Mars Pathfinder Mechanically Pumped Cooling Loop

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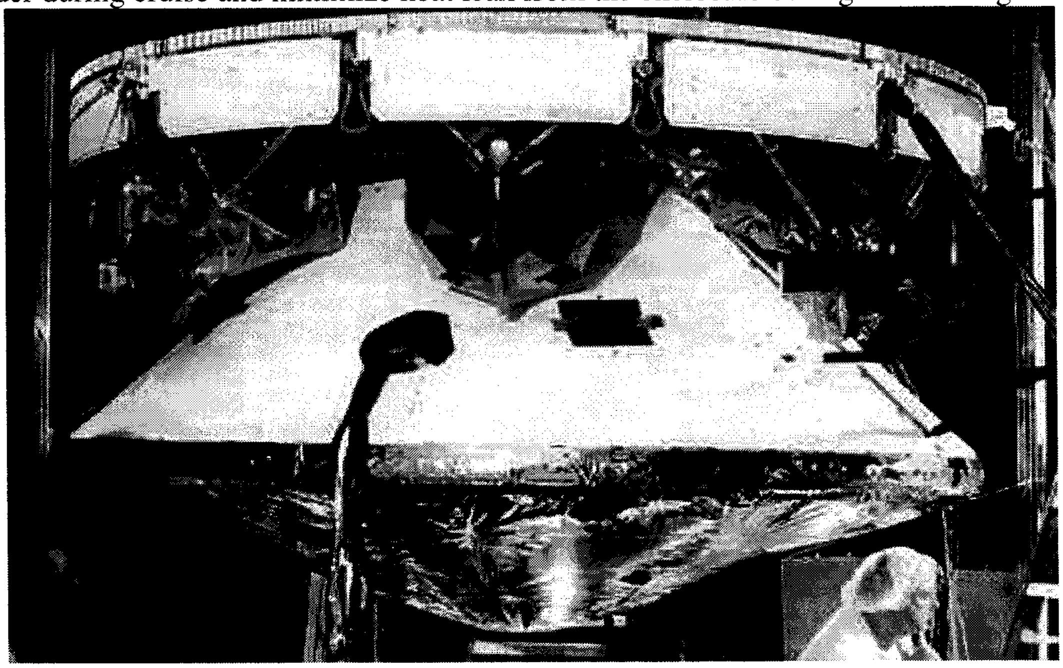
Introduction

A mechanically pumped single-phase cooling loop was successfully flown on the Mars Pathfinder (MPF) Spacecraft which safely landed on the Martian surface on July 4, 1997 after a seven-month cruise in space. For the next three months, it sent valuable data collected by the lander and the microrover to Earth. One of the key technologies that enabled the mission to succeed was an active heat rejection system (HRS) used to cool the electronics on the spacecraft during its seven-month cruise from Earth to Mars. This HRS consisted of a mechanically pumped single-phase cooling system for cooling the electronics and other spacecraft components on the Mars Pathfinder spacecraft. It was the first time an active pumped liquid cooling system was used in an unmanned earth orbiting or a deep space mission spacecraft in the U.S. space history.

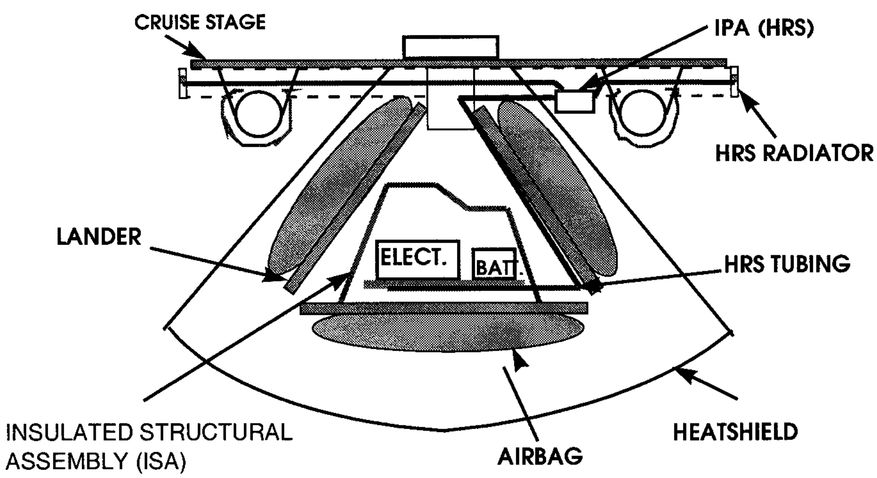
In terms of thermal control design, the Mars Pathfinder spacecraft could be considered as consisting of three separate parts. The first part is the Cruise Stage consisting of power, propulsion, and navigation equipment needed to take the spacecraft to Mars. The second part is the entry, descent, and landing stage consisting of an aeroshell and deceleration module to help the lander safely enter the Martian environment and land on the surface. The third part is the Lander that houses the instruments including the Sojourner microrover. A detailed description of the mission is given in Reference 1.

The mechanically pumped loop was developed for the Mars Pathfinder mission because of the unique requirements and constraints posed by the mission. A description of the reasons for selecting the active cooling loop is given in References 2 and 3. Several thermal control concepts such as variable conductance heat pipes, constance conductance heat pipes, and detachable thermal/mechanical links were evaluated before selecting the pumped cooling loop.

A schematic of the spacecraft and a picture of the assembled spacecraft are shown in Figure 1. The same communication and data analysis electronics are used both during cruise and landed operations. This equipment is located on the base petal of the lander and is completely enclosed in very high performance insulation to conserve heat during the cold Martian nights (as cold as -80 C). During cruise, the same equipment is operated continuously at about 90 Watts of power to communicate with ground. It is very difficult to passively dissipate this heat because of: 1) high power level, 2) high temperature (15 C near earth) outside the insulated enclosure, and 3) additional insulation from the stowed airbags. These conditions in the spacecraft configuration necessitated a heat rejection system (HRS) for Pathfinder. The main functions of HRS were to transfer heat from the lander during cruise and minimize heat leak from the enclosure during Martian nights.



a) Mars Pathfinder spacecraft completely assembled



b) Spacecraft schematic showing the thermal control system configuration

Figure 1. Mars Pathfinder Thermal Control Configuration

Several new approaches were used for the design, qualification and verification of the HRS system because of the short time available for the implementation of the system on the spacecraft. The engineering and flight development were done in parallel; the whole cooling system was designed, built, tested and installed on the spacecraft in less than two years. A description of this design, fabrication and testing is given in References 3, 4, and 5.

The Active Heat Rejection System Design

The Mars Pathfinder active Heat Rejection System was designed to keep the key spacecraft components within the allowable temperature range. This was accomplished by using a mechanically pumped single-phase liquid loop to transfer excess heat from the components inside the spacecraft to an external radiator. After choosing the mechanical pumped cooling loop to serve as the HRS for MPF, a system level design study was performed on the spacecraft and the following requirements were developed for the HRS.

Performance requirements

The performance requirements for the HRS were developed based on The Pathfinder mission requirements. These requirements are given below:

Physical:

1. Mass of the HRS system; less than 18 kg
2. Input electrical power: less than 10 Watts

Thermal:

1. Cooling power: 90 - 180 W
2. Allowable temperature range of equipment: -60 to –20 °C (low limit), 5 to 70°C (high limit)
3. Freon liquid operating temperature of -20 to +30 °C
4. < 3 W parasitic heat loss on Martian surface (from any remnants of the cooling loop)

Integrated Pump Assembly (IPA):

1. 1.26×10^{-5} m^3/s (0.2 gpm) freon flowrate @ > 0.27×10^5 N/m^2 (4 psid) pressure rise
2. < 10 W total power consumption during cruise
3. < 8 kg weight
4. > 2 years of continuous operation without failure

Leakage:

1. Meet specified (very low) leak rate (liquid & gas) to maintain liquid pressure well above saturation pressure - at least 2×10^5 N/m^2 (30 psi) higher

Venting:

1. Freon to be vented from HRS prior to lander entering Martian atmosphere to prevent contamination of Martian surface (freon would interfere with chemical experiments to be performed by Pathfinder on Mars)
2. Freon lines from lander to cruise stage to be cut by pyro cutter after freon has been vented to allow separation of cruise stage from the lander
3. Negligible nutation torque of spacecraft due to venting process
4. Negligible contamination of spacecraft components during freon venting

HRS Design Description and Trade-offs

The HRS consisted of six distinct parts. A schematic of this system is shown in Figure 2. The key components of the HRS are the following:

a) Integrated Pump Assembly (IPA)
b) Freon-11 working fluid
c) HRS tubing
d) Electronics assembly
e) Freon Vent system
f) Radiator

The primary spacecraft electronics (the key heat source) is located in the lander basepetal in a highly insulated enclosure. The IPA flows the freon through the HRS tubing from the electronics equipment shelf to the cruise stage radiator. The vent system is used to vent the freon prior to Martian entry.

