A 30-cm, Low-Specific-Impulse, Hollow-Cathode, Mercury Thruster

H. J. King,* R. L. Poeschel,† and J. W. Ward†
Hughes Research Laboratories, Malibu, Calif.

A 30-cm-diam, mercury electron-bombardment thruster has been designed with emphasis on low-specific-impulse operation. Scaling laws previously derived were applied to a SERT II design. As a result, the radius was doubled, the magnetic field halved, and the length unchanged. The complete thruster weighs less than 10 lb. The results of initial experiments have been used to improve the discharge chamber to the point where it now approaches SERT II performance. This basic discharge chamber has served as a test vehicle for three ion optical systems: 1) a conventional two-grid system with 0.406-cm apertures and 0.175-cm spacing; 2) a two-grid system with 0.25-cm apertures and 0.125-cm spacing; and 3) a single electrode with 0.175-cm apertures, coated on one side with a 0.050-cm layer of insulating material. The relative perveances of the three arrays are 1, 2, and 8.

Introduction

CURRENT solar electric mission studies[1] indicate that a thruster nominally of 2.5-kw size operating at a specific impulse of 2500–3000 sec would be generally useful as a modular unit in many systems. A 30-cm-diam mercury thruster with a beam voltage of 1000 v operates in this power range. Assuming that the basis for this design is the SERT II thruster which has recently undergone extensive development at NASA Lewis Research Center[2] in preparation for a space test in 1970, two design changes are required: 1) extrapolate the discharge chamber design from 15- to 30-cm diameter without loss of efficiency, and 2) redesign the ion optical system to operate at 1000-v rather than 3000-v beam potential. These two tasks have been pursued independently, and the results of each have been integrated into the final thruster design after a series of tests optimized the magnetic field shape and baffle geometry for the complete thruster system.

Thruster Design

Scaling Laws

A relatively comprehensive understanding of discharge-chamber operation for oxide-cathode thrusters has been developed under a NASA supported study[3] and reported in a companion paper.[4] The basic scaling laws derived therefrom have been applied to the design of a larger thruster which will operate at high efficiency. To preserve the performance characteristics of the 15-cm-diam unit which served as the basis for the scaling study, the following criteria were applied: 1) the electron energy (discharge voltage) must not increase with thruster size; 2) the extracted ion current density (plasma density) should remain constant to permit the use of existing ion optical designs; and 3) both the propellant utilization (hence, the rate at which neutrals are ionized as they traverse the discharge chamber) and the energy losses in the discharge per extracted ion (ev/ion) should be independent of thruster size.

Since the extracted ion current increases with the square of the thruster diameter, and the current density and discharge voltage must both remain constant, the discharge current must also vary as the square of the thruster diameter. The resultant scaled thruster is predicted to have these properties if both the discharge plasma length (discharge chamber length) and the product of the magnetic field strength and discharge chamber diameter are held constant. In addition, the features of the SERT II design which are considered essential to good performance can be summarized in the following design guidelines:

1) The magnetic field must be so shaped that "critical field lines" which originate close to the location on the cathode housing where electrons are injected into the discharge must extend to near the outer edge of the screen electrode.

2) The anode must be so located that it remains at least one electron cyclotron diameter from the critical field lines.

3) The average plasma length, which is independent of thruster diameter, should be about 7–10 cm.

4) The opening between the hollow cathode housing and the baffle must be so restrictive that discharge potentials on the order of 35–40 v are required to draw the required electron currents from the hollow cathode.

5) The ion optical system must possess a high transmission (on the order of 70%).

The coupling between the hollow cathode and the discharge plasma is known to depend critically on the cathode magnetic pole piece and baffle configuration. Unfortunately, the details of this coupling and its consequent effect on discharge performance were not understood sufficiently to permit a guideline for scaling the cathode pole-baffle structure; therefore, they had to be determined empirically, as described below.

The thruster designed in accordance with the aforementioned criteria is shown in Fig. 1. The construction techniques were intended to provide maximum flexibility for interchanging component parts to facilitate optimization. The thruster, which weighs 10 lb, is formed primarily from 0.008-in. stainless steel with 0.040-in. soft iron magnetic poles.

