**Nationaal Lucht- en Ruimtevaartlaboratorium**
National Aerospace Laboratory NLR

NLR-TP-99062

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# Development of Liquid Flow Metering Assemblies for Space

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**ABSTRACT**

As it is not possible to directly use commercial liquid flow meters in spacecraft fluid loops, a study was carried out for the European Space Agency to adapt commercial flow meter assemblies for space applications.
The various activities (described in detail) eventually led to the selection of two commercial units, which were re-designed/adapted to be used in spacecraft single-phase (water) and two-phase (ammonia) thermal control loops.
These flow meter assemblies were tested according to an agreed test programme, that included performance and calibration tests in a test bench (developed during the study), vibration testing and EMC/EMI testing.
The results are discussed in order to assess to what extent the study objectives were met. Recommendations for future work are given also.

**INTRODUCTION & APPROACH**

Fluid loops onboard spacecraft often need one (or more) flow meter(s) to monitor or control the performance of the loop or its components. Typical examples are:

- Flow meters in single-phase thermal control loops, to control pump speed and valve settings to have the right mass flow, hence the right amount of heat collection, transport and rejection.
- Flow meters in two-phase thermal control systems, to control pump speed and valve settings to optimise system response and stability, in conjunction with vapour quality sensors.
- Flow meters in propulsion systems to monitor (by bookkeeping) the total of propellant used, providing information for end-of-life determination, for optimising mission strategy, for decision on satellite replacement

Flow metering technology has dramatically evolved in the last twenty years, producing a wide range of methods and measurement systems, each of them being specifically related to specific fields of application. Unfortunately, it is difficult to directly use one of these flow meters for space applications, as either the sensor or the measurement chain or both are not suitable for such conditions.

The goal of the study (by prime contractor NLR, Bradford Engineering/SPPS, SABCA) was Flow Meter Assembly (FMA) "spatialisation": adaptation of commercial FMAs for space applications. Following the Statement of Work (SOW), the project was done in three phases (Table 1).

Table 1: Project Logic

| | |
|---|---|
| **Literature and Product Search & Selection of Concept** | **Phase 1** |
| Market Survey of Commercial Items | |
| Trade-off Analysis & Pre-Selection of Five Commercial Flow Meters & Development of Test Bench | |
| Testing of the Pre-selected Commercial Flow Meters | |
| Trade-off and Selection of Water and Ammonia Flow Meters | |
| **Detailed Design & Adaptation for Space Use & Definition of Test Programme** | **Phase 2** |
| **Manufacturing and Assembly & Testing** | **Phase 3** |
| Assembly | |
| Calibration & Functional Testing | |
| Evaluation of Test Results & Conclusions | |
| Final Reporting | |

The study started with an overview of various flow meter concepts, being:

- Weighing/Volumetric
- Laser Doppler
- Laser Time of Flight
- Variable Area
- Ultrasonic Doppler
- Ultrasonic Time of Flight
- Differential Pressure
- Coriolis
- Turbine
- Thermal Time of Flight
- Electromagneticy
- Vortex Shedding
- Thermal Calorimetric
- Rotary Displacement

A second step consisted of making an inventory of available FM and screening the properties of the 72 commercial units found. To evaluate these with respect to performance, accuracy and space qualification prospects, a FM trade-off matrix form (including ranking figures) was established. Based on this form and on the evaluation criteria and ratings, trade-offs were done, yielding FM rating lists for ammonia, water and propellants as working fluids.

Five FMs were pre-selected out of these lists. It was agreed with the Agency to focus on FM for water and ammonia only, as the primary goal of the study concerned applications for single- and two-phase thermal control systems. In addition it was unlikely to obtain permits, from the Dutch Institute for Pressure Vessels, required to execute tests with propellants. The five meters were subjected to a preliminary test programme. This programme included functional performance, accuracy, calibration, and temperature tests in a test rig specially developed within this study, and also vibration tests of the meters, while in operation. Based on the test results, the two best ones were re-designed for actual spacecraft applications foreseen, being an 8 - 80 g/s water single-phase and a 2-15 g/s ammonia two-phase thermal control system.

A critical analysis of the two selected FMs was made to identify the modifications, of mechanical parts and electronics, needed to meet the specified requirements. Finally, the re-designed and modified FMAs were thoroughly tested according to a test programme defined earlier in this study. This programme included calibration tests, accuracy tests, leak and proof pressure tests, and EMC tests.
From the test results it was concluded to what extent the objectives of the study were met. Recommendations for further work are given. More detailed information is given in NLR-CR-98442: Flow Meter Assembly Spatialisation – Final Report.

**EVALUATION OF COMMERCIAL UNITS**

Based on the SOW and the Technical Requirements Document (TRD), the important parameters were identified and listed on the form to be used for the trade-offs: the Trade-off Matrix Form. This form contains weight factors and evaluation criteria, which will yield, when applied to the commercial units, a list of flow meters sorted such that the best one is on top. This not necessarily means that the top ones meet all requirements, as the target is to identify meters that are most promising for “spatialisation”.

An inventory of commercial flow meters was made next. Information on 72 commercial units was gathered from brochures, and by direct contacts with suppliers. The information was stored on FM Data Evaluation Forms, for each flow meter three forms, one per fluid.