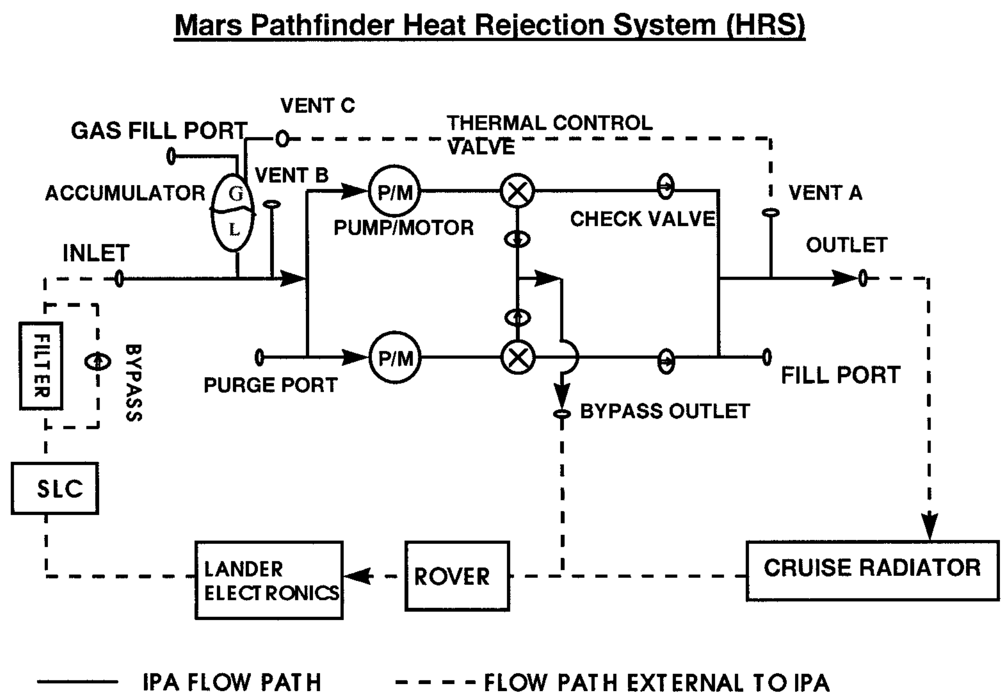


Figure 2. Mars Pathfinder Heat Rejection System

a) Integrated Pump Assembly:

The IPA has two centrifugal pumps, one of them being the primary, whereas the second one serves as the backup in case of failure of the primary; only one pump is on at any time. Each pump(powered by its own motor) produces more than 0.27×10^5 N/m^2(4 psid) pressure differential at 1.26×10^{-5} m^3/s (0.2 gpm). The pump/motor assembly has hydrodynamically lubricated journal bearings to minimize bearing wear and frictional power loss, and to maximize the life of the system. Each pump/motor assembly has its individual radiation hardened electronics to power it.

Two wax actuated thermal control valves automatically and continuously split the main freon flow between the radiator and a bypass to the radiator to provide a fixed (mixed) temperature fluid to the inlet of the electronics shelf - this is to account for the continuously decreasing environmental temperature for the radiator on its journey from earth to mars and the constantly changing heat load on the electronics. The thermal control valves use an enclosed wax pellet with bellows to open and close two ports leading up to the radiator and its bypass depending on the freon temperature entering the valve - the set point of the valves is 0 to –7 °C which was chosen to be approximately in the middle of the operating temperature limits of the electronics being cooled by the HRS. When freon enters the thermal control valves at temperatures higher than 0 °C all the flow is allowed to go through the radiator, whereas when the temperature drops below –7 °C all the flow bypasses the radiator; for intermediate values of temperatures, the valve opens partially in each direction.

Four check valves in the IPA prevent the flow from recirculating from the primary (active) pump to the backup (inactive) pump and bypassing of either the electronics or the radiator whenever only one pump is on and the thermal control valves are either diverting the flow fully or partially to the radiator. Due to the changing environment temperature, the bulk of the freon liquid undergoes a temperature change (-40 to +50 °C) during the flight and ground testing - to accommodate this the IPA employs a bellows accumulator to maintain the liquid pressure at least 2×10^5 N/m^2 (30 psi) above its saturation pressure throughout the flight to prevent cavitation of the centrifugal pumps. The accumulator bellows has a stroke of 1.7×10^{-6} m^3(24 cubic inches) and is sized to account for a liquid volume change of 9.93×10^{-7} m^3 (14 cubic inches) due to temperature changes and liquid leaks of as large as 9.93×10^{-7} m^3 (10 cubic inches) during the flight (7 months or 5100 hours). A detailed design description of the IPA is provided in Ref. 3.

b) Freon-11 Working Fluid:

About fifteen fluids (Ref. 2) were traded-off as candidate working fluids before choosing Freon-11 (CCl_3F, Trichloroflurometthane) a commonly used refrigerant for building air-conditioners. The working fluid is designed to remain in the liquid phase under all conditions to allow the mechanical pumps to work satisfactorily - this and other considerations lead to several criteria used to trade-off these liquids. Some of the liquids traded-off were: various freons, methanol, ethanol, glycols, Dowtherms and trichloroethylene. The criteria used were:

1. Freezing point (less than about –90 °C because during the radiator bypass the freon in the radiator could get as cold as –80 °C)
2. Boiling point (as high as possible to ensure that the operating pressure required to maintain the liquid state is low; also higher than room temperature for ease of handling during ground operations)
3. High specific heat and thermal conductivity; low viscosity (for high heat transfer rates and low pressure drops)
4. Excellent compatibility with commonly used materials like aluminum and stainless steel (for long term corrosion proof performance)

The important properties of Freon-11 are:

1. Freezing point = -111 °C
2. Normal boiling point = 24 °C
3. Vapor pressure at $50^{o}C$ (highest operating temperature) = 20 psig
4. Specific heat = 900 J/kg-K
5. Thermal Conductivity = 0.084 W/m-K
6. Viscosity = $5x10^{-4}$ N-s/m^2
7. Density = 1459 kg/m^3
8. Prandtl Number = 4
9. Very compatible with stainless steels; very compatible with aluminum at low moisture levels (~ 10 ppm), quite corrosive at high moisture levels (~100 ppm); compatible with some elastomers like VITON and materials like TEFLON

c) Tube Diameters and Materials:

Tube diameters of 12.7, 9.53, and 6.35 mm (1/2", 3/8" and 1/4") were traded-off for heat transfer, pressure drop, pumping power and weight. 6.35 mm (1/4") diameter tubing was used for the electronics shelf for high heat transfer and the fact that the length there was short (1 m) enough that the consequent pressure drop was not excessive. 9.53 mm (3/8") tubing was used for the radiator because the heat transfer coefficient was not critical in the radiator (large available area, about 8.22 m long); 9.53 mm(3/8") tubing was also used for the transfer lines. Since the radiator and the transfer lines had long lengths of tubing this also minimized the pressure drop in the loop. Freon flow rates were traded-off in terms of heat transfer and pressure drops to come up with an optimum value of $1.26x10^{-5}$ m^3/s (0.2 gpm).

The electronics shelf & radiator use aluminum tubing because the tubing in these zones is brazed to aluminum surfaces which are used to ensure high heat transfer rates with minimum weight. The transfer lines were made of stainless steel for ease of welding, better compatibility with freon, shorter lengths, and lack of heat transfer requirements.

d) Electronics Shelf Tubing Layout:

Several tubing layouts were investigated to minimize component temperatures, Freon pressure drop & pumping power. The key constraints were the temperature limits of the Solid State Power Amplifier (SSPA; 40 °C) and the battery (-20 to +25 °C) and the highly localized heating in the SSPA (43 W in a relatively small area). The cooling loop tubing was strategically routed and wrapped near the high power dissipation area of the SSPA to minimize its temperature rise; the other electronic boxes have a relatively uniform power dissipation and did not require strategic routing of the cooling loop tubing to pick up their heat.

The shelf's facesheet thickness was varied to trade-off heat transfer & mass. Local thickening of facesheet near hot spots was also investigated. A basic thickness of 1.5 mm for the facesheet (no local thickening) was chosen which satisfies all the thermal requirements. After entry into the Martian atmosphere and landing, the HRS is no longer functional, and the electronics in the lander relies on its thermal mass to manage its temperatures within its limits. Since the SSPA power density is so high, the facesheet was thickened near the SSPA to 4.5 mm to satisfy the entry and Martian surface requirements (coupling the high power, low mass SSPA to the low power, high mass IEM box to improve the transient response).

In addition to the lander electronics shelf two other components were cooled by the cooling loop: the Shunt Limit Controller (SLC) and the Rover cold finger. For the Rover the cold finger is coupled to a split clamshell which grabs onto the HRS tubing to reject its heat (2 W). The SLC has a heat dissipation varying from 0 to 60 W (depending on the shunted power) and its cooling is achieved by bonding a cold plate to its interface - the cold plate has two feet of the cooling loop tubing brazed to it for freon flow.

e) Venting:

Before Martian entry, the freon needs to be removed from the lander (to minimize contamination of the Martian surface) by either venting all of it to space or repositioning it to the cruise stage (which is separated from the lander before entry) several schemes to vent the freon were investigated to come up with a scheme which minimizes the resultant torque on the spacecraft:

Two concepts evaluated for venting of the freon to space are: 1) Use high pressure gas (N_2) in the accumulator to "piston-out" freon from the HRS by opening a pyro valve which connects the gas side of the accumulator to the liquid - the liquid in turn is vented to space via a nozzle which is opened to space via another pyro valve and 2) Discharge from opposing (T-shaped) nozzles to cancel the torques, or, through a single nozzle with the nozzle axis passing through the spacecraft center of gravity (c.g.) (with the nozzle outlet pointed in a direction opposite to the c.g.)

The main reason for the torque on the spacecraft is the reaction from the momentum of the venting freon, hence the rationale for entertaining this possibility because until the spacecraft is intact (cruise stage connected to the lander), repositioning the freon within the spacecraft should minimize the reactional torque. The scheme was to use the accumulator gas to push the freon into a separate (extra) thin walled & light weight "holding" tank in the cruise stage (sized to hold the entire volume of liquid freon) - an extra check valve would prevent backflow from the holding tank to the HRS.

