Performance Verification of the Eurostar Propulsion Subsystem

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Following the design of the EUROSTAR bipropellant combined propulsion subsystem (CPS), a test program has been undertaken to assess performance to and validate supporting analyses. The program has involved both simulant, cold-flow tests and live, propellant firings using flight standard hardware. The test platform is fully representative of the flight geometry and, in addition to providing a model of in-flight performance, has permitted a full checkout of fill/drain procedures and operations in advance of the flight activities. This test bed has promoted a deep understanding of the performance of bipropellant systems and the constituent key components in addition to enhancing expertise in analytical methods, instrumentation techniques, and propellant handling.

I. Introduction

REFERENCE 1 describes the EUROSTAR platform, which has been developed for medium sized communications satellite applications. The combined propulsion subsystem (CPS) is designed to provide both apogee injection and on-station control functions using a common bipropellant supply. A scheme depicting the layout of the CPS in a three-dimensional format is presented in Fig. 1. Figure 2 shows integration of the propulsion subsystem taking place for the first flight application of EUROSTAR, INMARSAT 2.

As part of the development program, a series of tests were undertaken in order to verify performance against software models and to provide experience in the handling of the system. The tests involved both cold flow with simulated propellants and hot firing of engines using real propellants [mixed oxides of nitrogen (MON-3) and monomethyl-hydrazine (MMH)]. Other tests involved the operation of live pyrotechnic valves and simulated pyrotechnic valves in order to evaluate the hydraulic shock levels that would occur during flight.

The tests were performed at a dedicated test site with a full propellant handling capability. The facility included extensive instrumentation and control systems to provide data and to permit remote operation when necessary for safety reasons. Data were recorded on both ultra-violet (UV) sensitive paper and magnetic tape to provide a full and permanent record of the tests.

II. Test Objectives

The test program was devised to provide an in-depth comparison between actual performance achieved and predictions generated by prior subsystem analysis. Particular areas where comparisons were required were the following: 1) pressure losses in the delivery lines from the propellant tanks to the liquid apogee engine (LAE), 2) relative flow rates between fuel and oxidant tank pairs, 3) characteristics of propellant delivery to the Reaction Control Thrusters (RCTs), 4) thermal behavior of the pressurant gas as it expands through the regulator to the propellant tank ullage, 5) venting behavior of the propellant lines to the RCTs, 6) hydraulic shock effects while priming evacuated lines with propellant, and, finally, 7) regulator/relief valve behavior during the, "slam start" when an upstream pyrotechnic valve is opened to the high pressure supply.

In addition to these areas where detailed modeling had been required, the tests also provided valuable data concerning a large number of relatively minor design aspects relevant to the operation and interfacing of the CPS.

A further major purpose of the tests was to provide an opportunity to "walk through" various fluid handling procedures in order to verify them (and refine where necessary) in preparation for their implementation on a flight program.

III. Test Setup

A schematic of the flight propulsion system components and lines together with the additional instrumentation used to support the tests is given in Fig. 3. Detailed descriptions of the philosophy of the flight configuration are given in Refs. 1 and 2; however the operation and function of components is summarized below.

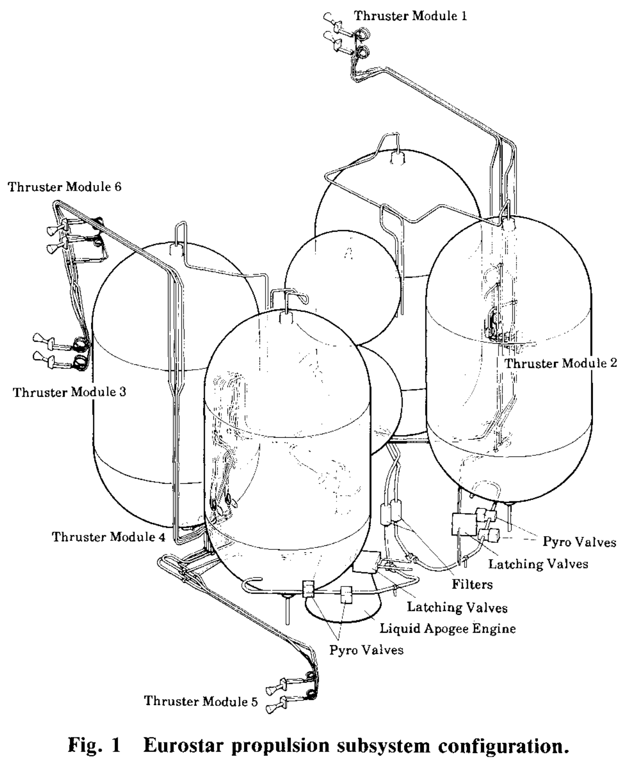

Fig. 1 Eurostar propulsion subsystem configuration.

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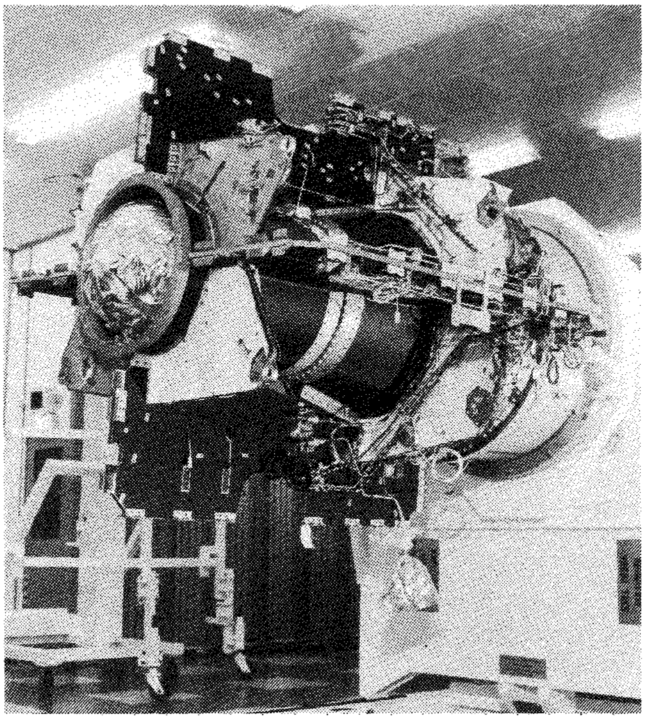

Fig. 2 Propulsion integration on flight model.

