Recent Hollow Cathode Investigations at the Royal Aircraft Establishment

C. M. PHILIP* AND D. G. FEARN†
Royal Aircraft Establishment, Farnborough, Hampshire, England

Studies of hollow cathodes, with special reference to the requirements of the RAE/Culham T4 mercury ion thruster, are described. Life tests in diode discharge systems and in an earlier thruster have shown that an operating time of at least 5000 hr is attainable for the discharge chamber application. An extensive investigation of performance under neutralizer conditions has indicated that operation at flow rates as low as 0.004 mg/sec with zero heater power can be achieved. The possibility of vibration damage to the conventional barium-containing insert has led to the successful development and test of a porous tungsten insert.

Nomenclature

d = cathode orifice diameter
I_A = anode current
I_k = keeper current
$\dot{m}$ = mercury vapor flow rate
n_e = electron number density
P_H = power supplied to cathode heater
T = cathode tip temperature
T_e = electron temperature
T_o = cathode tip temperature with $I_A = 0$
V_A = anode potential
V_k = keeper potential
V_{kb} = value of V_k causing discharge initiation
V_p = plasma potential

Introduction

UNTIL recently, hollow cathode research at the RAE has been principally directed towards an examination of the relevant physical processes in sufficient depth to establish reliable criteria on which to base future designs.[1-3] Although emission mechanisms have been proposed which are supported by experimental evidence, a fully comprehensive theory is not yet available. However, the combination of theory and extensive operational experience has enabled cathodes to be designed whose performance falls within certain well-defined limits. Recent cathode development work has been aimed at demonstrating that such devices are suitable for use in the RAE/Culham T4 thruster.[4,5]

It has long been recognized that the cathodes are probably the most vulnerable components in a thruster. Consequently, considerable attention has been devoted to several long duration tests in both bell jar facilities and in an operating thruster. An important feature of these tests has been the frequent monitoring of relevant plasma parameters. Improvements in cathode reliability have been achieved by replacing the conventional rolled-foil barium dispenser by an impregnated porous type[6]; these inserts have been investigated for both the discharge chamber and neutralizer applications.

The performance of cathodes operated under conditions applicable to ion beam neutralization has also been studied. Largely because of the very low flow rates envisaged, the discharge mode is very different from that observed when the cathode is operated under main discharge conditions. Attempts have been made to identify those parameters which determine power and propellant consumption, together with those of importance for control purposes.

Presented as Paper 73-1137 at the AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nev., October 31–November 2, 1973; received September 24, 1973; revision received April 19, 1974. This paper is published with the permission of the Controller, Her Britannic Majesty's Stationery Office.
Index category: Electric and Advanced Space Propulsion.
* Senior Scientific Officer, Space Department.
† Principal Scientific Officer, Space Department.

Apparatus

Cathodes

As shown in Fig. 1, all cathodes tested were similar to those employed earlier,[3] with a bifilar heater encapsulated in sprayed alumina covering the downstream end of the tantalum body.[7] The latter was protected from chemical attack by the alumina at high temperatures by a thin coating of plasma-sprayed tungsten. Normally, the barium dispenser was the conventional rolled-foil type.[3] In the experiments using porous dispensers, this component was replaced by a porous tungsten cylinder of controlled density, with careful surface treatment and impregnated with barium calcium aluminate.

Test Facilities

All test facilities were constructed from commercially available vacuum equipment. In studies of diode discharges, the experimental assembly was mounted in one arm of a glass vacuum chamber, other arms being used to carry gages and probes. The keeper (Fig. 1) was a refractory metal or stainless steel plate mounted 1–2 mm from the cathode, while the anode was generally a stainless steel disk situated 1–5 cm from the cathode. To prevent mercury condensation, a heated spacer was often included between the vaporizer and cathode.

In one life test to be mentioned, the cathodes were built into a T2 ion thruster,[8] which was mounted in a stainless steel vacuum chamber incorporating a cylindrical shroud cooled by liquid nitrogen and giving an ultimate vacuum of 5×10^{-8} torr. The thruster included electrical isolators, and a flight-type modular

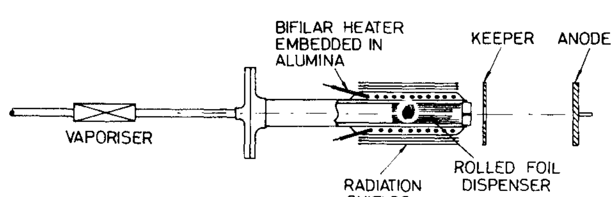

Fig. 1 Typical hollow cathode assembly.

power supply[9] was used to energize the ion beam. One cathode was used as a neutralizer, but its position was not optimized.

Mercury Feed Systems

Mercury vapor was in all cases supplied by a miniature vaporizer[10] using a porous tungsten plug as a liquid/vapor phase separator. The flow rate $\dot{m}$ was regulated by controlling the vaporizer temperature, using an accurate temperature controller.

Liquid mercury was introduced under vacuum into a glass feed system incorporating a large reservoir, precision bore capillary tubes for flow measurement, and appropriate valves. The volume of mercury between the capillary tubes and vaporizer was made as small as possible to minimize the thermometer effect caused by room temperature variations. A correction was made where necessary, particularly in the neutralizer work, where $\dot{m}$ was as low as 0.002 mg/sec. A further correction was made to account for the effect of the appreciable elasticity of demountable joints and curved tubing between the capillary tubing and vaporizer.

Cathode Tip Temperature

Throughout this work, all temperatures were monitored by thermocouples, with occasional checks on cathode tip temperature T using an optical pyrometer. The thermocouples employed for the latter measurement were fine platinum/platinum, 13% rhodium wires spot-welded to the edge of the tip and sheathed in thin-walled alumina tubes.

