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Sensors and components for aerospace thermal control and propellant systems

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ABSTRACT
Various aspects of different sensors and components, (being) developed or fine-tuned for aerospace thermal control and propellant systems, are discussed, i.e.: rotatable radial heat pipe joints, vapour quality sensors, controllable valves, condensers, flow metering assemblies and propellant gauges.

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ABSTRACT

Various aspects of different sensors and components, (being) developed or fine-tuned for aerospace thermal control and propellant systems, are discussed, i.e.: rotatable radial heat pipe joints, vapour quality sensors, controllable valves, condensers, flow metering assemblies and propellant gauges.

INTRODUCTION

Aerospace heat transport systems and propellant systems incorporate different sensors and components. Some are spatialised versions of existing terrestrial hardware, others are dedicated direct developments for space.
Various aspects of different sensors and components (being) developed or fine-tuned will be discussed in detail: background, applications foreseen, design, and terrestrial and (low-gravity) performance data.
The particular sensors and components, developed for ESA and NIVR (Netherlands Agency for Aerospace Programs), are:

- Rotatable Thermal Joints, to be used to minimise the temperature drop between e.g. a spacecraft thermal bus and a deployable or steerable heat pipe radiator, the latter resulting in minimum radiator size and mass.
- Vapour Quality Sensors, to measure or control the vapour quality (vapour mass flow ratio) of a flowing vapour/liquid mixture in the lines of mechanically (or capillary) pumped two-phase heat transport systems and propellant systems.
- From the Vapour Quality Sensor derived Propellant Gauges, to accurately measure the remaining level of the fuel (e.g. Mono Methyl Hydrazine) or oxidizer (Mixed Oxygen Nitrides) in the propellant tanks of spin-stabilised spacecraft.
- Flow Metering Assemblies, to measure and control the flow rate in aerospace life science systems and single or two-phase thermal control loops and to assess, by integrating the consumption during lifetime, the remaining level of fuel or oxidizer in the propellant tanks of three-axes stabilised spacecraft.
- High Efficiency Low Pressure Drop Condensers for direct or indirect condensation spacecraft radiators.
- Controllable (motorised, three-ways) Valves, to be used in single or two-phase loops to control fluid temperature setpoint, flow rates, pressure drop, vapour quality, etc.

ROTATABLE RADIAL HEAT PIPE JOINT

Recalling the discussions in reference 1, it is remarked that dedicated heat pipe radiators can be used to reject (spacecraft) waste heat into space. Such a radiator, if stowed during launch, has to be deployed in orbit (Fig. 1, Ref. 2). The radiator may even be chosen to be steerable to achieve maximum performance, hence minimum radiator size and mass.
In such radiator systems, the coupling to the central (two-phase) loop or heat pipe has to incorporate a rotatable/flexible thermal joint. Drivers for the design of such joints are low thermal resistance, hence limited temperature drop across the joint, and small deployment/retraction or steering torque.

A quantitative discussion on several moveable joint concepts (Fig. 2) identified the rotatable radial heat pipe to be a promising solution for steerable radiators (Ref. 1). Figure 3 shows a schematic of a possible rotatable radial heat pipe configuration.

An essential component is the wick configuration necessary to provide the capillary head to return the condensate from condenser to evaporator and to distribute the liquid properly over the evaporator surface. Therefore the fine gauze wick structure should be uniformly fixed to the evaporator surface, in the figure the outer surface of the inner tube. In this way burn-out, caused by blockage due to vapour bubbles

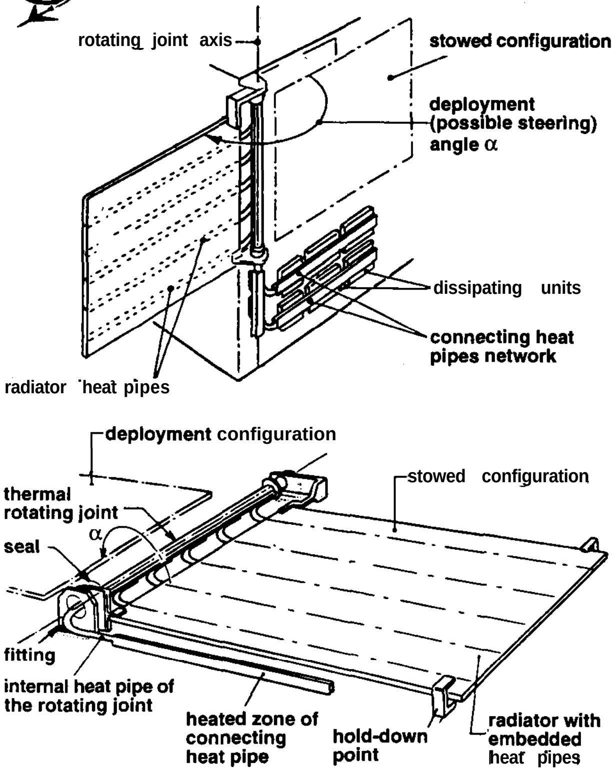


Fig. 1 Typical deployable/steerable radiator and joint configuration [Ref. 2]

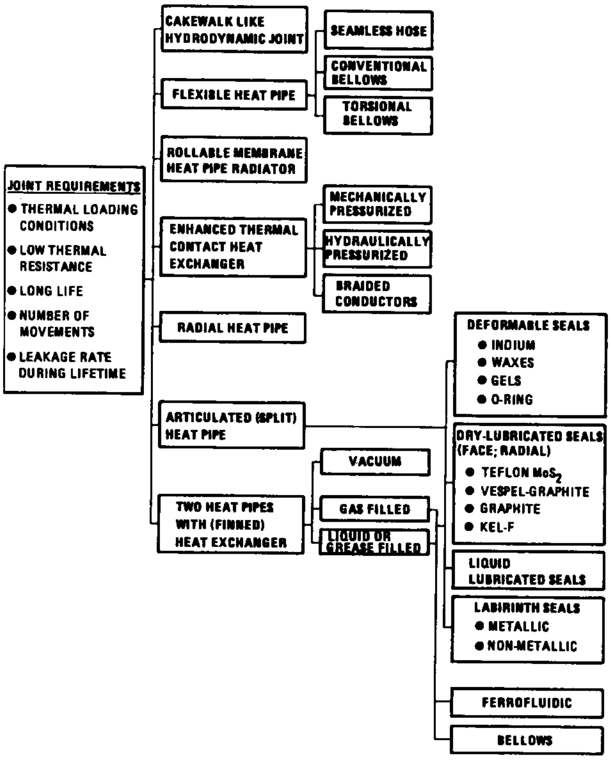


Fig. 2 Joint concepts [Ref. 1]

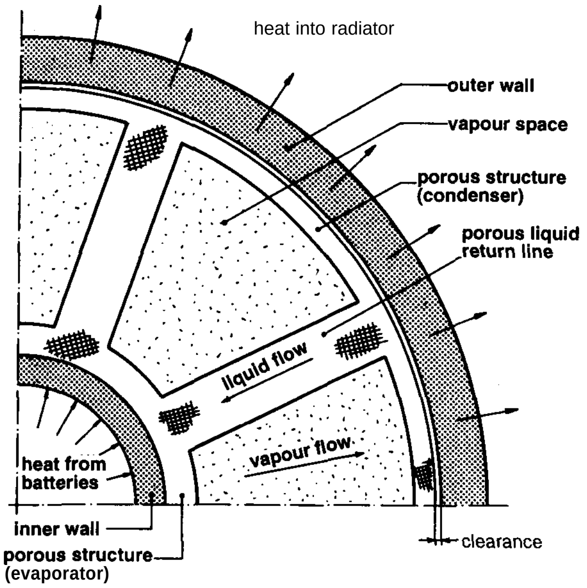


Fig. 3 Cross-section of a radial heat pipe joint [Ref. 1]

generated, is prevented. Since the outer tube must be rotatable with respect to the inner tube there must be a clearance between the porous structure and the tube wall. This clearance is located at the condenser, the less critical side of the heat pipe, where the condensate has to be collected only (a relatively easy task especially if the heat pipe is slightly overfilled with working fluid). An accurate design will combine proper condensate collection and transport, hence good heat pipe performance, and a low rotation torque, hence a long lifetime even for a steerable radiator.

