

Development of Passively Actuated Thermal Control Valves for Passive Control of Mechanically Pumped Single-Phase Fluid Loops for Space Applications

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ABSTRACT

Passively activated thermal control valves were developed for use in a mechanically pumped single-phase fluid liquid loop (MPFL) of the Mars Science Laboratory (MSL) rover. A key approach to the thermal control of the rover with the fluid loop is to control the flow through the rover's heat generating or heat rejecting components. This is achieved by either splitting or mixing the fluid stream coming from different branches of the system at different temperatures; actively or passively controlled flow valves are typically used for such purposes. To meet the thermal control requirements of the Mars Science Laboratory (MSL) rover, a splitting and a mixing thermal control valves with gradual control capabilities using a linear thermal actuator and a spool was developed at Jet Propulsion Laboratory (JPL). The key feature of these control valves is the balancing of the flow through the various branches of the fluid loop in order to balance the heat loads of the whole thermal system. This paper describes the general design and testing used in the development of the valves.

INTRODUCTION

Mechanically pumped single-phase fluid loops are increasingly considered for the spacecraft thermal control of future space missions. These fluid loops are currently employed in the two of the National Aeronautics and Space Administration's (NASA) earth orbiting space missions – National Space Transportation System (STS) Shuttles⁽¹⁾ and the International Space Station (ISS)⁽²⁾⁽³⁾. In both missions, these fluid loops are used as part of the environmental thermal control system for the crew and the equipment used on the STS Shuttle and the ISS station. Both of these missions involve human rated space vehicles. For the robotic space missions, the MPFL system was first used on Mars Pathfinder mission in 1996⁽⁴⁾⁽⁵⁾⁽⁶⁾ and subsequently on the two spacecraft that carried the Mars Exploration

Rovers (MER) to the Martian surface in 2003⁽⁷⁾⁽⁸⁾. The successful use of MPFL system for thermal control has generated significant interest among the spacecraft thermal control community, both in the United States and at international space organizations.

The thermal control of the past robotic rovers and landers built for Mars missions has been based on passive architectures⁽⁹⁾. As future Mars rovers are expected to perform increasingly complex tasks in the extreme thermal environments of Mars, the MPFL system has emerged as an excellent candidate to meet the challenging thermal control requirements of the rovers. The thermal control architecture of the next Mars rover, Mars Science Laboratory, is based on MPFL which provides for the thermal management of engineering and science equipment along with the waste heat generated by the radio-isotope-power system (RPS) used on the rover. A new RPS, called Multi Mission Radioisotope Thermoelectric Generator (MMRTG), developed by NASA and Department of Energy (DOE) is used as the power source in MSL rover.

There are several key components in the MPFL such as the pumps, fluid accumulator, check valves, flow control valves, working fluid, tubes for transporting the fluid, and tubes for heat transfer. For spacecraft with time dependent heat loads and environmental loads, the thermal control valve plays an important role. Both electrically and passively activated thermal control valves have been used in the past MPFL. The STS shuttle and ISS use electrically activated flow control valves in their fluid loops, whereas, the MPFL on Mars Pathfinder and Mars Exploration Rovers used passively actuated flow control valves⁽¹⁰⁾⁽¹¹⁾. The challenging thermal control requirements of MSL rover during its round-the-year operations on the Martian surface required a flow control valve in its fluid loop of much higher precision than was used in the past Mars missions. The development and testing of a passively actuated thermal control valves are described in this paper.

The external configuration of the MSL spacecraft looks similar to that of MPF and MER. At 4.5 meters (m), the diameter of the MSL spacecraft, shown in Figure 1, is almost twice that of the MPF and MER spacecraft (2.6 m). The MSL rover in surface configuration is shown in Figure 2. At over 750 kilograms (kg), the MSL rover weighs almost four times that of MER rovers (~185 kg).