The relative importance of parameters can be expressed by the assignment of weight factors. The weight factor values indicate that “Flexibility on changes for spatialisation” is considered to be the most important (weighed 12). This weight factor accounts for efforts related to structure, electronics, vibration, configuration, accuracy, temperature and lifetime. Other important trade-off parameters are “Lifetime, maintainability, calibration sensitivity” and “Accuracy” (both weighed 10), “Flow range” and “Leakage” (both weighed 8), “Temperature range of fluid”, “Pressure drop and response time”, “Structural strength”, “Gravity & orientation” (all weighed 6) and “EMI & EMC” (weighed 5). Lower values are assigned to parameters, which are most likely to be improved by a spatialisation: “Mass”, “Vacuum “ (compatibility), and “Power” (all weighed 3), and also “Volume”, “Mechanical environment”, “Environmental temperature” (all weighed 2). “Purchase costs” are considered to be minor also (2), certainly when compared to spatialisation efforts, hence spatialisation costs.
The criteria to rate the flow meters range from 0 (unacceptable) to 10 (excellent).

More than 200 evaluation forms were filled out. The trade-offs were done according to the above guidelines. The final score for each FM was calculated by addition of all products of Rating (R) and Weight Factor (W), normalised (dividing the resulting number by the maximum possible value), and then multiplied by 10. The final score ranges from 0 (unacceptable) to 10 (excellent).

From the best scoring units, five FMs (Table 2) were pre-selected, based on the above scores, and by keeping in mind that:

- At this stage the study was restricted to ammonia and water only, as discussed.
- The pre-selected five had to represent different concepts.
- Availability, co-operation of the supplier, delivery time and price were very important issues.

Table 2: Pre-Selected Flow Meters

| Type | Manufacturer/Distributor | Principle | Ammonia | Water | Notation |
|---|---|---|---|---|---|
| DS012S | Rosemount / Brooks | Coriolis | x | | DS012S |
| FTO | EG&G | Turbine | x | | EG&G-FTO |
| PT868/6068 | Panametrics | Ultrasonic | | x | PT868 |
| 7283 series | ITT Barton | Turbine | | x | Barton |
| DS025S | Rosemount / Brooks | Coriolis | | x | DS025S |

## TEST BENCH

In parallel to the pre-selection activities, a test bench was to be built to be used both for the preliminary testing of pre-selected units and for the final acceptance testing of the spatialised FMAs at a later stage. This chapter describes the test bench (Fig. 1), the design and the characterisation of performance.

Liquid flow, produced by moving a piston inside the cylinder via the actuator, flows via valves (2V4, 2V5, 2V6, 2V9 and 2V11) and through the FM test section to the exchangeable tank. The test section can contain two FM's in series, together with a reference FM. Pressure differences across the FM's can be measured by differential pressure sensors, one for each FM. At the end of each test, when the actuated cylinder is empty, it is automatically refilled by applying the maximum system pressure (20 bar) to the exchangeable tank. The liquid then flows back through the valves 2V11 and 2V10 (valve 2V9 closed), in this way moving the piston back downwards in the cylinder. The pressure on the exchangeable tank is controlled by inert gas and a floating piston. The test fluid temperature can be controlled by cooling or heating the test set-up, which is placed in a climat chamber (adjustable from -20 to +60 °C). The temperature of the FM section can be controlled by using an extra insulating module around this section. A vacuum connector, filters and a dump tank are integrated in the bench for tests with special fluids (e.g. propellants). The bench is partially automated to perform unattended tests, if required by safety.

The cylinder, designed for 20 bar (wall thickness 14 mm), consists of stainless steel (AISI 304) to secure compatibility with the test fluids. The inner volume is 13 litres. The seals on the piston/shaft (minimum 3 in a row) are of Virgin PTFE with a stainless steel spring inside. The seal on the bottom flange is also made of PTFE. A spherical flange is placed on top of the cylinder. A pressure safety valve and an extra connection, for water refill and cleaning purposes, are also integrated in/on the cylinder. To vent the system a venting valve is installed on the cylinder and the cylinder is placed upside down.The exchangeable tank, also designed for 20 bar, is larger (20 litres) than the cylinder. The extra volume is used to provide a gas cushion on top of the floating (not sealed) piston, to give a good pressure distribution on the fluid. The tank (also AISI 304), has a spherical, seal-welded flange on the bottom where provisions are made for the entering liquid, a dump tank (for special fluids) and an exit to a balance (for weighing the fluid). The top flange has a PTFE seal and is bolted onto the cylindrical part of the tank. A venting valve, a pressure safety valve, an a pressure indicator (safety) and a connection to a gas bottle, are integrated in the top flange.

The bench structure, made of welded stainless steel profiles, is designed to handle all the expected forces and vibrations. All tubing is made of stainless steel, chosen to withstand at least 70 bar. All couplings, elbows and valves (with PTFE seals) are standard Swagelok© items (stainless steel) and able to withstand the required maximum pressure. The isolation chamber is made of ISOCAP© (140 mm) panels compatible with the required temperatures. The extra insulation module around the FM section, is also made of these panels.
The actuator is a stationary head with integrated drive, a travelling cross-head, two guiding columns and backlash free re-circulating ball screw bearings. The motor inside the actuator, equipped with a gearbox (ratio $1{:}10^6$), gives a pulsed output signal (encoder) to create an accurately feedback controlled movement.

