AD-A061 035 ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) F/G 21/3

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ROYAL AIRCRAFT ESTABLISHMENT

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Technical Report 78045

April 1978

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UDC 621.455.4 : 5.001.58

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 78045

Received for printing 28 April 1978

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SUMMARY

A study of the design, development and application of a mercury ion thruster performance simulator is presented. Although based on previous successful experimental work on the simulation of the discharge mechanism and ion beam extraction characteristics of the UK T4 thruster, the design has been considerably extended to accurately represent all aspects of thruster operation relevant to station-keeping missions. These functions include all relevant time-dependent parameters associated with thruster warm-up during the starting sequence and the appropriate, performance related, loading of the various thruster power supplies. Its application is discussed in terms of satisfying a pressing requirement for a pre-launch check-out facility, when thruster operation is not practicable. It provides an independent means of assessing both the flight status of the thruster power processing and sequencing electronics and possible interactions with other spacecraft sub-systems.

Departmental Reference: Space 548

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1 INTRODUCTION

The development of an electron-bombardment ion thruster system in the UK commenced in 1967, under the technical direction of the RAE, the eventual aim being to produce a highly efficient, durable 10 mN thrust device for the north-south station-keeping application[1,2]. Although most of the available effort was devoted to the very successful thruster development programme, a highly efficient power conditioning unit (PCU)[3] was designed, manufactured and tested by MSDS Ltd, and propellant feed system components were also given adequate attention[4,5,6].

It was also realised that a device would be needed to simulate the operation of the actual thruster during pre-launch check-outs of the PCU, because it is not possible to run a thruster on the ground once it has been installed in a spacecraft. Although a simple system of fixed resistors would probably have been adequate to represent the thruster during steady-state operation, the need for repetitive starting cycles in the station-keeping application made it essential to achieve a more accurate simulation. Once this was accepted, it was also recognised that such a simulator could be a valuable aid to PCU development, in that individual modules or the complete PCU could be operated into realistic loads without the need to involve a thruster. It was anticipated that this would allow considerable savings to be made, both of development time and of money.

Initial development of the simulator concept was extremely successful[7,8], an accuracy of 5% being achieved in representing the complex discharge chamber and ion beam extraction characteristics of the T4 thruster[9]. A loading regulator was also produced, which correctly loads the discharge power supply according to the current and voltage values derived in the simulator.

Towards the end of 1976, the European Space Agency (ESA) began to plan a flight-test of competing European ion thruster systems on the spacecraft to be launched in 1980 by the Ariane L04 vehicle. ESA issued a Work Statement[10] to the developers of those systems which specified the objectives of the necessary development programmes. ESA also requested that Development Cost Plans (DCPs) be prepared to meet those objectives[11]. At that time, it was considered probable that the UK T4A[12] or T5[6] thrusters would be included in this experimental flight, so there was a considerable acceleration of those parts of the project associated with space qualification and the mission itself.

The response of the RAE[11] to the request from ESA for a DCP included plans for extending the simulator to represent the complete thruster with considerable accuracy, so that, in particular, the performance of the PCU during the start
045 sequence could be established. In fact, ESA had stipulated[10,13] that such a device

should be produced. In anticipation of proceeding to the flight programme, the necessary design work was carried out, making extensive use of the concepts already applied successfully to the initial stages of the simulator's development. This design is described in broad detail in the present Report , which also includes an assessment of the possible uses of the simulator in a flight project.

Unfortunately, it must be recorded that the design study has not been followed by experimental work, owing to the cancellation of the UK's participation in the L04 flight experiment.

2 AIM OF SIMULATOR DEVELOPMENT

As well as the development and manufacture of thrusters, PCUs and other flight hardware, it is also essential, for the success of a test flight of an electric propulsion (EP) system, to produce sophisticated check-out equipment for use at various times during the program. This check-out equipment should include a thruster simulator, which is capable of electrically loading the PCU with considerable accuracy under all conditions likely to be encountered during start-up and steady-state operation. This device is necessary because it is not possible to operate a thruster on the ground, unless it is mounted within a special test chamber[14].

Development of such a thruster simulator has been carried out at the RAE, and it has reached the state where the discharge chamber characteristics and the ion beam current response of the UK T4 thruster[9] can be represented to an accuracy of 5% or better. However, a considerable amount of additional work is required in order to complete the simulation of the entire thruster; thereby allowing realistic loads to be presented to every section of the PCU and enabling the starting sequence[15] to be fully exercised. This additional work is specified in this Report, and a design is proposed which should satisfy the most rigorous requirements.

At the time of commencing this study, the aim was to provide enough information, including appropriate references, to enable a DCP to be formulated by the organisation to be responsible for future work on the simulator. It was therefore necessary to take account of the work carried out earlier by the RAE and the requirements specified by ESTEC and the possible L04 spacecraft contractor[10]. Consequently, the work was heavily biased towards meeting these requirements. However, it is envisaged that all similar flight experiments and every subsequent operational mission will need to make use of an accurate thruster simulator of the type being developed by the RAE, thus providing adequate justification for presenting the information contained within this Report. 045

3 THE ELECTRIC PROPULSION SYSTEM

The relevant information relating to a typical EP hardware package, as defined by ESTEC for the L04 test flight, may be found in Ref 10. Essentially, the package was to include two thrusters, two PCUs and a single propellant tank. Originally, ESTEC specified that a double-thruster package should be produced for bolting to the external face of the spacecraft, but it was later stated that the package could be split in any way, with components mounted within the spacecraft if necessary.

A system designed for north-south station-keeping on an operational spacecraft would probably be very similar in concept, except that four thrusters and four PCUs would be employed[2] to limit the running time expected of any individual thruster and to provice adequate redundancy. A single propellant tank might still be used, but it may be necessary to include two, with appropriate interconnecting pipelines and valves, to ensure that the centre of mass of the spacecraft remains within acceptable limits as propellant is consumed. To provide thrust vectoring, each thruster could be mounted on a gimbal arrangement, although, before adoption of such a scheme, the benefits and associated mass penalty should be carefully assessed for the spacecraft configuration in question[16].

As shown in Fig 1, the PCU includes the thruster power supplies and a sequencer based on a microprocessor[15]. The latter is expected to provide the logic for the following four separate operational functions:

(a) Flight starting sequence

This is a pre-evolved and optimised switching-on sequence for the individual power supplies, the automatic program being stored in appropriate memories and implemented by the microprocessor. The major objectives are to minimise the use of starting energy and the mass of propellant consumed, while bringing the thruster to operational status in the shortest possible time, without overstressing its components. A detailed description of the starting sequence may be found in section 5.2.

(b) Fast scan sequence

On command from the microprocessor, input signals are applied to the individual power conditioner supply modules which will, in turn, briefly apply voltage and power to the loads available. This latter facility will enable a
045 final pre-launch check to be carried out on the PCU-ion thruster electrical continuity, without unduly stressing or heating any component.

(c) Set-point control and throttling

Although not a definite requirement for all missions, thrust throttling[17] may be necessary for certain thruster installation schemes, particularly for those where the thrust vectors do not pass through the centre of mass of the spacecraft. In addition, it may be desirable, for experimental purposes, to be able to alter certain set-point references in the PCU, such as that governing the neutraliser potential. These functions can be accomplished by use of the microprocessor.

(d) Operation of a switching matrix

ESTEC originally specified that a switching matrix should be provided for the L04 mission, to allow either PCU to operate with either thruster. Although this requirement was later deleted, reliability analysis[2] may show that such a device should be included in certain missions. In that case, it would also be controlled by the microprocessor.

A schematic of how these above functions may be implemented is shown in Fig 2. More detailed information concerning the switching philosophy, involving the microprocessor, is contained in Ref 15.

4 THRUSTER SIMULATOR BACKGROUND WORK

The operating principles and performance evaluation of a thruster simulator, relating to earlier work conducted in Space Department RAE, is described in detail in Refs 7 and 8. Although, at the time of its original concept, the more immediate application was seen to be as an aid in control system studies, its future possible use, as a substitute for the ion thruster in the check-out phases of spacecraft integration and launch, was a guiding influence in the design.

The basic design, as it exists in breadboard form at present and which forms the foundation of this follow-on work, is capable of providing realistic loading to critical parts of the PCU, in both steady-state and dynamic modes of operation. In particular, the complex characteristics associated with the main discharge in the thruster's ionization chamber, together with the final extracted ion beam current, are computed in the simulator from the various input parameters previously set up on the PCU. These are functionally reproduced to give the required performance-related loading to the discharge power supply and, with some further development, described in Refs 7 and 8, the ion beam current supply modules. This enables corresponding values of the discharge current, the discharge voltage and the beam current to be monitored and checked against those derived from thruster calibration tests.

The present design uses analogue principles for scaling, summing and multiplying functions, with the various ion thruster performance characteristics stored in diode function generators. As will be mentioned later, the concept results in good accuracy, but setting-up procedures are tedious and long-term drift may represent a significant problem. Standard integrated circuits are used throughout the device, with the exception of the loading regulators, where the relatively high power levels demand the use of discrete transistors. Bulky heat sinks are, of necessity, associated with the discharge and beam power loading circuits, but these could be contained within a packaged device, using force-cooling if necessary.

A schematic block diagram of the simulator is shown in Fig 3. As already mentioned, it is based on the exact analogue representation of measured thruster characteristics by diode function generators (DFGs). Those shown in Fig 3 represent the following functions:

G1 - the output represents the main vaporiser mercury flow rate $\dot{m}_M$ as a function of vaporiser current I_{VM}, including thermal delay effects.

G2 - the output represents the hollow cathode vaporiser mercury flow rate $\dot{m}_{HC}$ as *a function of vaporiser current* I_{VHC}, including thermal delay effects.

G3 - simulates the variation of ΔV as a function of solenoid current I_m for a range of total flows $\dot{m}_T = \dot{m}_M + \dot{m}_{HC}$, at a standard discharge current I_{DO}. Here ΔV is the difference between anode and keeper voltages, which is a measure of the primary electron energy in the discharge chamber. The output is designated ΔV_0.

