LONG TERM LIFE TESTING OF A MECHANICALLY PUMPED COOLED LOOP FOR SPACECRAFT THERMAL CONTROL

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ABSTRACT

The Mars Pathfinder (MPF) Spacecraft launched to Mars in December 1996, uses a mechanically pumped loop to transfer dissipated heat from the insulated lander electronics to an external radiator. Due to the lack of long term flight experience of this kind of cooling system for spacecraft, a life test was conducted on a system which simulates the flight design This development loop has clocked about 15 months of operation until now, far exceeding the 7 months required for the flight system. This paper first describes the design and predicted performance of the MPF flight cooling system. After this it discusses the design and performance of the development cooling loop used to simulate the long term performance of the flight system.

IN'IRODUCTION

The Mars Pathfinder (MPF) Spacecraft was launched to Mars in December 1996 and is scheduled to land in July 1997. The spacecraft shown in figure 1 is composed of two distinct parts: the cruise stage and the lander. The cruise stage is separated from the lander by several explosive bolts, just prior to the lander portion entering the Martian atmosphere. Safe entry of the lander into the Martian atmosphere is achieved by an ablative heat shield surrounding it. Upon reduction of the spacecraft speed to a predetermined level, the heat shield is detached and discarded followed by deployment of a parachute to slow it down further. At a predetermined low altitude, this is followed by firing of retro-rockets to bring the lander to a near standstill. Finally, airbags surrounding the lander system are deployed to cushion the impact on the Martian su[-face.

Following landing, the airbags are vented and retracted and the tetrahedral shaped lander deploys its self righting petals which exposes the three solar arrays and the insulated electronics enclosure. Finally, a rover located on one of the solar panels is released and allowed to discover the landscape of the Martian surface.

The same communication and data analysis electronics is used both during cruise and landed operations. It is located in the lander basepetal and is completely enclosed in a very high performance insulation to conserve heat (power) during the cold Martian nights (as cold as -80°C). Because the same electronics is used both during cruise as well as landed, and since it is highly insulated (insulation and stowed airbags), it is very difficult to remove its dissipated heat passively during the cruise phase (temperatures outside the insulated enclosure are as high as 15°C near earth). Further, 90 Watts of power is continuously dissipated by the lander electronics during cruise. 'I'his necessitated the need for a heat rejection system (HRS) for MPF. In addition to rejecting heat during the cruise phase, the HRS was also required to minimize any heat leaks from the insulated electronics once MPF has landed on Mars.

SELECTION OF MECHANICAL. PUMPED COOLING LOOP FOR HRS

"I'he HRS serves as the thermal link from the equipment shelf to the heat sink - it picks up the heat from the electronics and transfers it to the radiator which in turn rejects it to space via thermal radiation. The heat shield and a cruise stage radiator were investigated as possible heat sinks for the HRS. The concepts traded-off for the HRS were pumped fluid loops (single phase, liquid), heat pipes (variable & constant conductance, VCHP and CCHP) and detachable thermal/mechanical links. Mass, cost, schedule, power & technology readiness were traded. A mechanical pumped fluid cooling loop using Freon- I I was chosen for the HRS due to the following attractive features (which other concepts lacked partially or fully):

- Ease of integration with spacecraft

- Easily severed link before Martian entry (pyro-cutting of tubes)
- No need for power during Martian nights (unlike VCI [1'])
- Flexibility of ground operations & tests (no orientation constraints)
- Control temperatures of remotely located components (thermal bus)
- Modulate temperatures with changing thermal environment and equipment power
- Low entry mass (most mass located in cruise stage)
- Ease of fine tuning performance after tests
- Vet-satilc thermal control system for future (small, light, cheap) missions

PERFORMANCE REQUIREMENTS

After choosing the mechanical pumped cooling loop to serve a.. the HRS for MPF, a system level design study was performed on the spacecraft and requirements were developed for the HRS.

