Development of a Cesium propellant tank for FEEP Application

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Abstract: A propellant tank for the Cesium FEEP (Field Emission Electric Propulsion) system developed by ESA at ALTA is being designed, qualified and manufactured at Astrium. The product is the result of a large European collaboration involving the more than two decades experience of Astrium in the field of PMD technologies (Propellant Management Device). The propellant tank is a key component of the FEEP sub-system, which allows guarantying leak tight storage and delivery of the liquid Cesium for capillary feeding of the emitter where the thrust is generated. A wide range of technological solutions has been deployed to treat the issues of mechanical design, thermal design, and functional design. They finally provide answers to the two main requirements that are the tank sealing/opening functionality thanks to a so called TSD (Tank Sealing Device) and the functionality of delivery of the propellant thanks to a specific and newly design PMD. The propellant tank follows a two-part design logic including the reservoir itself and a new enhanced PMD/TSD cap mounted at the exit of this reservoir body that provides both functionalities of tank sealing/opening and capillary feeding of the tank exit. The qualification phase included specific qualification steps at component levels finally converging to the thruster hot firing tests with Cesium at ALTA S.p.A. In particular, a Neutral Buoyancy test campaign focused on the qualification of the capillary behavior of the whole tank during all its operational phases, from the tank opening with the PMD priming until the full draining of the tank. The paper presents a general view of the architecture of the propellant tank, of its achieved performances, of its operational modes and sequences, and finally of the its qualification phase including a more detailed presentation of the Neutral Buoyancy test campaign results and the first tank filling and burst test with Cesium.

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Nomenclature

Cs	=	Cesium
FEM	=	Finite Element Model
FEEP	=	Field Emission Electric Propulsion
Isp	=	Thruster Specific Impulse [s]
MAIT	=	Manufacturing Assembly Integration and Test
PMD	=	Propellant Management Device
QM/FM	=	Qualification Model / Flight Model
TSD	=	Tank Sealing Device

I. Introduction

The Cesium Field Emission Electric Propulsion (FEEP) system requires liquid Cesium with a high purity level. This Cesium has to properly flow and be delivered at the thruster emitter slit, where it is ionized and sprayed thanks to a high electrostatic field (thus generating the thrust).

A newly designed propellant tank has been developed in order to secure contamination free storage of this Cesium, and also proper capillary feeding in the emitter flow path.

This development was undertaken by Astrium, who has long experience in propellant tank design. This was done in parallel to the whole thruster development at ALTA S.pA.

This challenging tank development first aimed at freezing the new tank design; selecting at this occasion, the internal tank and Propellant Management Design (PMD) geometries, the tank material, the seals and Tank Sealing Device (TSD) technologies. It was followed by a validation campaign covering functional, mechanical and corrosion aspects that ended with successful qualification late 2008. The FEEP Tank project, in the frame of the Lisa Pathfinder program, is now entering its last development phase, that is full qualification testing, including environmental functional and lifetime testing, at thruster level. In parallel, the manufacturing and delivery of the flight models is ready to be kicked-off.

II. Tank and PMD heritage – Tank Functionalities

A. General overview

The FEEP tank is the reservoir of the FEEP thruster. FEEP thrusters are usually used in cluster configuration, with e.g. 12 thrusters on Lisa Pathfinder arranged in 3 clusters of 4 thrusters each. Typical FEEP Isp is in the range 3000 to 5000 s for thrust ranging from 0.1 to 150 µN

Figure 1 shows pictures of Alta FEEP Cluster assemblies during testing.

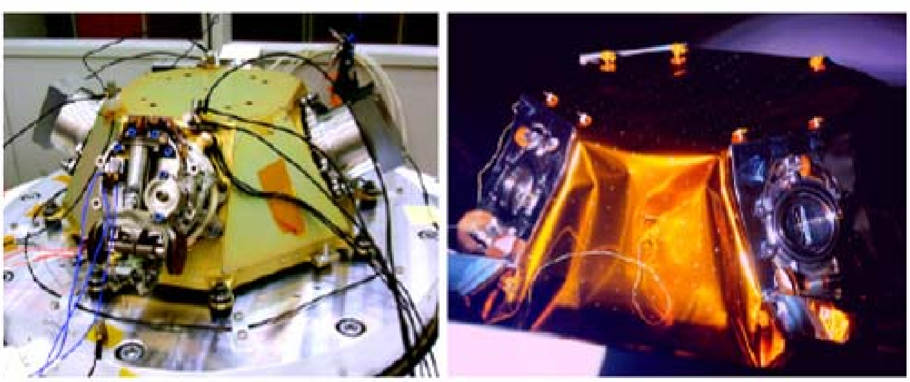

Figure 1. Mechanical testing and thermal balance of FEEP Cluster Assembly *(2008)*

