DEVELOPMENT TESTING OF A NEW BIPROPELLANT PROPULSION SYSTEM FOR THE GMP-T SPACECRAFT

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ABSTRACT

A new small geostationary platform, capable of supporting variable communications payloads with up to 3kW of power and 250kg in mass, is currently under development at SSTL. The platform shall utilise a conventional MMH/NTO bipropellant propulsion subsystem to provide the necessary delta-V required for transfer orbit manoeuvres and station keeping for up to 15 years. The system comprises a 400N main engine, and 16 smaller reaction control thrusters all fed from 2 x 700L propellant tanks individually pressurised with helium by means of an electronic (bang-bang) pressure regulation system. This paper presents an overview of the system architecture and details the preliminary analysis performed, along with the results obtained from the first phase of design verification tests carried out on an engineering model of the propellant feed system. The results provided confirmation of the steady-state flow characteristics and retired the risks associated with hydraulic shock transients (water-hammer) occurring in the propellant lines during priming, which could have an adverse effect on subsystem performance.

NOMENCLATURE

The following symbols and abbreviations are referred to throughout this paper:

EM	Engineering Model
ESPSS	European Space Propulsion System Simulation
ΔP	Pressure Drop (delta-P)
CoG	Centre of Gravity
FDV	Fill & Drain Valve
HFE	Hydrofluoroether
LAE	Liquid Apogee Engine
LV	Latching Valve
$\dot{m}$	Mass Flowrate
MMH	Monomethyl Hydrazine
MON	Mixed Oxides of Nitrogen
NTO	Nitrogen Tetroxide
PT	Pressure Transducer
PV	Pyrotechnic Valve
RCT	Reaction Control Thruster
ρ	Density

INTRODUCTION

Background

The primary objectives of the project, co-funded by ESA's ARTES 3-4 programme, are to evolve SSTL's existing small low-medium earth orbiting satellite heritage technologies and design an adaptable Geostationary Mini-satellite Platform (GMP-T), with low production costs and a reduced order-to-launch schedule.

The increased delta-V requirements for this GMP-T mission have driven SSTL to replace its proven cold gas propulsion systems with a more efficient higher energy chemical propulsion system and an initial trade-off of existing propulsion technologies against cost, mass and structural design complexity resulted in the selection of a conventional bipropellant system using Monomethyl Hydrazine (MMH) and Mixed Oxides of Nitrogen (MON-3) propellants. The initial phase of the development involved a detailed design study to retire major subsystem risks, specification of baseline tanks and components, supplier selection and identification of materials, processes and facility upgrades required for the subsystem manufacture. The overall subsystem platform layout is shown in Figure 1.

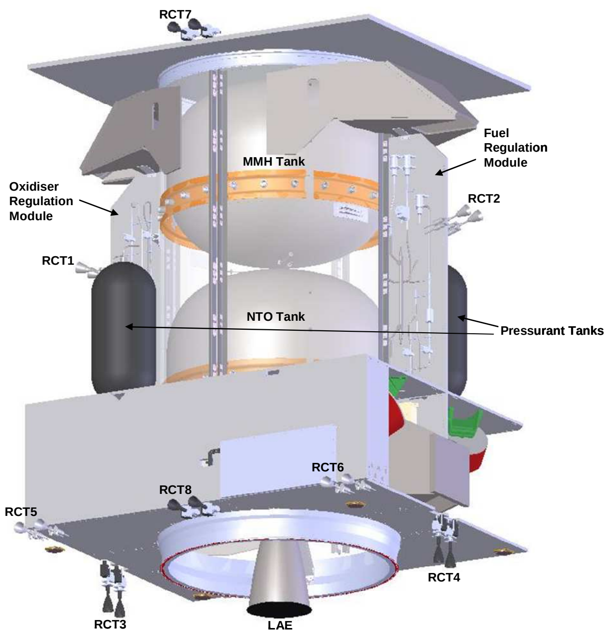

Figure 1. GMP-T Propulsion Subsystem Configuration

Subsystem Design Overview

The GMP-T propulsion subsystem is shown schematically in Figure 2. The system comprises a single 400N liquid apogee engine (LAE), eight 22N and eight 10N reaction control thrusters (RCTs) arranged in primary and redundant pairs, all fed from two 700 litre propellant tanks mounted within the central thrust tube of the spacecraft. The heavier oxidiser is stored in the lower tank to reduce structural loads and keep the CoG as low as possible. The propellants are individually pressurised with helium by means of an electronic pressure regulator.