Venting freon to space through a single nozzle with its axis passing through spacecraft c.g. was chosen and implemented - it is a simple scheme to implement with minimum contamination and minimum hardware changes to the spacecraft. The diameter of the nozzle is 1 mm which meets the attitude control system's requirements of the disturbing torque - the time to vent all the freon is predicted to be about three minutes. The initial thrust from the nozzle is estimated to be about 0.5 N with an initial exit speed of 21 m/s. The thrust, of course, decays very rapidly (exponentially) and is less than 0.05 N at the end of the vent process.

f) Radiator:

The radiator used to reject the 180 W of heat (maximum) is a 8.22 m(27 feet) long by 0.2 m (8") wide circumferential strip of aluminum (0.75 mm thick and thermally attached to the 9.53 mm diameter HRS tubing) and located at the circumference of the cruise stage. It is mechanically attached to the cruise stage ribs and thermally (conductively) decoupled by isolators. Both sides are painted white (NS43G on the outside surface, Dexter Crown Metro gloss white on the inside surface; high α, low ε) to maximize its heat loss potential. The inside surface is radiatively coupled to the warm cruise stage underside and the backshell to preclude freezing of the freon in the radiator when the radiator faces a cold environment and most of the freon bypasses the radiator (94 % bypass).

The reason for relying on the radiative coupling instead of conductive coupling to pick up some heat from the cruise stage is that the radiative coupling (and heat input) is much easier to predict and implement than the conductive coupling because the conductive coupling is via a very convoluted and complex thermal path which also involves contact conductances. For the coldest conditions the cruise stage is at –30 °C while the backshell is at –65 °C - these surfaces provide enough heat to the radiator in the coldest conditions to maintain the temperature of the coldest portion of the radiator above –80 °C, which is well above the freezing point of the Freon-11 (-111 °C). The radiator temperature would not fall below – 80 °C even if there were no freon flow through the radiator.

Integrated Pump Assembly - Design, Fabrication, and Test

The IPA, which is a major element of the HRS, circulates and controls the flow of Freon-11 in the mechanical cooling loop. It consists of mechanical centrifugal pumps, an accumulator, thermal control valves, and control electronics. The specifications, design, and implementation of the IPA in the Pathfinder HRS are described in Reference 3. The key new technologies developed and used in the system are the use of Freon-11 as a single-phase working fluid and a wax-actuated thermal control valve to control the fluid temperature in the loop. A description of the thermal control valve is given in Reference 3.

IPA Specifications

The IPA design specifications were developed based not only on the spacecraft thermal control considerations but also on the spacecraft system level considerations of reliability, mass, power, and cost. As a consequence, the overall system consisted of redundant pump systems: each unit consisting of its own pump/motor, motor control electronics, check valves, and thermal control valve to bypass the flow. The only non-redundant component in the IPA is the accumulator. The specified arrangement of the components in the IPA is shown in Figure 2.

The specifications developed for the IPA consisted of the following topics: 1) Hydraulic and electrical performance, 2) Component description, 3) Mechanical and electrical design, 4)Electronic and mechanical parts, 5) Electromagnetic compatibility, 6) Operating and non-operating environments, 7) Fabrication and assembly requirements, and quality assurance provisions. The key specifications are listed in Table 1.

Table 1. Integrated Pump Assembly Specifications

Design and Fabrication

The detailed mechanical and electrical design of the IPA was developed by the vendor based on the specification provided by JPL. The mechanical design consisted of three major components mounted on a base plate. These are: 1) accumulator, 2) pump/thermal control manifold, 3) electronic box housing all the motor control electronics, and 4) front panel housing the service valves. The materials used for the IPA are 304L stainless steel, Inconel 718, and aluminum. Stainless steel is used for all the wetted paths of the IPA except the accumulator bellows which uses Incinel 718, whereas, aluminum is used for the baseplate and the electronic box. The electronic box is designed as modular unit so that it can be removed from the pump assembly during welding of the pump assembly to tubing that that would circulate freon in the spacecraft.

The accumulator features a welded Inconel 718 double-walled bellows to contain the freon liquid with the pressurant gas (nitrogen) on the outside of the bellows. The stroke volume of the bellows is 24 cubic inches. A service valve is mounted on the housing to provide access to charge the accumulator with gas to the required pressure. A strain gauge type pressure transducer is welded to the accumulator housing to measure the gas pressure during ground operations and testing. The pump manifold is machined from wrought stainless steel, which houses the check valves, thermal control valves, pump/motors, and the inlet and exit ports.

A centrifugal pump was chosen over other types of pumps based on life and reliability data on pumps and the suitability for the current application. The hydraulic performance and electrical power requirements of the Pathfinder HRS favor the centrifugal type pump. The Pathfinder HRS requires a small pressure rise at large flow rate and had very small power available for the pumps. At the required performance point of 0.2 gpm at 4 psid, the specific speed of 1267 predicted a pump head efficiency of 10% for a centrifugal pump, meeting power requirements. Use of a positive displacement pump was rejected due to a lower service life and material restrictions. The selected pump featured a radial vane Barsky type impeller, driven by a brushless DC motor with Hall effects sensors embedded in the stator. The impeller is a four-vane design without side shrouds to minimize viscous losses, and is attached directly to the motor shaft. The motor rotor which rotates about 12,000 rpm, is supported by two carbon graphite journal bearings, lubricated by the working fluid. The rotor consists of permanent magnet poles made of Samarium Cobalt. A stainless steel sleeve isolates both the rotor and stator from the working fluid. This wet design negated the need for a shaft seal, improving the pump life.

The vendor used this design a few years earlier for a developmental unit for another program. This unit was ground tested and had run for about 3000 hours and experienced over 300,000 start/stops. The clearances in the pump vary from about 6 micron in the journal bearings to 125 micron in the bypass loop for wetting the journals. Two developmental pumps were first built for the Pathfinder program as life tests unit pumps. These pumps went through thermal cycles and random vibration tests and one of the units, shown in Figure 3, was life tested. This pump operated for over 14,000 hours as of August 1997. Details of these tests are given in Reference 5.

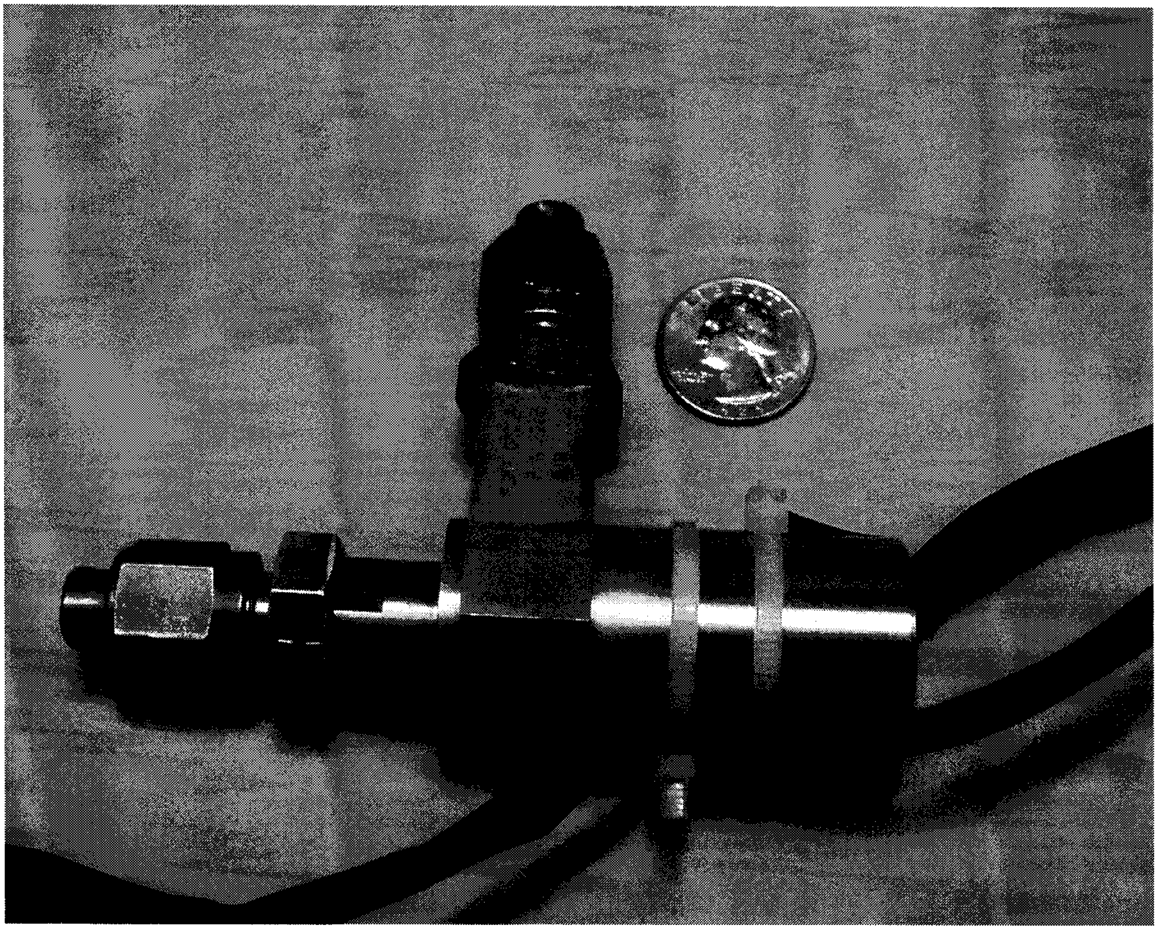


Figure 3. Engineering model of the centrifugal pump used in the IPA life tests at JPL

The check valves used were made of stainless steel with a cracking pressure of 0.2 psi. These valves used Teflon O-rings as seals. The thermal control valve is an assembly of a wax actuator which provides an actuation of 20 mils over a temperature range of -7 to 0 °C. The actuator moves a spool in the valve that opens or closes the bypass port depending on the temperature of the freon flowing through the valve. The wax is hermetically sealed from the working fluid by a stainless steel bellows, preventing wax loss through a dynamic seal as is common to most wax actuator designs. The original design consisted of stacked bimetallic discs. However, after some developmental tests, it was found that the disc material were not compatible with freon and that they did not produce smooth linear motion due to stiction. Because of this, a new development effort was undertaken to build a wax actuator which would meet the Pathfinder needs.