The FEEP reservoir internal design together with the PMD geometry respects the Astrium standards for PMD design. This design logic is in particular the same as the one used on the PMD of the Astrium Eurostar propellant tanks series. (See reference [1]).

Figure 2 shows pictures of the tank assembly, composed of the PMD CAP and the TANK that are bolted one onto the other. The tank is indeed divided into two parts: the TANK BODY where the Cesium is stored, and the PMD CAP that closes the tank on the emitter side.

A two parts design allowing easy dismounting of the pieces together with decoupling of parts functionalities has been preferred in order to ease and shorten the qualification phases.

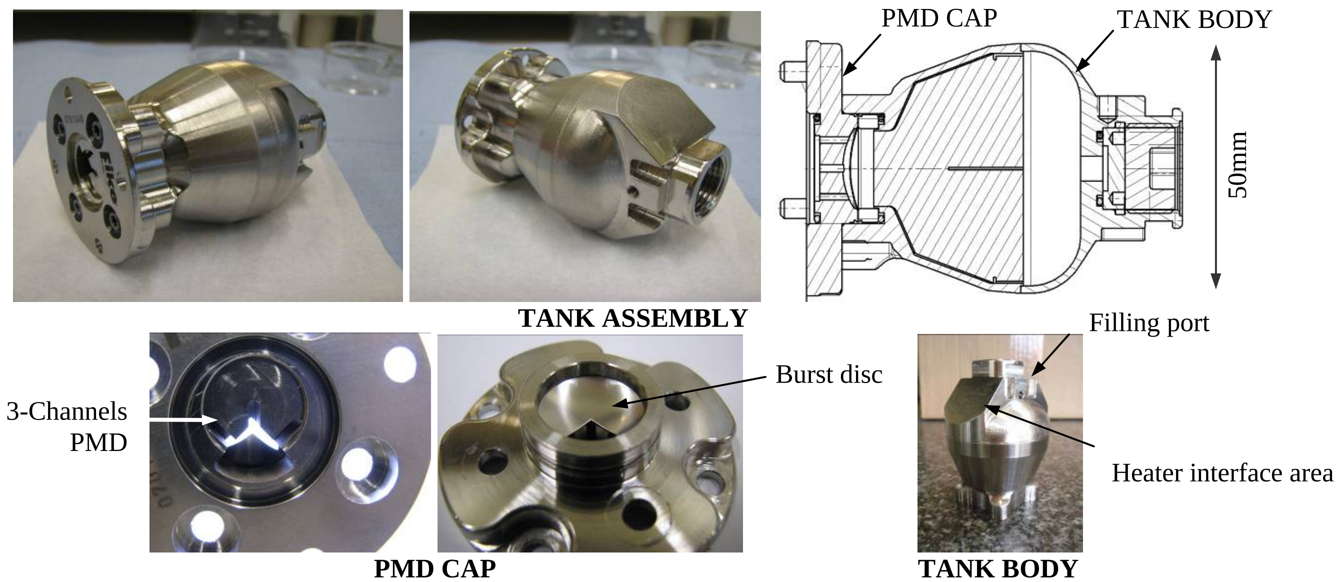

Figure 2. QM FEEP Tank assembly. *PMD CAP and TANK BODY assembly.*

The PMD CAP has then the following functionalities:

- Closure of the tank on emitter side (with bolts and metallic seal)
- Normally closed valve (for tank in-flight opening with a burst disc)
- Capillary feeding of the emitter flow path (with a channels PMD design)
- Mounting of the tank onto the emitter support (with bolts and metallic seal)

And the TANK BODY:

- Cesium leak tight storage (filling port with metallic seal)
- Expulsion efficiency optimization and PMD supply with liquid (conical shape with vanes)
- Management of the thermal gradient (flat interfaces for heaters positioning)

B. Tank Functioning

At room temperature Cesium is solid. The melting point of Cesium is 29°C. For FEEP thruster application, the cesium needs to be liquid.