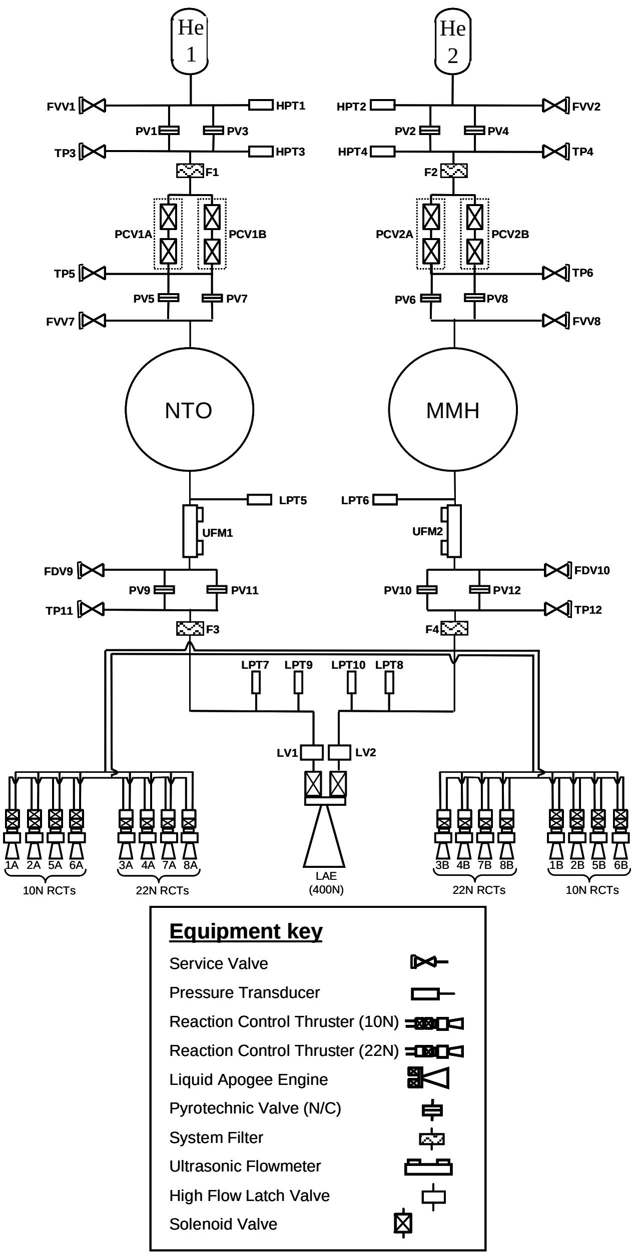

Figure 2. GMP-T Propulsion Subsystem Schematic

To allow a classical SSTL modular approach to propulsion subsystem integration the oxidiser and fuel regulation subassembly components and pipework will be populated on structural panels off-line, tested at module level and then integrated to the primary structure. These will then be connected to the tanks and thrusters with a minimum number of final welds required at spacecraft level.

Electronic Pressure Regulator

The subsystem design maximises the use of existing flight-qualified equipment in order to reduce the amount of non-recurring effort required to achieve full subsystem qualification however, it introduces some non-conventional features designed to reduce the cost, schedule and complexity of operations. One such feature is the electronic pressure regulation system, which has been specified for the GMP-T subsystem primarily due to SSTL having significant design experience and flight heritage in electronic pressure regulators. Whereas conventional propulsion systems typically make use of mechanical pressure regulators combined with non-return valves, in this case a series of solenoid valves are used to control the flow of helium into the propellant tanks based on electronic feedback from a downstream pressure transducer. The solenoid valves can either be activated in a bang-bang mode, or be closed for blow-down mode. This type of system offers the following advantages over a conventional mechanical pressure regulator:

- LAE feed pressures can be controlled using the feedback from PTs installed in the oxidiser and fuel lines upstream of the engine inlet, allowing the LAE to be fired in flight with the same inlet conditions as it was tested on the ground;
- The LAE fuel and oxidiser feed pressures can be varied independently, to control the mixture ratio. This means that complex delta-P analysis and orificing is not required to control the mixture ratio;
- The fuel and oxidiser tank pressures can be topped up separately to allow the RCTs to be fired at the nominal mixture ratio, so as to ensure that fuel and oxidiser are being depleted equally;
- Mid-life propellant tank re-pressurisation becomes a possibility;
- The system is potentially lighter, less costly and requires less panel area for layout;
- The regulation solenoid valves themselves provide mechanical inhibits, which isolate the propellant tanks from the high pressure sections of the subsystem, thus reducing the total number of pyrotechnic valves required.

Initial tests on a breadboard bang-bang pressure regulator and control system were performed early on in the development phase, for the purpose of validating an existing, flight-qualified high pressure solenoid valve as a suitable pressure regulator valve and testing the pressure regulation control logic over a range of inlet pressures, tank ullage volumes and engine inlet pressure regulation bands. The results of these breadboard tests were successful and the valve was baselined for the GMP-T propulsion subsystem.

TEST OBJECTIVES

In order to finalise the design of the subsystem and address the remaining technical risks associated with the hardware and system layout, a series of analyses and subsequent development tests were defined. The primary objectives of these tests were as follows:

- Perform steady-state flow simulations on the propellant feed system using simulants in order to verify a preliminary delta-P analysis;
- Evaluate/mitigate hydraulic shock (water-hammer) and pressure surging effects occurring during propellant line priming, which may affect subsystem performance;
- Characterise any transients and/or flow oscillations in the propellant feedlines resulting from LAE/RCT start up/shutdown that may be sufficient to perturb the pressure regulation control logic;
- Conduct a system performance verification test of the bang-bang regulator and bread-board controller.

To date, the steady state flow characterisation and hydraulic shock tests have been fully completed and shall be discussed in detail from here on. The empirical data obtained from these tests was used to validate a flow model created in EcosimPro, which shall subsequently be utilised to compute theoretical predictions for system performance with real propellants and perform further flow analyses. The EcosimPro software and analysis performed to date for GMP-T shall be discussed in detail in a subsequent section of this paper.

TEST CONFIGURATION

The hydraulic tests were conducted on a representative engineering model of the propellant feed system (see Figure 3) with pipework and components laid out in a horizontal 'Flatsat' configuration in order to simplify manufacturing and eliminate head losses due to gravity. Only one side of the system was fabricated since the pipework design and layout in both oxidiser and fuel feed systems is sufficiently similar to allow the same model to be used to assess both NTO and MMH flow characteristics in the flight system. The corresponding section of the GMP-T propulsion subsystem schematic is highlighted in Figure 4.

