Abstract. The UK Ion Propulsion Subsystem is based on the UK-10 electrostatic ion thruster which uses xenon propellant to produce thrust in the range 3 to 50 mN. This paper describes the design of the subsystem for use on a geostationary communications satellite for north-south stationkeeping. The thruster and its performance have been documented in previous papers, references 1, 2, so the design, development and performance of the subsystem aspects with particular emphasis on spacecraft interfaces, including ground support equipment, are described in this paper.

Introduction
The UK-10 Ion Propulsion Subsystem (IPS) currently in development in the UK is designed around a packaged assembly which consists of the ion thruster, the Power Conditioning and Control Equipment (PCCE) and the Propellant Supply and Monitoring Equipment (PSME). A four thruster subsystem would include four of these packaged assemblies. In addition a set of Propellant Storage Equipment (PSE) is used to store the mission propellants and is common to all the thruster assemblies.

This configuration is shown in Figure 1 for the four thruster subsystem.

It should be noted that the packaged assembly may be readily split into separate equipments, should these be more convenient to locate on the spacecraft.

Each thruster pair is isolated from the propellant storage tank by a latch valve with status indication. When open, propellant is allowed to flow through the valve to a pair of thruster assemblies. The PSME controls the flow of propellant to the thruster through a feedback loop in the PCCE. As a result each thruster is controlled independently allowing performance optimisation. The PCCE provides power for all the thruster, PSME and PSE requirements at a design efficiency of 88%.

The PCCE also includes a sequencer to generate activation signals in the required order. It interfaces with both the spacecraft power and data busses.

The positively charged exhaust produced by each thruster is neutralised by the emission of electrons from a neutraliser mounted on the thruster. The neutraliser maintains the spacecraft at close to space potential during thruster operation, and is capable of being used independently of the thruster to eliminate charge build up on the spacecraft due to space charging effects. The thruster design incorporates three propellant flows; for the cathode, main flow and neutraliser, which are independently controlled, and, with the variable magnetic field, maximum flexibility and stability of operation over long periods of time are realised. With this combination of control variables, the thruster may be throttled from 3 mN to 50 mN, and the effects of long term degradation, particularly to the cathode emission characteristics, can be tolerated without incurring any loss of propellant utilisation efficiency or thrust. Thus grid sputtering is kept at a very low value throughout the mission, and high stability of operation is maintained.

Equipment Description

Thrust
The UK-10 ion thruster was developed from the successful T5 version which originally was designed for use with mercury propellant. To accommodate the change to xenon, the modifications required were the removal of mercury vapourisers and removal of heaters from the inlet pipes, backplate and electrical isolators.

The thruster mechanical interface is shown in Figure 2.

Propellant Supply and Monitoring Equipment

A design trade-off study was conducted in order to establish a reliable, high performance PSME. Three types were considered; mechanical pressure regulator with restrictors; solenoid valve and plenum regulator with restrictors; and servo-driven needle valve regulator.

A great deal of flight experience has been achieved with mechanical pressure regulators on chemical propulsion systems, but the regulator operating lifetime is generally restricted to the duration of the geostationary orbit acquisition manoeuvre which is no more than a few hours. This type of regulator was used for a long duration mission, the Viking Orbiter Propulsion System, but reference 8 relates problems due to regulator internal leakage. This lack of long-term experience plus the active flow control requirement of the UK-10 effectively eliminated the mechanical regulator design from the trade-off.

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The servo-driven needle valve design is available commercially and includes a flow monitoring device for flow control. These units are currently successfully used for ground testing. However the design has two inherent weaknesses. The first is the needle valve which is a tightly tolerated part which it is felt would be susceptible to particulate contamination which would prevent satisfactory operation and may induce excessive leakage. The second area of concern is the flow monitoring device which is a heated element which relies on heat transfer to the propellant gas. Again, this works well for ground tests, but in a zero-g environment the heat transfer rates may be significantly altered. As a result the flow control calibration could not be guaranteed.

The regulator design using solenoid valves in conjunction with plenum tanks and pressure monitoring is a flight proven concept with long term flight experience. The use of qualified soft seat solenoid valves provides confidence that the leakage requirements can be achieved, and by controlled pulsing of the solenoid valve the plenum pressure and hence flow rate can be adjusted and the active control requirement realised.

