Cyclic Life-Test of an Ion Thruster Hollow Cathode

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To assist in assessing the durability of the U.K. T4A and T5 10-cm mercury ion thrusters when used for North-South stationkeeping, cyclic life-tests of thruster components have been carried out. This paper reports a cyclic discharge test of a hollow cathode in a diode configuration, together with thermal cycling tests of cathode heaters. The automatically controlled discharge test consisted of repetitive on and off periods with normal durations of 3 h and 40 min, respectively. The test was terminated voluntarily after 4200 h of discharge operation and 1343 starts. The rate of degradation of performance, as indicated by keeper and plasma potentials, was fully acceptable for the envisaged missions, as were the time, power, and energy required for discharge initiation. The thermal cycling tests demonstrated that the heater technology is satisfactory. It was concluded from a consideration of various aspects of the long-term operation of hollow cathodes that diode tests are adequately representative of thruster conditions.

Nomenclature

I_A = anode current
I_k = keeper current
$\dot{m}$ = mercury vapor mass flow rate
T = cathode tip temperature
T_e = electron temperature
T_v = vaporizer temperature
V_A = anode voltage
V_k = keeper voltage
V_p = plasma potential

Introduction

A MAJOR feature of the use of any ion propulsion system is that long operating times are necessary, with values of 1000-10,000 h covering the requirements of most missions. Consequently, lengthy and time-consuming life-testing is mandatory for space qualification purposes, and ideally this should be carried out on a number of complete systems to gain statistical information regarding operational reliability. However, it is possible to reduce the expense and effort required by identifying critical components and testing them separately under conditions designed to be as realistic as possible.

This philosophy of life-testing components has been adopted throughout the development of the U.K. 10-cm mercury ion thruster system,[1,2] and this paper refers to recent aspects of this continuing program of work. It has always been recognized that the hollow cathode[3,4] employed in the discharge chamber and for the neutralizer is the component most likely to suffer failure, so considerable emphasis has been placed on proving its durability under varying conditions.

Although early life-test work concentrated primarily on operation for long periods of time under steady-state conditions, it soon became clear that an early application of ion thrusters might be to the North-South stationkeeping (NSSK) of communications spacecraft.[5,6] Such missions involve thrusting at regular intervals of time for periods of a few hours. For example, a 750-kg spacecraft, equipped with a system of two pairs of 10-mN thrusters mounted at 30 deg to the North-South axis, would require each pair to be operated for 2.52 h each 3 days or for 3.36 h each 4 days.[6] Consequently, the startup phase of operation becomes of much greater importance, and testing under cyclic conditions is then necessary.

The startup phase is particularly significant because it includes severe thermal stressing, especially if rapid starts are required. In addition, heating to higher than normal temperatures may often be needed, thereby accelerating certain performance degradation mechanisms, such as the loss of barium from the dispensers within the cathodes.[7]

In view of the potential importance of the startup process, much of the recent life-testing has been concentrated on this area. In particular, several cyclic life-tests have been carried out of cathode heaters, and a cyclic discharge test of a cathode/vaporizer assembly has also been undertaken. The cathode heaters have exceeded 5000 rapid cycles without failure, and the discharge test was voluntarily terminated after 1343 starts.

These results, together with earlier steady-state investigations[3] and thruster life-tests,[8] indicate that the components in question are adequately durable for typical NSSK missions. This conclusion is further confirmed by the long-term operation of other stationkeeping thrusters[9,10] and by successful multiple starting tests performed in orbit.[11]

Cathode Discharge Cycling Test

Although a considerable amount of cathode life-testing has been carried out as part of the U.K. ion thruster project,[2,3,12] most of this has been concentrated on operation under steady-state conditions. The main exception to this was a discharge-initiation test in which a single laboratory-type cathode was started automatically 840 times.[13]

This test showed that multiple starting was possible; however, it was not completely representative of operation in an actual mission, because the time at full current, 10 min, was very short, and the time allowed for cooling was not adequate to give thermal cycling over the temperature range likely to be encountered in practice. Nevertheless, several interesting observations were made. These included a general trend toward longer start times and definite evidence that contamination of the cathode by residual vacuum-system gases caused starts to be prolonged. Removal of the contaminants, or the production of fresh barium from the dispenser, reduced the recorded times to a level consistent with the underlying gradual trend.

It was concluded that repetitive starting degrades the overall performance of a cathode, and analysis of the residual

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barium content suggested that barium loss was responsible. It was surmised that this loss occurred because, for each start, it was necessary to provide barium coverage of the surfaces in and around the cathode orifice. The subsequent discharge removed this barium by evaporation or ion bombardment sputtering, and it therefore had to be replaced from the dispenser during the next start. The effect of contamination was probably similar, in that the free barium chemically combined with other materials, necessitating its replacement from the dispenser.

The feasibility of multiple starts was also demonstrated during the SERT II mission.[11,14] Approximately 160 starts were performed on one thruster and over 200 on the other, spanning a period of 5 years and thruster operating times of 3889 and 2175 h, respectively. Over this long period of time, there was no performance degradation and contamination effects after long intervals of storage were also absent.

Cathode Assembly

The cathode assembly (Fig. 1) was basically a standard T4A/T5 thruster device,[1] but with an orifice diameter of 0.25 mm, slightly smaller than normal. The cathode consisted of a tantalum tube into one end of which was welded a 1-mm thick tungsten disk having a central parallel-sided orifice. Surrounding the downstream end of the tantalum tube was a bifiliar heater made from split-free tungsten wire encapsulated in flame-sprayed alumina. The alumina was separated from the tantalum by a thin layer of tungsten, which formed a barrier to prevent the occurrence of chemical reactions between the alumina and tantalum at elevated temperatures. The heater resistance was about 0.7 Ω when cold, increasing to about 5 Ω with a cathode tip temperature of 1100°C.

