VENUS EXPRESS CHEMICAL PROPULSION SYSTEM – THE MARS EXPRESS LEGACY

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ABSTRACT

ESA's ambition of inter-planetary exploration using a fast-track low cost industrial programme was well achieved with Mars Express. Reusing the platform architecture for the service module and specifically the Propulsion system enabled Venus Express to benefit from several lessons learnt from the Mars Express experience. Using all existing components qualified for previous programmes, many of them commercial telecommunication spacecraft programmes with components available from stock, an industrial organisation familiar from Mars Express was able to compress the schedule to make the November 2005 launch window a realistic target.

While initial inspection of the CPS schematic indicates a modified Eurostar type architecture, "a similar system using some Eurostar components" would be a fairer description. The use of many parts of the system on arrival at the destination (Mars or Venus in this case) is a departure from the usual mode of operation, where many components are used during the initial few weeks of GTO or GEO. The system modifications over the basic Eurostar system have catered for this in terms of reliability contingencies by replacing components, or providing different levels of test capability or isolation in flight.

This paper aims to provide an introduction to the system, address the evolution from Eurostar, and provide an initial assessment of the success of these modifications using the Mars Express experience, and how measures have been adopted specifically for Venus Express.

1 INTRODUCTION

In November 2002 ESA signed the contract to re-use components and structural equipment not used during the Rosetta and Mars Express (MEx) programmes. The aim of this re-use was to provide sufficient cost and time savings to make an exploratory mission to Venus feasible in the time frame of a November 2005 launch. The industrial organisation set up for MEx demonstrated once again how collaboration and cooperation between the various companies and sites could benefit a programme, picking the combined expertise and experience available in Europe.

Many of the individuals working on Venus Express (VEx) have joined the programme directly from MEx bringing with them various lessons learnt to improve the design (where possible), manufacturing and test methods, and operations. "New blood" in the project has also facilitated lessons and improvements from other programmes such as Rosetta and the wealth of telecommunication spacecraft experience.

This paper describes the VEx Chemical Propulsion System (CPS) and illustrates how this MEx heritage has been employed to improve the design for the new application.

2 MARS / VENUS EXPRESS SYSTEM

[2][7][9][10] The Venus Express CPS is a helium-pressurised bipropellant system, using monomethyl hydrazine (MMH) as the fuel and mixed oxides of nitrogen with 3% nitric oxide (MON-3) as the oxidant. The main engine, used for Venus orbit insertion, has a thrust of ~416 N and a specific impulse of ~317 seconds. Four pairs of 10 N thrusters (4 primary, 4 redundant) are provided for trajectory corrections and attitude control / reaction wheel unloading.

The CPS is designed to operate in a constant pressure mode during main engine firings using a regulated helium supply. Following completion of the orbital injection manoeuvres, the regulated helium supply and the main engine are isolated. The remaining propellant is supplied to the thrusters in blow down mode, i.e. the system pressure reduces as propellant is consumed. There is no appreciable loss of performance because the thrusters are capable of operation over a much wider range of inlet pressures than the main engine.

Propellant is delivered to the main engine and thrusters by the propellant feed subsystem, which is supplied with helium by the pressurant subsystem. Each of these contains pipe work (with associated fittings) and CPS units. The subsystems are examined below (refer to Figure 1).

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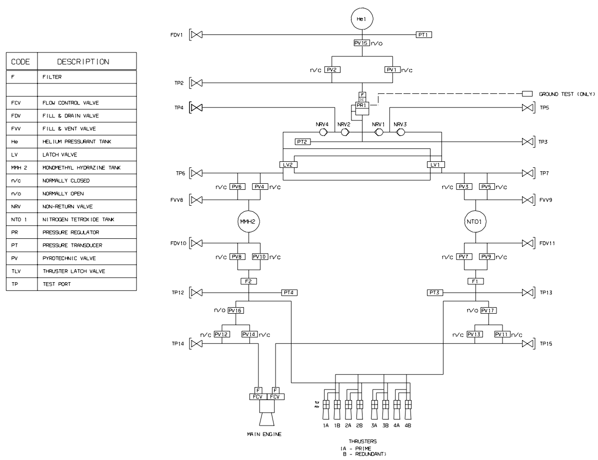

Fig. 1. CPS Schematic

2.1 Pressurant Subsystem

The helium pressurant subsystem is commonly referred to as the “gas side”. It may be considered as two “sections”, the high pressure gas side and the low pressure gas side.

