ABSTRACT

With increasing spacecraft mass and mission durations, the demands on ion thruster systems intended for north-south station-keeping are becoming more onerous, especially as regards thrust level and lifetime. The impact of these requirements have been considered in the development of the T5 10cm diameter thruster through a programme of cyclic life-testing. This has involved both double and triple-grid ion extraction systems, and thrust levels of 10, 18 and 25 mN. These tests, with xenon propellant, have shown that both internal and grid erosion are more severe than suggested by earlier work with mercury. However, adequate grid lifetime can be achieved by using the triple-grid configuration, especially with a negative bias applied to the decel grid. Discharge chamber erosion can be almost eliminated by reducing anode potential to below 40 V, although this does require the acceptance of a performance penalty.

1. INTRODUCTION

As the masses of typical communications satellites increase and mission durations extend towards 20 yr\(^1\), the demands on platform systems, sub-systems and components become more difficult to meet. Not only must demonstrated lifetimes be adequate to satisfy requirements, which often stipulate a margin of up to 50%, but account must be taken of the additional radiation dose received. In many recent missions, the latter feature is of particular concern, since modern, high performance electronics systems are involved which can be more susceptible to radiation damage.

These stringent demands of present and future comsats must be properly considered in the design and development of ion propulsion systems for north-south station-keeping (NSSK) and other applications. When spacecraft were of relatively low mass and missions were of less than 10 yr duration\(^2\), thrust levels were modest, typically 10 mN, and thruster life-limiting factors were not often crucial to success. Indeed, predicted lifetimes were frequently well in excess of requirements\(^3\). This situation has now changed, with the imminent launch of such spacecraft as Intelsat VII\(^1\), for which thrust levels of 25 mN are more appropriate\(^4\). Life-limiting processes are accelerated by the higher thrust operation, a potential problem exacerbated by missions of much increased duration. Not only is the durability of the thruster a concern, but also its interaction with the spacecraft, notably the deposition of erosion products on sensitive surfaces, such as solar arrays.

The universal change of ion thruster propellant from mercury to xenon was introduced in order to eliminate any possibility of adverse chemical reactions with typical spacecraft materials. Although successful from this point of view, it now appears that sputtering damage with xenon exceeds considerably that found with mercury, compounding the problems mentioned above.

This paper considers these matters in the context of the T5 Kaufman-type ion thruster\(^5\), which is currently scheduled to fly in the NSSK role on ESA's ARTEMIS experimental communications satellite\(^6\) as part of the UK-10 ion propulsion system\(^7\) (IPS). It has also been selected for experimental flight on the Topaz 2 nuclear electric propulsion mission\(^8\).

To be specific, the paper examines the results of three long duration tests of T5 thrusters. Two of these tests, conducted at the AEA Technology Culham Laboratory, were of 500 hr duration, using successively double and triple-grid ion extraction systems. The third test, of 1500 hr, was carried out by Philips Components Ltd. as part of an investigation of cathode durability.

It was shown that discharge chamber and screen grid erosion can be reduced to acceptable levels by avoiding operation at or near maximum performance. Similarly, accelerator (accel) grid erosion, dealt with in more detail in a companion paper\(^9\), can be reduced to a rate commensurate with the more ambitious present-day missions by operating with a triple-grid extraction system.

It has been concluded that the sputtering data obtained earlier using mercury propellant\(^3\) were anomalously low, possibly due to a protective mechanism operating under those conditions. Those data suggested that the ultimate life-
limiting component was the discharge chamber hollow cathode\textsuperscript{10}. With xenon, it now seems that the grid system provides this limitation.

2. **THE T5 ION THRUSTER**

The T5 ion thruster\textsuperscript{5} is a conventional Kaufman-type device having several special features which provide exceptional versatility, primarily a very wide thrust range\textsuperscript{11} extending to beyond 70 mN. The thruster, shown in double-grid form in section in Figure 1, is of 10 cm nominal diameter and utilises a beam extraction voltage of typically 1100 V. It was originally developed in the 1970s for the NSSK mission\textsuperscript{2} using mercury propellant; a change to xenon was made in 1985 and all subsequent work has used this gas. In this form, its initial intended application remains NSSK\textsuperscript{12}, although the Topaz 2 mission\textsuperscript{8} will test it in the orbit-raising role. Whilst the excellent performance achieved with mercury has been repeated with xenon, it has been found, as already mentioned, that the two propellants do differ in important respects, with significant impact on cathode physics\textsuperscript{13}, discharge chamber erosion and sputtering of the ion extraction system\textsuperscript{9}.

Practically no mechanical changes were necessary to accommodate the new propellant, although the version now recommended for flight incorporates the triple-grid system, which has necessitated modifications to the downstream end of the earth screen. Similarly, the different behaviour of the cathode using xenon\textsuperscript{14} caused the adoption of an enclosed keeper configuration. Minor changes to the rear end of the thruster followed the deletion of mercury vaporisers, and isolator and backplate heaters.