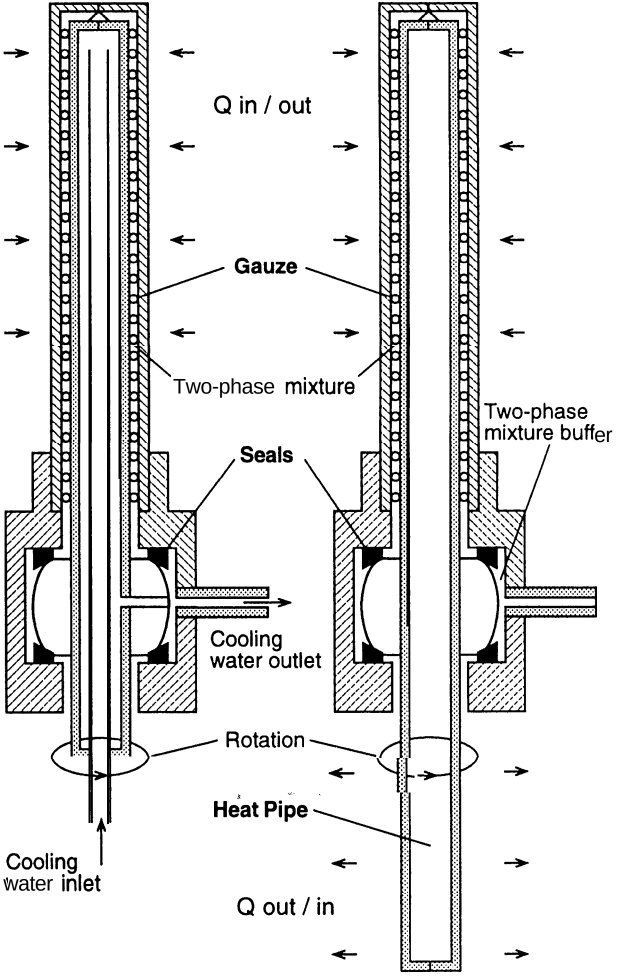
It is obvious that the end caps of a rotatable radial heat pipe must be leak-tight. This problem must be solved using appropriate seals.

The thermal performance of a radial heat pipe is hard to predict. A rough estimate can be derived from flat plate vapour chamber data i.e. a heat transfer coefficient up to 4000 W/m^2. K, for methanol as the working fluid, within the temperature range 250 to 305 K. For a radial heat pipe joint wit an external diameter of say 4 cm this means a conductance of 500 W/K per meter joint length.

To prove the feasibility of the joint concept, a simple 100 mm long test specimen has been manufactured (Fig. 4a), simulating the realistic configuration shown in figure 4b.

consists of:

- An inner tube (10/12 mm), cooled by liquid flow (simulating the heat pipe).
- An outer tube (13/15 mm), heated by a heater (simulating the real heat source, e.g. a condensing two-phase mixture).



a) Test specimen b) Actual configuration

Fig. 4 Rotatable radial heat pipe joint

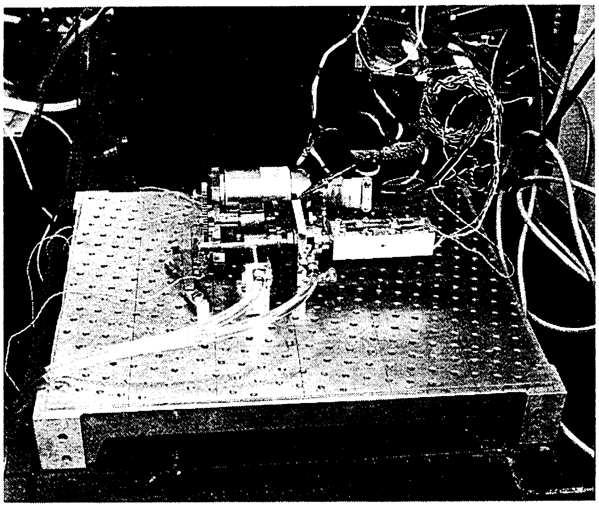


Fig. 5 Rotatable radial heat pipe joint (length=100 mm, average diameter=12.5 m, working fluid: R114)

- A rotatable section (ball valve) allowing the outer and inner tube to rotate with respect to each other.
- The 0.5 mm spacing between the two tubes containing a metal gauze (simulating the wick) and a working fluid (R114).

Figure 5 shows a photograph of the test setup.

Figure 6 presents the results of a test to determine the optimum working fluid content. Starting with pure liquid, the temperature drop across the joint is close to 13 °C. By stepwise blowing off part of the R114, the above temperature drop is reduced down to a minimum of 7 °C, at the optimum mixture quality. Continuation of the blowing off causes increase of the temperature drop up to a maximum value around 26 °C (pure vapour conduction and/or solid conduction of the gauze). The optimum joint conductance is 3 W/K for this 0.1 m long, say 13 mm diameter R114 joint, which means roughly 600 W/K for the above mentioned 40 mm diameter, 1 m long methanol filled joint, and consequently approximately 1500 W/K if ammonia is the working fluid.

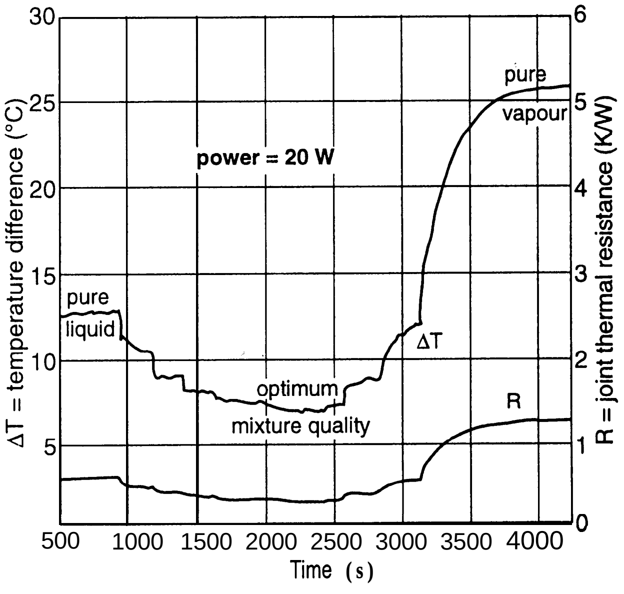


Fig. 6 Determination of optimum filling

Figure 7 presents the (optimally filled) joint performance during rotation (at 17 revolutions per hour) and in non- rotating periods, for different power values (45, 35 and 20 W).

The figure clearly confirms the aforementioned joint conductance value both for the rotating and non-rotating case. This conductance, showing the more stable values in the non-rotating case, increases slightly with power (temperature) level.

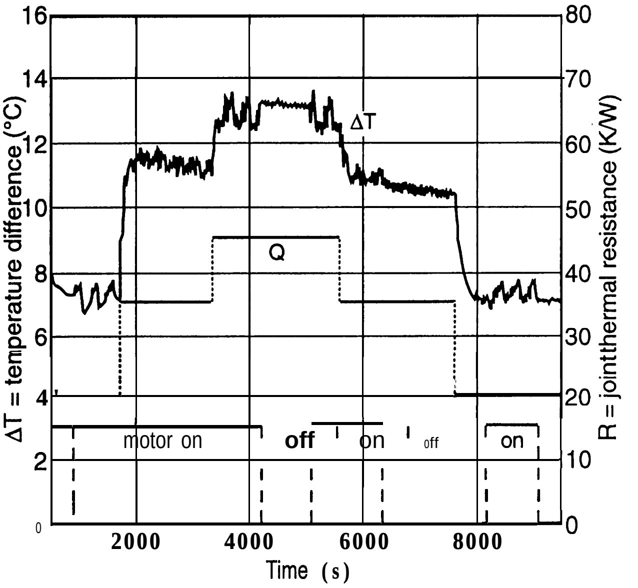


Fig. 7 Power dependence of joint resistance (non-rotating and rotating at 17.5 rpm)

Summarizing: the concept is feasible: the joint did not show leakage, the performance figures are promising. Seal improvements and the use of a buffer volume (also filled with the working fluid at approximately the same heat pipe temperature) are expected lead to the realisation of a mature long lifetime rotatable radial heat pipe joint.