Once filled under vacuum with pure liquid Cesium and assembled onto the thruster, the tank will remain sealed until in-flight commissioning of the thruster. At this stage, the tank will have to be opened and the thruster will need to be primed with liquid Cesium.

The opening of the tank is obtained by heating up the tank. The amount of the initially filled Cesium is indeed such that it is almost filed at 100%. Then, when heating the tank, the pressure will rise inside that tank thanks to the confined liquid thermal expansion. When the pressure reaches the burst disc opening pressure, the petal of the burst disc opens and the PMD is filled with liquid. Once this step has been completed the flow path until the emitter slit is primed thanks to the combined effect of capillarity and further liquid thermal expansion if required.

During thruster operation, the emitter is continuously supplied with liquid Cesium thanks to the optimized capillary design of the whole flow path: from the tank bottom to the emitter slit (as depicted in Figure 3). The flow path geometry has been designed in order to cope with the desired mass flow rates and in-flight acceleration levels.

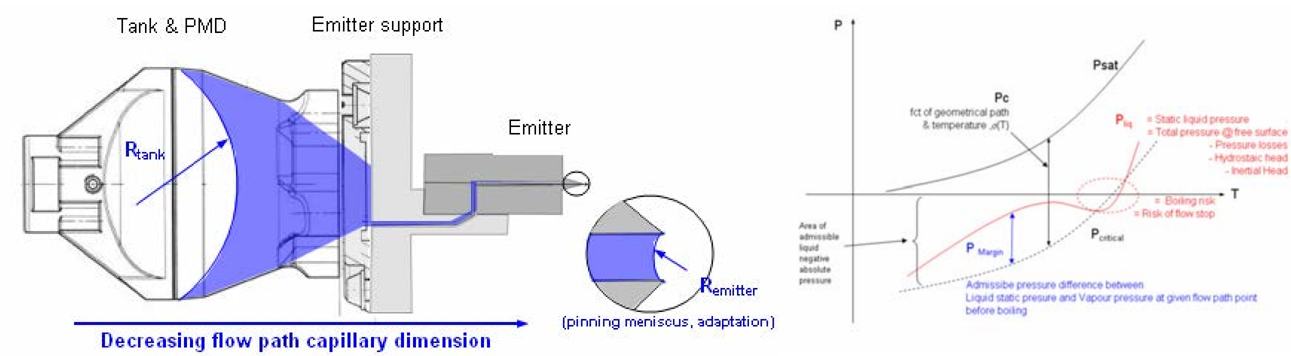

Figure 3. FEEP Capillary design. *Liquid flows to the slit while always remaining in the liquid phase*

The mechanism for the slit feeding with liquid Cesium can be compared to the transpirational pull mechanism in plants, where the evaporation of water from the surfaces of the leaves causes the surface of the water to recess into the pores that are then immediately capillary re-filled (sometimes generating enough force to lift water as high as a hundred meters from ground level to a tree's highest branches). This mechanism relies on the assumption of molecular scale cohesion forces allowing liquid to sustain tension forces, i.e. negative pressures. In the FEEP case, this is not evaporation that generates the flow, but ion extraction via direct field emission ionization from the liquid phase; the continuous refilling mechanism is however the same.

III. Tank design

Cesium being a high reacting material, the tank design complies with hazardous vessels design and handling constraints.

The tank design has been chosen in order to optimize secured storage, contamination free storage, reliable opening of the tank and capillary functioning of the tank (priming and operating flow).

A. Material Choice

A full and exclusive single material design has been selected for corrosion issues and because of the need of good wettability of liquid Cesium onto the tank material.

B. Tank internal volume

The tank is a ~50cm^3 reservoir, whose shape has been optimized in order to reduce end of life residuals and feeding of the tank exit with liquid Cesium. It features two vanes (See Figure 4) whose function is to both damp eventual liquid sloshing and feed the PMD volume.