The main structural component is the soft iron backplate (Figure 1). To this is bolted the cathode/isolator assembly, the main xenon feed tube with its electrical isolator, the inner polepiece and main flow distributor, and the cylindrical discharge chamber. In addition, the conical rear enclosure and the alumina electrical terminal blocks are mounted on the backplate, the rear enclosure via 6 sputter-shielded insulators. Those insulators act as the supporting
Figure 2 Diagram of the triple-grid ion extraction system

points for attachment of the thruster to the spacecraft, and also hold the rear ends of the solenoids in place. The rear flat face of the conical enclosure supports the cathode and main flow isolators, the neutraliser xenon feed pipe, and the electrical leads to the thruster.

Although the outer polepiece is located at the downstream end of the discharge chamber, it is physically attached only to the ends of the 6 solenoids. This polepiece carries the grid system via 6 attachment points, and also the neutraliser cathode/keeper assembly. The screen grid butts against the downstream face of the polepiece, and is supported in 6 places by a mechanical arrangement (Figure 2) allowing both longitudinal and radial thermal expansion, whilst maintaining accurate alignment and separation of the grids. The accel grid is mounted on 6 sputter-shielded insulators which define its separation from the screen grid. Similar insulators located at the same positions carry the decelerator (decel) grid, when fitted; this has supporting tabs that project forward at the front face of the earth screen. As illustrated in Figure 2, these tabs and the associated insulators are shielded by cylindrical screening cups.

Unlike many other Kaufman-type thrusters, the grids are dished inwards. This configuration was chosen to promote thermal stability and to assist in minimising beam divergence. The grids are made from molybdenum sheet and are perforated using a spark erosion process employing carbon tools; this is relatively inexpensive.

The cylindrical anode is supported from the discharge chamber by three sputter shielded insulators. Its position, together with the configuration of the magnetic field and the size and location of the baffle disc, was selected to optimise propellant utilisation efficiency.

The thruster as described above is incorporated into the T5 IPS selected for the Topaz 2 mission. Owing to the need for formal space qualification, minor mechanical changes have been necessary in the design of the device for the UK-10 IPS. However, the basic configuration remains as shown in Figures 1 and 2.

The advantages of the T5 thruster remain the same as when mercury was used. The most important of these concerns the control philosophy employed, although this leads to extra complexity in the power conditioning and control equipment (PCCE), the flexibility provided by the 4 control loops available is unsurpassed. With no mechanical changes whatsoever, the thrust can be increased from 1
to above 70 mN by altering only xenon flow rates, supply voltages and currents and, most significantly, the applied magnetic field. Over the whole of this range the propellant utilisation efficiency $\eta_m$ can be maintained at a level above 80%. This parameter can also be kept constant throughout a mission, despite inevitable erosion of the thruster and cathode degradation.

The 4 controlled parameters are the beam current, and thus the thrust, $\eta_m$ via the discharge voltage which, in turn, is dependent upon the magnetic field, and the main and neutraliser keeper voltages. The latter two parameters are maintained constant by controlling the xenon flow rates through the respective cathodes, thereby minimising degradation. The use of a variable magnetic field to adjust anode voltage and, in effect, primary electron energy, is an almost unique feature in modern ion thrusters.

Another unusual feature is the use of inward dishing of the grid assembly to promote thermal stability, as indicated in Figure 2. Since the inner, screen grid reaches the highest temperature under normal conditions it will suffer the greatest expansion. With inward dishing, it expands away from the accel grid, reducing the chance of inter-grid arcs. A consequence of this configuration is that the beam is focussed at a point roughly 14 cm downstream of the grids. There, the individual beamlets from opposite sides of the grids cross, giving a waisted appearance to the beam profile.

The divergence of the beam can be controlled by adjusting the positions of the holes in the screen grid with respect to those in the accel grid\textsuperscript{17}. In the standard twin grid configuration\textsuperscript{15}, a 1% difference in geometry gives a divergence, measured at the 95% of beam current streamline, of about 8° far from the thrust. However, this produced some direct ion beam impingement around the outer accel grid holes, so 0.5% was selected for production grids, with a divergence of 10 to 12°. To avoid direct ion beam impingement on the decel grid, a value of rather less than 0.5% is appropriate for this component, although this has not yet been fully optimised.

The performance of the thruster can be very high, with propellant utilisation efficiency exceeding 90% under some conditions, as indicated in the conventional performance map reproduced in Figure 3. Similarly, the electrical efficiency, as measured by the beam production energy cost, can be as good as 200 W/A, albeit at low utilisation efficiency. For high performance, an operating point such as P in Figure 3 might be selected; this would yield the parameters listed in Table 1, which are very attractive for certain missions. As indicated in Figure 3, further enhancements may also be possible by operating at reduced cathode flow rate. Values for 18 mN operation are also included for completeness in Table 1.

Unfortunately, lifetime considerations do not allow such high performance to be sustained for long periods of time, owing to a relatively high rate of internal discharge chamber erosion when the anode voltage exceeds about 40 V. Consequently, for missions lasting many thousands of hours, operation at below 40 V is recommended; the appropriate performance data under these conditions are given in Table 1.