The helium pressurant storage system consists of two pressurant tanks connected to the high-pressure, normally closed pyrotechnic valve (PV1). This manifold incorporates a pressure transducer (PT5) and a fill and vent valve (FDV1). The pressurant tanks can be charged to a maximum pressure equivalent to 276 bar at 311 K. The PV1 isolates this high pressure supply from the regulator valve (PR1) and relief valve (RV1) until priming occurs in transfer orbit. Further normally closed pyrotechnic valves (PV2, PV3, PV4, and PV5) provide positive separation of the propellant tanks during the launch and prevent transfer of propellant vapors. Upon opening of the five pyrotechnic valves PV1 to PV5, the tank pressure rises to the nominal regulated pressure of 17.2 bar. During the transfer phase, the fuel and oxidant propellant tank ullages are separated by nonreturn valves (NRV1, NRV2, NRV3, and NRV4). To alleviate the problem of possible excessive transient pressure surges during the priming operations and to avoid the possibility of overpressurization of the propellant tanks, a relief valve (RVI) which vents open when a nominal pressure of 18.4 bar is exceeded at the inlet, is incorporated. Furthermore normally open pyrotechnic valves (PV6, PV7, PV8, and PV9) isolate the high-pressure supply once the apogee injection burns are complete to reduce the risk of leakage during the service life. Test ports are added to the pressurant system to gain access to lines and to permit component checkout during acceptance testing.

The propellant storage system consists of four tanks, two containing fuel and two containing oxidant. Each tank is serviced by a pair of fill and vent valves for ground loading opera-

CODE	DESCRIPTION
SPV	PYROTECHNIC VALVE-SIMULATED (n/c)
LV	LATCHING VALVE
FDV	FILL/DRAIN VALVE
PT	PRESSURE TRANSDUCER
TP	TEST PORT
PR	PRESSURE REGULATOR
RV	RELIEF VALVE
NRV	NON-RETURN VALVE
F	FILTER
LAE	LIQUID APOGEE ENGINE
DMW	DEMINERALISED WATER
TO	TEST ORIFICE
He	HELIUM
FM	FLOW METER
n/c	NORMALLY CLOSED
h/f	HIGH FLOW
l/f	LOW FLOW
PTa	ABSOLUTE-PRESSURE TRANSDUCER
DP	DELTA-P PRESSURE TRANSDUCER
OPV	ORIFICE
-----	ADDITIONAL LINES TO FLIGHT SYSTEM
SRCT	SIMULATED REACTION CONTROL THRUSTER
CV	CAVITATING VENTURI
HS	HYDRAULIC SHOCK

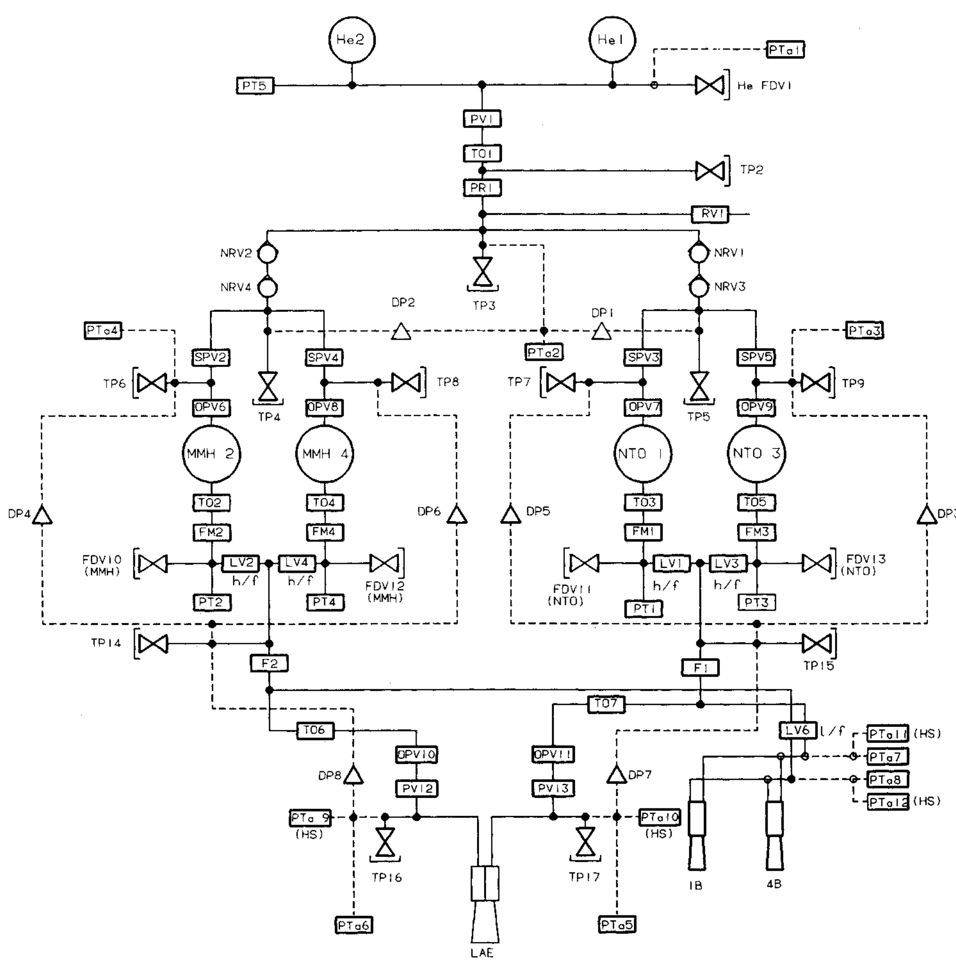

Fig. 3 Schematic of propulsion subsystem and test lines.

