Leak Mitigation in Mechanically Pumped Fluid Loops for Long Duration Space Missions

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Mechanically pumped fluid loops (MPFLs) are increasingly considered for spacecraft thermal control. A concern for long duration space missions is the leak of fluid leading to performance degradation or potential loop failure. An understanding of leak rate through analysis, as well as destructive and non-destructive testing, provides a verifiable means to quantify leak rates. The system can be appropriately designed to maintain safe operating pressures and temperatures throughout the mission. Two MPFLs on the Mars Science Laboratory Spacecraft, launched November 26, 2011, maintain the temperature of sensitive electronics and science instruments within a -40°C to 50°C range during launch, cruise, and Mars surface operations. With over 100 meters of complex tubing, fittings, joints, flex lines, and pumps, the system must maintain a minimum pressure through all phases of the mission to provide appropriate performance. This paper describes the process of design, qualification, test, verification, and validation of the components and assemblies employed to minimize risks associated with excessive fluid leaks from pumped fluid loop systems.

Nomenclature

CFC = Chlorofluorocarbon
CHR = Cruise Heat Rejection System
CIPAS = Cruise Integrated Pump Assembly System
FEM = Finite Element Model
GHe = Gaseous Helium
HRS = Heat Rejection System
JPL = Jet Propulsion Laboratory
MMPDS = Metallic Materials Properties Development and Standardization
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
MPFL = Mechanically Pumped Fluid Loop
MSL = Mars Science Laboratory
RAMP = Rover Avionics Mounting Plate
RHRS = Rover Heat Rejection System
RIPAS = Rover Integrated Pump Assembly System
SCC = Standard Cubic Centimeter

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I. Introduction

MSL rover ‘Curiosity’ landed on the surface of Mars on August 5, 2012 in Gale Crater after an eight and a half month journey. The cruise stage uses avionics and a propulsion system to adjust the spacecraft trajectory on the way to Mars. It includes both radiators and solar arrays to reject excess heat from inside the spacecraft and to provide power. The rover and a descent stage are enclosed in an aeroshell for protection during entry and descent onto the planet’s surface. Just prior to entering the Martian atmosphere, the cruise stage is separated and the entry vehicle continues the descent onto Mars. A parachute deploys and begins to slow the entry vehicle as the aeroshell separates and the vehicle gets its first look at the surface. The descent stage slows the rover after backshell separation and lowers the rover to the surface using its own dedicated propulsion and avionics systems (Fig. 1). Curiosity then takes control using power from a Multi-Mission Radioisotope Thermal Generator (MMRTG) producing approximately 110 W of power and 2000 W of waste heat.

Thermal control of the MSL spacecraft is achieved through a variety of heaters and radiators as well as two mechanically pumped fluid loops (MPFLs). The first fluid loop, cruise heat rejection system (CHRS), removes waste heat from the MMRTG as well as various cruise and descent avionics during the cruise phase via large radiators on the cruise vehicle. The second loop, rover heat rejection system (RHRS), recovers and rejects MMRTG and electronics waste heat as needed during Mars surface operations depending on environmental conditions. This approach minimizes electrical power needed for the thermal control, simplifies the mechanical and thermal designs, and provides a robust approach to thermal control throughout the mission.  

II. HRS Overview

Separate MPFLs service the spacecraft during cruise and surface operations (Fig. 2). The CHRS includes tube routing through the cruise, descent, and rover stages to transfer heat from the MMRTG and cruise/descent electronics, enclosed in the aeroshell, to the cruise stage radiators for heat rejection. The CHRS is integrated in pieces with tube jumper assemblies installed during spacecraft stacking between the various stages. The loop circulates approximately 6 L of CFC-11 at less than 200 psia and at fluid temperatures in the -55°C to +70°C range. Prior to separation of the cruise stage when approaching Mars, the working fluid is vented and interconnecting tubes between the cruise stage and aeroshell severed using pyrotechnic cutters. During this time, the rest of the system relies on its large thermal mass to slow temperature rises. Similar connections are severed upon backshell separation from the descent stage and descent stage and rover separation.