To ensure that they were of relatively low resistance and temperature, the tungsten leads to the heater were sheathed with tantalum tubes, which were anchored in the final alumina coating. These coaxial tungsten/tantalum leads were joined to the 0.5-mm-diam molybdenum wires that emerged from the rear flange of the cathode assembly. These wires passed through the flange in alumina tubes and finally terminated on insulators fixed to the cathode mounting flange.

The complete assembly was surrounded by a stainless steel tube of 11.5 mm o.d., which was welded to the Kovar rear flange. Between this tube and the heater was positioned a multiturn radiation shield system, constructed from dimpled molybdenum foil. The tip of the cathode protruded through a central hole in a stainless-steel disk welded at its periphery to the end of the outer tube.

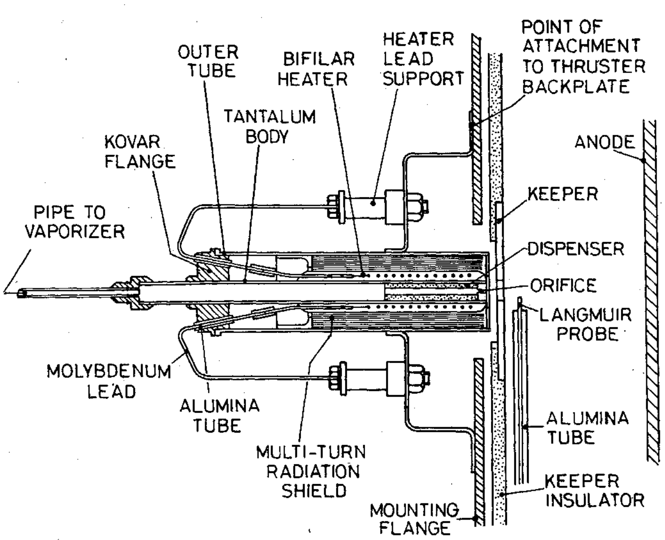

Fig. 1 Cathode configuration used for cyclic discharge test.

A hollow cylindrical barium dispenser was situated adjacent to the tip of the cathode. This was fabricated from porous tungsten and was impregnated with barium-calcium aluminate in a carefully controlled high-temperature process. Detailed examinations of sectioned dispensers[7] have revealed that impregnation is very uniform.

Test System

The cathode assembly wws supported in the same manner as in the thruster, the mounting point being a stainless-steel plate equipped with a heater to allow its temperature to be raised to simulate that of the backplate of the thruster. The keeper electrode consisted of a stainless-steel plate 1 mm thick, with a 3-mm-diam orifice concentric with the cathode orifice. Its upstream surface was 1.5 ± 0.2 mm from the cathode tip when cold, and it was supported on a boron nitride insulator. The 6-cm-diam stainless-steel anode was situated 2 cm from the cathode tip.

A cylindrical Langmuir probe was mounted 2 mm downstream of the keeper, with its tip 0.75 mm radially displaced from the center of the keeper orifice. It was constructed from 0.4-mm-diam tungsten wire, with all but the end 2 mm length shielded with thin-walled alumina tubing.

The cathode was connected by a short length of thin-walled stainless-steel tubing to a vaporizer.[15] Liquid mercury was fed to the vaporizer from a glass storage system, which incorporated a capillary tube used for flow measurement. In deriving flow rates from the fall of the mercury meniscus in this capillary tube, corrections were made for changes in laboratory temperature and to account for any slight volume change resulting from variations of pressure with meniscus height.[3]

Temperatures were monitored in several positions by chromel-alumel thermocouples, and that of the cathode tip by a platinum/platinum-rhodium thermocouple. The latter had earlier been shown[3] to give data consistent with other measurement techniques.

In view of the problems encountered in the previous cyclic test due to contamination and poisoning,[13] the vacuum system employed in the present study was capable of a much improved performance. The background pressure of residual gases was below 5×10^{-7} Torr, and a specially designed liquid-nitrogen-cooled trap was utilized to condense and collect mercury, thus minimizing pump contamination.

Separate power supplies were provided for the cathode-keeper discharge, the cathode-anode discharge, the cathode heater, the vaporizer heater, and the auxiliary heater on the mounting plate (see Fig. 2). The switching of these supplies was controlled automatically by a master controller, which incorporated appropriate timers, relays, and logic circuitry. The controller also switched recording instruments on and off at preset times.

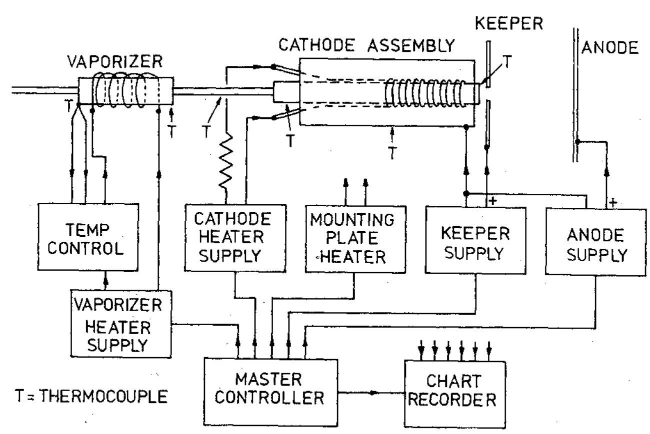

Fig. 2 Power supply connections used for cyclic discharge test.

