High Temperature Mechanically Pumped Fluid Loop for Space Applications – Working Fluid Selection

Anthony D. Paris, Pradeep Bhandari, and Gajanana C. Birur
Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

Mechanically pumped single-phase fluid loops are well suited for transporting and rejecting large amounts of waste heat from spacecraft electronics and power supplies. While past implementations of these loops on spacecraft have used moderate operating temperatures (less than 60°C), higher operating temperatures would allow equivalent heat loads to be rejected by smaller and less massive radiators. A high temperature (100 to 150°C) mechanically pumped fluid loop is currently being investigated at the Jet Propulsion Laboratory for use on future Mars missions. This paper details the trade study used to select the high temperature working fluid for the system and the initial development testing of loop components.

INTRODUCTION

MECHANICALLY PUMPED SINGLE-PHASE FLUID LOOP (MPFL) – As spacecraft designs become more sophisticated and capable, various features – mechanical configuration, power dissipation, and electronic component power densities – are increasing in magnitude and complexity. For spacecraft thermal control, this trend has necessitated the development and use of advanced technologies to meet increasing thermal requirements. One technology that has shown enormous potential to meet the demands of future spacecraft thermal control in this regard is the mechanically pumped single-phase fluid loop (MPFL)[1].

By definition, a mechanically pumped single-phase fluid loop is a system that circulates a working fluid, via routed tubing, to any and all parts of the spacecraft structure. MPFL systems are attractive because they are simple, robust and have an extensive heritage in terrestrial applications. When compared to other thermal control technologies, the advantages of MPFL for spacecraft thermal control include:

1. flexibility in locating heat dissipating equipment inside the spacecraft
2. ability to accept and reject heat at multiple locations
3. ease of integration into the spacecraft due the use of mechanical field joints in the loop
4. ease of accommodation with deployable radiators
5. ability to incorporate late design changes in the spacecraft
6. ease of predictability of thermal performance
7. relative immunity to gravitational effects,
8. ease of scalability to meet changes in power dissipation requirements
9. command of operation
10. working fluid can be adapted to match the required thermal environment

At present, passive fluid loops such as loop heat pipes and capillary pumped loops are more commonly used for spacecraft thermal control. However, these devices have a number of limitations when compared with the MPFL. These include the number of locations where heat may be absorbed, difficulties in performance testing in a terrestrial environment, issues surrounding startup and shutoff operation, lack of mechanical field joints, and inability to accommodate late changes in spacecraft design. While MPFL systems have limitations of their own (mainly due to power consumption and reliability concerns for the mechanical pump), they have the potential to greatly increase the capabilities of active thermal management on future spacecraft.

PAST MPFL APPLICATIONS – While MPFL systems are still under development for spacecraft applications, there are several examples of space flight heritage. MPFL systems have been used on earth-orbiting missions such as NSTS Shuttles[2] and the International Space Station (ISS)[3,4]. For deep space missions, MPFLs were successfully developed and used on both Mars Pathfinder[5] and the two Mars Exploration Rover missions[6]. Details of the MPFLs incorporated in these missions are shown in Table 1. On the space shuttle, the fluid loop is used to remove the waste heat generated by the payload bay equipment. The heat is rejected at the radiators that are incorporated in the shuttle doors. There are two MPFLs used in the ISS for the thermal management. An internal loop uses water as the working fluid and an external loop uses ammonia. The choice of the working fluid is based on both the temperatures at which the fluid loop operates as well as safety concerns. The internal loop operates in the temperature range of 20 to 60 C.