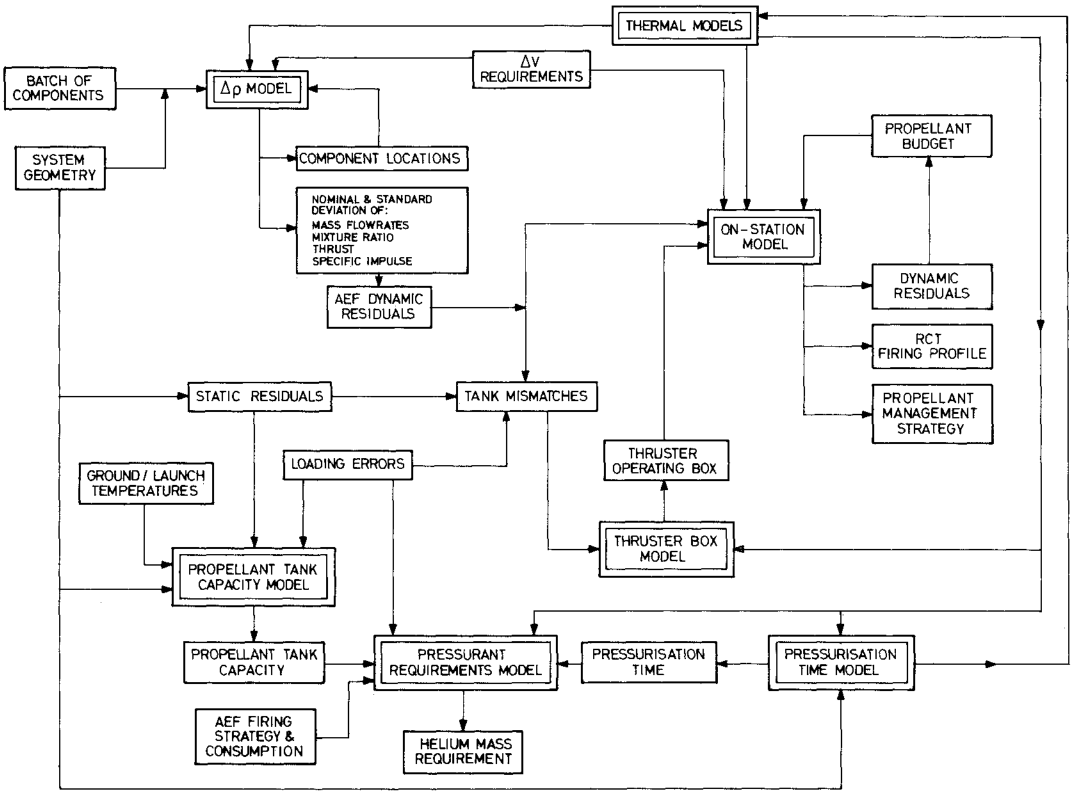

Fig. 4 Software and analysis logic structure.

tions. The liquid outlets from the tanks are isolated from one another by means of latch valves LV1, LV2, LV3, and LV4. Each like pair of tanks is then manifolded together to provide the feeds to the LAE and two sets of six RCTs. Filters F1 and F2 are incorporated into the main feed lines. Liquid-pressure measurement in each tank is provided by PT1, PT2, PT3, and PT4. The manifold to the LAE includes a pair of normally closed pyrotechnic valves (PV10 and PV11) to isolate the lines during launch and a pair of normally open pyrotechnic valves (PV12 and PV13) to reisolate the lines once the LAE function is complete.

For the purpose of the tests, instrumentation was added to the basic system as follows.

1) Twelve absolute pressure sensors were added to provide pressure level data in key areas. These were supplemented by the five existing flight pressure transducers. Typical accuracy was ±0.5%.

2) Eight differential pressure transducers provided information concerning pressure losses across critical components and manifolds. Typical accuracy was 0.35% in a 1-bar sensing range.

3) Four turbine flow meters were installed, one on the outlet of each propellant tank to monitor consumption rates. Each tank was also mounted on a load cell to give an approximate indication of contents at various stages during the filling operations and tests.

4) Thermocouples were installed in 35 locations to provide information on thermal behavior during operational conditions. These were modulated such that up to 20 could be continuously monitored and recorded during any one test.

5) Further, 29 high-resolution and 22 low-resolution channels were allocated to monitoring of events such as valve voltage/current during actuation, position indicators, etc.

Further to this quantitative instrumentation, qualitative information was acquired through the use of cine and video records taken, in particular during the hot-fire testing with live propellants.

IV. Predictions

As indicated in Sec. II above, a suite of software models was created to enable detailed design analyses to be performed in critical areas. Each of the component programs is described in turn in the following sections. The overall logic structure is shown in Fig. 4.

A. Apogee Engine Firing Performance Model

This model was constructed to enable predictions of subsystem, and in particular, LAE performance during apogee engine fire (AEF) to be made. Inputs are feed system geometry, component pressure loss data, LAE hot-fire data, and all associated uncertainties. By an iteration technique, the model calculates pressure levels and mass flow rates to the LAE inlet by assessment of pressure losses across components in manifolds. Given the inlet conditions, LAE thrust, and specific impulse performance can be estimated based on test data and influence coefficients. Mass flow rate from each tank is also predicted, and trimming orifices can be either built into the model or recommended sizes given as output. The model is typically run many times with randomly allocated uncertainties on the flow performance of all components (including all aspects of LAE performance) to obtain a statistical prediction of overall performance with mean and standard deviation values for flow from propellant tanks, thrust level, specific impulse, etc.

