DEVELOPMENT OF A FLIGHT STANDARD POWER CONDITIONING AND CONTROL SYSTEM FOR THE T5 ION THRUSTER.

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ABSTRACT
This paper reports on the development status of the Power Conditioning and Control System (PCCS) being developed for a test flight of the T5 ion thruster. A brief outline of the power and control requirements of the thruster is followed by a description of how these were provided in the prototype PCCS, built to breadboard standard. Problems presented by the thruster are highlighted and details of the techniques used to resolve them are given. This is followed by a description of the development of the flight packaging of the PCCS. An account is given of the approach adopted to ensure reliable operation of the PCCS in the face of the extremities of the space environment, thermal stresses in particular.

1. Introduction
The UK has successfully developed a 10 cm diameter Kaufman-type ion thruster [1]. Designated the T5 ion thruster, it is the result of considerable effort expended by a team led by the Royal Aerospace Establishment, Farnborough (RAE) [4]. Its design has been carefully refined to produce a highly efficient thruster that exhibits stable operation over a wide range of thrust. Changes have been introduced to allow operation with xenon gas rather than mercury. Spacecraft compatibility is therefore enhanced by eliminating the possibility of condensation of a chemically reactive propellant onto spacecraft surfaces. Furthermore, it has undergone vibration and life tests and is approaching flight demonstration standard.

The Power Conditioning and Control System (PCCS) described in the paper is designed for a thrust of 10 mN, although the thruster can operate at up to 70 mN. The T5 and the PCCS, together with the associated tanks, valves, flow controllers, and pipework, are designated the UK-10 ion thruster system. A breadboard PCCS has been constructed and following integration with the thruster it will be used in an extended cyclic life test of the UK-10 system at the RAE. In parallel, a cyclic life-test at 25 mN is to be undertaken at the UKAEA Culham Laboratory, using a PCCS developed by Marconi Space Systems.

Development of the PCCS has always necessarily lagged behind the development of the thruster. However, the current advanced status of the T5 thruster has intensified the need for a space-flight standard PCCS. This paper starts by describing the needs of the T5 ion thruster, followed by an overview of how these are provided by a breadboard PCCS. The paper continues to describe the problems encountered when packaging the PCCS to flight standard. The performance of the power supply modules is heavily dependent on their ability to endure extreme thermal and vibrational stress. The effectiveness of a thermal modelling computer aided design (CAD) package is demonstrated by using it to optimise the mechanical layout of the PCCS. The paper also includes a discussion on the advantages and disadvantages of applying this CAD package to space-based power systems.

2. Requirements of the T5 Ion Thruster
Efficient operation of the T5 Ion Thruster requires nine regulated power supplies and three flow controllers which must be sequenced in a precise order. The function of the PCCS can thus be summarised as follows:

(i) To provide suitable power supplies to the thruster.
(ii) To start-up, shut-down, throttle, and maintain steady-state operation of the thruster.
(iii) To accept commands from and send diagnostic data to the telemetry subsystem.

The power supply modules are connected to the thruster as shown in figure 1. Here it can be seen that the outputs of some of the power modules are referenced to thruster potential (approximately 900 volts and provided by the beam module). Such a high voltage level is detrimental to the reliability of

electronic components and steps should be taken to minimise the number of components referenced to it. Another hazard is thruster inter-grid arcing. Although very rare on the T5 thruster, its occurrence is unpredictable and can cause safe operating levels of components to be exceeded. Supplies vulnerable to its effects should have some form of current limiting.

Information on the power levels and supply characteristics required by the T5 in its engineering model form was provided by Culham Laboratory, who have extensively evaluated its performance. Table 1 gives details of the voltages and currents required by various components of the thruster when operating to produce a thrust of 10 mN. These parameters were optimised using thruster performance envelopes [2]. These envelopes are generated by measuring electrical and mass utilisation efficiencies for different permutations of power and propellant supplied to the discharge process in the thruster. More specifically, this is done by varying, at constant thrust, the discharge voltage and current, the magnetic field, and the fraction of the propellant fed into the discharge chamber through the hollow cathode. These envelopes are used to determine the threshold voltage and current levels for stable operation of the thruster. To maximise thruster efficiency, operating levels are chosen to be as close to the threshold levels as practical. The safety margin chosen defines the performance required (and therefore the complexity) of the power modules. In practice, the degree of regulation readily achievable has dictated the choice of normal operating levels (as shown on Table 1) and of safety margins (10% has been selected).

