to pick up the MMRTG waste heat and transport it to large radiators on the cruise stage. Both

the HRS fluid loops use CFC-11 (Freon) as the working fluid.

Both of these HRS fluid loops pose significant technical challenges in terms of their design, qualification and implementation. The spacecraft and rover are currently going through final testing. The design and implementation of the two HRS fluid loops have been completed during the last three years and the testing of the spacecraft is in progress. This paper describes the HRS design developed to overcome the technical challenges posed by the MSL mission and the results of the tests performed to characterize them. This paper builds on the paper presented at the 2005 International Conference on Environmental Systems in Rome that dealt primarily with the architecture of the HRS for MSL.

INTRODUCTION AND OVERVIEW OF MSL SPACECRAFT AND ROVER

CRUISE CONFIGURATION – 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 MSL⁸ 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.

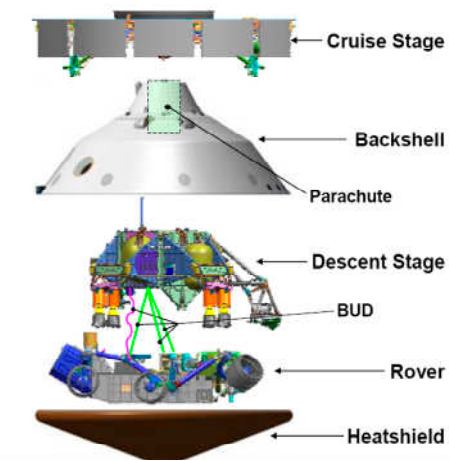


Figure 1: MSL Spacecraft

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.

SURFACE CONFIGURATION – The surface system consists of a large rover that is capable of traversing large distances on the Martian surface. Figure 2 shows a current rendition of the deployed rover with the MMRTG attached to it. At over 750 kilograms (kg), the MSL rover weighs almost four times that of MER rovers (~185 kg).

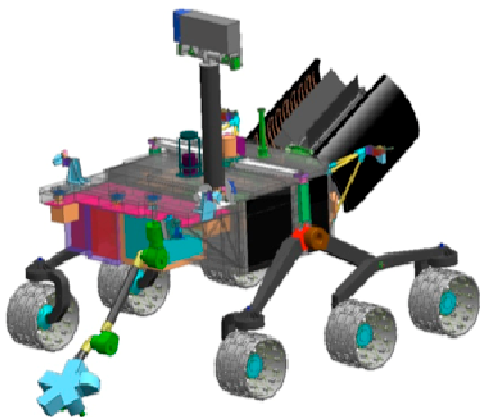


Figure 2: MSL Rover

OVERALL THERMAL ARCHITECTURE

The MSL spacecraft and the rover utilize mechanically pumped single phase pumped 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 chlorofluorocarbon-11 (CFC-11) as the working fluid. Figures 3a and 3b show the overall thermal architecture.

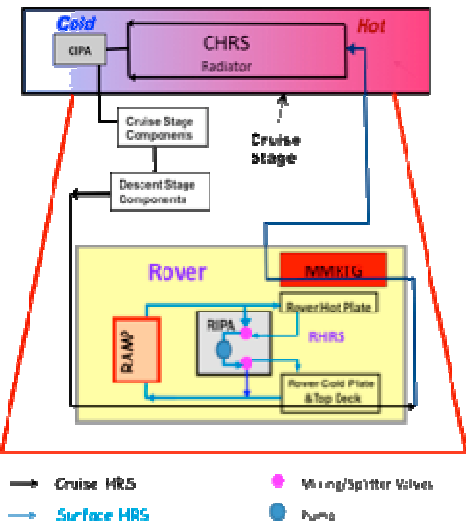


Figure 3a: Schematic of Two HRS Fluid Loops

The CHRS operates during the cruise portion of the MSL mission, from launch pad 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.

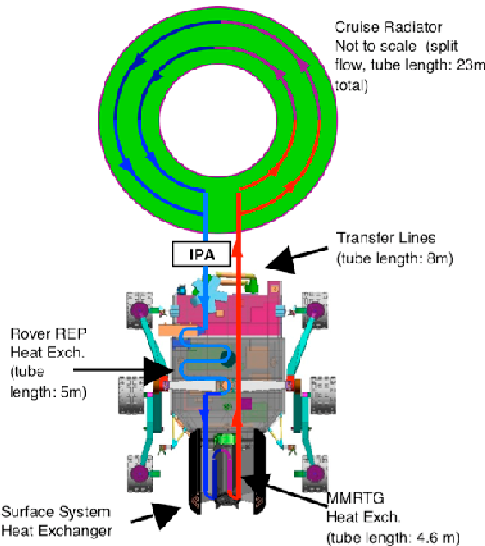


Figure 3b: CHRS Fluid Loop Architecture

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.

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

KEY HRS REQUIREMENTS

The flight allowable temperature requirements of the key HRS controlled components are shown in Table 1. The instruments have more detailed temperature and interface conductance requirements that pertain to day or night operation. In addition, Table 2 shows the key derived (flowed down) requirements for the HRS like the flow rates, pressure drops, pump input powers, etc

Table 1: Key HRS Controlled Components Allowable Flight Temperature 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

The wetted materials, primarily aluminum and 316L Stainless Steel tubing, should also be compatible for the duration of ground testing, launch, cruise and Mars

surface operations, for a total duration of about 3-1/2 years for the rover HRS and 1-1/2 years for the cruise HRS. The two passive thermal control valves, which are used in the rover HRS, automatically direct the working fluid (CFC-11) to the heat exchanger hot plates to pick up heat or to the cold plates/radiators to reject heat^{9,10}.