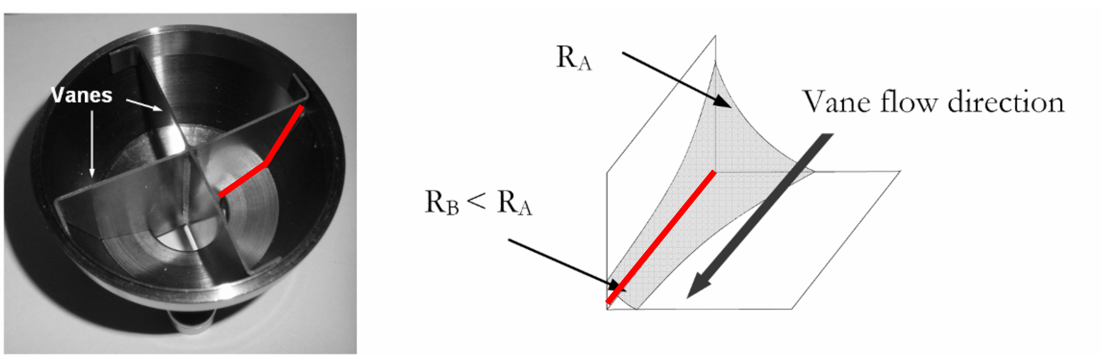

Figure 4. Tank Vanes . *Capillary feeding of the PMD*

C. PMD volume

The internal volume of the PMD CAP has a specific capillary geometry in order to guaranty delivery of liquid Cesium at the outlet of the tank, i.e. the inlet of the emitter flow path. The chosen geometry adopts a channel like pattern.

D. Burst disc

The burst disc used for FEEP application is an already available and intensively used technology in the oilfield industry and fire protection for instance. Its use as a Tank Sealing Device is however an innovating application that has required additional characterization tests because of the burst disc petal opening being a single mode failure.

Figure 5. Burst discs . *closed and open*

E. Metallic Seals

Several seals are used on the FEEP tank. These are full metallic seal.

Figure 6. Metallic seals

F. Tank cleanliness

Tank cleanliness requirements are a full part of FEEP design parameters. A dedicated process for molecular and particulate cleaning has been developed and qualified to cope with the FEEP system low required level of contaminants.

IV. Design Justification

Justification analyses were conducted to validate the tank shell against the ground, launch and flight environments. These analyses involved the use of several commercially available design tools as shown in Figure 7.

Not only static mechanical aspect but also fluid and dynamic ones were investigated.