Discharge Cycle

The master controller initiated each start sequence at a preset time after the end of the previous operational cycle. It first turned on the anode and cathode heater supplies. The former, which was run in a current-stabilized mode, gave its maximum output voltage of 50 V at this stage. The latter supply was also initially operated in a current-stabilized mode, because the cathode heater had a low resistance when cold. As the cathode heated up, the resistance of its heater rose and, eventually, the preset maximum output voltage of the supply was reached. At this point, the current began to fall, causing the rate of increase of power dissipation in the heater to decrease. To avoid this power level reaching a peak and then decreasing again due to the further rise of heater resistance, an external ballast resistance was provided.

At a preset time during the above process, the keeper and vaporizer heater supplies were turned on. The vaporizer temperature controller was inoperative at this stage and power was therefore fed to the vaporizer at a constant rate, depending on voltage and current settings. The keeper supply was preset to give an output of approximately 1 kV.

When the tip temperature T and mass flow rate $\dot{m}$ had attained appropriate values, a cathode-keeper discharge occurred. Usually, this immediately transferred to the anode. The keeper supply then automatically switched to a low-voltage current-stabilized mode, as did the anode supply. The master controller detected the occurrence of the discharge to the anode and switched off the cathode heater supply. It also caused the vaporizer supply to revert to its temperature-controlled mode of operation, registered an additional start on a counter, and started a clock that recorded the accumulated discharge time.

After a preset time, usually 3 h, the master controller turned off all supplies, apart from that to the anode. The discharge thus continued for about 1 min as the flow rate fell, but the anode voltage rose gradually to the maximum of the supply, then the output current fell until inadequate power was being provided to sustain the discharge. This switchoff mode was chosen to simulate the most damaging procedure likely to be encountered in thruster operation.

Start Sequence

To provide a severe test of the durability of the cathode heater, both the rate of rise of power during the start sequence and the maximum power attained were selected to be larger than in the normal thruster starting process.[16] As shown in Fig. 3, the peak power of over 21 W was reached in under 2 min, with 20 W being attained in 55 s only, as compared with 9 min in the thruster sequence.

The resulting increase of T as a function of time is depicted in Fig. 4, together with the corresponding variations of vaporizer temperature T_v and of $\dot{m}$. These curves were recorded during a sequence in which a start occurred at 4 min 15 s, with keeper voltage $V_k = 950 \pm 50$ V. The values of flow rate illustrated were derived from prior calibration of the vaporizer and were thus subject to errors due to thermal transient effects; these result from a temperature difference between the monitoring point and the porous tungsten plug.[15] However, it can be seen that the start in question occurred with $T = 1020°$C and $\dot{m} \sim 0.23$ mg/s. As the discharge transferred to the anode, ion bombardment caused T to rise to 1160°C, despite the fact that the master controller turned off the cathode heater power supply. The flow rate also fell toward its normal operational value of about 0.16 mg/s.

Although it was found in the earlier study[13] that starts always occurred when the prebreakdown keeper current I_k reached a certain value, a previously identified random behavior[3,4] was still apparent, in that a variable time was taken to attain the critical current. This was also the case in the present work, the time taken being as short as 2 min 30 s, with $T = 860°$C and $\dot{m} \sim 0.06$ mg/s. In such early starts, the anode discharge was usually in the luminous "plume" mode initially, only changing to the "spot" mode as $\dot{m}$ increased. Conversely, the time taken for initiation was as long as 8 min, usually after the test facility had been unused for some while. The cause was probably contamination by residual gases.

The prebreakdown keeper current was monitored during a number of start sequences by using a chart recorder connected across a series resistance. As shown in Fig. 5, the current rose with tip temperature in an erratic manner, there being many sharp high-amplitude pulses superimposed on the underlying gradually increasing trend. These pulses appeared to become larger as T approached the value at which initiation occurred; at this value, I_k was consistent with the data reported by Newson et al.,[13] although these authors did not observe the

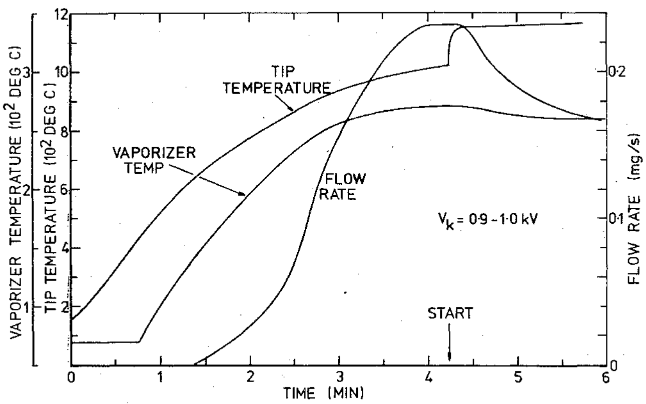

Fig. 4 Tip temperature, vaporizer temperature, and mercury flow rate as functions of time during the start sequence.

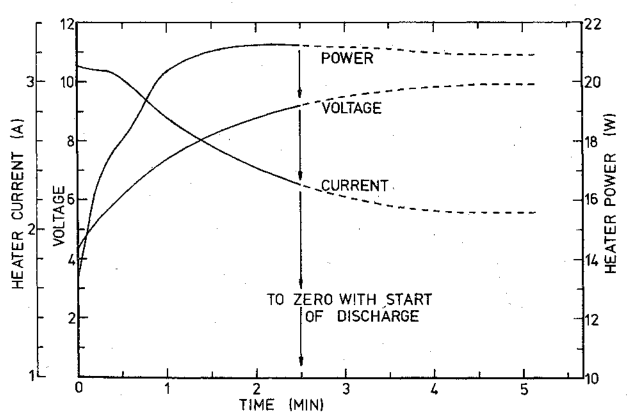

Fig. 3 Heater current, voltage, and power profiles used in cyclic discharge test.