Space Application	Working Fluid	Fluid Temp. Range, C	Capacity
NSTS Shuttle	Freon-21	TBD	TBD
Mars Pathfinder	Freon-11	-80 to 50	150 W
Mars Exploration Rover	Freon-11	-80 to 50	TBD
ISS	Water	20 to 60?	TBD
ISS	Ammonia	- 70 to 40	TBD

Table 1. Past Space Applications of MPFL

HIGH TEMPERATURE APPLICATIONS - Previous applications of single-phase MPFLs have used working fluids operating at temperatures below 70 C. The operational temperature depends on such factors as the heat source maximum temperature, radiator minimum temperatures, and the allowable flight temperatures for the mechanical pump and other components. In general, most of the components cooled by MPFLs must be kept at moderate temperatures (0 to 50 C) for operation and survivability. However, there are applications where the temperatures of the heat sources can be as high as 200 C. Examples of such components include radio-isotope power sources, laser instruments, high temperature rated electronics. In such cases, operation of the fluid loop at elevated temperatures may allow the radiator area of the spacecraft to be significantly reduced. Additionally, when the high temperature heat sources dissipate a large amount of heat (e.g. radio-isotope power sources), the efficiency of the MPFLs in transporting this heat can be quite beneficial in the design of the overall thermal architecture.

HIGH TEMPERATURE MPFL FOR FUTURE DEEP SPACE MISSIONS

A high temperature (100 to 150°C) MPFL is currently being investigated at the Jet Propulsion Laboratory for future Mars and deep space mission thermal control. In particular, the Mars Science Laboratory (MSL) mission[7], to be launched in December 2009, may incorporate Radioisotope Power Sources (RPS) capable of producing upwards of 2000 W of waste heat per unit. Whereas previous deep space missions such as Galileo[8] and Cassini[9] have used passive technology to reject heat from their Radioisotope Thermal Generators, certain design choices for the mechanical configuration of the MSL spacecraft may limit the amount of waste heat from the RPS that may be directly radiated to space during cruise. These same configuration issues (e.g. an insulated aeroshell enclosure, complex mechanical integration) also limit the applicability of high temperature heat pipe designs for thermal control. As a result, this technology development effort has been initiated by the Mars Focused Technology Program to develop a high temperature MPFL system.

WORKING FLUID SELECTION

While the MSL mission is still in the earliest stages of its design cycle, the mission will follow the general design paradigm of the previous JPL rover missions to Mars (Mars Pathfinder, Mars Exploration Rovers.) MSL will feature a rover enclosed in a heatshield for entry and descent onto the planet's surface. A cruise stage will carry the lander and aeroshell enclosure from Earth to Mars and will separate from the lander just prior to entry. Figure 1. shows a rendition of the rover packed into the aeroshell enclosure with the cruise stage attached at the top.

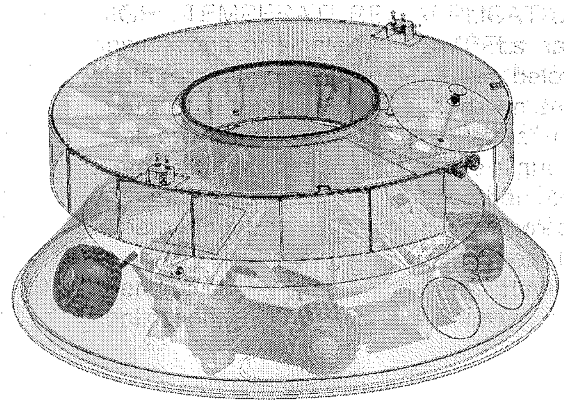


Figure 1. Mars Science Laboratory Cruise Configuration Concept[7]

The Heat Rejection Systems (HRS) that were designed to remove dissipated heat from the insulated electronics in the Mars Pathfinder (MPF) and Mars Exploration Rover (MER) rovers during the cruise portion of those missions forms the basis for the mechanically pumped cooling loop being designed for MSL. Figure 2 shows a schematic of the High Temperature MPFL concept. A mechanical pump circulates fluid through the Radioisotope Power Supplies on the MSL Rover and then carries the heat to the cruise stage avionics, propulsion system, and radiators. By using the MPFL concept, heat that is collected at the RPS units may be flexibly and selectively applied where needed for survival heating.