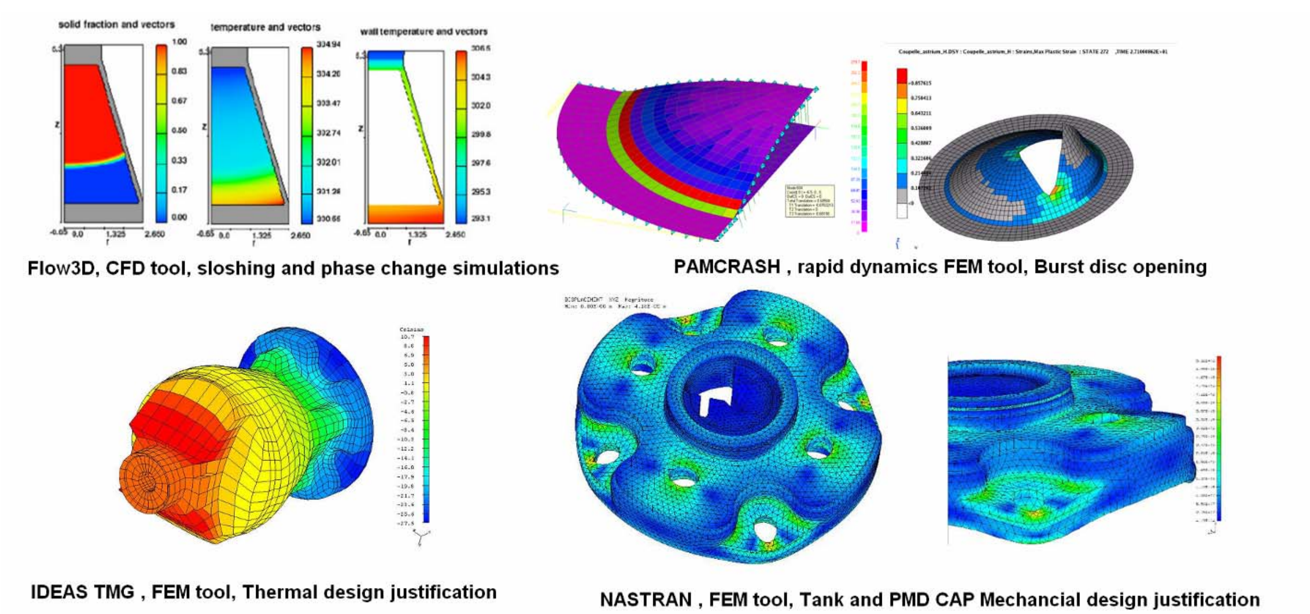

Figure 7. Justification & Simulation. *Numerical tools*

V. EM/QM Tank manufacturing – Acceptance testing

In order to manufacture, assemble and test the more than 20 full tanks assemblies that have been required for ASTRIUM and ALTA qualification needs, a fully operational industrial organization has been built. This European industrial team gathers the required capability for:

- Manufacturing
- Welding
- Controlling
- Cleaning
- and Assembling

all the FEEP tank components and elementary parts.

Each sub-contractor or supplier has been qualified for Flight Models (FM) delivery to Astrium.

Figure 8. FEEP Tank bodies manufacturing and welding

VI. Tank Qualification

The Tank qualification campaign was conducted both at mechanical and functional levels.

A. Qualification at Tank level

Corrosion test campaign (all tank parts)

Corrosion assessment tests have been performed at Cesium Supplier premises. This was motivated by both the need to verify the low contamination levels of the high purity Cesium and the marginal impact of corrosion on the tank materials.

Mechanical qualification – (Tank and TSD)

A mechanical pressure test campaign was conducted in order to validated the tank mechanical design, the leak-tightness of the interfaces and the reliability of the Tank Sealing Device

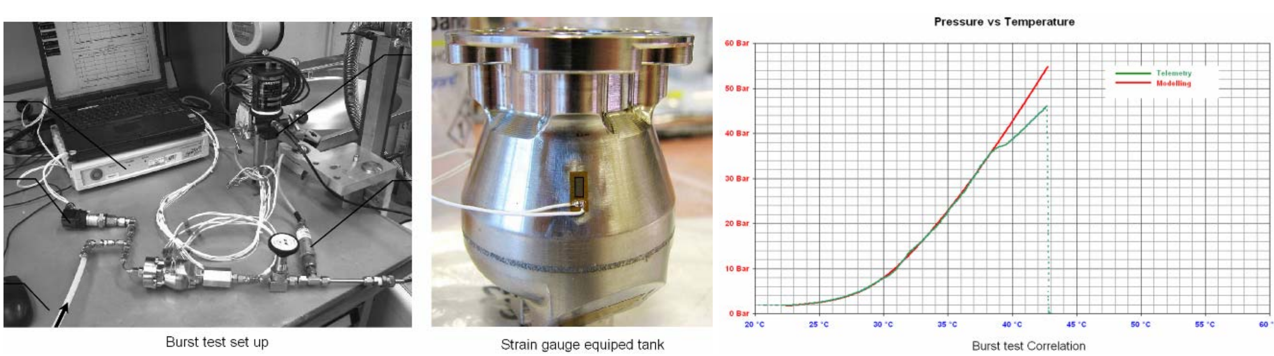

Figure 9. Mechanical and TSD functional Qualification. *Proof and burst tests / Burst disc opening test*

The core equation of the correlated pressure prediction model is the liquid state equation of Cesium; see Equation (1). This equation is coupled with the tank FEM predicted thermal and pressure related volume expansions

$$-\frac{dV_{liq}}{V_{liq}} = \frac{d\rho}{\rho} = \frac{dP}{\varepsilon} - \alpha \, dT \qquad (1)$$

With V_{liq}, the volume of liquid in the tank [m^3], ρ the Cesium liquid density [Kg/m^3], P the pressure [Pa], ε the Cesium compressibility, α the Cesium thermal expansion [K^{-1}] and T the Cesium temperature [K].