Thermal

- Cooling power: 90 -1 SO W
- Allowable temperature range of equipment: -60 to -20°C (low limit), 5 to 70°C (high limit)
- Freon liquid temperature of-40 to +50°C

Integrated Pump Assembly (IPA)

- 1.26x 10^{-5} m^3/s (0.2 gpm) freon flowrate @ > 0.27x 105 N/m^2 (4 psid) pressure rise
- < 10 W total power consumption during cruise
- > 8 kg weight
- > 2 years of continuous operation without failure

Leakage

- Meet specified (very low) leak rate (liquid& gas) to maintain liquid pressure well above saturation pressure - at least $2x10^5$ N/m^2 (30 psi) higher

DESIGN DESCRIPTION AND TRADE-OFFS

The HRS design consisted of six distinct parts[1,2]:

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

The primary 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 assembly to the cruise stage radiator (aluminum tin, painted white) A vent system is used to vent the freon prior to Martian entry.

Integrated Pump Assembly

A schematic of the tooting loop along with the IPA is shown in Figure 2. The 1PA[2] 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 0.27x 10^5 N/m^2 (4 psid) pressure differential at 1.26x10-' 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.

Four check valves (with VITON seats) 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 stainless steel welded bellows accumulator to maintain the liquid pressure at least 2×10^5 N/m² (30 psi) above its saturation pressure, throughout the flight, to prevent cavitation of the centrifugal pumps

Freon-11 Working Fluid

About fifteen fluids' were traded-olT as candidate working fluids before choosing Freon-11 (CCl_3F) 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 - tbisand 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:

- Freezing point (less than about -90°C because during the radiator bypass the freon in the radiator could get as cold as -80°C)
- 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)
- High specific heat and thermal conductivity; low viscosity (for high heat transfer rates and low pressure drops)
- Excellent compatibility with commonly used materials like aluminum and stainless steel (for long term corrosion proof performance)

The important properties of Freon-11 are:

- Freezing point= -111 °C
- Normal boiling point = 24°C
- Vapor pressure at 50°C (highest operating temperature) = 1.36x105 N/m² (20 psig)
- 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 VI-ION and TEFLON

Tubing Materials

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.

PERFORMANCE PREDICTIONS

Tables 1 and 2 contain the predicts from a detailed multi-nodal thermal model (SINDA/TRASYS) of the radiator/electronics for the worst case hot and cold conditions. The radiator is sized to be large enough that even in the worst hot case the radiator is nearly beginning to be bypassed; in the worst cold case 94 % of the flow bypasses the radiator to maintain the correct fluid temperature. In the worst cold case the coldest radiator zone is at -80°C which implies a 30°C margin above the freezing point of Freon- 11 (-111 °C).

All the electronics interfaces meet their flight allowable limits with margins (all except one component have margins larger than 10°C for the worst hot & cold cases). The maximum heat dissipation for the hot case is 190 W and the minimum is 70 W for the worst cold case. The temperature rise of the freon through all the electronics is about 11°C for 190 W of heat removal at a freon flow rate of 1.26×10^{-5} m³/s (0.2 gpm).

DEVELOPMENT 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-}lvdrattlic

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.

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 night

Helium leak tests were conducted on each joint under vacuum and under internal pressure of 6.8x 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 additional insurance against leaks in 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 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.