![Diagram of T5 Ion Thruster](image)

**Figure 1**: PCCS integrated to T5 Ion thruster.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Beam supply voltage</td>
<td>940 V</td>
</tr>
<tr>
<td>2. Beam current</td>
<td>210 mA</td>
</tr>
<tr>
<td>3. Magnet voltage</td>
<td>17.3 V</td>
</tr>
<tr>
<td>4. Magnet current</td>
<td>0.3 A</td>
</tr>
<tr>
<td>5. Anode voltage</td>
<td>45 V</td>
</tr>
<tr>
<td>6. Anode current</td>
<td>1.2 A</td>
</tr>
<tr>
<td>7. Discharge keeper potential</td>
<td>600 V</td>
</tr>
<tr>
<td>(a) starting</td>
<td>600 V</td>
</tr>
<tr>
<td>(b) operating</td>
<td>16 V</td>
</tr>
<tr>
<td>8. Discharge keeper current</td>
<td>0.4 A</td>
</tr>
<tr>
<td>9. Anode grid voltage</td>
<td>-300 V</td>
</tr>
<tr>
<td>10. Anode grid current</td>
<td>0.5 mA</td>
</tr>
<tr>
<td>11. Hollow cathode heater current</td>
<td>0-1.0 A</td>
</tr>
<tr>
<td>12. Hollow cathode heater voltage</td>
<td>8.2 V rms</td>
</tr>
<tr>
<td>13. Neutraliser cathode heater current</td>
<td>0-1.0 A</td>
</tr>
<tr>
<td>14. Neutraliser cathode heater voltage</td>
<td>8.2 V rms</td>
</tr>
<tr>
<td>15. Neutraliser keeper potential</td>
<td>600 V</td>
</tr>
<tr>
<td>(a) starting</td>
<td>600 V</td>
</tr>
<tr>
<td>(b) operating</td>
<td>24 V</td>
</tr>
<tr>
<td>16. Neutraliser keeper current</td>
<td>0.4 A</td>
</tr>
<tr>
<td>17. Neutraliser bias potential</td>
<td>0-50 V</td>
</tr>
<tr>
<td>18. Neutraliser bias current</td>
<td>210 mA</td>
</tr>
</tbody>
</table>

3. Control of The T5 Ion Thruster

The control of the thruster can be separated into four distinct operating modes -

(i) Start-up
(ii) Steady-state
(iii) Throttle
(iv) Shut-down

3.1. Start-up

The start-up of the thruster takes approximately five minutes. This delay is due mainly to the thermal time constants of the hollow cathodes used in the discharge chamber and the neutraliser. To minimise consumption of electrical energy and propellant, it is desirable to turn on at the start of the sequence only those modules or gas valves that are necessary. Furthermore, to reduce thermal stressing of the thruster, some modules should only be turned up gradually. An optimised control sequence is shown in figure 2. This relies on a hot hollow cathode to initiate a discharge in the thruster. The sequence operations are a function of both time and thruster status.

A simplified start-up sequence has been developed as an alternative that shown in figure 2. This method is called gas pulse striking and does not rely upon the hollow cathode heater to start the ionisation process. Instead, a pulse of gas is released into the thruster through the cathode, and breakdown between it and the nearby keeper electrode causes a surge of current from the keeper power module whilst it is in its high voltage mode. The discharge then transfers immediately to the anode. This starting technique was developed recently and demonstrates the
flexibility obtainable from a microprocessor-based controller: the sequence stored in memory can easily be modified for start-up by gas pulse striking. By using a microprocessor-based controller in the flight version of the PCCS, new sequences can be devised and tested in flight.

3.2. Steady-state

During steady-state operation of the thruster the controller maintains thrust and mass utilisation efficiency at pre-determined values by adjusting the flow controllers to the thruster. Accelerator grid and beam current are monitored to ensure that the thruster is operating normally. If these are out of range, corrective action is taken. This may require switching off the accelerator and beam modules or in some cases switching off all the supplies. An additional control loop regulates the operation of the neutraliser.