2.1.1 High Pressure Gas Side

The high pressure gas side comprises: a 35.5 litre helium tank, normally open (N/O) and normally closed (N/C) pyrotechnic valves (PVs), a high-range pressure transducer (PT), a fill & drain valve (FDV), and a test port (TP). This section has a maximum expected operating pressure (MEOP) of 276 bar, and during all ground operations and through launch it is isolated from the pressure regulator (see below) by a pair of N/C PVs. These are arranged parallel to each other, providing redundancy in the design. Helium usage is monitored by the high-range PT. The purpose of the N/O PV is to isolate the pressurant tank from the rest of the CPS after the final main engine (ME) firing. There is no need for a redundant N/O PV since successful tank isolation is not critical to the mission. The helium tank is loaded via the FDV. The TP is used for pressure regulator performance testing on the ground.

2.1.2 Low Pressure Gas Side

The low pressure gas side comprises: a pressure regulator, non-return valves (NRVs), a pair of low flow latch valves, a low-range PT, N/C PVs, TPs and FDVs.

This section has a MEOP of 20 bar, controlled by the regulator which senses downstream pressure. The regulator is the dual, series redundant type. This design features both a primary and a secondary regulator. In the event of failure of the primary regulator (~17 bar regulated pressure), the secondary regulator will control the system pressure (at ~17.5 bar). Another feature of the regulator is the dynamic flow limiter fitted at its inlet. The limiter restricts the rate of rise of downstream pressure in the unlikely event that the firing of a N/C PV in the high pressure gas side delivers helium too rapidly for the regulator to respond.

During ME firings and over the on-orbit life of the spacecraft, there exists a potential for propellant vapours to migrate from the propellant tanks toward the pressure regulator. To prevent possible mixing of fuel and oxidant vapours, a pair of NRVs are fitted in the helium lines to both the fuel and the oxidant sides of the system. To increase reliability each pair of NRVs is arranged in series, providing two inhibits to prevent mixing of propellant vapours. The potential for propellant vapour migration is particularly relevant to the long cruise to Venus, during which the ME is isolated and the thrusters are fired only intermittently. Therefore, further protection is provided by the addition of a pair of parallel redundant low flow latch valves in the low pressure gas side. These allow the pressurisation lines to be closed off for the greater part of the time. The latch valves are located upstream of the N/C PVs. This eliminates any risk of debris, possibly generated by the firing of the PVs, entering the latch valves. The low-range PT is used to monitor the pressure in this section in flight and during testing on the ground. The purpose of the N/C PVs is to keep the propellant feed subsystem isolated from the pressurant subsystem until the time comes to bring the propellant tanks up to regulated pressure (~17 bar).

As in the high pressure side of the pressurant subsystem, the N/C PVs are positioned in parallel for redundancy. The fill & vent valves (FVVs) and TPs are used on the ground, e.g. to vent gas during propellant tank filling, to pressurise section volumes, and to obtain system pressures via ground instrumentation.

2.2 Propellant Feed Subsystem

The propellant feed subsystem, commonly referred to as the “liquid side”, supplies propellant to the ME and thrusters. It comprises: a pair of 267 litre propellant tanks, N/O and N/C PVs, propellant filters, low-range PTs, ME, reaction control thrusters, TPs and FDVs.

This section is pressurised with helium by the low pressure gas side, and has a MEOP of 20 bar. Propellant is demanded from the fuel and oxidant tanks by the ME and thrusters, at oxidant-to-fuel mixture ratios of ~1.67 and ~1.54, respectively.