LIFE TEST COOLING LOOP

Since the cooling loop is being used throughout the flight for 7 months (5 100 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 3-it simulates the long term operation (> 5100 hours flight duration) of pump assembly& particle filter, in conjunction with rest of the HRS (Al, Stainless steel, Teflon tubing, accumulator, check valves, etc.). This system has clocked about 15 months (11000 hours) of uninterrupted operation until now 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 nonflowing 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 I IRS, particularly due to mechanical joints (AN fittings, H-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 11ow 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 flowrate 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°A 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 1 5%, 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 duc 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 b}pas.see! after 3600 hours or 5 months (flight filter has at least 6 times higher capacity *for* particles). The night filter uses a check valve to bypass it when the filter's pressure drop is higher than O. 17×10^5 N/m^2 (2.5 psid). Since the [['A produces a pressure rise of more than 0.41$\times10^5$ Nhn^2(6 psid) at the required flow rate of 1.26x 10-^{5}m^3/s (0.2 gpm), and the pressure drop in the cooling loop system is expected to be only O. 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. It is planned to be disassembled after MPF lands on Mars. 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 thepitch 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 (hat these particles could create enough friction to increase the starting current significantly. The planned disassembly of the life test loop after MPF's landing in July 1997 will shed more light on this theory.

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 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 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.

CURRENT STATUS AND NEAR TERM PLANS

Before launch in December 1996, the fully assembled MPF spacecraft successfully underwent tests related to acoustic, radiated emission and susceptibility. It also successfully completed a Solar Thermal Vacuum test. The spacecraft heat rejection system has performed flawlessly until now' and will be landing on Mars in July 1997.

The life test has undergone 11000 hours (15 months) of continuous operation (more than twice the 5100 hours or 7 months required for flight). It will be run until MPF lands on Mars, following which it will be disassembled and examined for corrosion and generated particles. Also, the filter will be examined along with the pump. Following this examination, the test loop will be assembled, filled and run again to serve as a test bed for future cooling loops.

CONCLUSIONS AND NEXT GENERATION LOOPS

A successful performance 01 this system in the Pathfinder mission will remove some reluctance (and the associated paranoia) on the part of projects to try out bold new approaches to thermal control of spacecraft. The current Mars Pathfinder I IRS life test fluid cooling loop serves as a test bed for developing better cooling loops t'or future spacecraft. Even though the current loop is designed for Pathfinder, the technology developed will be of generic use for future missions, The knowledge gained will be useful to develop more flexible, robust, compact, lightweight, modular and autonomous mechanically pumped cooling loops - examples would be the development of accumulators which can accommodate large system leaks, different operating fluids, better temperature modulation schemes, gathering of more life cycle data (e.g. pumps with or without filters) to develop more optimal strategies for component redundancies.

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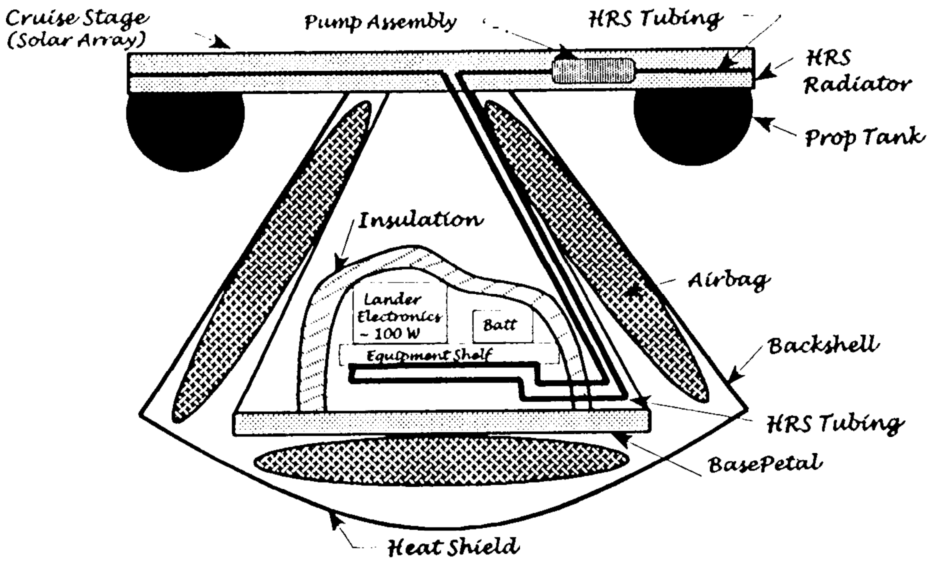