Magnetic Field

The shape and intensity of the magnetic field in the discharge chamber control the efficiency and stability of the thruster, as well as the radial plasma density and hence the ion beam profile. Figure 2 shows the intensity of the axial magnetic field at various locations in the discharge chamber of the SERT II thruster, as well as the shape of the magnetic field lines determined by an iron filing magnetic field

Presented as Paper 69-300 at the AIAA 7th Electric Propulsion Conference, Williamsburg, Va., March 3–5, 1969; submitted March 24, 1969; revision received December 3, 1969.

* Head, Propulsion Technology Section.
† Member of the Technical Staff.

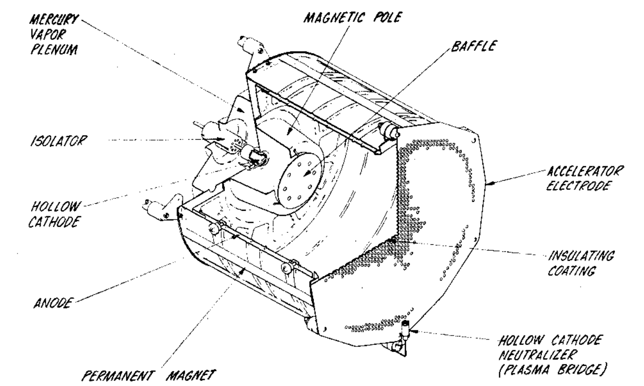


Fig. 1 The 30-cm hollow cathode thruster.

map. Note in particular the "critical field line" which leaves the tip of the anode near the screen electrode and crosses the discharge chamber to the cathode pole tip at a point very near the point where the electrons emerge between the pole tip and the baffle. Once electrons reach this critical field line, they are collected by the anode on their next traversal of the discharge chamber. As the distance between the point at which the electrons enter the discharge chamber and the critical field line and the strength of the magnetic field in this region increase, the discharge chamber impedance increases. Excessively high impedance forces the discharge voltage above the desired value or causes unstable discharge chamber performance.

Field line A of Fig. 3 shows the critical field line obtained by simply increasing the radius of a SERT II thruster as suggested by the scaling relationships. Note that it does not follow the desired path between screen and cathode pole pieces. Thus, the scaling requirements of a fixed discharge voltage, a magnetic field strength which varies inversely as the radius, and a discharge current which increases as the square of the radius cannot be achieved simultaneously with this configuration. The screen pole piece and collar, the

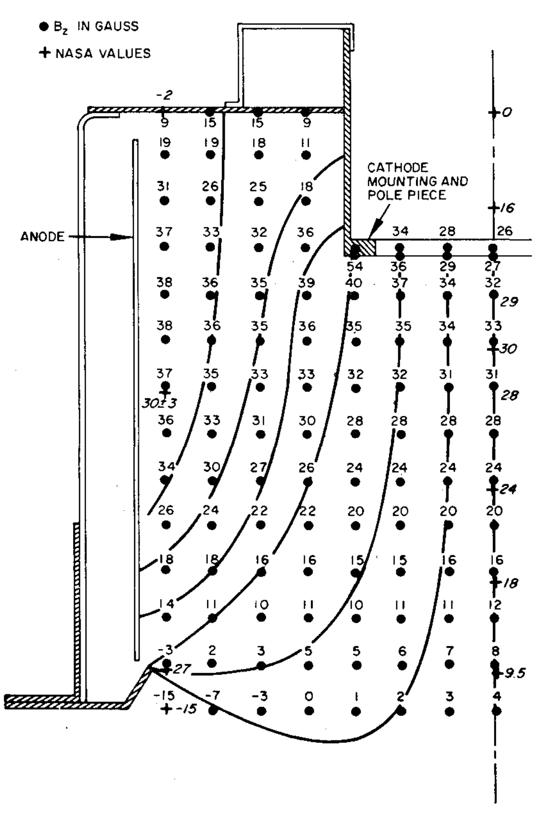
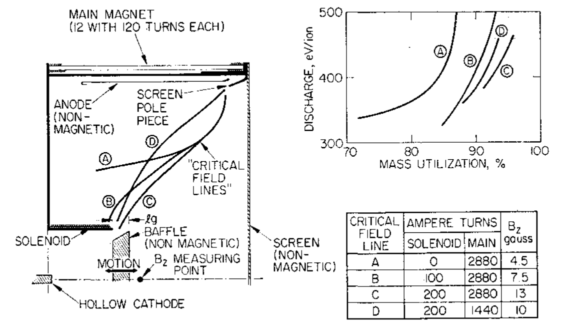


