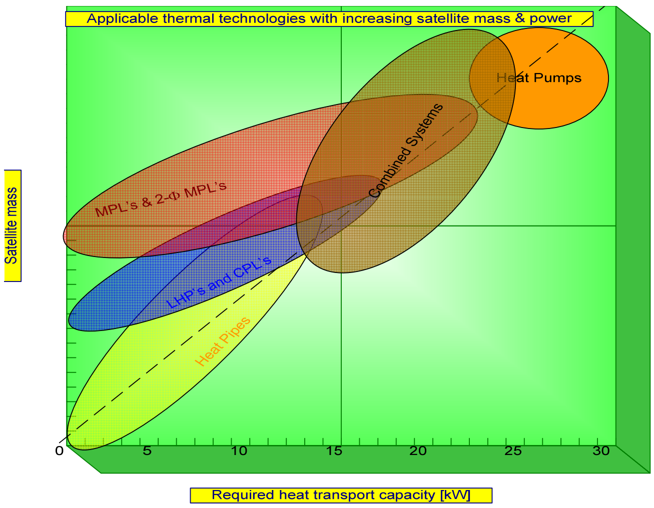
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Development of a Mechanically Pumped Fluid Loop for 3-6 kW Payload Cooling



Trends in thermal cooling systems

Problem area
With the growing dissipation of high density electronics the demand for more efficient cooling systems for space based applications such as scientific and telecommunication satellites is steadily increasing, up to a point that implementation of high performance cooling technologies are required in combination with conventional (Loop) Heat Pipe systems. Implementation of advanced cooling systems will most likely be a combination with existing technologies (roughly indicated by the overlap in the figure above) and will depend on the overall system mass, in-orbit load requirements, heat rejection variations, number thermal interfaces and testing constraints. Since the point is approaching that advanced technologies are additionally required for the next generation of large telecommunication platforms such as AlphaBus, ESA initiated in 2004 the development of two 3-6kW cooling systems in competition. The systems are based on a single and a two phase mechanically pumped loop.Application of mechanically-pumped fluid loops offer specific advantages over conventional two-phase capillary pumped loops or heat pipe networks.

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Payload cooling
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Pump
Valve
Accumulator

This report is based on a presentation held at the 39th International Conference on Environmental Systems, Savannah (GA), U.S.A., July 12-16, 2009.

Description of work

This paper focuses on the development of and qualification of the 3kW single phase system presenting the Qualification Model (QM) hardware and test results performed as outcome of the development started in 2004 under ESA contract.
The industrial team responsible for the development was Bradford Engineering BV, (The Netherlands), Realtechnologie AG (Switzerland) and the National Aerospace Laboratory NLR (The Netherlands).
Currently an accelerated life test is conducted at NLR for continuous operation of QM hardware under worst case conditions for one year (2009-2010).

Applicability

Payload cooling systems

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This report is based on a presentation held at the 39th International Conference on Environmental Systems, Savannah (GA), U.S.A., July 12-16, 2009.

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ABSTRACT

With the fast growing demand for space based telecommunication capabilities in combination with application of high density electronics, the cooling requirements for future telecommunication satellites is steadily increasing, up to a point that conventional cooling technologies using (loop) heat pipes are no longer enough to cope with in-orbit load and heat rejection variations, large number of thermal interfaces and testing constraints. To prepare for future high performance cooling requirements, the European Space Agency, ESA initiated the development of a Single-Phase Mechanically Pumped Fluid Loop (MPFL) which was one of the two heat transfer element options for the large Alphabus deployable radiator (see Figure 2). The purpose of the project was to design, develop and qualify an European manufactured single-phase cooling loop components such as pumps, valves, an accumulator and coolant fluid that can be used as high performance heat transfer device for extended payload power ranges between 3-6kW. The main requirements for MPFL were: operational temperature range of -20°C to +90°C, non operational -100°C to +100°C, 3KW heat transportation, <30°C increase of fluid temperature in the PHX, piping length PHX 70m and RHX 90m, Lifetime >15 years. As the temperature, reliability and lifetime requirements are severe, this put highly challenging requirements to the coolant (temperature range), pump (bearings, motor) and accumulator design. The selected and (space) qualified fluid was H-Galden Zt85 (manufactured by Solvay Solexis) which gives the best overall performance. The baseline selected MPFL pump is a design with a demonstrated accelerated life test for 10 years. The pump provides for an almost constant fluid flow through the Payload Heat Exchanger (PHX) branch whereas the By-pass Valve regulates the flow through the Radiator Heat Exchanger (RHX) branch. The accumulator compensates for fluid expansion over the operation and non-operational temperature range. A modular design which can be used for applications within a 3-6 kW payload range and compatibility with a variety of coolants was the result of this approach. Hence the qualified equipment for MPFL is suitable for multiple applications.

1. INTRODUCTION

With the growing dissipation of high density electronics the demand for more efficient cooling systems for space based applications is increasing such that high performance cooling technologies are required in combination with conventional (Loop) Heat Pipe systems.

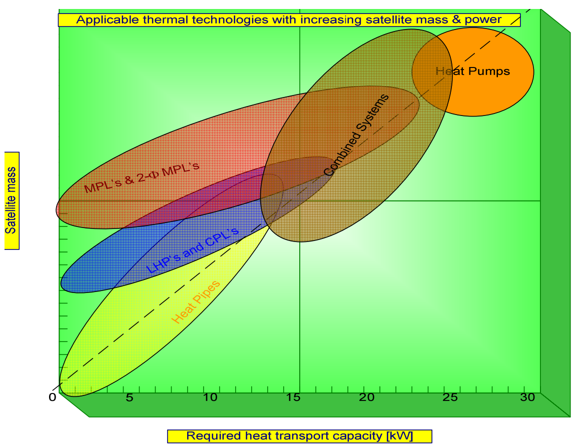


Figure 1 Trends in thermal cooling systems

In figure 1 some general trends are indicated between heat transport and system mass for Heat Pipe networks, Loop Heat pipes and 1-2 phase Mechanically Pumped Loops, combined systems and Heat Pumps. Due to its components and electronics the initiation mass of pumped systems is higher than for conventional (L)HP networks up to about 15kW total cooling power were combined systems start to come in. At the cost of more electric power, Heat Pump systems could be implemented in the future to raise the radiator temperature thus increasing radiative heat rejection without increasing the radiator size. Implementation of advanced cooling systems such as MPFL and 2 phase pumped systems will most likely be a combination with existing technologies (roughly indicated by an overlap in Figure 1) and will depend on the overall system mass, in-orbit load requirements, heat rejection variations, number thermal interfaces and testing constraints. Since the point is approaching that advanced technologies are additionally required for the next generation of large telecommunication platforms such as AlphaBus (Figure 2) ESA initiated in 2004 the development of both a single and two phase mechanically pumped cooling systems in the range of 3-6kW in competition. This paper focuses on the development of the single phase system. Application of a single mechanically-pumped fluid loops offer specific advantages over conventional two-phase pumped loops or heat pipe networks, such as:

- ease of integration with spacecraft: application of simple tubing connections.
- flexibility of ground operations and test: no restrictions related to gravity vector.
- design flexibility by less geometrical constraints on payload/external surface arrangements compared with heat-pipe networks.
- simplified in orbit commissioning and start-up w.r.t. 2-phase systems.
- smaller radiator by a reduction of the temperature gradients between payload and radiator (less interface connections) Since the payload electronics temperature is the limiting factor this allows the system to run at a higher radiator temperature.