The validity of this method of temperature measurement was confirmed by an auxiliary experiment in which 3 thermocouples were attached to the tip in different ways. The results differed by only 20°C at 400°C and by 40°C at 1500°C.

Langmuir Probe Technique

Langmuir probes were employed to monitor plasma potential V_p, electron temperature T_e, and electron number density n_e. Although small, they caused finite perturbation of the plasma. This was avoided in some cases by using keeper voltage-current characteristics to determine T_e and V_p,[3,11] a permissible method provided that the anode current I_A was always much larger than the keeper current I_k, and the keeper was in contact with the main plasma stream from cathode to anode.

Probes were constructed from tungsten wire of 0.5 mm diameter or less, protruding 1–3 mm from the end of a thin-walled alumina tube. Under certain discharge conditions, probe contamination gave completely erroneous results. To avoid this, each probe was always cleaned by heavy electron or ion bombardment immediately prior to recording a characteristic.

In the plasmas investigated, the Debye length was much smaller than the probe diameter and typical mean free paths. Consequently, the thin, collisionless (free-fall) sheath approximation[12] was used in evaluating T_e and V_p. However, the probe was not, in general, much smaller than relevant mean free paths, so it perturbed the plasma, and values of n_e were thus appropriate to the sheath edge rather than to the undisturbed situation. Although it is possible to make a correction,[13] this was not done because values of n_e were not used in any critical way and there were indications that data derived from the ion saturation branches of the characteristics were reasonably accurate.

Barium Dispenser

In the past, investigations of hollow cathodes for use in mercury ion thrusters have almost exclusively been devoted to devices in which the low work function material has been contained as a deposit on a rolled tantalum foil within the cathode, or has simply been applied to the internal walls.[3,14,15] Rolled foil inserts have two major drawbacks. First, there is evidence that insufficient barium is available to maintain efficient operation throughout the desired life of a cathode and second, particles of loose material could be dislodged under vibration during launch and could cause blockage of the orifice or vaporizer. In an attempt to overcome these difficulties, a series of experiments was initiated in which the foil insert was replaced by a porous structure impregnated with a low work function material.

Dispenser Configuration

Each dispenser was a hollow cylinder of sintered tungsten having a known porosity and a length of 1 cm. It was found that a satisfactory method of impregnation was to prepare a mixture of $BaCO_3$, $CaCO_3$, and Al_2O_3 with molar concentrations in the ratio 5:3:2. This was placed, together with the insert, in a refractory metal boat. On raising the temperature to approximately 1800°C in vacuo or in a dry hydrogen atmosphere, the mixture fused and was drawn into the porous tungsten by capillary action.

In the cathodes discussed below, all having an orifice diameter d of 0.3 mm, a recess was provided in the downstream end of the dispenser to simulate the geometry of the conventional foil insert.[14] The outer cylindrical surface and the upstream end were swaged to minimize barium loss.

Activation and Discharge Initiation

Although laborious activation procedures are described in the literature[6,16] for dispenser cathodes, these were found to be unnecessary in the present case. It was sufficient to increase T slowly to about 1300°C and to hold it steady for about 1 hr. Discharge initiation could then be accomplished by passing a sufficient flow rate of mercury vapor through the cathode while applying a potential V_k to the keeper.

In order to compare dispenser cathodes with those using rolled foil inserts, a study of the initiation procedure was undertaken. The method was similar to that described previously,[2,3] V_k being slowly raised at constant $\dot{m}$ and T until breakdown occurred at a voltage V_{kb}. This process was repeated hundreds of times at different values of T and $\dot{m}$. The results were similar to those obtained earlier,[3] values of V_{kb} being randomly distributed within an envelope determined by T and $\dot{m}$. As either was increased, V_{kb} became smaller and more predictable. This is shown in Fig. 2 in which the lower and upper limits of V_{kb} are plotted as functions of T for four different values of $\dot{m}$. With $\dot{m}$ and T exceeding 0.25 mg/sec and 1350°C, V_{kb} was consistently below 25 v and the discharge could often be initiated at voltages as low as 15 v.

On closer examination, it was found that discharge initiation was not as unpredictable as at first thought. After the discharge had been off for several hours, V_{kb} was generally high at any given values of $\dot{m}$ and T. In contrast, it was considerably lower if V_k was reapplied shortly after the discharge had been switched

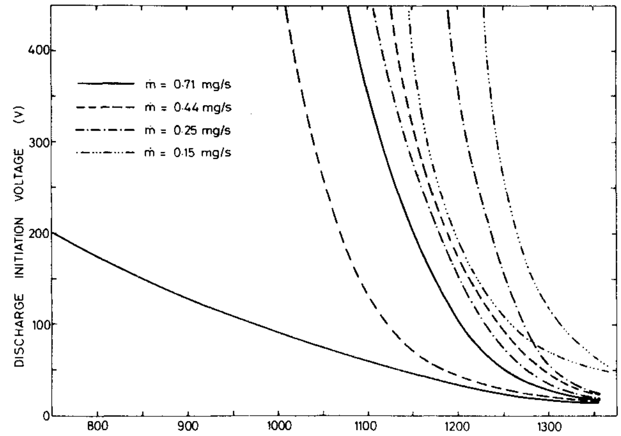

Fig. 2 Envelopes of discharge initiation data as functions of temperature for a porous dispenser cathode.