Figure 1: *Mars Pathfinder Heat Rejection System*

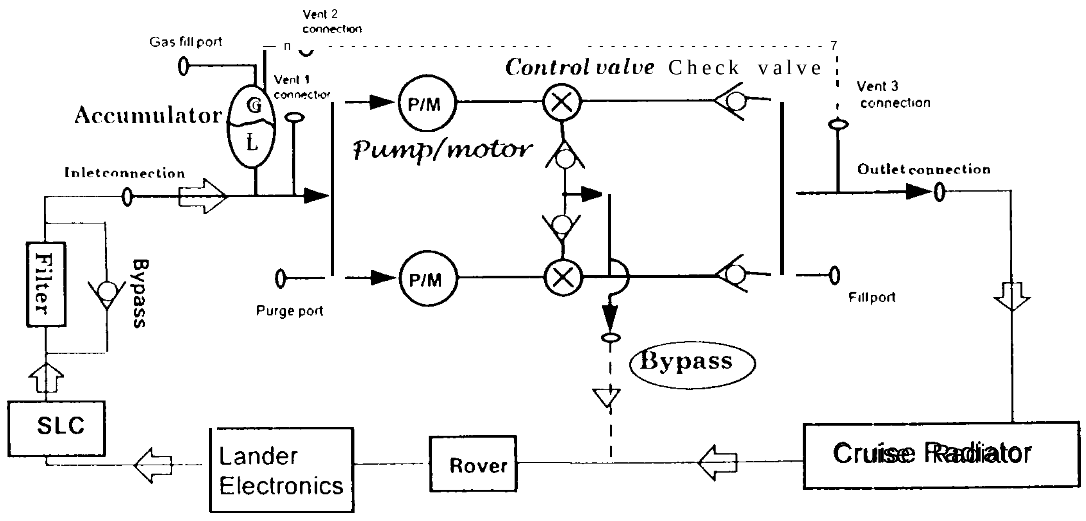

Figure 2: *Integrated Pump Assembly*

- RADIATOR

CASE	PHASE	AU	SUN-SOLAR ARRAY z - (")	CRUISE STAGE BACK TEMP. ("c)	BACK SHELL TEMP. (°C)	NO FLOW RAD. TEMP (°C)	PUMP OUT. TEMP (°C)	MIXED FLUID TEMP (°C)	BYPASS (%)
WCH	NEAR EARTH	I	30	39	12	-24	4	-5	o
WCC	NEAR MARS	I .55	40	-30	-65	-80	-3	-7	94

Table 1: ***HRS performance prediction***

- **INTEGRATED MODEL**
  - WORST CASE HOT& WORST CASE COLD (HOT/COLD SPOTS)
- **ELECTRONICS SHELF**

ZONE	PREDICTED MAX/MIN (°C)	FLIGHT ALLOWABLE MAX/MIN ("c)	MARGIN ON FA MAXIMIN ('c)
SSPA(ISLAND)	14/-7	40/-20	26/13
SSPA (STRIP)	19/-7	401-20	21/13
IEM	15/-7	50/-40	35/33
DST	5/-7	70/-45	65/38
SLC	20/-7	45/-40	25/33
ROVER	01-7	5/-60	5/53