Figure 3. Propellant Feed System EM

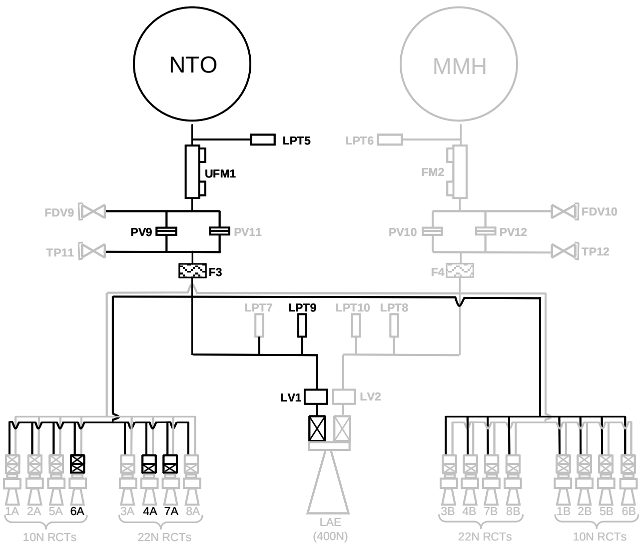

Figure 4. GMP-T Feed System Schematic with Test Section Highlighted

Pipework and Components

The EM pipework consists of a combination of ¼" (6.35mm) and 3/8" (9.53mm) diameter tubing. The main feedlines to the LAE and active RCTs are fully representative, being manufactured from flight-standard titanium 3Al2.5V tubing with equivalent bends, lengths and wall thicknesses as that of the flight system. The remaining lines to non-active RCTs and FDVs are represented with commercial grade stainless steel 316 tubing with equivalent total internal volumes. Flight-like valves, filter and fittings are also utilised in the main flow lines with a single flight-like pressure transducer installed at the location of LPT9 to monitor LAE inlet pressure and provide feedback to the controller during bang-bang regulator testing (to be performed).

A solenoid-driven, fast actuating pneumatic ball valve (Swagelok® Series 40) was used to simulate one of the parallel redundant pyrotechnic valves (PV9) downstream of the propellant tanks, which are fired open in flight to initiate priming of the propellant lines. Initial functional tests on this valve demonstrated a mechanical response time of <10ms, which providing a fully open ¼" flow path within 25 ms of solenoid actuation and thus a comparable yet safe and economical alternative to a real pyrotechnic valve.

Three of the eight primary RCTs (4, 6 & 7) and the LAE flow control valves, were implemented for test, with the redundant feedlines being either blanked off at the location of the RCT valves or fitted with a pressure transducer for monitoring during tests. The LAE and RCT valves were fitted with appropriately sized trim orifices to simulate the pressure drop across the absent injector and thrust chamber and provide the correct steady-state flow conditions during testing at sea level. The rest of the system was suitably instrumented with static and dynamic pressure sensors, flow meters and thermocouples to capture and record all of the necessary test data. The Flatsat pipework layout is shown diagrammatically in Figure 5.

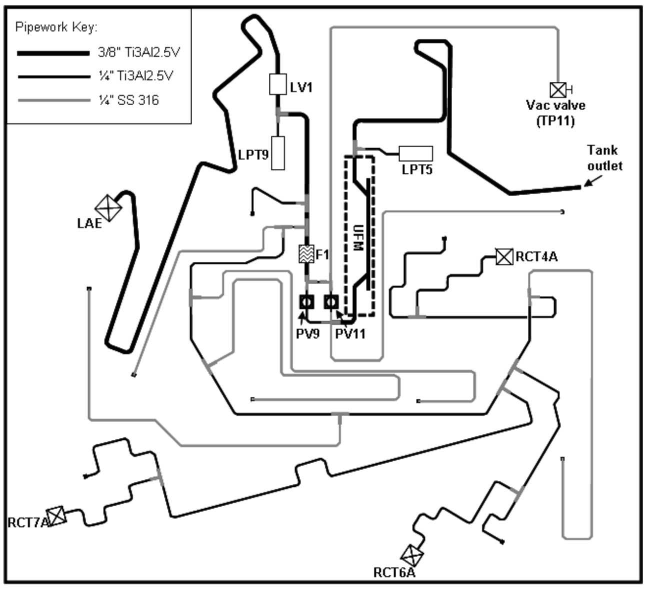

Figure 5. Flatsat Pipework Diagrammatic

COMPONENT DELTA-P TESTS

In order to provide empirical data for calibration of the GMP-T flow model in EcoSimPro, it was necessary to perform individual delta-P tests on the flight components prior to their integration to the EM. This was done using demineralised water, with a coriolis flowmeter to measure varying mass flowrates and a differential PT to measure the pressure drop across each component in turn. The components tested were those with the most significant pressure drops namely the high-flow latch valve, the propellant filter and one of the ¼" ball valves used to simulate PV9/PV11 in the main flow line. Pressure loss coefficients were then generated for each component through linear regression of the test data according to the standard pressure drop law defined by:

$$\Delta P = K\frac{\dot{m}^2}{\rho}$$

The minor pressure losses associated with the pipework and fittings were accounted for in the model by performing straight-pipe frictional loss calculations and using standard loss coefficients for tees and bends.

GMP-T MODELLING AND PREDICTIONS

EcosimPro is a user-friendly simulation tool developed by EA International for modelling simple and complex physical processes, expressing the behaviour in terms of Differential-Algebraic equations and discrete events.

ESPSS is a library developed on the EcosimPro kernel to model the complete propulsion system from the tank to the Combustion chamber [1]. The components are modelled in EcosimPro with the standard pressure drop law, linear against $\dot{m}^2/\rho$ as indicated in the previous section. The pressure drop coefficients for the specific GMP-T flight components were calculated through linear regression of the experimental calibration data obtained. A polynomial law was used in the case of the filter, as described in Figure 6.