The motor control electronics is enclosed in a wrought aluminum box housing the circuit card assemblies of both the pump/motors. A connector is mounted on one end of the box for the input power and another connector on the bottom box connects the motor controller to the pump/motors. The circuit cards are multilayer boards with lead-in components soldered to the boards. The circuits are designed to meet the Pathfinder fault tolerance requirements for radiation susceptibility. The parts used met the reliability requirements (MIL-STD-975 Grade 2 and MIL-STD-883C Grade B). The single event effect sensitive parts used were JPL-approved rad hardened parts. EMI filters were included to meet the conducted and radiated emissions and susceptibility requirements of the Pathfinder spacecraft.

The fabrication was done in three major subassemblies before the whole unit was put together. The three assemblies are 1) Accumulator assembly, 2) Pump manifold assembly, and 3) Motor controller electronics subassembly. The accumulator and the pump manifold are all welded stainless steel units, whereas, the controller electronics housing is in a hogged out aluminum box with a bolted-on lid. The welds were made to qualified weld schedules by MIL-STD-1595 certified weld operators. The sample welds were made on the day of the flight weld and inspected under high magnification for sound weld quality (depth of penetration, porosity, cracks etc.) before welding the actual hardware. The unit was leak tested before proceeding with the next series of welds.

The accumulator assembly consisted of the machined housing, the bellows, service valve, pressure transducer, and purge tubing. All the parts were cleaned thoroughly to remove the particulates above 25 microns in size before the parts were assembled, tested, and welded. The unit was tested for leak rate and bellows performance between each series of welds. Electron beam welds were used for all the welds in the accumulator subassembly. After completing the assembly, the pressure transducer output was calibrated against pressure gage readings.

All the motor assemblies, valves, and inlet and outlet tubing are assembled into the wrought stainless steel pump manifold. All these parts are welded into the block using laser welding. Because of the magnetic properties of the motors, electron beam weld could not be used for this assembly. As in the case of the accumulator fabrication, the pump manifold parts were cleaned and the unit tested between each series of welds. The tests consisted of checking the performance of each pump, thermal control valve, and the check valves before the next series of welds were made.

The motor controller was designed using discrete electronic components. Two reasons led to this option over an integrated circuit based design. The first was the tight schedule for the design and fabrication of the controller. The second reason the flexibility the discrete component design allowed in using of the available electronic parts. The motor controller electronic box fabrication consisted of fabricating the circuit cards and populating them with parts. The multilayer circuit cards were fabricated to MIl-P-55110. All the lead-in components were soldered to the boards per the MIL-STD-2000. The boards were conformally coated before they were installed in the box.

The final dry mass of the IPA before it was installed on the spacecraft came out to be 8.3 kg. The IPA in its final assembled state is shown in Figure 4.

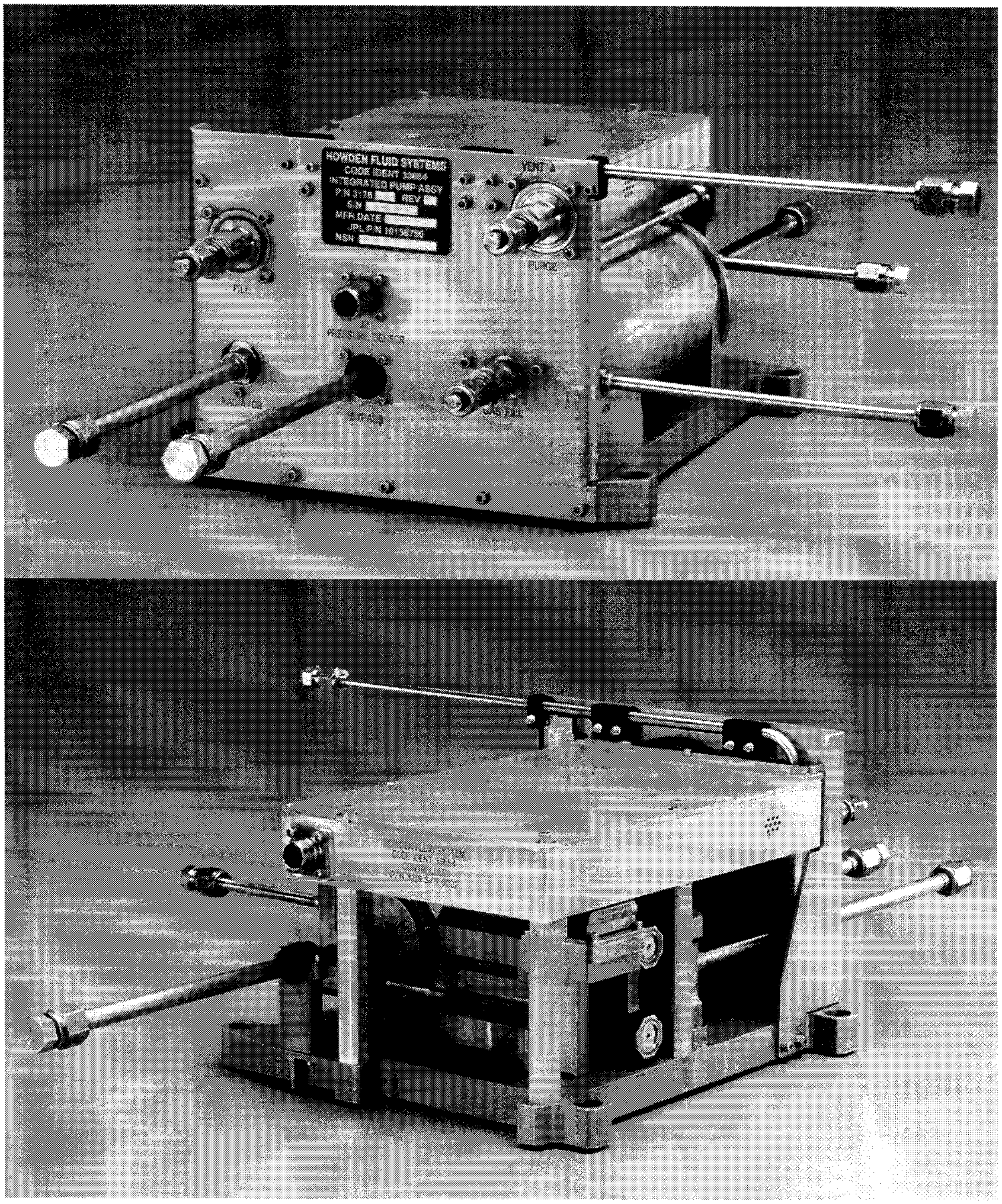


Figure 4. Mars Pathfinder Integrated Pump Assembly

Performance Tests

Three types of performance tests were done on IPA: 1) Hydraulic, 2) Electrical, and 3) System proof and leak. The hydraulic performance tests were conducted to verify that IPA met the specification requirements. These requirements related to the flow rate and pressure rise at various temperatures. The IPA flow rate at various pressure rises is shown in Figure 5 for the IPA with one pump operating.

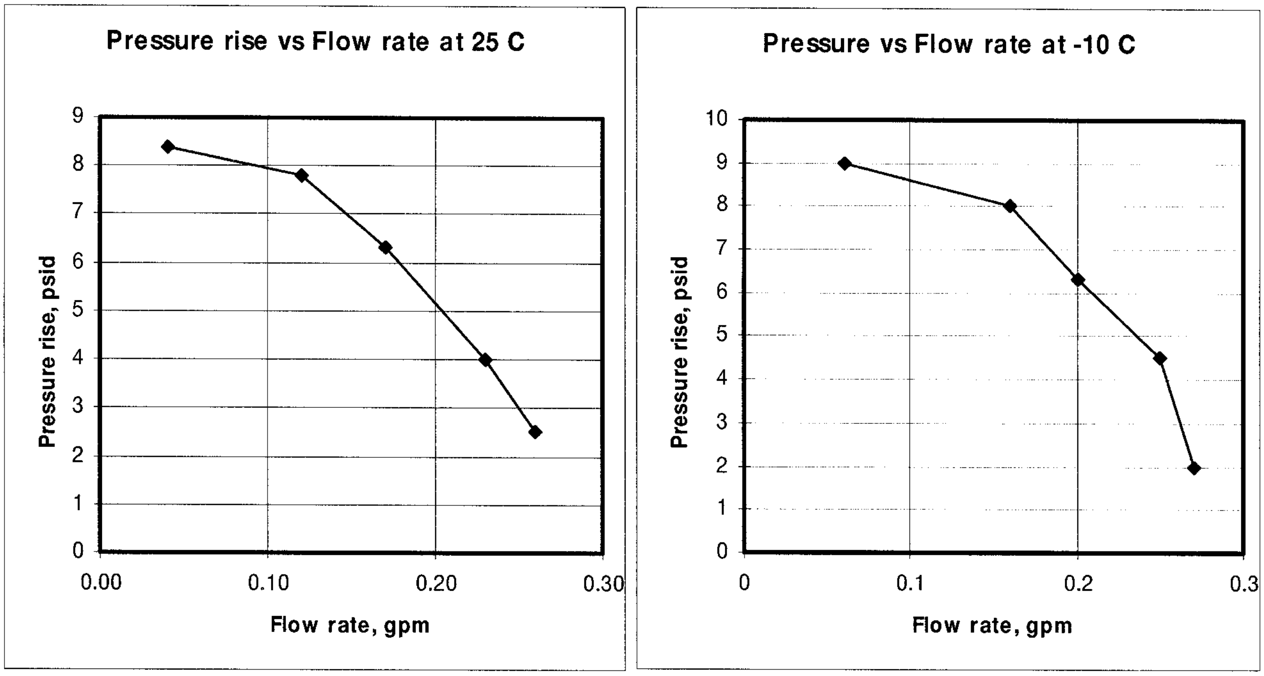


Figure 5. Pressure rise vs flow rate performance tests on IPA

In the electrical performance tests, the current draw of the IPA at various flow rates was measured. The input voltage to the IPA was varied between 27 Vdc and 36 Vdc and the IPA current draw was measured. The IPA electrical performance is shown in Figure 6.