VAPOUR QUALITY SENSOR

Thermal management systems for future large spacecraft must be able to transport large amounts of dissipated power over large distances. Conventional single-phase heat transport systems (based on the heat capacity of the working fluid) are simple, well understood, easy to test, relatively inexpensive and low risk. But to realise a proper thermal control task with small temperature drops from equipment to radiator (to limit radiator size and mass), they require noisy, heavy, high power pumps and large solar arrays.

As an alternative for these single-phase systems one currently considers mechanically pumped two-phase systems, being pumped loops which accept heat by evaporation of the working fluid at heat dissipating stations (cold plates, heat exchangers) and release heat by condensation at heat demanding stations (hot plates, heat exchangers) and at radiators, for rejection into space. Such a system relies on heat of vaporisation: it operates nearly isothermally and the pumping power is reduced by orders of magnitude, thus minimising the sizes of radiators and solar arrays.

The stations can be arranged in a pure series, in a pure parallel or in a hybrid configuration. The series configuration is the simplest, it offers the possibility of heat load sharing between the different stations, with some restrictions with respect to their sequence in the loop. However, it has limited growth potential and the higher flow resistance.

In the low resistance modular parallel concept, the stations operate relatively independently, thus offering full growth capability. However, the parallel configuration is more complicated, especially when redundancy and heat load sharing (some cold plates operating in reverse mode) is foreseen. In addition, a parallel configuration requires a control system consisting of various sensors, monitoring the loop performance at different locations, control logic and actuators to adjust e.g. pump speed, fluid reservoir content and throughputs of valves. Sensors necessary for control are pressure gauges, flow meters, temperature gauges and vapour quality sensors (Fig. 8), measuring the relative vapour mass content of the flowing mixture (Refs. 3, 4). An important application for Vapour Quality Sensors (VQS) is at the cold plate exits, as a part of a control (sub-) system adjusting the liquid fed into a cold plate to prevent evaporator dry-out or to maintain a prescribed quality value at evaporator exits, independent from transient heat sources and heat sink conditions (Fig. 9).

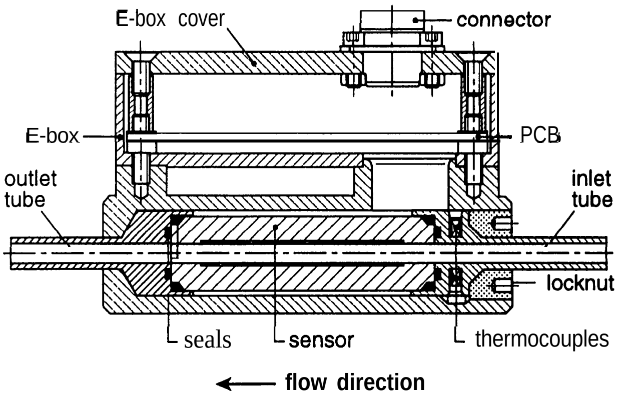


Fig. 8 TPX 11 Vapour Quality Sensor

As two-phase flow characteristics and heat transfer differ when subjected to a 1-g or a low-gravity environment (Refs. 4 to 6), the technology of such two-phase heat-transport systems and their components has to be demonstrated in orbit. Therefore, a Dutch Belgian two-phase loop experiment (TPX) has been developed within the ESA In-orbit Technology Demonstration Programme TDP 1, by NLR (NL, prime contractor), SABCA (B), Fokker Space (NL), Bradford

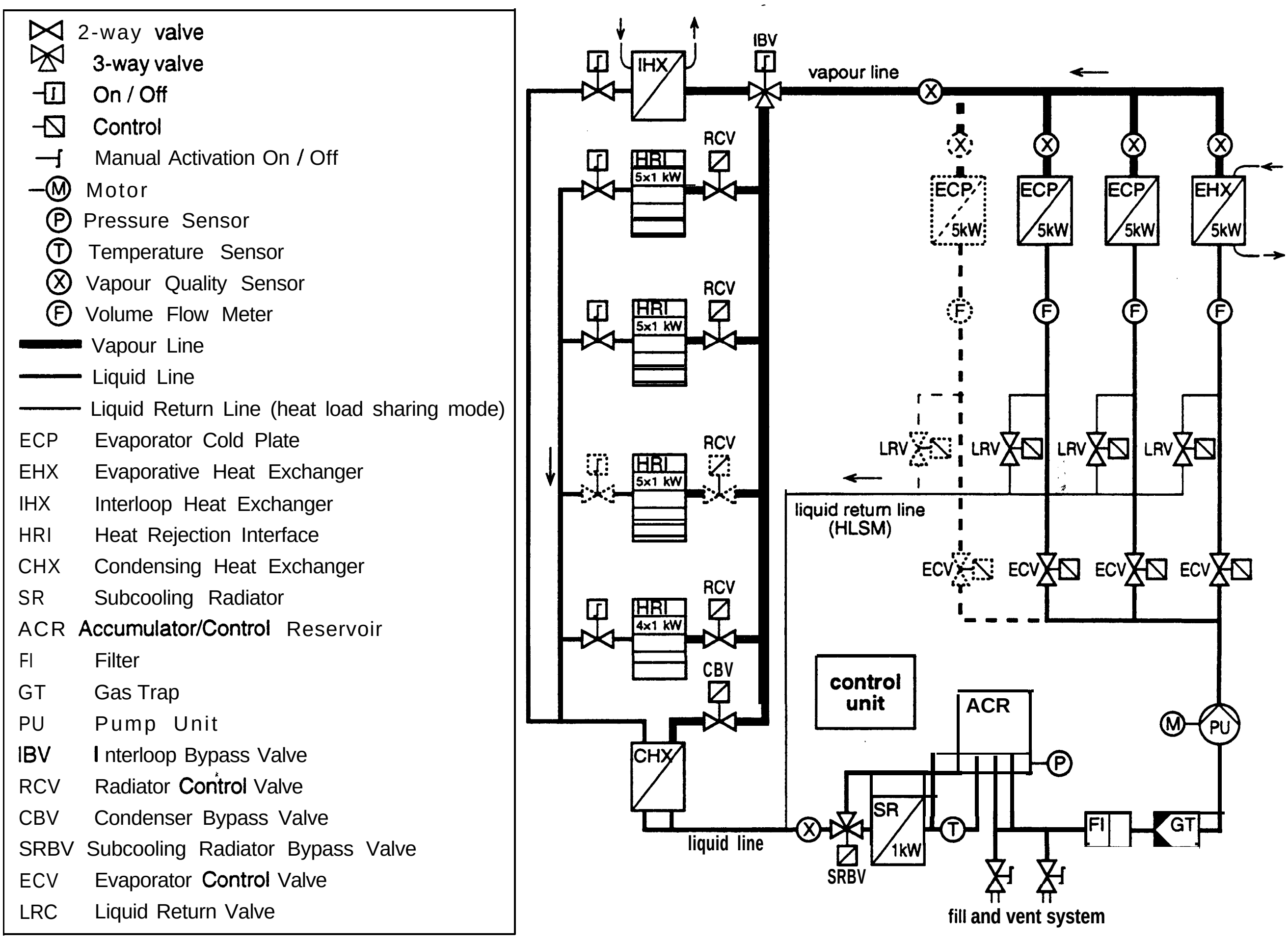


Fig. 9 Two-phase heat transport systems reference configuration

Engineering (NL) and Stork Products Engineering (NL). The flight experiment is a scaled-down capillary pumped two-phase ammonia system together with scaled-down components of a mechanically pumped loop: multichannel condensers, vapour quality sensors and a controllable three-way valve.

The baseline of the experiment is schematically depicted in figure 10.

The complete experiment, integrated into a Get Away Special (GAS) container (5 ft^3, gaseous Nitrogen filled), has successfully flown as G557 aboard the US Space Shuttle (STS-60) in February 1994. The experiment has run autonomously, using own power supply, data handling and experiment control after a switch-on command from the Shuttle crew.

One of the objectives of TPX was the calibration of the VQS in orbit. This was done by setting the vapour quality for VQS 11 by adjustment of the three-ways controllable valve (Swalve), mixing the by-passed vapour and the liquid leaving the condenser.

Figure 11 depicts the in-orbit test results, which considerably differ from the terrestrial VQS calibration curves (Fig. 12) obtained in the NLR ammonia test rig.