Table 2: Key HRS Requirements

MSL HRS	MER HRS
Two Fluid Loops	One Fluid Loop
Cruise Stage HRS - Removes RTG waste heat ~2000 W - Fluid (CFC-11) in the 0 to 100 C range; pump in the of -35 to 50 C range - Pump flow rate of ~1.5 lpm - No thermal control valve - One-year life time	Cruise Stage HRS - Removed ~200 W - CFC-11 operating temperature range of -80 to 50 C; pump & valves operating range of - 35 to 50 C
Rover HRS - Recovers RTG waste heat during Mars surface operations, ~350 W - Fluid (CFC-11) in - 100 to +100 C range; pump & valves - 40 to 100 C range - Pump flow rate of 0.75 lpm - Passive mixing and splitter-type thermal control valve (liquid-based actuator) - Three-year life time	Rover HRS - Pump flow rate of 0.75 lpm - Passive splitting-type thermal control valve (wax based actuator) - One-year life time

HRS DESIGN DESCRIPTION

HRS DURING CRUISE – Figure 4 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 m²) are employed to dissipate this heat to space while maintaining reasonable temperature levels in the rover and the MMRTG. 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. The radiators are constructed of aluminum honeycomb with two face-sheets with the inner facesheet thermally and mechanically attached to the fluid tubing.

In the launch pad environment, directed flows of cooled air onto these radiators afford similar amounts of heat rejection.

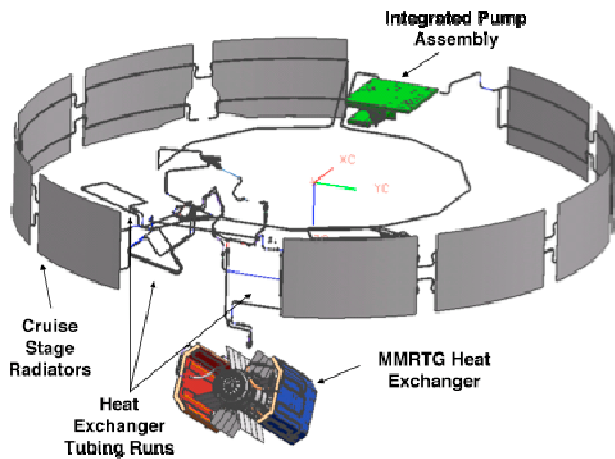


Figure 4: Cruise HRS Routing

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 mission¹⁴.

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 3/8" O.D. with 0.028" wall thickness in the loop, primarily constructed of Aluminum.

White paint (HINCOM: $\alpha = 0.15$; $\epsilon = 0.9$ @ BOL) is utilized as the thermo-optical surface for the radiators to minimize the heat deposition on them from the sun. The resultant small solar loading on the radiator is then overpowered by the large heat loading from the MMRTG waste heat (1200 out of the 2000 W dissipated there), ~700 W from the spacecraft and rover electronics. As a result, the fluid temperatures within the CHRS vary by only a moderate amount (less than 50°C) as the MSL spacecraft journeys from Earth to Mars.

The CHRS interface with the Rover occurs on the two MMRTG Heat Exchanger plates (Figure 5), 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 purpose of the cold plates (outside surfaces of the heat exchanger plates) is to serve as radiators for the heat from the rover electronics/instruments. 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.

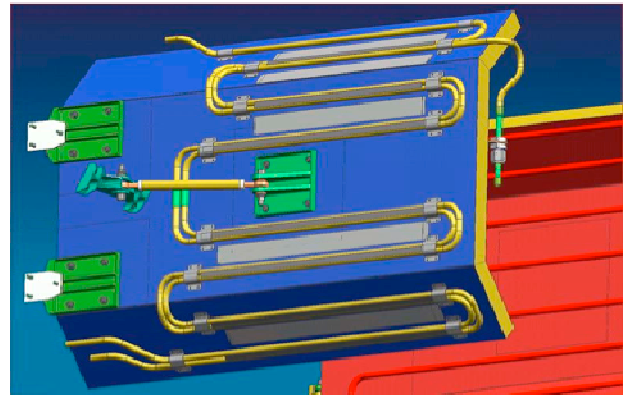


Figure 5: Rover Heat Exchanger Cold Plate

The function of the Rover HRS is to transfer heat from the rover to the cold plates on the MMRTG Heat Exchangers or to pick up waste heat (radiatively) from the hot MMRTG and transfer it to the rover. During the cruise phase of the mission, the RHRS loop moves waste heat from the inside of the Rover to these cold plates. 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.

ROVER HRS DURING MARS SURFACE OPERATIONS – The RHRS fluid loop picks up heat from the MMRTG and supplies it to the rover avionics and payloads during cold conditions. The rover avionics and payloads are mounted on the rover avionics mounting plate (RAMP) that is thermally controlled by tubing that is part of the RHRS loop.

A hydrodynamically lubricated, brushless, mechanical pump circulates the fluid around the loop. These centrifugal pumps² have a heritage from the highly successful Mars Pathfinder (MPF) and Mars exploration Rover (MER) missions.