B. Propellant Tank Capacity Program

A program was written to permit estimation of the maximum allowable mass of propellant, which could be loaded into the fuel and oxidant tanks. The program incorporates the effects of several factors affecting ullage pressure and the liquid volume, e.g., propellant vapor pressure, helium gas pressure, and solubility in the propellant, propellant density variation with temperature, etc. Thermal data were inputted based on the environmental conditions at launch and during the transfer orbit phase together with tank volume and loading conditions. The program output provides the maximum allowable loading capacity for the propellant and the ullage volume.

Verification of the program was achieved off line from the main EUROSTAR development model tests under a parallel test program described in Ref. 3.

C. Pressurization Time Program

This program arose as a result of a requirement to achieve rapid pressurization of propellant tank ullages in order to bring thrusters on line in readiness for active nutation damping (AND). The objective was to calculate, for given subsystem geometry and flow performance characteristics, the time for the propellant tank ullages to rise from the launch pressure level to the regulated level. The operation is initiated by the opening of a pyrotechnic valve PV1. The program operates by estimating the pressure rise over a short time-step in a line element, based on the element flow characteristic. The pressures are updated for each time step, and an overall pressurization time characteristic is produced for each section and, in particular, the propellant tank ullages.

D. Pressurant Requirement Program

This program provides a predictive capability to evaluate pressurant loading levels for a given spacecraft mission. The thermodynamic behavior of the pressurant as it is drawn from the storage vessel and expanded through the regulator into the propellant tank ullage is modeled taking into account boundary thermal conditions for each of the LAE burns. The program runs in an iterative mode starting with an assumption for the pressurant required and refining this value in successive mission simulations until convergence is achieved giving the true requirement for the mission. This value will be based on providing sufficient pressurant to perform the mission such that the inlet level to the regulator is at the minimum acceptable level at the end of the injection phase.

E. On-Station Model

The on-station simulation model permits trial of a variety of propellant depletion strategies based on selection of the active propellant tanks in conjunction with the thermal conditions applied to the spacecraft during the service life. One mode of the program steps through a mission allowing changes of propellant management strategy at any time (i.e., selection of the tanks supplying the RCTs). The mass of propellant required for each burn is calculated taking into account predictions for propellant temperature evolution in the tanks and lines while on station. Different management strategies can be compared in relation to their ability to maximize the service life. The second mode of operation steps through the same mission strategy many times. Any input having an uncertainty is varied randomly between calculations. Averages and standard deviations of the propellant remaining at the end of life, or an equivalent criterion, can be calculated to compare strategies and to obtain probabilities of achieving a given mission without encountering a tank depletion.

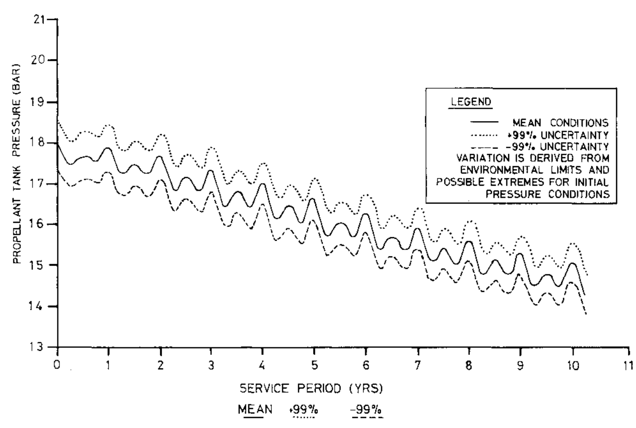

Fig. 5 Example output from on-station model.

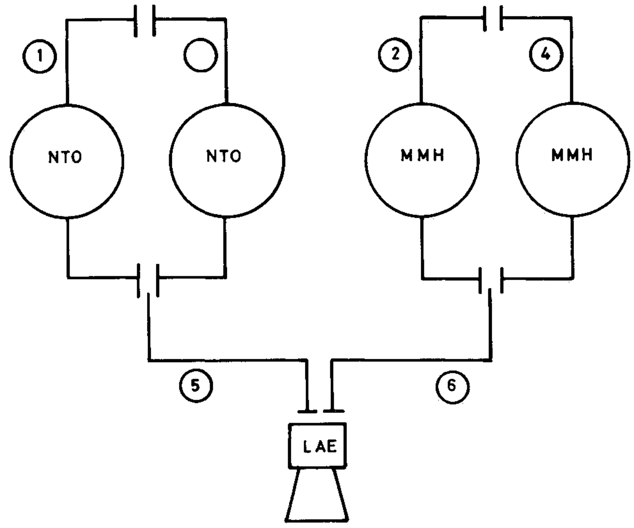

Fig. 6 Schematic of flow segments.

A sample output from the program is shown in Fig. 5.

F. Reaction Control Thruster Inlet Pressures Program

This program provides a means of calculating the ranges of fuel and oxidant inlet pressures for which the RCTs will be required to operate. As with the on-station model, predictions are required for the propellant temperatures while on station together with the isolation conditions at the end of the transfer orbit phase. The program calculates the feed pressures of the propellants as a function of temperature and propellant used taking into account the mass of helium in the propellant tank ullage at the time of isolation together with losses through absorption into the propellants and subsequent burnoff via the RCTs.

V. Tests Performed

A. General

The tests were intended to verify the operation of the system as a whole rather than performance test individual units. Unit qualification is covered under separate programs by the manufacturers.

B. Cold-Flow Tests

Cold-flow testing of the liquid segments was performed with simulants of water representing the fuel (MMH) and Freon representing the oxidant (NTO). Liquid flow through the delivery lines to the LAE was adjustable by means of a continuously variable cavitating venturi on both fuel and oxidant lines at the LAE valve inlet. Measurements of the flow rate were taken for a given venturi setting and propellant tank storage pressure using both flow-meter readout and collect and weigh over a given time interval.