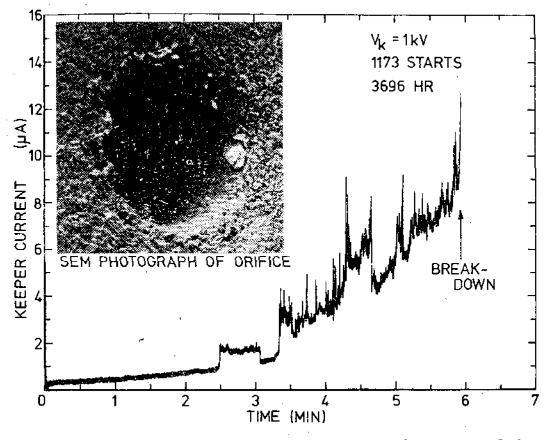

Fig. 5 Keeper current prior to breakdown as a function of time, and SEM photograph of a cathode orifice after 840 starts.

transient behavior illustrated in Fig. 5. As an example of this agreement, breakdown occurred in the case shown with $I_k \sim 8\text{-}10\mu A$ and $\dot{m} \sim 0.2\text{-}0.25$ mg/s. Values of 5-8 μA were recorded in the earlier study under these conditions.

The erratic rise of I_k during the start can be explained in qualitative terms by considering the electron emission processes responsible for the observed current. Apart from the high temperature, three factors can contribute: these are the partial- and varying-surface coverage by free barium, the application of an electric field with a mean value of approximately 10^4 V/cm, and the microscopic roughness of the surface. It has been shown in earlier work that ion bombardment etches the surface to expose sharp edges; Fig. 5 includes a scanning electron microscope (SEM) photograph of the resulting rough surface around the orifice of the cathode that was subjected to 840 start cycles.[13] Rough edges produced in this way will be the sites of field-enhanced emission, which will vary strongly with the degree of barium coverage and with detailed geometry.

This type of mechanism is consistent with the variability observed in starting times and with the dependence of these times, mentioned later, on the output capacitance of the high-voltage section of the keeper supply. With regard to the latter, if emission occurs from a point or edge that is covered with barium, the resultant local heating will evaporate the barium, decreasing the emission. Only if the initial current can raise the temperature adequately to overcome this self-quenching action will the emission continue; this is a function of the energy available and therefore of the output capacitance of the supply.

Steady Discharge Characteristics

To simulate thruster operation with reasonable accuracy,[1,2] the standard conditions set for the steady phase of each cycle were $\dot{m} \sim 0.16$ mg/s, anode current $I_A = 1.25$ A, and $I_k = 0.5$ A. The duration of each steady-state period was 3 h and, throughout this time, several parameters were continuously monitored; these were T, T_v, I_A, I_k, V_k, and anode voltage V_A. From the typical single cycle of data reproduced in Fig. 6, it is apparent that the discharge was generally very quiet, with only slowly varying changes of voltage and temperature, due mainly to thermal effects.

This quietness was confirmed by examining the noise on all electrodes, including the Langmuir probe, with a wide-bandwidth oscilloscope. It was of about 20 mV peak-to-peak amplitude, which was of no concern as regards thruster operation. Rather more interesting was the waveform, which was almost purely sinusoidal with a frequency of 8-9 MHz. This was close to the electron cyclotron frequency appropriate to the plasma in the cathode-keeper region. For example, if it is assumed that the full discharge current was constrained to the diameter of the keeper orifice near the keeper, the azimuthal magnetic field produced there was just over 2 G, giving a cyclotron frequency of 6-7 MHz. Nearer the cathode, the frequency rose as the discharge became more constricted.

Although quiet characteristics, as depicted in Fig. 6, were recorded during the major part of the 4200 h of operation, on some occasions a transition to the "plume" mode[17,18] oc-

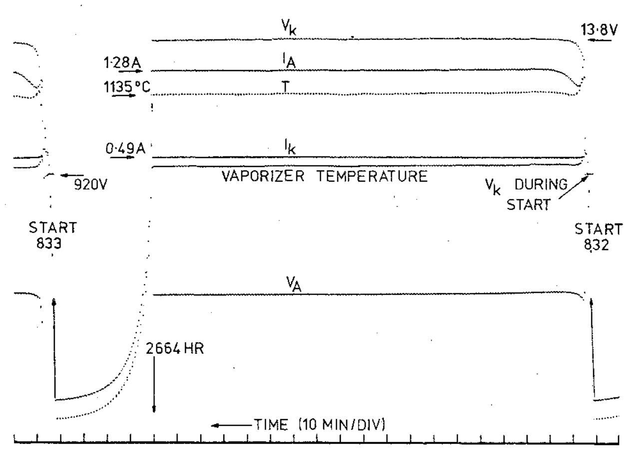

Fig. 6 Chart recording of test parameters over one discharge cycle.

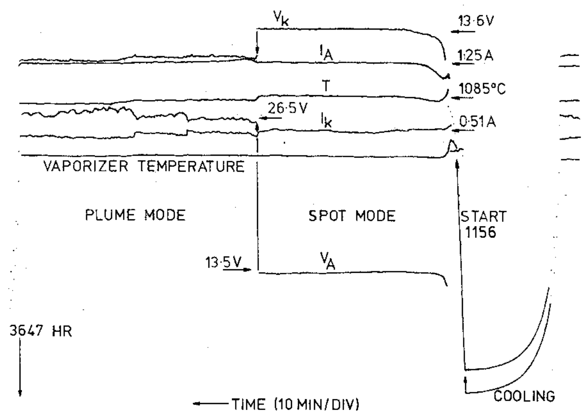

Fig. 7 Chart recording of test parameters, showing spot-to-plume mode transition.

