RAE/Culham T4 Ten Centimeter Electron-Bombardment Mercury Ion Thruster

D. G. FEARN,* R. HASTINGS,† AND C. M. PHILIP†
Royal Aircraft Establishment, Farnborough, Hampshire, England
AND
P. J. HARBOUR‡ AND H. H. H. WATSON§
UKAEA Culham Laboratory, Abingdon, Berkshire, England

The RAE/Culham T4 thruster is described with particular reference to its suitability for N-S stationkeeping on planned European communication satellites and for many other possible missions. Details are given of the design, construction, testing, and performance, including the characteristics and life test experience of components such as vaporizers, isolators, and grids. The accuracy of the physically-based scaling laws used in the design is demonstrated. Special reference is made to the excellent thermal stability and performance of the grid system, to efforts made to minimize grid erosion, and to the flexibility offered by a large throttling range.

Introduction

THE RAE has been actively engaged on the development of electric propulsion systems since 1967. Most of the effort has been aimed at producing a 10 cm diam mercury ion thruster system intended for N-S stationkeeping on communication satellites. Initial experiments on a simple electron-bombardment thruster led to the design of a more efficient device[1] which achieved a good performance, and 3 models operated for an aggregate of several thousand hours. In parallel, critical components and associated instrumentation were being developed to an advanced state.[2,3,4] During this period, the UKAEA Culham Lab. studied plasma and ion beam phenomena, using thrusters similar to SERT II[5] and extensive instrumentation, including advanced Langmuir and ion probe techniques. This gave an excellent understanding of the basic processes which influence performance and lifetime[6,7,8] and allowed scaling laws to be evolved.[8,9]

The program culminated in the design of the T4 thruster that is currently the subject of an industrial development phase aimed at qualifying it for experimental flight. The performance is fully adequate for proposed European missions,[10] and the component life testing already accomplished suggests that its durability should be satisfactory. This paper describes the design and performance of the T4 thruster, emphasizing areas where recent advances have been made. A power conditioning and control system[11] is under parallel development, together with an electronic simulator to be used for checkout purposes.

Mission Suitability

In his recent analysis of European electric propulsion capabilities, Pearson[10] discussed N-S stationkeeping of communication satellites in the 400 to 800 kg mass range, with lifetimes of 5 to 7 yr. A major conclusion was that a viable propulsion system is more readily obtainable if operating times are low, implying the use of higher thrust levels than had often been envisaged previously. Although this approach requires more power, the power per unit thrust is lower because the power consumption of ancillary equipment does not change appreciably with thrust. More important, the lifetime required of the system can be dramatically reduced and the duration and cost of ground testing can be correspondingly decreased.

A typical example is a 400 kg satellite having a 7 yr life. With the particular thruster deployment schemes selected by ESRO,[10] 10 mN Kaufman or RF ion thrusters with a power/thrust of 23 to 30 W/mN require about 1100 hr of operation and are 35 to 45 kg lighter in gross system weight than the equivalent hydrazine system. In comparison, 1.5 mN contact ionization cesium thrusters with power/thrust of about 70 W/mN require 7600 hr of operation and save about 47 kg. These values include allowances for the additional solar array masses necessary.

Based on earlier calculations similar to these, a nominal 10 mN thrust level was selected for the RAE program. It was also decided to aim for the largest throttling range attainable without altering the structure of the thruster, to allow the same design to be used for a variety of missions. The exhaust velocity was chosen to be 30 km/sec as a compromise between high efficiency and low power consumption.

The performance already achieved is summarized in Table 1. and is adequate for the missions in question. The throttling range of 7 to 12 mN is satisfactory, and an in-flight throttling capability could be provided if necessary. A major objective of the design has been to eliminate as far as possible any interactions with spacecraft. Consequently, the grid optimization procedure[6] minimizes beam divergence, with the result that 90% of the beam current is within a cone of half angle 15°. In addition, the mounting arrangements minimize heat transfer to the satellite, and an investigation is proceeding[12] to determine the distribution of material sputtered from the accel grid.

In view of anticipated European requirements,[10] the original aim of achieving a lifetime of 5000 hr with 1000 restarts seems reasonable. This has caused considerable attention to be paid to the durability of such items as cathodes[13] and to the mechanisms of grid erosion.[8] Extensive tests have indicated that the aim should be attained in all cases. Considerations of grid erosion led to the requirements that the mass utilization efficiency should be as high as possible and that the neutralizer mass flow should be minimized, to reduce bombardment by charge-exchange ions. Both have been achieved, with values of 87% and

Received September 24, 1973; presented as Paper 73-1130 at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, October 31–November 2, 1973; revision received February 27, 1974. Published with the permission of the Controller. Her Britannic Majesty's Stationery Office.