This VQS, with updated electronics, will refly on TPX 11, the follow-up of TPX, early 1998, as Get Away Special G467 aboard STS-89 or STS-90. Figure 13 shows the TPXII schematic.

APS	Absolute Pressure Sensor
DPS	Differential Pressure Sensor
E_c	Cylindrical evaporator
E_f	Flat evaporator
EMP	Experiment Mounting Plate (GAS canister lid)
GAS	Get Away Special
LFM	Liquid Flow Meter
$\dot{m}$	Mass flow
T_c	Temperature condenser
T_v	Temperature vapour
T_l	Temperature liquid
VQS	Vapour Quality Sensor

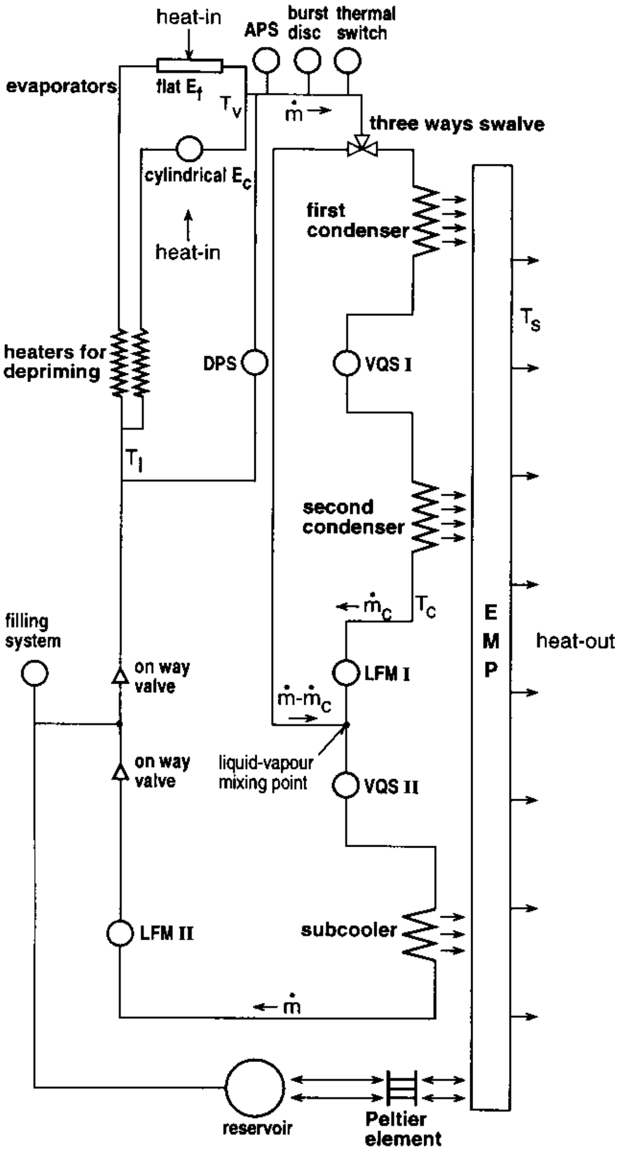


Fig. 10 TPX baseline

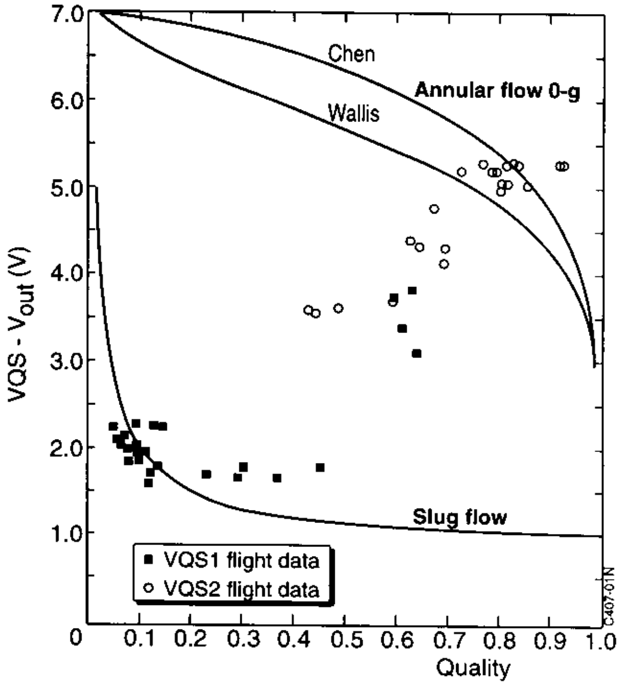


Fig. 11 VQS 0-g theoretical responses and flight data

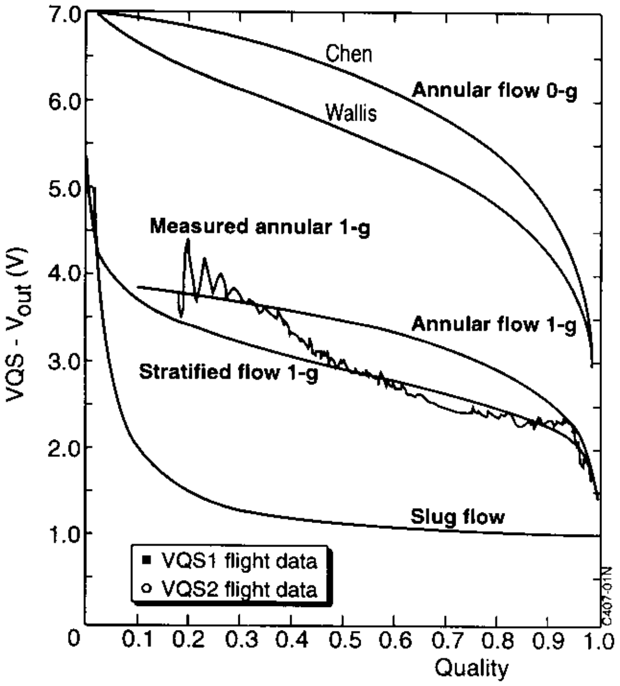


Fig. 12 Terrestrial VQS calibration curves

APS	Absolute Pressure Sensor
DPS	Diff erential Pressure Sensor
CV	Controllable 3-way Valve
TV	Vapour Temperature
T_ℓ	Liquid Temperature
EMP	Experiment Mounting Plate (GAS canister lid)
GAS	Get Away Special
LFM	Liquid Flow Meter
ril	Mass flow
$\dot{m}_C$	Flow Rate in Condenser Branch
Q_{EF}	Flat Evaporator Heater Power
Q_{EC}	Cylindrical Evaporator Heater Power
Q_{COND}	Condenser Imbalancing Power
VQS	Vapour Quality Sensor

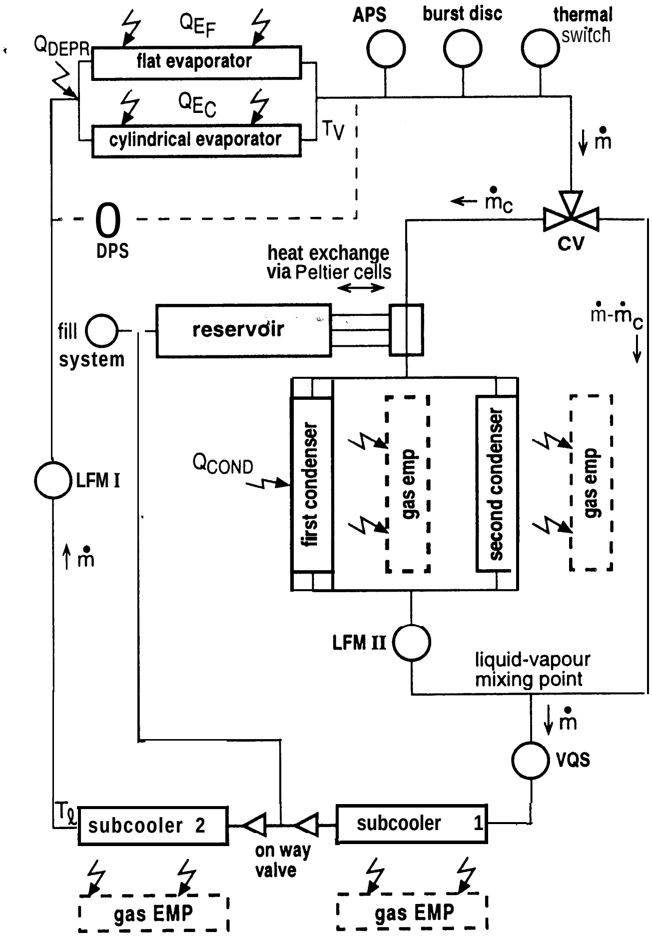


Fig. 13 TPX 11 schematic

CONTROLLABLEVALVE

Control exercises with VQS and Swalve forseen in TPX could not be carried out because the vapour quality control setpoint chosen turned out to lie in the unstable churn flow pattern regime (Fig. 11).