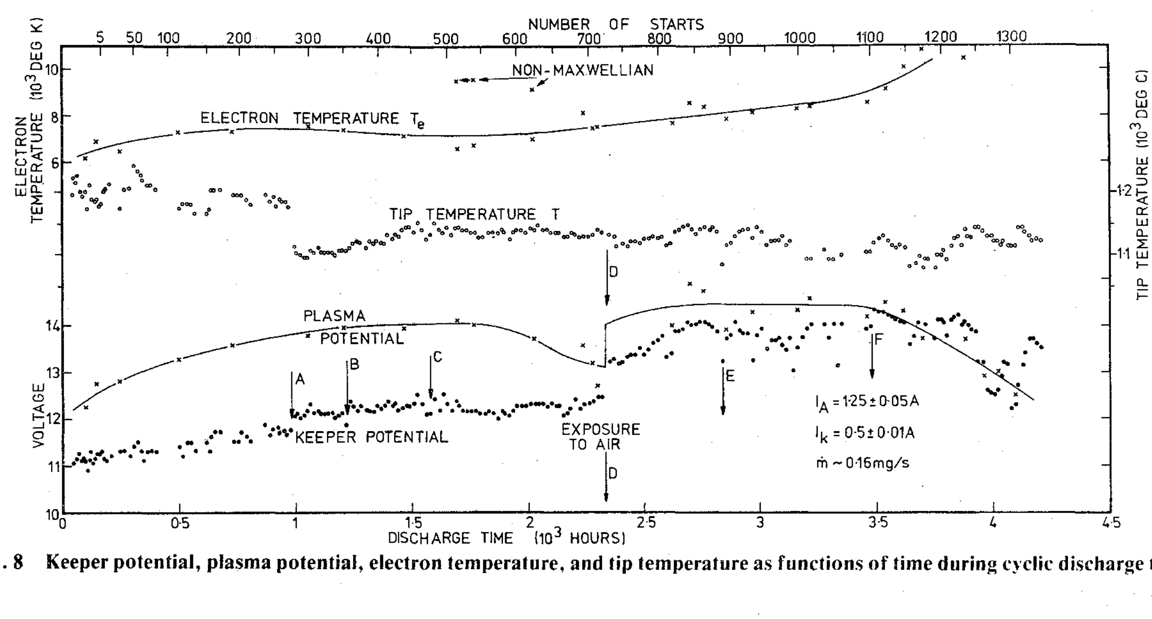

Fig. 8 Keeper potential, plasma potential, electron temperature, and tip temperature as functions of time during cyclic discharge test.

curred, as illustrated in Fig. 7. This was usually due to an accidental reduction of $\dot{m}$, and was accompanied by a change from a nonluminous to a luminous discharge. As indicated in Fig. 7, at the transition, V_A increased by a factor of 2, whereas V_k fell slightly. There was little change in T, suggesting that the total power input from ion bombardment remained constant. Invariably, an increase of $\dot{m}$ caused the discharge to revert to the spot mode.

It should be pointed out that this mode change is predominately a pressure-dependent phenomenon, and it is therefore modified when a cathode is mounted in a thruster, owing to the presence of the baffle disk/inner polepiece assembly and to the increase in pressure caused by the main vapor flow system. Consequently, the pressure within the inner polepiece is much higher than in a diode system (5-10×10^{-5} Torr in the present test), and the electron flow to the anode is modified by this, together with the application of a magnetic field within the thruster. As a result, the cathode flow rate in a thruster can be reduced to a low level with no sign of the type of mode change observed in diode systems. In this respect, a diode system is not fully representative, but it may be postulated that the difference is not significant in the context of life-testing, owing to the small change of T resulting from the transition between modes.

Langmuir probe characteristics were taken at a regular intervals throughout the experiment, with careful cleaning by electron bombardment[3] immediately prior to each recording. The probe characteristics were of the expected shape, with a pronounced ion saturation of approximately 400-600 μA and extremely good reproducibility over short periods of time. The characteristics were analyzed using the standard procedure.[19] As only electron temperature T_e and plasma potential V_p were derived, corrections[20] were not applied to allow for perturbation of the plasma by the probe. Such corrections would, however, have been necessary in the calculation of meaningful values of electron number density.

Long-Term Trends

This long-term cyclic test was commenced with a steady-state run of approximately 170 h duration to characterize the performance of the cathode and thereby provide a standard for judging the extent of subsequent degradation. The results obtained during this time included Langmuir probe characteristics, which indicated that the electron temperature was about $6\text{-}7 \times 10^3$ K and the plasma potential between 12 and 12.5 V. Under these conditions, V_k was about 1 or 2 V less than V_p and V_A was a fraction of a volt greater. The cathode tip was at a temperature of approximately 1170-1210°C, the observed variation depending on $\dot{m}$. These initial values of the recorded parameters are plotted in Fig. 8 together with data for the later cyclic phase of the test. Also recorded were the times for starting, defined here as the time between switching the cathode heater power supply to the cathode and the attainment of the full discharge current of 1.25 A.

From the point of view of thruster operation, a good guide to cathode performance is the value of V_k. As shown in Fig. 8, this rose gradually from around 11 V early in the test to about 12.3 V by 2400 h, at which point about 730 cycles had been recorded. The major part of this increase was confined to the first 1000 h, at a rate of 1 V/1000 h. The scatter of about ± 0.2 V was due mainly to flow rate changes but, in addition, the shut-down of the vacuum system for any appreciable length of time generally caused a small, temporary rise of V_k of up to 0.5 V, such as occurred at points A and C in Fig. 8. This was attributed to contamination by residual gases. Conversely, heating for prolonged periods with a vapor flow but no discharge (point B) sometimes caused V_k to fall, possibly due to the greater coverage of barium at the orifice achieved in this longer than normal time.