The three main design drivers for the high temperature MPFL system are the total heat rejection capacity, the available pump performance specifications, and the maximum allowable radiator mass/size. The MSL mission may use as many as two RPS to supply electrical power, so upwards of 4000 W of waste heat will be rejected to space. Preliminary system thermal models for MSL indicate that approximately 30% of this heat load may be rejected through the backshell and aeroshell of the lander with the balance of the heat rejection (approximately 2800 W) accounted for by the MPFL and cruise stage radiators. This applies for the worst-case environmental heating that occurs when the spacecraft is near the Earth. For pump performance, the same type of pump used in the MPF and MER systems (centrifugal pumps with brushless DC motors and hydrodynamic journal bearings) will be assumed in the design of the high temperature MPFL. These long-life pumps can provide e a volumetric flow rate of up to 1.5 liters per minute at a pressure drop of up to 70 kPa (approximately 10 psid.) While these parameters greatly constrain the MPFL design, pump operation is a critical failure path in the system thermal architecture and components with some flight heritage are greatly preferred. The size of the radiators in the system are largely determined by the amount of heat to be rejected and the average temperature of the radiator surface. Figure 3 shows the trend for decreasing radiator size and mass with increasing radiator temperature. These calculations assumed an Aluminum radiator with white paint (emissivity of 0.85) and a thickness of 1.5 mm.

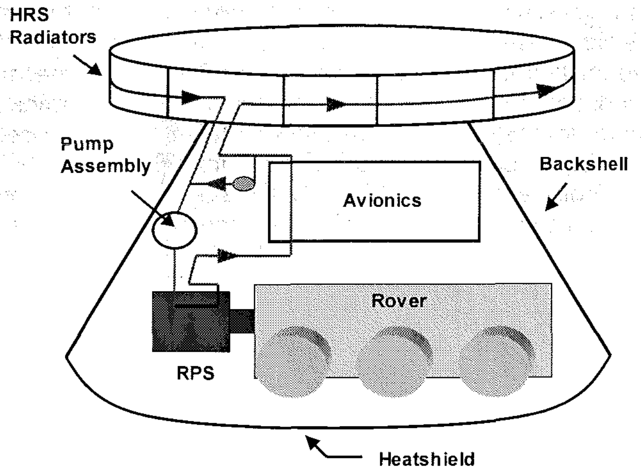
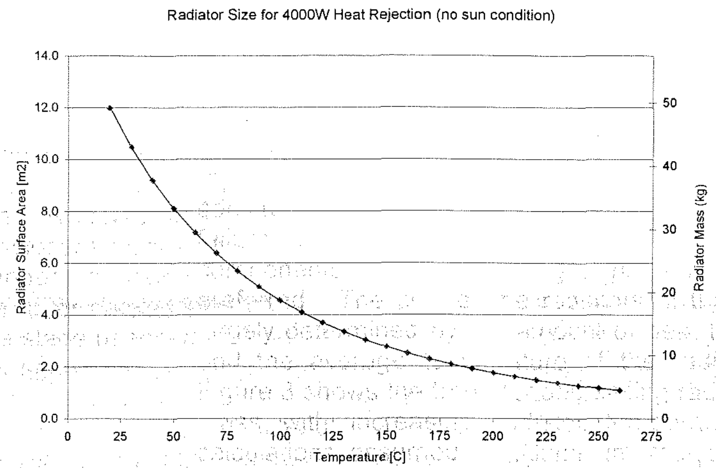


Figure 2. Mechanically Pumped Fluid Loop for MSL Cruise

Given the aforementioned system constraints, the choice of working fluid in the MPFL is the main design criterion. In addition to having the capacity to efficiently transport the required magnitude of thermal energy in the system, the working fluid must also remain in its liquid phase to allow the mechanical pumps to work satisfactorily. In general, the working fluid should possess a combination of high specific heat, high thermal conductivity, and low viscosity. A higher specific heat allows a greater amount of thermal energy to be transported for a given mass flow rate of fluid while a higher thermal conductivity increases the convective heat transfer in the heat exchanger portions of the system. A fluid with a lower dynamic viscosity will decrease the required pressure rise across the pump for a given volumetric flow. Additional important criteria include a low vapor pressure (to decrease the system pressure) and excellent material compatibility with aluminum and stainless steels. Finally, space flight heritage for the working fluid is an important consideration for accurately assessing the risk and cost of developing the high temperature MPFL concept.