Fig. 2 Magnetic field of SERT II thruster.



CRITICAL FIELD LINE	AMPERE TURNS SOLENOID	AMPERE TURNS MAIN	B_z gauss
A	0	2880	4.5
B	100	2880	7.5
C	200	2880	13
D	200	1440	10

Fig. 3 Critical magnetic field lines and strengths (tabulated) and their effects on discharge chamber performance.

cathode pole piece, and the baffle were all modified in both size and shape in order to improve the performance. After this series of experiments, typical performance was mass utilization of 75 to 80% at 350 ev/ion. Stable operation could not be maintained at magnetic fields greater than one quarter the scaled SERT II value.

At this point it was decided that a basic change in the magnetic circuit was required, and a solenoid was wrapped around the cathode pole piece. Proper choice of the polarity of this solenoid with respect to the main discharge chamber field makes it possible to adjust the divergence of the magnetic field lines over a wide range. This is best shown in Fig. 3, where the shape of the critical field line is shown for several different current ratios in the main and solenoidal fields. Note in particular that the position of the critical field line may be moved from a position 5 cm outside the cathode pole piece to a point inside the pole, and that it may be pulled away from the screen electrode. The shape of the field lines does not change as the field intensity is varied, provided the ratio of the solenoid to main magnet currents is unchanged (because all parts of the magnetic circuit are designed not to saturate). With this additional variable it is now possible to optimize the thruster performance during operation by choosing the magnetic field shape as well as the intensity which gives the best performance.‡ One such set of data is presented in Fig. 3, which shows the thruster performance for different magnetic field shapes.

Discharge Voltage

For an acceptable thruster design the discharge voltage must lie within a relatively narrow range. If it is too low the ionization efficiency suffers; if it is too high the cathode lifetime may be too short. Figure 4 shows a conceptual thruster model and illustrates where voltage drops occur in the discharge chamber. There is a cathode sheath of approximately 10 v between the plasma immediately in front of the

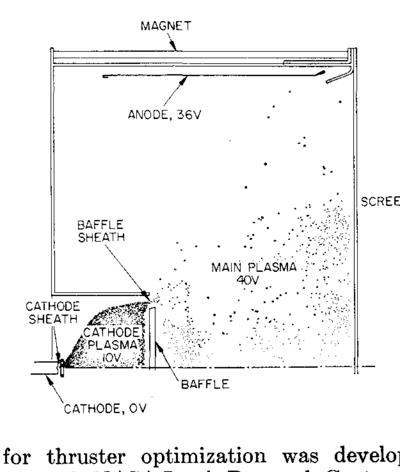


Fig. 4 Plasma regions in hollow cathode thruster.

‡ This technique for thruster optimization was developed under Contract NAS 3-11523, NASA Lewis Research Center.