Readings were taken for a wide ranging flow regime including both the volumetric equivalent and Reynolds number equivalent flow rates for the simulants compared to the live propellants. Pressure losses across various components and manifolds in the system during the test were indicated by the various differential pressure transducers. Compensation of the results was necessary to account for the liquid head in the propellant tanks at the time of the test. Once this adjustment had been made, direct comparison with predictions was possible.

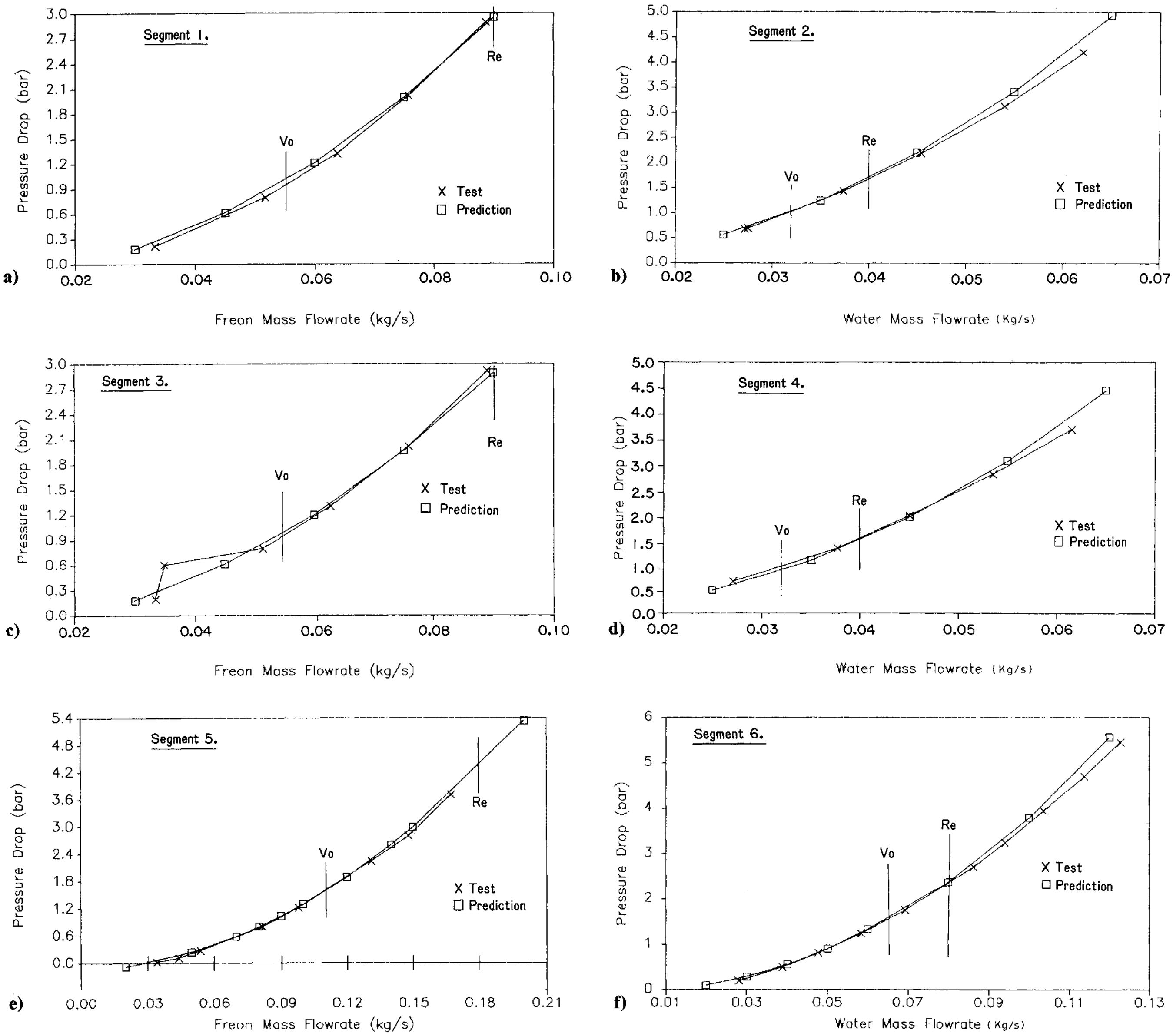

Fig. 7 Cold flow test results for segments

Tests were performed for the six main engine-flow delivery segments indicated in Fig. 6. A second series of tests examined the interactive effect of flow through multiple RCTs, including startup and shutdown of additional thrusters in parallel with a unit operating in steady state. These tests were performed both with and without concurrent LAE operation; although the latter case was not an anticipated operational requirement. Flow behavior from the units was evaluated by reading absolute and differential pressures and fluid catch and weigh over calibrated time intervals for each of the RCTs under test.

C. Hydraulic Shock Tests

The hydraulic shock tests were aimed at verifying the capability of the lines and components to withstand the fluid shocks which occur during the line priming and actuation of pyrotechnic valves. Tests were performed both with live pyrotechnic valves and with solenoid valves in place of these to allow several repeats.

Areas of concern were the LAE inlet valves downstream of PV12 and PV13, and the RCT control valves downstream of the bipropellant latching valves.

Tests were performed for a variety of conditions in order to cover the full range of mission eventualities. These included maximum and minimum propellant storage pressures, water, Freon, fuel, oxidant, and various upstream valve configurations. Lines to be primed were dried and evacuated in order to minimize residual gas and vapor pressure and to properly replicate the conditions expected in flight.

Generally speaking these tests were incorporated as a preliminary to the cold-flow or hot-fire tests.