Figure 3. Variation in Radiator Size and Mass with Temperature (assumes 4000W heat load with no solar loading)



Five candidate fluids were investigated for possible use in the high temperature MPFL system: deionized water, an ethylene glycol aqueous solution (50% by weight), Freon-11 (Ccl3F), and two synthetic heat transfer fluids. The first synthetic, THERMINOL® 59, is manufactured by Solutia, Inc. and is an alkyl substituted aromatic composed primarily of ethyl diphenyl ethane. The second synthetic, SYLTHERM® XLT, is manufactured by Dow Chemical Co. and is a high performance silicone polymer. These candidate working fluids were chosen to represent a small cross-section of the available working fluids for terrestrial high temperature cooling applications. A qualifier for each fluid was a critical temperature above 150 C. Deionized water and the ethlyene glycol aqueous solution were selected due to the superior thermal properties of water and the large amount of heritage in the automotive industry. Freon-11 was chosen because of its flight heritage from the MPF and MER missions. The synthetic fluids are representative heat transfer fluids used in the chemical processing industries and both have very low freezing points.

Table 2 shows the relevant heat transfer properties of the five fluids as evaluated at 150C. At this temperature, water has a significantly higher specific heat and thermal conductivity than the other fluids. Additionally, water has a very low dynamic viscosity, especially when compared to the synthetic heat transfer fluids. Freon-11 also has a low viscosity, but its relatively poor specific heat would necessitate higher flow rates to transport the same quantity of heat and lead to higher pressure drop in the MPFL. The main advantage of THERMINOL 59 is its low vapor pressure at 150 C, while the advantage of SLYTHERM XLT is its low freezing point.

Working Fluid	Freeze Point	Vapor Pressure	Specific Heat	Thermal Cond.	Dynamic Visc.
	C	MPa	kJ/kg•K	W/m•K	mPa•s
Water	0	0.48	4.3	0.69	0.18
Ethylene Glycol, 50% Wt	-35	0.32	3.9	0.39	0.37
Freon 11	-111	2.11	1.0	0.05	0.16
Therminol 59	-45	0.003	2.1	0.11	0.75
Syltherm XLT	-111	6.8	2.0	0.08	0.34

Table 2. Working fluid thermal properties evaluated at 150 C. See References 10-13.

An analytical model for the high temperature MPFL was created to assess the performance of the candidate working fluids. The following system parameters were assumed:

1. The total heat rejection through the radiators is 2800 W
2. The spacecraft is at 1 A.U. and sees an incident solar load of 1370 W/m2
3. All tubing is 3/8 inch (X mm) OD tubing with a 0.035 inch (X mm) wall thickness
4. Five meters of tubing is allocated for each RPS
5. Eight meters of tubing is allocated for the transfer tubing between the RPS and the radiators
6. The radiators are painted white ($\varepsilon = 0.85$, $\alpha = 0.2$)
7. There are 4 meters of tubing for every 1 square meter of radiator area
8. The radiators have a fin efficiency of 0.8

When given the maximum and minimum fluid temperatures in the loop, the model returns the radiator size and tubing length, the required volumetric and mass flow rates, the total pressure drop in the loop, and the minimum required system pressure. Table 3. shows the model results when the maximum and minimum fluid temperatures are specified to be 140 and 100C, respectively. Since this temperature range is fixed, the radiators in each case are the same size. Although each of the fluids maintained a reasonable RPS temperature and required pressure drop well below 70 kPa, only water and the ethylene glycol solution allowed for pump flow rates in the desired range (less than 1.5 lpm.) These two fluids, along with the Therminol 59, also required less system pressure to prevent the onset of boiling.