At point D, the vacuum system failed. Although the fail-safe mechanisms protected the cathode, an overhaul of the vacuum system was necessary, causing the cathode to be exposed to air. Although it ran very well afterwards, V_k had increased by nearly 1 V to over 13 V, and a rapid rise to 14 V then occurred over the next 400 h. Thereafter, behavior was more erratic than before, with V_k usually between 13.5 and 14.0 V, but with some much lower values being recorded. There was also a greater tendency for plume mode operation to occur at low $\dot{m}$. This evidence suggests that, although it does not appear to be detrimental to its subsequent performance to expose a cathode to air early in its life, this is a more serious event at much later times, causing long-term degradation.

The last 700 h of the test suggested, however, that this long-term degradation was not permanent. Although the values of V_k recorded during this period were much more scattered than those obtained prior to the exposure to air, a gradually decreasing trend was evident. As illustrated in Fig. 8, this trend was also visible in the plasma potential, thus confirming that the electron emission process became more efficient during this time. Two possible causes may be postulated. One is the enlargement of the tip orifice by ion bombardment, which is known to reduce V_p, and the other is the gradual dispensation of barium from the cooler, upstream section of the dispenser.

It was shown at point E that a temporary reduction of V_k, and thus of V_p, can be achieved by additional heating, and that such a decrease persists for a longer time than earlier envisaged. On this occasion, this heating was due to the failure of the keeper supply, which, as a result, delivered a keeper current exceeding 1 A. Subsequently, after the supply had been replaced, V_k was found to be approximately 0.6 V lower than before, and the following increase was quite slow, taking approximately 70 h to reach the earlier value.

Throughout the first 2400 h, V_p followed V_k reasonably closely, suggesting, as had been concluded during previous studies,[4] that V_k provides a reasonable guide to plasma potential. However, beyond point D, V_k became much closer to V_p, the difference then being 0.5-1 V, rather than the previous 1.5-2 V. At 3500 h, point F in Fig. 8, V_k and V_p became identical within the random scatter of the data, and this continued to the end of the test. The reasons for these changes are unknown, although they appear to have been caused, at least initially, by the exposure to air.

An unexplained feature also occurred in the records of tip temperature. For the first 1000 h, T was within the range of 1160-1240°C, with a tendency to stabilize at around 1190 °C toward the end of this period. Then, following the shutdown of the vacuum system at point A, T was found to have dropped to about 1100°C. It was also much more reproducible. During the next 500 h a rise to 1140°C occurred, following, as expected, the increase of V_k. The temperature stabilized at around this value, remaining there for the next 1500 h. At point D, only a very small fall was observed, which was surprising in view of the rise of V_k at that time. Later, a substantial fall was recorded at point E; this was consistent with the enhanced barium production that may then have occurred. Subsequently, T decreased in a rather erratic manner, reaching well below 1100°C at 3700 h. An increase was then observed, with T fluctuating between 1100 and 1150°C for the last 400 h of the test.

The electron temperature, depicted in Fig. 8, rose gradually throughout the test, exceeding 10^4 K at 4000 h. These values were derived from the Langmuir probe characteristics, which indicated that the electron velocity distribution was Maxwellian up to 1600 h. At that time, their form became non-Maxwellian, with the appearance of two reasonably distinct groups of electrons. In calculating V_p for these cases, a mean value of T_e was assumed. After 2000 h, the probe characteristics became closer to Maxwellian again. The reason for these changes is unknown.

Values of T_e were also obtained during plume mode operation. These tended to be rather higher than those reported above, usually in the range $1.1\text{-}1.4\times10^4$ K. The semilogarithmic probe traces remained linear, suggesting that the electron velocity distribution was still Maxwellian.

Throughout the first 4000 h of the test, starting times were generally within the range 2-6 min, apart from one period when a modified keeper power supply was used with a smaller than normal output capacitance (3200-3700 h). With this supply, times were consistently between 6 and 7 min. There was no evidence of an overall systematic variation of starting time, such as the slow degradation detected by Newson et al.[13] over a much shorter period. A possible explanation is that the ultimate pressure provided by the vacuum system was one to two orders of magnitude better in the present case, suggesting that barium losses through poisoning were much less. The few very long times recorded were usually due to a defect of the apparatus. For example, at point F in Fig. 8, a time exceeding 9 min was due to a faulty cathode heater supply.

In the last 150 h of the test, some much longer times were observed, which often exceeded 10 min. As mentioned below, the post-test inspection of the cathode showed that the tip weld had developed a crack, and it is suggested that mercury vapor leakage through this may have been responsible for these longer times.

To examine the data for evidence of a short-term periodic variation of starting time, the results for every start recorded between numbers 590 and 680 were analyzed in detail. The times in question fell within the range 2.5-5.0 min, but there was no clear suggestion of any regular pattern.

Post-test Analysis

Following the voluntary termination of the test, the cathode was sectioned and analyzed by a variety of processes.[7] With the exception of an oxidized tip weld that had been leaking, it was found to be in good condition.

There was adequate barium remaining in the dispenser for a considerably longer operating lifetime, and the heater was in sound condition. Although the usual orifice erosion had taken place, it was not thought to be significant, and the chemical reaction between the dispenser and the inner wall of the tantalum body[7] was not of serious concern.

The oxidation of the tip weld was thought to have resulted partly from the higher-than-usual tip temperature, which was, in turn, caused by the use of a smaller orifice than normal. It clearly illustrated the importance of environmental considerations in planning and carrying out a test of this kind, and suggested that a background pressure of atmospheric gases of 5×10^{-7} Torr is barely adequate for durations of several thousand hours.

Cathode Heater Cycling Tests

It has already been pointed out that the cathode heater is one of the most highly stressed parts of a thruster. For this reason, the power levels supplied to it during the cyclic discharge test were greater than those recommended for flight use and the rates of rise were very considerably increased. However, it was thought desirable to demonstrate that the heater is capable of withstanding successfully treatment that is even more severe. This was accomplished by means of cyclic tests without discharges, and these gave very encouraging results.