The qualification campaign successfully demonstrated:

- The Tank robustness to pressure (proof – burst)
- The TSD opening reliability (burst pressure and petal opening)
- The validity of pressure prediction model
- The limited and acceptable level of debris generation
- The Interfaces leak tightness

Functional qualification (Tank and PMD)

The tank and PMD functional design was qualified by test using the ASTRIUM Neutral buoyancy test facility (See reference [2]). A mock up of the FEEP tank and PMD was used to verifying all the functional capillary mechanisms: from the PMD priming after TSD opening to the full tank draining until the low tank residuals.

The principle of the neutral buoyancy tests is to compensate the gravity forces with the Archimedes forces. Two liquids are used: the water that simulates the gas/vapor phase and an especially on-purpose prepared mixture that simulates the propellant (colored in blue). In order to obtain the adequate Archimedes forces equilibrium, the water and the mixture are chosen to have similar densities. These two liquids being furthermore non-miscible, It is then possible to simulate environments under 0g or very weak accelerations by simply adjusting the bath temperature.

Figure 10 shows The Neutral buoyancy test bench and test results pictures.

The qualification campaign successfully demonstrated:

- The full draining of the tank and then associated low tank residuals
- The PMD suitable capillary geometry for priming

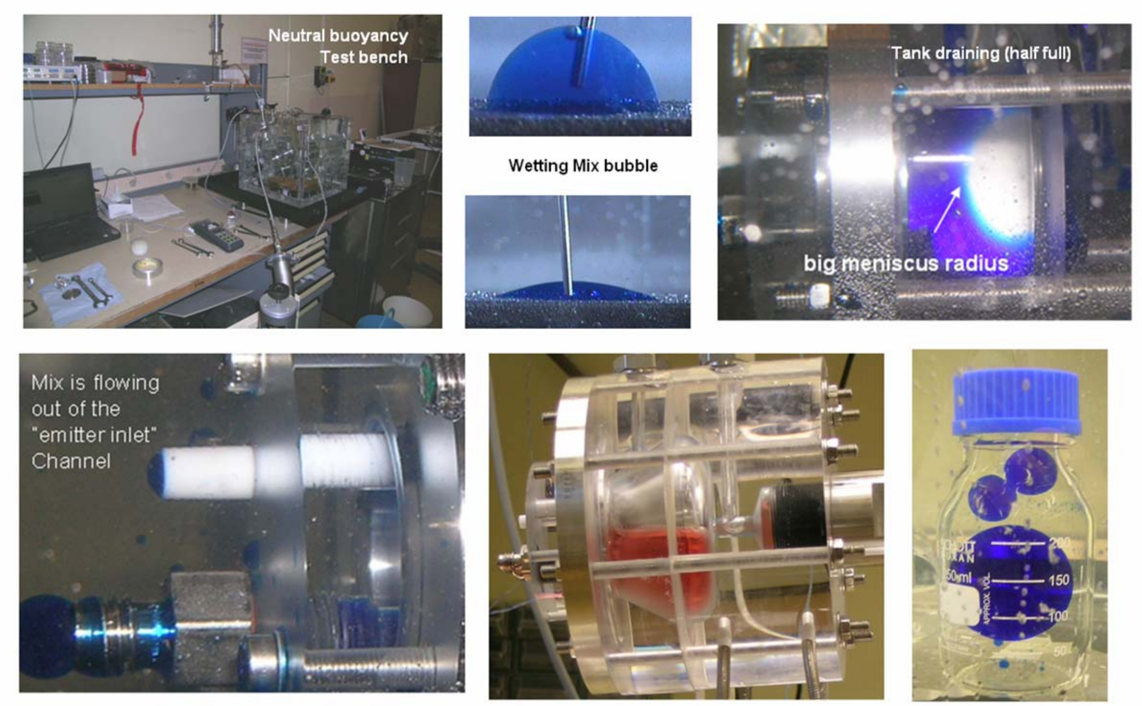

Figure 10. Functional Qualification. *Capillary mechanisms validation with Neutral buoyancy testing (Fluids Zero-g on-ground Simulation)*

Functional qualification with Cs.