D. Regulator and Relief Valve Interactive Tests

A series of tests was undertaken to investigate the performance of the pressurization system and in particular the interactive behavior between the regulator and the relief valves during the start transient when PV1 is opened. Tests were performed both with simulated and live pyrotechnic valves upstream of the regulator and for a variety of pressure conditions applied to the reference ports of the regulator and relief valves. The tests also covered simulated failure cases such as regulator failed open to confirm the flow handling capability of the relief valve. The reset point and subsequent leakage be-

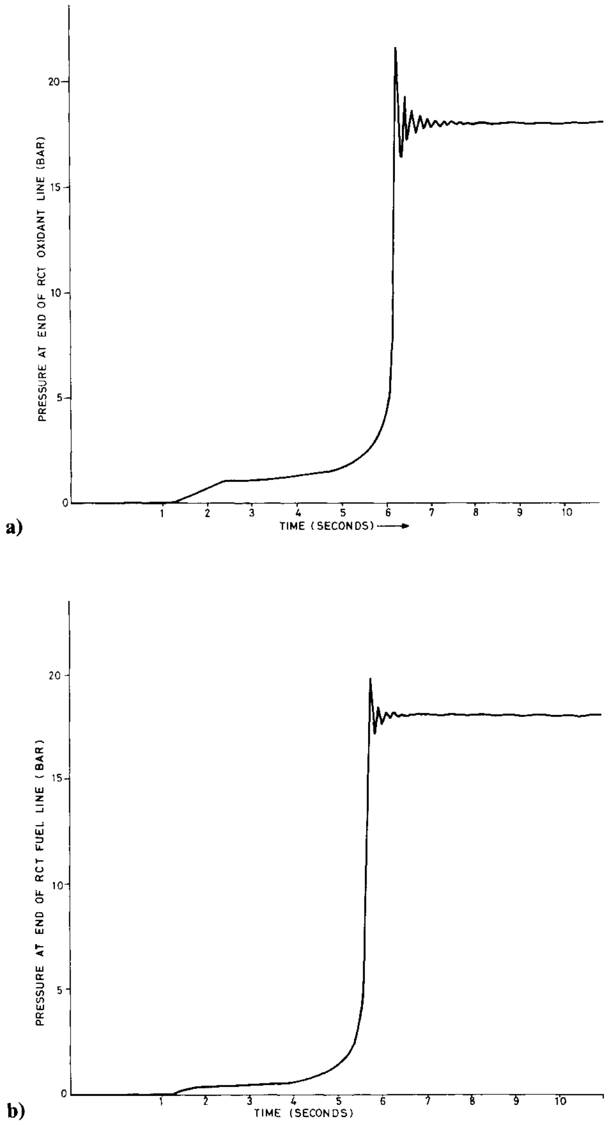

Fig. 8 Liquid priming of oxidant lines.

havior of the relief valve were also examined to confirm system integrity in off-nominal situations.

The interactive tests were devised to demonstrate that no inlet or reference pressure conditions existed which could lead to unstable or "talkback" behavior and result in abnormal or out-of-specification performance.

E. Hot-Fire Tests

The hot-fire test program was designed to represent a simulated mission consisting of the following basic stages: 1) line priming, 2) pressurization of propellant tank ullage, 3) simulation of AND operations using two RCTs, 4) operation of LAE to simulate apogee injection burns, 5) operation of RCTs to simulate stationkeeping burns, and finally, 6) depletion of propellants.

Some variations, which were not anticipated as part of a mission, were introduced. These were to expedite tests and to cover other interesting cases. Also included were simultaneous operation of LAE and RCTs and additional LAE burns to shorten the RCT depletion time.

Further tests were introduced as described under Sec. VII below in order to investigate oscillatory phenomena, which occurred during some LAE burns.

VI. Analysis of Results

A. Cold-Flow Tests

Figures 7a-7f show correlation of predictions vs test results for the various flow segments (shown in Fig. 6) delivering propellants to the LAE. The figures also indicate the equivalent volumetric and Reynolds number flow rates for live propellants MMH and NTO under nominal operating conditions. This range is much greater for the Freon simulating NTO than it is for the water simulating MMH.

It can be seen that the correlation is in general good, especially in the nominal operating range as defined by the above flow conditions, although some minor deviations do occur.

For the case of water, a slight overprediction of the pressure loss occurs at the high-flow rates. This is a result of the model persevering with a laminar representation for Reynolds numbers extending up to 10,000 (based on the pipe diameter as a characteristic length) where transition to turbulence is likely to occur. It can be anticipated that flow losses in the turbulent case will differ from those for the laminar case as evidenced by the test data. The effect is not seen in the case of Freon as the flow regime is always turbulent (of the order of 30,000 based on pipe diameter). In this case the correlation is good throughout the test range. The abnormal data point appearing in the low-flow end of the segment 3 test is believed to be a spurious test anomaly; it was not repeated in other similar tests.

The errors between test results and predictions never exceed 0.1 bar, a band which is small when errors in flow measurement data for components are taken into account. The accuracy of the predictions has removed the need for flow characterization of assembled flight systems, a possibility once considered necessary.

B. Hydraulic Shock and Priming Tests

Figures 8 show pressure characteristics as sensed by PTa7 and PTa8 (oxidant and fuel lines respectively) following the actuation of the high-flow latch valves isolating the propellants at the full regulated pressure of 17.2 bar nominal. These are typical of the hydraulic shocks observed during a wide range of tests including pyrotechnic valve operation. In all cases lines were evacuated and held to a pressure level of the order of 3 mbar before the valve was opened.

The peak pressures observed were 25.6 bar and 31 bar for oxidant and fuel lines respectively (both levels were actually observed in the simulant tests). The shock levels were surprisingly small compared to expectations, although accurate predictions for real cases are very difficult to estimate. Calculations ranged from a few to several hundreds of bar, dependant on assumptions for pipe elasticity and evolution of propellant vapor at the liquid/vacuum interface. The main reason for the low levels observed was considered to be the effect of

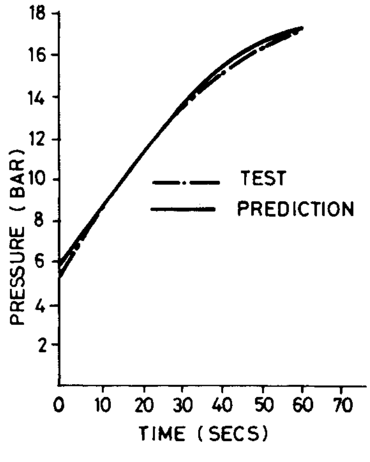

Fig. 9 Propellant tank ullage pressurization time.

tank balancing orifices installed immediately downstream of the propellant tanks (nominal pressure drop is 1 bar). These would damp the flow and promote vapor generation. This damping also accounts for the long rise time exhibited in Figs. 8.