Table 2: Throttle range data for xenon. (The total power \(P_{tot}\) does not include power consumed by magnets, heaters and neutraliser)

<table>
<thead>
<tr>
<th>THRUST (mN)</th>
<th>BEAM CURRENT (mA)</th>
<th>ACCEL. CURRENT (mA)</th>
<th>(P_{tot}) (W)</th>
<th>ELECTRY EFNCY (%)</th>
<th>TOTAL EFNCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.55</td>
<td>70</td>
<td>0.4</td>
<td>101.0</td>
<td>65.2</td>
<td>45.6</td>
</tr>
<tr>
<td>3.32</td>
<td>105</td>
<td>0.7</td>
<td>138.1</td>
<td>71.5</td>
<td>50.0</td>
</tr>
<tr>
<td>7.10</td>
<td>140</td>
<td>1.0</td>
<td>178.8</td>
<td>73.6</td>
<td>51.5</td>
</tr>
<tr>
<td>8.87</td>
<td>175</td>
<td>1.1</td>
<td>225.0</td>
<td>73.1</td>
<td>51.2</td>
</tr>
<tr>
<td>10.65</td>
<td>210</td>
<td>1.4</td>
<td>262.1</td>
<td>75.3</td>
<td>52.7</td>
</tr>
<tr>
<td>12.42</td>
<td>245</td>
<td>1.6</td>
<td>304.3</td>
<td>75.7</td>
<td>53.0</td>
</tr>
<tr>
<td>14.20</td>
<td>280</td>
<td>1.8</td>
<td>345.7</td>
<td>76.1</td>
<td>53.3</td>
</tr>
<tr>
<td>15.97</td>
<td>315</td>
<td>2.1</td>
<td>388.3</td>
<td>76.3</td>
<td>53.4</td>
</tr>
<tr>
<td>17.75</td>
<td>350</td>
<td>2.4</td>
<td>422.8</td>
<td>77.8</td>
<td>54.3</td>
</tr>
<tr>
<td>19.53</td>
<td>385</td>
<td>2.9</td>
<td>463.2</td>
<td>78.1</td>
<td>54.7</td>
</tr>
<tr>
<td>21.30</td>
<td>420</td>
<td>3.2</td>
<td>503.8</td>
<td>78.4</td>
<td>54.9</td>
</tr>
<tr>
<td>23.08</td>
<td>455</td>
<td>3.5</td>
<td>542.2</td>
<td>78.9</td>
<td>55.2</td>
</tr>
<tr>
<td>24.60</td>
<td>485</td>
<td>3.6</td>
<td>571.7</td>
<td>79.7</td>
<td>55.8</td>
</tr>
</tbody>
</table>

Figure 2: Thruster control sequence, including start-up, steady-state, and stop.
3.5. PCCS controller

The thruster modes listed above are executed by controlling the power applied or the propellant supplied to the thruster, or both. This is performed by a microprocessor-based controller. From a short-list of several candidates, the 8086 microprocessor was chosen. A wide range of support devices, the availability of development systems, and plans to space qualify and to radiation harden by using silicon on sapphire technology were important factors in selecting this device. Other devices required include read only memory (ROM) containing the PCCS operating software; read/write memory (RAM) containing alternative thruster sequences; input/output ports to control the power modules; and analogue to digital converters to convert the monitored current and voltage data into a format suitable for the telemetry subsystem.

It is likely that the operational PCCS will be controlled from Earth via the on-board telemetry subsystem. For example, the four modes described above can be initiated as a result of an appropriate command to the telemetry subsystem. Another purpose of the telemetry interface is to pass diagnostic data to Earth. The data includes voltage and current levels at various points in the PCCS, as well as thruster status and hazard signals. By designing the breadboard PCCS to be as representative as possible of the operational PCCS, then any problem or limitations in the software can be detected at an early stage of the test program. This has resulted in the PCCS being a stand-alone system without any controls. The only means of controlling and monitoring the PCCS is through its data network port. In operational use this would be linked to the spacecraft telemetry system.