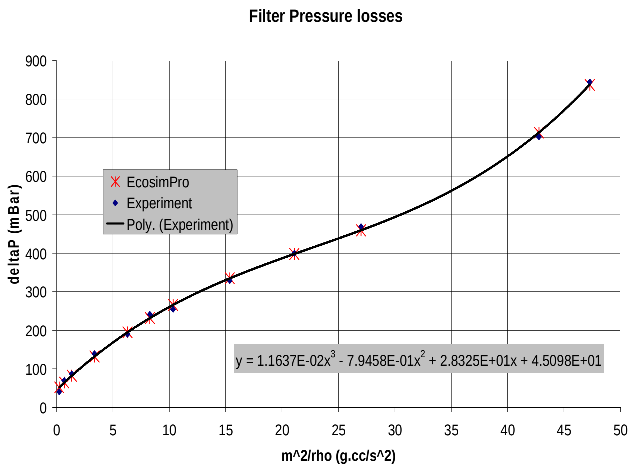

Figure 6. Pressure drop in the Filter

This resistive behaviour can be encountered in porous materials. The pressure loss in the flatsat pipework shown in Figure 5 is driven by the pressure losses of the valves and filter. The modelling done in EcosimPro takes into account second order pressure losses along the pipe and their bends due to viscous effects. The pipes where the mass flow rate is zero can be replaced by non resistive component to reduce the CPU time. The steady state model is described in Figure 7.

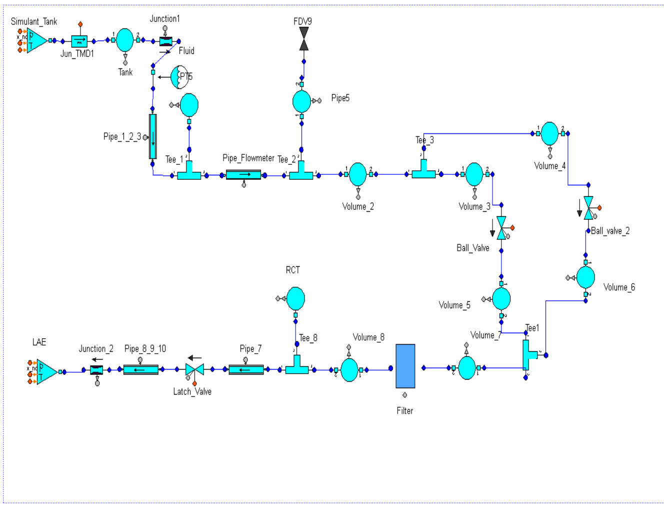

Figure 7. Simplified model for steady-state

STEADY-STATE FLOW TESTS

Test Justification

Since electronic pressure regulation is to be used in the flight system to control oxidiser and fuel pressures, it is not necessary to pre-determine and calibrate precise line pressure drops between propellant tanks and LAE inlet, as would be required for a mechanical regulator with a single set point. The electronic regulator will compensate for unknown or varying line pressure losses by adjusting the oxidiser and fuel 'set points' independently to meet the demand of the LAE, based on feedback from PTs located downstream. It is necessary however to have some predetermined knowledge of the total line losses present in the system in order to perform preliminary system performance analyses and subsequently to allow for optimal pressurisation of the propellant tanks in flight prior to the initial LAE burn. In order to determine/verify analytical predictions for the line delta-P therefore a series of representative steady-state flow tests were performed on the EM using propellant simulants.

Test Results

Measurements of tank pressure, differential pressure and LAE valve inlet pressure were made for a range of different flowrates incorporating the volumetric equivalent LAE flowrate and equivalent delta-P mass flowrates. The tests were performed firstly with demineralised water and then repeated using Novec™(HFE) 7100 in order to obtain data for a higher density fluid more representative of NTO. The simulant flow test results were used to validate the EcosimPro model and provide accurate correlations for real propellants. A comparison of the simulants fluid properties with those of propellants is given in Table 1 with a summary of the delta P predictions and test results given in Tables 2 and 3.

Fluid	Density @20˚C/1 atm (kg/m^3)	Dyn.Viscosity @20˚C/1 atm (Pa.s)	Vapour Pressure @20˚C (bara)
Water	1000	$1.002\text{x}10^{-3}$	0.023
HFE 7100	1527	$0.610\text{x}10^{-3}$	0.218
MMH	876	$0.855\text{x}10^{-3}$	0.049
NTO	1444	$0.419\text{x}10^{-3}$	0.958

Table1. Fluid Properties

Simulant	Tank Pressure (bara)	Mass Flowrate (g/s)	*Predicted Line dP (bar)*	Measured Line dP (bar)	Test Notes
Water	12.62	52.2	*0.643*	0.703	Equal MMH dP
Water	14.72	56.5	*0.748*	0.801	Equal Volumetric
Water	16.40	59.7	-	0.888	Nominal LAE inlet pressure
Water	16.46	66.1	*1.000*	0.945	Max flow demand (LAE + 3 RCTs)
Water	20.69	67.1	*1.012*	1.092	Equal NTO dP
HFE 7100	16.29	72.3	-	0.839	Nominal LAE inlet pressure
HFE 7100	19.891	79.8	*0.913*	1.000	
HFE 7100	-	83.6	*0.988*	>1.034	Equal NTO dP

Table 2. Steady State Flow v Delta P Results

The test results agreed reasonably well with the Ecosim predictions of delta P for each flowrate with a <8% error for water. This error is mainly due to the linear interpolation used for the valve in the whole range of mass flowrates. Their pressure losses were not completely proportional to $\dot{m}^2 / \rho$.

The measured delta P values for HFE 7100 flowrates were higher than expected, which meant that it was not possible to obtain an accurate comparison for the predicted delta P at the equivalent NTO mass flowrate, due to the differential transducer used in the test exceeding its upper calibrated limit. This condition was believed to be a result of the fact that the trim orifice installed in the LAE valve had been designed to provide the correct pressure drop for water only, giving rise to erroneously high pressure drops when the higher density simulant was used. Table 3 below gives the predicted total line delta Ps for real propellants at nominal mass flowrates in the flight system.