Priming of the ullage following the opening of PV1 gave reasonable correlation with predictions (see Fig. 9). The small variation in slope is likely to be a consequence of variation in predicted to actual values of the nonreturn valve (NRV) pressure loss during this high-flow case.

C. Regulator and Relief Valve Performance Tests

As described in VD, a series of tests were performed to evaluate the performance of the regulator and relief valve network.

Forced cracking of the relief valve was achieved by gradual pressurization of the line downstream of the regulator valve via TP3. Shutdown of the pressure supply resulted in reseat of the relief valve; no effect on the regulator was observed.

A failed open regulator was simulated by introducing an increased pressure above ambient into the regulator reference port. It was confirmed that the relief valve was capable of venting flows such that the pressure downstream of the regulator would never exceed 20.5 bar. The test was performed both for high and low inlet pressure levels to the regulator (276 and 100 bar, respectively). Figure 10 shows results for the high inlet pressure level test.

Slam start testing was performed to evaluate tne response of the network upon opening PV1. This was simulated for the tests by a solenoid valve denoted SPV1. An initial series of 6 slam starts was performed for a variety of conditions covering possible cases in flight. A second series of tests was performed to investigate off-nominal conditions in order to understand better the behavior of the valves. During the two series, upstream and downstream pressures were varied together with the pressure levels providing reference settings for both valves. A typical regulator characteristic corresponding to a slam start transient is shown in Fig. 11. No abnormal or interactive behavior was observed between the valves during the large number of tests performed, and valve performance remained within specification throughout.

D. Hot-Fire Tests

The hot-fire test series began with a propellant and pressurant loading exercise strictly controlled by procedures generated to cover the equivalent flight operations. The aim was to prove techniques and to familiarize personnel with equipment and safety aspects which are vital when dealing with these hazardous fluids. The system was then primed and pressurized as detailed in the preceding paragraphs.

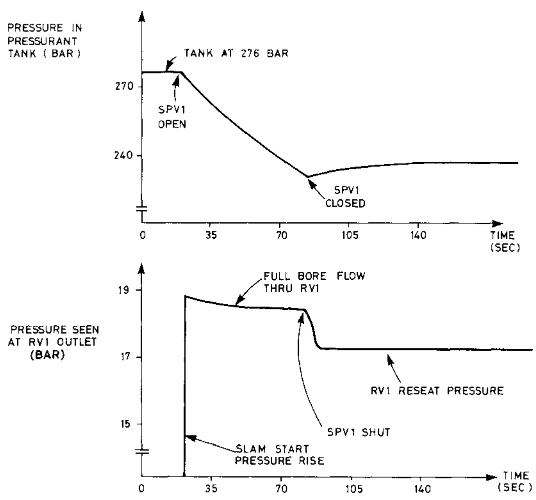

Fig. 10 Regulator failed open test.

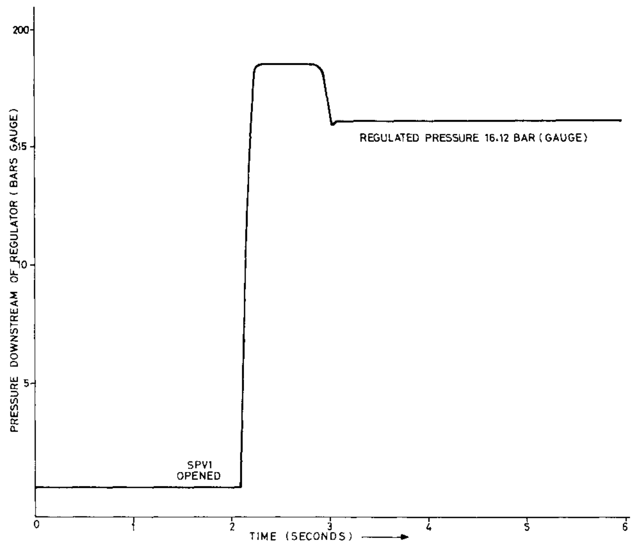

Fig. 11 Regulator response to a slam start transient.

The operational tests encompassed RCT and LAE firings, both separately and in combination. The principle of the tests was to envelope a typical mission with AND, AEF burns, and stationkeeping functions simulated by the appropriate thruster operations and duty cycles.

The AND pulses were performed by alternate 1 s on, 1 s off cycling of two thrusters. Two tests were performed of 30 and 20 cycles, respectively. Water cooling was applied to the nozzles to help reduce the risk of nozzle burnout due to plume attachment (the nozzle being designed for operation in vacuum was effectively overexpanding the plume in these sea-level tests, which can lead to instability of plume shape). Thruster operation was detected by observation of the pressure traces from PTa7 and PTa8, thermocouple response and video recording. No anomalies were observed, and flow behavior was consistent with predictions and the cold-flow test results.

The LAE main test sequence consisted of a series of long duration burns; the maximum time was 30 min. Prior to initiating these, a series of short burns was also performed in order to verify the integrity of the installation and to check performance levels.

Apart from the safety aspect, these precautions were taken to confirm no adverse effects from plume overexpansion. The test unit (which was identical to flight units) embodied a 160:1 area ratio nozzle for expansion to vacuum; whereas a ratio ofthe order of 10:1 would provide full expansion at sea level. The continued expansion beyond this level in an oversized nozzle can lead to plume instability and local heating effects. To protect against this possibility, the engine nozzle was continuously cooled by jets of water directed to impinge on the outer wall and a cooled blast plate used to deflect the plume and associated thermal radiation away from the test area. The initial tests, therefore, were designed to evaluate and ensure the effectiveness of these measures.

