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# A 5-CENTIMETER-DIAMETER ELECTRON-BOMBARDMENT THRUSTOR WITH PERMANENT MAGNETS

*by Joseph F. Wasserbauer*
*Lewis Research Center*
*Cleveland, Ohio*

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# A 5-CENTIMETER-DIAMETER ELECTRON-BOMBARDMENT THRUSTOR WITH PERMANENT MAGNETS

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## SUMMARY

An attempt was made to optimize a permanent magnet thrustor version of an electromagnet ion thrustor suitable for station keeping and attitude control of a synchronous earth satellite. Results from the investigation showed that a permanent magnet version of the electromagnet thrustor gave ion-chamber performance comparable or slightly better than the electromagnet thrustor for all electrical parameters investigated. Comparison of chamber performance over a range of propellant flow rates showed that the best ion-chamber performance for both thrustors was obtained for propellant flow rates from 0.035 to 0.050 equivalent ampere. Comparison of both thrustors on the basis of the power to thrust ratio showed that the permanent magnet thrustor had an improvement in performance of approximately 12 percent over that of the electromagnet thrustor. A power to thrust ratio of 165 watts per millipound was obtained at a thrust of 0.69 millipound and a net accelerating voltage of 3000 volts for the permanent magnet thrustor when the neutralizer and vaporizer power losses were neglected. Reasonable estimates of these losses would increase the power to thrust ratio to only 200 watts per millipound.

## INTRODUCTION

One of the uses of electric propulsion in the near future is for station keeping and attitude control of synchronous earth satellites. In reference 1 a thrust requirement of 0.5 to 1.5 millipounds is indicated for a representative attitude-control and station-keeping mission. Several thrustors suitable for this purpose have been investigated at the Lewis Research Center. Reference 2 demonstrated the possibility of obtaining thrust in more than one direction by use of a single ion thrustor with two separate grid systems. Reference 3 presents the overall design and performance of a flight-type ion thrustor (both electromagnet and permanent magnet versions) that would be suitable for control of a synchronous earth satellite.

In an effort to optimize further the performance of the permanent magnet thrustor described in reference 3, an experimental investigation was conducted to study the effects of the various magnetic field shapes of the permanent magnet thrustor (resulting from geometrically different pole pieces) on thrustor performance. Reference 4 demonstrated that definite gains are made by proper selection of pole pieces to obtain the desired magnetic field. The experimental results of the program described herein and a comparison with the optimum electromagnet version of this thrustor are the subject of this report.

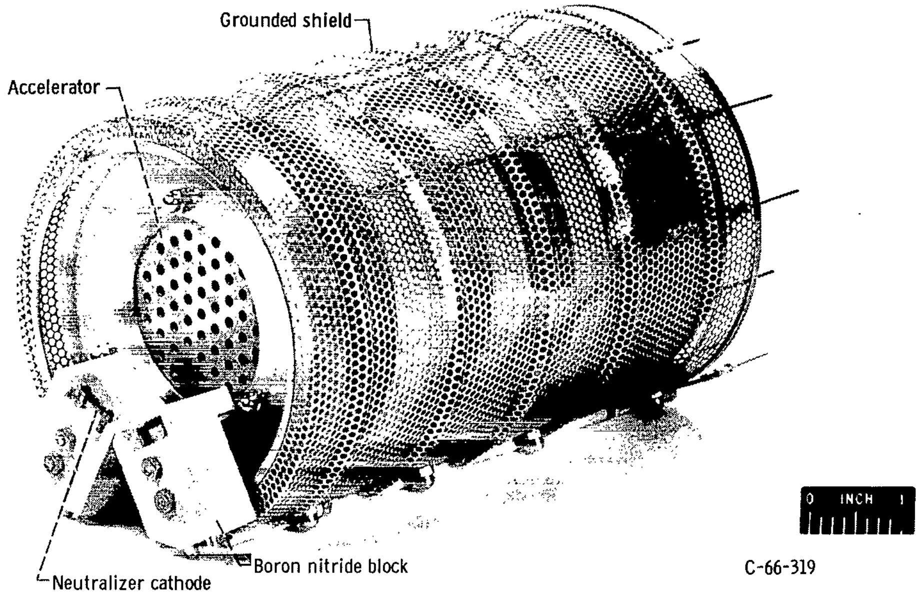
The magnetic fields of the electromagnet and the various permanent magnet thrustor configurations are presented. A comparison is made of all the electrical parameters affecting the performance of the electromagnet and permanent magnet thrustor configurations. Finally, a comparison is made between the best permanent magnet thrustor configuration and the electromagnet thrustor over a range of propellant flow rates, and the power to thrust ratio is compared over a range of thrust values. Mercury was used as the propellant throughout the investigation.