G4 - simulates the dynamic impedance of the discharge chamber, $\delta(\Delta V)\delta I_D$, at I_{DO}. This representation is valid because the impedance is linear over a wide range of I_D and is only weakly dependent on $\dot{m}_T$.

G5 - represents the variation of mass utilisation efficiency η_m as a function of ΔV for an extended range of values of I_D. The actual characteristic used is fixed by the output of G6; this is possible because the characteristics are parallel and of the same shape.

G6 - determines the value of η_m appropriate to the computed value of I_D, at an arbitrary pre-set value of ΔV, ΔV_S.

G7 - simulates the beam current I_B produced by the computed values of η_m, I_D
045 and ΔV for the given value of $\dot{m}_T$. It effectively multiplies η_m by $\dot{m}_T$,
but also introduces the 'break-points' between the linear regions of the
$I_B - \dot{m}_T$ characteristics.

In Section 1 of the simulator, signals appropriate to the vaporiser heater currents I_{VM} and I_{VHC} are fed into G1 and G2, which simulate the appropriate thermal delays as well as the variation of flow rate with heater current. The simulated flow rates are passed to G3, which also receives a signal representing I_m. The output of G3, representing ΔV_0 as a function of the flow rates and magnetic field, is used in conjunction with G4 and multiplier M to derive a signal simulating the amount $\delta(\Delta V)$ by which the actual value of ΔV in the thruster deviates from ΔV_0 due to a deviation δI_D from an arbitrary standard, I_{DO}. Differential amplifier A1 is used to give δI_D; it compares an input representing I_{DO} with another, representing I_D, derived at a later stage in the simulator. $\delta(\Delta V)$ is then added to ΔV_0 to give the actual value of ΔV appropriate to the inputs in use, although a negative output is provided.

Section 2 uses the derived value of ΔV to provide the appropriate loading to the current-controlled discharge power supply; the principles employed here can be used in a similar manner for loading the other supplies. Basically, the loading regulator is driven until the difference between the applied values of the anode and keeper voltages, V_A and V_K, is equal to ΔV. A signal representing the resulting value of I_D is then passed from amplifier A2 to Section 3, also back to A1.

Section 3 generates I_B as a function of $\dot{m}_T$, I_D and ΔV, by first deriving the value of η_m appropriate to the inputs, in a two-stage process. In the first stage, G6 is used to find the value of η_m appropriate to the value of I_D already obtained, at some arbitrary fixed value of ΔV, ΔV_S. This value of η_m is then inserted into G5, at the set voltage ΔV_S, to determine the actual position of the appropriate characteristic in that DFG; this is a valid procedure because the wide variety of possible curves are all approximately parallel, there is merely a move upwards or downwards with change of I_D. The final DFG, G7, multiplies the value of η_m appropriate to the value of ΔV computed by Section 1 by $\dot{m}_T$, and modifies the result in accordance with the detailed shape of the thruster's beam extraction characteristics, to give I_B.

The overall accuracy of the simulation is excellent. As an example, thruster and simulator performance maps are compared in Fig 4, where it can be seen that a ±5% agreement is achieved over a very wide range of conditions. Similar results are attained if other parameters are compared.

5 CONSIDERATION OF SIMULATOR APPLICATIONS

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It is anticipated that an accurate thruster simulator will find numerous applications during the development of a typical EP flight system, partly due to its ability to allow comprehensive tests to be made of the PCU and sequencer without incurring the expense and inconvenience of operating the thrusters themselves. Such applications should also make a significant contribution towards reducing development timescales. A number of such uses of the simulator are covered below, and the design necessary to accomplish them is described in section 6. Although the development programme required for the ESTEC L04 mission has been taken as an example of a typical application for the purposes of the design exercise, the results are generally relevant to a wide range of possible projects.

5.1 Acceptance testing and check-out

The detailed acceptance check-out of a PCU is likely to be undertaken first at the unit level, prior to the PCU being integrated with the appropriate thruster for performance tests in a vacuum chamber (see programme bar chart). Further check-outs will take place later at the package assembly level and during EPS-spacecraft integration, the PCU having been operated with the thruster previously in accordance with an acceptance test and calibration schedule[18]. Finally, a check-out on the launch vehicle will be required.

It is anticipated that a thruster simulator will be employed in all instances. Indeed, it will be mandatory during the integration and final check-out phases, because thruster operation will then be impossible.

5.1.1 PCU unit acceptance level tests

As the final stage of the assembly and test of a packaged PCU, before integration with the appropriate thruster, the PCU will be operated with a thruster simulator. Ideally, the simulator should accurately represent the complex load presented by the real thruster and confirm the PCU's operational status in the following areas:

(a) To demonstrate operation under steady-state conditions and with adjustments to appropriate control set-points. An examination of control loop accuracy and stability could be included, together with confirmation of any thrust throttling ability required.

(b) To establish that the self-protecting operating modes, under conditions of (simulated) extraction grid short circuit, function correctly.

(c) To exercise the complete thruster starting sequence logic. In this context, the simulator must provide realistic time-dependent loading of the PCU, including pre-heating, warm-up of cathodes and vaporisers, initiation of
045 main and neutraliser discharges, and switch-on of the beam extraction voltages. This is discussed in section 6.

5.1.2 Check-out at package assembly and spacecraft integration acceptance levels

It is not usually regarded as practicable to carry out 'live' operational tests of the thruster, following final integration with the flight package and its subsequent integration with the spacecraft, because of the vacuum requirements and problems of mercury contamination. Therefore the philosophy[18] normally adopted is to thoroughly test the EPS at the sub-system level, with the object of demonstrating that the performance of the flight thrusters meets specification, and to follow this by checks on the PCU at the package and spacecraft integration levels. The final checks will take place in the preparation area close to the launch pad.

As well as repeating the tests outlined in the previous section, the simulator would additionally be useful in confirming the operational status of the fast scan sequence (section 3) and in providing confidence that noise conducted from the EPS cannot interfere with other spacecraft sub-systems, such as telecommunications or attitude control systems.

5.2 Functional simulation of starting sequence

The main criteria for judging what overall check-out facilities the simulator should provide were determined by examining the starting sequence. The way in which this sequence relates to the generated functional equivalents of the various ion thruster parameters and corresponding power supply loadings is described below, with the aid of the simulator block schematic shown in Fig 5. This includes the parts already developed and tested[7,8], together with the additional functions described in more detail in the sections following.

The starting sequence currently in use, which is summarised in Table 1, was devised following an extensive study of the T4A thruster[19] to determine the correct switching procedure for the various power supplies and the optimum rates of change of a number of critical voltages and currents. The aim was to minimise the time, propellant mass and energy used during start-up, whilst not over-stressing cathode heaters. Another requirement was to avoid the dispensation of excessive quantities of barium from the cathodes[20,21], which would severely diminish lifetime.

For the north-south station-keeping application, it was originally considered that a start time of 15 min and an energy consumpation of 25 W h represented reasonable targets. In fact, the sequence in Table 1 surpasses both values, the beam being first extracted at 12 min, with 12 W h having been supplied at that time[19]. The propellant used is between 50 and 70 mg. Moreover, it should be pointed out that all these values can be further reduced, particularly if a more rapid sequence is chosen; times as short as 5 min have been studied experimentally. 045

5.2.1 <u>Description of starting sequence</u>

With reference to Table 1, at Event 1 the backplate (BP) heater supply is switched to the thruster to warm up the discharge chamber to prevent condensation of mercury vapour. The isolator supplies are turned on for the same reason. Although not specifically required at this time, the keeper, main discharge, neutraliser bias and magnetic field supplies are also turned on. The stabilised current setting for the discharge supply is, at this stage, considerably lower than the steady-state setting, to reduce the severity of the excess beam and accelerator grid current transients when the beam is first extracted (Event 12).

At Event 2, after a delay of 1½ min, the neutraliser hollow cathode heater supply is switched on. Initially the cathode is cold and the heater resistance is below 1 Ω, so a very large current would flow if the supply was not current limited; this is accomplished by means of appropriate pulse width modulation (PWM) under control of the microprocessor[15]. As the heater winding increases in temperature, its resistance rises and the power consumed at constant current becomes larger. This is also regulated by the PWM technique, to avoid over-stressing the heater.

After a further delay, the discharge chamber cathode heater is switched to its power supply, which is also regulated by the microprocessor system to keep both mean current and maximum power within safe levels.

To initiate discharges to these cathodes, mercury vapour flows are required from the associated vaporisers. Thus, at Event 4 the discharge chamber cathode vaporiser heater is energised and, a minute later, the neutraliser and main flow vaporiser heater supplies are turned on. In each case, the current levels are higher than normal, to allow temperatures, and therefore flow rates, to increase rapidly.

The rates of rise of the temperatures of the cathodes and of the mercury flow rates are chosen to ensure that the discharge to the neutraliser cathode is initiated first. Although this process is essentially random in nature[22,23], it usually occurs at about 9 min after commencement of the sequence. Once the neutraliser keeper current has risen above 0.1 A, the cathode heater power supply is turned off and the vaporiser heater current reverts to its normal setting. From this point, ion bombardment heating of the cathode is adequate to maintain the temperature required for electron emission.

At between 10 and 11 min, a discharge is initiated between the main cathode and its keeper electrode, and this immediately transfers to the anode. At this point, the cathode heater supply and auxiliary heaters are turned off, and the cathode and main flow vaporiser heater currents are adjusted to their normal settings.

About 1 min is then allowed for all flow rates to approach their normal steady-state values, before turning on the beam and accel grid supplies; these high voltages are applied in a controlled manner to avoid large transients. After a few seconds to allow the discharge to stabilise, the discharge current is increased to its normal value and the control loops are closed. The beam current, thrust, mass utilisation efficiency and neutraliser conditions then quickly attain their design values.