Tests and computations were done to qualify the test bench. Qualification testing included:

- Leak tests, proving that the bench is leak-tight up to $10^7$ std cc/s Helium, consisted of a standard leak test at ambient temperature (Helium inside the bench, sniffing outside), and a reverse leak test at -20, +20, and +60°C (Helium outside, vacuum inside).
- Proof pressure tests up to 35 bar, using nitrogen as pressurising gas, showing no physical damage, and the same performance before and after the testing: the bench meets the required operating pressure range.
- Response time tests showing a test bench response time (time to establish a given flow, from zero flow, with accuracy better than ± 0.1 %) of less than 1 s (mostly an order of magnitude better) over the whole range.
- Accuracy tests, showing that the test bench accurately handled flows between 10 and 256 g/s for water, between 0 and 15 g/s for ammonia, and yielding a flow accuracy of 0.025 % of reading. Therefore it was decided that the reference flow is not the flow measured by a reference FM (as originally planned), but will be the flow following from the displacement speed of the test bench piston, as the latter flow proved to be at least one order of magnitude more accurate than the flow derived from the best commercial FM.

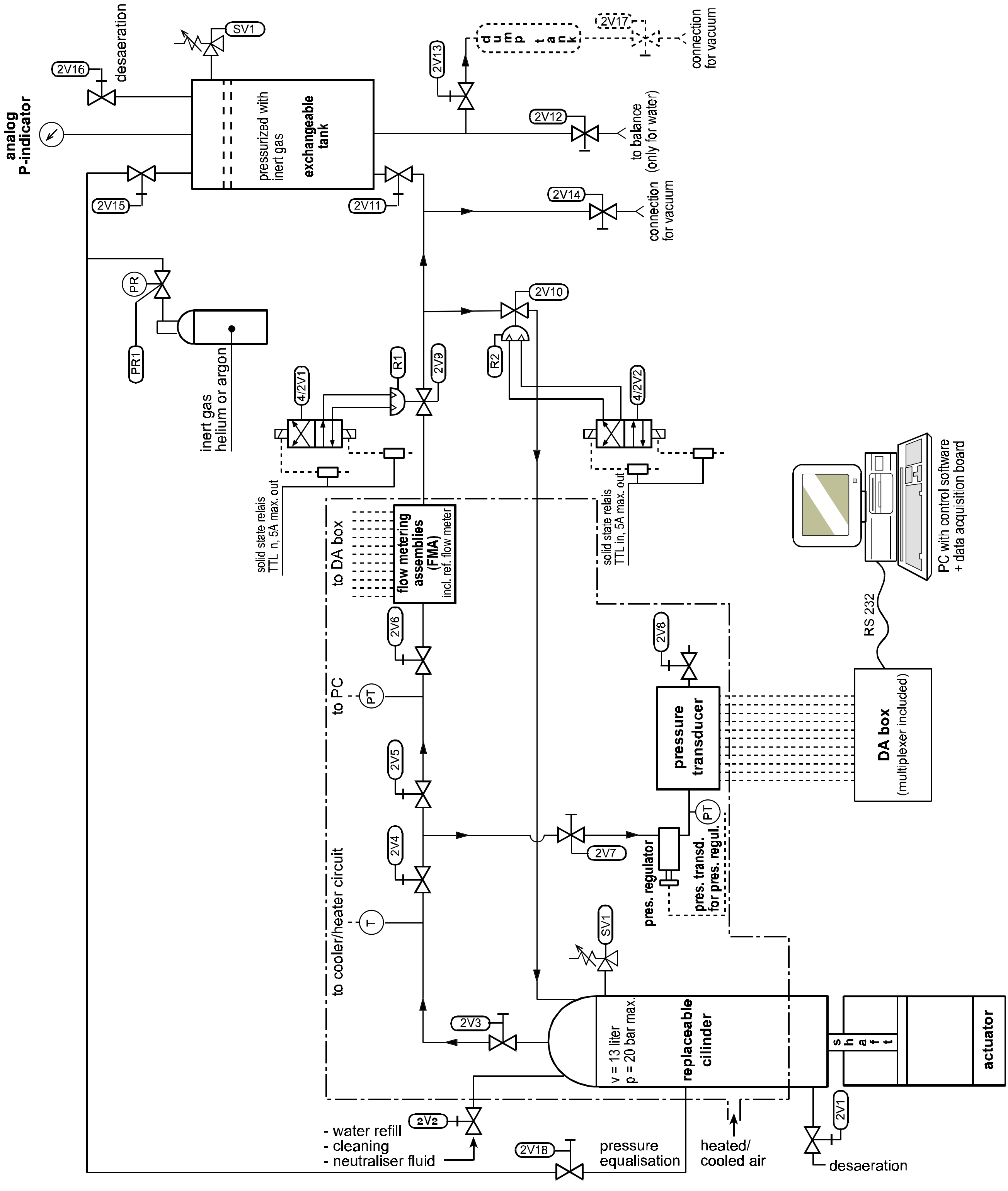


*Fig. 1 Test Bench*

## PRE-SELECTION OF METERS & FINAL SELECTION

All five pre-selected meters were compatible with water and ammonia, but they could not cover the mass flow rates required for both liquids. Therefore they were divided in meters for water and meters for ammonia, as shown in table 2. The five meters were subjected to a preliminary test programme, consisting of a check of the fluid compatibility, inspection of the physical dimensions, Helium leak test, proof pressure test and functional tests, which included measurement accuracy, response time, pressure drop, and power consumption. The latter tests were completed by vibration tests on meters in operation. For safety reasons the meters were tested with water only. All meters sustained the high level random vibrations. However they did not function properly during the vibration. After vibration testing they again measured properly. But in some cases a rest time of 30 minutes (and more) or a re-set action became neccesary.