Index category: Electric and Advanced Space Propulsion.

* Principal Scientific Officer, Section Head, Space Department.

† Senior Scientific Officer, Space Department.

‡ Project Leader, Mercury Ion Thruster Group.

§ Head of Special Techniques Laboratory.

Table 1 Comparison between measured and predicted operating parameters

Parameter	Predicted Value	Measured Value	Units
Propellant utilization efficiency η_m[b]	0.87	0.87[a]	...
Ion production energy	227.0	245.0	ev/ion
Beam accelerating potential	940.0	940.0[a]	v
Beam current I_B	160.0	167.0	ma
Cathode mass flow rate $\dot{m}_c$	0.101	0.160	mg/sec
Total mass flow rate $\dot{m}_T$[b]	0.382	0.398	mg/sec
Thrust (calculated)	10.0	10.4	mN
Accel potential	−550.0	−600±50	v
Accel current	<0.7	0.54	ma
Discharge current $I_D = (I_A - I_B)$	0.88	0.97	amp
Anode current I_A	1.04	1.14	amp
Keeper current I_k	0.40	0.40	amp
Anode potential V_A	41.4	42.2	v
Keeper potential V_k	13.0	14.1	v
$\Delta V_P = V_A - V_k$	28.4	28.1	v
Maximum magnetic field B_m (on axis, 1 cm from baffle)	7.1×10^{-3}	6.8×10^{-3}	Tesla
Discharge current stability $\Delta I_D/I_D$	>0.10	0.10[a]	...
Magnetic field stability $\Delta B/B$	>0.10	0.12	...

[a] Thruster operating point defined by these values.
[b] Excluding neutralizer.

0.008 mg/sec and, moreover, the relatively low accel grid potential further reduces sputtering damage. Initial tests indicate that these measures will give the required grid life and will further lessen any contamination of spacecraft structures; a computer simulation of the sputtering process has indicated that the latter will be well within acceptable limits.

Scaling Laws and Performance

The scaling laws[9] used in the design of the T4 thruster were tested using an instrumented laboratory version of T4, the C3 thruster. This was extensively studied in its original configuration, and with a number of changes to the baffle/inner polepiece region to increase stability or operating range. A comparison of predicted and measured parameters is given in Table 1 for the original configuration, from which it will be seen that the design accuracy was generally of the order of or better than 10%. An allowance for the presence of doubly-charged ions can be made using data from a time-of-flight mass spectrometer.

Figure 1 shows propellant utilization efficiency η_m as a function of energy cost per beam ion (ev/ion) for ranges of values of magnet and discharge currents, discharge voltage being a dependant variable. It should be noted that a higher performance than quoted in Table 1 is available, but at the sacrifice of the margin of stability allowed at the chosen operating point. This margin was provided by operating at a discharge current 10% higher than that at the limit of stability shown in Fig. 1, and with a magnet current 12% lower than at the limit.

The power consumption totals about 216 w excluding the neutralizer system, optimization of which has not so far been completed. However, separate tests in a diode system[14] and on an earlier thruster[13] indicate that an additional 14 w may be required for this, giving a total of about 230 w, or 23 w/mN. It is assumed here that the heaters of both discharge chamber and neutralizer hollow cathodes are used at about 18 w, for starting only. The power consumptions of the various components are shown in Table 2.

The total power may be reduced by replacing the electromagnets with permanent magnets, but with a decrease in operational flexibility. In addition, the thermal losses of the 3 vaporizers may be reduced to below 1 w each if long time constants are accepted.

Table 2 Steady-state power consumptions of thruster components

Component	Power (w)
Discharge (anode supply)	41
Discharge (keeper supply)	5
Beam	157
Accel grid	0.3
Magnet	7
Each vaporizer (3 used)	3
Each cathode heater (2 used)	0
Neutralizer keeper	7
Neutralizer bias	4

Design and Construction of the Thruster

Figure 2 shows the thruster in its original form, with integral propellant tank but no electrical isolators or neutralizer. Suitable isolators to enable operation of the thruster at a different potential from the propellant feed system have been developed.[3,4] The total mass, excluding mounting structure and tank, is 1.1 kg.

Discharge Chamber and Magnetic Circuit

The grid system is mounted on the iron front polepiece, and axial loads resulting from the mass of this assembly are resisted

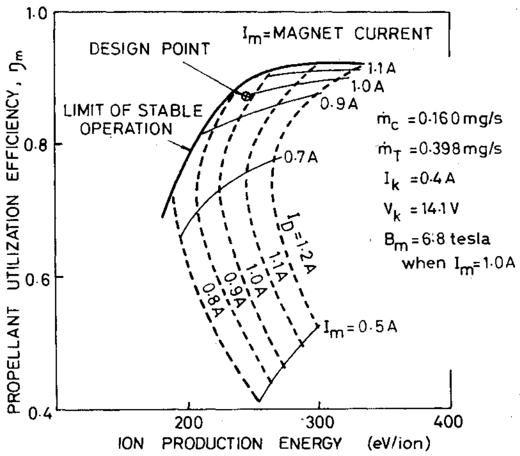

Fig. 1 Thruster operating characteristics, showing effects of discharge current and magnetic field.