The RHRS thermally connects the MMRTG to rover electronics mounted on the rover avionics mounting plate (RAMP) and integrated rover radiators (cold plates on the back end of the rover and the rover top deck) to transfer and reject heat. Due to low avionics allowable temperature requirements, the loop passes cold fluid directly from the

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cruise stage radiators to the RAMP before picking up MMRTG waste heat. A passive valve (oil-actuated) directs flow as needed from the MMRTG heat acquisition plates to the RAMP (cold conditions) or to the radiators (hot conditions). The loop circulates approximately 4 L of CFC-11 at a less than 200 psia operating pressure and temperatures from -100°C to +90°C. A backup pump provides redundancy to overcome a pump failure; however, fluid leaks exceeding the accumulator’s capacity will lead to system failure.2,3

The loops use various components to connect 130 m of tubing including flex lines, bi-metal joints, aluminum unions, micro elbows, and mechanical fittings (Table 1). These components are integrated with inertial, hand, and orbital welds and put through a number of non-destructive tests to verify their leak rate. Additional verification must also be done on mechanical fittings, valves, and other potential leak sources such as metal bellows utilized in flex lines and pump accumulators.

All the fluid loop assemblies are designed to pass leak checks to minimize leaks over the mission life of one Martian year.

### III. Leak Mitigation

Leak mitigation is achieved through system design and qualification and constant non-destructive testing throughout the fabrication and integration process of the fluid loops. Loss of fluid from the many welded or mechanical components could prove catastrophic to the thermal control system and the spacecraft. Although equipped with backup pumps for each loop, any excessive leak is a single point failure.

The accumulator in the fluid loop ensures that the loop operating pressure remains in a safe range during diurnal and seasonal temperature changes and above the saturation pressure of the working fluid to ensure a single phase (liquid). The local liquid pressure minus the saturation vapor pressure must be greater than the net positive suction head to avoid pump cavitation and damage to the impeller to ensure adequate pump performance.1

The system is designed to accommodate small leaks with excess working fluid stored in the accumulator. Acceptable leak rates, verified during the build process, are determined based on this excess accumulator fluid volume, mission life, and quantity of potential leak locations. A leak in an MPFL can occur in any wetted component in the fluid loop: 1) welded joints, 2) mechanical field joints, 3) flexible bellows, 4) service valves, and 5) welded pump assemblies. Further, a leak can also occur on the gas side of the accumulator at the service valve and at weld locations. During and prior to fabrication and integration on the spacecraft of the two MSL fluid loops, the team employed several leak mitigation measures to ensure that no excessive leaks occur during the entire mission. These measures developed and employed for the MSL spacecraft are described in the following sections.

### IV. Leak Tests

A portable Helium leak detector provides leak rate resolutions needed for confidence in the system (Fig. 3). The required leak rate accounts for the size difference between Helium and CFC-11 molecules.

Vacuum leak testing occurs following the welding and integration of every assembly from component to system level. With the assembly connected to the leak detector and under a vacuum, Helium is sprayed on the exterior of each new weld, fitting, valve or bellows. If an increase in leak rate is seen, the component is either rewelded or replaced.

Pressure proof and Helium sniff leak tests follow the vacuum leak test. With the assembly under the expected operating pressure with Helium, the leak detector is transferred to sniff mode and the sniff probe passed over each component. If no noticeable rise in leak rate is observed, the system is considered leak-tight. A sharp rise indicates a leak and the component is either rewelded or replaced. This test is often limited by the Helium background level present in the surrounding environment.

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**Table 1. HRS Components**

<table>
<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>Aluminum Tube</td>
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<tr>
<td>Stainless Steel Tube</td>
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<tr>
<td>Flex Line</td>
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<tr>
<td>Flex Bellows</td>
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<tr>
<td>Bi-Metal Joints</td>
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<tr>
<td>Aluminum Unions</td>
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<tr>
<td>Micro Elbows</td>
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<tr>
<td>Omnisafe® Glands</td>
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<tr>
<td>Hand Welds (105)</td>
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<tr>
<td>Inertial Welds (50)</td>
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<tr>
<td>Mechanical Fittings (60)</td>
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</tbody>
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**Figure 3. Cruise Stage Leak Tests after Interconnect Installation**
environment. The assembly is then taken to proof pressure (1.5 times the maximum operating pressure) and held under pressure for five minutes to verify that no leaks exist.

V. Welded Joints

Three weld types are utilized in the HRS to assemble a combination of aluminum and stainless steel tubing: inertial, hand, and orbital welds (Fig. 4). Extensive qualification tests are performed prior to flight execution and each weld in the flight system verified upon completion.