6 FURTHER DEVELOPMENT AND ADDITIONAL REQUIREMENTS

As described in section 4, a considerable amount of design and development work has already been accomplished[8]. In particular, the complex characteristics of the main discharge and the beam extraction system have been successfully simulated, as illustrated by the derived performance map shown in Fig 4. The success achieved in this phase of the project clearly suggests that it should be feasible to simulate accurately all aspects of thruster operation, including the time-dependent nature of the starting sequence. It is proposed below that the design principles already employed can be extended to realise this aim.

A block schematic of the complete simulator is shown in Fig 5, which also identifies the existing sections. As the latter have been compressed into a small space to allow the newly designed parts to be depicted more clearly, it should be emphasised that the simulation of the discharge chamber and ion extraction system, which has been completed, is the most complex and difficult to achieve. Consequently, in relative terms, the further development discussed below should be comparatively straightforward.

6.1 Function requirements of the starting sequence

In simulating the behaviour of the thruster during the start-up sequence, it is necessary to perform functions of several different types, in addition to those required for the case of steady-state operation. The following may be identified:

(a) The simple connection and disconnection of power supplies feeding fixed resistive loads, such as the backplate heater.

(b) The correct loading of the supplies feeding the cathode heaters, whose resistances increase strongly with temperature, and therefore with time, during the sequence. 045

(c) The switching of the loads applied to the keeper supplies from high impedance (about 1 MΩ) to low impedance (about 20 Ω) at times appropriate to the simulated cathode temperatures, applied keeper voltages and cathode mass flow rates.

(d) The accurate representation of the discharge impedance during the non-standard conditions of high flow rate and low current encountered during the early phase of the start to enable the power supply to be correctly loaded.

(e) The correct evaluation of the mass utilisation efficiency during all stages of the start where the beam might be extracted. Only if this is done can the transient loads of the beam and accelerator supplies at switch-on be properly applied. Accurate simulation in this area is particularly important in the case of the accelerator supply, because it has a limited overload capability.

(f) The accurate application of the correct changing loads to the discharge, beam, accelerator and neutralising bias supplies as the discharge current is increased to its normal operating value, following initial extraction of the beam.

6.1.1 Function generators and loading regulators

In the part of the simulator already developed, diode function generators[8] (DFG) are used very successfully to represent the way in which one parameter is influenced by others (Fig 3). Specially designed loading regulators (LR) then employ the outputs of certain of these generators to appropriately load individual PCU supplies, according to the existing conditions (Figs 6, 7 and 8). It is proposed that this scheme be adopted for the remainder of the simulator, requiring the development of the following generators and regulators:

(a) DFG 1 To give backplate temperature as a function of heater power, with a correction for ambient temperature. The latter correction can be applied using the technique devised previously[8], where the mass utilisation efficiency-primary electron energy characteristic was adjusted in response to changes of discharge current (G5 in Fig 3).

Backplate temperature is required to be sensed and used as an additional function in controlling the starting sequence.

(b) DFG 2 To relate backplate temperature to discharge power. An adjustment to the input has again been included, this time to account for the smaller ther-
045 mal contributions from vaporiser and isolator heaters, solenoids and keeper discharge, which can all be considered as an additional 'lumped' constant.

(c) DFG 3 To represent the cathode temperature as a function of heater power. This can be used to simulate both main discharge and neutraliser cathodes.

(d) DFG 4 To relate cathode temperature to keeper discharge power. Excluding the need for minor adjustments, the same design can again be used for discharge chamber and neutraliser applications.

(e) DFG 5 To give the contribution to cathode temperature of the main discharge power.

(f) DFG 6 To simulate the cathode heater resistance as a function of cathode temperature, the latter parameter being derived by combining the outputs of DFGs 3, 4 and 5, where appropriate.

(g) DFG 7 To represent the discharge initiation characteristics[23] of the cathode-keeper combination. This should take account of mass flow rate, cathode temperature (from DFGs 3, 4 and 5) and applied keeper voltage.

(h) DFG 8 To simulate the variation of accel grid current at constant potential with discharge chamber mass flow rate and mass utilisation efficiency.

(i) LR 1 (Fig 7) To correctly load the keeper power supplies. Sufficient accuracy can probably be attained by using two fixed resistances for this, one simulate the high impedance prior to discharge initiation, the other to represent normal operation. The relay switching between the two should be controlled by DFG 7.

(j) LR 2 (Fig 7) To absorb the power given by each cathode heater supply. Its impedance will be controlled by DFG 6.

(k) LR 3 (Fig 8) To simulate the loading of the accel grid supply. This acts in response to the output of DFG 8, and could utilise the rugged features of a thermionic vacuum tube, as shown in Fig 8.

(l) LR 4 (Fig 5) To provide appropriate loading for the neutraliser bias supply, which operates at constant voltage, in response to demands derived from the beam current simulation.

In addition to the DFGs and LRs described above, the design depicted in block form in Fig 5 requires the development of the thermal response circuits included in Figs 3, 6 and 7. These are necessary owing to the appreciable thermal capacity of all thruster components, which causes heating delays of the order of several minutes. These delays are of major importance in determining the time scale of the start sequence[19]; those associated with the cathodes, vaporisers, isolators and backplate are of particular significance. 045

6.1.2 Operation of the simulator during the starting sequence

Referring again to Table 1, at Event 1, the backplate (BP) heater supply is switched to its equivalent fixed value resistance (a nichrome heater), which feeds the BP heater electrical analogue circuit as illustrated in Fig 6. A parallel circuit, including DFG 2, relates the BP temperature to the discharge power (now off). These heating contributions are related to the BP temperature through their respective steady-state and dynamic (simplified as a first order time lag) temperature transfer functions and are summed to produce the functionally related BP temperature. As already mentioned, a BP ambient temperature adjustment is included in DFG 1 to allow for the effects of this parameter on the starting sequence. The remaining supplies that are switched on at this time feed either constant resistance loads, such as isolator heaters, or no appreciable current is drawn at this stage, as in the case of the keeper supplies.

At Event 2, the neutraliser hollow cathode (HC) heater supply is switched on. The functional block diagram of the cathode temperature simulation is shown in Fig 7. This includes contributions from the keeper discharge power (DFG 4) and the heater current (DFG 3), and represents an extension of the operating principles already applied in the case of the discharge simulation and described in detail in Ref 8. The time-dependent cathode temperature equivalent is ultimately fed into a threshold trigger circuit whose output is used to control a relay of LR 1. This relay switches in the appropriate load to the neutraliser HC keeper supply (now on), indicating that the cathode discharge has stuck. The trigger circuit is preceded by DFG 7, which simulates the keeper striking characteristics in terms of the neutraliser mass flow (now off), cathode temperature, and applied potential[23].

The simulated cathode temperature is also fed to DFG 6, in which the equivalent heater resistance is derived. The output of DFG 6 is then used to control LR 2, which correctly loads the heater power supply at all times during the start sequence.

At Event 3, (time $t = 2$ min), the discharge cathode heater supply is switched on. Simulation of the subsequent heating and discharge initiation is similar in principle to that previously described for the neutraliser cathode heater and keeper (Fig 7), with the exception that a third cathode heating contribution from DFG 5 is added, which allows for the presence of the main discharge. For this, the discharge voltage and current are generated in the
045 'Discharge and beam simulation' section in Fig 5 (existing breadboard system), this being actuated by a switch in parallel with the previously described keeper

supply relay switch (Fig 7). It is therefore assumed that the keeper and main discharges are initiated simultaneously.

At Events 4, 5 and 6 the neutraliser, discharge and main flow vaporiser heater supplies are switched to constant resistances which simulate the vaporiser's heaters. The sequence then continues as described previously, with neutraliser keeper discharge simulation and loading becoming necessary at Event 7 and main discharge simulation[8] at Event 9.

At t = 12 min (Event 11), the beam and accelerator supplies are switched on. A method of providing the loading for the positive beam supply modules, appropriate to the ion beam current computed in the existing simulator design, is described in Ref 8. Loading by LR 3 for the negative accelerator supply (see Fig 8) is decided by the output from a function generator (DFG 8) which relates total mass flow rate and propellant utilisation efficiency to accelerator current. This automatically allows for variations in beam current, but it should be remembered that computed values of both accelerator and beam currents are valid for a fixed, optimum value of extraction voltage only. Loading of the neutraliser bias supply, via LR 4 (Fig 5), is determined by the derived value of the beam current.

At $t = (12 + \delta t)$ min (Event 12), the main discharge current is increased to its normal set-point. Time δt will depend on the rate of attainment of discharge stability after switching on the beam voltage. The need for simulating this transient beam-discharge coupling effect is not clear and will require further experimental investigation.

The method adopted to provide ion beam power supply loading is described in principle in Ref 8. This involves an extension of the previously applied loading principles to the beam supply modules, with regulation by the functional beam current which has been computed from the input parameters provided by the circuits shown in Fig 3. Here again, as an alternative, the application of a thermionic vacuum tube may be considered for current regulation purposes, offering the additional benefit of good voltage isolation.

6.2 Performance transients

Voltage and current transients due to switching, and to possible intermittent extraction grid short circuits, may have detrimental effects on the PCU and contribute to spacecraft system contamination by EMI. For this reason, it is desirable to include a realistic simulation of these occurrences in any complete test programme. In this context, the transient behaviour associated with the magnetic circuit power supply during start-up and shut-down demands the use of a representative inductive load (or an electrical equivalent). At the frequencies employed in the PCU, no other loads are sufficiently inductive to require similar special treatment, and none have appreciable capacitance.

The simulation of the very rare[24] (for T4A and T5) grid-grid short circuits involves the application of a shorting switch, situated at the simulator. The design of this switch may need careful attention to avoid current limiting or slowing the transient rise times, which should be dominated by the beam and accelerator supply output impedances and leads. However, it is likely that a magnetically actuated reed relay having a fast response will prove adequate. For associated information on the physical nature of shorts on a similar thruster, attention is drawn to Ref 25.