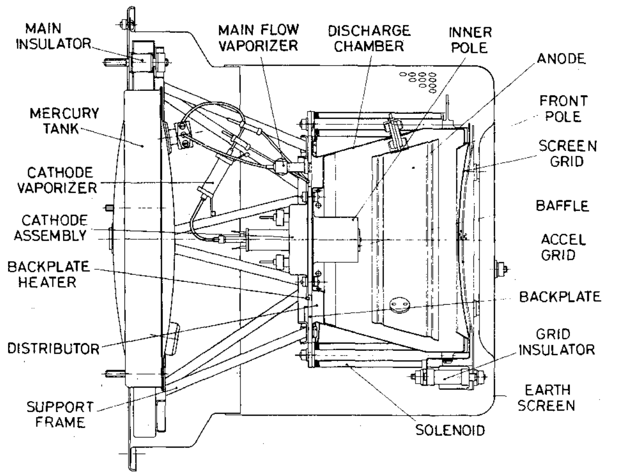

Fig. 2 T4 thruster (schematic).

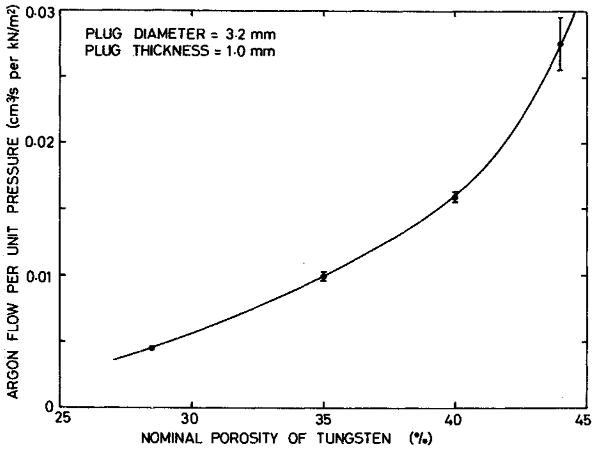

Fig. 3 Argon flow rate per unit pressure as a function of tungsten plug porosity.

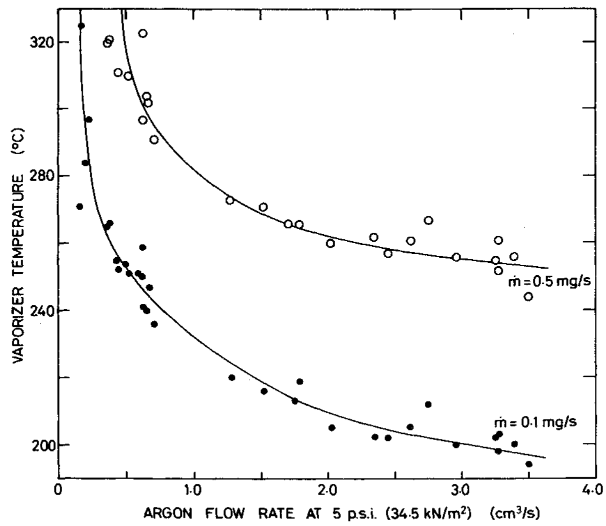

Fig. 5 Experimental correlation between mercury and argon flow rates for 35 vaporizers.

by the 6 solenoid cores. The conical stainless steel chamber is made a sliding fit in the bore of the front pole to permit differential expansion between itself, the pole and the solenoids. The inner cylindrical magnetic polepiece, baffle disc, hollow cathode and keeper assembly, and main flow vaporizer are carried on the ferromagnetic backplate. The latter is provided with a heater for rapid starting, and also forms part of the annular main flow distribution chamber. The tubular support structure was designed to give a complete experimental package incorporating the tank and all propellant feed components, including electrical isolators[4] when required.

Propellant Tank

Although a tank incorporating a flexible diaphragm to separate the mercury from the pressurizing gas would be lighter than the all stainless steel concept adopted, the latter should avoid any possibility of gas leakage[15] into the mercury during missions lasting several years. Experience has shown that it is almost impossible to prevent gas from diffusing through rubber or elastomer diaphragms; this would cause loss of pressurization and, more seriously, bubbles of gas within the mercury would give erratic operation.