The presence of the N/C PVs allows the propellant feed subsystem downstream of the propellant tanks to remain isolated before flight. Thus the tanks may be loaded with simulated propellant for ground testing (not envisaged for VEx), and later with propellant at the launch site. Loading of these liquids is performed through the FDVs, during which gas in the tanks is vented out through the FVVs. The N/C PVs also isolate the tanks from the rest of the propellant feed subsystem for proof pressure testing of the pipe work without pressurising the propellant tanks, and to satisfy launch vehicle requirements of 2 inhibits between propellant supply and any thruster combustion chambers. As is the case throughout the CPS, the N/C PVs are positioned in parallel for redundancy.

Downstream of the PVs are the filters, one for fuel and one for oxidant. These provide an additional level of protection to the ME and thrusters, which have filters built into them. The low-range PTs are used to monitor propellant tank pressures in flight, following the opening of the N/C PVs between the tanks and the PTs. Downstream of the filters the pipe work divides into separate branches, supplying the ME, and the reaction control thrusters (RCTs).

In the feed lines to the ME are the N/O PVs. Their purpose is to isolate the engine after its final firing. Because ME isolation is not critical to the mission, the N/O PVs are not duplicated for redundancy. The purpose of the N/C PVs in the feed lines to the ME is to allow it to remain isolated until required without compromising the use of the thrusters during Venus transfer. Again, the N/C PVs are positioned in parallel for redundancy. The ME is fitted with its own filters and flow control valves (FCVs). The dual valve thrusters are arranged in pairs, primary and redundant. Direct switching between the primary and redundant thruster of any pair can be implemented in the unlikely event of failure of any primary thruster. Each unit incorporates a filter, and a thruster latch valve (TLV) upstream of a flow control valve (FCV), providing further redundancy in the system. As for the gas side, the TPs are used on the ground.

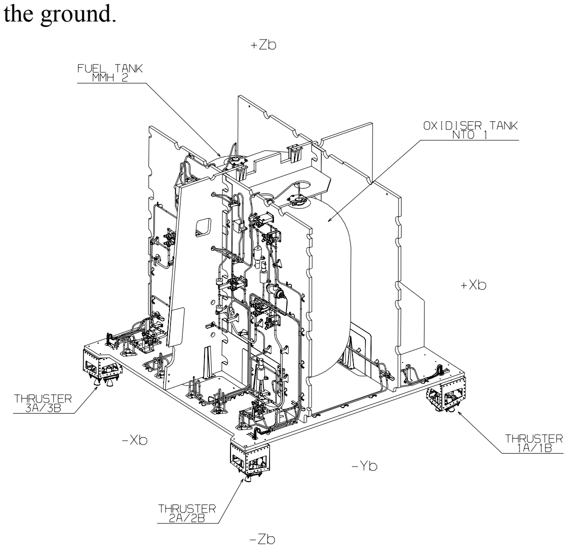

Fig 2. CPS on Structure

3 SYSTEM HERITAGE

To maximise the reliability of the system, many features of the flight proven Eurostar schematic have been employed on Mars and Venus Express. [3]

The high pressure side of the pressurant subsystem is identical to the current Eurostar design. The low pressure side, between the Pressure regulator and the Propellant tank inlets are very similar; however the following modifications have been introduced:

- As a result of the use of only 2 tanks versus the Eurostar 4 tank system the need to isolate the propellant tank ullages of like tanks is no longer required, so N/O PVs in the propellant tank inlet lines have been omitted.
- For the same reason a latch valve used to close the link between the inlets of the propellant tanks is not required.
- An additional low-range PT has been installed to monitor the pressure regulator outlet.
- 2 additional TPs have been mounted between the NRVs. These additional TPs allow individual NRV testing, whereas combined testing is employed on Eurostar.
- 2 low-flow latch valves (LFLVs) have been introduced in the pressurant lines above the propellant tanks. As briefly described in section 2.1.2, these provide an additional barrier against the mixing of propellant vapours in the pressurant sub-system during the long transfer periods between Earth and Mars or Venus.