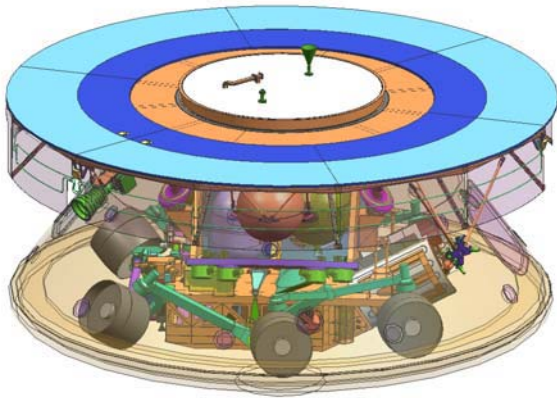


Figure 1. Mars Science Laboratory Spacecraft in Cruise Configuration

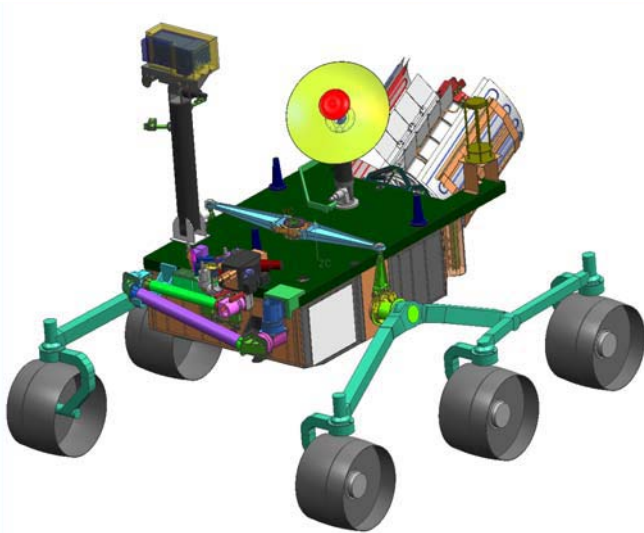


Figure 2. Mars Science Laboratory Rover in Surface Configuration

The thermal architecture of the MSL spacecraft is based⁽¹²⁾ on two MPFL systems shown in Figure 3: the Cruise Heat Rejection System (CHRS) and Rover Heat Rejection System (RHRS). Both fluid loops use chlorofluorocarbon-11 (CFC-11) as the working fluid. 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 RPS and the equipment on the rover and also on the Cruise Stage and Descent

Stage of the MSL spacecraft. A total of about 2000 Watts of waste heat will be removed by the CHRS.

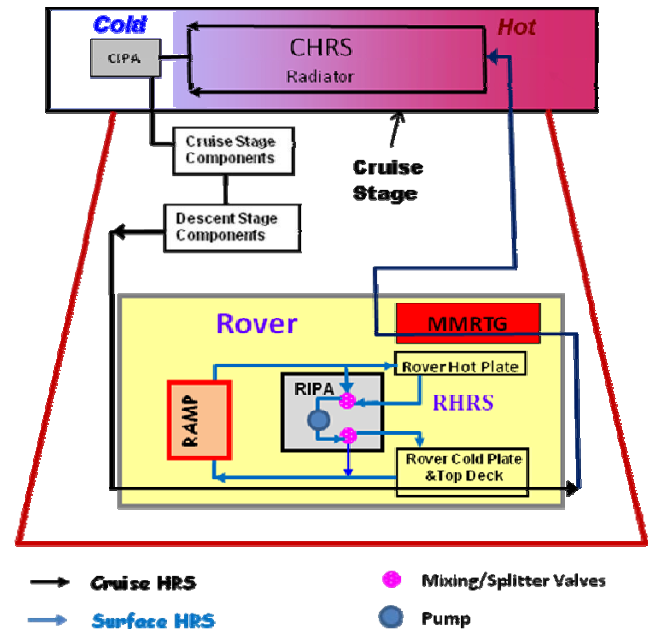


Figure 3. MPFL Based MSL Thermal Control Architecture

The RHRS fluid loop operates during the entire mission, from launch pad to the end of its one Martian year (about two Earth years) mission on the Martian surface. The RHRS fluid loop performs two key thermal control functions in keeping its engineering and science instruments at safe allowable temperatures. Its first function is to remove waste heat (about 300 Watts) from its equipment during three phases of the mission: on launch pad, during the cruise to Mars, and during Martian surface operations. Its second function is to recover waste heat; the RHRS loop recovers waste heat from the RPS (about 300 to 400 Watts) to keep its engineering equipment and science instruments warm during the cold Martian nights and both during days and nights in the winter season. A comparison of the MPFL on MSL is made with the fluid loop used in MPF and MER spacecraft in Table 1. Because of these demanding requirements, the RHRS fluid loop required more precise flow control valves than those used previously in the MPFL of MPF and MER spacecraft.

Several heat rejection system technologies were developed for the MSL rover as part of the MSL Focused Technology Program during 2003 to 2007⁽¹³⁾. An advanced thermal control valve was one of the key technologies developed in this program. The valve design improved the performance of the thermal control valves used previously on MPF and MER fluid loops. The advances made were in the areas of the actuator design and the spool configuration used in the valve⁽¹³⁾.