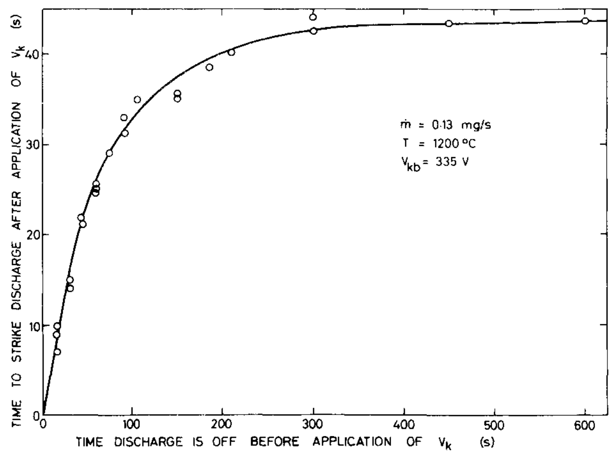

Fig. 3 Time dependence of discharge initiation.

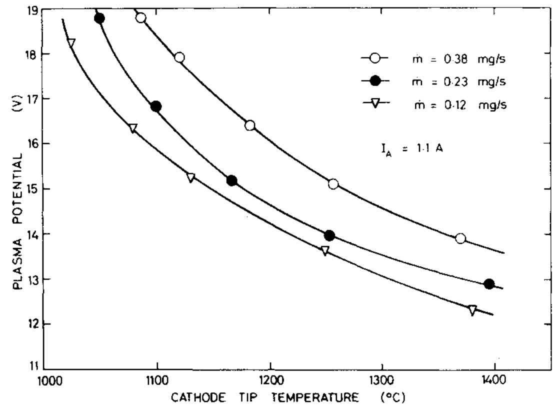

Fig. 4 Plasma potential as a function of temperature in a spot mode discharge.

off. The time taken for the discharge to strike after application of V_k was also dependent upon the recent history of the cathode, a typical result being shown in Fig. 3. In these experiments, the values of T and $\dot{m}$ were held constant, the discharge was extinguished and a known time was allowed to elapse before a fixed value of V_k was applied. At this stage, a very faint glow emerged from the cathode orifice; this was accompanied by a prebreakdown current of several microamperes. The luminosity gradually increased, as did the current, until a discontinuous rise to several hundred milliamperes indicated discharge ignition. The maximum prebreakdown current was approximately constant at given values of $\dot{m}$ and T.

The relatively long times involved in these phenomena suggest that chemical changes or the surface migration of barium are responsible. If the initiation mechanism discussed earlier[3] is applicable, adequate thermionic emission is essential from areas close to the cathode orifice, implying that sufficient barium must be available there. Once the discharge is switched off, it would appear that barium is gradually lost from the emitting zone, so that, after reapplication of V_k, a finite time is required for replenishment. The situation is undoubtedly extremely complex, and no attempt has been made to ascertain the nature of the chemical and surface processes taking place. It would be reasonable to assume, however, that the geometry and position of the dispenser have by no means been optimized.

Cathode Performance

The keeper discharge was easily transferred to the anode and the cathodes behaved almost identically to previous models.[1] The heater power P_H could be reduced to zero, while maintaining stable operation, and both spot and plume modes were obtained under similar conditions to those found before. In addition to using the keeper characteristics to determine T_e and V_p,[3] these parameters were also obtained from a Langmuir probe placed closed to the keeper. A Maxwellian electron velocity distribution was indicated, and T_e was found to increase with increase in I_A and decrease in $\dot{m}$, and was largely independent of T within the range investigated. For example, at $I_A = 1.10$ amp and $1000°C < T < 1400°C$, T_e was 0.52, 0.35, and 0.19 ev at $\dot{m} = 0.12$, 0.23, and 0.38 mg/sec respectively. These values were slightly lower than those found using a rolled foil dispenser under similar conditions.

Values of V_p were somewhat higher than those found with earlier cathodes having slightly different orifice diameters. V_p could be reduced by decreasing $\dot{m}$ or increasing T (Fig. 4), although the latter would probably be unacceptable because of the increase in P_H required and the enhanced rate of barium depletion.

So far these cathodes have not been subjected to long-term durability tests. However, no degradation in performance has been observed throughout periods of hundreds of hours, including several exposures to atmosphere. This type of cathode is mechanically strong and suffers from few disadvantages. One is the higher value of V_p, but this can probably be reduced by more careful positioning of the dispenser and possibly by increasing d.

Neutralizer Application

Hollow cathode plasma-bridge neutralizers are suitable for the neutralization of the ion beams produced by most types of ion thruster. They require comparatively little power, and potential lifetime is high. Although several investigations have been reported of cathodes intended for this application[17,18] and flight experience has been encouraging,[19] there is little information available relevant to small thrusters. These produce relatively low beam currents and their neutralizers must operate at extremely small flow rates, if erosion of the accelerator grid by charge-exchange and slow ions is to be minimal. For the T4 thruster,[5] the beam current is below 200 ma and the total flow rate is 0.4 mg/sec. The aim is to operate its neutralizer at well below 0.02 mg/sec, whereas most reported data apply to higher flows. Consequently, this region of low flow and current has been extensively studied, using cathodes with both conventional and porous dispensers.

Studies with Rolled Foil Dispenser

In one series of experiments,[20] conventional cathodes having $d = 0.15$–0.7 mm were studied, with I_A below 500 ma and $\dot{m}$ down to 0.002 mg/sec (1 ma equivalent). A disk-shaped anode 40 mm from the cathode was used. The discharge was unlike either the spot or plume modes.[1,2] It was fairly luminous, but extremely stable, and noise levels were low. In addition, the keeper discharge exerted a controlling influence, whereas T seemed relatively unimportant in determining the form of the $V_A - I_A$ characteristics, where V_A is the anode voltage.