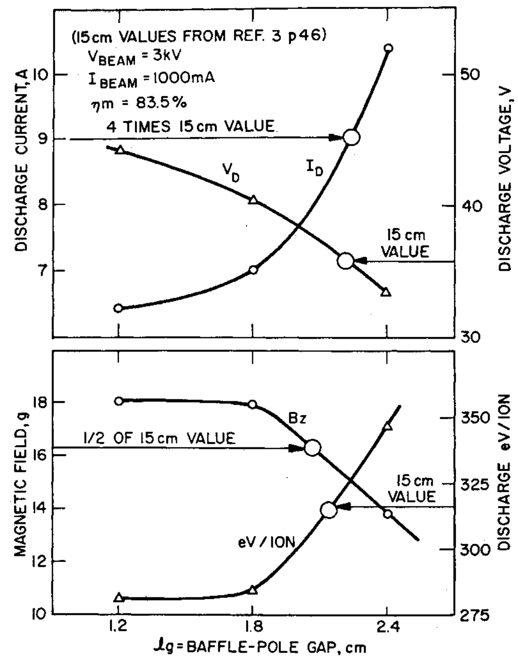


Fig. 5 Comparison of 30-cm thruster performance with scaled 15-cm values.

cathode and the cathode itself. Next there is a large voltage drop between the cathode plasma and the main discharge plasma which floats a few volts above anode potential. It is apparent that in order to design for a particular discharge voltage it is necessary to control the voltage drop across the plasma sheath which separates the cathode and main discharge plasmas (i.e., the sheath in the baffle region). This voltage drop, which is nominally 25 v, is primarily a function of three variables.

The first is the neutral density. A relatively high neutral pressure in the baffle region lowers the discharge voltage (for a given discharge current) because the baffle is not as effective in restricting the flow of electrons from the hollow cathode plasma to the main discharge plasma when the neutral or plasma density is increased within the baffle-pole piece enclosure. Hence, more electrons can be drawn through the open area around the baffle for a given voltage. Furthermore, more ionization occurs directly downstream from the baffle, and the resultant low-energy electrons diffuse more readily across field lines than do the primaries (which are accelerated through the baffle-pole gap). This neutral density is controlled primarily by the flow through the hollow cathode, and may thus be adjusted only over a range determined by the limits of the cathode operation.

The second variable is the strength and shape of the magnetic field in the aperture between the baffle and the pole piece. A strong field transverse to the direction in which the electrons must diffuse provides a high impedance, thus increasing the voltage drop for a given discharge current. Some adjustment is possible, but it must be consistent with the general shape of the magnetic field within the main discharge chamber required for good thruster performance.

The third variable is the physical size and shape of the aperture between the baffle and the pole tip. This gap may be used to adjust the rate at which both electrons and neutrals pass from inside the pole piece to the main discharge chamber.

In order to examine the effect of the gap width, a conical baffle was fabricated and installed in the discharge chamber (Fig. 3) in such a manner that it could be moved axially back and forth while the thruster was operating. Because of the angle of the cone, this motion opened or closed the gap.

The data shown in Fig. 5 were taken with this arrangement. The 30-cm thruster was operated at a beam current of 1 amp, which is four times SERT II beam current. The propellant efficiency during the run was 83.5%. The data demonstrate how the critical variables behave as the baffle is repositioned to modify the discharge conditions. At a baffle position of 2.2 cm, all the variables are in the range of the SERT II values,§ indicating the validity of the scaling relationships and the design procedures. This program is continuing, and it is anticipated that small modifications in the screen pole and collar and possibly the cathode pole will further improve the agreement between the optimized SERT II and observed values.

Discharge Chamber Performance

The thruster was first tested with a "flower" oxide cathode,[3] which was mounted with its forward surface flush with the front of the 6.3-cm-diam by 3.4-cm-long cathode pole piece. No cathode baffle was used. A conventional ion optical system with 0.27-cm-thick accelerator with 0.406-cm apertures, and a 0.077-cm screen with 0.406-cm apertures were used. The data are summarized in Fig. 6 with η_m = 87% at 225 ev/ion as a representative point. Operation was stable and limited in beam current by the vaporizer, which could not provide stable propellant flow above 1400 ma. This test was taken as a confirmation of both the scaling laws and the discharge chamber design.