The tank consists of a cylindrical pressurized vessel with domed ends containing valves and feed pipe connections. The propellant is stored within a cylindrical stainless steel bellows giving a measured expulsion efficiency exceeding 92%. The capacity may be altered by changing the length of the bellows.

Vaporizers

The vaporizers[3,4] employ the usual porous tungsten plug as a liquid/vapor phase separator, with flow rate being controlled by adjustment of the power fed to an external heater. The plug is usually a disk, but a more complex geometry[4] can be used to give a large surface area and a high flow rate, without changing over-all dimensions. Although power consumption can be lower than 1 w, the thermal designs of the vaporizer mountings are chosen to dissipate 2 to 3 w to give reasonably short time constants. Flow rate requirements vary considerably, the design point values (Table 1) being 0.24 mg/sec (116 ma equivalent) for the main flow, 0.16 mg/sec (77 ma) for the cathode and 0.004 to 0.008 mg/sec (2 to 4 ma) for the neutralizer. This 60:1 range can be partially accommodated by varying the porosity and dimensions of the tungsten plug, values of the porosity being controllable to better than 2%.

A simple gas flow calibration technique is used to aid selection of porous plugs. In this, the volumetric flow rate of argon into a vessel at NTP is obtained as a function of pressure difference applied to each plug tested. Although in the transition regime between molecular and viscous flow,[4] an approximately linear relationship is obtained, and the resulting gradients are plotted against plug porosity in Fig. 3. These data may be related to mercury flow rate using the theory developed by Pye,[3,4] which provides good agreement with experiment.

The above calibration technique may also be used at an early stage of fabrication to check the effect of variable weld penetration into the edge of the plug during manufacture, without the complications of using mercury, heater power supplies, and vacuum systems. The results shown in Fig. 4 for nominally identical devices indicate that the variability introduced by the weld can be small. It will be seen from Fig. 5 that there is reasonably good correlation between the vaporizer temperature required to give a particular mercury flow rate $\dot{m}$ and the equivalent gas flow rate measured at a pressure difference of 5 psi.

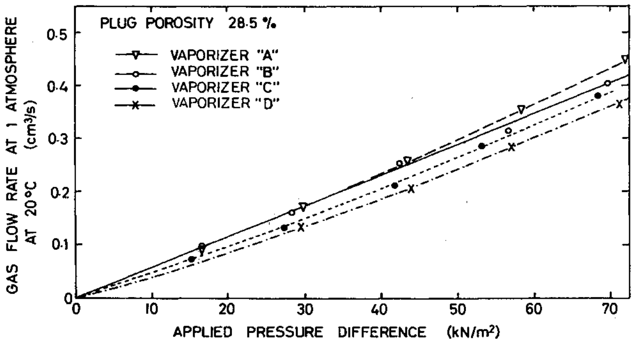

Fig. 4 Gas flow calibrations for 4 nominally identical vaporizers.

Isolators

The electrical isolator design[3,4] employs a large internal surface area of insulating material to encourage electron-ion recombination and thus inhibit breakdown. This technique has proved remarkably successful in raising the minimum of the Paschen curve by large amounts and displacing it to higher pressures and thus to higher flow rates.[4] Initial experiments using glass and alumina spheres in alumina tubes gave the relationship shown in Fig. 6. This was confirmed by tests of devices incorporating sintered alumina spheres. Breakdown was satisfactorily explained[4] by a mechanism involving distortion of the applied electric field, with the highest values adjacent to the cathode, and an avalanche type of discharge spreading from void to void.

The small degree of dependence of breakdown voltage on length and the performance improvement gained by reducing diameter allowed second-generation production devices to be

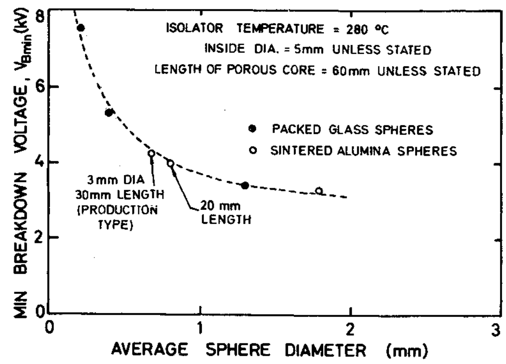

Fig. 6 Minimum breakdown voltage as a function of sphere diameter for porous sructure isolators.

very small. The internal diameter is 3 mm and the length 30 mm, while the minimum breakdown voltage is about 4 kv at 35 torr (Fig. 7). The outer surface is finned to give a long external breakdown path. Ceramic to metal brazing techniques[16] are employed to join the isolators to cathodes and vaporizers in fully integrated structures, which are currently undergoing thermal cycling and vibration testing. Heaters are provided to give rapid warmup on starting, but power dissipation during steady operation is minimized by careful mounting and radiation shielding.