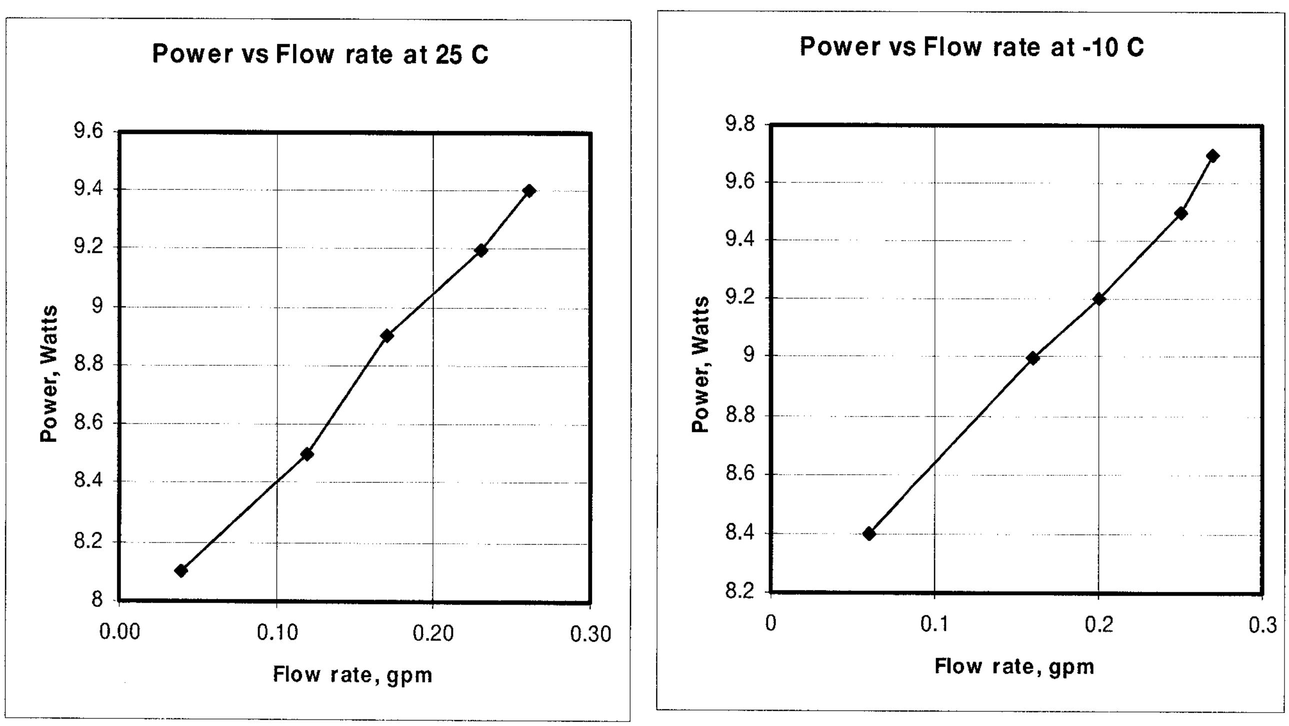


Figure 6. Power vs flow rate performance tests on IPA

In order to verify the integrity of the IPA fabrication, the unit was proof tested and leak checked. The unit was successfully tested to a proof pressure of 185 psig. Two leak rates were specified for the IPA - one for the gas side of the accumulator and a second for the rest of the unit which is the liquid side. For the gas side, the maximum leak rate was specified at 2×10^{-7} scc/sec of helium, whereas for the liquid side, it was specified as 1×10^{-4} scc/sec helium. The leak rates for each weld and valve were computed based on these total leak rates and were tested to the computed levels during the leak check of the assembly.

Qualification Tests

Three types of qualification tests were done on IPA besides the performance tests. These are vibration tests, thermal vacuum tests, and Electromagnetic compatibility and susceptibility tests. The levels to which the unit was tested were protoflight levels since the flight unit was used instead of an engineering model to flight qualify the IPA. The order of the acceptance tests are given in Table 2.

Table 2. IPA acceptance tests

The test requirements for the Sine and Random vibration are given in Table 3. The IPA successfully underwent these tests while both the pumps were operating. The performance was monitored during the actual vibration. The sine vibration test consisted of sweeping at the specified sinusoidal amplitude levels from the lowest frequency to the highest frequency and back to the lowest frequency at a rate of 2 octaves/minute in each of the three orthogonal axes. The random vibration tests was conducted one minute per axis. Accelerometers used to monitor the responses during both the tests.

Table 3. IPA specifications for sine and random vibration

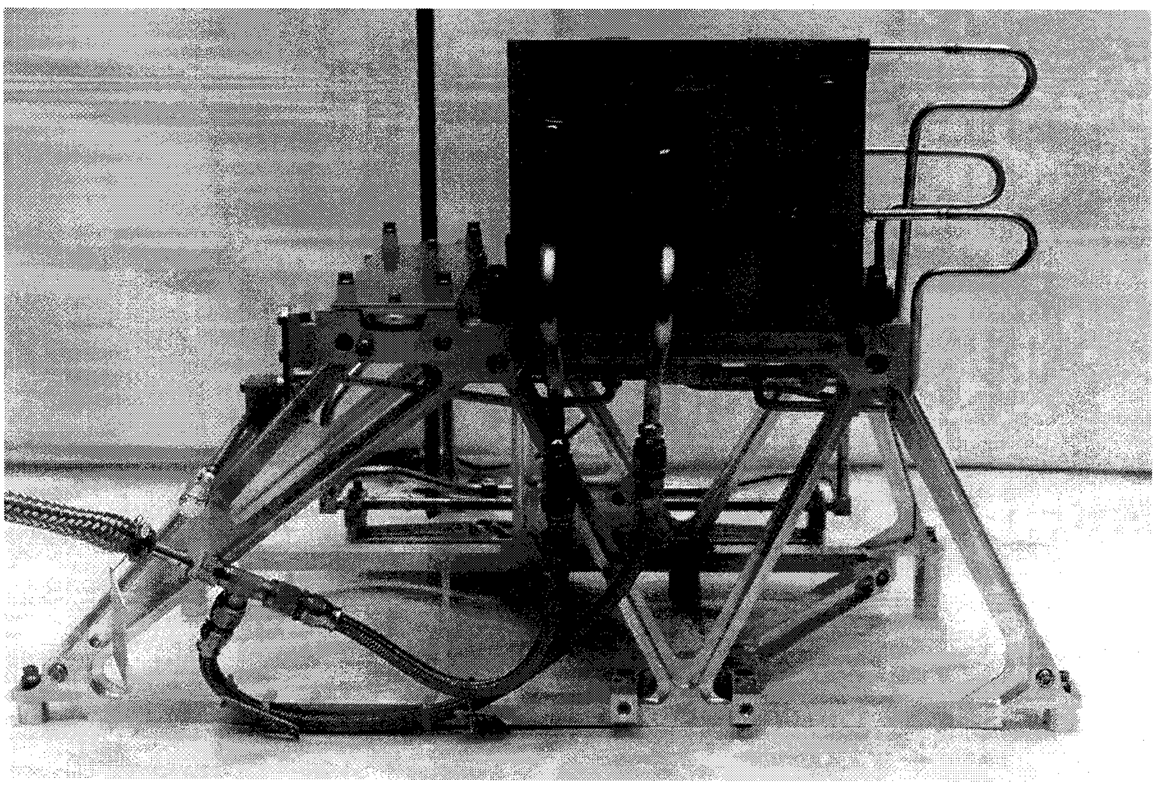
The thermal vacuum test on the IPA consisted of two types of tests. The first test was done on the motor controller electronics separately. The electronic box was mounted on a base plate which maintained at 70 C while both pumps were continuously on for a seven-day period. Electrical simulated loads were used for the pumps in this test. The second thermal vacuum test was conducted on the whole IPA and consisted of one-day cold and two-day hot soak.

The flight cooling system was tested at two levels – assembly level and the spacecraft level. At the assembly level, tests were done to verify the performance of the subassemblies such as the Integrated Pump Assembly. Here the hydraulic, electrical, and thermal performance of the IPA was tested. In addition, the IPA was subjected to the thermal vacuum, random and sinusoidal vibration, and Electro Magnetic Interference and Compatibility (EMI & EMC) tests to qualify it for the flight.

The EMI qualification tests for conducted emissions and susceptibility were done on a separate life test pump/motor unit which was of the same design as the flight pump/motor unit and the flight electronics. The EMI tests performed for the power line ripple and power line transients for both emissions and susceptibility. The EMI qualification tests for radiated emissions and susceptibility were performed at the spacecraft level. The IPA went through the tests and satisfactorily met the spacecraft requirements.

The IPA was bolted and welded on to a structure called IVSR before installed on the spacecraft. Apart from the IPA, the IVSR structure housed HRS filter, pyroo/vent system, and a heat exchanger for the shunt electronics box. Two views of the IVSR are shown in Figure 7.