Apparatus

To ensure that unwanted chemical effects were absent, the cathodes tested were mounted in a vacuum system providing an ultimate background pressure of $1\text{-}2\times10^{-7}$ Torr. The thermal characteristics of the mounting arrangement closely simulated those in the thruster.

A power supply similar to that employed in the discharge cycling test was used. Initially, a series resistance was not included, causing the power level to peak well above its steady-state value. For example, with a steady-state power input of 30 W and peak current and voltage settings of 4.5 A and 12 V, the power input rose to a maximum of 54 W after only 50 s. Later, the use of an external resistance of 2-4 Ω damped out this peak; in a flight system, the same result may be achieved by appropriate pulse-width modulation.

In all cases, both the maximum power and the rate of rise were far in excess of those used in the thruster.[16] Consequently, they represented a very severe test of the cathode heater technology.

Switching of the supply was accomplished automatically at times determined by the attainment of preset temperature levels. In particular, the heater supply was turned on when the cathode tip temperature had fallen to a suitable value around 100°C, and the supply was turned off when T had reached an appropriate high value. Immediately afterwards an auxiliary a.c. supply was connected to the heater for a preset time of about 5 min; this held the cathode at peak temperature to simulate the starting delay that sometimes occurs in operational circumstances. At the end of this period, the auxiliary supply was turned off and the cathode allowed to cool.

Test Results

Several T4A/T5 thruster cathodes, as depicted in Fig. 1, have been tested as described above. Apart from a single failure at 519 cycles attributed to the application of the excessive peak power of 54 W mentioned above and another due to the malfunction of the vacuum system, the cathodes tested have behaved remarkably well. All tests have been terminated voluntarily at several thousand cycles, and the heaters have been in good condition.

The test of longest duration occupied 5395 cycles, each with the power and tip temperature-time variation illustrated in Fig. 9. The temperature of the upstream end of the dispenser was also monitored, and was found to be a maximum of about 100°C hotter than the tip temperature, owing to its position within the center of the heater. These temperatures and the heatup and cooling times were monitored continuously throughout the test. The former time was generally between 150 and 170 s. The cooling time to between 120 and 140°C was initially 26-29 min, the variation being due to a lack of precision in switching at the lower set temperature level. Toward the end of the test, these times had decreased by approximately 2 min, presumably owing to changes in the overall thermal emissivity of the cathode assembly. No other systematic variations were observed.

Examination of the cathode after the 5395 cycles showed two defects. One was the usual cracking of the alumina heater encapsulant, which had occurred azimuthally in one position only. The other defect consisted of a mechanical distortion of the tantalum body away from the crack; however, X-ray photographs showed that this had not fractured the body.

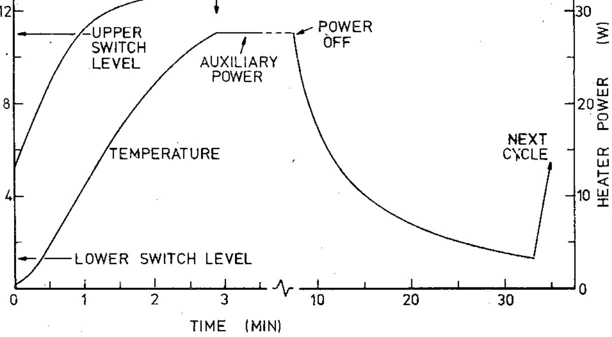

Fig. 9 Heater power and tip temperature as functions of time during 5395-cycle test of cathode heater.

These X-rays and a longitudinal section through the cathode also showed that the heater was in excellent condition.

A test involving the use of a pulse-width modulated heater supply was voluntarily terminated at 2024 cycles. There was no degradation of performance during the test, and the visual appearance of the cathode was good afterward. There were a few barely discernible azimuthal cracks in the alumina, and one more significant axial crack near the tip.

This cathode was then subjected to a further experimental study, to ascertain its maximum power absorbing capability. A current-regulated power supply was connected to the cathode and a poower meter was used to measure continuously the power supplied. When the supply was turned on the heater current was regulated at its preset maximum. As the heater resistance rose with temperature, the voltage and pvower also rose. When the power reached a previously decided maximum, it was maintained at that value by reducing the current and therefore the voltage. The supply was switched off when the tip temperature reached approximately 1300 °C.

In this way, it was established that the cathode would withstand very rough treatment. Currents of up to 5 A were used and power levels of up to 85 W, The latter gave a heatup time from room temperature to 1300 °C of only 80 s, with the more usual 1100°C being reached in 70 s. The heater finally failed at 90 W.

Concluding Discussion

The primary aim of the work described in this paper was to obtain information concerning thrust durability under cyclic operating conditions by means of a reduced cost program of hollow cathode life-tests. For these tests to be relevant to thruster development, it was necessary to simulate as accurately as possible the environment experienced by a cathode in a thruster. The evidence suggests that this was accomplished with respect to the thermal aspects of operation and as regards the chemical effects resulting from thousands of hours of running or due to exposure to certain contaminants. In addition, it is probable that the internal plasma and that immediately outside the cathode orifice closely resembled those in an operating thruster, but the plasma located between the keeper and anode was almost certainly not representative in certain significant respects.

It may thus be concluded that diode tests simulate the thruster situation in many important areas and that they provide an excellent guide to the long-term cathode performance changes to be expected in thruster operation. Consequently, it has been demonstrated that the cathodes developed for the T4A and T5 thrusters should be able to withstand successfully the type of cyclic operation required to accomplish a typical North-South stationkeeping mission, with large margins of safety.