4. Operation of Power Supply Modules

Although the prototype PCCS is intended for a laboratory environment, constraints usually applied to space subsystems played an important role in the design process. The result is a design that can readily be upgraded to flight standard and has the benefits of a long trial period. As mentioned before, the T5 thruster requires nine separate power supplies. They output a total of about 300 watts and should be highly efficient. This requirement is necessary as power is limited on the spacecraft and also as it eases the problem of thermal control. Another important feature of the design is the commonality of the supplies, allowing rapid conversion to flight standard production models. Each module is capable of supplying up to 50 watts. For the higher power output required from the beam supply, several modules are connected in series. The modules are based on the commonly used forward converter topology operating under constant current or voltage control. Although this is not the simplest configuration, it does exhibit a much reduced output ripple voltage. A block diagram of the PCCS modules is shown in figure 3. The main transformer and those used in the current and voltage monitoring circuitry provide isolation and help to minimise the number of components referenced to high voltages.

4.1. The drive circuitry

To describe the operation of the circuit we will begin at the point where the pulses are produced, the pulse width modulator (PWM). The period of the pulse is controlled by an external capacitor and resistor. The values used result in a duty cycle of 0.8. A 36 kHz square wave signal provides a trigger. Another two inputs serve as module enable signals. These are used by an overcurrent protection mechanism, disabling the monostable during arcs, and by the PCCS controller.

The outputs of the PWM are two 18 kHz pulse trains in antiphase. These are applied to the power stage. The load presented to the output transistors is almost a pure inductor, causing applied voltage and current to be 90 degrees out of phase. The consequence of this is the power loss during switch on is extremely low, whereas during switch off the loss is extremely high. The power stage therefore incorporates drive circuitry designed to allow a fast switch off and therefore increase efficiency. The negative potential applied to the base of the transistor sweeps away the stored charge and thus ensures that a fast switch off is achieved.

4.2. The power processing stage

The power transistors thus alternately apply the 50 volts rail to the two ends of the primary winding in the main transformer. A centre tap on the primary is connected to the 50 volts line.
Over-current protection is provided by two mechanisms. A comparator in the PWM detects when the output of the module rises above a preset threshold and sends a signal to the two protection mechanisms. The first is to disable the output of the PWM, allowing the discharge current to decay away. The second mechanism is to open the constant current control loop and to reduce the duty cycle of the pulse width modulation to 4%. This condition is allowed to exist for a duration of 2 msec, followed by the restoration of the constant current loop. If the cause of the short-circuit remains, the current rises until the comparator once again switches. The module thus alternates between 0 and 4% duty ratio at a rate of 2 kHz until the cause of the over-current is removed or the PCCS controller shuts down the ion thruster.

The output on the secondary winding is rectified by fast recovery diodes and smoothed by an output filter. The overall recorded efficiency of the PCCS is about 88%, with individual high power modules reaching over 90%. The inductors used in the filter also limit sudden increases in current during arcing, thus providing some over-current protection.

The switching frequency was selected after studying the variation of losses with frequency in the power transistors, rectifiers and the main transformer. Transistor losses are of three types: "on", "off", and switching. The latter increases with frequency and may become significant if the switching time is more than about 1% of the cycle time. The losses in the rectifier follow a similar pattern. Transformer losses are due mainly to copper loss and hysteresis loss. The frequency selected results in the lowest total loss.

4.3. Output regulation

Stable and efficient operation of the thruster requires the output of the module to be accurately controlled. Current and voltage monitors are used to sample the output. Since the output is connected to the high voltage rail (typically 600 to 1000 volts), transformers were used to provide isolation and to minimise the number of components referenced to high-voltage. Figure 4 shows the current monitoring circuitry. The output from the secondary is then fed to a scaling amplifier which generates an appropriately mapped signal in the -5 to +5 volts range. The voltage monitoring circuit operate in a similar manner, but is simplified because the sensing resistor is not needed.

To obtain current or voltage control, the duty ratio of the pulse train generated from the PWM must be variable. The output is compared to a reference and an error signal is generated. This signal alters the duty cycle of the pulse train accordingly.