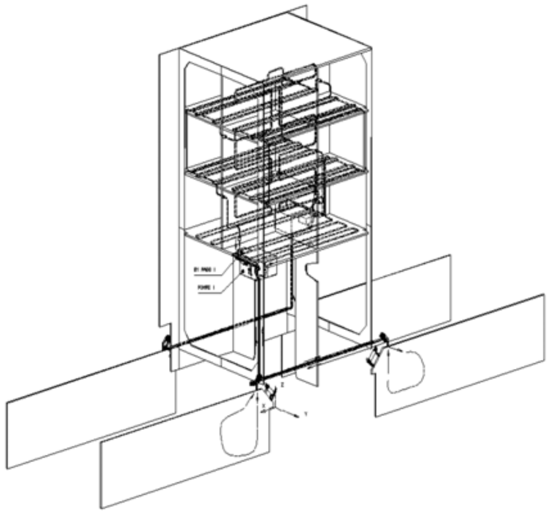


Figure 2 Envisaged application of MPFL in AlphaBus platform

Mechanically pumped cooling systems have already been used occasionally on interplanetary missions in the past, e.g. Mars Pathfinder and the Mars Exploration Rovers. The need for an Active Thermal Control Subsystem was necessitated here by the combined envelope of temperature control requirements of the spacecraft during launch, cruise and Martian surface operations. Furthermore, in human spaceflight mechanically pumped loops have been employed (e.g. shuttle cargo bay, EVA-suits, etc.), and will be a required technology in future programs such as human-rated trans-lunar or interplanetary spacecraft and surface bases.

This paper presents the Qualification Model (QM) hardware and test results performed as outcome of the development started in 2004 under ESA contract. The system design, fluid selection (H-Galden Zt85, Solvey Solexis) & qualification and DM hardware results were are already discussed in ref 1. The industrial team responsible for the development was Bradford Engineering BV, (The Netherlands), Realtechnologie AG (Switzerland) and the National Aerospace Laboratory NLR (The Netherlands). Currently an accelerated life test is conducted at NLR for continuous operation of QM hardware under worst case conditions for one year (2009-2010).

2. GENERAL SYSTEM DESIGN

2.1 OPERATING PRINCIPLE

The MPFL subsystem operating principle is depicted in Figure 3 below. The AlphaBus payload dissipates its heat into fluid circulating the Payload Heat Exchanger (PHX). The Radiator Heat Exchanger (RHX) radiates the heat from the coolant to the space environment.

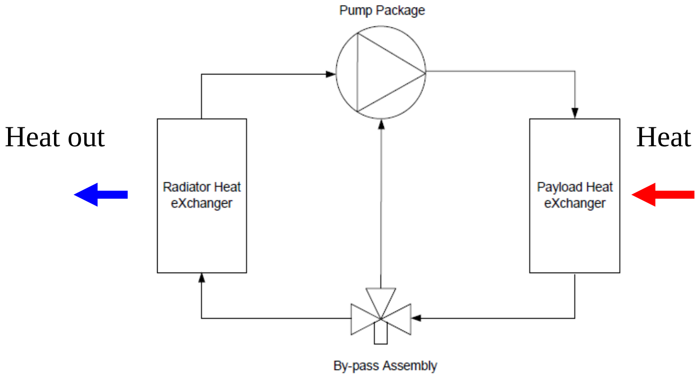
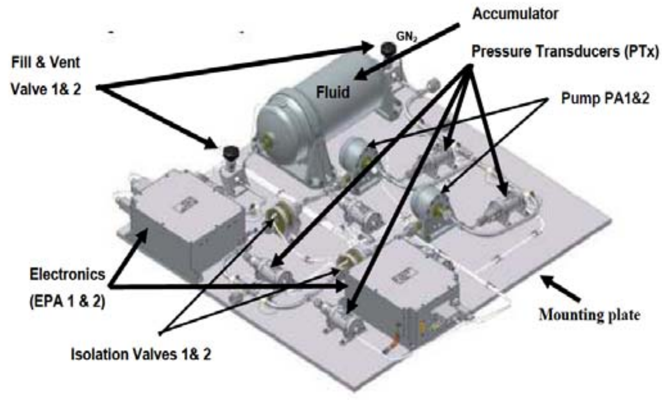


Figure 3 MPFL Subsystem operation principle

The "heart" of the MPFL is the centrifugal pump in the Pump Package Assembly operating at an almost constant fluid flow. The By-Pass Assembly regulates the flow through the RHX (and bypass) between 0% and 100% with a 3-way valve and controls the heat rejection capacity of MPFL via the radiator. The advantage of using the 3WV is that the hydraulic characteristics of the fluid loop remains almost constant during operation, minimizing the number of pump speed variations and on/off cycles. In addition, with the 3WV, the PHX temperatures can be kept within acceptable limits (for the electronics) by closing the radiators during a cold start-up or emergency cases with low dissipation and/or large variations of solar radiation on the radiators. The pump inlet temperature (mix-point) can be adjusted on-ground (via a tele-command) to control the temperature set-point of the system (ref 2.). Below the QM hardware assembly is described as outcome of the MPFL development. The QM Pump Package (Figure 4) includes the following items:

- Two parallel redundant Brushless sensor less DC (BLDC) motor driven centrifugal pumps;
- Two redundant electronics boxes for pump motor driving, speed control and for the monitoring equipment;
- A 1.8 liter fluid accumulator to control the system pressure by compensating fluid expansion caused by temperature variations;
- Two Isolation valves for selection of main or redundant branch;
- Flow, temperature and six pressure sensors.