6.3 Performance boundaries

The degree to which ion thruster performance boundaries, which define the operational limits (see Ref 8), should be included in the simulation is uncertain. These boundaries are shown in Fig 4 for the T4 thruster and in Fig 9 for T4A; the latter are extended upwards, to higher values of ΔV , in T5[26]. At these boundaries, performance reaches a peak and then falls away, while many thruster parameters are not as steady as during normal operation. However, the term 'instability limit', which was applied to earlier thrusters, is not appropriate.

Simulation of these boundaries would not normally be necessary if operation was restricted to start-up, steady-state running, and shut-down as in, for example, a typical station-keeping application. This is because the thruster control system is designed to ensure that operation is well away from the performance boundary[9]. However, it may be necessary, under some circumstances, to simulate throttling or long-term thruster degradation. If so, it would be advisable to include the performance boundaries. As they represent parameter limits rather than the onset of instabilities, it should be possible to incorporate them in the simulation by extending the ranges of certain of the diode function generators, particularly those associated with the discharge chamber and beam extraction. There should be no need to devise methods of introducing additional noise or oscillations, unless further thruster studies indicate that such features are essential.

6.4 Digital techniques

There are inherent disadvantages to the use of diode function generators in such complex systems as the one proposed. These are, predominantly, the tracking
045 errors arising from diode threshold voltage shifts with ambient temperature variations, and problems of setting-up, using tedious curve fitting techniques.

A method of quickly approximating non-linear functions with a digital computer subroutine has been reported[27]. In principle, this method looks to be a promising aid to design, particularly if it allows break points on the curves to be conveniently set up using a 'dialling-up' procedure on the appropriate function generator. It is also claimed[27] that the effects of changes in ambient temperature are reduced by using thermally-matched diodes in comparator circuits. For convenience, future development work involving analogue methods could well follow this approach.

To avoid some of these problems, however, it may be advantageous to consider as an alternative the application of digital function generators[28], for storing the data pertaining to the ion thruster steady-state characteristics. In addition, the operational flexibility offered by advanced microprocessor technology may lend itself to the simulator, so this possibility should also be investigated. Of course, any change from analogue to digital techniques would completely alter the design of the simulator. Consequently, it would be necessary to make a decision concerning any such change very early in any further development programme.

6.5 Auxiliary check-out equipment

Although this Report has so far considered only the development of the thruster simulator, there is obviously a need to produce, in parallel, other associated equipment, to be used in conjunction with the simulator during check-out procedures. As with the simulator, the exact requirements will depend to some extent on the details of the mission in question and on the design of the spacecraft. In the absence of a specific mission, there is inadequate definite information concerning the exact interface of the thruster system package with the spacecraft. Consequently, for an initial definition involving, in particular, the electrical connectors for power, telemetry and telecommand (TM/TC) and ground testing, an ESA work statement[10] has been used as an interim guide to what might be required. Based on this early information, the auxiliary test equipment would probably include the following items:

(a) 50 V external power supply (stabilised to $\pm 1\%$) to substitute for the solar array power for ground tests. It is possible that a facility for reducing this supply voltage in discrete steps (to simulate solar cell ageing, for example) will be an additional requirement.

(b) A control test set to provide the various commands to the flight starting sequencer to represent, as nearly as possible, normal ground TC requirements. It would also be required to command valves open and closed and any PCU set point variations specified.

(c) A TM data recording facility for monitoring the simulated ion thruster parameters. It would be an added advantage if this facility could also be directly coupled to the simulator monitoring output, for use in the PCU unit acceptance tests described in section 5.1.1.

(d) Electrical connectors to enable check-out of the PCU sub-system to be accomplished, using the simulator after spacecraft integration (Ref 10). If a switching matrix is fitted, it is envisaged that these connectors could be joined directly to the PCUs, as indicated in Fig 2. In this case, the changeover switch would be used for disconnecting the ion thrusters, thus avoiding disturbing the wiring within the EPS package during this critical testing phase. However, this will not be possible if the switching matrix is not employed, and the thruster must then be physically disconnected from its PCU.

It is very important that the interconnecting cable from the PCU to the simulator shall be as nearly identical as possible to its spacecraft internal equivalent. This is to ensure that EMI effects, including arcing and starting transients, which are influenced by cable parameters, may be reproduced realistically.

6.6 Design considerations

Although it is not possible to specify the complete simulator design in detail in this Report, previous work[8] suggests certain guidelines. For example, the accuracy of the simulated thruster performance should be 5% or better for a system using analogue techniques. However, it is expected that, with the substitution of digital function generators, the accuracy would be mainly limited by errors in obtaining performance data.

In a normal operating environment, there is likely to be a wide temperature excursion. This demands that, for an analogue system using diode function generators (see section 6.1.1), some form of temperature control will be required for the simulator if the accuracy quoted above is to be realised and maintained.

In an analogue system, the supply voltage should be chosen to give a wide operating region, consistent with the need to use commercially available IC amplifiers. In addition, it is desirable that these amplifiers have a high enough bandwidth to reproduce the harmonic content of any noise produced by switching transients.

045 The power dissipating sections must be capable of supporting a continuous load of 40 W and short duration peaks of 60 W in the case of the discharge supply

loading regulator, with corresponding values of 160 and 200 W for the ion beam power.

A modular construction is advocated for the final simulator packaging, in which the components are arranged in modules of small functional groupings on plug-in printed circuit boards. This would facilitate fault finding and maintenance.

7 DEVELOPMENT PROGRAMME

A tentative simulator development programme bar-chart is shown in Fig 10. It consists, essentially, of three phases of activity: an initial study period followed by hardware development and testing. During the study period, a decision will be made as to the overall concept to be employed, the choice being between analogue and digital techniques (section 6.4).

8 CONCLUSIONS

The study reported here has extended the design of the T4 thruster simulator to include all functions necessary to accurately represent all those aspects of thruster performance relevant to station-keeping missions. In particular, techniques have been proposed which will allow realistic simulation of the thruster start sequence, including time-dependent parameters associated with the thermal response of the hollow cathodes, discharge chamber, and other components. It is explained how these various parameters can be derived using diode function generators, how appropriate power supply loadings can be achieved, and how the complete system can be constructed.

It is pointed out that previous experimental work on the simulation of the complex discharge chamber and ion beam extraction characteristics provides an adequate guide as to the methods to be employed in developing the remaining parts of the simulator. This earlier work achieved a simulation accuracy of better than 5%, suggesting that a similar figure should be attainable by the complete device.

Consideration has also been given to the tasks for which the simulator is suited. These are primarily associated with the check-out of the power conditioning unit at various stages of its development and construction, and after it has been integrated with a spacecraft. As a thruster cannot be operated once it has been installed in a spacecraft, the simulator is then an essential item of equipment if the PCU is to be tested in any meaningful way. Its use must therefore be regarded as mandatory for all space missions.

Acknowledgments

The author would like to express his appreciation to Dr D.G. Fearn for valuable discussions and suggestions concerning the manuscript. Thanks are also due to Mr R.C. Hughes for information relating to the power processing and control and Mr R. Hastings for supplying data on ion thruster operation.

Table 1

T4A THRUSTER STARTING SEQUENCE

NOTATION

NKV	Neutraliser keeper voltage	DCI	Discharge cathode isolator
NBV	Neutraliser bias voltage	NCH	Neutraliser cathode heater
DKV	Discharge keeper voltage	DCH	Discharge cathode heater
DAV	Discharge anode voltage	DVH	Discharge vaporiser heater
DAI	Discharge anode current	NVH	Neutraliser vaporiser heater
DMF	Discharge magnetic field	MVH	Main vaporiser heater
BPH	Backplate heater	PBV	Positive beam voltage
MFI	Main flow isolator	NAV	Negative accelerator voltage

TIME (min)	THRUSTER EVENT	EVENT	SEQUENCE SWITCHING
0	Warm-up commencing	1	NKV ON NBV ON DKV ON DAV ON DMF (ON) BPH (ON) MFI (ON) DCI (ON) (DAI SET POINT low)
$1\frac{1}{2}$		2	NCH ON
2		3	DCH ON
6		4	DVH (High)
7		5	NVH (High)
		6	MVH (High)
$8\frac{3}{4} - 9\frac{3}{4}$	$I_{NK} > 0.1$ A	7	NCH OFF
	(Neutraliser starts)	8	NVH (To Normal)
10 - 11	$I_K > 0.1$ A	9	DCH OFF
	(Discharge starts)	10	BPH OFF DVH (To Normal) MVH (To Normal) DCI (off) MFI (off)
12	Beam on	11	PBV ON) NAV ON)
$12 + \delta t$		12	DAI SET POINT to normal
13		13	Close control loops

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δt = a time of the order of a few seconds; it depends on rate of attainment of discharge stability after switching on the beam.