5. Mechanical Design of Flight Standard PCCS

In preparation for a possible low-cost flight test of the UK-10 system on a technology demonstrator satellite [3], an investigation of flight packaging techniques has started. The objective is to develop the breadboard PCCS into a flight standard version without expensive space qualification procedures, yet capable of withstanding the stress encountered in the space environment, and provide good reliability. As a starting point a reliability of greater than 95% for 2000 hours operation was selected to be a realistic target.

Each of the nine modules processes up to 50 watts. With an average efficiency of 88% this implies that there is as much as 6 watts dissipated in each module. The losses are due mainly to four sources: transformer, biasing/feedback network, transistor switching, and finally rectification. For increased reliability it is essential that components operate at temperatures well within their specified operating range. Due to the lack of convective cooling within the space environment, thermal design of electrical systems is crucial. In the mechanical design of the PCCS, thermal control is considered as the prime constraint. The cost and complexity introduced by adopting an active cooling system is prohibitive. More suitable is a passive system where heat is conducted from the printed circuit board (pcb) to an external spacecraft surface to be radiated into deep space [5]. However, some heating elements to limit the temperature excursions within the PCCS are unavoidable when non-operation or eclipsed conditions are considered.

Figure 4: Current isolator circuit.
5.1. Constraints on mechanical design

Before thermal optimisation can begin consideration should also be given to other constraints that are likely to affect the mechanical design of the PCCS. As yet details regarding volume and shape available for the PCCS on board a spacecraft are unknown. A flexible design is therefore adopted. Each power module is considered a separate unit. These units can either be distributed over the spacecraft or housed in a single container, depending on the space available on the spacecraft. For the latter a frame measuring approximately 550mm x 250mm x 150mm, (figure 5(i)), will be manufactured in aluminium alloy with internal webs to provide stiffness, screening and support for the individual modules. Depending on the spacecraft orbit, the PCCS will be exposed to varying doses of trapped electron and proton radiation. This results in atomic dislocation is semiconductors, leading to the eventual failure of the device. By suitable selection of the thickness of the PCCS frame the damage can be minimised. The discharge modules. Depending on the spacecraft anode supply will be described here as a representative module. The results of this study indicates the existence of undesirable hot spots as well as provide useful information for designing the mechanical layout of a flight packaged PCCS. To aid development, a printed circuit board (pcb) heat transfer analyser for computer aided design (CAD) was utilised. By using the analyser the thermal characteristics of a pcb layout design can readily be simuate

5.2. Thermal design of PCCS

Exploratory studies have commenced to investigate the thermal behaviour of the PCCS modules in vacuum. The discharge anode supply will be described here as a representative module. The results of this study indicates the existence of undesirable hot spots as well as provide useful information for designing the mechanical layout of a flight packaged PCCS. To aid development, a printed circuit board (pcb) heat transfer analyser for computer aided design (CAD) was utilised. By using the analyser the thermal characteristics of a pcb layout design can readily be simulate

5.2.1. The heat transfer analyser

The system allows a pcb to described at two levels;

(a) Physical.

Physical definition include:-

(i) pcb size and properties.

(ii) Component parameters (e.g., size, shape, type, power dissipation, thermal resistance and surface area).

(iii) Component placement.

(iv) Heat sink type and properties.

(b) Environmental.

Environmental definition include:-
The analyser allows a vast number of variables to be altered and hence provides the means to model a typical board in most environments. Data input is achieved through comprehensive menu and on-screen editing facilities. Two graphical output formats are available, these are:

(a) Board isothermal distribution
In this case, the board is defined thermally by various multi-coloured bands, each band covering a range of temperatures as specified within a given bar scale

(b) Component Temperatures
The board is defined with components in place, each component temperature is represented as in (a) above.

5.2.2. Thermal design of a PCCS power modules

The approach taken to thermally optimise the discharge supply module is to examine various board layouts and select one that attains an acceptable temperature distribution (so that all component temperatures are well below their specified maximum operating temperatures). Thermal design was restricted to the high power board containing the largest heat dissipaters. An initial component layout derived by considering the following factors:

(a) Knowledge of requirements of components.
(b) Vibration constraints.
(c) Routing constraints when designing the printed circuit board.
(d) Constraints incurred through placement of large components.