A. Hand Welds

Aluminum hand welds transition various configurations of thin-walled and finned aluminum tubing with unions and bi-metals. All heat exchangers (radiators, avionics mounting plates, RTG exchangers, etc.) use aluminum tubing to increase heat transfer and require hand welds to join long lengths. A welder with filler material is used by a lab technician to perform, in the case of MSL, over 100 welds.

B. Orbital Welds

Orbital welds are performed with a welder and custom weld schedules based on stainless steel tube thickness and diameter. Transport tubes, tubing used solely to transfer fluid from one point to another and not for heat transfer, are made of stainless steel and use orbital welds. All weld schedules are qualified prior to flight welds and results are repeatable and reliable. Visual inspection shows even weld thickness with a weld center over the junction of the two components.

C. Inertial Welds

Inertial welds transition HRS assemblies from aluminum to stainless steel (also referred to as bi-metal welds) and are needed to integrate mechanical fittings into the system. Lot acceptance tests, provided by the manufacturer, consist of bend testing the first, last, and 25th piece of each lot with the requirement that failure occur in the parent materials and not in the weld. Additional tests at JPL verify that the weld is indeed the strongest point.

D. Weld Qualification

Prior to performing flight welds, an extensive qualification program is administered. Qualification performed on hand and orbital welds include both non-destructive and destructive tests to qualify the welds, welders, and weld schedules for flight. Over 40 hand and 100 orbital weld samples went through leak check, x-ray, and dye penetrant tests (see Section V Part E for non-destructive test descriptions) prior to cross-section, tensile, and burst tests. Both sample welds that passed and failed x-ray are subjected to the destructive tests for comparison.

Success criteria of samples subjected to tensile loads in a pull test are based on the location of the failure and calculated stress values versus expected values per the Metallic Materials Properties Development and Standardization Handbook (MMPDS-01). All assemblies are expected to fail in the heat-affected areas and within the expected strengths.

Hydrostatic burst tests are used to obtain the burst pressure. All samples are expected to fail well above maximum operating pressure and away from the welds.

Samples are axially cut for further visual inspection (Fig. 5). Observations may include uneven spacing between the couplings and tubes and/or alignment, but should be within a specified tolerance. Minimal drop-through is expected with little restriction on inside diameter.

Stress analysis using FEM idealization identifies weld locations in need of clamps for additional support and these modifications are

Figure 4. Bend Test Samples (top three samples: orbital, fourth from top: inertial and orbital, bottom: inertial and hand)

Figure 5. Orbital Weld Section (top) and Hand Weld Section (bottom)
integrated into the structure.

Fatigue tests investigate the requirement that welds are to survive four times life at design bending stress. A simple single-end rotating cantilever test setup using a drill press to rotate test articles mimics a cyclic motion. Bearings attached to a dead-weight load subject the welds to sinusoidal stress amplitudes from tension to compression with each rotation. Test samples are pressurized with nitrogen to simulate fluid pressure and tested with bubble leak tests a) before testing, b) after two times life, and c) after four times life. Samples exceed the design fatigue strength.

Component level vibration tests occur in conjunction with Omnisafe® vibration tests during which all three weld types are present without any sign of leakage. See Section VI.

E. Weld Verification

All flight welds created at JPL go through the following non-destructive tests for verification:
1. Visual Inspection
2. Leak Test (vacuum and pressure)
3. Dye Penetrant (aluminum only)
4. X-Ray

Per ASTM-E1316, non-destructive tests look for (not exclusive):
- Defects: one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.
- Discontinuities: lack of continuity or cohesion; an intentional or unintentional interruption in the physical structure or configuration of a material or component.
- Flaws: an imperfection or discontinuity that may be detectable by non-destructive testing and is not necessarily rejectable.

1. Visual inspection is performed on the exterior and interior (using a boroscope whenever possible) of the weld. Any change to the weld including machining, welding, heat treatment, or etching requires additional inspection. Incomplete fusion, excessive drop-through, cracks, inclusions, shape, and discoloration are assessed.
2. See Section IV for leak test descriptions.
3. Dye penetrant performed only on aluminum welds is inspected per ASTM-E1417-055, Type 1 (fluorescent dye), Method A (water washable), Sensitivity Level 2 (medium) with MIL-HDBK-1890, Class 1 acceptance criteria. Welds are immersed in penetrant, dried, developer applied, examined, and cleaned. Examination looks for indications and discontinuities present in the weld that would render the weld unacceptable with the potential for leak or fatigue. Unacceptable welds are rewelded or replaced.
4. X-ray inspection of all welds is per ASTM E1742-06 and acceptance per MIL-HDBK-1890, Class 1. Two films of each weld are taken at ninety degree angles to verify no cracks, discontinuities, inclusions, porosity, or irregularities might exist (Fig. 6). If the weld fails, it is rewelded or replaced.