Following these tests the thruster was modified to incorporate a hollow cathode in order to be compatible with current system designs. Dual feed systems and vaporizers were used for supplying propellant separately to the hollow cathode and to the discharge chamber to provide separate flow control. In addition to performance data, extracted ion beam profiles were measured with a probe at several locations downstream from the accelerator electrode. Beam neutralization was achieved with a directly heated tungsten filament immersed in the extracted beam. Data from these tests are also summarized in Fig. 6 which illustrates the best performance obtained to date (η_m = 85% at 300 ev/ion). Figure 7 shows a beam profile taken 5 cm downstream from the thruster while operating at 650 ma. The relatively flat profile is desirable for use with high-perveance optics.

Low-Specific-Impulse, Ion Optical Arrays

As discussed below, reducing the ion extraction voltage (specific impulse) requires an increase in the number of apertures through which the current is extracted and a consequent reduction in their size. This change influences the construction techniques employed, the permissible mechanical tolerances, the structural integrity of the system, and its useful lifetime. A number of mechanical designs and possible materials were considered, based on the aforementioned criteria and a computer analysis of the ion optical

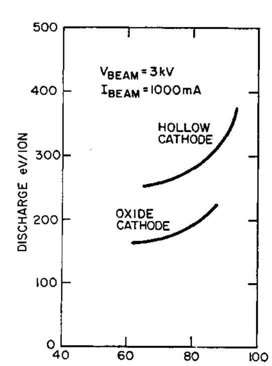


Fig. 6 Discharge chamber performance for 30-cm thrusters.

§ As reported in Ref. 2, p. 46, for an early SERT II configuration.

trajectories. Two approaches were chosen to be exploited as fully as possible consistent with the available resources. The first was simply to modify a conventional two-grid array. The reduced hole size necessitated an equivalent reduction in plate thickness and in the space between the plates, which, in turn, required the development of a new electrode mounting technique and a miniaturized insulator design, as well as careful annealing of the plates to maintain the uniform electrode spacing and high-voltage standoff capability. The second approach was to use a single perforated metal plate that could be coated on one side with an insulating material.[5] When this insulating material is set facing the plasma it is possible to apply the extraction voltage between the plate (negative) and the surface charge on the insulating surface generated by the plasma, providing the necessary conditions for ion extraction.

Design Criteria

A beam voltage of 1000 v coupled with a mass utilization of 87% gives an effective specific impulse (I_{spe}) of 2750 sec, which is the midpoint of the desired operating range. Coupled with an electrical efficiency of 75%, this leads to a beam current requirement of 1.87 amp from a 2.5-kw thruster module. In the analysis of the extraction system, the governing factor is the total extraction voltage V_T, which is the sum of the absolute values of the beam voltage and the negative voltage applied to the accelerator electrode. In practice it may be 1.2 to 3 times the beam voltage. With conventional high-I_{spe} systems, values near 2.5 are typically used. With the low-I_{spe} systems tested to date, the value has been limited to $\sim$1.5 V_B by voltage breakdown. This value (i.e., 1500 v) will be used throughout the subsequent design analysis. It should be appreciated, however, that improvements in the materials or structures that will allow the extraction voltage to be increased from 1.5 V_B to 2.5 V_B will increase the current-handling capability of a given ion optical system by at least a factor of 2.

The perveance of an ion optical element consisting of a single round aperture extracting ions from a plasma has been calculated for a number of cases using either an electrolytic tank–analog computer combination or a digital computer. The results of two recent studies of conventional and insulated ion optics pertinent to this design are shown in Figs. 8 and 9. The perveance for mercury ions for the case shown in Fig. 8 is 6.6×10^{-9} and that shown in Fig. 9 is approximately 5.5×10^{-9} amp/v$^{3/2}$. Because of the nonuniformity of the plasma density in the thruster, it has been demonstrated experimentally that the effective perveance of a single aperture is approximately one-third that of the theoretical value calculated by the aforementioned techniques (i.e., 2.2×10^{-9} amp/v$^{3/2}$). In other words, the elements at the center of the discharge chamber where the plasma density is highest operate at the calculated value, but there are insufficient ions created at the periphery of the discharge chamber to fully utilize the capabilities of the ion optical system at this point. Based on the preceding criteria, 2.2×10^{-9} is used as an average perveance value P_A in the design of the ion optical array. The beam current I_B is given by

$$I_B = nP_AV_T^{3/2}$$

where n is the number of apertures. Solving with these conditions, n = 14,500 apertures for the 30-cm thruster. For a hexagonal close packed array of apertures the center-to-center spacing is 0.236 cm. The aperture diameter is 0.193 cm for 60% open area, and 0.208 cm for 70% open area.