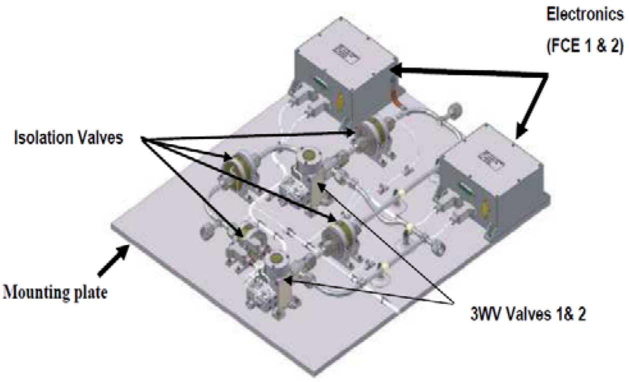


(835 x 740 x160 mm)

Figure 4 MPFL QM Pump Packages Assembly

The By-Pass Assembly (Figure 5) consists of:

- Two redundant stepper motor driven 3-way valves equipped with a position sensor and passive end-switches for housekeeping data and controls.
- Two redundant electronic boxes for valve control and monitoring.
- Four Isolation Valves for main and redundant flow control.



(715x600x90 mm)

Figure 5 MPFL QM Bypass Assembly

2.2 MPFL PERFORMANCE

The MPFL design points for a Low Power Loop (LPL) and High Power Loop (HPL) are listed in Figure 6. Focus for the design in this paper is the 3kW loop.

	LPL	HPL	
Heat Transfer	3000	6000	W
Fluid Temperature Gradient	30	30	°C
Flow	200	350	L/hr
Pressure Head	3.5	5	Bar
Pump RPM	20000	30000	RPM
Pump Power	100	200	W

Figure* 6 *MPFL design requirements for LPL & HPL

Temperature gradient is 30°C for both LPL and HPL due to the payload temperature range. The MPFL performance characteristics for the Low Power Loop (LPL) are:

- Heat removal: 3 kW, with 30°C increase of fluid temperature (e.g. > 18 kW DC payload power, with two 4.5 m^2 dual active faces Deployable Radiators);
- Piping length (Al6060 50ST) PHX 70m (i.d. 8.5mm) and RHX 90m (4*22.5m, i.d. 4.25mm tubing);
- Working point at: 3.5 Bar, 21.000 RPM, 200 l/hr (=300Kg/hr), 23% pump efficiency, ~100W electrical power. See Figure 7 for the pump performance field mapping.
- Brushless sensor less DC (BLDC) motor driven centrifugal pump* from RealTechnologie AG (Switzerland)
- Power consumption: 57 – 157 W;
- Total subsystem mass (excl. mounting plates):ca 45 Kg
    - Tubing: 8 Kg
    - Fluid: 12 Kg (• 8 liter)
    - Accumulator: 4 Kg
    - Pump Assembly: 11 Kg (excl. accumulator):
    - Bypass Assembly: 10 Kg
- Cooling fluid: H-Galden Zt85**
- System Pressure: 3.5 Bar (boiling point >120°C)
- Operational range: -50°C to +100°C;
- Non operational: -100°C to +120°C;
- Design Lifetime: >15 years.

*The breadboard pump (BBM) is operated since 2004 has a demonstrated life-time of 5 years. A similar Brush Less Sensor less DC (BLDC) motor driven centrifugal pump design from Real Technologie AG (Switzerland) has a demonstrated life time of 10 years flawless operation

**The H-Galden Zt85 was selected after a system & fluid trade-off and qualified (Ref 3) with an extensive thermal cycling test at NLR. H-Galden Zt85 is a hydrofluoropolyether manufactured by Solvay Solexis is non–explosive, non toxic fluid and has a low environmental impact. Boiling point: 85°C @ 1 Bar, Pour-point: -120°C, Density: 1.6Kg/liter @ 20°C, Heatcapacity: 1263 J/kg/K@ 20°C, Conductivity: 0.102 W/mK @ 20°C)

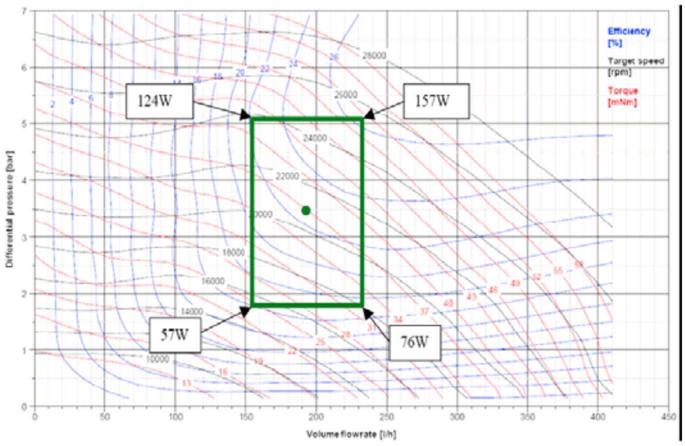


Figure 7 Working point of MPFL Low Power Loop

2.3 MPFL SCALABILITY

For future extension of the AlphaBus platform capabilities, an adaption of the MPFL architecture to higher power levels is needed. The High Power Loop (HPL) is able to transport heat up to 6 kW. Tests have shown that with the current LPL configuration a heat transfer up to 4.3 kW is achievable, simply by increasing the pump RPM, at the cost of a lower efficiency. For other then 3-4.3kW heat transport capability range a few of MPFLs components needs to be adapted. As the centrifugal pump provides flexibility to enable both low and high power operation, the pump assembly (actuator and hydromechanics part) can be identical. The following steps need to be taken to estimate which MPFL components need redesign to match the heat transfer requirements for a new application:

1. Define required heat transfer and allowed fluid temperature gradient.
2. Calculate required fluid mass flow.
3. Define pump working point (mass flow versus pressure head) preferably use a working point in the LPL – HPL range.
4. Estimate required tubing length.
5. Estimate tubing diameter (RHX, PHX) to match selected working point.
6. Estimate total coolant volume.
7. Estimate Accumulator size from operational temperature range.

A preferred approach for low power designs (<4.2kW) is to start from the LPL working point (e.g. accept the mass flow) and adjust the tubing diameter to match the pump head For lower and higher heat transfers using MPFL components, only the tubing diameter and the accumulator size needs to be adapted to cope with numerous space missions. Conclusion is that a large variety of heat transfer rates from 1kW up to 6 kW can be addressed using the currently qualified MPFL components by adjusting the pump RPM, changing the system tube diameters and/or tailoring the accumulator design.

2.4 DESIGN IMPROVEMENTS

Despite the technical progress and advantages of MPDLs the telecommunication market remains hesitative applying new cooling technologies. This is related to the following concerns with respect to pumped driven systems:

1. No proven life time of the pump for over 10 years of continuous operation.
2. Micro-meteoroid impact in radiator tubing might result in fluid loss (single point of failure)
3. Accumulator sizing related to application.
4. Insertion point for advanced cooling technologies unclear.
5. In-orbit demonstration needed.