LIST OF SYMBOLS

DFG	diode function generator
f( )	functional equivalent
G	function generator
I_B	ion beam current
I_D	discharge current
I_{DO}	arbitrary standard value of I_D
I_m	solenoid current
I_{VHC}	hollow cathode vaporiser heater current
I_{VM}	main flow vaporiser heater current
K	constant of proportionality between heater current and vaporiser temperature
LR	loading regulator
$\dot{m}_{HC}$	hollow cathode vaporiser mass flow rate
$\dot{m}_{MF}$	main flow vaporiser mass flow rate
$\dot{m}_N$	neutral mass flow rate
$\dot{m}_T$	total mass flow rate supplied to discharge chamber
P	Laplace transform operator
T	vaporiser thermal time constant
T_1	backplate heater thermal time constant
T_2	thermal coupling time constant between discharge and backplate temperature
T_3	discharge cathode thermal time constant
T_4	thermal coupling time constant between keeper discharge and cathode temperature
T_5	thermal coupling time constant between main discharge and cathode temperature
T_V	vaporiser temperature
V_A	discharge anode voltage
V_B	screen grid voltage
V_{ac}	accelerator grid voltage
V_K	hollow cathode keeper electrode voltage
ΔV	main discharge plasma potential ($V_A - V_K$)
ΔV_0	discharge plasma potential at I_{DO}
ΔV_S	arbitrary fixed value of V
η_m	propellant utilisation efficiency

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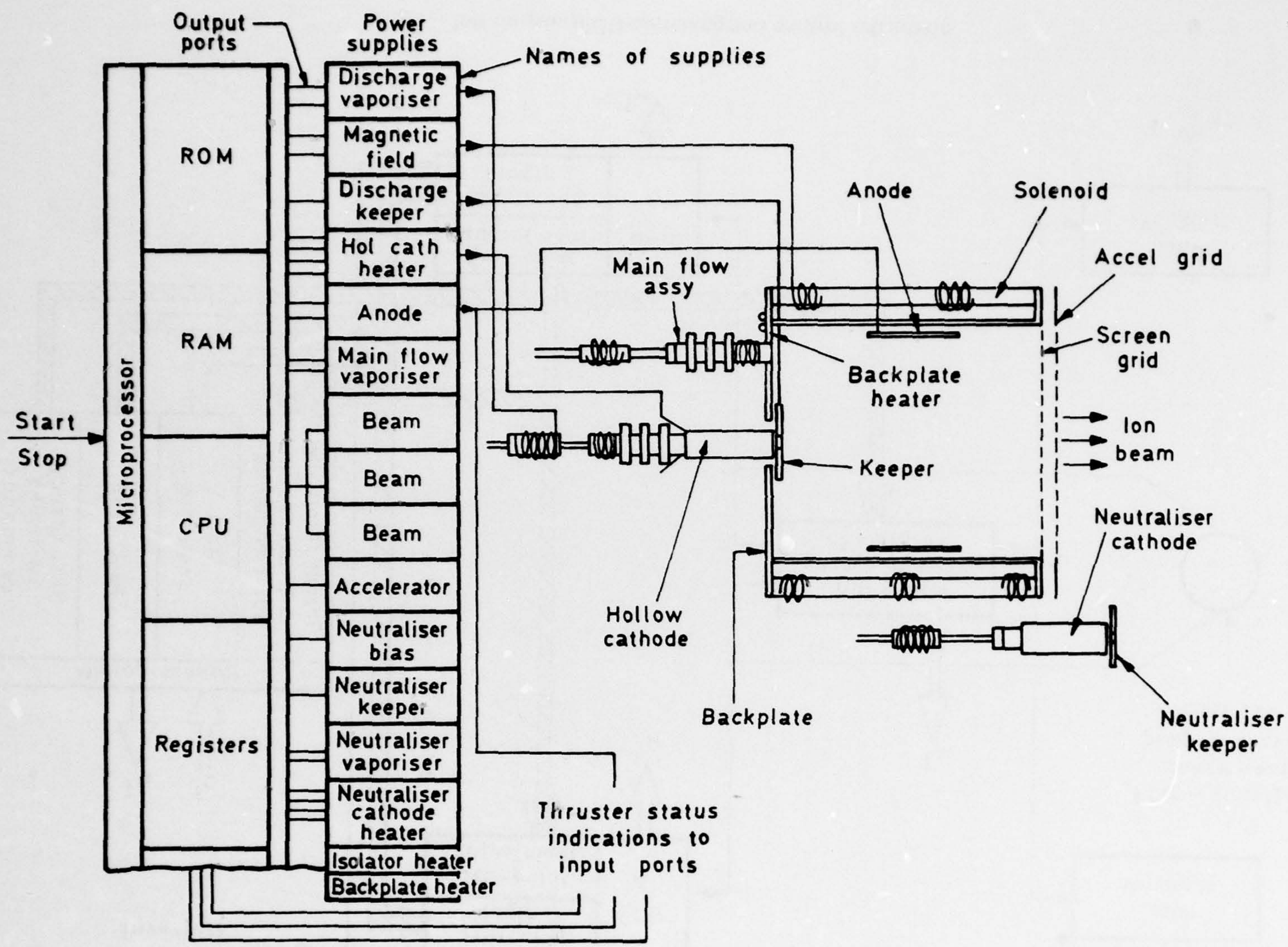