At any particular value of $\dot{m}$ and low I_k, the characteristics were steep, with a tendency for I_A to saturate. As I_k was increased, the slopes decreased, so that at any value of I_A, V_A fell rapidly with increase of I_k. The variation of V_k with I_A or I_k was small, and T was barely influenced by I_A, rising typically from 1000–1050°C as I_A increased from 0–400 ma. Variation of T_o, the value of T at $I_A = 0$, caused only very small changes in the $V_A - I_A$ characteristics, contrary to previous experience at larger flows.[2] Surprisingly, all the cathodes tested remained in stable operation with only minor changes in other parameters as P_H was reduced to zero and T_o fell to as low as 300°–400°C. The effect on V_k was also slight.

As shown in Fig. 5, an increase in d caused voltages to fall rapidly and instabilities to occur at higher currents. A decrease in $\dot{m}$ caused the characteristics to slope more steeply and all voltages to be increased.

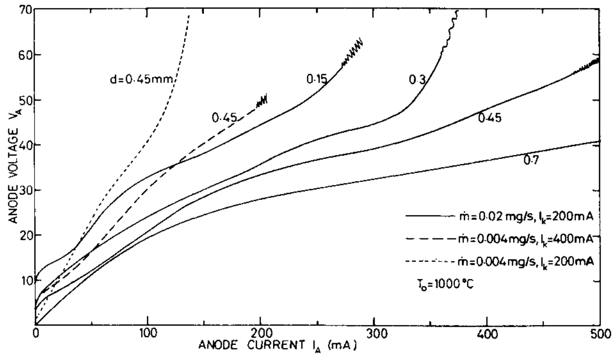

Fig. 5 Neutralizer characteristics for rolled-foil dispenser cathodes of several orifice diameters.

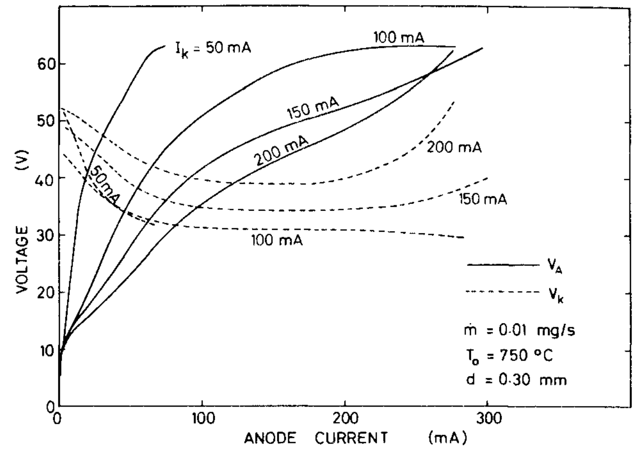

Fig. 7 Neutralizer characteristics for a porous dispenser cathode at several keeper currents.

It is difficult to explain these new data on the basis of any form of thermionic emission. It thus seems necessary to invoke either secondary emission by the impact of metastable atoms,[3] or an entirely new mechanism. The former is adequate, at least qualitatively. It appears that the primary discharge is to the keeper, current reaching the anode only by diffusion in the applied electric field.

Porous Dispenser Neutralizers

Two cathodes, both with $d = 300$ μm and having porous tungsten impregnated dispensers, were operated under neutralizer conditions. With some exceptions, the results were similar to those obtained with the conventional cathodes.

In Fig. 6, both V_A and V_k are shown as functions of I_A for several values of T_o. A reduction in T_o caused the voltages to increase, but the saturation value of I_A, about 300 ma, was hardly affected. Agreement with previous data[20] is illustrated by the results for various values of I_k shown in Fig. 7, where $T_o = 750$°C. At this flow rate only values of I_k below 100 ma had a marked effect on the saturation of I_A, but both V_k and V_A were strongly dependent on I_k throughout the entire range studied. At lower values of $\dot{m}$, saturation occurred at smaller anode currents, a result also found with rolled-foil inserts.

In contrast to the earlier findings, it was almost impossible to guarantee stable operation with $P_H = 0$, unless I_k was 200 ma or greater. Even then, T_o never fell below 750°C and V_k remained very high (Fig. 8). Attempts were made to reproduce the low temperature operation of the rolled-foil dispenser by operating at many different values of $\dot{m}$ and I_k, but T_o could not be reduced below 750°C. This was the only major difference between the two types of cathode; however, as pointed out earlier, the position and geometry of the dispenser were in no way optimized, and studies of these factors and of larger orifices are in progress.

Cathode Testing

Of a number of thruster components likely to fail prematurely, one of the most critical is the hollow cathode, which has therefore been subjected to a program of life testing. In addition to preventing failures due to unsuitable materials or manufacturing techniques, this has yielded information concerning long-term degradation of performance, which considerably influences the design of total thruster systems.

Many cathodes have been tested for over 1000 hr, with several exceeding 3000 hr, and a current maximum of over 5000 hr. Most of this work has been done using diode discharge systems, but considerable experience has also been gained from a T2 thruster.[8,11] The most serious degradation consists of a slow rise in V_p, accompanied by increasing tip temperature. This confirmed results reported elsewhere,[21,22] and was probably due to a reduced rate of production of barium within the dispenser, following earlier losses. To utilize the less accessible barium, a higher temperature is required, necessitating more ion bombardment heating and thus increased V_p. This explanation is consistent with the emission theory proposed earlier.[1,3]

As might be expected, V_p was found to be influenced by many

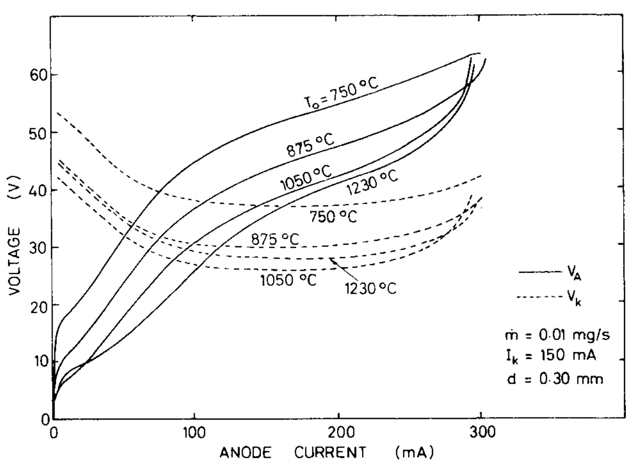

Fig. 6 Neutralizer characteristics for a porous dispenser cathode at several initial tip temperatures.