To achieve an optimum layout the following parameters were varied:

(a) Component Placement
Initially various components were found to be too close to each other, hence providing possible hot spots. By use of the simple editing facility available within the analyser, the layout was re-arranged accordingly.

(b) Thermal Plane Thickness
To conduct heat from the components to the radiating surface a thin sheet of aluminium is bonded to the component side of the pcb before the components are mounted [7]. The effect of varying the thickness of this thermal plane was
simulated. Over the thickness range 1mm to 2.5mm the effect of change upon component temperatures proved negligible. This minimised the overall mass of the board, a thermal plane thickness of 1mm was therefore considered appropriate for further analysis and experimentation.

(c) Boundary Temperatures

Throughout much of the thermal analysis, a board boundary temperature of 10°C was assumed. In reality this condition will vary according to the attitude of the radiating plate in space [6], hence the boundary temperature was also simulated over the temperature range 10°C to 50°C.

In addition to varying the above parameters, attempts were made at restricting heat flow from the main heat sources to the remaining components by introducing slots within the thermal plane which would interrupt the flow of heat from the problem components. Such modifications considerably increased the heat source temperature and had an adverse effect on power transistors, increasing the risk of thermal runaway. Consequently, the technique of restricting heat flow was abandoned.

The thermal characteristics of the final design are shown on figures 7 and 8. These represent the temperature distribution across the thermal plane and components, respectively. When considering normal operating conditions (e.g. board boundary temperatures of 10°C), and assuming good thermal contact exists between the component and thermal plane the maximum simulated component case temperature is 44.7°C, however, junction temperatures can increase to 44.7°C. Such temperatures are acceptable since they fall within the component temperature specification range of -65°C to +150°C.

Before the thermal design layout could be transferred to a production PCB, knowledge was required as to the susceptibility of components to vibration [8]. For this purpose, sinusoidal excitations over a frequency range of 10 to 200Hz at a constant acceleration were applied to a duplicate layout of the thermal design. The tests bore the following conclusions:

(a) Additional supports are required for large components.
(b) Encapsulating wound components is necessary.

The resulting mechanical design was then constructed. To evaluate the effectiveness of the thermal analyser, the temperatures measured on a test circuit operating within a vacuum were compared to a simulation of the same board. The results of this simulation are shown on Table 3.

These results show that under vacuum conditions the thermal analyser can closely simulate the temperatures of non-semiconductor components. However, temperatures of semiconductor devices, rectifying diodes in particular, are more difficult to predict. This discrepancy is due to approximations made when estimating certain input parameters to the thermal analyser, namely the power dissipation of semiconductors. This is difficult to calculate and furthermore rises with temperature. Another reason is the awkward shape of the diodes which makes it difficult to establish good thermal contact with the thermal plane. However, the thermal analyser does establish a temperature trend which can be readily related to the experimental results.

Overall, the analyser provides an effective means of initial thermal layout optimisation provided that a worst case power dissipation of semiconductor components is assumed.

Having validated the simulations, the analyser can now be used to model various fault conditions and thus assess the safety margins provided by the design chosen. Such conditions may be too expensive or impractical to create in a laboratory, but using the analyser simulations carried out readily.

Conditions currently being investigated include the thermal effects of degradation in efficiency of the power modules, and also of the partial illumination of the radiating wall by the Sun or the Earth.

6. Summary

The UK-10 ion thruster system has reached an advanced state of development and is awaiting flight to demonstrate the viability of this new technology. In expectation of this, work has started on converting the breadboard PCSs to flight standard. To maximise reliability, it is essential that components operate well within their rated minimum/maximum parameters. In the initial design of the PCSs electrical parameters were sufficiently derated for laboratory use. However, in space component operating temperatures are much more dependent on the physical structure of the system. Therefore, to obtain sufficient derating under operating conditions, mechanical layout of the PCSs is being carefully designed.

Thermal analysis provides reasonable estimates of component operating temperatures, and thus provides valuable guidance in designing the mechanical layout of flight packaged electrical systems. When used with other CAD/CAE systems, such as automatic PCB routing systems, it allows layouts to be devised, assessed and altered within hours rather than days, providing reduced turnaround time between design and production.
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