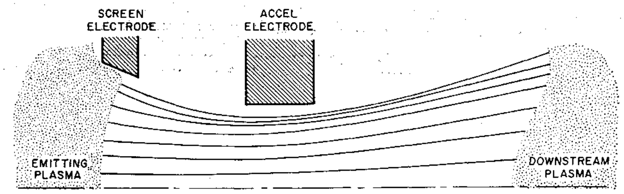


Fig. 8 Computed ion trajectories for conventional two-grid ion optical system.

Conventional Close Spaced Optics

The conventional ion optical arrays used for several years have employed flat plates (screen and accelerator electrodes) which have been match drilled with a hexagonal, close-packed array of holes. The holes have been of equal size in each plate, or the accelerator hole diameter has been $\sim\frac{2}{3}$ that of the screen hole. The latter increases the mass of the accelerator electrode, and hence its useful lifetime which is limited by sputtering due to charge exchange ions. The nominal aperture diameter has been $\frac{1}{8}$ cm. Drilling such apertures in 0.075-cm- to 0.30-cm-thick molybdenum sheet to provide open areas of 50% to 70% has proven tedious but has not presented real fabrication problems. These systems perform well at beam voltages of 2000 v and greater. A 30-cm-diam thruster of this design has $\sim$4000 apertures in the electrode system. In small thrusters (<20 cm), it has proven quite satisfactory to support the electrodes only at the periphery. For a 30-cm-diam thruster this support arrangement becomes marginal and a single axially-located insulating standoff has proven desirable, even for these relatively thick electrodes.

The scaling of this type of structure to thinner material containing nearly four times as many smaller apertures per unit area raises the problems of 1) economically machining the holes to sufficiently high tolerance that the two electrodes will match, and 2) supporting the electrodes so that the alignment and spacing will be maintained during operation. For the machining, cost estimates for the problem may be approached in several ways. Tape-controlled drilling ranged from \$500 to over \$2000 per electrode. Chemical milling appears promising in materials of thickness up to 0.020 in., provided that tapered apertures are acceptable; after a \$1000 setup charge, the cost would be $\sim$\$200 per electrode. Only punched material has been used to date. A commercial

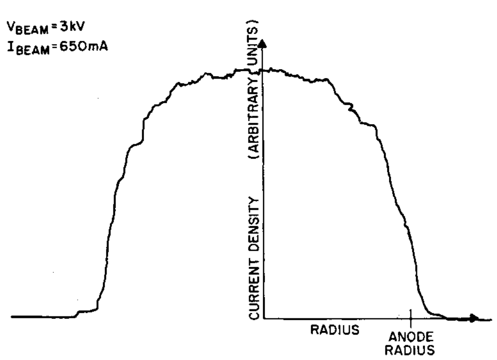


Fig. 7 Ion beam profile for 30-cm thruster.

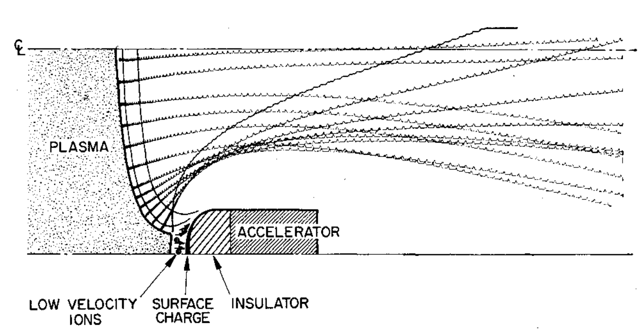


Fig. 9 Computed ion trajectories for single-grid insulated ion optical system.