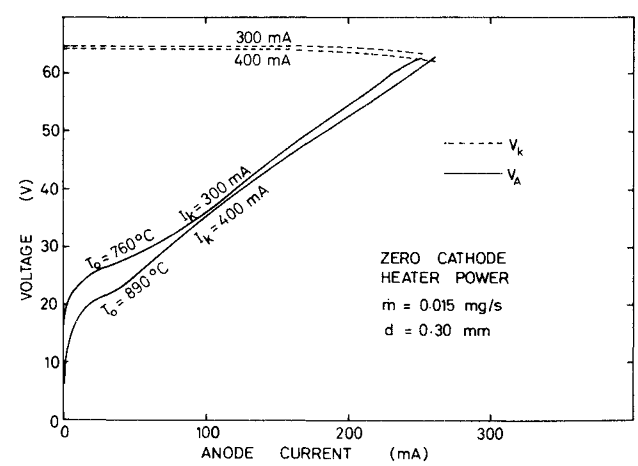

Fig. 8 Neutralizer characteristics for a porous dispenser cathode at zero heater power.

parameters, such as $\dot{m}$, I_A, P_H, and I_k. These also affected the onset of instabilities, which was typified by a reluctance to remain in the spot mode. After extensive studies, it was concluded that the thruster control system should accommodate increases in V_p, but that alterations to $\dot{m}$ and I_k could be employed to maintain stability. This would minimize the additional power required.

The possibility that orifice erosion would cause premature failure has been eliminated by reductions in I_A and by the use of larger orifices.[7] The problem of behavior under thermal cycling has been examined by testing for many more cycles than would be required operationally,[5] heaters having been subjected to 15,000 cycles, tip welds to 8000 and a complete cathode assembly to 7000, all without damage.

Life Tests at High Discharge Current

These tests were conducted at the higher discharge currents appropriate to the earlier, less efficient T2 thruster.[8] One cathode was operated in a T2 thruster, while the other was run in a diode system. In both cases, d was 0.35 mm, I_A was 2 amp, and $\dot{m}$ was about 0.1 mg/sec. Total flow rate to the thruster was 0.4 to 0.6 mg/sec. The only differences between the operating conditions concerned I_k and P_H; in the thruster I_k was typically 60–70 ma and P_H was zero, while in the diode system I_k was 100 ma and P_H was adjusted during the test.

A feature of the diode test was the rapid initial degradation of performance, the keeper voltage V_k and T rising during the first 400 hr from 8 to 13 v and from 1100° to 1170°C. Plasma parameters were monitored by analysis of $V_k - I_k$ characteristics, and these showed a corresponding rapid rise of T_e and of V_p, the latter being about 2 v higher than V_k. At 400 hr, an increase of P_H from 10–15 w caused T to rise by 130°C. Both V_k and V_p fell slightly, as expected if more barium was released by the increased temperature. T_e also fell from 1.4 ev to about 1.1 ev, at which level it remained for the next 1500 hr.

Further degradation occurred slowly at first, then accelerated as T reached about 1300°C and, it is assumed, the barium became exhausted. Confirmation for the latter view was obtained by increasing P_H to 25 w. This produced only small reductions in V_p and V_k, and both parameters continued their increasingly rapid upward trend. At 2200 hr, V_p had reached 22 v and V_k was 20 v. T_e also increased rapidly beyond 1900 hr, implying that sheath voltages within the cathode were larger, probably because higher electric fields were necessary to extract the desired current.

The test ended at 2700 hr as a result of a tip weld failure, caused by chemical reactions with residual gases in the vacuum system. Very little barium remained in the dispenser. There was virtually no orifice erosion, in contrast to tests with smaller orifices.[7,17]

This test led to the conclusions that the temperatures involved were excessive and caused rapid barium depletion and short life, that the use of heater power to reduce V_p and V_k is very inefficient, that a large orifice diameter suffers low erosion, and that a good vacuum system is essential for long-duration testing. These were confirmed in the 1700 hr thruster test, which also included 177 starts. At the voluntary termination of this, orifice erosion was small, and the tip weld area was free from chemical attack, confirming that this mainly results from a poor vacuum. The expected rise in V_k occurred at a much slower rate than in the diode study, the initial increase to 12 v taking 1000 hr rather than only 100 hr. This was attributed to the much lower value of T, caused by P_H being zero.

4600 Hour Diode Test

The initial aim of this study was to examine the degradation of a cathode containing a known quantity of barium in a definite location. The insert was therefore constructed from a tantalum tube, and barium carbonate was coated into a recess cut in its inner wall. Initial operating conditions were $P_H = 0$, $I_A = 1.5$ amp, $I_k = 300$ ma, and $\dot{m} = 0.13 \pm 0.01$ mg/sec. Plasma parameters were monitored using a Langmuir probe. In general, V_p was 2–3 v above V_k, as found before, but the correlation was not so good as previously, possibly owing to the larger keeper orifice in this case.