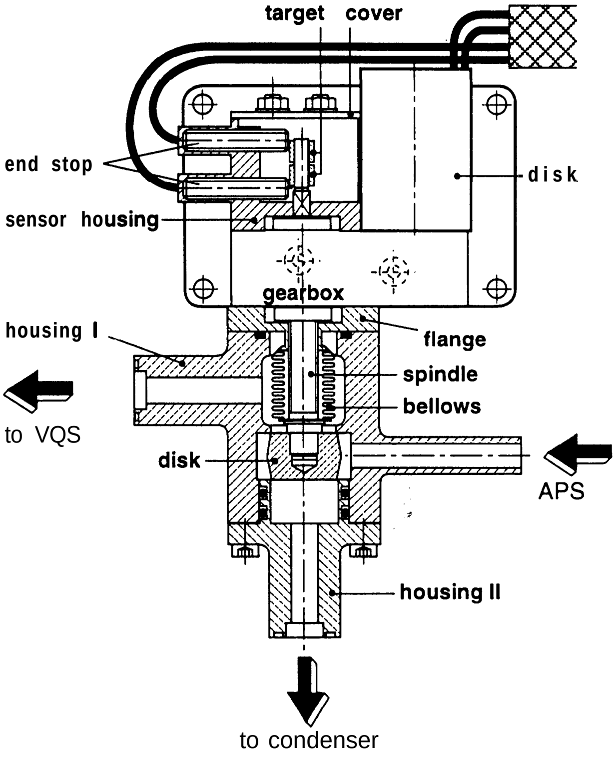


Fig. 14 TPX 11 Controllable Valve

The control excercises will be redone in TPX 11 for control around two quality setpoints, one in the slug flow regime, the other in the annular flow regime.
The TPX 11 Control Valve is depicted in figure 14.
Figure 15 shows a schematic of the ammonia test rig used to assess the valve characteristics to control not only vapour quality, but also a pressure drop across a flow resistance.

CONDENSERS

High efficiency low pressure drop condensers/radiators are important components in spacecraft two-phase heat transport systems.
Two possible radiator solutions can be distinguished:

- One for a direct condensing radiator: the condenser is directly attached to the radiator surface, radiating the condensation heat into space.
- One for a hybrid condenser radiator, where the condenser is not an integrated part of the radiator. The condensation heat is transported from the condenser via a central heat pipe to heat pipes that distribute the heat over the radiator surface.

Direct condensing radiator

Two direct condensing radiators have been designed and manufactured for the ATLID Laser Head Thermal Control Breadboard (Fig. 16), developed for ESA by