![Figure 3 Typical T5 thruster performance map under nominal 25 mN conditions. Operating parameters at point P are given in Table 1.](image)

3. **LIFE-TESTING WITH MERCURY PROPELLANT**

During the early development of the T5 thruster, the Fulmer Research Institute conducted a comprehensive life-test programme\textsuperscript{2}, which showed that both internal and grid erosion were of little concern for typical missions under consideration at that time\textsuperscript{2}, and that cathode degradation\textsuperscript{10} was probably the most important life-limiting process. This programme was undertaken at 10 mN thrust, using a purpose-built vacuum facility having a solid mercury target. This provided an excellent environment, a typical background pressure close to the thruster during operation being 6 to $8 \times 10^{-7}$ torr, with only mercury sputtered by the beam from the target at a distance of 1.3m. The use of this target had an additional advantage, in that the only material collected by the sputter detectors
Table 1

PERFORMANCE OF T5 ION THRUSTER

<table>
<thead>
<tr>
<th>Point P, Figure 3</th>
<th>Nominal 18 mN</th>
<th>Recommended 25 mN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net beam accelerating potential (V)</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>Exhaust velocity (km/s)</td>
<td>40.2</td>
<td>40.2</td>
</tr>
<tr>
<td>Total flow rate to thruster (scc/min)*</td>
<td>7.70</td>
<td>5.21</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>498</td>
<td>329</td>
</tr>
<tr>
<td>Discharge current (A)</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>ΔV (anode-keeper voltage) (V)</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td>Anode voltage (V)</td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td>Doubly-charged ion content of beam (%)</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>Data corrected for doubly-charged ions:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust mN</td>
<td>27</td>
<td>18</td>
</tr>
<tr>
<td>Propellant utilisation efficiency (%)</td>
<td>87.5</td>
<td>85</td>
</tr>
<tr>
<td>Specific impulse (s)</td>
<td>3586</td>
<td>3483</td>
</tr>
<tr>
<td>Beam power (W)</td>
<td>548</td>
<td>362</td>
</tr>
<tr>
<td>Discharge power (including keeper) (W)</td>
<td>132</td>
<td>101</td>
</tr>
<tr>
<td>Additional power (W)</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Electrical efficiency (%)</td>
<td>78</td>
<td>74</td>
</tr>
<tr>
<td>Total efficiency (%)</td>
<td>68</td>
<td>63</td>
</tr>
<tr>
<td>Power thrust (W/mN)</td>
<td>26</td>
<td>27</td>
</tr>
</tbody>
</table>

* 5% additional flow required for neutraliser

deployed outside the thruster at various angles to the plane of its grids originated within the device itself.

The test programme involved 2,295 hr of thruster operation under steady-state conditions. The same thruster was used throughout, with three different sets of ion extraction grids to study their erosion characteristics. The thruster was the engineering model of the T5, designated T4A. The three separate periods of operation can be summarised as follows:

A. 200 hr with a double-grid ion extraction system having hexagonal holes, a screen grid open area ratio of 81%, no difference in hole patterns between the grids, and a hot wire neutraliser.

B. 1050 hr with a grid set having circular holes, an open area ratio of 70%, a difference in hole pattern geometries (termed "compensation") of 1%, and a hot wire neutraliser.

C. 1045 hr as in test B, but with 0.5% compensation and a plasma bridge neutraliser.

It was shown that all grid designs were viable, but that direct ion beam impingement on the accel grid was significant with the hexagonal holes. This seemed to be due to local aberrations of the ion optics and occurred near the angles of the hexagons. There was also evidence of direct impingement in tests B and C in holes around the periphery of the accel grid, and in other holes, in test C, due to an initial misalignment. In all cases, the sputter deposition rates decreased quickly with time as this direct impingement eroded the accel grids to the optimum profiles. The results for tests A and B are given in Figure 4 and for test C in Figure 5.
Although the 1% compensated grids gave the lowest beam divergence, $7.7^\circ$, examination of the erosion due to direct impingement suggested that the optimum for future work was the 0.5% design, and this was therefore adopted. The associated beam divergence was $10.3^\circ$.

The thruster operated throughout these tests at a very high performance level, summarised for B and C in Table 2, with the values of $\eta_m$ confirmed by weighing the mercury consumed. Table 2 also includes the measured mass changes of the grids. The potential lifetime was estimated from the mass losses and from microscope examinations of the damage to the downstream surfaces of the accel grids. In the optimum case, test C, the lifetime on the basis of mechanical failure following extensive erosion at a linear rate in time was about 50,000 hr. A rather lower figure of 30,000 hr was derived on the assumption that failure would follow penetration of the erosion pits, seen in Figure 6, completely through the accel grid. On the basis of these results it was concluded that grid erosion was not a dominant life-limiting factor.