## APPARATUS AND PROCEDURE

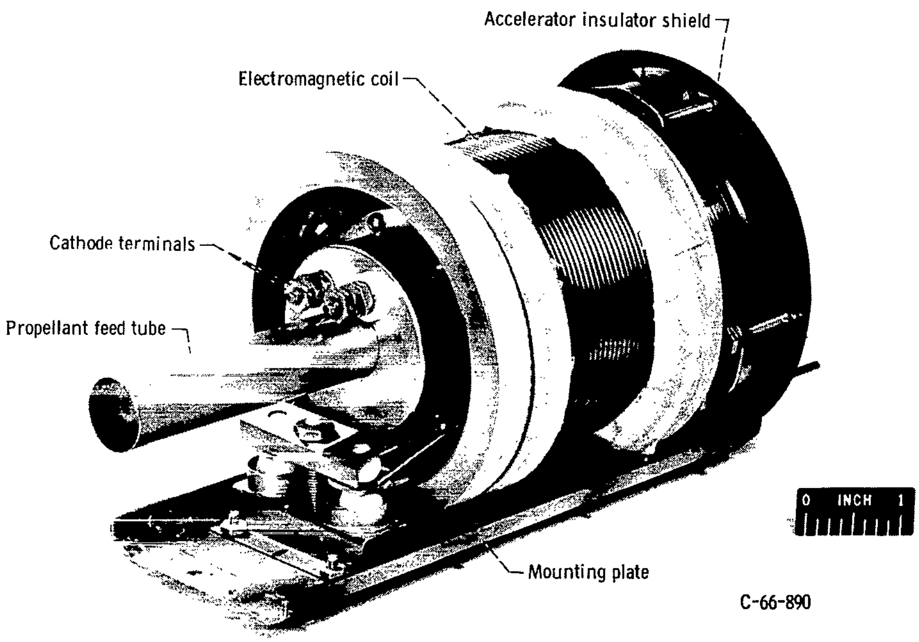
### Electromagnet Thrustor

Figures 1(a) and (b) are photographs of the electron bombardment thrustor with an electromagnetic field coil (electromagnet thrustor). Figure 1(c) is a schematic diagram of the thrustor, indicating the relative locations of the discharge chamber, cathode distributor, magnetic coil, accelerator grids, and the associated power supplies used in the investigation.

The discharge chamber was designed with an anode diameter of 5 centimeters and a length of 7.5 centimeters. The accelerator and screen grid design was 5 centimeters in diameter, and both were fabricated from a 0.16-centimeter-thick molybdenum sheet. Holes were drilled in both grids on a 0.635-centimeter equilateral triangular spacing. The screen grid and accelerator holes were 0.476 and 0.317 centimeter in diameter, respectively. The accelerator holes were made smaller both to increase the web material between the holes (thus increasing the lifetime) and to decrease somewhat the loss of neutral propellant through the grid system. The screen-accelerator grid separation was held at 0.15±0.01 centimeter by shielded aluminum oxide ball insulators. The propellant distributor was of a radial type. The inner hole diameter of the distributor plate was 2.54 centimeters, and the distance between the cathode mounting block and this plate (through which passed the propellant) was about 0.3 centimeter. The propellant feed tube was 1.9 centimeters in diameter and 7.6 centimeters long. The design considerations

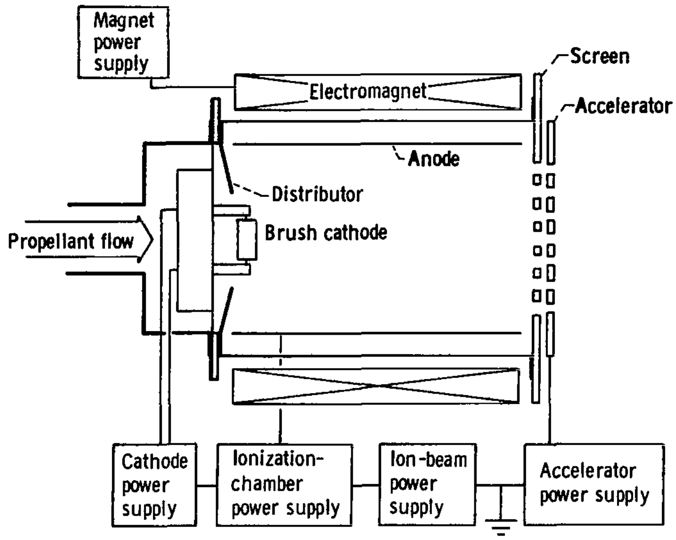



(a) Exhaust or accelerator end.