Downstream of the 2 propellant tanks, the schematic has been simplified to provide increased reliability, and leak protection.

- High Flow Latch Valves (HFLVs) for tank selection are no longer required, so are replaced by a pair of N/C PVs.
- Mismatch orifices are not required with a 2 tank system.
- Individual tank PTs are not fitted. Feed line pressures are monitored by PTs in the lines downstream of these PVs.
- Individual propellant tank outlet line filters are omitted. Propellant filtering is still performed in the feed lines by filters fitted immediately downstream of the propellant tank PVs.
- PVs isolate the ME section from the RCT feed lines as ME priming is not required until shortly before the Orbit insertion manoeuvres.
- RCT branch isolation LFLVs are omitted, as dual valve RCTs can be individually isolated.

4 COMPONENTS HERITAGE

The following components fitted to Venus Express have been previously qualified and flown in the frame of the various Eurostar programmes: (Note this list is not exhaustive, but provides an illustrative sample.)

Table 1. Component Flight Heritage

Component	Eurostar Programmes Flown	Other Missions flown
Fill / Drain Valves (and Test Ports)	All Eurostar.	Cluster, Mars Express
Low Flow Latch Valve	All Eurostar	Mars Express
Main Engine	none	Cluster, Mars Express
Non Return Valve	E 3000 (W3A)	Rosetta
Pressurant Tank	E1000, E2000 (Inmarsat 2, TC2, Nilesat) E2000+ (HB2)	Cluster, Mars Express
Pressure Regulator	E2000 (Nilesat) All E2000+, E3000	Cluster, Mars Express
Pressure Transducers	None	Cluster, Mars Express
Propellant Filter	All Eurostar	Cluster, Rosetta, Mars Express
Propellant Tank	E2000 (Nilesat)	Mars Express
Pyrovalves	E3000 (W3A)	Rosetta
Thruster	None	Rosetta, Mars Express

As indicated above, the ME (EADS-ST GmbH, Lampoldshausen), 10N dual valve Thrusters (EADS-ST GmbH, Lampoldshausen) and PTs (Snecma) are the only non-standard Eurostar components used for VEx.

Whilst many alternative components could have been used in place of those above, components already in stock, or in the procurement cycle where chosen wherever possible to reduce the schedule risk associated with any new item of hardware, or new procurement cycle. In some cases, the components utilised for VEx were originally procured in support of previous ESA programmes including Rosetta and MEx, and as such required little additional effort in confirming suitable qualification for this application.

5 ADDITIONAL QUALIFICATION FOR MARS / VENUS EXPRESS APPLICATION

For VEx, no additional qualification testing was required for any component. As illustrated in table 1, all equipment was fully qualified for the MEx mission with the exceptions of the NRVs and PVs, both qualified to levels encompassing the loads predicted for VEx with a Soyuz launch.

Only two components were considered not fully qualified for MEx. The propellant tanks and ME were both tested to proto-flight levels during their respective environmental test campaigns, to ensure adequate margins existed against the predicted loads.

In addition, the ME valve seats were subject to a long duration propellant soak test, to ensure there was no risk of leakage or failure to open the valves due to valve seat swelling. This 100 day test was to provide margins for MEx, as it was expected to perform a flight test firing of the ME during the cruise phase some months prior to the MOI (Martian Orbit Insertion) manoeuvre. Flight experience has shown this full duration was used with no anomalous behaviour of the ME valves.