Table 2: ***Electronics shelf performance prediction***

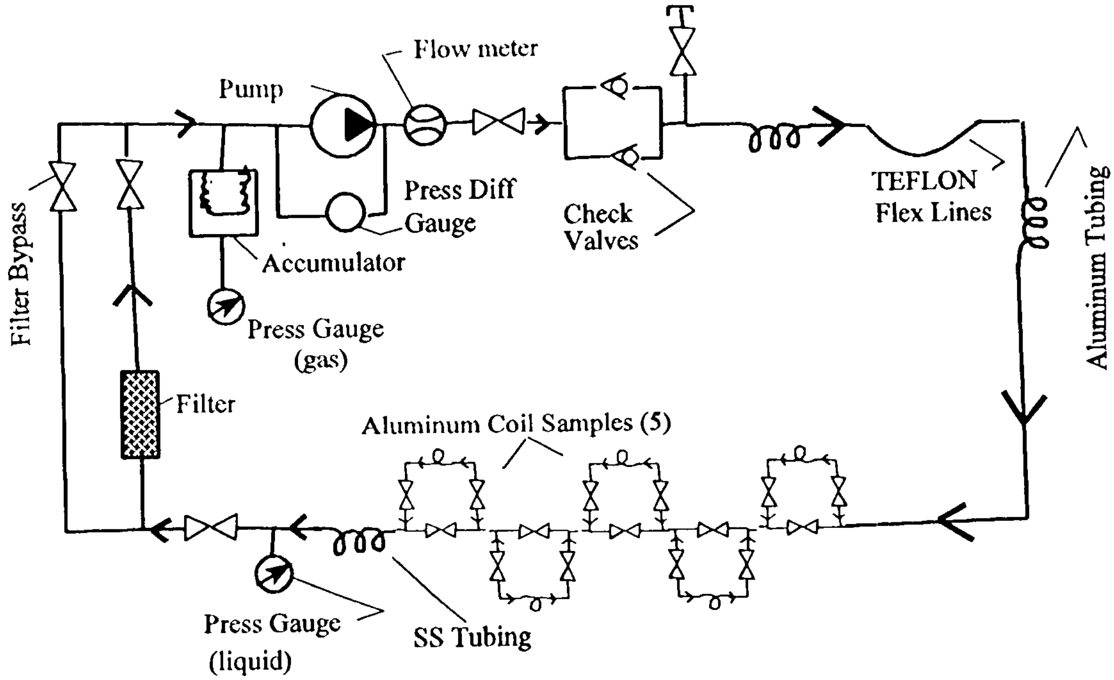

Figure 3: *Life test schematic*

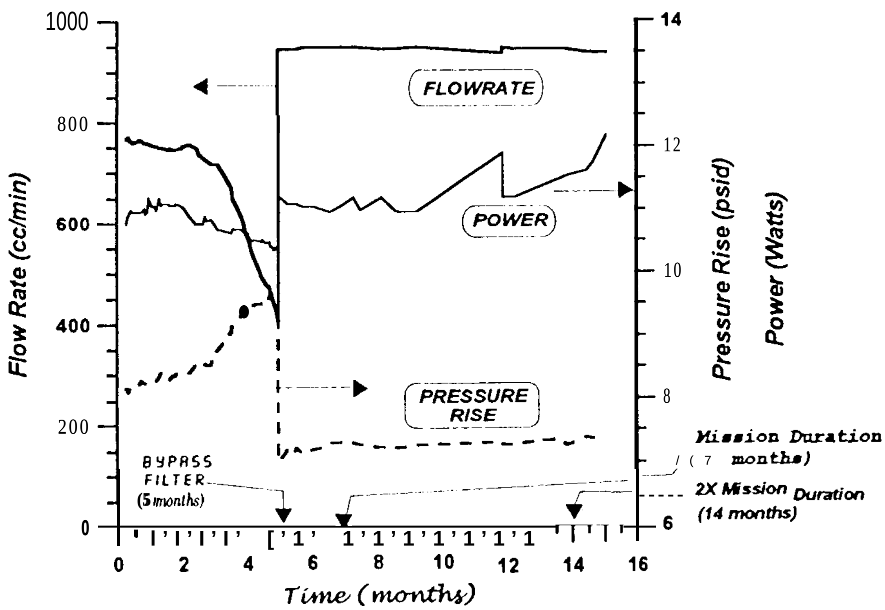

Figure 4: *Life test performance*