Larger values of V_p and V_k were required than before, possibly due to a higher electric field being necessary to extract electrons through the 0.2 mm orifice.[3] For the first 200 hr, $V_k \sim 14.5$ v, $T_e \sim 0.7$ ev, and $V_p \sim 17$ v, while T dropped from 1260°C to 1100°C. A period of nonsteady operation followed, with V_k and T rising occasionally to 17 v and 1300°C and unpredictable transitions to the plume mode.[1] Attempts were made to retain stable operation by increasing I_A, and thus T, in several steps, but each had only a temporary effect. The alternative of accepting plume mode operation was successful, in that a steady discharge resulted at $I_A = 1.0$ amp, $V_k \sim 20$ v, and $T \sim 1000$°C. However, increasing I_k to 400 ma caused a transition to a stable spot mode discharge, with $V_k \sim 15$ v, $T \sim 910$°C, $V_p \sim 17$–18 v, $T_e \sim 1.4$–1.6 ev, and n_e about a factor 5 lower than before.

For the next 2000 hr, slow degradation was observed, V_k and T reaching 17 v and 1000°C at 2500 hr, with periods of instability. The latter were suppressed by slight increases in $\dot{m}$ or I_k, these parameters reaching 0.16 mg/sec and 500 ma at 4600 hr. During this period, T rose slowly to about 1050°C, while V_k varied erratically between 16 and 18 v, with a final rise to over 20 v. For the last 2000 hr, V_p was 19–20 v and T_e decreased to 1.1 ev.

At 4600 hr the tip weld was less attacked than in the 2700 hr test, but orifice erosion was greater. The former was probably due to the lower values of T, while the latter was to be expected from the smaller orifice.[7] Thus, although this cathode was not a flight version, it demonstrated adequate durability for many envisaged missions[23] and showed that operation with $P_H = 0$ is possible for very long periods if small variations of I_k and $\dot{m}$ can be used to maintain stability.

Test of Large Orifice Cathode

On theoretical grounds,[3] it is desirable to maintain a certain concentration of free barium atoms and ions within a cathode to obtain the required electron emission, without using excessively high voltages, flow rates, or temperatures. However, cathode temperatures are often too high, causing barium to be produced and lost more rapidly than necessary. The cathode then degrades relatively quickly. It is likely that high rates of dispensation are of benefit only during starting,[3] when T can be increased briefly.

Studies of discharge characteristics[1,3,7] have revealed that d has a considerable influence on T, confirming data obtained elsewhere.[22] This may be explained qualitatively by reference to the strong electric field set up in the orifice to extract the emission current from the interior of the cathode.[3] The required voltage is inversely proportional to the cross-sectional area of the orifice, so an increase in d reduces the voltage, and V_p in the external plasma falls, thus diminishing both the ion bombardment heating and the sputtering damage. A life test was started to determine whether these potential benefits could be realized over long periods of time.

The cathode was operated in a standard diode facility, with a Langmuir probe 4 mm from the keeper used to monitor plasma parameters. Conditions were $I_A = 1.0$ amp, $I_k = 400$ ma, $\dot{m} = 0.15 \pm 0.01$ mg/sec, and $P_H = 0$.

Data obtained during the first 3100 hr of the test, which is continuing, are shown in Fig. 9. As predicted, the most notable difference between this and previous tests was the very low tip temperature, T being below 700°C for almost the whole 3100 hr. V_p was also low, being always under 12 v, and under 11 v for the first 900 hr. One unexpected result was the lack of close correlation between V_p and V_k; this may have been due to the relatively large keeper orifice employed, which may have caused the keeper to be out of contact with the plasma plume emerging from the cathode tip.

Throughout the test T_e was slightly less than 1 ev, with a tendency to increase with V_p. Slight changes in $\dot{m}$ appeared to influence n_e, with a normal value of about 5–6×10^{17} m^{-3}. Noise on the various electrodes increased with V_p and T_e, with below 10 mv peak-to-peak on the anode. The amplitude of the keeper

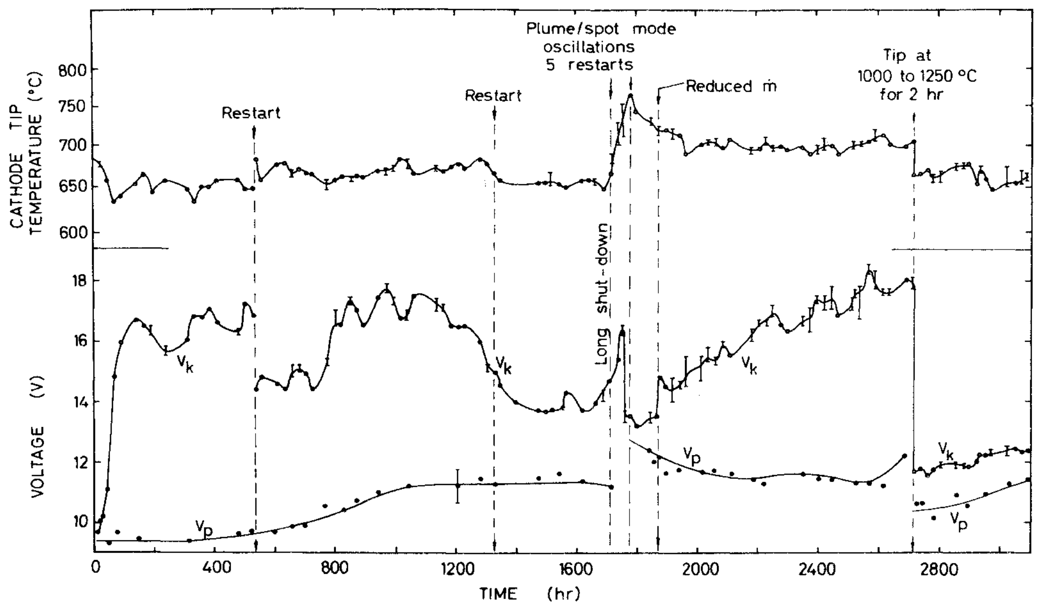

Fig. 9 Variation of V_p, V_k, and T during a life test of a large orifice cathode.

noise was generally 2–4 times greater, while the probe exhibited less than 1 mv.