Possible solutions for the above mentioned drawbacks are discussed below:

<u>Pump life time</u>

Demonstration of the pump life time (>15 years) is a matter of time. The BBM pump (MPFL design) already showed operation for 5 years and precursor designs are already running for over 12 years without problems. Mechanical parts of these pumps do not show any sign of degradation. It is to be expected that before the first MPFL systems are commercially introduced pump life time will no longer be an issue.

<u>Micro-meteorite protection</u>

A commercial satellite Express-AM11 from the Russian Communications Company's RSCC reported in 29 March 2006 a failure of its cooling system after almost two years of continuous operation in Geostationary orbit which has been related to "a sudden external impact". Telemetry from the craft indicates that the fluid circuit that was part of the satellite's thermal control system depressurized very rapidly. Clearly a puncture of a tube is a single point failure for these systems. (ref 4) Although it is considered as an extremely rare and very unlikely event it might be worthwhile to think about solutions to minimize the chances of a micro-meteorite or space debris impacts for pumped systems. Only external parts of the system are directly exposed to a space environment such as radiator tubing. These need to be minimized and/or need additional protection. A straightforward solution is to apply Heat Pipes in the radiators with a (protected) heat exchanger connected to MPFL. Another solution which might be applied to improve the reliability is a (partly) redundant tubing system. In case one loop fails the redundant loop takes over its function.

<u>Modular Accumulator Designs</u>

Clearly the required size of an accumulator to compensate fluid expansion scales with the loop dimensions. The idea is to apply a few standardized accumulators in the system saving qualification effort and providing some redundancy instead of a big one which needs to be qualified for each application. The design of a small accumulator is more robust with respect to the mechanical requirements. Disadvantage is that additional S/C volume/room is needed for accommodating the set of accumulators. However, the location(s) of the accumulator(s) are unrestricted with respect to the loop. A few light weight accumulators might even result in less overall mass due to thinner walls and less heavy mountings than a single big one.

<u>Insertion-point</u>

Since the requirements for cooling systems gradually increase there will be a point in time (projected >2010) that single phase cooling systems such as MPFL become an attractive addition to conventional systems such as (Loop) Heat Pipe networks. Work needs to be done for component simplification & electronics improvements that contribute to ease of operation, weight reduction and reliability will help to accelerate the acceptance of MPFL.

<u>Flight demonstration</u>

Bradford, NLR and ESA are currently looking for a flight demonstration that proves component performance in orbit which is essential for market acceptance. The components for this demonstration (MPFL FX, ref 1) are already fully prepared waiting for a flight opportunity in the nearby future.

3 QM COMPONENTS DESIGN

The status of the following MPFL QM components is briefly presented:

- Pump
- Accumulator

- Isolation Valve
- Pressure Transducer

3.1 PUMP

In the development process the most promising pump configuration matching the MPFL requirements has been selected. The Engineering Model, with a drive concept close to the later DM and QM models has verified the adaptability of the BBM design to DM and QM level. See Figure 8 for the main differences between the pump models. The pump configuration main characteristics are:

- A single stage centrifugal pump with an impeller diameter of 20mm.
- Maximum design speed of 33'000 rpm, a pressure head of 8.4 bar and a flow of 450 liter/hour with a fluid H-Galden ZT 85
- A key feature of the REALTECHNOLOGIE AG (CH) pump design is the hermetically sealed fully welded concept without any rotating parts penetrating the housing.
- Demonstrated life-time of 5 years for the BBM. Precursor design already showed 10 years of flawless operation.

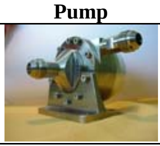
Bread Board Model Pump	**Development Model Pump**	**Qualification Model Pump**
		
• Commercial of the shelf motor and motor drive electronics • The motor is an independent, to the pump attached unit • The torque is transmitted by a magnet coupling • The hydraulic design covers 6kW thermal loop requirements	• Integrated case adapted motor design with MPFL project specific motor drive electronics • Direct torque transmission from the motor stator to the pump rotor • The hydraulic design covers 3kW thermal loop requirements	• Hydraulic and drive concept equal to the Development Model Pump • Pump outlet shifted close to the base plate • Better thermal coupling of the foot bracket to the pump housing front face

Figure 8 Main differences between the pump models

Centrifugal pumps relay on the forced increase of kinetic energy imposed to a fluid flow. Liquid which enters the pump at the centre of a rotating impeller gains kinetic energy as it moves to the outer diameter of the impeller and is forced out by the energy obtained from the rotating impeller. A centrifugal pump does not generate pressure, it simply moves liquid. The pressure rise is the result of the flow restrictions in the loop for the required flow. This makes the centrifugal pump a self adapting device which is able to survive a total hydraulic blockage for some time without a pressure limiting or overflow valve. The materials used for the QM pump are:

- Titanium Grade 5 (Ti6AL4V) for the housing parts
- Stainless steel 316L (1.4435) for the rotor
- Carbon against plasma sprayed chrome oxide ceramic for the radial bearings
- Carbon against stainless steel 316L (1.4435) for the for the axial bearing

The QM pump including the motor has a mass of 0.9 kg. The electronics box has a mass of 4kg.

With the motor drive electronics (MDE) by Bradford Engineering B.V. (NL) the pump covers the specified operating range of 230 l/hr flow and 5.1 bar pressure rise as the maximum for a 3kW thermal loop. An adaptation of the pump for a 6kW loop would only require the adaptation of the MDE. A Bread Board Model Pump life test is in progress since 2004. It has passed 50'000 continuous running hours on 7th May 2009. The following two diagrams visualize the verified operation capability of the pump.