The PSME consists of the following components:

- Intermediate pressure regulators
- Intermediate plenum
- Main flow pressure regulator
- Main flow plenum
- Cathode pressure regulator
- Cathode plenum
- Neutraliser pressure regulator
- Neutraliser plenum
- Main flow inlet valve
- Cathode inlet valve
- Neutraliser inlet valve
- Test ports

The xenon propellant is supplied to its associated thruster through 3 lines as shown in Figure 3: one for the thruster cathode, one for the thruster main flow, and one for the neutraliser. Each of these flows is independently controlled so allowing thruster performance to be optimised at any specified thrust rating.
The block diagram of the PACE is shown in Figure 4.

The ion thruster requires a total of ten supply rails. Some provide constant current output or constant voltage output irrespective of load or bus voltage variation. Some of the outputs are referenced to spacecraft or to beam potential. Each output can be independently switched on or off by the sequencer which performs a preset switching sequence. The sequencer also controls the various gas valves. The gas flow regulators are used in the control loops to maintain the various parameters at constant levels by adjusting the plenum pressures and hence gas flow rates.

A detailed description is given below for the various individual blocks shown in Figure 4.

a. The Discharge Voltage Regulator

The function of this unit is to provide constant voltage DC outputs for each of the regulator controlling the following power supply outputs, the discharge keeper output, the cathode heater output and the anode output. The converter uses a half bridge topology formed from mosfets. The primary bus voltage is used to control the ramp slope of the pulse width modulator. By these means the output voltage is kept constant even though the primary bus voltage changes. A transformer with multiple output windings provides isolation between the primary bus and the secondary side which is at a potential of nominally 1100 volts. Power for the control circuit is provided by the auxiliary power supply. The output transformer is operated at a fixed frequency of 100 KHz.

b. The Neutraliser Voltage Regulator

This unit uses exactly the same design concept as the Discharge Voltage Regulator. The control circuit and mosfet driver circuit are identical. A different transformer will be used and different input filter.

c. The Constant Current Regulators

The Magnet, Cathode Heater, Discharge Keeper, Anode, Neutraliser Heater and Neutraliser Keeper are all supplied from constant current regulators.

All these regulators use the same design concept. A buck regulator is used with saturating magnetic elements as the switching device. On/off control is also provided by the magnetic switch. Output filtering is achieved with MPP cores which give low losses at the operating frequency. Operation at constant current is achieved by sensing the current and comparing it with a reference value.

The resulting error signal drives a power amplifier which resets the magnetic switch thus controlling the duty cycle.

d. The Beam Converter

This converter has the highest power rating and dominates the overall efficiency of the PACE. A standard non isolated boost configuration has been used for this converter. The power switch is formed from paralleled power mosfets. This minimises the steady state power loss. The drive circuit which interfaces between the control circuit and the power mosfets has been developed to provide the high peak currents required for fast switching and provides a negative bias for turn off. Negative turn off bias is essential to ensure switch off of the mosfet after exposure to radiation. To further improve the efficiency the switch snubber has been optimized to reduce the turn off switching loss.

e. The Discharge and Neutraliser Keeper Trigger Converters

This converter provides the high voltage necessary to ionise the propellant. Since it is run in parallel with the keeper power supply its voltage output is made load dependant. The design is based on a free running fixed duty cycle flyback converter operating at 100 KHz.

f. The Accelerator Converter

The accelerator power supply is a flyback discontinuous mode converter. The output voltage is kept constant by a feedback controller which adjusts the pulse width of the primary switch. In this way the output voltage is held constant though the load current may alter between 1 and 6 mA. The control circuit for this converter uses the well proven SG1524 pulse width modulator integrated circuit.
g. The On/Off Sequencer

This unit provides on-off commands for the various power supplies and gas valves. Three separate sequences are built in. The first one is activated by the high level command 'Neutraliser Enable'. The sequencer then turns on the Neutraliser Heater Supply and both Neutraliser Keeper supplies, as well as the required gas valves. When the discharge is triggered and the Neutraliser keeper voltage indicates stable conditions, the sequencer turns off the heater and trigger supplies. The second sequence operates to turn on both Neutraliser and Ion thruster in a controlled manner which includes checking plasma stability before starting the next event. The third sequence provides for shutdown which can be initiated by command or by the protection circuits in each power supply. The design of the sequencer is based on CMOS integrated circuits. The output command lines transmit pulse commands to isolating transformers in the receiving units.

h. The Gas Flow Regulators

Three control loops are used in the PCCE which use gas flow to control parameters and in turn ion engine performance. The thrust is kept constant by maintaining constant beam current. Beam current is held constant by controlling the main gas flow. The mass utilisation efficiency is held constant by measuring the difference between Anode Voltage and Discharge Keeper Voltage. This voltage difference is held constant by controlling the cathode gas flow. Similar principles apply to the loop keeping Neutraliser keeper voltage constant. Conventional amplifier techniques are used for all these analogue control loops.