To assist in planning future diagnostic experiments aimed at studying basic cathode physical and chemical processes, and also manufacturing technology, in greater depth, a further qualitative discussion of the results described above seems justified. This follows, under three broad headings.

Thermal Aspects of Cyclic Operation

The tests reported here have demonstrated that the cathode heater technology employed in this project is entirely adequate, with the proven capability of withstanding at least 5000 extremely severe thermal cycles. In particular, the choice of heater wire, its geometrical configuration, and the method of termination are all satisfactory. The alumina encapsulant, although it has performed well and has caused no failures, could perhaps benefit from further investigation, with the aim of preventing the occurrence of cracks.

The heater power required for starting, approximately 20 W, is only a small proportion of that allocated to the thruster system (approximately 260 W at 10 mN thrust), so further efforts to reduce it would not be justifiied, especially as zero power is consumed after the discharge has been initiated. Similarly, the energy required is acceptable.[16]

A major concern at the beginning of the cyclic-discharge test was that the barium loss during the start transients would cause a rapid degradation of cathode performance. It was shown that this did not occur, the degradation being no more rapid than in earlier steady-state tests.[2,3,12] The implication that the barium loss due to thermal cycling is not large has been subsequently confirmed by an experiment in which the loss was directly measured.[21] Nevertheless, it appears prudent to design the thruster start sequence to minimize both the maximum temperature to which the cathode is raised and the time during which it is held at that temperature.

As regards the degradation due to steady-state operation, it appears from the experience gained to date that the dominant factor is the cathode temperature. Although this can be reduced by appropriate thermal design techniques, the most effective method of decreasing it is to use a large cathode orifice.[2,3]

Chemical Effects

The tests reported here confirmed that the tungsten barrier layer covering the tantalum cathode body provides adequate protection against chemical attack by the alumina heater encapsulant. It was also confirmed that there is a significant effective loss of barium through the formation of barium tantalate on the inner wall of the body.[7,21] Both reactions are strongly dependent on temperature, providing a further reason for minimizing this parameter.

The chemical reaction[7] responsible for producing free barium from within the impregnated dispenser is also a strong function of temperature. As the rate of dispensation largely determines the values of V_k and V_p at which a discharge operates, high temperatures will give low voltages, which are beneficial, but life will be drastically shortened. However, the form of the relationship between life and temperature is not known[7]; this is an area where more work is required. All that can be stated at present is that the values of T in the present test, approximately 1100°C, produce an adequate cathode life, together with acceptable operating potentials. Of course, lower values of T should give an even slower rate of degradation.

It was shown that the admission of air into the apparatus at approximately 2300 h adversely affected the performance of the cathode for more than 1000 hours. It is surmised that this was due to chemical reactions within the dispenser, but it is difficult to explain the long time needed to achieve a recovery, especially in view of the absence of changes in T, T_e, and starting time.

It is tempting to postulate that the barium at the downstream end of the dispenser became chemically bound, and that it therefore became necessary to produce additional free barium from the cooler upstream end. To do this, an overall increase of temperature would have been required, necessitating a higher power input from ion bombardment. Thus V_k would have increased, but so would have T and, to a lesser extent, T_e. An alternative possibility is that the active surface of the dispenser near the cathode tip became semipermanently poisoned, reducing the current density it could emit, whatever the barium distribution. As a result, previously nonactive upstream areas of the dispenser were obliged to take part in the emission process, requiring the internal plasma to extend deeper into the cathode. Owing to the appreciable electrical resistivity of this plasma,[4] this process would have required an increase of V_p in all regions. The later performance recovery would then be explained on the basis of a gradual removal of the poisoning compounds from the dispenser, possibly by evaporation or by ion bombardment.

As in most previous life-tests, environmental conditions were particularly significant at the cathode tip. The combination of an exposed tantalum/tungsten weld and high temperatures again caused difficulty, despite the low pressure of the atmospheric contaminants attained. This, rather than any inherent life limitations of the cathodes themselves, has restricted the test durations so far achieved in the present program. Consequently, to attempt to further reduce the accessibility of the cathode tip to contaminants, future tests will be conducted using a simulated thruster polepiece/baffle structure to provide a high-pressure region of mercury vapor at the tip.

Plasma Effects

As mentioned above, in a diode test, the plasma upstream of the keeper probably exhibits similar characterisitcs to those found in an operating thruster, whereas that between the keeper and anode is not fully representative. For this reason, plasma parameters in the present test were monitored only adjacent to the keeper orifice.

This deficiency of the diode arrangement is not thought to invalidate the results obtained, because the main influence of the external plasma on the cathode is through ion bombardment heating and erosion. In the moderately ionized collisional plasmas that exist in the region of the cathode tip, it can be shown that the ion mean free path is of the order of the keeper-cathode separation. Thus the energy possessed by the ions on reaching the cathode is determined by V_p near the keeper, and the plasma between the keeper and anode has little influence on the heating and erosion processes.

In general, the plasma is very quiet in the normal operating regime, with a Maxwellian electron velocity distribution. The ion temperature is assumed to be slightly greater than T, owing to collisional energy transfer from the electrons, whereas T_e is determined directly by the power supplied to the discharge. Although the proportion of doubly charged ions present has not been measured in a diode discharge, it must be negligibly small, owing to the relatively low voltages and values of T_e.

In one other important respect, the diode discharge does not accurately simulate the Kaufman thruster. This concerns the spot-to-plume mode transition, which limits diode tests in that low values of $\dot{m}$ are not readily accessible. This does not appear to be the case in a thruster, where behavior is dominated by the geometry of the inner polepiece/baffle assembly[1,2] and by the applied magnetic field. However, at the flow rates employed in the T4A and T5 thrusters, this is not of serious concern.

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