VI. Mechanical Fittings

Over 100 mechanical fittings allow the HRS to be assembled as electrical subassemblies and heat exchanger plates are integrated onto the spacecraft and as all three stages (rover, descent, and cruise) are stacked in preparation for launch. Most importantly, use of mechanical fittings allows the thermal team to a) reroute around absent components such as the MMRTG with GSE flex lines for leak tests, b) perform preliminary working fluid fills, and c) more easily install components on the launchpad with limited access.

Past Mars missions utilized AN fittings but with a requirement for a three to four order magnitude reduction in leak rate due to the long mission life, Omnisafe® fittings were chosen. The Omnisafe® fitting had been successfully implemented on the DAWN spacecraft in the Xenon gas delivery system for the Ion engines and now on MSL.
These fittings must adhere to leak rate requirements, be able to mate/demate numerous times without degradation of the leak surfaces or leak rate (at least 10 times), and be easy to install during HRS integration on the spacecraft.

The Omnisafe® fitting utilizes seven components to create a reliable seal. The female nut and male nut each slide over a gland welded to the tubing assemblies. Torque eliminators, located at the gland interface, eliminate the differential torque between the male and female glands and thus allow only compression of the gasket and prevent damage. Figure 7 depicts the fitting details.

A tight seal is formed by indentation of the gland torroids into both sides of a deformable steel gasket. Assembly torque can be affected by the friction between the male and female nuts and their respective torque eliminators, friction between the male and female threads, and hardness of the gasket depending on material. If these variables fluctuate, variations in seal quality based on tightening by torque alone may exist. Thus the amount of indentation needed for an effective seal is defined by geometric tightening of the fitting and thread count. As defined by flight assembly procedures, the fitting must be rotated 1/6th of a turn past finger tight, thus resulting in a 0.005” penetration into both sides of the gasket. Although this operation should generate a value of approximately 300 in-lb of torque, the fitting is properly assembled based on this geometric value. Laser profilometry allows measurement of the indentation depth in the gasket (Fig. 8).

Visual inspection of the gasket upon a new mate or after a de-mate for unusual indentations, blemishes, or scratches provides insight into the 360 degree consistency of the seal and condition of the mating surfaces. Mate/de-mate logs as well as the label and bag of the used gasket during a de-mate provides a history for each fitting. Scratches more than 1-2 mils deep along the radial direction are cause for concern and possible replacement due to fear of providing a potential leak path.

Vibration tests (Fig. 9) of a series of Omnisafe® fittings is performed for flight qualification. For MSL, six individual articles included fittings, welds, and flex lines in flight-like configurations pressurized with liquid Freon at 200 psia. Configurations represented all flight configurations and were subjected to random vibration tests performed on all three axes. Helium leak tests before and after the test along with intermittent pressure data collection and sniff tests using a CFC-11 probe satisfied leak rate requirements. Deflections were within expected minimum and maximum values predicted by analysis.

VII. Flex Lines

Utilization of twenty-nine stainless steel flex lines between structural components throughout the spacecraft provides a method to accommodate relative displacement. Specific areas of utilization include between the rover and descent stage, between the cruise stage radiators, and to connect to damper-mounted heat exchanger plates for electronics. Past Mars spacecraft (Mars Pathfinder and Mars Exploration Rovers) used hard line omega loops, tubing
in the shape of an omega, to accommodate these displacements without excessive tube stresses. Using flexible tube assemblies on MSL, necessitated by accommodation of larger displacement loads, requires extensive testing and careful handling so as not to damage the bellows inside the protective steel braid.

Fatigue life tests are performed on both 3/8” and 1/2” inner diameter flex lines to look at the highest mean stress, maximum strain, and lowest margin cases (predicted versus required life cycles) based on finite element predictions. Tests are performed in a similar manner to the weld fatigue tests (see Section V Part D). Test results for the 3/8” lines indicate a fatigue life over three to five times that predicted by analysis and over five to forty times that of the 1/2” line, showing significant margin. The test setup and a bellows taken to failure are shown in Fig. 10.