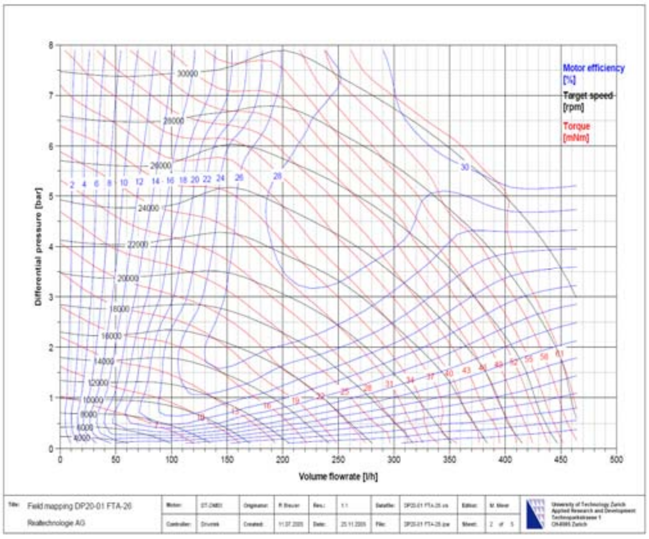


Figure 9 Field mapping of the QM pump

3.2 ACCUMULATOR

The fluid reservoir (accumulator) is an essential component for a single phase thermal control loop to control fluid expansion and system pressure. The thermal expansion of the coolant H-Galden ZT 85 over the specified temperature range dictates an accumulator working volume of 1.85 liter. The volume change is compensated with a flexible diaphragm membrane stack bellows (Figure 10) with a GN_2 gas compartment at the counter side. In the sealed, fully welded, gas compartment the GN_2 amount is constant and the pressure characteristic follows the general gas equation:

$$p \times V = m \times R \times T$$

p= pressure
V= enclosed Volume
m= mass
R= Gas constant
T= Temperature

The resulting system pressure therefore depends on the volume change of the fluid and the local temperature in the gas compartment of the accumulator. This pressure characteristic applies for the location of the accumulator in the loop which is near the pump inlet. The total loop Maximum Equivalent Operational Pressure (MEOP) is the system pressure plus the pump head due to the loop resistances.

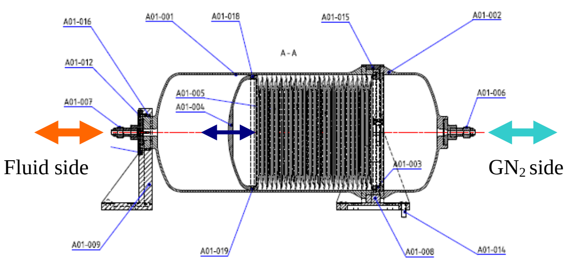


Figure 10 QM Accumulator design & picture of welded bellows

3.3 3 WAY VALVE

The 3-way By-Pass and Isolation Valves are designed and qualified by Bradford. Bradford has extensive heritage in the design and qualification of on/off valves and flow regulation valves for numerous space programs (Columbus, ATV, SOHO, MPLM). The By-pass 3-way Valve consists of a stepper motor with reduction gear box that moves the spindle up and down. The valve drive section is sealed from the fluid by means of a welded bellows. The use of bellows avoids the use of any dynamic seals in view of (up to) 15 year life time requirements. At the fluid side of the valve there are three fluid ports extending from the valve housing. A position sensor housing with end-switches is installed for detection and control of the valve position. The valve interfaces with a dedicated electronics box for TM/TC and power supply.

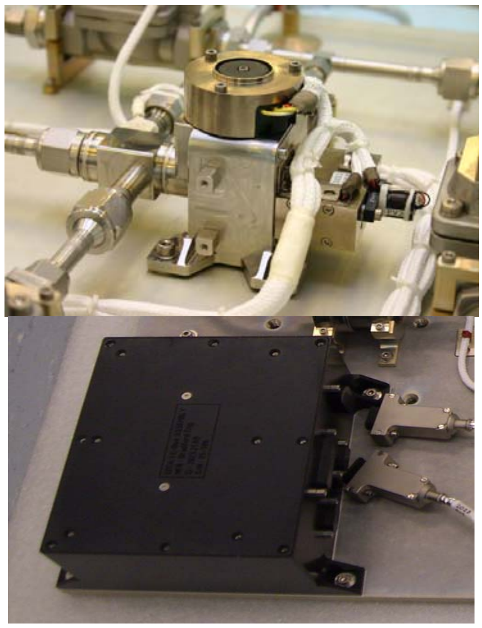


Figure 11 MPFL QM By-Pass 3-Way Valve and Electronics Box

In order to satisfy the hydraulic performance requirements, a dedicated seat-seal configuration is designed, providing a customized hydraulic resistance variation (i.e. $\Delta p / \dot{m}^2$). The valve seat is an integral part of the seat plate and consequently made of AISI 316L. The disc, which is the counterpart for the seat, is made out of glass reinforced PEEK for optimum lifetime stability. The shape of the disc is engineered to provide near-linear control in terms of number of step increments versus delta-pressure change to allow for minimum system shocks. The last part of the disc is shaped such that a reliable and leak-tight construction, with limited contact pressures, is accomplished. The motor is driven by the stepper motor drive electronics, which are integrated into the dedicated Flow Control Assembly (FCA) electronics box. The hold torque of the motor combined with the gear ratio are sufficient to prevent the valve form being driven by forces acting on the disc when fluid is passing through the valve (i.e. self-braking principle). The 3-way flow control valve includes a linear potentiometer mounted on top of the sensor housing in order to provide valve position feedback. The Flow Control Assembly (FCA) electronics provides the following functions:

- Controlling and driving the two-phase stepper motor;
- Monitoring the position of the 3-way valve;
- Monitoring the flow rate to the RHX branch;
- Provide I/F with satellite power and data handling.

3.4 ISOLATION VALVE

For selection of the pump package main or redundant branch, Isolation Valves are installed. In addition, isolation valves are installed in the By-pass assembly for selection of the main or redundant 3-way valve. The IV is a normally closed single stage valve. The single stage valve consists of a coil-actuated poppet. A single coil surrounded by a magnetic actuator attracts the poppet.

Figure 12 MPFL QM Isolation Valve

Power supply is required during the whole time, although can be reduced after opening of the valve to the “hold-down voltage”. This hold-down voltage is less than 30% of the 28 Vdc voltage required for opening the valve. Internal tightness is obtained by a PTFE (aged) sealing on a dedicated metallic seat. A spring load is applied to the poppet in order to reach the required tightness. The internal geometry is optimized to minimize pressure drop over the valve. In order to exclude external leakage, the design is fully welded.

3.5 PRESSURE TRANSDUCER & FLOW SENSOR

The MPFL selected pressure sensor is the Bradford Standard Accuracy Pressure Transducer (SAPT), qualified under ESA contract and used in various space programs. The design consists of a piezo -resistive pressure sensor and conditioning electronics. In order to enable quantitative measurement of the fluid flow rate in the loop, a delta-pressure based flow sensor is integrated into each pump branch in the pump package. Additionally, the flow sensors provide a fault indication of the pump and the inputs for the control system in case a switch-over to the redundant branch needs to be made. The flow meter consists of a defined orifice and two absolute pressure transducers before and after the Isolation Valve of each branch. The Isolation Valve seat is utilized as orifice for the measurement, in order to avoid additional pressure loss in the loop.