Figure 4 Sputter deposition rate as a function of angle for mercury propellant (Tests A and B)

Figure 5 Sputter deposition rate as a function of angle for mercury propellant (Test C)

Figure 6 Erosion pattern on the downstream face of the accel grid after 1045 hr in Test C (0.5% grid compensation)
Table 2
MEAN OPERATING PARAMETERS AND GRID EROSION DATA FROM LONG-DURATION TESTS WITH MERCURY

<table>
<thead>
<tr>
<th></th>
<th>Test B</th>
<th>Test C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (hr)</td>
<td>1050</td>
<td>1045</td>
</tr>
<tr>
<td>Beam accelerating potential (V)</td>
<td>940</td>
<td>940</td>
</tr>
<tr>
<td>Propellant flow rate (mg/s)</td>
<td>0.395</td>
<td>0.390</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>164</td>
<td>168</td>
</tr>
<tr>
<td>Discharge current (A)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Anode potential (V)</td>
<td>40.0</td>
<td>39.7</td>
</tr>
<tr>
<td>Keeper potential (V)</td>
<td>14.1</td>
<td>12.9</td>
</tr>
<tr>
<td>Accel grid potential (V)</td>
<td>-490</td>
<td>-375</td>
</tr>
<tr>
<td>Accel grid current (mA)</td>
<td>0.47</td>
<td>0.50</td>
</tr>
<tr>
<td>Doubly-charged ion content of the beam (%)</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Thrust (mN)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Propellant utilisation efficiency (%)</td>
<td>86.4</td>
<td>89.5</td>
</tr>
<tr>
<td>Ion production cost (W/A)</td>
<td>244</td>
<td>237</td>
</tr>
<tr>
<td>Accel grid mass loss (g)</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>Screen grid mass loss (g)</td>
<td>0.19</td>
<td>0.18 (gain)</td>
</tr>
</tbody>
</table>

The condition of the thruster following these tests was excellent, with only a small amount of internal erosion damage. As an example, the inner polepiece is shown in Figure 7. This shows some evidence of sputtering around its tip, as confirmed by a mass loss of 0.12 g, but nothing so severe as has been observed more recently with xenon. The baffle disc lost only 0.013 g. There were some deposits of sputtered material within the discharge chamber, as indicated by an anode mass gain of 0.23 g, and flaking of these occurred from the chamber wall on either side of the anode. Iron was the principal constituent of the flakes analysed, with less than 5% of molybdenum. The latter probably originated from the screen grid during test B (see Table 2).

When the propellant change to xenon occurred, a careful examination of the life-test data then available suggested that the loss of barium from the cathode remained the ultimate life-limiting process, even with the thrust increased to 18 or 25 mN. This conclusion was based on the small recorded mass losses from both the discharge chamber and grids in tests B and C, aided by the theoretical treatment by Harbour, reported in reference 17. As described below, subsequent experimental work has indicated that certain unexpected effects caused this conclusion to be erroneous.

4. LIFE-TESTING WITH XENON PROPELLANT

As part of the development programme devised for the T5 thruster, two 500 hr cyclic tests were planned to compare the erosion characteristics of double and triple-grid ion extraction systems. These tests also provided an opportunity to examine in some detail the internal sputtering of the discharge chamber. They were undertaken by AEA Technology's Culham Laboratory, using a specially designed and constructed test facility, and are described in detail elsewhere, as are the results insofar as grid erosion is concerned.

Simultaneously, cathode life-testing commenced, using 4 almost complete T5 ion thrusters, but without beam extraction for simplicity and economy. This work, carried out by Philips Components Ltd., also provided valuable information concerning discharge chamber erosion under conditions exactly matching the parameters recommended in Table 1 for 25 mN operation. In particular, one of these thrusters reached 1500 hr when analysis of the first 500 hr cyclic test at Culham was being completed, thus providing an excellent opportunity for comparison of the results obtained in the two cases.
4.1 Double-grid cyclic 500 hr test

This test had similar objectives to that performed earlier using mercury propellant, but the diagnostics employed were much more comprehensive. They included a quartz crystal microbalance (QCM) to permit the deposition rate of sputtered material to be determined as a function of time, a probe carriage capable of moving a Faraday cup probe and a time-of-flight ion analyser in three dimensions under computer control, and calibrated solar cells placed at various angles to the beam to augment the QCM and passive sputter detectors. The Faraday cup probe allowed beam profiles and thrust vectors to be measured, together with any changes in these parameters that might occur in time.

The thruster was a T5 Mk 3 device produced by DRA Farnborough to engineering model standards (Figure 1). It was operated under manual control using laboratory power supplies, with the xenon flow provided by an engineering model propellant supply and monitoring equipment (PSME). Apart from a short initial period at 10 and 18 mN thrust, the conditions were selected to be close to those indicated by point P in Figure 3, although with the thrust level reduced slightly to 25 mN and \( \eta_m \) to 85%.