A second way to compare the candidate fluids is to fix the pump flow rate at 1.2 Lpm and the maximum temperature at 140C. Depending on the properties of the fluid, a greater or lesser minimum temperature will be required to reject the 2800 W heat load. As this minimum temperature decreases, the radiator average temperature will also decrease and necessitate a larger radiator to reject the same amount of heat. Results from this case are shown in Table 4. Again, it can be seen that the water and ethylene glycol solutions are superior to the other fluids in almost all categories. Additionally, the use of the synthetic fluids at this lower flow rate incurs a large increase in the RPS temperatures. Based on the results of this study, water was chosen as the baseline working fluid for the high temperature MPFL development tests.

Working Fluid	Flow Rate	P drop	System P	RPS Temp.
	Lpm	psid	psia	C
Water	1.0	0.9	83	140
Ethylene Glycol, 50% Wt	1.1	1.3	69	143
Freon 11	3.2	7.6	295	140
Therminol 59	2.3	4.9	35	177
Syltherm XLT	2.7	4.8	616	155

Table 3. Working Fluid Model Results given Tmax = 140C and Tmin = 100C

Working Fluid	Min Temp.	P drop	Radiator Area	Tubing length	RPS Temp.
	C	psid	m2	m	C
Water	105	1.1	3.3	13.2	140
Ethylene Glycol, 50% Wt	102	1.4	3.4	13.4	142
Freon 11	41	2.1	4.8	19.3	140
Therminol 59	63	1.4	4.2	16.8	526
Syltherm XLT	50	1.5	4.5	18.0	618

Table 4. Working Fluid Model Results given Tmax = 140C and Pump Flow Rate = 1.2 Lpm.

HIGH TEMPERATURE DEVELOPMENT TESTS

The initial development process for the MPFL system involves identifying candidate loop components, performance/functional testing of these components at elevated temperatures, and material compatibility studies. It is expected that the high temperature MPFL system for the Mars Science Laboratory mission will incorporate many of the same components that comprised the cruise stage heat rejection systems on MPF and MER spacecraft. These components include one or more mechanical pumps, a thermally actuated bypass valve, a fluid accumulator, filter, tubing, radiator heat exchanger, and fluid venting system. While some of these components, such as the tubing and filters, are fairly well understood in a high temperature environment, the mechanical pump, bypass valve, and fluid accumulator require the most investigation and validation. Laboratory development tests will be used to discover potential problems related to the elevated operational temperature range and suggest potential solutions or design changes.

HIGH TEMPERATURE PUMP TESTBED - The first development test initiated under this effort is a high temperature pump testbed. A centrifugal pump similar in design to the one flown on the MER mission was designed by Pacific Design Technologies, Inc. for this test. The pump is made of 300 series stainless steel and was designed to operate with water as the working fluid at temperatures up to 130 C. The pump is capable of delivering up to 1.5 liters per minute of water at this maximum temperature while incurring a pressure drop of less than 139 kPa (20 psid.) For this testing effort, the pump was designed with O-ring seals and metal fasteners so that it may be disassembled and inspected before and after tests.

A high temperature test setup was constructed to monitor the performance of the pump under a continuous environmental temperature of 120 C. Figure 4. shows a schematic of this setup. The testbed is largely comprised of ¼" OD (6.35 mm) stainless steel tubing and has a large number of valves to allow individual component isolation from the rest of the loop. A series of sample coils and valves are placed in the loop to allow the effective length of the loop tubing to be changed. A dual valve assembly at the base of each coil permits their removal without disturbing the operation of the test. A stainless steel filter is placed in the loop to remove all particles greater than 25 microns from the flow. This filter may be disassembled after a test has been completed to access and analyze trapped particulate material. A stainless steel sample cylinder is positioned vertically and pressurized with gaseous nitrogen to serve as an accumulator for the test loop.