Propellant Storage Equipment

The propellant storage equipment, PSE consists of the propellant tank, latching valve, fill/vent valve, pipework and pressure transducer. The tank stores the xenon propellant at high pressure to minimise the volume required, and releases it to the PNS. The beginning of life storage pressure is 50 bar, which allows a safe margin of pressure variation with expected temperature change. Monitoring of tank pressure and temperature allows an estimation of propellant mass to be made during the spacecraft lifetime.

Latching valves are used to isolate the propellant tank from the PNS during ground tests, launch and periods of inactivity.

Performance

The thruster measured performance at 20 and 25 m/s is listed in Table 1. Thrust vector alignment can be measured to within an accuracy of 1 degree with respect to the geometric centreline. The period of 2.5 minutes is required for the thrust build up from the initiation of the thruster 'on' command to nominal thrust level. This build up consists of cathode and neutraliser heater warm-up of 2 minutes, neutraliser discharge initiation of 15 seconds and cathode discharge initiation of 15 seconds. The neutraliser and cathode discharge actually occur instantaneously, but time for verification of initiation is required.

TABLE 1 Measured performance of UK-10 thruster

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thrust (m/s)</th>
<th>25 m/s</th>
<th>20 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam voltage (V)</td>
<td>1.100</td>
<td>1.100</td>
<td></td>
</tr>
<tr>
<td>Anode voltage (V)</td>
<td>-350</td>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>Beam current (A)</td>
<td>0.457</td>
<td>0.385</td>
<td></td>
</tr>
<tr>
<td>Anode current (mA)</td>
<td>3.0</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Thrust (m/s)</td>
<td>25.0</td>
<td>20.1</td>
<td></td>
</tr>
<tr>
<td>Exhaust velocity (m/sec)</td>
<td>40.233</td>
<td>40.233</td>
<td></td>
</tr>
<tr>
<td>Utilisation (µ)</td>
<td>0.53</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Ion production onset (MA)</td>
<td>250</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>Discharge current (A)</td>
<td>1.5</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Anode voltage (V)</td>
<td>47</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Keeper voltage (V)</td>
<td>13</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Keeper current (A)</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Beam power (W)</td>
<td>70</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Discharge power (W)</td>
<td>11.2 (2)</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Additional power (W)</td>
<td>24</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Power-to-thrust (W/m²)</td>
<td>25.4 (1)</td>
<td>29.0 (1)</td>
<td></td>
</tr>
<tr>
<td>Electrical efficiency</td>
<td>0.78 (3)</td>
<td>0.78 (3)</td>
<td></td>
</tr>
<tr>
<td>Total efficiency</td>
<td>0.61 (1)</td>
<td>0.61 (1)</td>
<td></td>
</tr>
<tr>
<td>Xenon press fraction</td>
<td>0.74</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>Beam divergence (1/2 angle at 95% of beam current)</td>
<td>9.5°</td>
<td>9.5°</td>
<td></td>
</tr>
</tbody>
</table>

(1) Uncorrected for doubly-charged ions and beam divergence.
(2) Includes discharge keeper power, neutraliser keeper power assumed to be 15%, anode power, and magnet power (assumed to be 6%).

Subsystem Mass

Table 2 indicates the subsystem mass for a typical 4 thruster ion propulsion subsystem, including a propellant mass sufficient to produce a total impulse of 800,000 Ns. Subsystem dry mass is 56.5 kg and total subsystem mass including a margin of 5.5 kg is 91.8 kg.

The equivalent mass of chemical propellant to produce the same total impulse assuming a specific impulse of 285 sec is 286 kg.
Thermal Interfaces

The total power dissipated by the subsystem when two thrusters are operating at 25 mN is 470W. Of this 141 watts is dissipated by each thruster, 88 watts by each FOCX and the remainder by the propellant storage and supply equipment. Thermal control of the FOCX in particular is therefore extremely important. The thruster operating temperature is approximately 200°C, so much of the heat generated by the thruster is radiated directly to space. Radiated and conducted heat paths back into the spacecraft are restricted by the earth screen which surrounds the thruster and by thermally isolating mounting brackets.