The cycle consisted of a start-up sequence, followed by 3 hr of steady-state running. The cool-down period prior to the next cycle occupied 1 hr. During each cycle, all electrical parameters were monitored by a computerised data acquisition system, as were the outputs of the QCM and the solar cells. On selected cycles, the beam diagnostics were employed, using the same system to record the resulting data.

Owing to the difficulty in pumping high flow rates of xenon, even with cryogenic techniques, it was not possible to achieve the low background pressures in the test facility that were reached in the case of mercury. Depending on the state of the cryopumps, the pressure was typically in the range \( 6 \times 10^{-6} \) to \( 1.5 \times 10^{-5} \) torr, up to an order of magnitude greater than in test B with mercury. This considerably enhanced the production of charge-exchange ions close to the accel grid, thereby increasing accel grid current and ion bombardment erosion. The variation of grid current with pressure is indicated in Figure 8.

![Figure 7](image1.png)

**Figure 7** Photograph of the inner polepiece after 1045 hr in Test C

![Figure 8](image2.png)

**Figure 8** Accel grid current as a function of facility pressure for the double-grid configuration
4.2 Triple-grid cyclic 500 hr test

This test followed the double-grid exercise and used the same thruster, but with a new grid set (Figure 2), cathode and inner polepiece/baffle disc assembly. The cathode change was necessary due to a cathode heater failure, and severe erosion of the polepiece made the fitting of a new unit advisable. In addition, the thruster was thoroughly cleaned and all components were re-weighed prior to assembly.

Experience gained in the earlier test and in the 1500 hr run at Philips Components (Section 4.3) suggested that discharge chamber erosion might be reduced by operating at an anode voltage of below 40 V. This necessitated a sacrifice in \( \eta_m \) of 5%; the resulting operating parameters for 25 mN thrust are listed in the right-hand column in Table 1. Similar changes were made at 10 and 18 mN and, to document more fully the performance at these thrusts, the associated total operating periods were increased to 24 hr in each case.

The test was conducted throughout with the decel grid at earth potential, and with the accel grid at the same potential, -350 V, as in the double-grid case. Later work using an identical thruster established the benefits of applying a negative bias to the decel grid, confirming earlier work by Brophy et al. It was found that the total erosion rate of the complete grid set could be reduced substantially by applying a bias of about -50 V to the decel grid, allowing the accel potential to be improved by about 100 V to -250 V.

4.3 1500 hr cathode test

As part of the space qualification programme, Philips Components Ltd. are conducting endurance tests of T5 thruster hollow cathodes and neutralisers, using purpose-built cryogenically pumped test facilities. The facility constructed for the cathode tests, shown in Figure 9, consists of 4 independent chambers separated by gate valves from a large central cryopump. The ultimate vacuum is in the \( 10^{-8} \) torr range.

Each of the 4 chambers contains a T5 Mk 3 ion thruster in which the grids have been replaced by a blanking plate having multiple adjustable apertures. These apertures are set to provide the correct impedance to xenon flow, such that the discharge chamber conditions, primarily the currents, voltages and magnetic field, exactly simulate the recommended 25 mN parameters listed in Table 1. In this way, the cathode and discharge chamber experience an environment appropriate to actual operation of the thruster, without the complexity and expense of beam extraction.

As a preliminary exercise, prior to the qualification test programme, the 4 thrusters were run for differing periods of time, a phase completed towards the end of the double-grid cyclic test described in section 4.1 above. It was therefore decided to examine in detail the state of the thruster which had accumulated the greatest running time, 1500 hr, and to compare the results of this examination with those obtained from the other test. This comparison led to the change in operating conditions selected for the triple-grid cyclic test.

Figure 9 Cathode life-test facility at Philips Components Ltd.

5. DISCHARGE CHAMBER EROSION

As mentioned in section 3, the condition of the discharge chamber of the thruster tested for about 2300 hr with mercury propellant was excellent, with no severe erosion evident. It was therefore concluded at the start of the test programme employing xenon propellant that no problems were likely to occur in this area, despite increases in flow rate and discharge current, and therefore in plasma density, to provide a thrust of 25 mN.

This conclusion was shown to be erroneous when the thruster was examined internally at the conclusion of the double-grid cyclic test. As can be seen in Figure 10, a considerable amount of sputtered material had accumulated in various
locations, and much of this was in the process of flaking away from those surfaces. Visual examination suggested that much of the deposited material had originated from the inner polepiece, distributor and backplate (Figure 1). This was confirmed later by weighing the various components; it was also found that significant mass losses had occurred from the outer polepiece and the discharge chamber body, with smaller amounts having been removed from the anode and the upstream face of the screen grid. The measured losses are compared with those found in the mercury test and in the triple-grid cyclic test in Table 3.

Figure 10 The thruster discharge chamber following the 500 hr double-grid test

While most eroded components had not suffered easily measurable geometric changes, this was not true of the inner polepiece and the screen grid, both of which were significantly damaged. The former component had been eroded preferentially about its tip to almost a knife edge, as shown in Figure 11a, from its initial thickness of about 0.5 mm. There had also been a slight reduction in length in the downstream direction. Conversely, the tantalum baffle disc had not been eroded seriously; there was a slight rounding of its originally square edges and a reduction of its diameter by 0.3 mm.