Propellant	Flowrate (g/s)	Line dP (bar)
MMH	49.4	0.637 ±0.050
NTO	81.5	1.015 ±0.075

Table 3. Delta P Predictions for Propellant Flowrates

LINE PRIMING TESTS

Test Justification

The GMP-T propulsion subsystem will be configured prior to launch with loaded propellant tanks, at anticipated pressures of between 5 and 10 bara, dependant on fill levels and temperature. The propellant feedlines downstream of the normally closed pyrotechnic valves (PV9-12) shall be pad pressurised with gaseous helium and the 2 high flow latch valves (LV1/2) closed to isolate the LAE. Following spacecraft separation, the propulsion subsystem is brought on-line and initialised by opening the latch valves, firing an RCT valve to vent the feedlines to space vacuum and then actuating the propellant isolation pyro valves to allow the evacuated feedlines to prime with propellant under pressure. This priming process results in high liquid velocities, which generate significant transients (water-hammer) and reflected pressure waves when the liquid comes to an abrupt stop at closed valves and line ends. These transients have the potential to significantly affect performance of the subsystem or cause catastrophic damage/loss of components/spacecraft if not properly quantified and mitigated. The GMP-T feed system EM was therefore utilised to perform a series of representative priming tests with simulants at different pressures to emulate the hydraulic shock levels likely to occur in the flight system. The main purpose of these tests was to validate the EcosimPro predictions for location, maximum magnitude and time of transient pressure peaks, as well as making an overall assessment to determine whether suppression orifices and/or a redesign of pipework would be required in the flight system in order to reduce hydraulic shocks to acceptable levels for the components and pipework.

Test Configuration

In order to capture the necessary data during the line priming tests the EM pipework was fitted with dynamic piezo-electric pressure sensors (Kistler™ type 6005/7005). This type of sensor, having a natural frequency of 70 kHz, is more suited to accurately measure the high frequency transient pressure peaks associated with hydraulic shocks. Accordingly, a high speed, multi-channel data acquisition system was also employed to capture data from the sensors at a frequency of 25 kHz. The dynamic PTs were generally installed at the locations where the highest peaks were expected to occur in each test, namely the ends of the longest RCT feedlines, as well as other specific points of interest. However, as only 4 dynamic PTs were available for testing, some of the tests were repeated with the sensors switched to alternative locations in order to fully characterise the entire feed system during the liquid priming process.

It should be noted that the highest peak predicted in the analysis for each case actually occurred at the end of the RCT2 feedline (147.8 bar for the highest tank pressure case). This was a non-active thruster line manufactured from stainless steel with a smaller internal diameter than that of the active (titanium) thruster lines and therefore the liquid velocity in this line is expected to be higher, leading to a higher water hammer peak. It was decided however not to obtain validation data for the water hammer occurring in this or any of the other non-active lines since their geometry was not representative of the flight model pipework and hence any data obtained would not be fully valid for the flight case.

In addition to the dynamic sensors, 4 regular PTs were also installed at specific positions to measure tank and line static pressures at the start of each test, as well as recording limited hydraulic response data at 2 kHz during line priming. Prior to each test the downstream line volumes were evacuated to a max pressure of 25mbar and then the fast pneumatic ball valve in place of PV9 was fired open via a solenoid to simulate pyro valve actuation. In order to reconfigure the system in between tests the downstream pipework was drained and purged with dry nitrogen before re-applying a vacuum pump for extended durations until a vacuum pressure of <30mbar could be achieved.

Analysis

For the priming tests, a complete transient simulation must be performed. In fact, pressure waves coming from any secondary branches of the propulsion system can influence each other, and potentially add-up in phase to get much higher peaks than expected in a simplified model. Therefore, the complete system needs to be modelled, including all branches with the correct lengths and volumes. The full model is described in Figure 8.

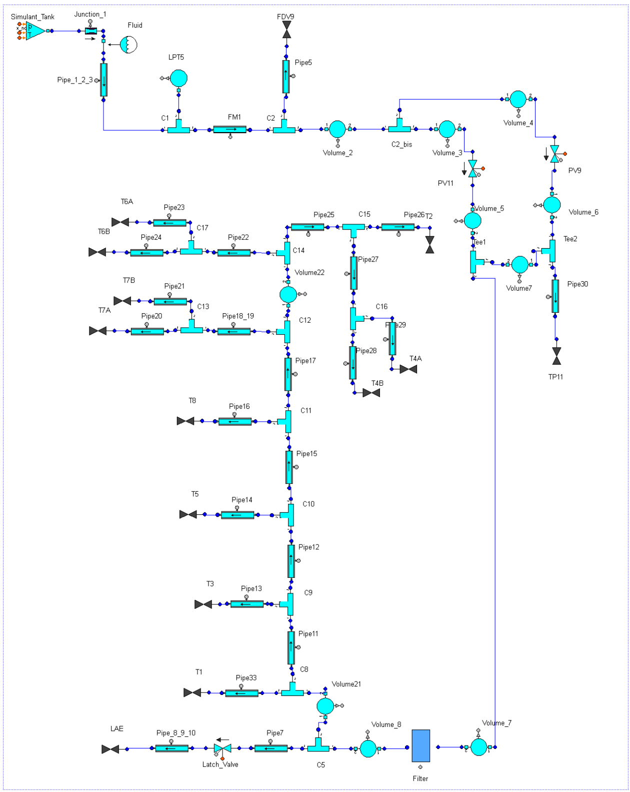

Figure 8. Complete model for priming

A resolution of 1 node per 10 cm is chosen for the pipes elements. Pipes were modelled with their actual materials and thicknesses in order to take into account wall elasticity in the water-hammer peak pressure calculations. Four of the water-hammer experimental test cases are simulated with this model. For each test, the tank pressure and temperatures were adapted to the experimental data. The water tests were simulated using a single real fluid (H_2O), by supposing water vapour is present in the lines downstream of the pyro valves, at a pressure slightly lower than the vapour pressure. The detailed input values are shown in Table 4.