Grid Sputtering

Contamination of spacecraft surfaces by material sputtered from the thruster grids has been estimated from test data produced during the life testing of the mercury ion thruster. References 3 and 4.

Sputtering of the accelerator grid is caused by bombardment of the grid by low energy xenon ions created immediately downstream of the thruster as a result of collision between neutral xenon propellant and ions in the beam. The ions produced by the collision are attracted to the negatively charged accelerator grid, and on impact dislodge atoms from the grid. These polonium atoms then tend to become deposited in the vicinity of the thruster.

The amount of polonium sputtered and eroded from the accelerator grid was measured in an earlier series of tests with mercury propellant and operating at 10 mN. The results were published in reference 4. This series of tests gave an average grid material loss rate of 0.14 mg/hour, a value which can be modified to allow for the higher thrust and xenon propellant of the UK-10 thruster. Reference 5, it was showed that the sputtering yield is proportional to the charge-exchange ion current. However, the higher beam current associated with 25 mN thrust compared with 10 mN is offset to some extent by the lower probability of ion exchange due to the higher propellant exhaust velocity, the higher velocity of the neutral propellant, and due to the smaller collision cross-section of xenon atoms when compared with mercury. The predicted sputtering yield for the UK-10 thruster at 25 mN is therefore 0.30 mg/hour, which, over 4500 hours of operation is equivalent to 1.35 gms.

The deposition rate of sputtered materials has been measured during thruster life tests, which also showed that the sputtering due to the neutraliser is much less than that due to the neutral efflux from the grids. From the data obtained the maximum deposition rate of polonium at a distance of 20 cm from the centre of the grid was approximately 8 x 10^-11 g/cm²s, the peak being at an angle of 35° to the plane of the grids. These data are for a 500 mg/hour life test with mercury propellant at 10 mN thrust. The deposition rates have been converted to deposition thicknesses at various distances from the thruster assuming the applicability of an inverse square law and a sticking coefficient of unity. It should be noted that deposition mainly occurs when the array in question is orientated to face towards a thruster. Consequently, due to the rotation of the array it will collect material for one half of the thruster operating time, on average.

To put this amount of sputtered material into context, it is useful to compare it with the amount of iron and particulates contained in the 286 kg of chemical propellant loaded into the equivalent bipropellant propulsion system, as mentioned above.

Nitrogen tetroxide propellant can contain a maximum of 1 ppm of iron when loaded and 26 mg/litre of particle material (from NAS 3620). This document is designed to update MIL-P-28593C which does not specify a maximum iron content but does limit particulates to 10 mg/litre.

Monomethyl hydrazine propellant, procured to MIL-P-27404B is allowed to contain a maximum of 10 mg/litre of particulates.

In 286 kg therefore, the amount of material exhausted from the north-south stationkeeping thrusters which is not propellant is 4.5 gms. This figure does not account for material generated as a result of chemical reactions within the propulsion system nor material lost from the thrusters due to surface erosion.

However, this value is rather higher than that predicted for the ion propulsion system, yet no significant problem has been reported as a result of surface contamination caused by chemical propulsion systems.

Reliability

A reliability assessment has been performed on the four thruster configuration described here and also on a two thruster configuration in which both thrust vectors pass through the spacecraft centre of gravity, so producing a redundant system.

The analysis identified certain critical components such as the regulator valves which exhibit between 1 and 3 million operations throughout a 10 year lifetime. Six of these values are due to undergo a life test programme designed to produce a statistically valid failure rate. No problems were detected during earlier development tests which terminated at 11 million operations using nitrogen gas.

Further, the assessment assumed that apart from tanks and pipework, the non-operating failure rate is one-tenth of the operational figure. This is usual for electronic parts but may be pessimistic for the electro-mechanical items.
The reliability figures based on these assumptions for the two subsystems are as follows:

<table>
<thead>
<tr>
<th>System</th>
<th>6 months</th>
<th>10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 thruster</td>
<td>0.9988</td>
<td>0.952</td>
</tr>
<tr>
<td>2 thruster</td>
<td>0.9997</td>
<td>0.9886</td>
</tr>
</tbody>
</table>

For the 4 thruster system the PSE was common to all thrusters, whereas in the 2 thruster analysis, the PSE was assumed to be redundant.