The damage to the screen grid consisted mainly of a chamfering of the upstream edges of the holes, as shown in Figure 12. This was particularly apparent in the centre of the grid, where the plasma density was highest, and was clearly a life-limiting phenomenon. Perhaps surprisingly, it was found that the hole diameters had not been enlarged during the test.

It was concluded from this examination that the thruster, when operated under these conditions, could not meet the ARTEMIS lifetime specification. However, the subsequent evidence from the 1500 hr cathode test (section 4.3) indicated that only a small change in conditions was necessary to virtually eliminate discharge chamber and screen grid erosion. This thruster, when dismantled, showed almost no internal sputtering damage whatsoever, as shown in Figure 11, where the two inner polepiece assemblies are compared. In the 1500 hr test, none of the dimensions of these critical components had changed, within the measurement error of ±0.01 mm.

The significant difference in conditions between the two tests was to be found in the discharge voltage. This was always below 40 V in the cathode test, typically 37 V, whereas it was above that value in the 500 hr double-grid cyclic case. Indeed, as shown in Figure 13, it fluctuated considerably during the first 120 hr, sometimes exceeding 50 V; this was due mainly to problems experienced with the PSME.

On the basis of these results, the magnetic field was adjusted to give an anode voltage of 38 ±1 V during the triple-grid cyclic test. This was extremely successful, since the subsequent examination of the thruster confirmed that there was no appreciable internal erosion, only the discharge chamber showing any mass loss (Table 3). All other components gained mass, due to thin deposits derived, in most cases, mainly from molybdenum sputtered from the grids. The condition of the edges of the baffle disc and polepiece, and of the upstream sides of the screen grid holes, can be seen in Figures 14 and 15, respectively.

5.1 Analysis of sputter deposits

Sample deposits from the thruster after both cyclic tests were examined in a scanning electron microscope, and their compositions were derived from electron microprobe spectra (energy dispersive x-ray analysis). In most cases, several readings were taken from different positions on a given sample, or from different samples from the same region of the thruster, and mean values were calculated, together with standard deviations. The method's limitations were checked by examining a sample of known composition (certified SS68 stainless steel). The results of this calibration and from some of the thruster samples taken after the double-grid test are presented in Table 4.
Figure 11 Polepiece/baffle disc assemblies after long duration tests

a. After 500 hr with anode at above 40 V
b. After 1500 hr with anode at 37 to 38 V

Figure 12 Enlarged view of upstream face of the screen grid following the 500 hr double-grid test

Figure 13 Thruster data taken during 500 hr double-grid test
Table 3

COMPONENT MASS LOSSES IN LONG DURATION THRUSTER TESTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Double-grids Mercury 2295 hr</th>
<th>Mass loss (g)</th>
<th>Double-grids Xenon 500 hr</th>
<th>Mass loss (g)</th>
<th>Triple-grids Xenon 500 hr</th>
<th>Mass loss (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge chamber</td>
<td>SS</td>
<td>NM</td>
<td>3.5</td>
<td>NM</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backplate</td>
<td>Soft iron*</td>
<td>NM</td>
<td>3.5</td>
<td>Gain 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner polepiece assy</td>
<td>Soft iron*</td>
<td>0.13</td>
<td>2.1</td>
<td>Gain 0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>SS</td>
<td>Gain 0.23</td>
<td>0.6</td>
<td>Gain 0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer polepiece</td>
<td>Soft iron*</td>
<td>NM</td>
<td>2.5</td>
<td>Gain 0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screen grid</td>
<td>Molybdenum</td>
<td>0.19†</td>
<td>0.9</td>
<td>Gain 0.42</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SS = stainless steel  
NM = not measured  
* protected with nickel plating  
† in test B, 1050 hr. See Table 2.

Figure 14 Enlarged view of the edges of the inner polepiece and baffle disc, following the 500 hr triple-grid test

Figure 15 Enlarged view of the upstream side of one screen grid hole following the 500 hr triple-grid test
### Table 4