Flow Monitoring

It is generally desirable to continuously monitor propellant flow rates in assessing the performance of a thruster, especially if η_m must be maintained constant. Vaporizer calibration cannot be relied upon, however, owing to the possibility of partial wetting or blockage of the porous plug. For these reasons, a thermal flowmeter has been developed.[4] In this device the center of a small diameter flow tube is heated while the ends are cooled, the temperature difference being maintained constant. Symmetrically positioned sensors between the heater and cooled ends register a difference in temperature which is linearly related to flow rate. Power dissipation is below 1 w.

Theory[4] indicates that thermal shunting by the tube wall reduces sensitivity, so recent efforts have been devoted to reducing the wall thickness. In addition, thermocouples have so far been employed as sensors, limiting the output to about 0.8 mv $(\text{mg/sec})^{-1}$, so thermistors[17] may be used in future to improve this.

A further method of determining flow rate has been developed. This is a peristaltic pump[18] which is driven at a known angular velocity by a stepper motor. A silicone rubber tube is used. This device has been tested for up to 3000 hr, and on an operating thruster. It has the additional advantage of providing electrical isolation because of each roller breaking the mercury column. The breakdown voltage exceeds 10 kv.

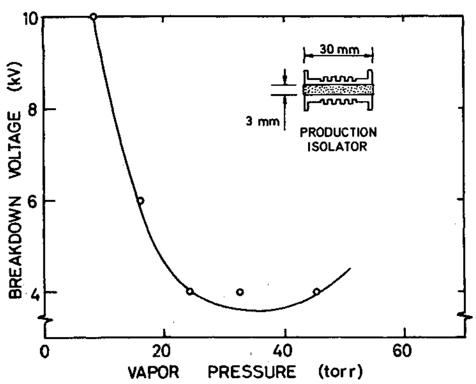

Fig. 7 Breakdown characteristic of production isolator.

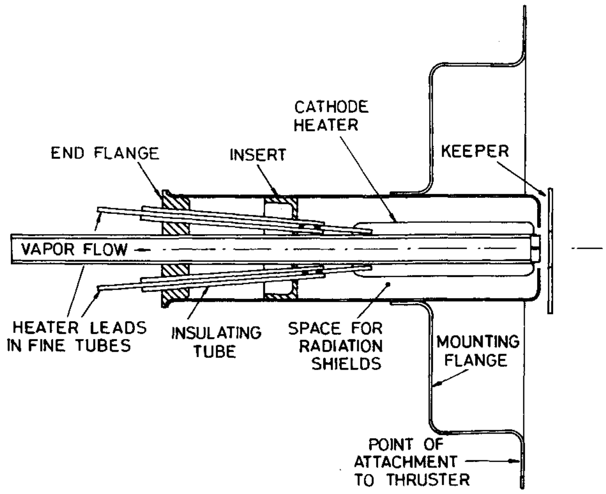

Fig. 8 Section through T4 cathode assembly.

Hollow Cathodes

The hollow cathode used in the T4 thruster (Fig. 8) is of conventional design,[2,3] except that it employs a bifilar heater winding. An extensive investigation of discharge behavior has led to the development of a two-part model of the electron emission mechanism,[19] which is broadly consistent with observation. A series of life tests is in progress,[13] and starting characteristics have been thoroughly investigated.[19]

While it has been established that a low work function material is not essential,[19] its presence considerably lowers the operating temperature and voltage, minimizes power, and aids starting. Until recently, this material has been coated on to the surface of a strip of tantalum foil rolled into a spiral to form a cylindrical dispenser. Doubts about the reproducibility and durability of this component have led to the use of impregnated porous tungsten inserts[20] which are mechanically superior. This results in similar operating characteristics to those obtained previously, but it is anticipated that lifetime should be improved, as well as resistance to vibration.

Considerable effort has been devoted to the thermal design of the assembly to minimize power. Several different radiation shield techniques have been investigated, both theoretically and experimentally. It was concluded that closely-spaced metal shields of low emissivity were most efficient. These were made from a tightly wound strip of dimpled metal foil, up to 40 turns being inserted into the space between the heater and the outer case (Fig. 8). Many different materials and dimpling techniques were studied which showed that, provided sufficient turns were used, conduction losses could be reduced to below 3 w at 1200°C.