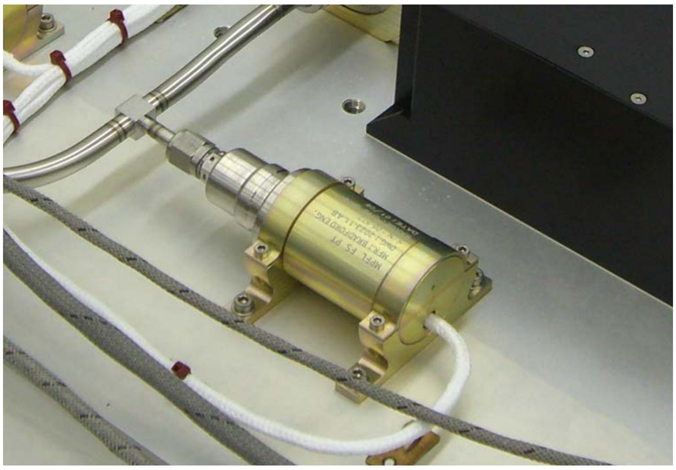


Figure 13 MPFL QM Pressure Transducer

4. QM TESTING

The following environmental tests that have been on the QM hardware are summarized below and high level described in the next paragraphs. Details about how the qualification tests are performed and discussions about the test results are outside the scope of this paper.

1. Leak Testing
2. Fluid Fill
3. Vibration Testing
4. EMC Testing
5. TV Testing
6. Performance Testing
7. Shock Testing
8. Life Testing

General conclusion of the environmental test is that the hardware is qualified for a space environment.

4.1 LEAK TESTING

Two basic methods have been applied for the leak testing of the MPFL loop components throughout the development stages and environmental testing:

1. Vacuum method
2. Sniffer method

Prior to every leak test the fluid is removed from the loop. For the vacuum test method, a dry test item is required to prevent damage to the test equipment.

4.2 FLUID FILL SYSTEM

A Fill & Vent System (Figure 14) is designed by NLR to fill and vent the assemblies with fluid and is able to measure fluid volume changes. The FVS is connected to the QM Fill & Vent Valve, has a vacuum pump, a GN_2 pressurized line and a fluid reservoir including a transparent section to monitor the fluid level.

Figure 14 Fill & Venting System as used for the MPFL tests

The Fill & Venting System was designed to:

1. fill a QM loop including assemblies and transport tubing with fluid (> 7.5 liter of fluid)measure of the total liquid within ± 20 ml.
2. be connected using flex-link.
3. be connected to a vacuum pump and is pressurized with GN_2.
4. check the accumulator operation by pressurization of the fluid.
5. be easily transported in-between test locations
6. withstand 15 bars

Since the coolant for MPFL (Galden ZT85) is non-explosive and non-toxic, no stringent measures were required for protection of the operators.

4.3 VIBRATION TEST

The MPFL QM has been vibration qualification tested against the applicable Alphabus requirements. The test was performed on components level for the critical components such as the pump, valve, electronics, and accumulator. The following requirements have been verified: For Sine Vibration, the following test levels have been applied:

Axis	Frequency (Hz)	Level
x, y, z	5 – 22	+/- 10mm
x, y, z	22 - 100	20 g

Figure 15 Sine Vibration Test Levels for Qualification

The following levels have been applied for the Random Vibration test for qualification:

Frequency (Hz)	Qual/DM/QM
20 – 80	+12 dB/oct
80 - 300	$1.5 g^2/Hz$
300 – 650	-15 dB/oct
650 - 850	$0.03 g^2/Hz$
850 - 2000	-3 dB/oct
Global	22.1 g Rms
Duration	180s

	Qual/DM/QM
20 – 80 Hz	+4 dB / oct
80 - 1000 Hz	$0.1 g^2$ / Hz
1000 - 2000 Hz	-3 dB/oct
Global	12.8 g Rms
Duration	180s/axis

Figure 16 Random Vibration Test Levels for Qualification (Z-Axis left and X- and Y-Axis right)

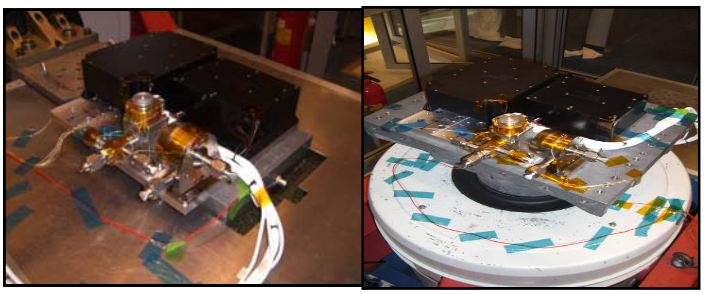


Figure 17 Vibration test setup (Z-Axis right and X- and Y-Axis left)

4.4 EMC TEST

During the Qualification test campaign a EMC test was conducted on the MPFL QM Assembly. The equipment successfully passed the tests. Tests conducted were Conducted Emission, Radiated Emission, Conducted Susceptibility, Radiated Susceptibility, Inrush Current, Voltage and Ripple Test, Electrostatic Discharge (ESD).

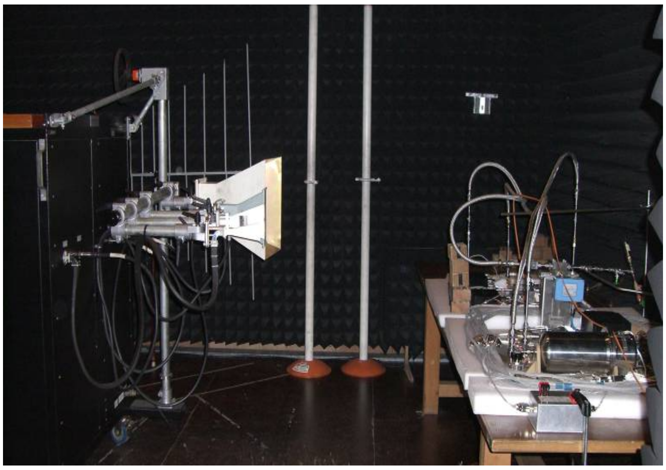


Figure 18 MPFL QM EMC Test Set-up

4.5 TV TEST

The full-redundant QM included two assemblies. The Pump Package Assembly (PPA) and Bypass Assembly (BPA) The QM assemblies were TV tested in sequence due to facility limitations and were connected via vacuum feed-through allowing for function operation during the TV test. No heater power was applied on the fluid during the TV test. One assembly is placed on a heat sink inside the vacuum chamber (see Figure 19) and the other assembly in an insulating box outside the vacuum chamber. Flex-lines and loops simulators were installed to circulate and bypass the fluid at representative pressures and for flow measurement, control and additional cooling. The TV Tests on the PPA and the BPA of the MPFL QM were successfully performed at qualification temperatures achieved for all components were.