ANALYSES OF SPUTTERED MATERIAL DEPOSITED WITHIN DISCHARGE CHAMBER DURING THE 500 HR DOUBLE-GRAID TEST

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition by weight (%)</th>
<th>Calibration</th>
<th>Inner edge, outer polepiece</th>
<th>Anode</th>
<th>Discharge chamber rear flange</th>
<th>Inner polepiece</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Standard</td>
<td>(4)*</td>
<td>(11)</td>
<td>(18)</td>
<td>(15)</td>
</tr>
<tr>
<td>Al</td>
<td>2.6 ± 0.4</td>
<td>1.98 ± 0.07</td>
<td>2.3 ± 0.2</td>
<td>5.7 ± 0.5</td>
<td>3.7 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>1.42</td>
<td>1.98 ± 0.07</td>
<td>0.3 ± 0.1</td>
<td>21.2 ± 0.7</td>
<td>34.2 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>8.2 ± 0.9</td>
<td>19.14 ± 0.06</td>
<td>2.4 ± 0.6</td>
<td>1.6 ± 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>18.5</td>
<td>19.14 ± 0.06</td>
<td>4.4 ± 1.1</td>
<td>1.6 ± 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>1.59</td>
<td>1.80 ± 0.08</td>
<td>1.7 ± 0.3</td>
<td>34.7 ± 2.6</td>
<td>33.2 ± 6.3</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>69.16</td>
<td>68.25 ± 0.11</td>
<td>28.3 ± 3.8</td>
<td>33.9 ± 2.7</td>
<td>28.2 ± 4.6</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>9.33</td>
<td>8.83 ± 0.06</td>
<td>13.7 ± 4.1</td>
<td>28.2 ± 4.6</td>
<td></td>
<td>4.7 ± 0.6</td>
</tr>
<tr>
<td>W</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* number of measurements made

Many of the data are extremely variable and are not easy to explain. For instance, silicon was detected in only two of the 4 samples listed, yet it is a standard constituent of stainless steel. Similarly, manganese was found in only one sample. The aluminium component was derived from sputtering of the beam target and of the ion beam probe assembly, and entered the thruster through the grids. Similarly, the molybdenum found in large proportions in most samples originated in the sputtering of the grids. Its concentration reached 74% in one sample taken from the inside surface of the inner polepiece. An explanation for the latter result is hard to find; it implies the movement of molybdenum atoms far into the thruster in copious quantities by a multiple bounce process.

The constituents of stainless steel were extremely variable in all locations within the thruster. For example, in two flakes taken from one location on the anode, the iron concentration was 4.5% and 57.8%. Conversely, the nickel values were 41.9% and 1.0%, respectively. A possible explanation for such variability can be found in the nickel protective layer on the soft iron components. Initially, nickel was the dominant element sputtered from such components. Once this layer was removed, iron became more significant. Thus a given flake often gave very different analyses; as an example, one side of a flake from the inner polepiece had a nickel content of less than 1%, whereas the opposite face gave up to 59%.

Samples taken after the triple-grid test were qualitatively similar, but showed less variability, probably because the sputtering of soft iron components had not penetrated through the nickel plating. The proportion of molybdenum was higher than before, approaching 80% on the anode. There was less aluminium, due to the smaller time that the ion beam probe was exposed to sputtering in this test. It is assumed that the titanium detected on this occasion was derived from the probe assembly. In the double-grid test, tungsten was found only within the inner polepiece, to which it has been sputtered from the cathode tip. In the triple-grid case, this element had migrated onto the backplate.

6. GRID EROSION

Reference has already been made to the screen grid erosion experienced in the double-grid test, and its subsequent elimination by reducing the anode potential to below 40 V. In this test, the accel grid suffered charge-exchange erosion which was much more severe than expected on the basis of the mercury results (Figure 6), even taking into account the higher background pressure in the vacuum facility and...
the increase of thrust to 25 mN. As shown in Figure 16, the erosion pattern was conventional in form, but the overall mass loss was such that there was some doubt as to whether the predicted lifetime at 18 mN was adequate for the ARTEMIS mission.

As reported by Martin et al in Ref. 21, the rate of deposition of sputtered material onto the QCM was approximately linear in time, apart from an initial high rate during acceptance testing and later perturbations correlated with beam probing and facility pressure increases. The mean rate deduced from all the diagnostics employed is shown in Figure 17, together with the data from the triple-grid test and the trend for mercury from Figure 5. All data are normalised to a distance of 50 cm, assuming an inverse square law relationship.

Theory suggests that the sputter rate observed in this test should have been approximately three times that found with mercury, whereas the ratio was in the range 60 to 120 times. Although a factor of two to three of this discrepancy can be accounted for by the much greater facility pressure with xenon propellant, a large difference remains. However, if the observed sputtering and accel grid currents are used to calculate an effective sputter yield, this is close to the accepted value for xenon, but is much lower in the case of mercury, as indicated in Figure 18. It is therefore clear that the mercury results were anomalously low, and that a protective mechanism was in operation.

Two possible mechanisms may explain the mercury data. One is that the molybdenum surface of the accel grid was protected by adsorbed mercury vapour. The other is that it was covered by an oxide or nitride film; this may have been absent in the case of xenon, because the cryopumps employed in that work were more effective in removing the nitrogen and oxygen from the facility than were the oil diffusion pumps in the mercury experiments.

As expected, the triple-grid configuration exhibited very different erosion characteristics, with the barrels of the accel grid holes suffering appreciable enlargement instead of material being removed from the downstream face of the grid. In addition, there was direct ion beam impingement on the decel grid, which caused the holes to become conical in shape, especially near its centre where the current density was highest. Other less severe erosion occurred on the upstream edges of the accel grid, which became rounded, and on the downstream face, where rings of material were removed concentric with the decel grid holes. It is possible that the latter effect was due to a potential profile in the beam immediately outside the grids causing charge
Figure 18 Sputtering yield of molybdenum as a function of the energy of xenon and mercury ions, comparing accepted values with data derived from thruster testing.