From the data in Fig. 9, degradation did not commence until a restart was necessary at 540 hr. This was followed by a rise in V_p of 2 v, occupying 1400 hr, with a mean increase in T of only about 15°C. At 1720 hr, after an extended shutdown, there was difficulty in establishing a stable spot mode discharge, although T remained low. Stability was finally attained at 1780 hr, but $\dot{m}$ was then rather higher than desirable. A reduction to 0.15 mg/sec was made at 1870 hr. Although further degradation was not apparent, at 2710 hr an attempt was made to improve the performance by raising T to 1000–1250°C for about 2 hr, with the aim of dispensing additional barium. Although this did not affect T_e or n_e, it greatly reduced discharge noise, and V_p fell by about 1 v. T was also reduced by about 40°C. The most dramatic result was to lower V_k by 6 v, although this was of unknown significance.

Conclusions

It has been shown that the cathodes under study have adequate performance and durability for envisaged European electric propulsion missions.[23] The use of a porous tungsten dispenser enhances resistance to vibration, while maintaining efficient operation. Starting characteristics are similar to those of conventional cathodes and lifetime capabilities may also be improved.

Studies of operation at the low flow rates and currents appropriate to neutralizers have shown the existence of a new discharge mode dominated by the keeper current. Provided that the latter is relatively high, operation with $\dot{m}$ as low as 0.004 mg/sec (2 ma equivalent) is feasible. The use of a large orifice gives further improvement. With the conventional insert, there is only a very small dependence on T and operation at 300°–400°C is possible, with $P_H = 0$ and considerably enhanced lifetime. Cathodes with porous dispensers also operate successfully at low $\dot{m}$. Unfortunately, they exhibit a greater dependence on T, so continual use of some heater power may be necessary to run at 700–800°C. However, the use of a larger d or different geometry may allow this requirement to be relaxed.

Life testing to 4600 hr has indicated the need to use properly designed vacuum facilities. If these are available, the necessary lifetime can be achieved, especially with large orifice diameters. Cathodes with the latter feature operate at low temperatures, with reduced V_p, and thus suffer less orifice erosion and a slower rate of degradation. The latter appears as a gradual rise in V_p and can be explained by depletion of the available barium. It has also been established that instabilities can be suppressed by slight increases in I_k or $\dot{m}$.

References

[1] Philip, C. M., "A Study of Hollow Cathode Discharge Characteristics," *AIAA Journal*, Vol. 9, No. 11, Nov. 1971, pp. 2191–2196.

[2] Fearn, D. G., Philip, C. M., and Pye, J. W., "The Development of Hollow Cathodes, Vaporisers, and Isolators for use in Mercury Ion Thrusters," Paper 71-044, 1971, Proceedings of the DGLR-Symposium Elektrische Antriebssysteme, Braunschweig, Germany.

[3] Fearn, D. G. and Philip, C. M., "An Investigation of Physical Processes in a Hollow Cathode Discharge," *AIAA Journal*, Vol. 11, No. 2, Feb. 1973, pp. 131–132.

[4] Philip, C. M., Hastings, R., and Watson, H. H. H., "The Design Concept of the T4 Ion Thruster," *Proceedings of the Conference on Electric Propulsion of Space Vehicles*, IEE Publication 100, 1973, Culham Lab., UK, pp. 31–35.

[5] Fearn, D. G., Hastings, R., Philip, C. M., Harbour, P. J., and Watson, H. H. H., "The RAE/Culham T4 10 cm Electron-Bombardment Mercury Ion Thruster," AIAA Paper 73-1130, Lake Tahoe, Nev., 1973.

[6] Beck, A. H. W., "High Current Density Thermionic Emitters—A Survey," *Proceedings of the IEE (Great Britain)*, Vol. 106B, July 1959, pp. 372–390.

[7] Charlton, M. G., Davis, G. L., and Newson, D., "Investigations on Hollow Cathodes for Ion Thrusters," *Proceedings of the Conference on Electric Propulsion of Space Vehicles*, IEE Publication 100, 1973, Culham Lab., UK, pp. 141–145.

[8] Day, B. P. and Hastings, R., "The RAE 10 cm Hollow Cathode Mercury Thruster," Paper 71-028, 1971, Proceedings of the DGLR-Symposium Elektrische Antriebssysteme, Braunschweig, Germany.

[9] Burton, G. E., "A New dc to dc Converter Design Philosophy," TR 68279, 1968, Royal Aircraft Establishment, Farnborough, UK.

[10] Pye, J. W., "Component Development for a 10 cm Mercury Ion Thruster," *Journal of Spacecraft and Rockets*, Vol. 10, No. 2, Feb. 1973, pp. 106–112.

[11] Fearn, D. G. and Williams, T. N., "The Behavior of Hollow Cathodes during Long-Term Testing in a 10 cm Ion Thruster and in a Diode Discharge System," *Proceedings of the Conference on Electric Propulsion of Space Vehicles*, IEE Publication 100, 1973, Culham Lab., UK, pp. 131–135.

[12] Bohm, D., Burhop, E. H. S., and Massey, H. S. W., "The Use of Probes for Plasma Exploration in Strong Magnetic Fields," *Characteristics of Electrical Discharges in Magnetic Fields*, edited by A. Guthrie and R. K. Wakerling, McGraw-Hill, New York, 1949, p. 48.

[13] Waymouth, J. F., "Perturbation of a Plasma by a Probe," *The Physics of Fluids*, Vol. 7, No. 11, Nov. 1964, pp. 1843–1854.

[14] Csiky, G. A., "Measurements of Some Properties of a Discharge from a Hollow Cathode," TN D-4966, Feb. 1969, NASA.