Trade-offs were done based on the test results for ammonia and for water.
They showed that the EG&G-FTO turned out to be the most promising FM for ammonia, because of:
- Its flexibility with respect to spatialisation.
- The fact that, based on vibration test results of the Barton FM (being a more or less similar design), it can be assumed that the performance before and after vibration is the same.
- The fact that repeatability and hysteresis are reported (by the supplier) to be small (0.1%), meaning that poor accuracy can be considerably improved by calibration.
  Unfortunately after a first run with ammonia the meter broke down. The interior showed that rotating elements had disappeared due to corrosion, although the supplier had explicitly stated that the FM was ammonia compatible. Because of loss of credibility and the fact that the supplier could not deliver ammonia compatible items, it was decided to replace this meter by a similar ITT-Barton type, with stainless steel, ammonia compatible, internal parts.

The results also showed that the Barton meter was most promising for water, because of:
- Flexibility with respect to spatialisation, extremely low pressure drop, acceptable accuracy.
- Identical performance before and after vibration.
- Relatively low response times.

Identified actions for re-design were for both flow meters the investigation of lifetime and maintainability, extension of the flow range, and an electronics development for electrical interfacing and for fluid properties related correlations. In general it can be said that only minor hydraulical and mechanical changes were required (machining and surface treatment). The major effort concerned the electronics issues.

## RE-DESIGN OF SELECTED UNITS

The final selection started with re-assessment of possible near-term space applications for FMAs. The following applications were indentified: a single phase water loop for the COF main loop or the ISPR Rack requiring flow rates ranging from 8 to 80 g/s (with a maximum pressure drop of 0.1 bar), and two-phase ammonia loops with a heat transport range of 2.2 to 15 kW (ammonia flow rates from 2 to 15 g/s). The requirements were adapted as it will be shown later in the verification matrices. It was concluded that:
- ITT Barton 7182 flow meter was the most appropriate for water, covering the 8-80 g/s range.
- ITT Barton 7506 flow meter was the most appropriate for ammonia applications (2-15 g/s).
- Both meters were to be spatialised, provided that two assumptions were confirmed, being: only minor development effort could be expected for the hydraulic parts of the water meter, and both ITT Barton meters could use the same electronics. However, the major effort was to be spent on the water meter, as near-term applications (COF and ISPR Rack) are foreseen.

**ITT Barton 7506** (Fig. 2) is an electro-mechanical volumetric FM, using a Pelton wheel. Pulses are generated by the rotor, passing a pick-up coil, positioned above the wheel. The frequency of the pulses generated is proportional to the flow rate of the liquid. The FM consists of four parts: Housing, Pelton Wheel, Pick-up Coil and Conditioning Electronics. Internal and external parts are mounted on the housing.

The main internal part is the rotor assembly, a rotor mounted on a sleeve bearing to allow free rotation. The bearing is kept in place by two spacer bushes, slid on a screw and locked up by the holding nut. The rotor is of AISI 430 to provide the magnetic properties required for the pick-up coil to function. The pick-up coil is not in direct contact with the fluid.

In **ITT Barton 7182** (Fig. 3), liquid (flowing first through a flow straightening section) is accelerated and forces a multi-blade, balanced, turbine rotor to rotate with a speed proportional to the flow rate. A pick-up coil senses the passage of each blade tip and generates a sine wave output, whose frequency is directly proportional to turbine speed and hence the flow rate.
The meter consists of a housing body to which internal and external parts are mounted. The internal parts are the tube assembly and the bushing assembly, being the rotor shrunk on the bearing, mounted on a shaft centre, supported by the tube straightener assemblies and locked in place by the retainer ring. The straightener assemblies consist of three tube straighteners, held together by a welding cap end and a flow diffuser. Two assemblies are mounted to the flow meter, one at the inlet, one at the outlet. These assemblies had to be post-

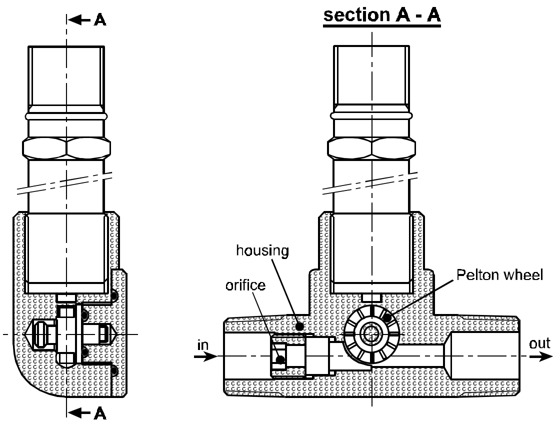


*Fig. 2 Pelton Wheel FM: ITT Barton 7506*

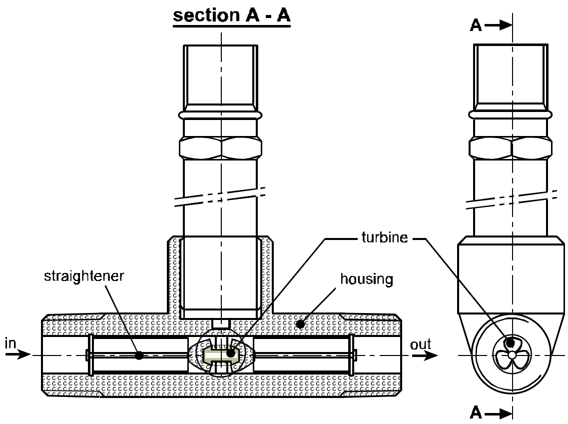


*Fig. 3 Turbine FM : ITT Barton 7182*

machined to establish the required accuracy. The only external part is the pick-up coil with a connector to the electronics. The rotor is of AISI 430, having the magnetic properties necessary for the pick-up coil to function. The pick-up coil is not in direct contact with the fluid.