At the spacecraft system level, the whole system went through a series of system level tests. These tests consisted of vibration, EMI & EMC, and system thermal vacuum tests. The end-to-end performance of the HRS was tested during the thermal vacuum test.



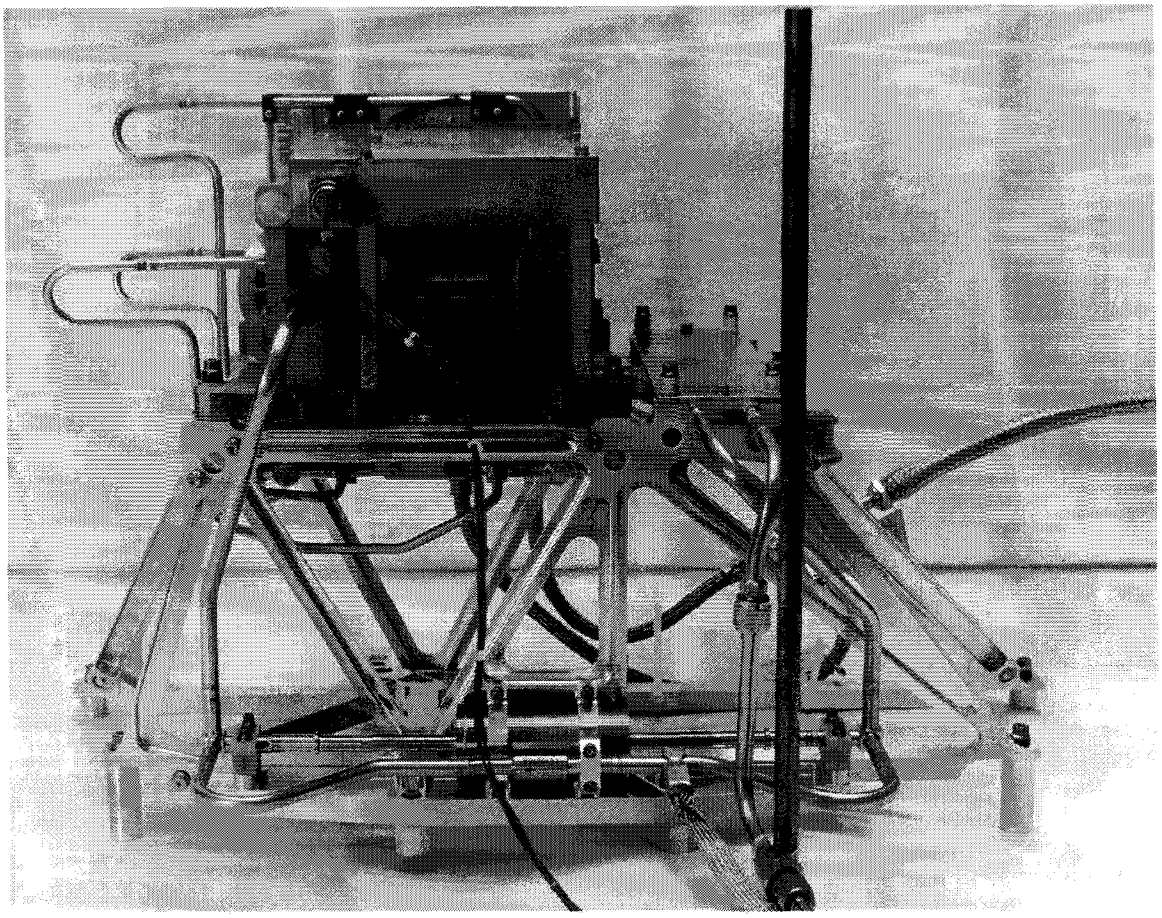


Figure 7. IVSR structure with the IPA installed

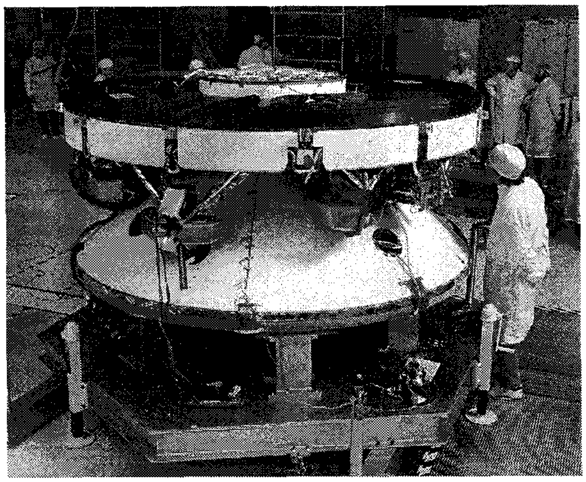


Figure 8. Assembled spacecraft with the IVSR installed on the cruise stage

HRS Developmental Tests

Several development tests were conducted to characterize the performance of the cooling loop. These tests were performed in parallel with the design effort and were very helpful to ensure that the final design would meet its requirements. These are described below:

Thermal-Hydraulic

A development test was performed to simulate the electronic shelf and the radiator to validate the thermal and hydraulic performance models used in predicting the performance of the cooling loop. Details of this tests are given in Reference 2.

Leaks

Due to integration constraints, 17 mechanical joints (B-Nuts or AN fittings) were used to complete the assembly - the rest of the assembly is welded. Any large leaks from the HRS during the 7 month flight to Mars would seriously jeopardize the mission. Welded joint were not deemed to leak any significant amount of freon. The B-Nuts, however, being mechanical in nature, could potentially leak and it was considered highly desirable to conduct tests on them to ascertain that they will not leak at rates substantial enough to deplete the flight accumulator during the mission. It was also desired to come up with better schemes for providing some extra insurance against any potential leaks (epoxying the joints).

An extensive test for assessing the freon leak rate through these mechanical joints (B-Nuts or AN fittings) used in the MPF Heat Rejection System (HRS) was conducted. All the combinations of materials (Al, SS) and sizes (1/4", 3/8") used in the flight HRS were simulated. Teflon flex lines identical to the flight ones were also tested for leaks through their joints. Use of epoxies to provide insurance against leaks was also assessed. Twenty four B-Nut joints were examined. These joints were subjected to cyclic mechanical flexing and torsion to simulate those encountered by the worst joint in the flight system during launch. This was followed by thermal cycling to simulate the excursions during ground testing and flight.

Helium leak tests were conducted on each joint under vacuum and under internal pressure of 6.8×10^5 N/m^2 (100 psia). In addition, all the joints were pressurized with liquid Freon-11 (used in flight system) and tested for freon leaks. All the tested joints exhibited leak rates which were much lower than those used to size the flight accumulator - the accumulator is sized to accommodate a leak of 17 cubic inches of liquid freon in the 7 month flight, whereas our tests showed that the total leak should be much less than half of this value even under the worst conditions. Use of soft cone seals and re-torquing was recommended. Also recommended was the use of an epoxy on the exterior surfaces of the joints' leak paths to provide flight.

Material Compatibility

Within the HRS Freon-11 is in constant contact with materials like aluminum, stainless steel and some elastomers. Concerns for potential corrosion of aluminum, particularly in contact with moist freon, were alleviated by conducting tests to investigate the compatibility of Freon-11 with aluminum and stainless steel. Several test samples of aluminum and stainless steel were inserted in Freon-11 with different levels of moisture (freon is supplied in drums at a moisture level of about 10 ppm (parts per million) and it saturates at 100 ppm). These samples were examined chemically, visually and under electron microscopes to measure the levels of corrosion as a function of time. For aluminum, no evidence of corrosion was observed for low moisture levels (close to 10 ppm) but there was a very strong evidence of corrosion at the high moisture levels (much higher than 10 ppm and close to 100 ppm). This test showed that it was extremely important to minimize moisture to prevent corrosion of aluminum, and elaborate safeguards were taken in the freon storage & loading process to minimize the moisture levels (not much more than the 10 ppm level, as in the manufacturer supplied freon drums).

No evidence of corrosion was observed for stainless steel for all the moisture levels tested. VITON (used in the check valves) was found to swell significantly when inserted in Freon-11, however, subsequent leak tests performed on the check valves demonstrated that the leaks through them in the check direction were very small and well within acceptable limits. All other materials in contact with the freon underwent long term compatibility tests and were found to be acceptable.

Performance of the Pumped Loop During Life Tests

A life test cooling loop was built and subjected to long term operation to verify the reliability of the various components of the flight HRS. A schematic of the set up is shown in Figure 9. The life test simulated the long-term operation of the pump assembly, particle filter, and the rest of the HRS (aluminum and stainless steel tubes, Teflon tubing, accumulator, check valves etc). A detailed description of this set up is given in Reference 3.

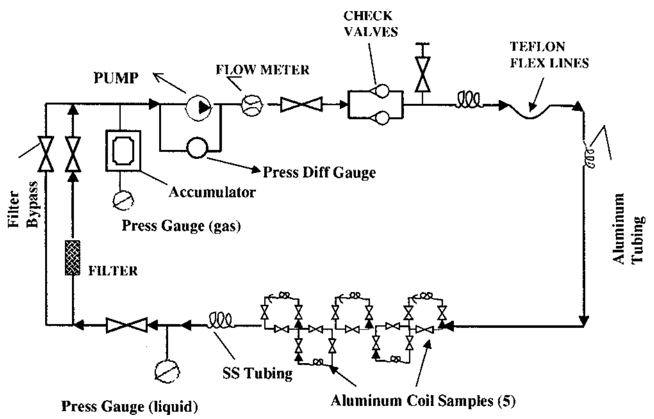


Figure 9. MPF HRS life test schematic

The life test was also used to investigate and measure the long term corrosion of the HRS tubing material (aluminum and Stainless steel) in a flowing environment with all the materials and components used in the flight system. Samples of tubing and the working fluid were taken out and tested periodically. Further, the long-term leak rates of the HRS were monitored during the life test.