[15] Goldstein, R., Pawlik, E. V., and Wen, L.-C., "Preliminary Investigations of Ion Thruster Cathodes," TR32-1536, Aug. 1971, Jet Propulsion Lab., Pasadena, Calif.

[16] Sandor, A., "Activation Process of Impregnated Dispenser Cathode Viewed in the Large-Screen Emission Microscope," *Journal of Electronics and Control*, Vol. 13, Nov. 1962, pp. 401–416.
[17] Rawlin, V. K., "A 13000-Hour Test of a Mercury Hollow Cathode," TM X-2785, June 1973, NASA.
[18] Fitzgerald, D. J., "Parametric Study of Mercury Hollow Cathode Neutralizers," AIAA Paper 72-422, Bethesda, Md., 1972.
[19] Kerslake, W. R., Goldman, R. G., and Nieberding, W. C., "SERT II: Mission, Thruster Performance, and In-Flight Thrust Measurements," *Journal of Spacecraft and Rockets*, Vol. 8, No. 3, March 1971, pp. 213–224.
[20] Fearn, D. G., "The Operation of Hollow Cathodes under Conditions Suitable for Ion Beam Neutralization," *Proceedings of the Conference on Electric Propulsion of Space Vehicles*, IEE Publication 100, 1973, Culham Lab., UK, pp. 146–150.
[21] Lathem, W. C., "1000-Hour Test of a Dual Grid, Electrostatic Beam Deflection Accelerator System on a 5-cm Diameter Kaufman Thruster," TM X-67907, Aug. 1971, NASA.
[22] Goldstein, R. and Pawlik, E. V., "Cathode Effects on Thrust Subsystem Performance Predictability," AIAA Paper 72-420, Bethesda, Md., 1972.
[23] Pearson, J. J., "Results of the Definition Study for the Application of Electric Propulsion to the Station-Keeping of European Communication Satellites," *Proceedings of the Conference on Electric Propulsion of Space Vehicles*, IEE Publication 100, 1973, Culham Lab., UK, pp. 187–191.

OCTOBER 1974 AIAA JOURNAL VOL. 12, NO. 10

Manufacture and Deflagration of an Atomic Hydrogen Propellant

GERALD ROSEN*
Drexel University, Philadelphia, Pa.

It is observed that the use of very low temperatures (in the range 0.1°K to 1.5°K) produced by advanced cryogenic apparatus and the use of very strong magnetic fields (in the range 50 kG to 100 kG) produced by superconducting magnets can yield a significant improvement in the atomic hydrogen trapping effectiveness of an H_2 matrix. The use of a radioactive β-ray emitter isotope may yield H-H_2 propellants (with $I_{sp} \simeq 740$ sec) by secondary electron impact dissociations of H_2 in an impregnated matrix maintained below 1°K in a strong magnetic field. Another method for manufacturing an H-H_2 propellant involves bombardment of supercooled solid H_2 with a cyclotron-produced beam of 10 Mev hydrogen atoms. The matrix-isolated atomic hydrogen must be used directly without prior melting as a solid propellant, and an analysis of the steady deflagration is presented.

I. Introduction

CONSIDERABLE interest has been attached to the research and development of an atomic hydrogen fuel for use as a rocket propellant, because markedly superior performance is predicted theoretically for such a propellant. It is well-known that the maximum for specific impulse with the best conventional chemical propellants is in the neighborhood of 500 sec. On the other hand, values for the theoretical specific impulse in the neighborhood and above 750 sec are predicted if it is possible to employ an atomic hydrogen propellant which contains at least 15% free H atoms by weight. Such a 50% increase in specific impulse would engender a dramatic concomitant increase in payload and a decrease in the number of stages in space vehicles.[5,35]

Free hydrogen atoms are known to be produced by a large variety of physical and chemical molecular dissociation reactions. Except under rather special conditions, however, atomic hydrogen cannot be produced in high concentrations and/or in large amounts, as required for propellant manufacture. Moreover, for the storage of free H atoms only one effective method is known, the so-called *matrix-isolation* technique in which the reactive species are trapped as isolated entities in an inert solid at a cryogenic temperature. Atomic hydrogen produced in a gas or liquid must be rapidly condensed and trapped by being frozen into normal or interstitial sites in an inert cryogenic lattice, while immediate storage of the species may be afforded by so-called in situ production methods which involve dissociation processes that take place exclusively within a preformed matrix.

A review of current experimental work related to the manufacture of an atomic hydrogen propellant is presented in Sec. II, where the two main technical aids now being employed to achieve higher concentrations of free H atoms with matrix-isolation, the use of very low temperatures and very strong magnetic fields, are described. It is shown that important progress toward the development of an atomic hydrogen propellant appears imminent with conventional methods of production and storage being augmented by these new technical aids. In Secs. III and IV it is observed that the manufacture of an H-H_2 propellant, 15% atomic hydrogen by weight, appears feasible by ultra-energetic hydrogen atom bombardment of solid H_2 or by impregnation of solid H_2 with radioactive phosphorus. The theoretical estimates given in Sec. V show that matrix-isolated atomic hydrogen must be used directly without prior melting as a solid propellant. Finally, the steady deflagration of an H-H_2 solid propellant, 15% atomic hydrogen by weight, is analyzed in Sec. VI.

Received August 21, 1973; revision received April 4, 1974. This work was supported by NASA through Contract 953623 with the Jet Propulsion Laboratory.
Index categories: Electric and Advanced Space Propulsion; Fuels and Propellants, Properties of.
* M. R. Wehr Professor of Physics.

II. Current Experimental Work and New Proposals

To achieve the high concentrations of atomic hydrogen required for useful propellants, it appears necessary to augment the conventional matrix-isolation method[11–14,17–25,27–29,33,34]