- Non-operational: -50°C to +80°C (1 cycle)
- Start-up:-45°C and +75°C
- Operational : -20°C to +70°C (6 cycles)

(*number of cycles required by ECCS-E-10-03A p73*)

During the first operational cycle a zero-flow test by closing an external valve for 10 minutes is started at a level of 15°C. The pump remained below 95°C during this test well below the maximum design temperature of 150°C.

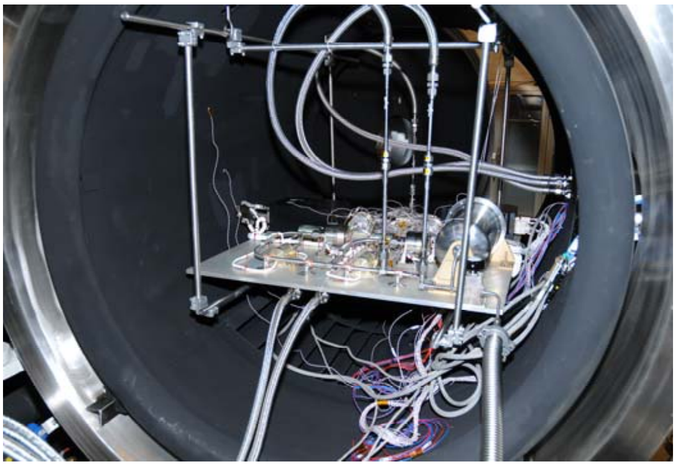


Figure 19 MPFL QM PPA in the thermal vacuum chamber

After applying vacuum to the chamber one non-operational cycle is performed. First the assembly is heated (for out-gassing) followed by a hot start-up (pump at nominal RPM) with the external valve open. After switching off the pump the assembly is gradually cooled down. When cold a cold start-up (pump at nominal RPM) is conducted again with the external valve closed. After the non-operational cycle, operational cycles were performed while heating or cooling the assembly between the operational temperature extremes. At the temperature extremes a Functional Test of the pumps and BPA was conducted. These temperatures were held for at least two hours stabilization time. During the last hot cycle the PP assembly is stabilized for at least 8 hours at the hot operational temperatures.

4.6 PERFORMANCE TEST

The Loop Performance Test on the MPFL QM was successfully performed at NLR. The LPT test consisted of two ambient functional checks, a cold, nominal and hot operation test at a 3000W load. For LPT the QM MPFL hardware was connected to a full-scale 3KW loop system simulating the Payload and Radiator heat Exchangers (see Figure 20). The same set-up is used for the life test. (Section 4.8)

Figure** 20 **Loop performance test setup

The main objective of the loop performance tests was verification of the thermo-hydraulic requirements. The tested loop is representative for the MPFL LPL design in terms of tube length, fluid flow and volume and thermal expansion. The set-up measured the heat transfer capability, thermal gradients, flow, pressure differences and electrical power consumption. Test cases were defined for performance verification @ 10, 30, 50°C mix-point temperatures for a 3000W load with ΔT_{phx}<30°C and corresponding valve positions at X=100%, 63%, 50% radiator flow respectively, as determined from thermal modeling. See Figure 21 for a graphical representation of the test cases with respect to the predicted systems performance as function of the mix-point temperature (combining radiator and bypass flows at the pump inlet) for a 4.7m^2 dual face radiator taken into account seasonal variations with respect to operational requirements (solid black line)

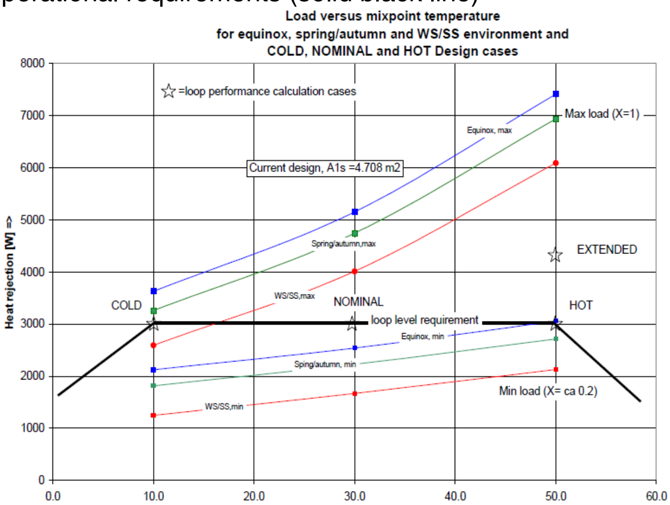
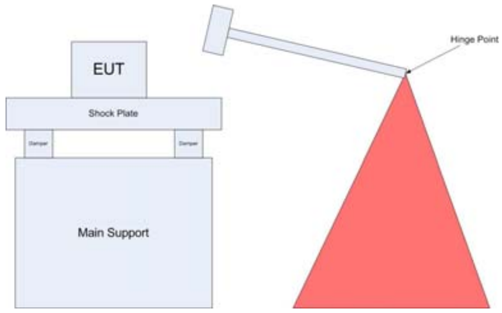


Figure 21 Test cases (indicated with stars) related to mix-point temperature [°C] and heat rejection [W]

4.7 SHOCK TEST

The shock tests were performed on equipment level and on the components rated potential susceptible for shock. The following equipment was tested: Pump, Three-Way Valve, Pump Electronics Box and Three-Way Valve Electronics Box. The test was conducted by means of a mechanical shock by an impact hammer. The impact spectrum was characterized on dummy masses prior mounting the Qualification Models. The test has been repeated for each individual axis.



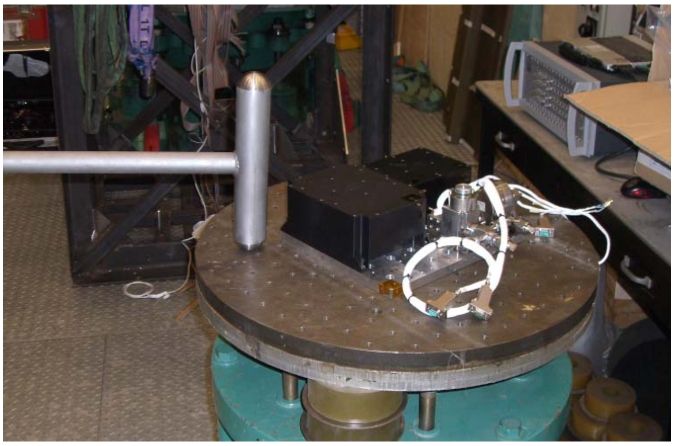


Figure 22 MPFL QM Shock Test Set-up

The Out-of-Plane (OOP) and In-Plane (IP) requirements for the shock test are given in Figure 23 and with a dotted line in Figure 24 and Figure 25. Due to the partly unpredictable nature of the hammer hit it appeared difficult to precisely obtain the required levels for all frequencies but the overall envelopes could be approached well enough. See the solid lines in Figure 24 and Figure 25 for the achieved levels.