Life Test Cooling Loop

Since the cooling loop is being used throughout the flight for 7 months (5100 hours), and it is crucial to function reliably throughout this duration to guarantee mission success, a life test set up was built and is undergoing long term testing. The schematic of this test is shown in Figure 9. It simulates the long term operation (> 5100 hours flight duration) of pump assembly & particle filter, in conjunction with rest of the HRS (Aluminum, Stainless steel, Teflon tubing, accumulator, check valves, etc.). This system clocked about 18 months (14000 hours) of uninterrupted operation with no pump failures, exceeding the 5100 hours required for flight by more than a factor of two.

In addition to the compatibility tests described earlier (performed on small sections of tubing materials in a non-flowing environment of freon), this life test was also used to investigate & measure the long term synergistic corrosion of the HRS tubing (Aluminum, Stainless steel) in a flowing environment with all the materials and components used in the flight system simulated. Samples of tubing & freon liquid were taken out periodically for analysis - no evidence of corrosion was found in the first 7 months. The sampling of the freon and the aluminum tubing was not followed up after this period due to the severe budgetary constraints.

This life test was also used to measure long term leaks from the HRS, particularly due to mechanical joints (AN fittings, B-Nuts) - relatively large leaks were observed in the beginning of test which were corrected and prompted a more elaborate leak test done separately (discussed earlier).

Figure 4 shows the variation in the flow rate, pressure drop and pump input power as a function of time for this life test. During the first 5 months of the test the filter was slowly getting clogged (at the end of this period the filter got clogged and was bypassed - discussed below), the flow rate dropped to about half of its value at the start of the test, the pressure drop across the system increased by 20% and the pump input power decreased slightly.

As soon as the filter was bypassed, the flow rate increased to a value even larger than at the beginning of the test (25% larger due to the lack of the pressure drop associated with even a virgin filter); the pressure drop in the system was lower than at the beginning of the test by 15%, and the power level was about the same. This does make sense because the bypassing of the clogged filter reduced the overall resistance of the loop allowing more flow rate at smaller pressure differences. Since even a virgin filter has a non-zero resistance, the flow rate without the filter is even larger than at the beginning of the test when there was an unclogged filter in the flowing loop.
The flow rate and the pressure drop across the system remained essentially constant after the filter bypass; however, the power level did fluctuate due to the pump being left idle due to inadvertent power outages. A more detailed description of these effects is presented next.

Filter Clogging

The filter used in this mock-up had inadequate capacity and was bypassed after 3600 hours or 5 months (flight filter has at least 6 times higher capacity for particles). In order to avoid the potential for significantly reduced flow rate due to a clogged filter, the flight filter uses a check valve to bypass it when the filter's pressure drop is higher than 0.17×10^5 N/m^2 (2.5 psid). Since the IPA produces a pressure rise of more than 0.41×10^5 N/m^2 (6 psid) at the required flow rate of 1.26×10^{-5} m^3/s (0.2 gpm), and the pressure drop in the cooling loop system is expected to be only 0.14×10^5 N/m^2 (2 psid), this additional pressure drop from a clogged filter should not pose a problem in providing the required flow rate of freon throughout the flight.

The exact reason for the clogging of the filter is not known yet because the cooling loop has been not disassembled. Even though the cooling loop was thoroughly cleaned and tested before starting the life test, the clogging of this filter was surprising. It is speculated that the possible reason for the clogging are particles generated by the graphite within the Teflon flex line. The Teflon line is impregnated with graphite on its inside surface to prevent electrostatic discharge (ESD), due to the flowing freon, from creating micro-holes in the Teflon which could lead to a leak within the cooling loop. A more definitive reasoning will be found after disassembly of the test loop. Since the flight filter has at least six times the capacity of the life test filter it is hoped that the flight filter will be less prone to clog. In addition, the flight filter's automatic bypass upon clogging provides further insurance.

High Current Draw of Stalled Pump

The flight system primary pump is programmed to be on for the entire duration of the flight, with the secondary pump idle. The secondary will be turned on automatically only if the primary fails. The main reason for leaving the secondary idle was to maximize its available life to serve as a full backup in case the primary failed. The power supply for the life test loop pump is connected to a relay which prevents the pump from restarting automatically after a power outage; a manual switch for the relay is used to restart the pump after a shutdown. This was done to prevent an unattended turn-on of the pump (and the possible consequent damage) during power surges typical during outages.

After almost 1 year of uninterrupted flawless operation of the life test loop, a power outage occurred and the pump did not restart automatically, as designed. Following this outage, the pump was idle for about a month due to its unattended status. However, upon trying to restart the pump manually, it was observed that the 500 mA fuse was blown (normal current draw is 400 mA). Replacements of the fuse with those rated for as much as 1.5 were unsuccessful in restarting the idle pump. Following this the pump was gently tapped twice and its restarted - the current draw was about 450 mA immediately after restarting and dropped down to its nominal value of about 400 mA in a few minutes.

During the period between this manual restart and the reaching of nominal steady state performance (a duration of less than 15 minutes), it was also observed that the current draw would momentarily rise to as much as 475 mA a few times. Simultaneous to these momentary peaks, an audible change in the pitch of the pump would be heard when one could "observe" a flock of particles travelling through the loop via the pump.

Following this outage the pump was allowed to run for a few days and deliberately turned off for 2 to 3 week periods to attempt repeating its failure to restart. Five such attempts were unsuccessful in repeating this failure. After this there were 5 more inadvertent power outage and in most instances the pump was off for about 2 or more weeks. In all cases the starting current required was higher than 500 mA. Also, in all cases except one, the pump started satisfactorily with a current draw larger than 500 mA, without any tapping of its body. In one instance the pump required a few gentle taps to restart it.

One possible theory to explain all these effects is that the clogging of the filter followed by its bypass allowed the generated particles to collect within the loop without being removed from the flowing fluid. As long as the fluid was flowing, it would not allow particles to collect in one zone. However, upon stoppage of fluid flow after a power outage, the particles could settle in local "valleys", for example the pump's bearings. Since these bearings are hydrodynamically lubricated, their gaps are very tiny

(6 to 18 micro-meters thick), which implies that these particles could create enough friction to increase the starting current significantly.

Implications for Flight System

The results from this long-term life test were used to design/operate the flight system differently than would be the case without these results. The following recommendations were implemented:

1) The primary pump is not being allowed to be turned off under any circumstance under the control of the mission operators.

2) The secondary or back-up pump, which is normally idle, is turned on for an hour once every 2 to 4 weeks to remove any settled particles, even though one would not expect any settling in zero-gravity (during the life test power outages the pump was always able to restart without any tapping as long as the idle period was less than 2 weeks and 2 to 4 week frequency was practical for the mission).

3) A filter much larger (6X) than used for the long-term development test loop was implemented for the flight system.

4) The mechanical fittings (B-Nuts) used for assembling the loop used soft-cone (aluminum) seals, they were re-torqued after a few days of the initial torquing, and epoxy was used on the exterior surfaces of the joints leak paths to provide as much insurance against leaks as possible.

The life test set up had operated continuously for 8,000 hours before the actual launching of the Mars Pathfinder spacecraft in December 1996. The results from the operation of the life test are described in Reference 6. The performance of the life test loop was continuously monitored and is shown in Figure 10. It shows flow rate, pressure rise, and electric power consumption of the pump. The test results showed no evidence of the corrosion after seven-month operation of the loop. The leak rate of the fluid from the system was minimal; it was much lower than the leak rate that was allowed in the flight system.

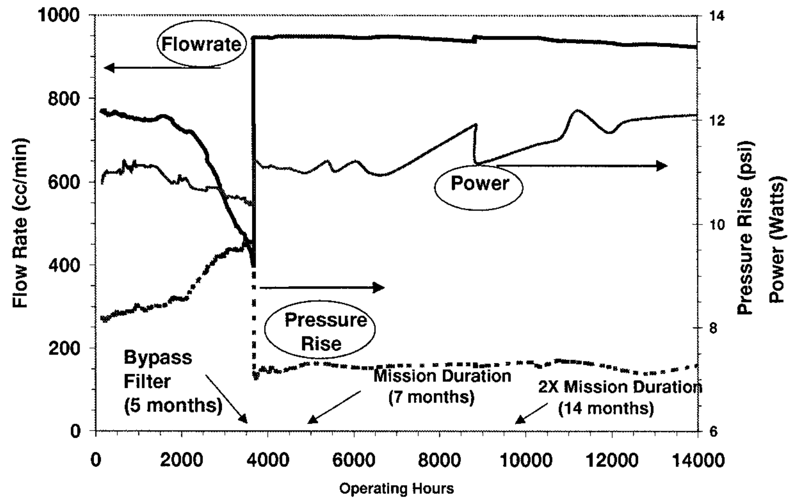


Figure 10. Life test performance

One of the lessons learned from the life test loop was that the back-up pump needed to be turned on regularly in order to flush any particles that might settle in the pump bearings. During the life test operation, it was noticed that the particles tend to settle in the bearings and impeller area if the pump is stopped for an extended period of over four weeks. Based on this information, the back-up pump in the flight system was turned on for an hour once every month.

After the successful landing of the Mars Pathfinder on Mars in July 1997, the life test system was stopped. By this time the life test pump had continuously operated for over 14,000 hours. The tubing and the fluid were investigated for the corrosion and other particulate material. Of particular importance was the particulate that had clogged the filter during the life test.