**Ground Support Equipment**

The type of ground support equipment (GSE) required to load propellant and test the ion propulsion subsystem at the launch site consists of a propellant loading system, a leak test system and an electrical test set.

The propellant loading system should be capable of processing cleaning fluids as well as pressurant gases and propellant gas. This leads to the following list of fluids: deionised water, isopropyl alcohol, helium gas, nitrogen gas and xenon gas. The loading system should be capable of operating safely at pressures of 1.5 times the maximum expected operating pressure of the propulsion subsystem to allow proof pressure tests and leakage tests to be conducted.

Cleaning of the propulsion system using liquids requires that drainage paths should be considered during the early design phases, and a vacuum pump is necessary as part of the loading system to remove as much of the cleaning fluids and pressurant gases as possible. A dewpoint meter is normally used to monitor the amount of cleaning fluid remaining.

Propellant loading may be through a booster pump to produce the high pressure, or from a specially filled high pressure tank. In either case it is important that the propulsion system is dry, clean and evacuated prior to loading, and that the mass of propellant transferred is measured.

The leak test system usually consists of commercially available helium mass spectrometer combined with a series of custom made covers which can be clamped around joints or test port connectors to allow leak rates to be measured.

The electrical test set should enable the electrical functions of the PCCE to be tested, plus continuity and insulation resistance of the thruster, PSE and PSE electrical components. The electrical test set is based on a self-contained rack containing a digital multimeter, plug board, microprocessor, VDU, keyboard, floppy disc drive and digital storage oscilloscope plus a plotter or printer. Interface links to the electrical connectors on the PCCE, PSME, PSE and thruster using break-out cables and saver connectors should be included. Dummy loads representing each of the equipments should be provided to enable electrical tests to be made without actuating propulsion system solenoid valves or heaters. The electrical test set should also allow monitoring of instrumentation with calibration tests as necessary.

**UK Development Programme**

The development schedule for the UK-10 ion propulsion subsystem is shown in Figure 5. Current work at Marconi Space Systems includes design and development of the power supplies, monitoring of tests on the breadboard PSME and defining the subsystem interfaces. Work due to start shortly includes design, manufacture, assembly and test of prototype versions of the PSME and PCCE, and further system level studies and interface definition.

At Culham, preparations for thruster testing at 10, 20 and 25 mN using the breadboard PSME or commercial flow controllers and a switching system to allow alternative versions of the PCCE to be fitted have been completed. Testing has now commenced, with investigations of start-up performance, stability and measurements of conducted and radiated noise levels. In addition, diagnostic instrumentation capable of being flown on a spacecraft will be installed and tested for its effectiveness.

Phillips Components Ltd who make the neutraliser, cathode and main flow assemblies have recently completed an order for the production of several sets and will be conducting life tests on cathodes and neutralisers at the 25 mN flow rates.

RAE are in the process of manufacture and assembly of 4 thrusters and an updated version of the 10 mN PCCE. In addition, test facilities are being prepared which will allow life tests to be conducted on thrusters at 10 mN and cathodes at the 25 mN flow rates. Life testing of the thruster at 25 mN is scheduled to commence early in 1990 using flight design equipment.

**UK-10 Ion Propulsion System**

![Figure 5: Development Schedule for the UK-10 Ion Propulsion System](image-url)
Conclusion

The programme for the design and development of a UK Ion Propulsion System for use primarily in north-south stationkeeping applications is well established. The sound heritage of component development and life testing during the 1970’s has provided a great deal of information and confidence in the thruster design, and the experience of Marconi Space Systems in power conditioning and propellant feed systems is being applied to the design and development of the power conditioning and control equipment and the propellant supply and monitoring equipment.

System studies of surface contamination, and testing for electro-magnetic noise have indicated that these potential problem areas will not have any noticeable detrimental effect on spacecraft performances when the UK-10 ion propulsion subsystem is flown.

Further testing is being conducted, mainly at the 25 mN thrust level to verify the results obtained previously and during recent short duration tests, and to verify the lifetime of the subsystem with xenon propellant at the 25 mN thrust level.

References

1. D G Fearn, A R Martin and A Bond; The UK ion propulsion programme: past status and new results. IAF-86-176.