Figure 19 Downstream face of accel grid, following 500 hr triple-grid test, illustrating the circular erosion pattern concentric with decel grid holes.

Figure 20 Section through central portion of the triple-grid system following the 500 hr test.

Figure 21 Upstream and downstream accel hole diameters are plotted as functions of radial position in Figure 21, which indicates that the central holes were cylindrical, whereas those towards the periphery became conical (Figure 22). A similar graph for the decel grid holes is presented in Figure 23, which shows that the direct ion beam impingement erosion was confined to the central region.

Following exposure to air, sputter deposits on various grid surfaces were removed and were analysed to determine their composition, as were samples taken from the front surface of the earth screen. The downstream face of the decel grid provided samples with a high aluminium content, in the range 32 to 38%, which was probably derived from the beam target and the probe system. There was also a high concentration of the constituents of stainless steel, which could have originated from the walls of the test facility and the earth screen of the thruster. A small proportion, just less than 1%, of tungsten probably came from the tip of the neutraliser cathode.
In contrast, the samples from the downstream face of the accel grid were primarily molybdenum, at the 92 to 97% level, although there remained 1 to 2% of aluminium and about the same proportion of tungsten.

The downstream flat surface of the earth screen showed over 40% of aluminium, with molybdenum only at the 1 to 3% level. Stainless steel accounted for the remainder of these samples. However, as the location of the samples moved towards the inner lip of the screen, the proportion of molybdenum, sputtered from the grids, increased rapidly, eventually reaching 95%.

During the triple-grid test, the QCM output varied considerably\textsuperscript{24}, although the ion beam probe data suggested that the grid system was completely stable mechanically. It is assumed that this variation was due to the erosion by direct ion beam impingement of the central decel grid holes (Figures 20 and 23) and of certain superfluous peripheral holes. Once this process had been completed, the residual charge-exchange erosion process dominated. In plotting the sputtering deposition rate as a function of angle in Figure 17, it has been assumed that the output of the QCM at the end of the test was representative of this latter situation.

It can be seen that the rates were well below those found with the double-grid system, but that they remained higher than with mercury.
However, a factor of between two and three of this can be attributed to facility pressure, and it was found subsequently that a further factor of two reduction can be achieved by applying a negative bias to the decel grid. As a consequence, it can be shown that the triple-grid system should be adequately durable for the most demanding missions currently envisaged, provided that a current modification programme can eliminate the direct ion beam impingement.

7. CONCLUSIONS

After describing the T5 Mk 3 ion thruster to place the work into context, this paper has presented and compared the results of a series of long duration tests, using both mercury and xenon propellant. Thrust levels of 10, 18 and 25 mN were investigated and the thruster had both double and triple-grid ion extraction systems.

The work with mercury had earlier established that the thruster was adequately durable for all envisaged missions and that the deposition of sputtered material onto vulnerable spacecraft surfaces would be at acceptable rates. It was predicted that the overall situation would be very similar following the change to xenon propellant, although it was recognised that an increase in sputtering rate by a factor of up to three might occur at 25 mN operation.

The initial 500 hr cyclic test with the double-grid configuration showed that both discharge chamber and grid erosion were considerably more severe than predicted, and it was concluded that, under those conditions, the inner polepiece and screen grid were more likely to be the life-limiting components than the hollow cathode. However, a simultaneous test to 1500 hr, as part of the cathode qualification programme, confirmed that the use of an anode potential of below 40 V should almost eliminate discharge chamber erosion. This was shown to be valid in the subsequent triple-grid cyclic test.

As anticipated from research conducted elsewhere, the triple-grid configuration provided a lower ion extraction system erosion rate than did the double-grid alternative, although direct ion impingement on the decel electrode masked this until the test was well advanced. However, the overall rate remained considerably higher than predicted from the mercury tests. Part of this discrepancy was due to the influence of the facility background pressure on the charge-exchange ion current to the accel grid, the pressure in the case of xenon being about an order of magnitude above that with mercury.

The remaining disagreement was explained by noting that the observed rates with xenon were consistent with published sputtering yields. This was not the case with mercury, for which those yields suggested sputtering rates much greater than measured. It was thus inferred that a protective mechanism had operated in the mercury tests; this might have been due to the adsorption of mercury vapour into the surfaces at risk, or to the formation of oxides or nitrides on them.

It was concluded that discharge chamber sputtering damage can be almost eliminated by a modest reduction in anode potential, albeit at the cost of a 5% reduction in mass utilisation efficiency. Grid erosion can be reduced by employing a triple-grid extraction system, assuming that the direct ion impingement problem can be solved by minor design changes. A further improvement can be realised by applying a moderate negative bias to the decel grid. It is predicted that, by these means, the thruster will provide a thrust, overall performance and life commensurate with the requirement of the ARTEMIS and similar missions.

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REFERENCES