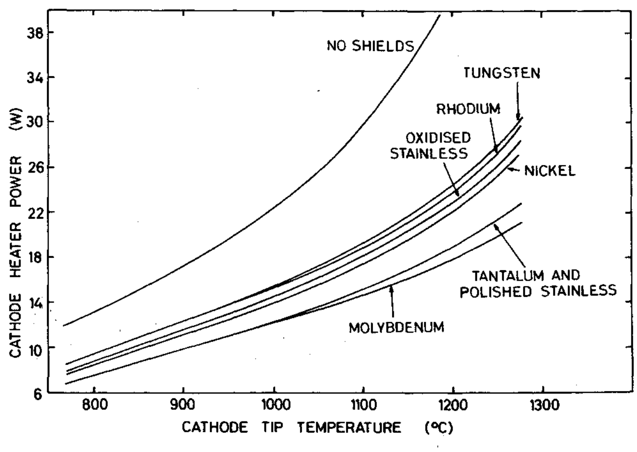

Fig. 9 Effect of radiation shields on cathode heater power requirement.

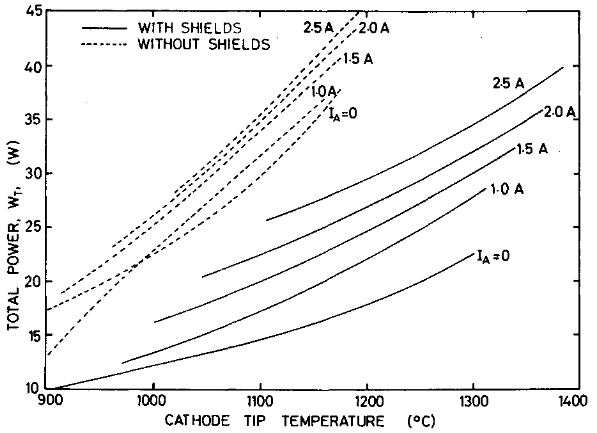

Fig. 10 Effect of radiation shields on total power required in a diode discharge system.

The radiated loss then depended largely on emissivity, as indicated by the results in Fig. 9. Molybdenum or tantalum were among the best materials, with the former having better mechanical properties. Rhodium was rejected owing to supply and fabrication difficulties. Using molybdenum, the total power loss at a cathode tip temperature of 1200°C was 18 w.

Heat shield assemblies fabricated in this way have been tested for long periods on operating cathodes and under thermal cycling. They have remained in good condition for 5000 hr and for more than 7000 thermal cycles. Degradation has been observed only in poor vacuum conditions, when oxidation tended to occur.

The effect of the radiation shielding on a spot mode discharge has been extensively investigated in a diode system at constant flow rate. It was shown that the total power W_T needed at a particular temperature and current was much reduced by the radiation shielding (Fig. 10), where W_T was defined as the power supplied to the heater, plus the keeper and main discharges.

Grid System

Although investigations have been carried out into the feasibility of using single insulated ion extraction grids, double grid systems have proved adequate at exhaust velocities of around 30 km/sec. The problem of thermal distortion on warm-up of the thruster has been solved by dishing the grids spherically inwards. Tests to determine the degree of distortion indicated (Fig. 11) that with a dishing depth of 6 mm and a radial temperature difference of 40°C the on-axis distortion is about 0.1 mm, or 7% of the value for flat grids.

The geometry of the grids was derived from the scaling laws formulated by Culham,[9] which allow the design to be changed to suit any chosen exhaust velocity. The holes are drilled after dishing, with the same hexagonal pattern in each grid. This causes the accel holes to be displaced from their positions for zero electrostatic deflection of the individual beamlets, and produces a deflection of about 7° for a dishing depth of 6 mm. The beam is therefore focused closer to the grids than expected geometrically, the focal point being 14 cm from the accel grid. The profile shown in Fig. 12 shows the resulting "waisting" of the beam and indicates that 90% of the current is within a cone of half angle 15°. To produce a more parallel beam, the holes in future accel grids may be located so as to reduce unwanted electrostatic deflections.

The thickness and geometrical open area ratio of the screen grid determine to a large extent the performance of the thruster.[1,6] The screen grid open area ratio is at present 70%, but the curvature of the plasma sheath[6] gives an effective value of 80% and a perveance of 2.39×10^{-6} $av^{-3/2}$ at 80 to 200 ma. Grids with spark-eroded hexagonal holes have been developed with an open area ratio of 80% or more, to achieve an even greater effective transparency. The thickness of the screen is 0.25 mm to minimize ion losses to its structure, and that of the accel grid is determined largely by the sputtering rate from charge-exchange ions and by the required lifetime. The inter-grid spacing is 1.5 mm and about 1500 holes are used. Molybdenum is employed for both grids.