In a vibration test conducted on mechanical field joints using Omnisafe® fittings, flex line tubings are included. Both mechanical joints and flex lines are exposed to spacecraft random vibration levels. The details of this test is described in Section VI.

VIII. Service Valves

Loading and unloading both the CHRS and RHRS occurs through valves (Fig. 11) welded to the respective pump assembly lines. The valves are required to adhere to leak requirements while connected to GSE and while closed and capped.

Prior to and after welding the valve into the system, both vacuum and pressure leak tests are performed to check the integrity of the weld as well as the seal of the valve. Valves are torqued closed by rotation of the valve itself and with the addition of a cap. Upon connection to the valves to load and unload the operating fluid, pre and post-opening, the same leak tests are performed to verify GSE connections.

IX. Integrated Pump Assembly Systems

Two pumps are found in each integrated pump assembly (cruise and rover assemblies) with the primary pump in constant operation while the secondary pump is considered backup and operated only during a failure of the first (Fig. 12). Laser and electron beam welds are present inside the pump (performed by the vendor) with orbital welds added to the system to integrate additional components such as valves, filters, and fittings (performed by JPL). Once the loop is charged with fluid, pressure transducers on the pump assemblies allow access to gas and liquid pressure readings to monitor system pressure.

The pump accumulator consists of a
cylinder encasing a metal bellows that expands and contracts with volume change. The total required bellows stroke includes the expected change in density of the liquid with temperature (minimum required stroke) plus an additional volume to account for volume errors, margins, and leaks. See Ref. 1 for details on the accumulator design.

For MSL, life tests performed at the vendor identified the need for a new design with greater fatigue life robustness after a leak was found along a weld on the accumulator outer diameter. Cyclic stresses were updated in the analysis and the new design put through life tests again, including cycles at temperatures representing various seasons, which it passed.

Cyclic pressure and burst tests are performed on a spare accumulator once delivered to JPL to satisfy mission requirements as well as range safety requirements for fatigue and pressure. Although accumulators are not normally defined as pressure vessels under the typical definition, range safety requires a burst test.

![Pressure Cycle Test of CIPA Accumulator](image)

**Figure 13: Accumulator Cyclic (left) and Burst (right) Tests**

The cyclic test, as seen in Fig. 13, mimics in level and sequence, the design pressure cycles of the accumulator. Burst is required after completion of four times life at the vessel’s operating pressure or two times life at 1.5 times the operating pressure. The burst test demonstrates that no burst occurs at the design burst pressure and then increases pressure until final failure.

### X. System Verification

The systems are charged with working fluid prior to system thermal tests. Temperatures throughout the spacecraft during expected hot and cold conditions are monitored and used for model correlation and design/build verification. During this test, fluid and gas pressures of the fluid loop are monitored and show no degradation or sign of leak.

Prior to loading the MPFLs for the final time, leak tests of the entire loop are performed to verify that the loop is leak tight. System pressure is monitored during fill and for extended time periods before disconnecting the GSE required to load the system (Fig. 14). This ensures correct fill pressures for both the gas and liquid sides, as well as records any drops that might indicate a leak. Continuous monitoring is performed up to and after launch.

### XI. Extended Performance Data During Cruise and Surface Operations

Data monitored by the pump pressure transducers shows no sign of leak during cruise (Fig. 15) or in surface operations (Fig. 16) over the past year. Pressure changes correlate with diurnal temperature variations.
XII. Conclusion

Leak mitigation is an extensive process requiring an understanding of the system from design through operation achieved by destructive and non-destructive tests as well as the incorporation of margins used in the fluid inventory. All components vulnerable to fatigue or incomplete seals in a MPFL must be characterized and tested to quantify this threat as a leak would cause a failure of the heat rejection system. The MSL spacecraft utilizes welded joints, pumps, valves, flex lines, and mechanical fittings which undergo a qualification process including leak, dye penetrant, x-ray, tensile, burst, section, cyclic, fatigue, and vibration tests. Leak tests are repeated over and over again as the system is assembled to provide continued confidence. The CHRS as well as the RHRS, monitored throughout cruise and surface operations, both show no sign of leaks due to the extensive preparations and test processes adhered to during fabrication and integration. The overall leak mitigation approach developed and utilized on MSL is applicable and beneficial for any future pumped fluid loop system.

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