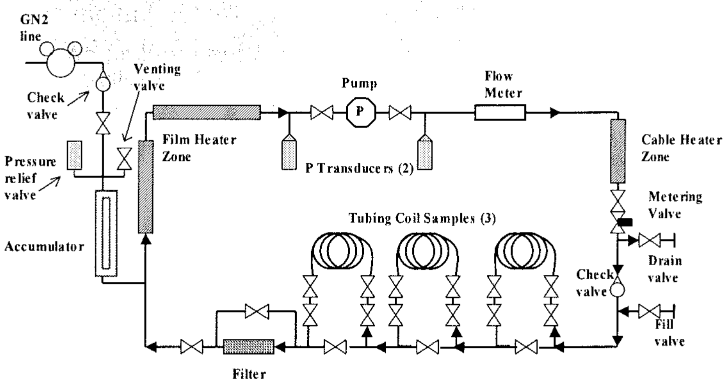


Figure 4. High Temperature Mechanically Pumped Fluid Loop Testbed Schematic

Two heater zones are used to provide heat to the circulating fluid and maintain the desired temperature in the closed-loop assembly. The primary heater zone is located downstream from the test fixture and provides the bulk of the heating. The heating element in this zone is a coiled stainless steel cable heater that is cemented to the tube surface by high temperature thermal epoxy. This electrical resistance heater was operated In a constant power mode. The secondary heater zone was located just upstream of the test fixture. The purpose of this zone was to adjust the amount of heat going into the loop so as to maintain the desired temperature at the location of the pump. The electrical resistance heaters in the secondary heating zone were comprised of film heaters wrapped tightly around the outer diameter of the tubing. Fiberglass insulation was used to insulate individual loop components and construct an overall enclosure for the test setup. A photograph of the test setup is shown in Figure 5. As fully insulated, the test setup required approximately 130 Watts of electrical heater power to maintain a pump temperature of 120C while situated in an ambient laboratory temperature of 21

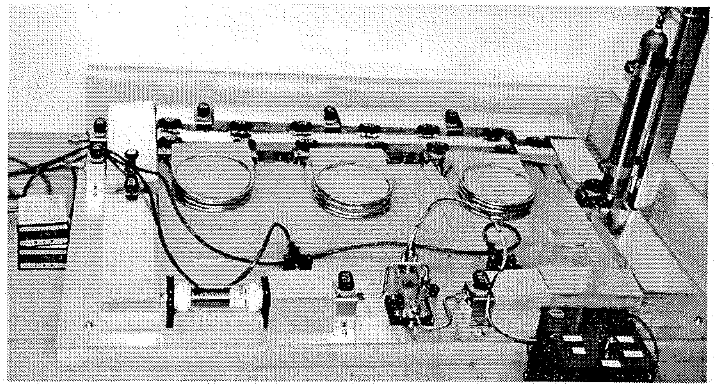


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Figure 5. High Temperature Pump Testbed

The pumped loop testbed was instrumented with a number of pressure and temperature sensors. Two pressure transducers, calibrated for temperatures up to 150 C, are positioned fore and aft of the pump to monitor the pressure drop. An in-line flow meter is positioned just downstream of the pump and is used to monitor the flow rate. Approximately 30 type-E thermocouples were installed on the various system components to monitor temperatures. A data logger was used to record measurements from the pump controller, pressure transducers, and thermocouples. A set of programmable DC power supplies controlled the power applied to the two heater zones. The data acquisition equipment and heater power supplies were computer controlled to maintain a constant thermal environment.

PERFORMANCE TESTS - The high temperature test bed was operated for 1900 hours during an initial assessment period. Figure 6. shows the pump performance over this timeframe. This test demonstrated that while the power consumption and flow rate of the mechanical pump was relatively steady, there were fairly sizeable fluctuations in the pressure drop. Although some of these fluctuations are due to the change in the viscosity of the water as the temperature in the loop increased (the spikes in pressure drop during the middle portion of the test correspond to brief periods in which the loop returned to ambient temperatures), this is an area that must be monitored as the testing progresses.