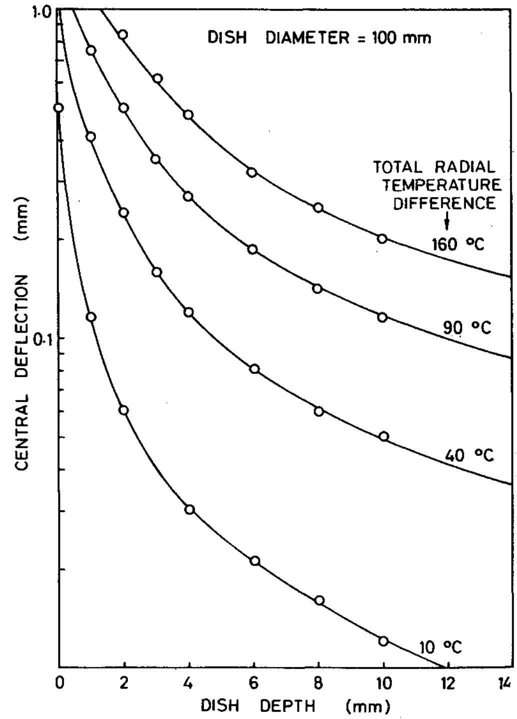

Fig. 11 Grid central deflection as a function of dishing depth and temperature.

The accel grid is insulated from the screen by 6 sputter-shielded insulators which define the grid spacing. They also maintain the hole arrays in alignment via flexible mounting strips, which form an integral part of the outer circumference of the screen. These strips are bent so as to combine high circumferential rigidity with good radial compliance to thermal stresses, and are used to mount the accel grid insulators and for attaching the grid set to the front pole. This allows the grids to expand freely with respect to each other and the pole without distortion or loss of alignment.

Neutralizer System

The plasma-bridge neutralizer system consists of a cathode similar to that employed in the discharge chamber, joined to a vaporizer via an insulating alumina section. The latter allows the cathode to be biased relative to spacecraft potential. Although tests have been conducted on an earlier thruster[13] and on the laboratory model of T4, the final position of the cathode has

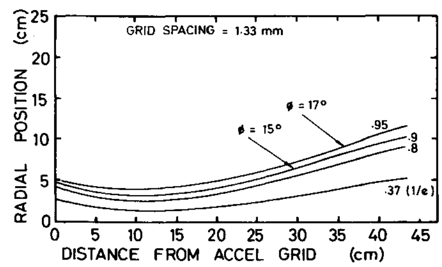

Fig. 12 Ion beam radius for a given fraction of the total current as a function of axial position.

not yet been decided; it will involve a compromise between efficiency and accel grid erosion.

Extensive tests in a diode system[14] have shown the existence of previously unreported phenomena, which are especially notable in cathodes with large orifice diameters. In particular, it is possible to operate at flow rates much lower than used before, at least down to 0.004 mg/sec (2 ma equivalent), and heater power is unnecessary provided that an adequate keeper discharge is maintained. Under these conditions, the cathode functions at below 500°C and durability is considerably enhanced. The discharge is then in an essentially different regime, where the plasma is entirely produced by the keeper discharge and the current reaching the anode diffuses there in the applied electric field.

Vibration

In the absence of a specific mission, the design of T4 was produced to withstand a severe vibration specification, similar to those for the Scout and Black Arrow launchers, to cater for a test flight on a small satellite orbited by such a vehicle. As such a test is now less likely, it is probable that the specification can be modified to a level consistent with the Thor-Delta launcher.

Vibration testing has commenced, with a resonance search of the complete thruster at 1 g in the frequency range 10 Hz to 2 kHz, and testing of selected individual components to up to 50 g. Few problems have arisen to date, the only serious resonance, in the grid structure, being outside the critical frequency range.

Durability

Although envisaged European N-S stationkeeping missions can be accomplished with operating times below 2500 hr[10] at 10 mN thrust, the current program is aimed at a proven life of 5000 hr with at least 1000 starts from cold. No thruster in the RAE program has yet approached these values because emphasis has been laid on life testing critical components. However, a total of about 2500 hr has been accumulated on several thrusters under widely varying conditions. In addition, an earlier design has been tested for 1600 hr with 177 starts, without component changes.[13] Although performance degradation has been observed, nothing has been encountered which suggests that the target life cannot be exceeded, and life tests of a T4 thruster, including isolators and neutralizer, are soon to commence in a fully instrumented facility with a frozen mercury target.[12]

Component Testing

In addition to the large number of cathodes and vaporizers used in thruster operation, many others have been subjected to controlled life tests in special facilities. Provided that triply distilled and thoroughly outgassed mercury is used, no problems have been encountered with the vaporizers. Operational times have exceeded 10,000 hr with only minor changes of characteristics.