The **Electronic Control Unit** (Fig. 4) includes a motherboard and three PCBs, placed on it, which makes the configuration modular. The motherboard is designed to handle all data, power and command signal transport for the PCBs. It actually represents the internal bus. Various connectors interface with the sensor control equipment, i.e. for temperature and flow input/output signals and power input. The modular configuration offers very compact, lightweight and versatile electronics with minimum system modifications. The function of the electronics is to translate the flow meter (sensor) output pulse rate into an analogue output voltage representing the mass flow in engineering units. Sensor non-linearities and temperature effects are compensated for. The electronics of the FMA are assembled on the PCBs, i.e. analogue, digital and micro-controller PCBs. Figure 5 shows the electronics system set up.

The flow signal is represented by the frequency of a sinusoidal signal, generated by a 7000 ITT Barton series

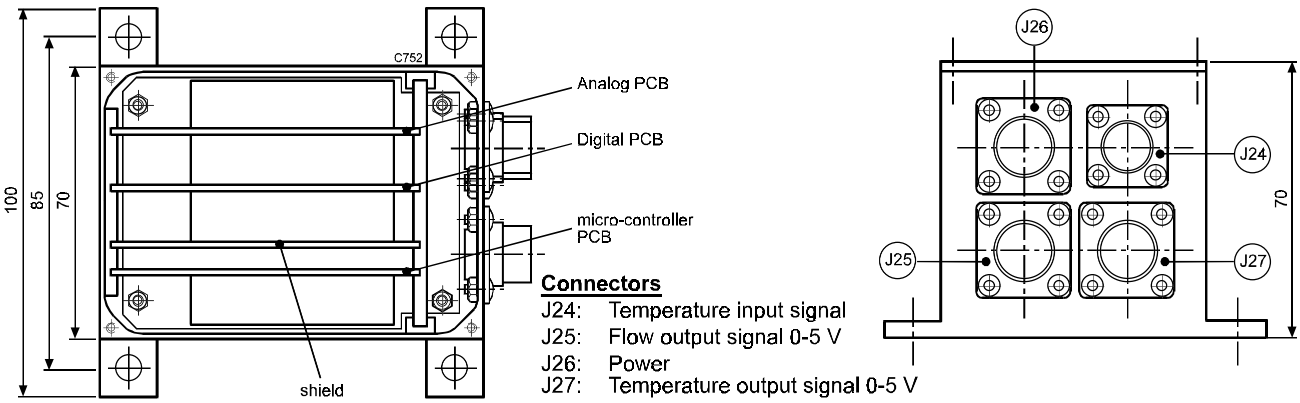


*Fig. 4 Electronics box mechanical design*

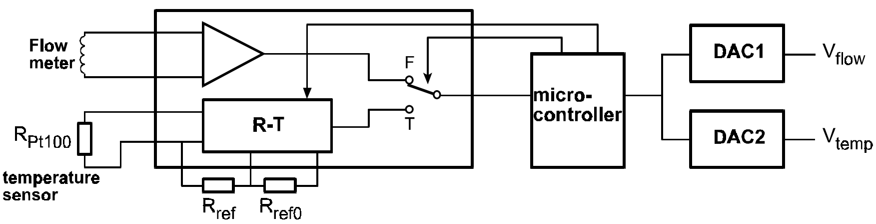


*Fig. 5 Basic set-up of the electronic configuration*

turbine FM. This frequency is in the range 45 to 1500 Hz, depending on the flow speed. A second-order effect, is that this frequency slightly depends on the temperature. To compensate this, a Pt100 temperature sensor measures the temperature of the fluid. The Pt100 is read according to the three-wire method, to ensure inherent good reliability and a good long-term stability. The measuring sequence is completed by measuring the reference resistors $R_{ref}$ and $R_{refo}$ for auto-correlation purposes. The measurements are executed by a micro-controller. With the R-T (resistance to temperature) converter, each of the three resistive signals is converted to a period length of a square-wave output signal for the micro-controller. Also the measured FM frequency is converted into a period length, so four period lengths/frequencies are measured.

The micro-controller determines the frequency or period length and calculates the value of $R_{Pt}$ and the temperature. From the calibration data, that characterise the flow meter behaviour (stored in an EPROM look-up table, containing 6 x 7 frequency data plus headers), the measured frequency can be translated to actual flow by linear interpolation between neighbouring flow frequency signals at measured temperatures.

## TEST AND TEST RESULTS

The results of the acceptance test programme, shown in the proper test sequence (Table 3), are given in the figures 6 to 9 and the verification matrices (Tables 4, 5).