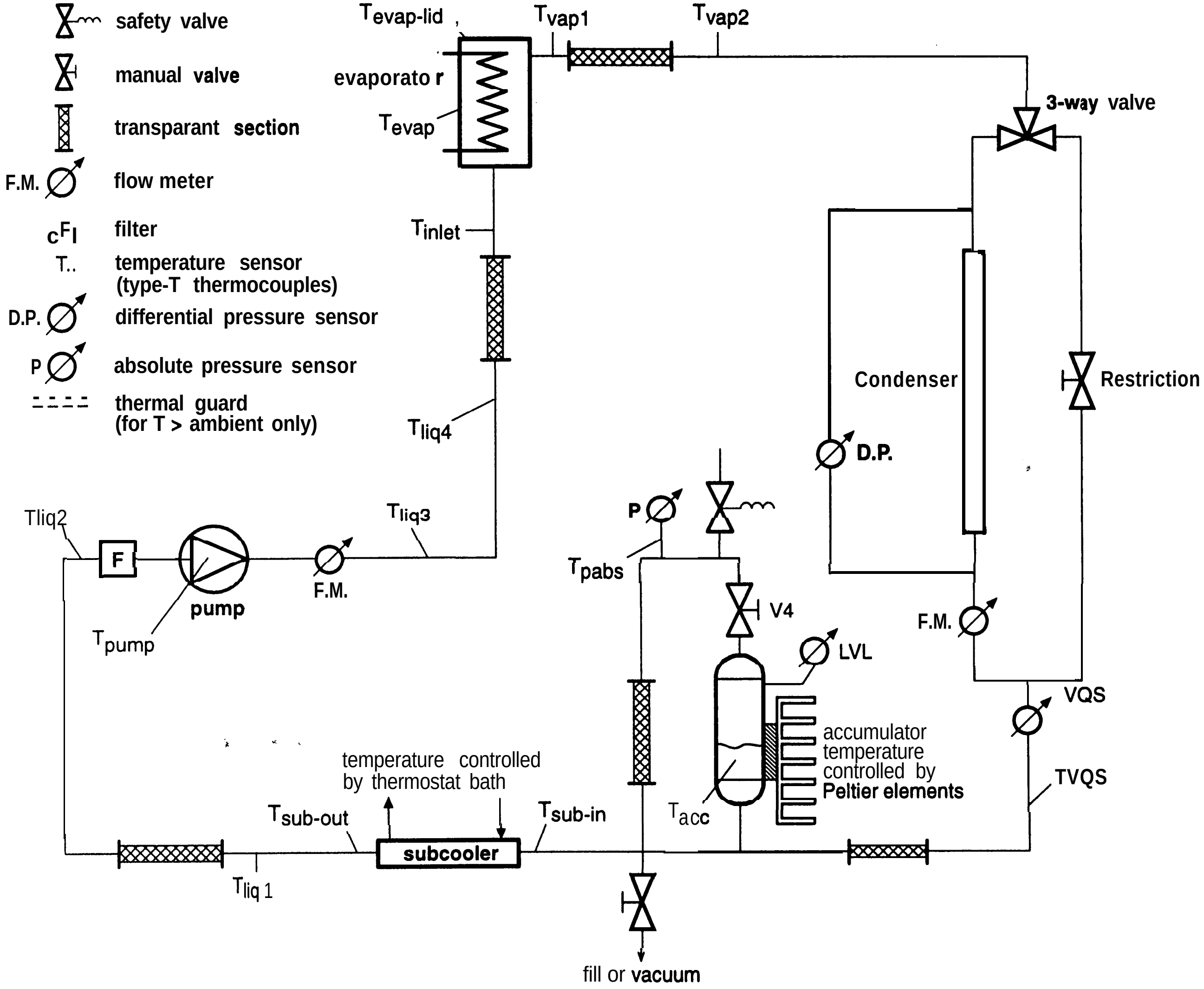


Fig. 15 NLR ammonia test rig for CV control tests

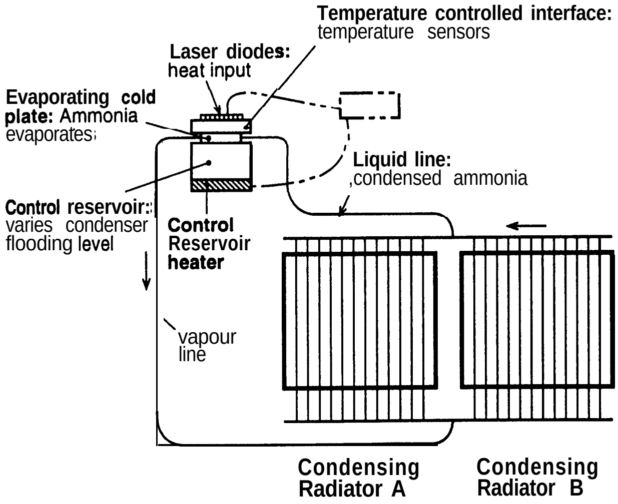


Fig. 16 ATLID laser head thermal control schematic

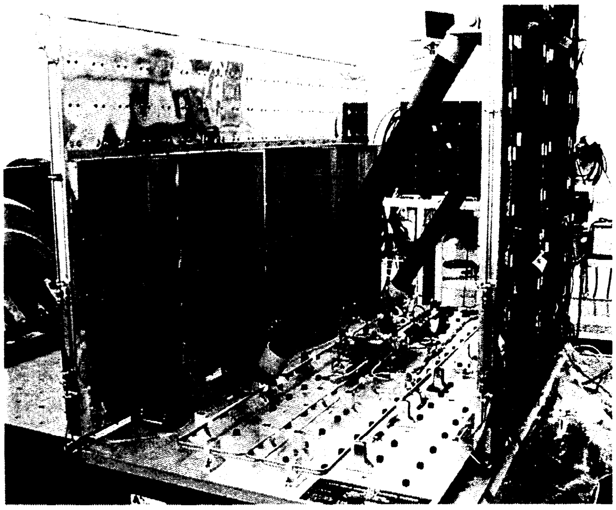


Fig. 17 ATLID breadboard hardware

MSS-UK (prime), NLR and Bradford (Ref. 7). Figure 17 shows the actual breadboard during the vibration test. The two radiators are configured to represent the allowable accommodation areas for the ATLID instrument on the Polar Platform.

One radiator 1.05 m x 1.0 m (called radiator A) is fixed to the instrument baseplate and supported by struts, while the other radiator (B), 0.8 m x 1.45 wide, is deployable and fixed only along its edge, using cantilever beams for support. The struts for radiator A are constructed from filament wound carbon fibre tubes with aluminium end fittings. The cantilever beams of radiator B are 10 cm deep to give adequate stiffness. The radiators are too small to reject the heat load in steady state conditions. They are only just capable of meeting the heat rejection requirements when a full orbital cycle is considered.

The radiator B deployable design incorporates a unique torsion/helical bending configuration to minimise pipe strain and allow multiple repetition of the deployment. Although the instrument requires deployment only for ground access, the design is equally suitable for flight deployment.

The radiator surfaces would for flight be covered with advanced glass OSR's to give low beginning and end of life solar absorptivities. For the breadboard tests sunlight has been simulated by altering heat sink temperatures. The radiators are simply black painted.

The radiators are constructed from extruded aluminium profiles rivetted together to form a continuous surface. Each profile section contains one 2 mm internal diameter condensing pipe, clamped into good thermal contact with a Channel in the extrusion. Isolators in each liquid line and one at the liquid header outlet ensure even vapour distribution and prevent differential dryout. The rivetted construction provides stiffness in two axes. The remaining axis is stiffened by the addition of a beam crossing all the profiles.

The ATLID test programme conclusions, given in reference 7, report the following achievements:

- The two-phase system is treated as just another thermal tool which must conform to installation, accommodation and structural requirements imposed by the overall instrument.
- The system has successfully completed severe sine and random vibration tests to qualification levels.
- The deployable radiator concept has been demonstrated.
- The tests have demonstrated that the ATLID breadboard meets or exceeds nearly all its performance requirements. In particular the principal requirement to maintain the laserdiode interface to within 1 °C of nominal temperature during simulated low earth orbits was met with a significant margin. Due to restrictions on radiator area the end of life heat rejection performance only just meets the requirements, and some additional margin is recommended.
- Some modifications will be necessary if the 125 Hz first radiator frequency is to be met for the actual flight units, but these have been identified and are not considered critical.

Detailed information can be found in the aforementioned reference.

Hybrid condenser

For ESA, a high efficiency low pressure drop condenser (Fig. 18) for a hybrid (heat pipe) radiator has been successfully developed, analyzed and brought up to pre-qualification level, by NLR (prime), Bradford and Daimler Benz Aerospace RI (Ref. 8). This condenser has been subjected to tests in the test rig (Fig. 19) under conditions reflecting as close as possible realistic in-orbit conditions, i.e. a vapour temperature in the range - 10 to 40 °C for a condensed power up to 300 W.

The tested hybrid condenser design (Fig. 20), consists of a concentric tube around a liquid cooled inner tube, simulating the heat pipe. Vapour entering the condenser is uniformly distributed by a cone. The condensing part is an annulus with inner 25 mm and outer diameter 28 mm, hence the gap width is 1.5 mm. Six wires with a diameter of 1.5 mm subdivide the annulus into six parts. The wires are coiled around the central tube, leading to helical condensation channels, that provide a desired swirling to improve the performance.

The tests confirmed the quality of the condenser design, being a good compromise between high-efficient thermal performance and low pressure drop (Fig. 21), say for 300 W conditions temperature drop difference below 7.5 °C at a pressure drop below 400 Pa (the latter can be considerably reduced by increasing the number of condenser outlet vapour stops).
The tests proved that there is no significant difference in performance for vertical and horizontal orientation. Furthermore the condenser design satisfied all additional requirements.

Three of these condensers in series, not liquid cooled but equipped with 25 mm OD central heat pipes, are part of the ESA Capillary-pumped Loop Engineering Model (CLEM) currently developed by MMS-UK (prime), MMS-F, Bradford and NLR.