Cathodes have been tested to 5000 hr, with the conclusion that vacuum facilities employed for this kind of work are often inadequate[13,16] and cause extensive oxide formation and both mechanical and performance degradation. It has been shown that orifice erosion is not a problem at the currents used (1 to 2 amp), and that the main cause of performance degradation is barium depletion. As barium is removed, emission can only be maintained by an increase in flow rate or temperature. An increase in flow has repercussions on thruster operating philosophy and perhaps degrades mass utilization efficiency, while an increase in temperature requires the application of heater power, or the plasma potential must be allowed to rise to increase ion bombardment heating. The loss of barium can be alleviated by operating at a low temperature. For this reason, tests are underway on large orifice cathodes, which can run for thousands of hours at under 700°C.[20]

Extensive thermal cycling and discharge initiation tests have been carried out[16] on cathodes. Heaters have survived for 15,000 rapid thermal cycles without failure and tip welds for 8000 cycles. Cathodes have been started 840 times from cold and many thousands of times from hot. A complete T4 cathode assembly has been successfully thermally cycled to 1200°C 7000 times, with a heatup time from cold of 3 min.

Experimental isolators employing the large surface area principle have been tested for 1600 hr on an operating thruster. No breakdowns occurred.

Grids

A major aim has been to minimize charge-exchange erosion of the accel grid to both improve lifetime and reduce the amount of sputtered material likely to be deposited on a spacecraft. Several factors contribute to this erosion and each has received attention.

Of fundamental importance is the flux of neutral mercury atoms leaving the thruster and available for charge-exchange reactions. This has been minimized by attaining high mass utilization efficiency (87%). In addition, it is desirable that the erosion be spread evenly over the surface of the grid, implying the need for a uniform beam distribution. With the present design, a very flat distribution can be achieved at the expense of a loss of efficiency, flexibility, or stability. As an example, the peaked distribution in Fig. 13 was obtained with the original configuration, while the much-improved flat profile resulted from minor changes in the inner polepiece region. The radius of the plasma at the points of 50% of peak density increased from 32 to 47 mm. The ratio of the peak current density to the mean was reduced from 2.34 to 1.36, giving an estimated increase of life of 2.25. However, it was impossible to satisfy simultaneously the magnetic field requirements for plasma containment and those for the acceleration of primary electrons from the baffle region plasma.[7] Consequently, the thruster was very unstable; this problem has been overcome by redesign of the magnetic circuit, incorporating active control of the field in the baffle annulus.

A new theory of charge-exchange erosion has been devised which does not assume a fixed position for the plane of neutralization, but takes it to be a function of perveance. This gives an expression for the depth of an erosion pit which depends on $j_H^{3/2}$ instead of j_H^2, where j_H is the current density through the relevant hole. Significantly, results from the C3 thruster indicate a dependence of the form $j_H^{(1.4 \pm 0.4)}$.

A contributory factor to the low erosion rate is the value of accel voltage. Although only 600 v, it provides optimum focusing of the ion beam and maximum perveance. Considerable effort has also been devoted to preventing the neutralizer from limiting accel grid lifetime. In particular, the mass flow rate of 0.008 mg/sec is below most other reported values and care is being taken to ensure that the remaining efflux causes minimum damage.

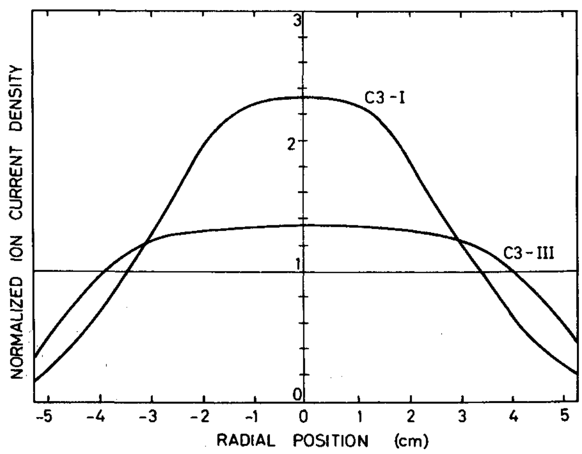

Fig. 13 Ion current density distributions at the screen grid for two configurations of the C3 thruster.

Conclusions

The design, performance, and construction of the T4 thruster and its critical components have been described. This device has been shown to be suitable for the N-S stationkeeping role on future European communication satellites, and the relatively high thrust of 10 mN allows short operating times, thus enhancing reliability. Perhaps of equal importance, this also results in reasonably short and inexpensive ground test programs. The wide throttling range allows the thruster to be used for a variety of similar missions, and the exhaust velocity can be varied by using the scaling laws to redesign the grid system, thus extending further the number of missions for which it is suitable.

The development program is very comprehensive, with close attention being paid to all important factors, such as the durability of cathodes, erosion of the accel grid, and resistance to vibration. Extensive lifetesting of most components has been carried out, including thermal cycling, and it is predicted that the target lifetime of 5000 hr with 1000 starts from cold will be exceeded.

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