Prior to verifying the tank functional behavior by means of testing at thruster level, the so called Tank Filling Calibration Test was performed by Alta aimed at calibrating the filling procedure with Cs and, in turn, achieving the required disk burst repeatability. The Tank Filling Calibration Test represents the first implementation of the tank filling procedure and disk breaking with Cs performed in the framework of Lisa Pathfinder. As a result of the Tank Filling Calibration Test, a comprehensive set of data was collected to validate/correlate the analytical models used to predict tank behavior and TSD rupture.

The test was performed on a tank engineering model, taken out of a batch of 16 items manufactured to comply with the FEEP thruster development/verification needs, fully representative, from the functional viewpoint, of the tank final qualified design. The test article was subjected to bake-out in the assembled configuration (PMD cap integrated on the tank body) and leak testing. Then it was filled through the rear port with a calibrated amount of Cs (89.9 grams, lower end of the nominal range), sealed and integrated onto the test set up. The test procedure then proceeded with heating the filled tank up to disk burst.

In order to monitor the test item temperatures during the heating phase, the test set up was equipped with a number of temperature sensors, as showed in Figure 11, which also show the test set up. The pressure inside the tank induced by thermal dilatation of cesium during the heating phase was indirectly monitored as a function of tank deformation detected during pressurization by means of two optic fiber strain gauges glued on the external surface of the tank body. In order to minimize the uncertainties related to the tank thermal model, the test was carried out in vacuum conditions (no convection) and the tank was installed in a quasi adiabatic configuration. A video-camera, accommodated outside one of the vacuum facility windows, was used to record the disk rupture sequence.

After completing the chamber vacuum procedure, the tank heating sequence started. Tank heating was performed very smoothly in order to limit any thermal gradient and keep the temperature of the tank surface and propellant temperature as close as possible to one another.

The tank pressurization started at a temperature 1.5 °C lower than the expected analytical temperature. The TSD rupture occurred only 0.5 °C below predicted value. Very good correlation was achieved between the collected experimental data and analytical data computed through the model used to predict tank behavior and disk burst. The post test inspection showed that disk opening was complete with a nice satisfactory clearance.

Figure 11. Thermocouple location on the tank & TSD Burst Test set up with Cesium

B. Testing at Thruster level

The tank functional behavior was validated at thruster level during tank activation for priming tests performed by Alta (at Alta's premises or in the ESTEC laboratories) in the framework of the technology development phase of Lisa Pathfinder.

The tank engineering models integrated into the thruster assembly to perform priming tests were taken out of the batch of 16 items already mentioned with reference to the tank filling calibration test. Apart from marginal updating/improving amendments induced by experience, tank preparation (bake out and leak testing), filling and activation by heating were performed in compliance with the procedures firstly implemented during the tank filing calibration test. Monitoring of the pressure inside the tank was indirectly performed by means of two fiber optic strain gauges glued on the tank body.

All tanks, which had successfully undergone full acceptance testing before usage for thruster priming tests, behaved in good accordance with predictions: in fact, the measured tank pressurization and disk burst temperatures were in agreement with relevant figures analytically computed through the models used to predict tank behavior and disk burst.

VII. Conclusion

The FEEP tank development program is a successful "rendezvous" of a complex technological need, off-the-shelf established parts and the capillary design experience of Astrium. It has lead to the development of a robust and reliable tank for a never-before attempted technology demonstration.

This has been a privileged occasion for Astrium to demonstrate its capability to satisfactory answer the need for space highly specific products. Such kind of products development requires the knowledge and experience of the European space network and all its affiliated sub-contractors. The proximity of the tank design team in Toulouse to Spacecraft system decision teams is also a valuable advantage thanks to the conscience of all its specific constraints and needs of such products.

Started mid-2006, the development phase of the FEEP tank ended late 2008 with its successful qualification at tank level. The product is now entering a second major phase, that is full qualification at thruster level. In parallel, manufacturing and acceptance of parts for more than thirty flight units is being started

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