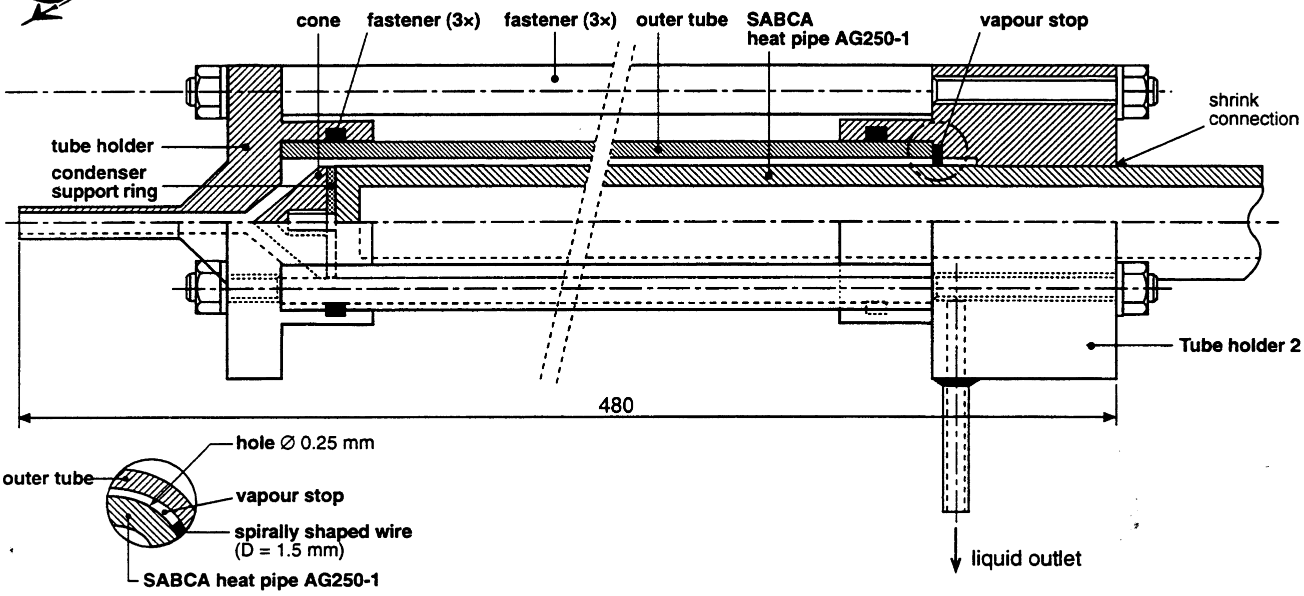


Fig. 18 High Efficiency Low Pressure Drop Condenser

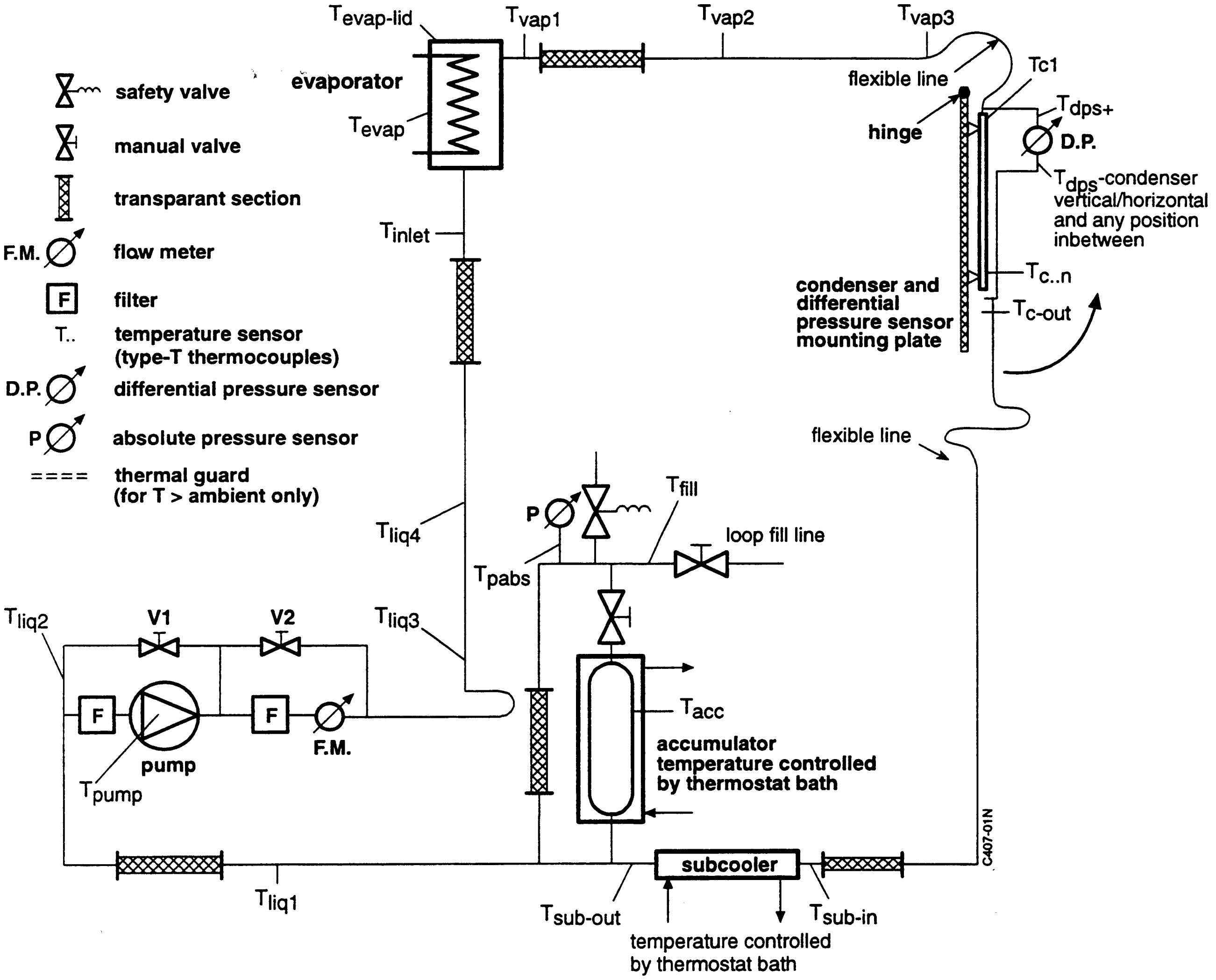


Fig. 19 NLR ammonia test rig for condenser testing

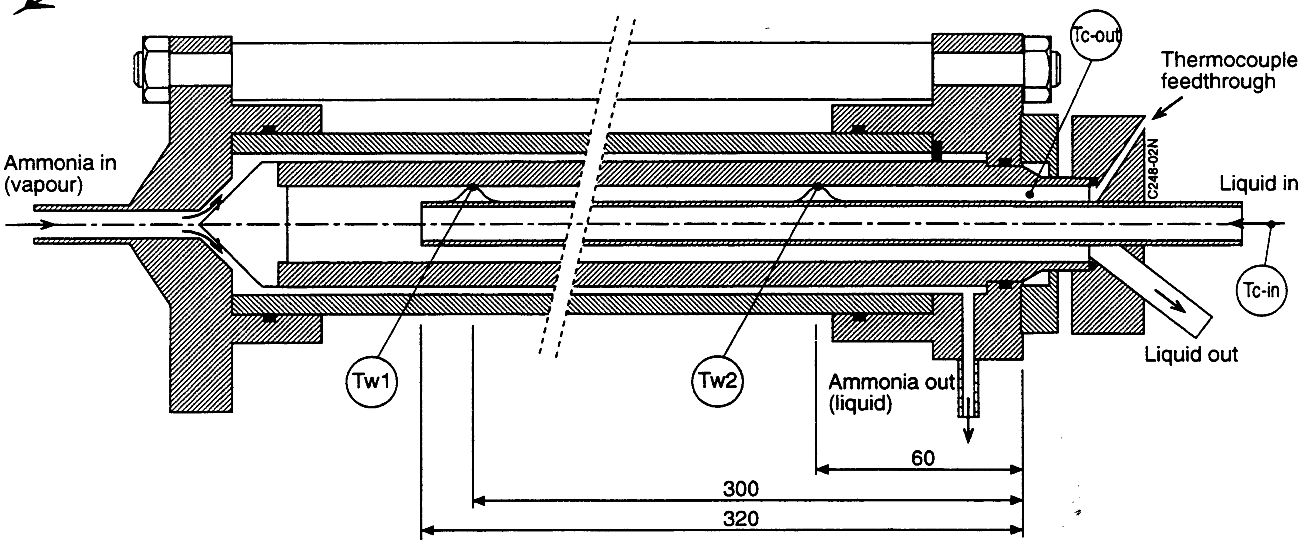


Fig. 20 HELPD condenser test specimen

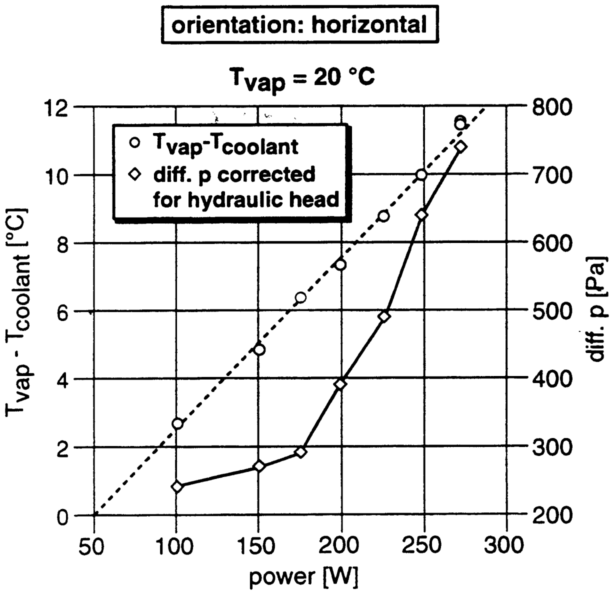


Fig. 21 Temperature and pressure drops as a function of power for the horizontal HELPD condenser

FLOW METER ASSEMBLIES

Activities to spatialise commercially available Flow Metering Assemblies (FMA) for ESA (by NLR, prime, SPPS/Bradford and SABCA), started with selecting and screening a large number (> 80) of commercial FMA.
Trade-offs identified possible candidates for applications in spacecraft thermal, life sciences and propellant systems. A subset of the most promising meters was subjected to a test programme that included qualification level functional performance and environmental testing.

For the performance testing and calibration, a dedicated test facility has been developed. The test rig accomodates all type of working fluids: thermal (e.g. ammonia or freons), life science (e.g. water) and propellants (e.g. MMH, MON).
Tests can be executed within the temperature range -40 to +85 °C, for flow ranges up to 3 g/s for ammonia, to 200 g/s for water and propellants.

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Tests can be executed within the temperature range -40 to +85 °C, for flow ranges up to 3 g/s for ammonia, to 200 g/s for water and propellants.
Obtainable test bench accuracy: 0.025 % Full Scale, flow meter accuracy 0.1 % Full Scale.
The system can be (pre-)pressurised up to 25 bar.

The results of extensive testing led to the choice of two meters to be spatialised: the ITT Barton 7182 turbine meter for water and the ITT Barton 7506 pelton wheel meter for ammonia.
The last activities will be concluded second half 1997.