Test of 15, 60, and 120 s indicated that the engine was operating smoothly with no significant signs of plume instability.

Combustion roughness was at one stage observed, which was traced to debris in the LAE inlet filter. Removal of this resulted, once again, in smooth operation. (In the case of the first flight program, concern relating to the sensitivity of the LAE to particulate debris had already resulted in the introduction of additional filters in the lines immediately upstream of the LAE. These were introduced at a late stage and were therefore not incorporated as baseline in the test model.)

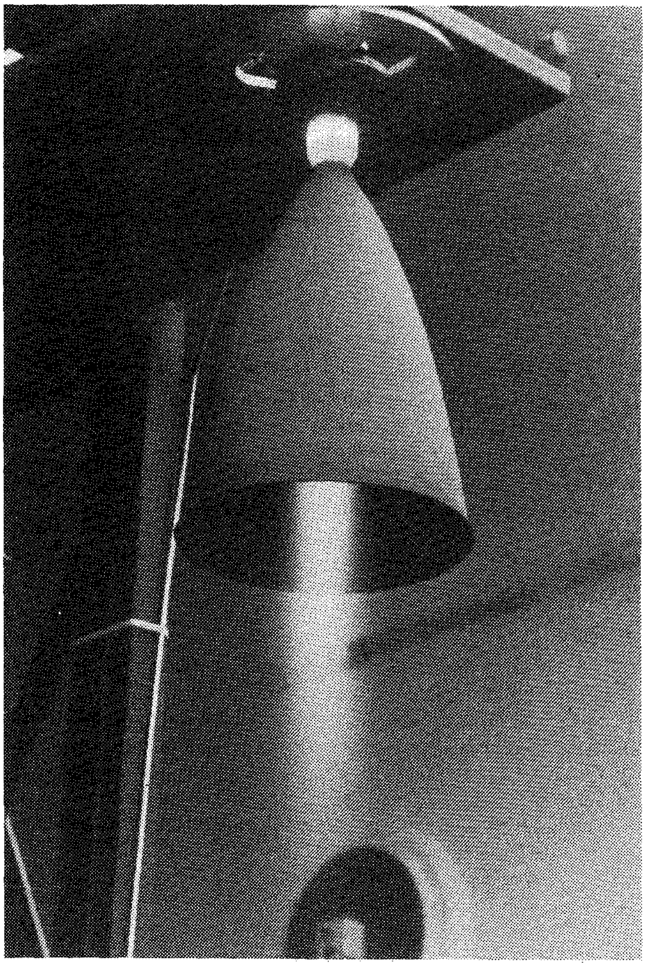

Fig. 12 LAE operation during hot-fire tests.

During the required test burns, the LAE delivered consistent performance. No unexpected thermal effects were observed with the LAE mounting flange reaching a maximum of 60C during running and soakback.

The RCT operational cycle consisted of stepped commands in parallel with the main engine burn (30 min): 1) at 8 min open RCT1, 2) at 10 min open RCT2, 3) at 12 min close RCT1 and RCT2, 4) at 18 min open RCT1 and RCT2, 5) at 20 min close RCT1 and, 6) at 22 min close RCT2.

No significant interaction between LAE and RCTs was observed. The maximum pressure effect in the line to the LAE was a drop of 0.137 bar when both RCTs were operated. Inlet pressures to all units remained undisturbed.

A final LAE depletion burn was performed until runout of the first propellant tank. Tank NTO1 depleted after approximately 12 min at which point the burn was terminated. The remaining usable propellants in the tanks were consumed in a series of RCT burns broadly replicating a mission through to the end of life.

During the hot-fire test program the total on times for the RCTs were 1080 and 1100 s comprising 57 and 58 open and close cycles, respectively. The total run time for the LAE was 4520 s (75 min). During this time the propellant delivery to the units was consistent with expectations and free of anomalies; all components performed within specification. Apart from the instance described above, no indications were observed of buildup of contamination or flow decay products in valves or filters, despite the large throughput of both propellants and simulants.

Evaluation of the propellant residuals at the end of the hot-fire test phase showed good correlation with expectations. The predicted masses of fuel and oxidant remaining at the end of the burns, which consumed approximately 760 kgs of propellant, were 1.51 and 3.05 kg, respectively; the actual measured masses were 5.06 and 4.49 kg.

The combined difference of 4.99 kg is well within the experimental accuracy of the test taking into account weighing accuracy of propellants during loading, loss of vapor during collection of residuals, and other errors introduced by handling limitations. The correlation of residuals, together with the pressure levels indicated via instrumentation observed during the burns, confirm that the desired mixture ratio of fuel and oxidant into the LAE was achieved and that flow levels were as predicted.

Figure 12 is a photograph of the LAE taken during one of the tests.

VII. Conclusions

The completion of the EUROSTAR development test program confirms the flight readiness of the propulsion subsystem. Close correlation was achieved throughout between predictions and test results providing confidence in the capability of the subsystem to achieve flight performance requirements well within specification.

During the program, a large number of varied tests were undertaken. In performing these and interpreting results, a deep and valuable understanding of the performance and characteristics of the system has been achieved. The successful conclusion of the program has led to vindication of the design and configuration for flight and has strengthened the capability within British Aerospace to develop new systems for the 1990s and beyond.

Acknowledgments

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References

[1]Hobbs, L. W., and Lukey, G., "A Combined Bipropellant Propulsion Subsystem for the EUROSTAR Communications Spacecraft," AIAA Paper 85-1376, July 1985.

[2]Hobbs, L. W, and Lawrie, A. "The design and development of a Spacecraft Propulsion System," *Aerotech '87*, Birmingham, England, UK, Oct 1987.

[3]Gibbon, D. M., and Bellerby, J. M., "Simulation of Conditions Inside a Spacecraft Bipropellant Tank," AIAA Paper 88-2923, July 1988.

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