Mass and dimensions checks were done before and at the end of the test sequences. Mass and dimensions of the flow meters and electronics did not change during the tests.
The values are:
- Electronics Box: Dimensions 100.0 mm x 89.8 mm x 69.9 mm, Mass 565.5 g.
- FMA7182: Dimensions 73.1 mm x 22.0 mm x 71.8 mm, Mass 182.9 g.
- FMA7506: Dimensions 62.0 mm x 23.8 mm x 78.0 mm, Mass 362.2 g.

EMC tests showed that the FMAs were only compliant with the relevant requirements for Conducted Emission CE01, and did not comply with the requirements for Radiated Emission RE01, Conducted Emission CE03, and Radiated Susceptibility RS03. This was expected because the commercial electronics components were non MIL-SPEC. Replacement by MIL-SPEC components (in a follow-up study) will most probably lead to compliance with all EMC requirements.

**FMA 7182** was tested with the target fluid water only. First a calibration test was performed to fill the electronics look-up table. This table corrects for the temperature dependence of FMA 7182. With this updated version of the meter the remaining tests were performed.

Flow range test results (Fig. 6) were used to update the look-up table. Figure 6 also shows the average mass per vane, deduced from the measured frequency. The mass transport per vane curves show considerable deviations from a linear relation between frequency and flow rate (due to slip) below a flow of 24 g/s. Update of the look-up table had to correct this.

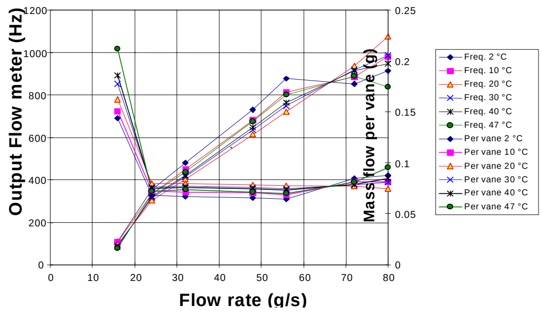


*Fig. 6 Flow range test FMA 7182*

With the above updated values implemented in the electronics, the FMA was calibrated in the following calibration test. The accuracy at 20 °C was encouraging: better than 3 % for flow rates bigger than 16 g/s.
Final results of the calibration tests of FMA 7182 with water, after three look-up table modifications, are shown in figure 7. From these results it could be derived that, for all temperatures, the accuracy is better than 2.5 % for a mass flow of 24 to 70 g/s. At 19 °C, the accuracy for mass flows bigger than 16 g/s is even better than 0.7 %.

Table 3: FMA Acceptance Test Programme and Sequence

| No | Test | No | Test | No | Test |
|---|---|---|---|---|---|
| 1 | Mass/dimensions Check | 10 | Collapse Pressure Test | 19 | Time Drift Test |
| 2 | Flow Range Test | 11 | Functional Check | 20 | Response Time Test |
| 3 | Calibration Test | 12 | Pressure Surge Test | 21 | Radiated Emission |
| 4 | Repeatability Test | 13 | Mass/dimensions Check | 22 | Radiated Susceptibility |
| 5 | Time Drift Test | 14 | Functional Check | 23 | Power Leads |
| 6 | Response Time Test | 15 | External Leakage Test | 24 | Linear Acceleration/Sinusoidal |
| 7 | Proof Pressure Test | 16 | Reverse Leakage Test | 25 | Random Vibrations |
| 8 | Mass/dimensions Check | 17 | Calibration Test | 26 | Insulation |
| 9 | Functional Check 2 orientations | 18 | Repeatability Test | 27 | Grounding & bonding |

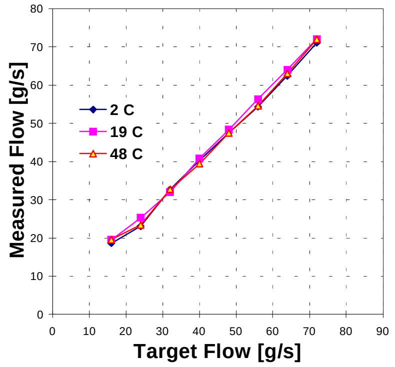


*Fig. 7 FMA 7182 after 3 modifications*

**FMA 7506** was tested for water and ammonia, but for ammonia not the full test programme, but only a reduced number of tests (as it had been agreed to put major effort on FMA 7182) was carried out.

First, a flow range test with water was done to compare with the ammonia calibration data. This first test was done with commercial electronics, this to obtain a first look-up table. The obtained results are given in figure 8. The left ordinate gives the output frequency of the flow meter, the right ordinate gives the corresponding mass flow per vane. The figure shows that the frequency is almost linear with the mass flow within the entire mass flow range. Deviations occur only at small mass flows, as it is illustrated by the mass transport per vane that shows increased mass transport per vane with decreasing mass flow (due to slip). For this effect corrections were to be made via a look-up table update.

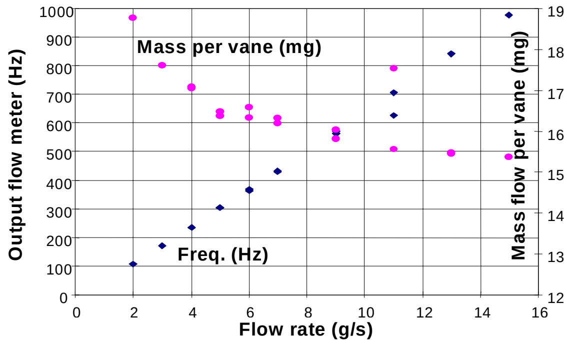


*Fig. 8 Flow range test FMA 7506 (water)*

Repeatability tests were performed, with water at 20 °C, to check whether FMA 7506 is able to reproduce measurements. The results showed a repeatability better than 1 % in the whole flow range. Repeatability was even better than 0.3 % for large flow rates (>8 g/s).