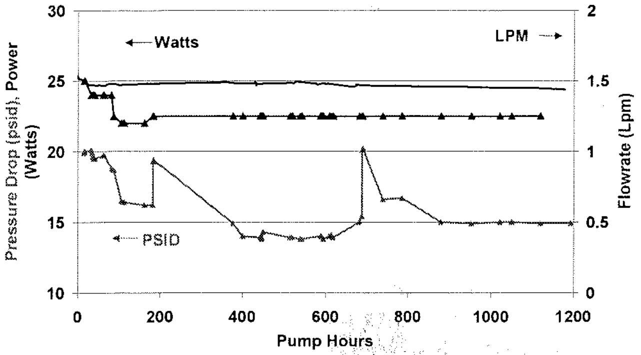

Figure 6. High Temperature (120 C) Pump Performance

MATERIAL COMPATIBILITY - In addition to performance testing, the long term material compatibility of the components in the high temperature MPFL system are also being monitored. Although the system was designed with materials compatible with water systems (e.g. stainless steels, teflon) it is known that high temperature water can be an aggressive solvent. Thus, to observe possible corrosion in the system, the water in the test loop will be periodically sampled and tested for particulates, anions, and dissolved metals.

Prior to the initial operation of the high temperature pump testbed, the deionized water in the system was analyzed. A Dionex Model LC20 Ion Chromatograph (IC) was used to interrogate a small sample of the loop fluid and detected no traces of F^-, Br^-, or NO_3^-, but small traces of Cl^- (0.18 ppm) and SO_4^{-2} (0.06 ppm). Analysis for dissolved metals was performed using a Perkin Elmer Model 3300DV Inductively Coupled Plasma/Atomic Emission Spectrometer. No dissolved metals were detected. After the initial 1900 hours of operation at high temperature, another sample was taken from the loop and analyzed in a similar manner. This sample showed moderate levels of anions: F^- (2.2 ppm), Br^-(0.04 ppm), NO_3^- (0.03 ppm), Cl^- (1.0 ppm), and SO_4^{-2} (1.6 ppm.) Analysis for dissolved metals showed a moderate nickel content (0.88 ppm) and a trace of iron (0.03 ppm). While these trace elements and ions do not exist in sufficient quantity to indicate extensive corrosion in the high temperature pump testbed system, the increased levels of anions and dissolved metals do indicate some corrosion processes are occurring. Since this initial test period of 1900 hours represents less than 25% of the estimated cruise time of the MSL mission, more observation and investigation of this test system is required.

CONCLUSION

A mechanically pumped, single-phase, high temperature (100 to 150°C) fluid loop is currently being investigated at the Jet Propulsion Laboratory for the Mars Science Laboratory and other future Mars missions. Under this work, several high temperature heat transfer fluids were investigated in order to select a suitable working fluid for the system. In addition to the thermal and hydrodynamic properties of the candidate fluids, their compatibility with hardware designs from MPFLs on previous Mars missions were considered. It was determined that water best offered the desired performance and design flexibility needed for continued development of this system. The development process for the high temperature MPFL was initiated by the fabrication of a high temperature testbed capable of evaluating system component performance at temperatures up to 150 C in a laboratory setting. Initial mechanical performance and material compatibility analyses of the test system indicated that the mechanical pump operates successfully with high temperature water. In addition to further life testing of the mechanical pump, future development efforts will investigate other flight-like components for performance and material compatibility.

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CONTACT

Dr. Anthony D. Paris
Jet Propulsion Laboratory
M/S 125-109
4800 Oak Grove Blvd
Pasadena, CA 91109
Phone: (818) 393-6732
Fax: (818) 393-1633
E-mail: Anthony.D.Paris@jpl.nasa.gov

ACRONYMS

MSL: Mars Science Laboratory
MPF: Mars Pathfinder
MER: Mars Exploration Rover
HRS: Heat Rejection System
ISS: International Space Station
NSTS: National Space Transportation System
MPFL: Mechanically Pumped Single-phase Fluid Loop

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, California 91109-8099

(818) 354-4321

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