6 LESSONS LEARNT

6.1 System Design

The different mission requirements for VEx impose different operational constraints on the spacecraft, and in particular the manoeuvres required to ensure a safe capture into Venusian orbit, whilst gaining the optimum scientific return. [1] The platform constraints discussed below have limited the overall wet mass of the spacecraft given the tank size, and structure load qualification. The pressurant and propellant tanks (Propellant Management Device - PMD inside the propellant tank) have imposed specific detailed limitations for the Venus Orbit Insertion (VOI) manoeuvre. These limitations will force subsequent apsis reduction manoeuvres to be performed with the 10N RCTs rather than the ME as originally foreseen and performed on MEx [8]. At the time of writing, further iterations of the pressurant analysis and propellant budgets were in preparation to define the proportion (if any) of the operations in Venusian orbit could be safely conducted using the ME, within these constraints.

The MEx system performance modelling and predictions utilised software and mathematical models developed and validated over many years of Eurostar operations. The MEx operational experience has shown that these models and predictions are accurate for non-Eurostar systems like MEx and VEx. [6] The same methods and tools are used for VEx.

6.2 Platform Design

There were two relatively minor changes to components used for VEx that were not used for MEx. [7]

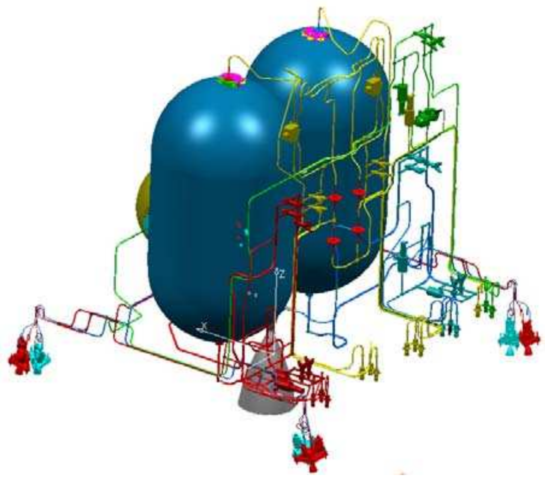

Fig. 3 CATIA model of CPS

6.2.1 Non-Return Valves

MEx used NRVs manufactured by Moog (USA) which were used by all the Eurostar 2000+ spacecraft. For Eurostar 3000, the Polyflex (UK) NRVs qualified for use on Rosetta were selected as a replacement. Since the Eurostar 3000 qualification programme more than scoped all requirements of VEx (assuming a Soyuz launch), units were selected from stock for this application. The change on interface had no significant impact on the layout design.

6.2.2 Pyrotechnic Valves

The MEx pyrotechnic valves were OEA (USA) units, again standard Eurostar 2000+ units taken from stock. VEx again took advantage of the Eurostar 3000 stock to use Conax (USA) pyrotechnic valves also originally qualified for Rosetta with a delta-qualification for Eurostar 3000. These PVs had a slightly different interface which forced a small but significant change to the layout and performance of the system, particularly in the feed lines to the ME.

Due to the tight volume envelope available to the CPS, the change in PV interface resulted in the need to replace many 90° pipe bends with machined elbows. This has increased the overall pressure drop between the propellant tanks and the ME inlets and thus changed the predicted performance of the ME during the long VOI manoeuvre. This small increase in pressure drop and subsequent loss in ME performance is actually a second order effect when compared to the different thermal environment, and how the tank temperatures and therefore pressures will affect performance and consumption.

6.3 Thermal

As already indicated, the thermal design has caused the largest design change between the two interplanetary missions as a result of the different mission scenario and external environment. [4] MEx used a thermal design similar to Eurostar 3000 by making use of panel mounted heaters around the CPS all enclosed by "tent" sections to allow efficient heating of relatively large volumes of pipe work and components. For VEx, the different thermal environment and power limitations has resulted in a return to the individual line and component heating strategy employed by the Eurostar 2000+ spacecraft. VEx has also required far more stringent controls of the pressurant side of the system, not normally thermally controlled for Eurostar spacecraft. Again this is partly due to the use of the pressurant side of the system through the transfer and approach to Venus, whereas in a GEO communications spacecraft, it is isolated a few days after launch, when the ME is no longer required for Apogee manoeuvres.