Other flow meter activities of Bradford/SPPS and NLR, focus on the development of an ultrasonic meter for applications in propellant tanks of three-axes stabilised spacecraft.
Such meters have to be non-intrusive.
The accuracy has to be better than 0.1 % Full Scale (design goal 0.05 % FS) as the meters are to be used to assess remaining propellant mass by totalising the propellant consumption.

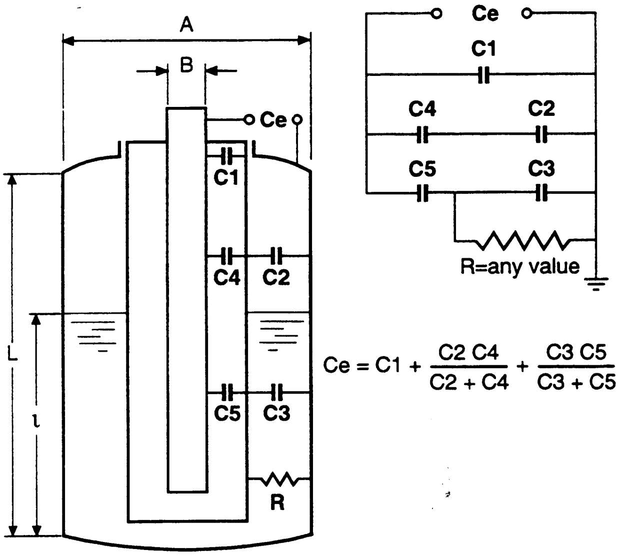
PROPELLANT GAUGES

Since the introduction of the de-orbit requirement for geostationary spacecraft, increased attention has been paid to accurate and reliable on-board gauging of propellants. Various gauging systems have been developed and are in use with a wide spreading of accuracy and complexity (Ref. 9).

Currently, a Vapour Quality Sensor derived capacitive gauge is being developed to very accurately determine the remaining amounts of fuel (e.g. Mono Methyl Hydrazine) and oxidiser (e.g. Mixed Oxygen Nitrides) in the propellant tanks of spin-stabilised spacecraft. The gauges will be integrated parts of the propellant tanks of the Meteosat Second Generation Unified Propulsion System (Ref. 9).

The so-called Gauging Sensor Unit (GSU) layout is depicted in figure 22, and consists of a measuring unit and a set of electronics.
The capacitive measurement principle is schematically shown in figure 23. The platinum covered central glass rod is the inner electrode of the GSU, the titanium holder is the outer one.
The combination of segmented inner electrode, intelligent electronics and a dedicated ground handling protocol, yields level accuracies ranging from 0.015 mm for chemically stable liquids (e.g. Freons) to 0.3 mm for less stable liquids (e.g. MON-1).

The GSU breadboard model has been subjected to extensive testing.
Figure 24 depicts the measured MON-1 level curves for the different segments.
Figure 25 presents the results of the resolution/accuracy verification tests with MON-1.



$$Ce = C1 + \frac{C2\,C4}{C2 + C4} + \frac{C3\,C5}{C3 + C5}$$

Fig. 23 Coated capacitance probe (schematic)

In order to correctly interpret the resolution/accuracy data the dielectric liquid properties (dielectric permittivity and electric conductivity) must be known. As this knowledge could not be found in literature, a test rig has been built to characterise the dielectric properties of propellants.
Successful testing has been recently carried out on MMH and MON-1 (Ref. 10).

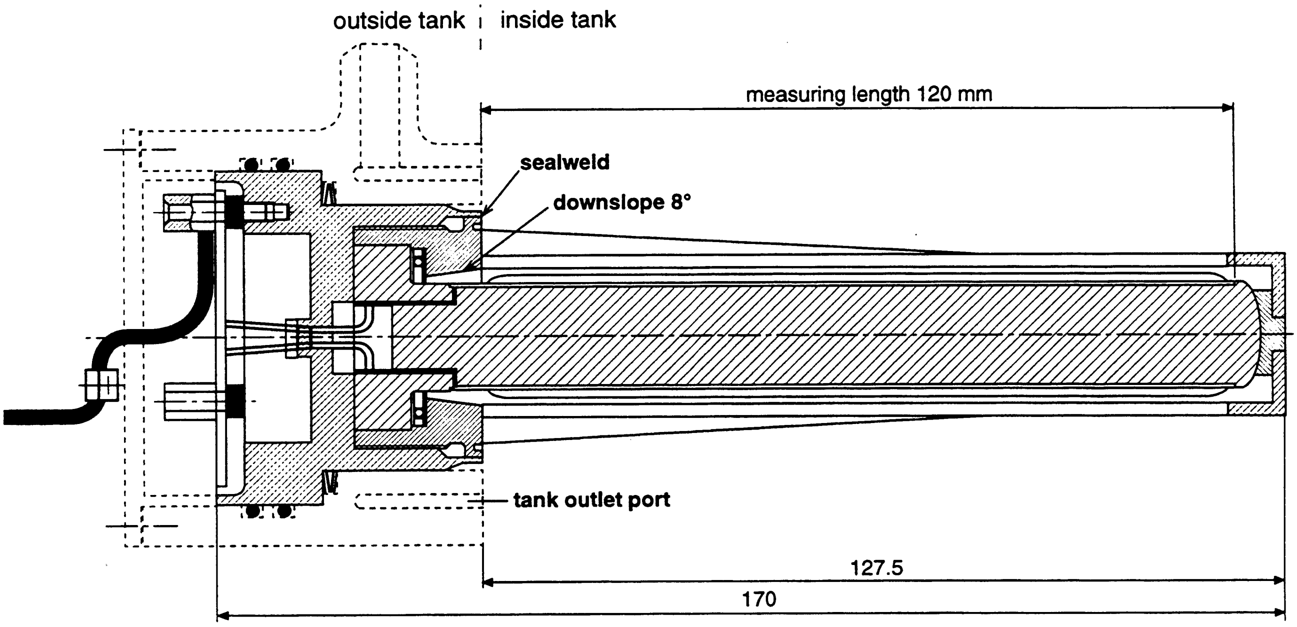


Fig. 22 Propellant Gauging Sensor Unit

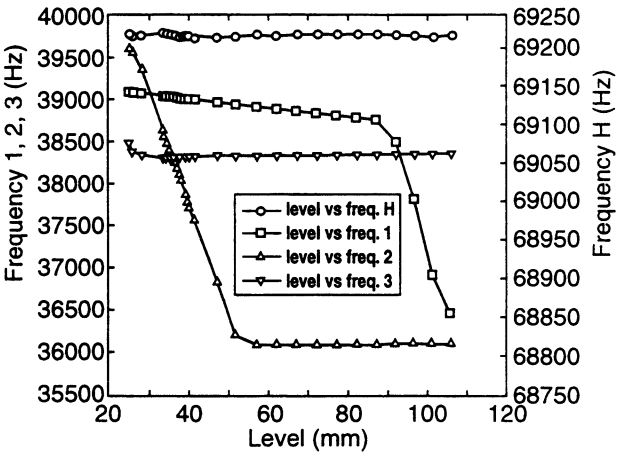


Fig. 24 GSU levels versus frequency test data (MON-1)

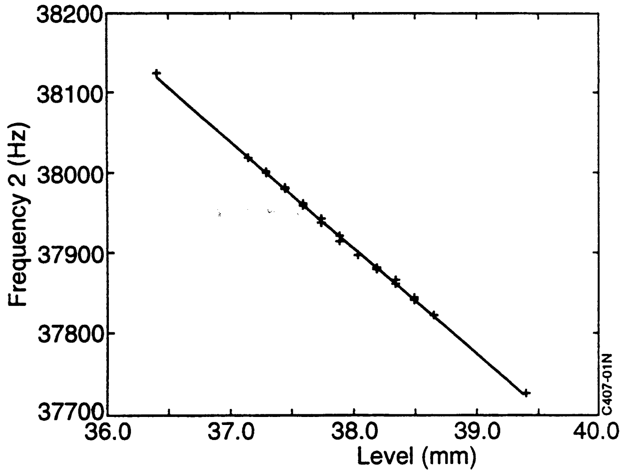


Fig. 25 GSU resolution test data (MON-1)

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