Fig 1 Schematic of microprocessor – PCU – thruster

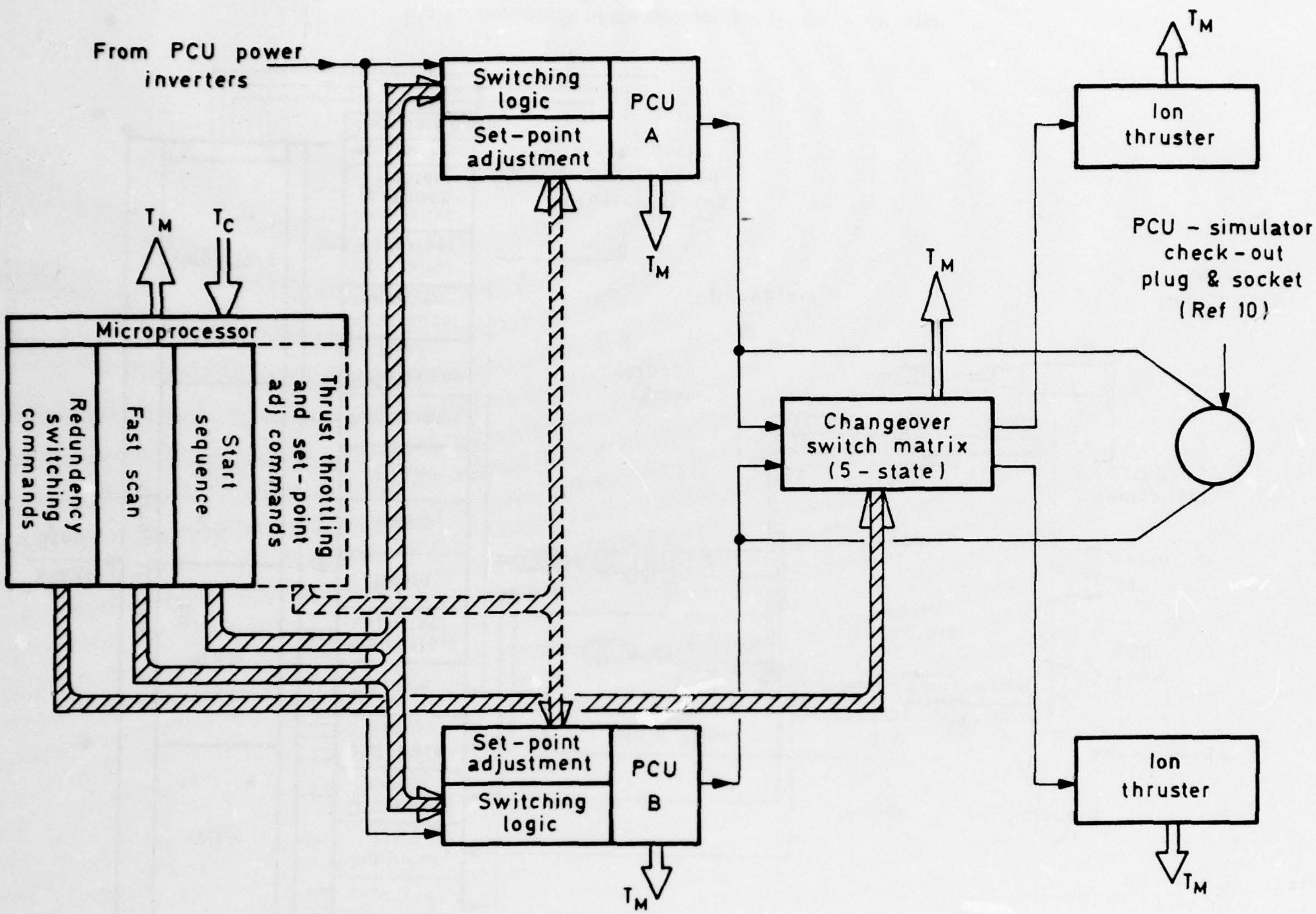

Fig 2 Ion thruster/PCU switching and control schematic

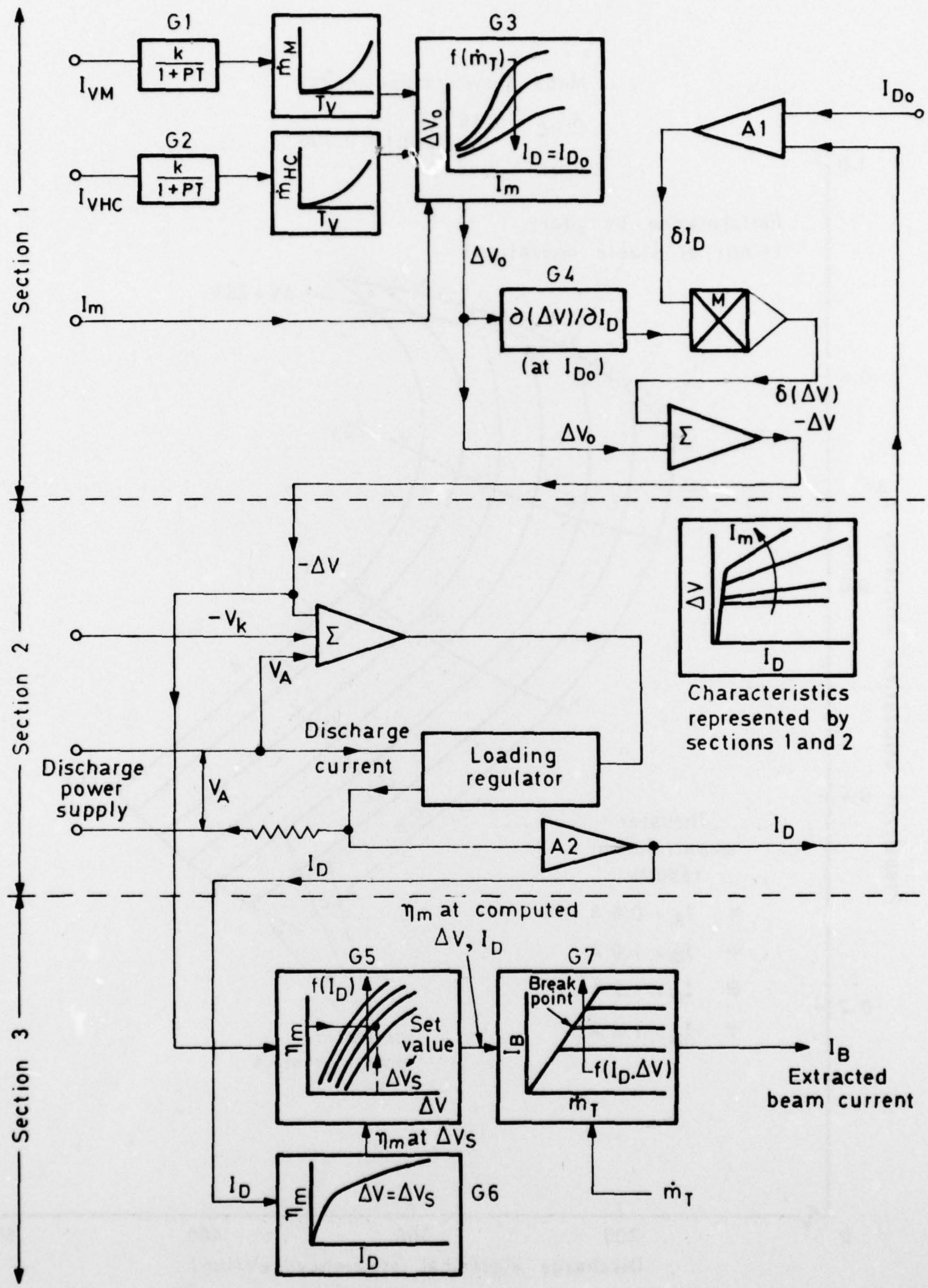

Fig 3 Schematic of existing simulator sections

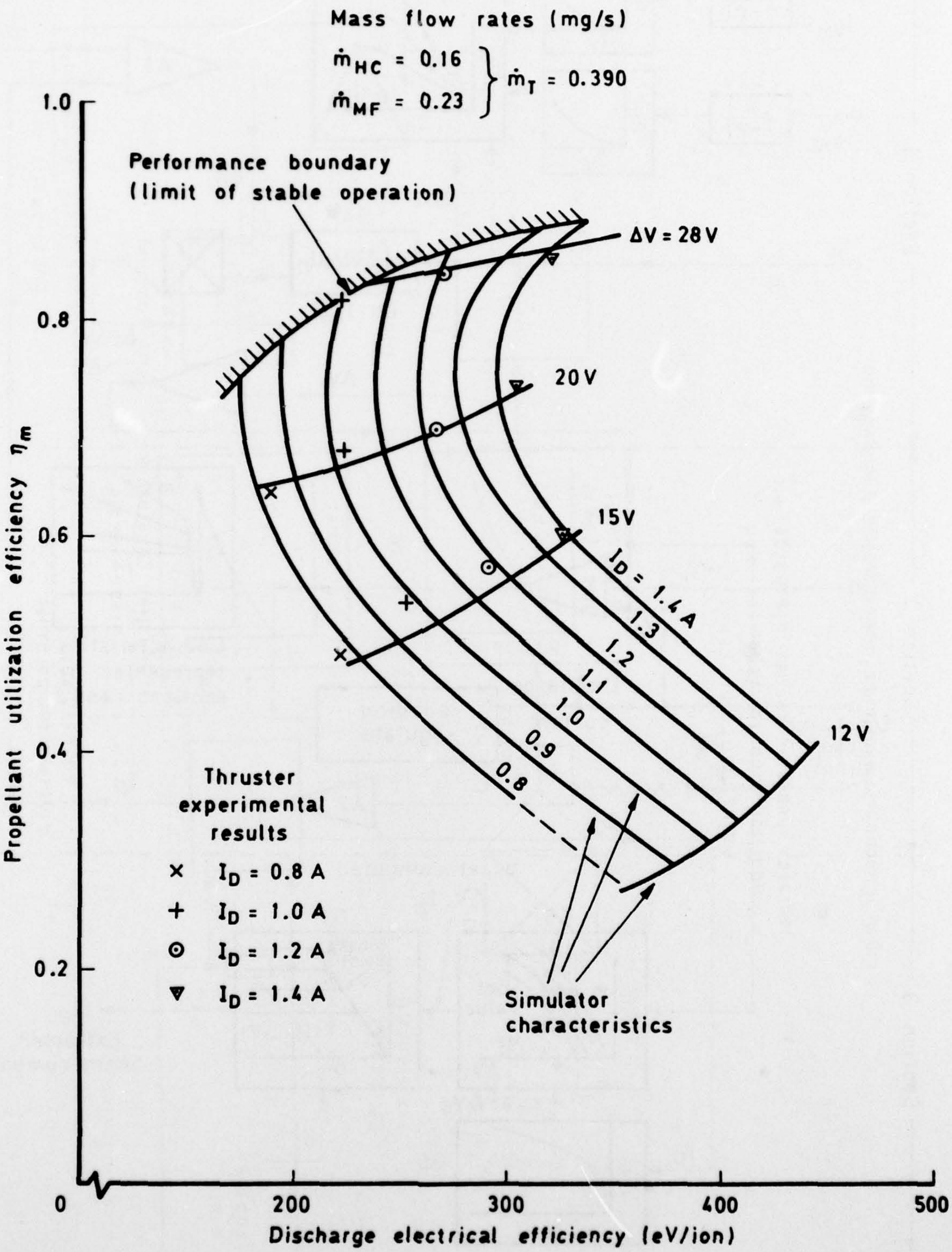

Fig 4 Comparison of simulator performance with thruster data

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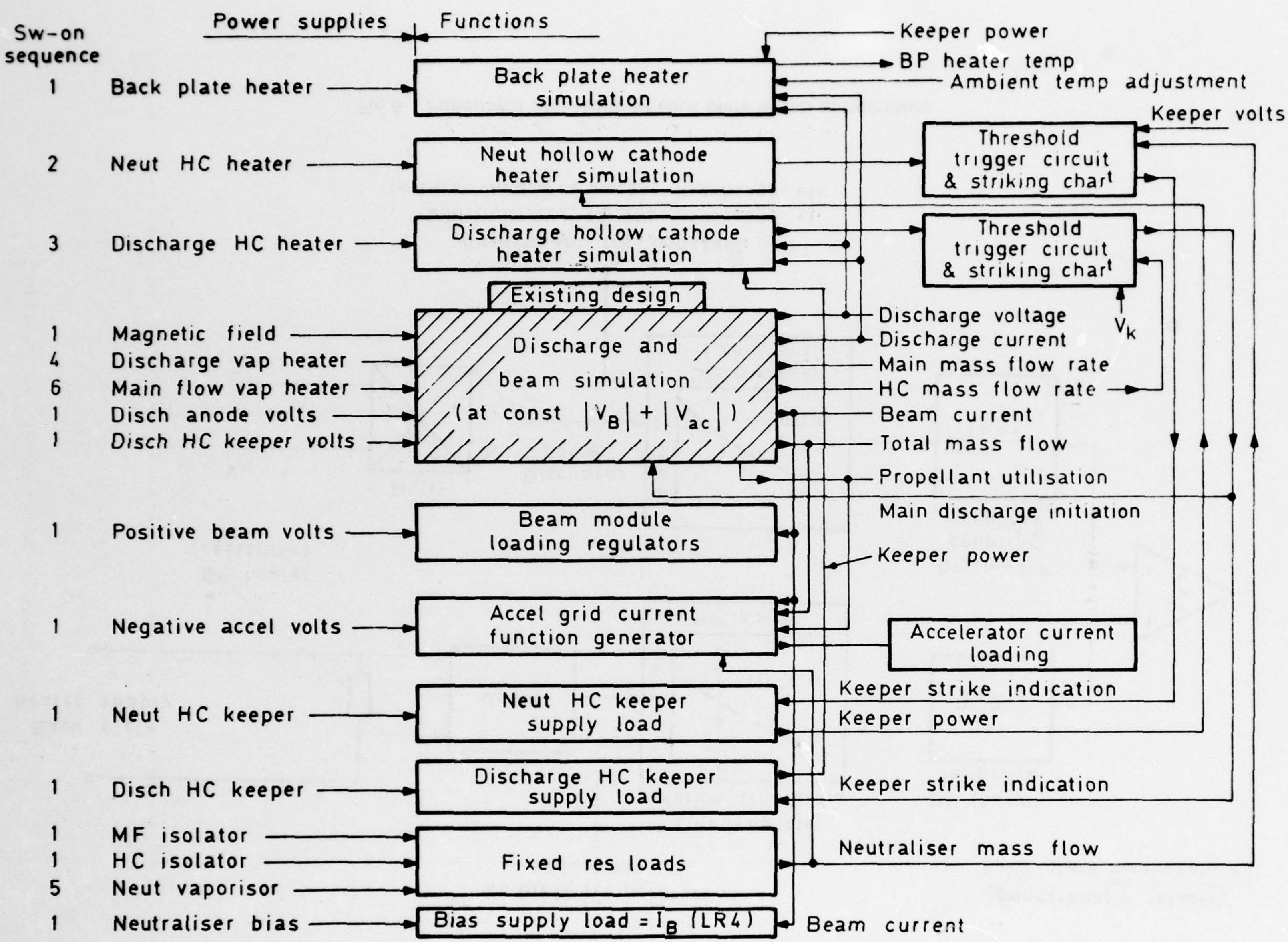