Case	*1*	*2*	*3*	*4*
Tank pressure P_t	16 bar	10 bar	5 bar	16 bar
Vacuum Pressure P_{vac}	20 mbar	20 mbar	17 mbar	25 mbar
Initial temperature T_0	292.65 K	292.65 K	289.35 K	289.55 K
Fluid (Real)	Water	Water	Water	Pl HFE
Gas	None	None	None	Air

Table 4. Inputs for the modelled cases

The valve is opened after 20 ms, with a 10 ms opening time, according to the characteristics of the fast-acting valve used in the tests. The CPU time is about 1-5 hours for each case. The presence of vapour is a driving factor for the CPU time.

Results

Tests were performed with both water and HFE 7100 at tank pressures of 5, 10 and 16 bara to scope the full range of likely launch pressures including a worst case. The maximum peak pressures measured at the ends of the active LAE and RCT feedlines are summarised in Tables 5-8. Data plots from the 4 high speed channels in 3 of the water tests, along with the HFE 7100 high pressure test for comparison, are shown in Figures 9 to 12. The corresponding Ecosim predictions for these 4 tests are shown alongside in Figures 13 to 16.

Simulant	Tank Pressure (bara)	LAE	
		Peak (bar)	Time (s)
HFE 7100	5	6.585	5.402
HFE 7100	10	15.525	3.519
HFE 7100	16	26.046	2.76
Water	5	25.609	4.503
Water	10	43.013	3.009
Water	16	59.843	2.319

Table 5. LAE Max Pressure Peaks

Simulant	Tank Pressure (bara)	RCT4	
		Peak (bar)	Time (s)
HFE 7100	5	6.67	5.306
HFE 7100	10	11.357	3.501
HFE 7100	16	34.48	2.741
Water	5	30.44	4.488
Water	10	80.076	2.999
Water	16	89.899	2.31

Table 6. RCT4 Max Pressure Peaks

Simulant	Tank Pressure (bara)	RCT6	
		Peak (bar)	Time (s)
HFE 7100	5	7.011	5.318
HFE 7100	10	11.269	3.496
HFE 7100	16	37.367	2.735
Water	5	29.648	4.488
Water	10	57.008	3.001
Water	16	72.486	2.309

Table 7. RCT6 Max Pressure Peaks

Simulant	Tank Pressure (bara)	RCT7	
		Peak (bar)	Time (s)
HFE 7100	5	5.846	5.423
HFE 7100	10	10.535	3.519
HFE 7100	16	47.007	2.752
Water	5	100.84	4.481
Water	10	131.16	2.992
Water	16	144	2.306