OOP		IP	
Freq[Hz]	Level (g)	Freq[Hz]	**Level (g)**
100	15	100	**15**
2850	1300	1200	**800**
5000	1300	5000	**800**
10000	**800**	**10000**	**600**

Figure 23 Shock level requirements

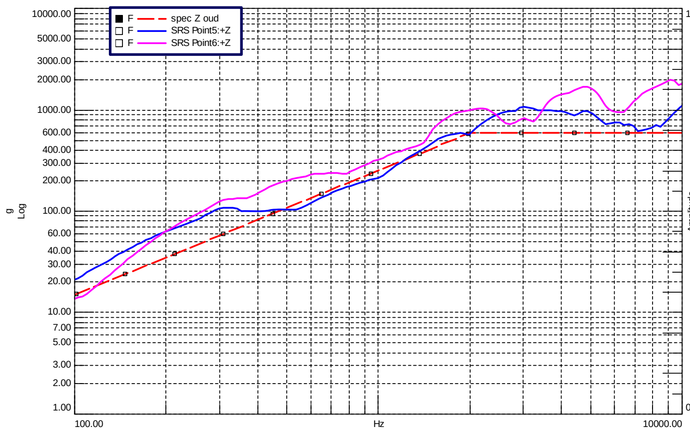


Figure 24 Required (dotted line) and achieved levels for the Z-Axis Shock Test (IP)

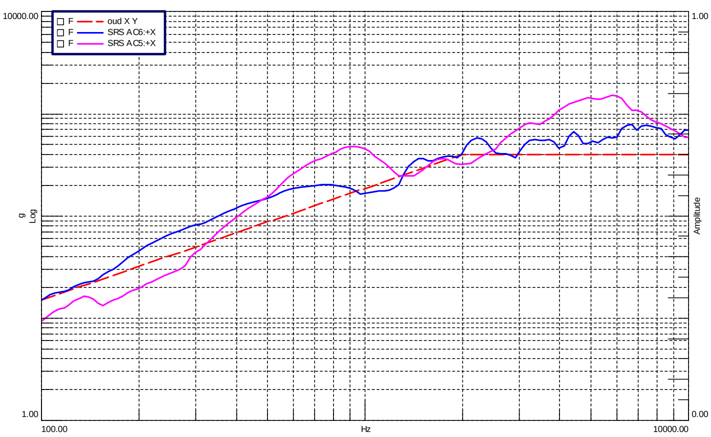


Figure 25 Required (dotted line) and achieved levels for the X- and Y-Axis Shock Test (OOP)

4.8 LIFE TEST

The life test is currently being performed at this moment (April 2009) at NLR. See Figure 26 for the life test sequence. The Life test setup is identical to the loop performance test setup (section 4.5). The life test loop is fully representative for the MPFL loop design as far as practically possible in terms of tube length and applied materials, fluid flow and volume and thermal expansion. The pump and valve are expected to operate without interruption for a period of one year at ambient conditions. Pump speed levels between 15.000-25.500 RPM are tested for a period of 10 weeks whereas the valve is continuously operated 20.800 times from 0-100-0% e.g. 12.4 cycles per hr The life test was successfully started in March 2009 with 200 on/off cycles at three specified temperature levels at -40°C, +20°C to + 70°C. The 3WV cycle tests at increasing pump speed is continued until March 2010. Fluid samples before and after the life test will be examined. All components will be visually inspected afterwards.

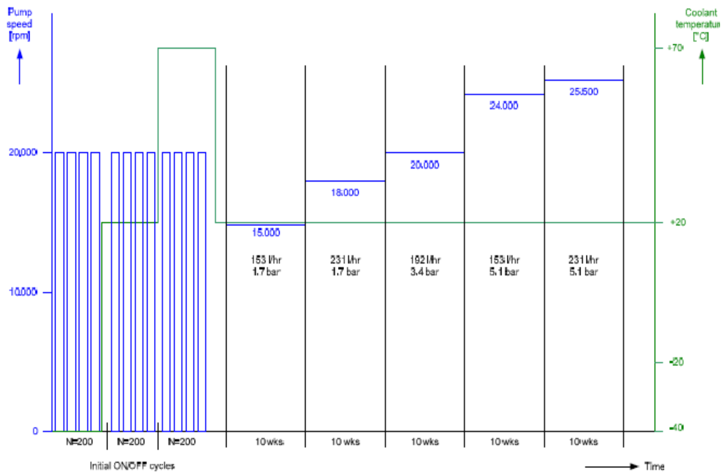


Figure 26 Test sequence accelerated life test of MPFL QM during 2009-2010

5. RECOMMENDATIONS

To increase the maturity of MPFL the focus in the upcoming period is on the pump and valve (extended) life test. Work on a flight demonstration is considered necessary to promote market acceptance of MPFL components. Further the vulnerability to micro-meteorites of extended loop systems such as MPFL can be reduced by minimizing the external exposure of the tubing by combination with HPs on the radiator. Also the flight qualification effort can be reduced using a (set of) standard accumulator(s) for several system sizes. All this leads to qualified MPFL components to be applied for space cooling systems were heat transfers up to 4.2 kW are needed. For the 6kW loop the accumulator needs to be enlarged and qualified based on the existing design. Also the pump needs to demonstrate a high operational speed up to 30000 RPM over its lifetime.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

3WV	3 Way Valve
BBM	Bread Broad Model
BPA	Bypass Assembly
DM	Development Model
EMC	Electro Magnetic Current
ESA	European Space Agency
ESD	Electric Spark Discharge
EVA	External Vehicle Activity
FCA	Flow Control Assembly
FVS	Fill & Vent System
HP	Heat Pipe
HPL	High Performance Loop (6kW)
IP	In Plane
IV	Isolation Valve
(L)HP	(Loop) Heat Pipe
LPL	Low Performance Loop (3kW)
LPT	Loop Performance Test
MPDL	Mechanical Pump Driven Loop
MPFL	Mechanically Pumped Fluid Loop
NLR	National Aerospace Laboratory NLR
OOP	Out-of-Plane
PHX	Payload Heat eXchanger
PPA	Pump Package Assembly
RHX	Radiator Heat eXchanger
SAPT	Standard Accuracy Pressure Transducer
TV	Thermal Vacuum Test
QM	Qualification Model