Fig 5 Ion thruster simulator block schematic

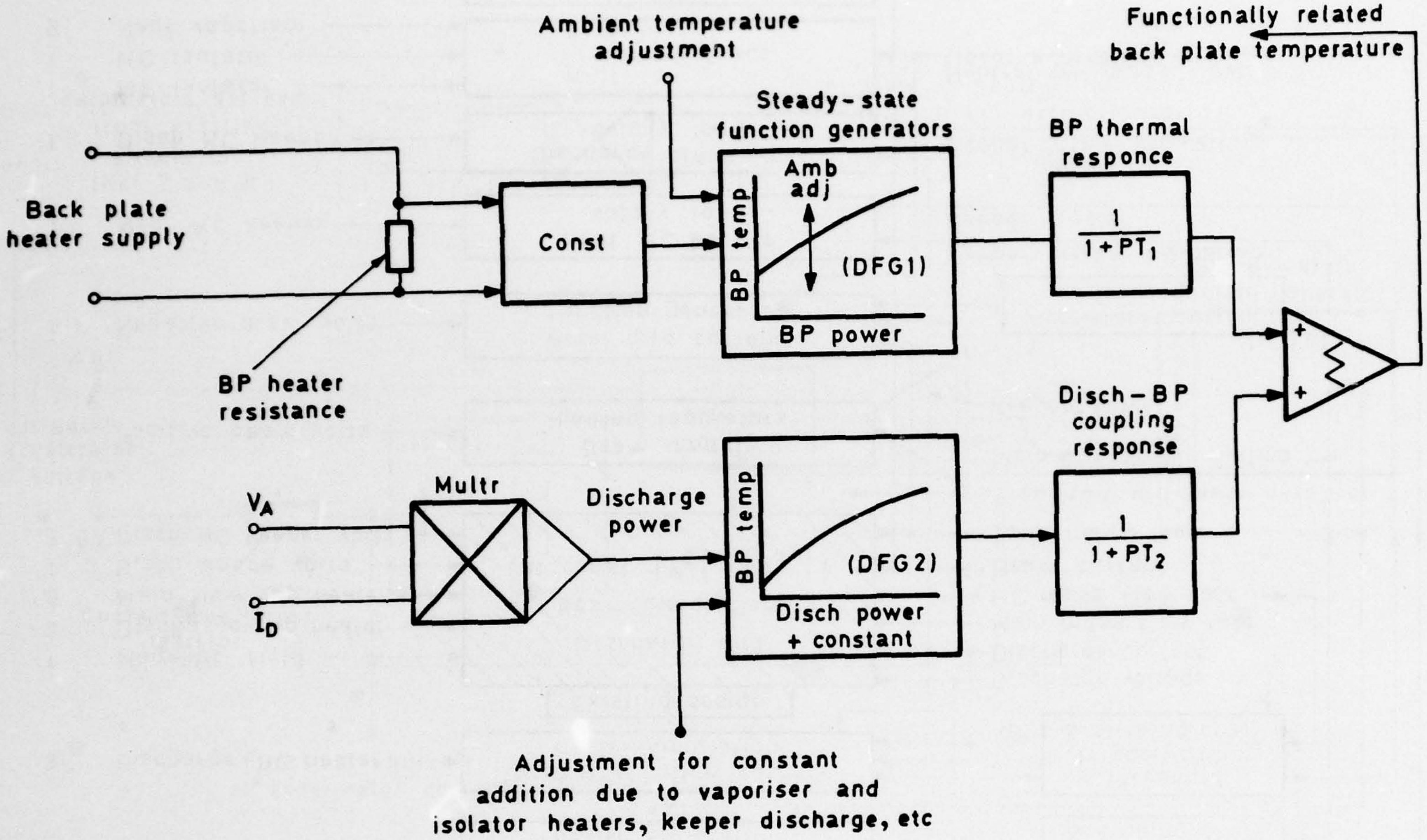

Fig 6 Functional simulation of back plate heater temperature

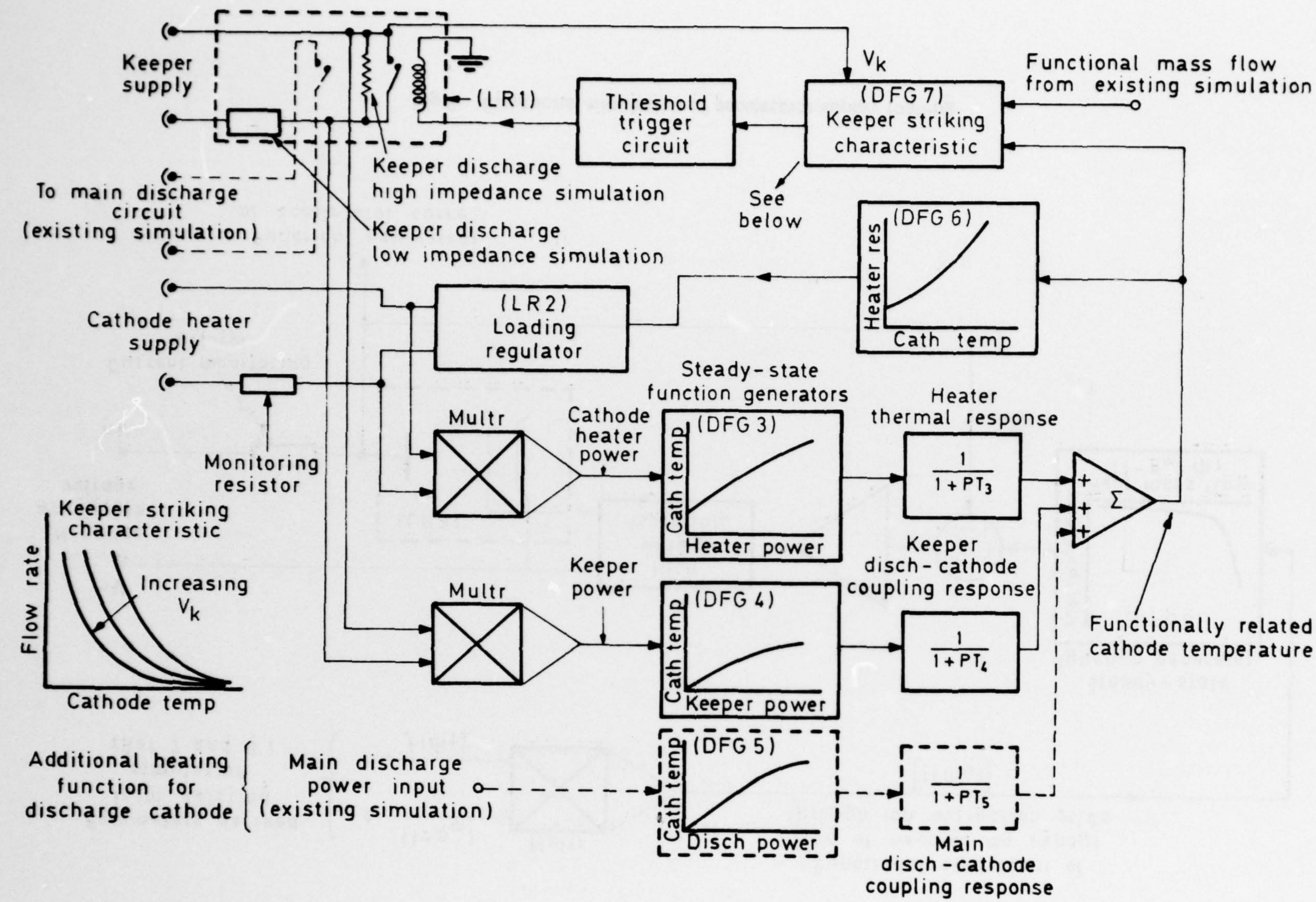

Fig 7 Functional simulation of cathode and keeper

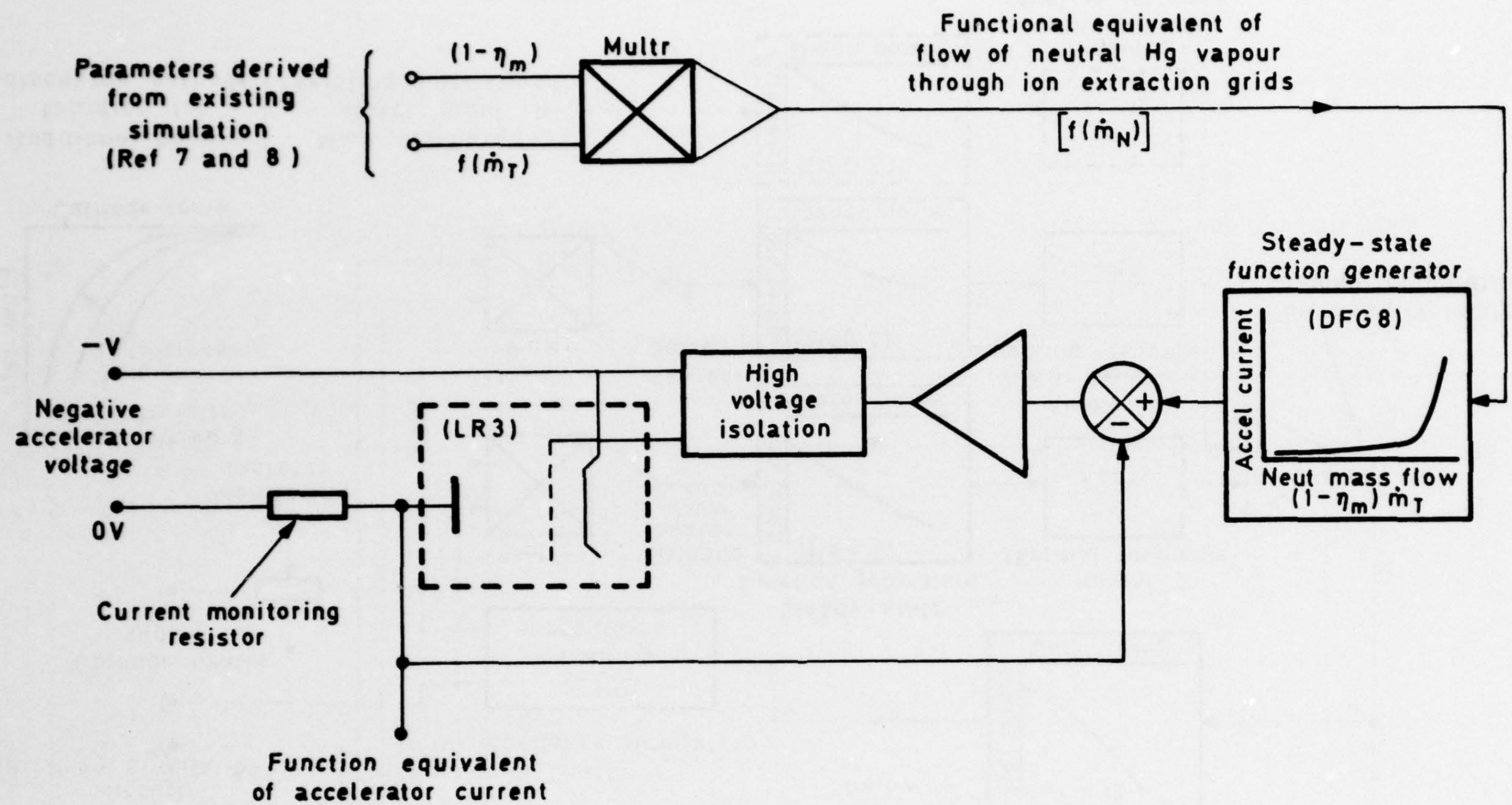

Fig 8 Functional simulation of accelerator supply loading

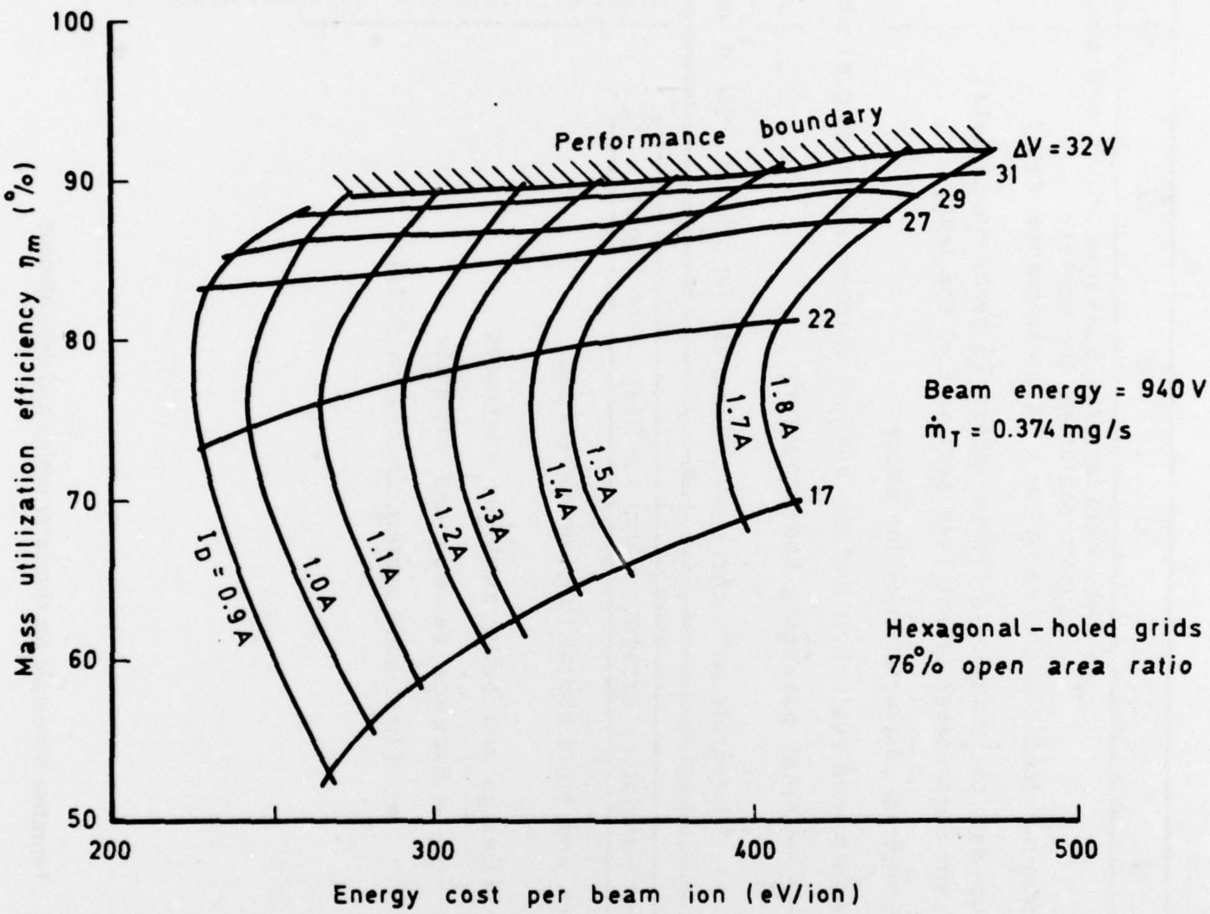

Fig 9 Performance map of T4A thruster, showing performance boundary

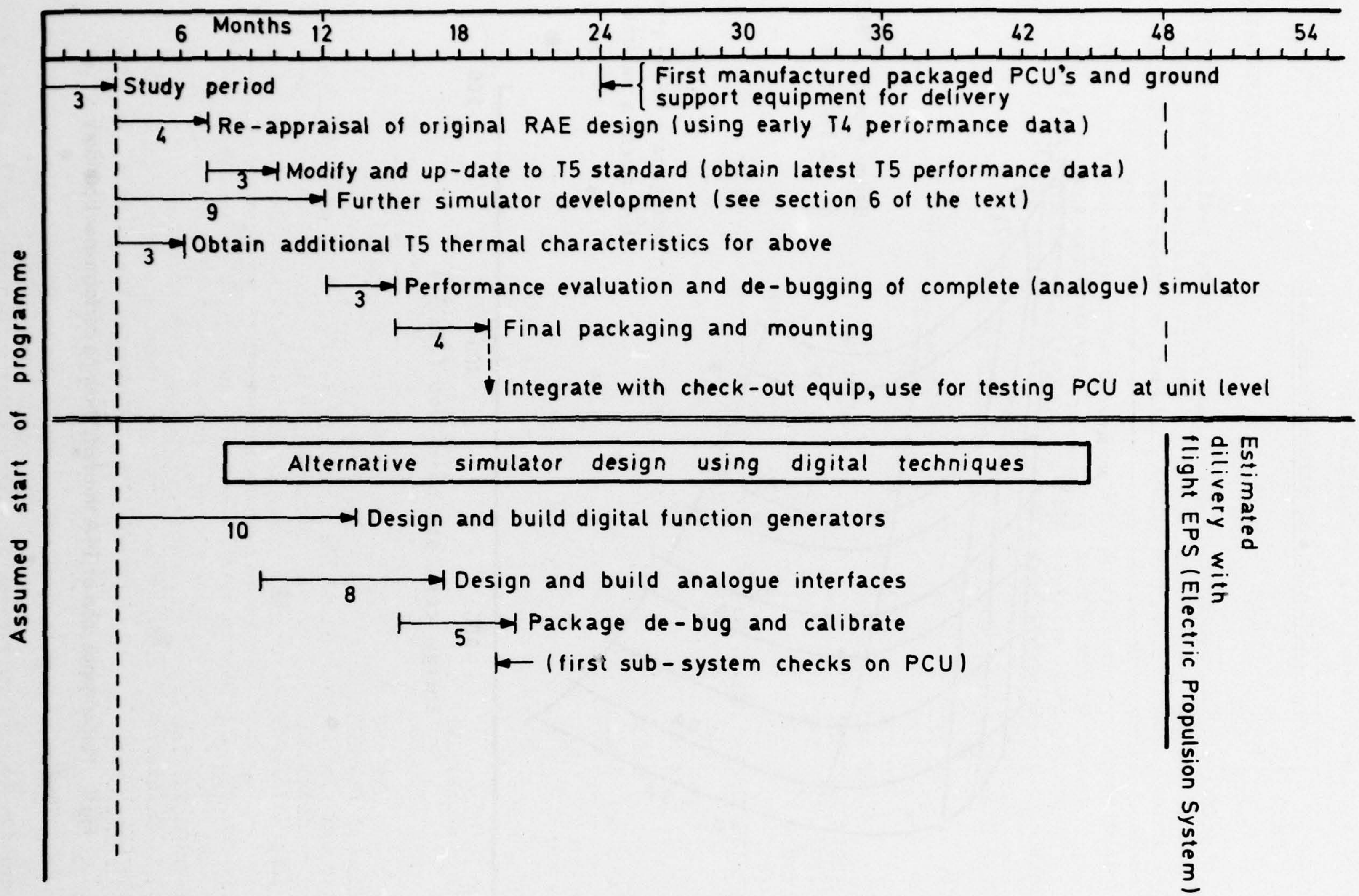

Fig 10 Tentative time scale for simulator design and development

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1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TR 78045	N/A	UNCLASSIFIED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
850100	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title The application and final design of an ion thruster simulator

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Pye, J.W.			April 1978	35	28

11. Contract Number	12. Period	13. Project	14. Other Reference Nos.
N/A	N/A		Space 548

15. Distribution statement

(a) Controlled by – MOD(PE) ASA, Mr P.M. Lavelle

(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Ion thruster simulation. Ion thruster check-out. Electric propulsion.

17. Abstract

A study of the design, development and application of a mercury ion thruster performance simulator is presented. Although based on previous successful experimental work on the simulation of the discharge mechanism and ion beam extraction characteristics of the UK T4 thruster, the design has been considerably extended to accurately represent all aspects of thruster operation relevant to station-keeping missions. These functions include all relevant time-dependent parameters associated with thruster warm-up during the starting sequence and the appropriate, performance related, loading of the various thruster power supplies. Its application is discussed in terms of satisfying a pressing requirement for a pre-launch check-out facility, when thruster operation is not practicable. It provides an independent means of assessing both the flight status of the thruster power processing and sequencing electronics and possible interactions with other spacecraft sub-systems.

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