Table 8. RCT7 Max Pressure Peaks

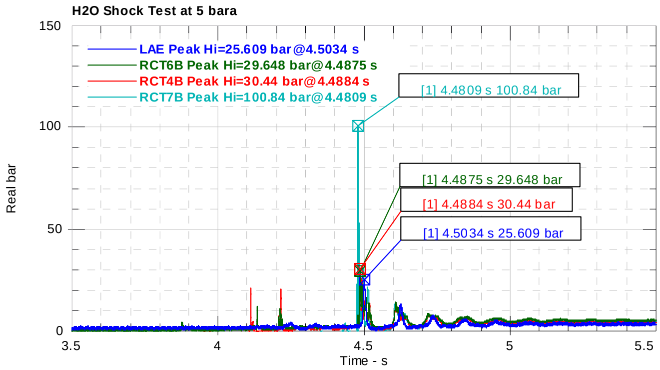

Figure 9. Water Priming Test at 5 bara

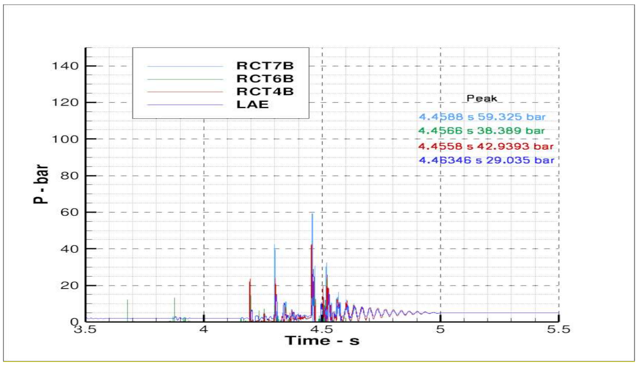

Figure 13. Water Priming Model at 5 bara

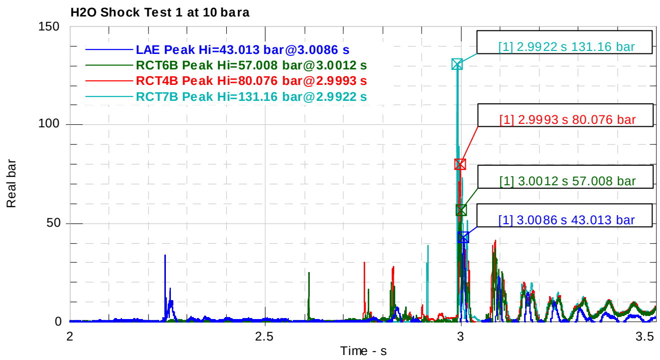

Figure 10. Water Priming Test at 10 bara

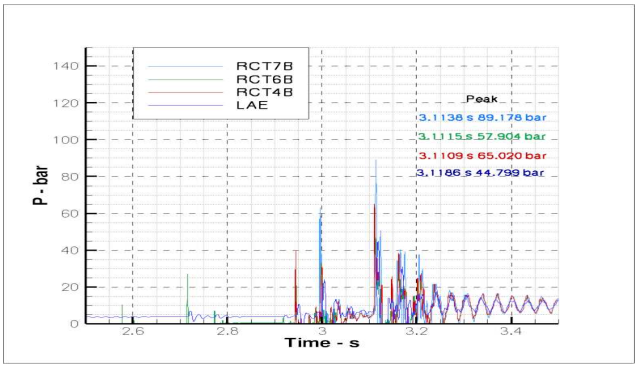

Figure 14. Water Priming Model at 10 bara

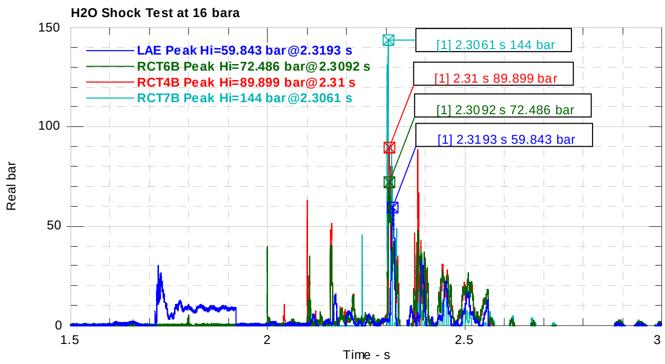

Figure 11. Water Priming Test at 16 bara

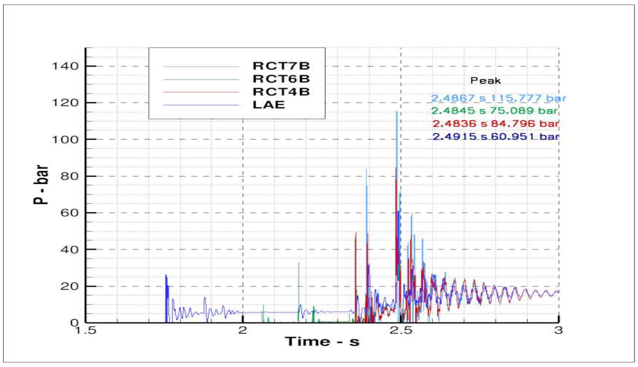

Figure 15. Water Priming Model at 16 bara

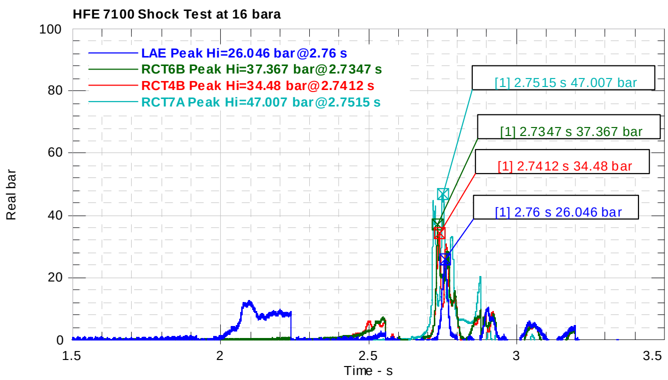

Figure 12. HFE 7100 Priming Test at 16 bara

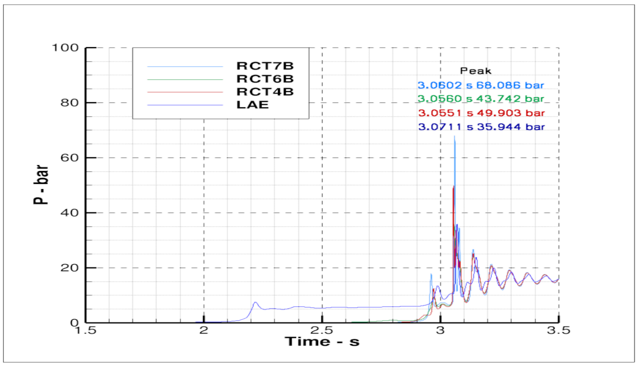

Figure 16. HFE 7100 Priming Model at 16 bara

Interpretations and Considerations

In general, the highest magnitude pressure peaks and peak times for water appear to agree very well with the Ecosim predictions. By comparing each test case between experimental sensor data and simulation results for the water cases, it is clear that the overall time history is well represented since the times of the main pressure peaks are very similar. This is an indication that the geometry (pipe lengths and volumes) is well modelled, but also that the fluid properties (speed of sound, etc…) are matching the actual ones in a very wide range of pressures. Unfortunately, the model is not as precise for predicting the peak amplitude, but still gives coherent results, e.g. for the water priming tests at 10 bar all calculated peaks are within 20 % of the experimental peaks as indicated in Table 9. An exception to this is represented by the RCT7B peak, where the experimental value is much higher than the calculated one. Investigations for explaining these discrepancies are ongoing.

The anomaly observed on the LAE dynamic PT reading in the test data plots for water at 10 bara and HFE at 16 bara (dark blue trace on Figures 11 & 12), whereby the charge output periodically resets to zero, is not fully understood but is thought to be attributed to an electrical grounding issue.

Water at 10 bara	*Test [bar]*	*Model [bar]*	*Rel. Error [-]*
LAE Peak	43.013	44.799	4.2%
RCT6BPeak	57.008	57.904	1.6%
RCT4BPeak	80.076	65.021	18.8%
RCT7BPeak	131.16	89.178	32.0%

Table 9. Comparisons between model and test for water at 10 bara

The HFE 7100 results show some differences in both time and amplitude. A reason for this might be the simplified fluid properties assumed for the HFE. For instance, the HFE in vapour phase is not modelled. For the low pressure priming tests with HFE 7100 it was apparent that the water-hammer effect was being significantly reduced if not eliminated in the lines, most probably due to its relatively high vapour pressure compared to water. When the fluid is introduced to the vacuum it has a tendency to flash vaporise in the downstream volume producing a decelerating cushion effect as it is compressed by the advancing liquid column [2]. Indeed for the 5 and 10 bar tests there were barely any peaks recorded above the static line pressure once the valve was fired open and the resulting liquid/vapour flow was audibly smoother with no signs of water-hammer.