The results of the calibration test of FMA 7506 for ammonia are given in figure 9. They show acceptable accuracy for flow rates above 7 g/s, for smaller flow rates the accuracy is unsatisfactory. Therefore the results of this test shall be used to create a new look-up table to improve the accuracy of this FM to the values of FMA 7182 (2.5 % of reading). The second look-up table update and the introduction of more sophisticated interpolation algorithms is expected to realise the required accuracy. The latter activities were not carried out and were considered to be part of a follow-up study, together with replacement of commercial components by MILSPEC components, following the agreement to focus on FMA 7182.

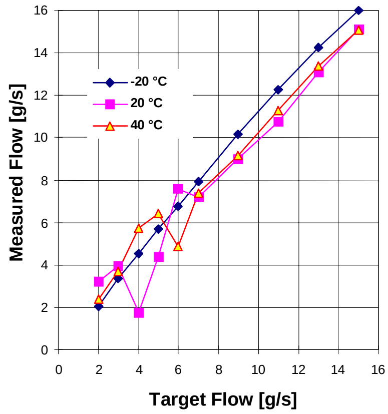


*Fig. 9 Calibration Test FMA 7506 (ammonia)*

In summary it can be stated that the tables 4 and 5 indicate that both delivered FMAs are compliant with the design, environmental, physical, safety, reliability and maintainability requirements, but only partly with functional, EMC and performance requirements.

## CONCLUSIONS

The conclusions, derived from the results given in the verification matrices (Tables. 4, 5), can be summarised by:

- A test bench has been developed, which is able to calibrate liquid flow meters with high accuracy (better than 0.025%) and a response time (smaller than 1 s). The test bench is perfectly suitable for calibration of FM in the relevant mass flow ranges, for different liquids (including water, ammonia, refrigerants, and propellants). Even though such an activity was originally not foreseen, the test bench development became absolutely essential, because no commercial test bench and reference flow meters were available (especially taking into account the variety of fluids under investigation). The quality of the test bench is such that it is currently investigated whether the bench can become a standard for flow meter calibrations, for different liquids and various mass flow rate ranges.
- With the water meter, FMA 7182, the majority of objectives are met. However the water meter has, for a flow range from 24 to 72 g/s, an accuracy of 2.5% of reading, in the whole temperature range. This has to be improved in a follow-up study. The time drift is less than 0.5%, which is very good. However, vibration and EMC tests indicate that there is more work to be done before FMA 7182 can be called “fully spatialised”.

- FMA 7506, having a flow range up to 15 g/s for water and ammonia, shows an accuracy that is not satisfactory, especially at lower flow rates. Improvements can be realised by implementation of a new look up tables, insertion of more sophisticated interpolation algorithms, and replacement of commercial electronic components by MILSPEC components. This FMA meets most objectives, but the results of vibration and EMC tests lead to the same conclusions as for the FMA 7182: there is more work to be done in this area, before FMA 7506 can be called “fully spatialised”.
- It is remarked that both meters perform properly after vibration tests. Though proper performance during (e.g. launch) vibrations was not a requirement in this study, it can be expected that special mounting measures (dampers, isolators, etc.) will yield FMAs correctly measuring even in a vibration environment.
- The response time of both flow meters is not sufficient. It has to be improved, though the required value (< 1.0 s) is to be questioned, because this value originates from propellant systems requirements, and might be non-realistic (hence not needed) for thermal or life science systems.
- It is remarked that the EMC test results suggest that requirements will be met by replacing all commercial electronics components by MIL-SPEC components.

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Table 4: Verification Matrix for the Water Flow Meter FMA 7182

| Issue | Requirements from SOW & TRD | Updated Requirements | Delivered FMA 7182 Final Version | Remarks |
|---|---|---|---|---|
| **Functional and Performance Requirements** | | | | |
| **Fluids Compatibility** | Variety of fluids | Water | Water | |
| **Operating Temperature** | 1.5 to 50°C | | 2 °C to 50 °C | |
| **Operating Pressure** | 0.2 to 1.0 Mpa | | 0.2 to 1.0 Mpa | |
| **Flow Rate Range** | 15 to 200 g/s | | 15 to 80 g/s | |
| **Allowable Pressure Drop** | 700 Pa at 15 g/s, 10000 Pa at 200 g/s | | 27000 at 140 g/s | Manufacturer’s specifications |
| **Accuracy (% of reading)** | 1.0 % | | 2.5 % for 24-70 g/s | To be improved in follow-up project |
| **Response Time** | < 1 s | | > 15 s | To be improved in follow-up project |
| **Design Requirements** | | | | |
| **Maximum Over- Pressure** | 1.0 Mpa | | Compliance met | |
| **Proof Pressure** | 1.5 Mpa | | Compliance met | |
| **Burst Pressure** | 2.0 Mpa | | Compliance met | |
| **Orientation** | In any orientation | | Compliance met | |
| **Leakage** | External: $<1 \cdot 10^{-9}$ mbar.l/s, Reverse: $<1 \cdot 10^{-8}$ mbar.l/s | | $<1 \cdot 10^{-8}$ mbar.l/s | Detection limit of equipment |
| **Environmental Requirements** | | | | |
| **Humidity** | 20 to 100 % | | | No problems |
| **External Pressure** | 115 kPa > P > $10^{-4}$ Pa | | Compliance met | |
| **External Temperature** | 2 to 50 °C | | Compliance met | |
| **Acceleration Requirements** | Linear acceleration +/- 13 g/s | | Compliance met | Model 7283 tested |
| **Physical Requirements** | | | | |
| **Mass** | < 3kg | | 182.9 g | Electronics 566 g |
| **Volume** | < 1400 cc | | 115.5 cc | Electronics 628 cc |
| **Power** | < 5 W | | < 1 W | Manufacturer’s specifications |
| **EMC Requirements** | | | | |
| **EMC-Conditions** | MIL-STD-462 | MIL-STD-461C | Not satisfactory | To be improved in follow-up project |
| **Reliability Requirements** | | | | |
| **Reliability** | 5 years operation in space | | MTTF 15.3 years | Based on reliability analysis |