Table 1 Performance of 15- and 30-cm-diam systems

Measured					Calculated		
Screen aperture, cm	Accel-screen spacing, cm	Thruster diameter, cm	Number of apertures	Average perveance per hole, 10^{-1} perv	Number of apertures	Thruster diameter, cm	I_{beam} at $V_T = 1{,}500$, amp
0.46	0.25	30	4,000	1.84	4,000	30	0.43
0.27	0.12	30	6,800	2.2	6,800	30	0.87
0.19	insulated	15	3,000	7.7	12,000	30	5.4
0.19	insulated	30	12,000	7.8	12,000	30	5.4
0.21	0.08	computed		2.2	14,500	30	1.87

vendor was found who was equipped to punch 0.183-cm holes on 0.314-cm centers in 0.05-cm TZM¶ sheet. This gave 30% open area. This material was successfully punched with no tearing or cracking between holes. The uniformity was such that when two 30-cm circles were cut from the material an orientation could be found where no apertures were misaligned more than 0.025 cm. One of the sheets was then drilled by hand to enlarge each aperture to 0.267 cm, thus providing 64% open area; this was used as the screen electrode, while the 30% open material was used as the accel electrode. The resulting relative electrode dimensions are very nearly equal to those shown in Fig. 8.

A computer modeling technique[6] has been used to analyze the stability of this type of electrode under thermal stress. It employs general but versatile computer simulation programs. The first, called TAS-1B, is used to solve for the temperature distributions and heat flows in the electrode system. The second performs, by a finite element method, structural analysis of shells of revolution subject to axisymmetric or asymmetric mechanical and thermal loads; it has been used to study the warping of the electrodes. To date this technique has not yet been used to alleviate the thermal mechanical problem associated with the supports, but only to define the problem quantitatively. Further parametric studies of the initial shape, support constraints, and electrode material are still required for an understanding of the controlling features and to assist in improving the electrode design.

Several intuitive improvements have been implemented during the test program. Initially the electrodes were mounted in the conventional manner, with the screen attached to the thruster shell with freedom for axial expansion and the accelerator attached to a stiffening ring which was mounted on six peripheral supports. Seven interelectrode (spacing) supports made of boron nitride were used. Subsequently, it was found necessary to stress-relieve the electrodes and slightly (~0.25 cm) dish them to improve rigidity. The supports were redesigned to provide sufficient mechanical strength so that the screen electrode can be directly supported from the accelerator without the need for peripheral attachment to the thruster shell. These modifications have materially improved the design. The thruster perveance is double that with the 70%-open, high-I_{spe} design (0.480-cm apertures). Because of the misalignment caused by the poor tolerance during the stress relieving process, the electrodes have been limited to operation below 600 ma, at which point the direct interception causes a thermal instability.

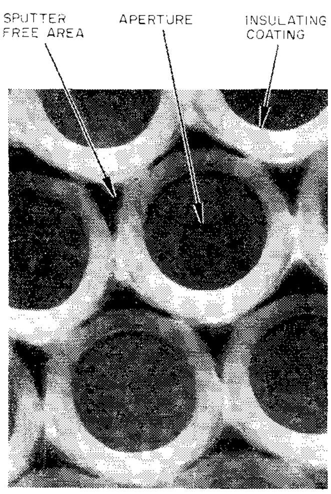


Fig. 10 Insulated ion optical electrode after test.

¶ TZM is an alloy of $\frac{1}{2}$% titanium, $\frac{1}{10}$% zirconium and the balance molybdenum; it was chosen over molybdenum because of its better workability.

Insulated Optics

The general concept here is to use a metal-insulator laminated structure to replace the conventional two plates described above. In principle, this could be a metal-insulator-metal laminate or simply a metal-insulator structure with either the metal or the insulator as the main structural element. Following the early work by NASA,[5] the effort was concentrated on the two-layer structure, which would then rely on the surface charge on the insulator generated by the plasma to form a virtual screen electrode (see Fig. 9). This study was extended to include both thin plates perforated with a hexagonal, close-packed array of apertures and an array of straight round rods similar in geometry to those used on the first Kaufman thruster.