VALVE SHUT-DOWN TEST

Hydraulic shock transients can also occur in propellant lines as a result of rapid reduction in flow velocities when valves close. This is of particular concern in the GMP-T subsystem when considering the potential risk to the critical downstream PTs required for pressure feedback. In order to make an initial assessment of this effect a number of tests were performed in which dynamic PTs were used to accurately measure the transients generated in the lines when the LAE valve closes, simulating engine shut down, following a period of steady-state flow with water at the nominal inlet conditions.

A data plot captured from one of these tests is shown in Figure 17. The results repeatedly showed maximum transient differential pressures of 12-15 bar occurring upstream immediately after valve closure. It should be noted that the charge output for the LPT9 sensor in this particular test was 40% lower than nominal resulting in an artificially low steady state and transient pressure measurement. This is due to the finite decay time constant attributed to the charge amplifiers used to process the dynamic PT signals. A failure to cycle the power between tests on this particular charge amplifier led to the signal attenuation seen (LPT9 pressure reading should effectively be equal to that of LPT7 taking minor calibration errors into account).

A subsequent test with all charge amplifiers synchronised showed very little variation in the magnitude and frequency of transient peaks measured at each point, with maximum pressures of 26-30 bar occurring at the locations of LPT7/LPT9. Upon consideration it was concluded that this relatively low transient would not affect the sensitive flight PTs at these locations, being well within component proof pressure levels.

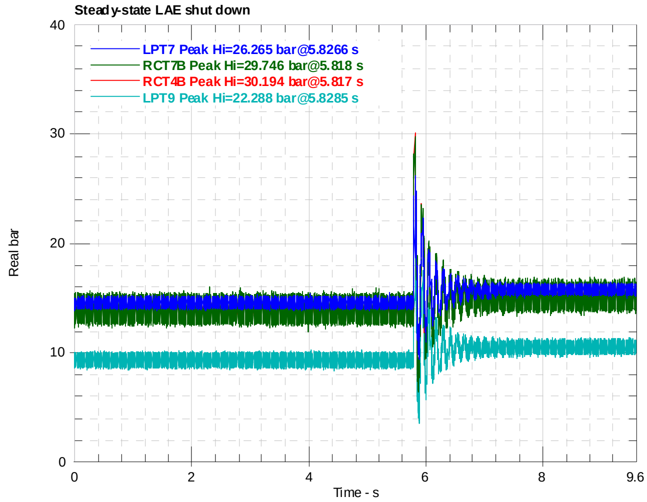

Figure 17. LAE Valve Shut-down Waterhammer Effect

CONCLUSIONS

The combination of analysis and tests performed to date, on a representative engineering model of the GMP-T propellant feed system has enabled SSTL to achieve two of the primary objectives for this development phase. The specific hydraulic tests performed were steady state flow and line delta P measurements and a comprehensive assessment of hydraulic shocks during the line priming process. The test results gained using simulants were used to validate analytical predictions made using a flow model in EcosimPro and subsequently provided confidence in the capability and accuracy of the tool to perform further flow analyses that may be required to verify other aspects of the propulsion subsystem design. The results have also provided useful knowledge on the hydraulic shock transients likely to occur in the feed system in its current configuration with the selected flight components and pipework layout.

The modelling performed with EcosimPro gives excellent predictions for the steady-state calculations. For the transient behaviour, the time history of the waterhammer pressure peaks is well predicted if the fluid properties are precisely implemented. The speed of sound can not be estimated properly for HFE 7100 since the fluid is implemented as a perfect liquid. The estimation of the pressure peak amplitude is close below 20% to the experimental results. Nevertheless, a larger difference is encountered for large amplitude peaks of about 100 bar. For this range, the fluid structure interaction model could be the origin of the discrepancy.

FURTHER WORK

The EcosimPro flow model will subsequently be used to correlate the line priming results obtained with simulants to real propellants, thus providing valid predictions for hydraulic shock transients likely to occur in the flight system. Once a detailed analysis has been made to determine nominal and worst-case propellant tank launch pressures then this, coupled with the test results and predictions, will allow an assessment of the suitability of the current feed system design and confirm whether modifications are required in order to suppress transient pressures to safer limits.

The final phase of development tests will involve a comprehensive characterisation of flow behaviour and interactions in the feed system during simultaneous LAE/RCT valve operations and during multiple RCT actuations to simulate both steady-state and pulse firing modes. Various anticipated mission operational cases will be investigated, as-well as non operational and back-up cases, to gain as much information as possible. In addition, the EM will be utilised for a series of bang-bang regulator tests to verify the performance of the valve and breadboard controller electronics at a representative system level, for a range of expected operating parameters.

It is intended to present the results and findings from this final phase of development tests in a future publication.

ACKNOWLEDGEMENTS

The primary author wishes to acknowledge the entire propulsion engineering team at SSTL as well as the following individuals and organisations, for their support of this recent test programme and for the valued contributions made to the overall GMP-T propulsion subsystem development:

- Mark Ford/François Cheuret/Marco De Rosa – ESA
- James Macfarlane – Airborne Engineering Ltd.
- AMPAC-ISP (UK) Ltd.
- MT Aerospace Satellite Products Ltd.
- Moog Inc. Space and Defence Group.
- Bradford Engineering B.V.
- 3M UK.
- Banner Chemicals Group UK.

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