The chemical analysis showed no evidence of corrosion in the aluminum tubing. The particulate in the fluid sample was found to consist of sizes in the 1 to 40 micron range. The large particles were mostly silica, fibers, and some metallic particles. The smaller particles were mostly chromium, iron, and aluminum. The moisture levels were less than 5 PPM (parts per million) compared to about 17 PPM found in sample taken at 5-month period. The organic residue found in the Refrigerant 11 was similar to the material used in the thread of the in-line filter. Most of the particles generated in the life test loop were found to be due to the materials used in the life test set up. Except for the Teflon tubing and the Chromium used in the pump, none of the other materials were used in the flight system.

The scanning electron microscopy done on the aluminum tubing indicated that the prominent mode of corrosion of the aluminum tubing is the physical erosion by the chromium particles being formed at the pump.

Performance of the Loop During Flight

The HRS performance was continuously monitored during the entire cruise to Mars. The HRS was first activated on the launch pad about two hours before launch. Both the pumps were turned on and the functioning of the system was verified by the current draw of the pumps. The temperature of the electronic equipment shelf and the radiator were also monitored to make sure the working fluid was flowing freely. About four hours after launch, the backup pump was turned off and only the primary pump was on during the rest of the seven-month cruise to Mars. The back up pump was turned on once a month for an hour to ensure that no particulate accumulated in the idle pump.

The performance of the HRS system during the initial periods was very close to the performance predicted and verified during the system level thermal vacuum test. The equipment shelf temperatures was maintained at around +5 C, whereas the radiator temperature was around –4 C. At these radiator temperatures, all the cooling fluid coming out of the equipment shelf was above 0 C and the thermal control valve is completely open. All the fluid flows through the radiator without any bypass. A temperature profile of the equipment shelf and the radiator is shown in Figure 11 for one-hour duration on January 28, 1997.

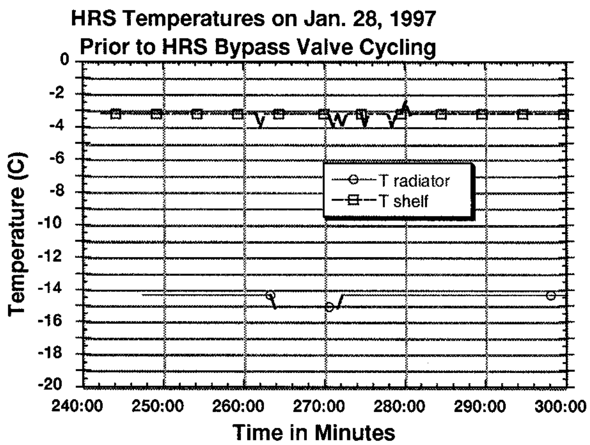


Figure 11. HRS Temperature during initial part of the cruise

The radiator temperature was a function of the distance from the sun and the sun angle on the spacecraft. This temperature dropped as the spacecraft cruised away from the earth towards Mars. The temperature dropped from –4 °C immediately after launch to below –12 °C after forty-five days into the cruise. At this time, the fluid temperature coming out of the shelf was below 0 °C. As this fluid enters the IPA, the wax actuated thermal valve would open the bypass port and part of the fluid would bypass the radiator. This bypass was designed to keep the electronic shelf above – 7 °C irrespective of what the radiator temperature was.

In Figure 12, the temperatures of the equipment shelf and the radiator are shown for the day when the radiator bypass had just started. In this case, the shelf was maintained between – 4 and –2 °C while the radiator temperature varied between –16 and

–14 °C. The small fluctuation in the radiator and the shelf temperature was due to the valve actuator continuously trying to adjust to the fluid temperature. This was observed and investigated during the system thermal vacuum test. The fluctuation was attributed to an under-damped flow system and was considered harmless to the system.

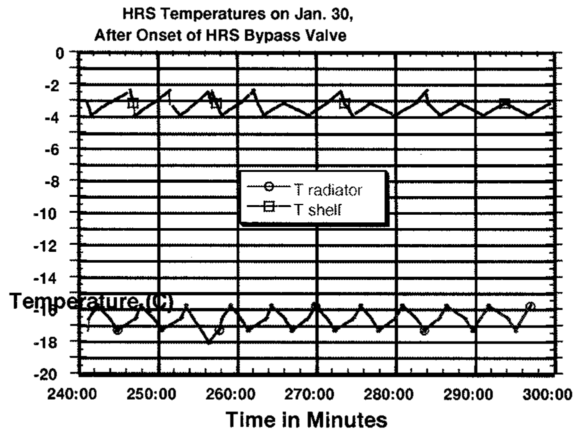


Figure 12. HRS temperatures during later part of the cruise

As the spacecraft neared Mars, the radiator temperature gradually dropped down to – 70 °C. However, the equipment shelf maintained its temperature at around -4 °C. The radiator and the electronic shelf temperatures during the complete mission are shown in Figure 13.

The HRS system was designed to vent all the working fluid just prior to entering the Martian environment. About 90 minutes before the entry, the vent system was activated by the opening of a pyro-valve that connects the high-pressure gas side of the accumulator to the liquid. The liquid was in turn vented to space via a nozzle, which is opened to space via another pyro valve (Reference 2). This event occurred on July 4 1997 around 8 AM Pacific Standard Time. The spacecraft navigational data received by the ground controllers indicated that the nutation due to venting was less than two degrees and did not affect the spacecraft course to the Martian landing site.

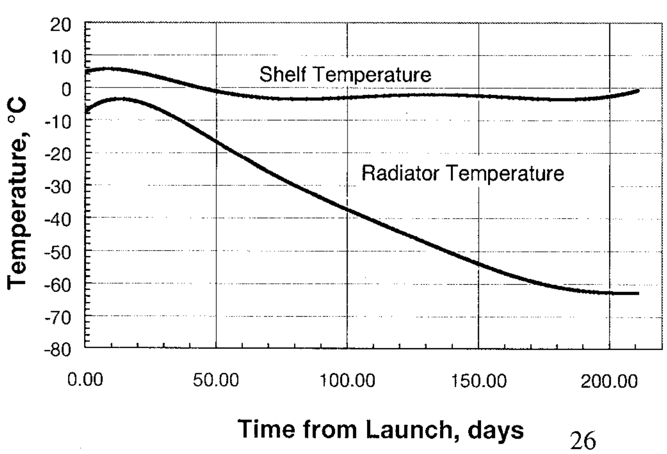


Figure 7. Radiator and electronic shelf temperature during the entire cruise to Mars

Conclusions

An active heat rejection system consisting of a mechanically pumped single-phase liquid was designed and developed for the Mars Pathfinder mission. The unique requirements of the mission necessitated the use of the pumped loop system for the thermal control of the spacecraft during the cruise to Mars. Because this was the first time that such a system was designed and flown, several new technologies were developed to make the loop successful. These technologies include the use of Refrigerant 11 (Freon-11) as a cooling fluid and a wax actuated thermal control valve to bypass the flow. The Refrigerant 11 system allows the operation of the system down –110 C. It was the first time that a mechanically pumped cooling loop was used in a deep space mission.

The successful flight demonstration of the mechanically pumped cooling loop on the Mars Pathfinder mission has shown that an active cooling system can be reliably used in deep space missions. The data from the life test pump combined with the flight data show that the mechanical pumps can be reliably operated for missions lasting over two years. The flexibility provided by the mechanical pump cooling systems in the design, integration, test, and flight operation of spacecraft makes this cooling system an ideal system for not only faster, better, and cheaper missions but also for other missions.

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Tables

Table 1. Integrated Pump Assembly Specifications

Section	Specification Detail
Thermal & Hydraulic	
Flow Rate and Pressure rise	Freon flow rate of 0.2 gpm, at 4 psid in the operating temperature range of -20 to 30 C
Max. Operating Pressure	100 psia
Operating Temperature Range	-30 C to 40 C
Bypass ratio	Above 0 °C, 100% radiator flow Below –7 °C, 100% bypass flow
Leak Rate	Helium leak rate of 10^{-7} scc/sec for the gas and 10^{-4} scc/sec for the liquid side
Storage temperature	-40 C to 50 C
Physical	
Mass	Maximum of 8 kg dry
Size	10 inch by 10 inch by 6.5 inch
Service Valves	One for gas charge and two for liquid fill and purge
Mounting	Mounted on a base plate
Operation	
Life	10,000 hours continuous, 3 calendar years
Start/stops	1000
Electrical	
Input Voltage	To operate in 27 Vdc to 36 Vdc
Power	10.6 Watts maximum
Isolation	One megohm electrical isolation
Electronics parts	MIL-STD-975 Grade 2, MIL-STD-883C Grade B for microcircuits, withstand a radiation environment of 500 Rads (SI), CMOS and MOSFETs meet single event effect parameters
Acceptance Tests	IPA hydraulic performance, sinusoidal and random vibration, thermal vacuum test, proof pressure, and leak rate tests

Table 2. Acceptance tests for IPA

Type of test	Verification Purpose
Performance tests	Performance of the IPA before the start of the qualification tests
Sine Vibration tests	Design for the protoflight launch loads
Random Vibration tests	Design for the protoflight launch loads
Functional tests	Functionality of the unit after an acceptance test
Thermal Vacuum test	Design for the protoflight temperature range
Functional test	Functionality of the unit after an acceptance test
Proof pressure test	Design for the operating pressure
Leak Detection test	Leak rates of the IPA
Performance tests	Performance of the IPA at the completion of qualification tests

Table 3. Sine and random vibration specifications for IPA

Axis	Protoflight Test Level	Frequency Band
Sine Vibration:		
All	1.27 cm double amplitude	5 - 20 Hz
	10.0 g (Acceleration 0-to-peak)	
Random Vibration:		
All	+ 6dB/octave	20 - 80 Hz
	0.2g2/Hz	80 - 700 Hz
	-12 dB/octave	700 - 2000 Hz
	13.2 g_{rms}	Overall