When the available insulator materials were surveyed, it became apparent that the most workable approach would be to apply the insulating coating to the perforated metal substrate as a liquid or powder and then heat the entire assembly and allow the insulator to form in place. The basic requirements set for the insulating layer were: 1) good mechanical strength, 2) good bond to the substrate, 3) minimum voltage breakdown of 1500 v, 4) stable operation to 500°C, and 5) coating thickness of at least 0.05 cm. A survey indicated that there was no available material or commercial process which satisfied all of these requirements.

In the ensuing development program,** over 200 separate samples and processing schedules were evaluated. The resultant process has yielded an electrically insulating, vitreous coating which adheres well to the molybdenum electrode over the full operating range. The coating thickness is built up by applying multiple layers of coating which are each fired separately until the desired thickness of approximately 0.05 cm is reached. This has proven adequate to withstand the required working voltage of 1500 v without excessive arcing. The arcing which does occur appears to be primarily a surface phenomenon rather than breakdown through the insulating material.

** Conducted by W. E. Lent of the Materials Sciences Department, Hughes Aircraft Company, Culver City, Calif.

Because of the difficulty of obtaining high-quality perforated molybdenum, it has not yet been possible to fully exploit the foregoing techniques. Only two electrodes have been tested—one 15-cm-diam and one 30-cm-diam electrode. The former was used in conjunction with a thruster of SERT II design and was capable of extracting 230 ma of ion beam current at a total voltage of 450 v (V_B = 250 v). The accel drain currents remained constant at 5% up to 1400 v, which was the maximum voltage used. The average perveance per aperture measured both during this test and a low-current test of the 30-cm-diam unit was approximately four times the average computed value used in the above design analysis, indicating the great potential of this technique.

Figure 10 is a photograph showing the appearance of the insulating coating after operation. The shaded portion is a thin coating which is deposited on the insulating surface, apparently by sputtering in the discharge chamber. Undoubtedly this is deposited over the total surface during operation but continuously removed from the clean region around the aperture by fast ions which are accelerated by the beam voltage but not focused out of the discharge chamber. The discolored area must then represent the virtual screen electrode which is adjacent to the plasma surface (see Fig. 9) and therefore is bombarded only with low velocity ions with insufficient energy to sputter it clean. If this model is correct the effective open area of the virtual screen is considerably greater than the 70% to 75% which can be achieved with an array of drilled holes in conventional systems. This may be the reason for the exceedingly high extraction efficiency of the insulated electrode system.

Comparative Performance

Although work is continuing on both the discharge chamber and the ion optical array development, it is of interest to compare the current performance of the various ion optical systems. This is done in Table 1, which shows recent results for 15- and 30-cm-diam thrusters all normalized to a total voltage of 1500 v on a 30-cm-diam thruster. The insulated optic has the highest perveance. It is also lower in weight and does not require either the precise alignment or the mechanical stability necessary for optimum performance with the two-grid system. The lifetimes and long-term stabilities of both systems have not yet been established.

Conclusions

A technique for adjusting the shape of the magnetic field has been demonstrated that should be generally applicable to optimizing thrusters of various size and design. A method for establishing the design parameters for the cathode pole piece and baffle geometry which permits the choice of a discharge voltage compatible with the cathode lifetime requirements has also been demonstrated. When these two techniques were applied to a 30-cm-diam thruster whose mechanical design was scaled from a 15-cm-diam thruster of SERT II design, all critical variables were found to scale within experimental error. Although the final high efficiency of the SERT II flight design has not yet been reached, this study has clearly demonstrated the validity of the scaling relationships.

Two types of high-perveance ion optics suitable for operation at low specific impulse have been designed and tested. The high perveance necessary for the application has been demonstrated at beam currents up to 600 ma. The development of both the above areas must now be completed and the complete system must be optimized to demonstrate the ultimate lifetime and efficiency.

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