This change in thermal design philosophy has resulted in some of the most significant lessons learnt from the manufacturing phase of the programme. The collaboration across different sites (EADS Astrium, Toulouse responsible for thermal design, Stevenage responsible for the CPS) was facilitated by a common reporting structure through the Mechanical / Thermal / Propulsion (MTP) department. Significant effort was required to ensure error free translation of requirements into acceptable engineering drawings and procedures, including the use of regular conference calls and meetings. This process clearly benefited from the co-location of disciplines during these critical phases, without which it is unlikely that the tight schedule imposed by the manufacturing programme could have been met.

6.4 Operations

The operational requirements of the CPS have also led to a departure from the standard Eurostar operating procedures. The long cruise phase on the interplanetary missions prior to the use of the ME instigated the return of PVs in the ME feed lines. Keeping the ME isolated from the feed line sections prevents the ME valve seats from long exposure to propellants. In the typical Eurostar scenario, they are only exposed to propellants in orbit, until the ME is isolated after the last Apogee manoeuvre, typically 7 to 10 days after launch. As discussed above, a long duration soak of the valves seats in propellants was qualified up to 100 days as part of the MEx programme.

Commercial GEO telecomms programmes tend to have much longer life times and propellant loads than the MEx and VEx spacecraft. To avoid inefficient burn strategies, they tend to employ multiple burn strategies to acquire their operational orbits. MEx and VEx have no such luxury and need to ensure planetary capture in a single manoeuvre. This gives rise to a long burn depleting the tanks to a much lower fill ratio than a typical telecomms spacecraft. Additionally GTO (Geostationary Transfer Orbit) manoeuvres are conducted with full visibility of ground control and monitoring for telecomms spacecraft, whereas for MEx this manoeuvre was conducted totally automatically, and without any ground visibility.

Once in orbit around Mars (or Venus) the operations are simpler than the Eurostar system, as there is no need for propellant management between pairs of tanks. The ME and pressurant system are isolated in a similar fashion, and the use of individual thruster isolation is more failure tolerant than the branch isolation philosophy.

With the exception of the key lessons learnt discussed below, the basic operational approach between MEx and VEx is the same.

The different thermal design due to the long cruise phase of the interplanetary missions requires a more active approach to the management of the CPS temperatures. Sections of the CPS are heated, controlled by thermostat groups. For VEx, these heater groups were optimised for the different thermal environments during cruise and “on station” in Venusian orbit, the different levels of power available, and also lessons learnt from MEx. [3] [4] The target solution was to ensure a simple operating strategy, with minimum ground intervention for switching of heater circuits.

The second key learning point from the MEx MOI December 2003 / January 2004 campaign came during the final isolation of the ME. After the N/O PVs 16 and 17 are fired to isolate the ME, the feed lines are vented to evacuate the lines. The venting avoids the risk of rupturing these sealed lines if thermal conditions heat and therefore pressurise the propellants. The venting is performed in a series of short duration commands of the ME, as the propellant is vented. This action does cause attitude disturbances. For heavy GEO telecomms spacecraft, these disturbances are small, and easily compensated by the AOCS (Attitude and Orbit Control System). For MEx, these disturbances proved to be significant and almost led to a “safe mode” being commanded by the s/c. For VEx, a more robust AOCS mode will be used throughout this operation to ensure the s/c pointing and control remains in nominal conditions.

7 CONCLUSIONS

The legacy of MEx is a CPS which has been flight proven, operating reliably with minimal ground intervention over 300 million km away. The use of spares and stock components ensured the CPS was delivered on time to the project for the next phase of the manufacturing process, against a challenging schedule and within the expected budget.

Whilst many may describe the MEx and VEx propulsion systems as a 2 tank Eurostar due to the extensive use of Eurostar components, a better description is a new, reliable propulsion system exploiting extensive flight heritage of both Eurostar and other scientific missions.

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