Table 1. Comparison of the fluid loops on MSL and MER/MPF Missions

MSL HRS	MER HRS
Two Fluid Loops	Single Fluid Loop
Cruise Stage HRS	Cruise Stage HRS
- Removes MMRTG & electronic waste heat ~2000 Watts (W) - Fluid (CFC-11) in the 0 to 90 C range; pump in the range of -35 to 50 C - Pump flow rate of ~1.5 liters per minute (lpm) - No thermal control valve - One-year life time	- Removed electronic waste heat ~200 W - CFC-11 in the - 80 to 50 C range; pump & valves, - 35 to 50 C - Pump flow, 0.75 lpm - Passive splitter valve (wax based actuator) - One year life time
Rover HRS	Rover HRS
- Recovers MMRTG waste heat during Mars surface operations, ~350 W - Fluid (CFC-11) in - 100 to +90 C range; pump & valves - 40 to 100 C range - Pump flow rate of 0.75 lpm - Passive mixing and splitter thermal control valve (liquid-based actuator) - Three-year life time	- No fluid loop in the Rover

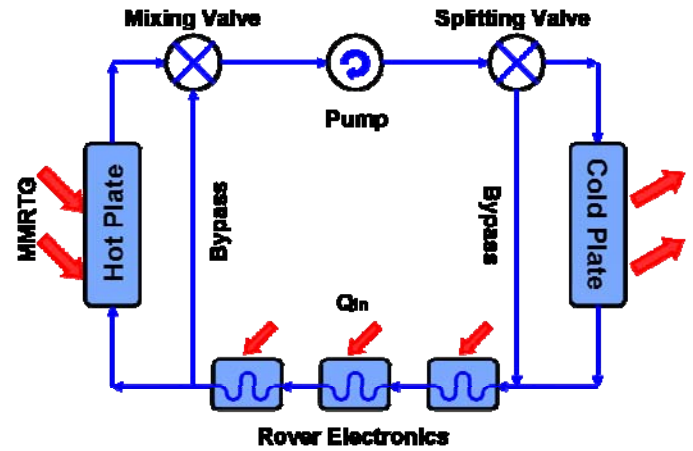


Figure 4. MSL Mechanically Pumped Fluid Loop with Thermal Control Valves

The thermal control valves used in the MSL rover fluid loop are based on passively controlled actuators, similar to the ones used in the fluid loops of MPF and MER. In the case of the mixing valve, the ratio of two inlet flow streams changes in response to the temperature of the outlet flow stream. In contrast, in the case of the splitter-type valve, the ratio of the two outlet flow streams changes in response to the inlet stream temperature. The key parts of the valves are the housing with three ports, a passive actuator, and a spool that proportions the flow based on its location in the housing. A schematic of the valves is shown in Figure 5. The actuator used in the MSL fluid loop thermal valves is based on the bellows with DC-200 fluid whereas for the MPF and MER fluid loops wax based actuators were used. The actuator responds to the temperature of the fluid and pushes the spool to proportion the flow streams to the desired ratios.

THERMAL CONTROL VALVE REQUIREMENTS

As described earlier, the flow control valve used in MPFL plays a very important role in managing the time dependent heat loads. A simplified schematic of the MSL RHRS fluid loop is shown in Figure 4. Two types of thermal control valves are used in the system – a mixing-type thermal control valve and a splitter-type thermal control valve. The mixing type valve is used for controlling the amount of heat recovered from the RPS waste heat to keep the rover equipment temperatures above the safe operating and survival temperatures. This situation occurs during Mars surface operations. The splitter-type valve is used for controlling the amount of heat rejected at the rover radiators during warm conditions to keep the equipment below the safe operating and survival conditions. The splitter valve operates during all three phases of the mission – on launch pad, during cruise, and on the Martian surface operation.

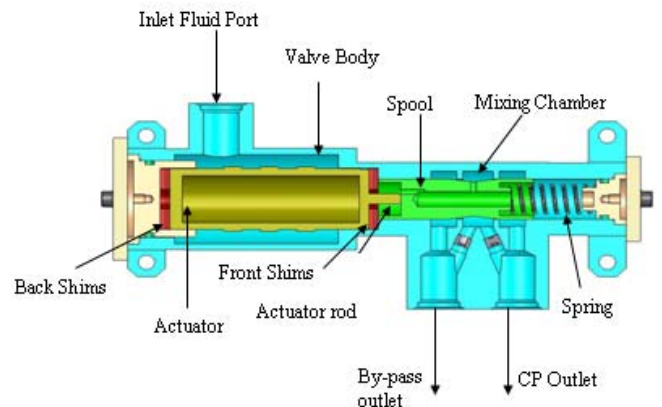


Figure 5. MSL Thermal Control Valve Configuration