Table 5: Verification Matrix for the Ammonia Flow Meter FMA 7506

| Issue | Requirements from SOW & TRD | Updated Requirements | Delivered FMA 7506 Final Version | Remarks |
|---|---|---|---|---|
| **Functional and Performance Requirements** | | | | |
| **Fluids Compatibility** | Variety of fluids | $NH_3$ and Water | $NH_3$ and Water | |
| **Operating Temperature** | $NH_3$ -20 to 40 °C<br>Water 1.5 to 50°C | $NH_3$ -20°C to 40°C | $NH_3$ -20 °C to 40 °C | |
| **Operating Pressure** | $NH_3$ 0.2 to 1.5 MPa<br>Water 0.2 to 1.0 MPa | $NH_3$ 0.2 to 1.5 MPa | 0.2 to 1.7 MPa | |
| **Flow Rate Range** | $NH_3$ 0.3 to 3.0 g/s<br>Water 15 to 200 g/s | $NH_3$ 0.3 to 3.0 g/s | 2.0 to 15 g/s | |
| **Allowable Pressure Drop** | $NH_3$ 50 Pa at 0.3 g/s, 250 Pa at 3 g/s.<br>Water 700 Pa at 15 g/s, $10^4$ Pa at 200 g/s | $NH_3$ 50 Pa at 0.3 g/s, 250 Pa at 3 g/s | 1400 Pa at 2.0 g/s<br><br>73000 Pa at 15 g/s | |
| **Accuracy (% in rading)** | $NH_3$ 0.5 %<br>Water 1.0 % | $NH_3$ 0.5 % | around 2.5 % at large flows, above 14 % at small flows | To be improved in follow-up project |
| **Response Time** | < 1 s | | > 15 s | To be improved in follow-up project |
| **Design Requirements** | | | | |
| **Maximum Over-Pressure** | $NH_3$ 2.0 MPa<br>Water 1.0 MPa | | Compliance met | |
| **Proof Pressure** | $NH_3$ 3.0 MPa<br>Water 1.5 MPa | | Compliance met | |
| **Burst Pressure** | $NH_3$ 4.0 MPa<br>Water 2.0 MPa | | 3.0 MPa tested | No problem expected |
| **Orientation** | In any orientation | | Compliance met | |
| **Leakage** | External: $<1 \cdot 10^{-9}$ mbar.l/s, Reverse: $<1 \cdot 10^{-8}$ mbarl/s | | $<1 \cdot 10^{-8}$ mbar.l/s | Detection limit of equipment |
| **Environmental Requirements** | | | | |
| **Humidity** | 20 to 100 % | | | No problems |
| **External Pressure** | 115 kPa > P > $10^{-4}$ Pa | | Compliance met | |
| **External Temperature** | 2 to 50 °C | | Compliance met | |
| **Acceleration Requirements** | Linear acceleration +/- 13 g/s | | Compliance met | Model 7283 tested |
| **Physical Requirements** | | | | |
| **Mass** | < 3kg | | 362.2 g | Electronics 566 g |
| **Volume** | < 1400 cc | | 115.1 cc | Electronics 628 cc |
| **Power** | < 5 W | | < 1 W | Manufacturer's specs. |
| **EMC Requirements** | | | | |
| **EMC-conditions** | MIL-STD-462 | MIL-STD-461C | Not satisfactory | To be improved in follow-up project |
| **Reliability Requirements** | | | | |
| **Reliability** | 5 years operation in space | | MTTF 11.8 years | Based on reliability analysis |

**ACRONYMS, ABBREVIATIONS**

| | |
|---|---|
| COF | Columbus Orbital Facility |
| D/A | Digital/Analogue |
| DAC | Digital Acquisition and Control system |
| ECU | Electronic Control Unit |
| EMC/EMI | Electro-Magnetic Compatibility/nterference |
| EPROM | Erasable Programmable Read Only Memory |
| FM(A) | Flow Meter (Assembly) |
| LUT | Look-Up Table |
| MOP | Maximum Operating Pressure |
| MTTF | Mean Time to Failure |
| PCB | Printed Circuit Board |
| R | Rating |
| SOW | Statement of Work |
| TBD | To be Determined/Defined |
| TRD | Technical Requirements Document |
| W | Weight Factor |