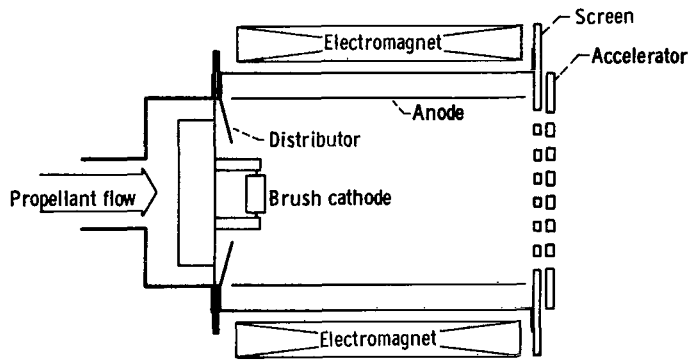



(b) Upstream end with grounded shield removed.

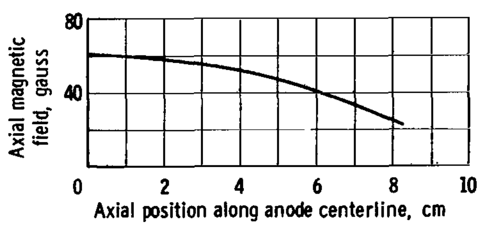
Figure 1. - Thrustor with electromagnetic field coil.




(c) Schematic diagram of electromagnet thrustor and associated power supplies. Permanent magnet thrustor is the same except for magnet power supply.




(d) Simplified schematic drawing (to scale).




(e) Magnetic field strength.

Figure 1. - Concluded.

for the propellant feed system are discussed fully in reference 3. All sheet-metal parts were made of nonmagnetic stainless steel. The magnetic coil was designed to produce a tapered field with magnitudes of 60 gauss at the distributor and 24 gauss at the screen (fig. 1(e)).

## Permanent Magnet Thrustor

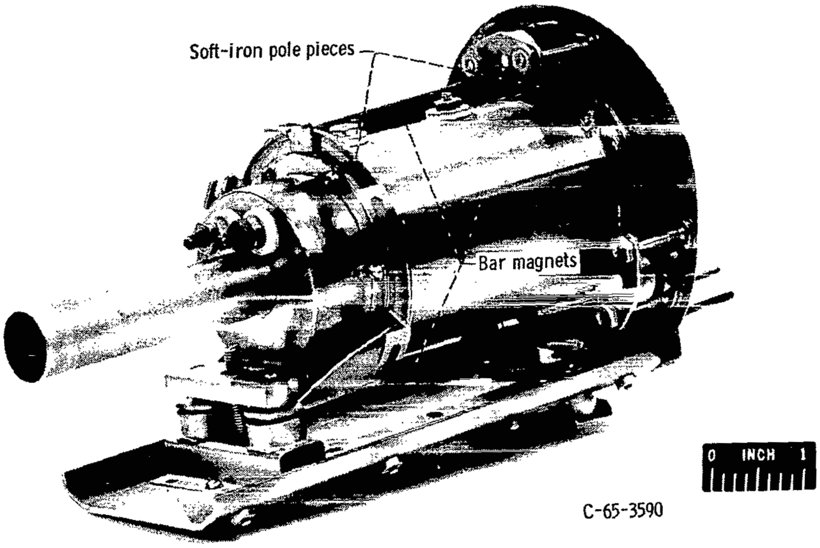
The thrustor is the same in all respects as the electromagnet thrustor except for the screen and distributor. Mild-steel screen and distributor pole pieces along with permanent magnets were used to form the magnetic field circuit. Figure 2(a) is a photograph of the flight-type thrustor with permanent magnets. Figures 2(b) to (e) are photographs of the mild-steel pole pieces used in the various permanent magnet thrustor configurations.

The screen-grid pole piece matched the screen grid of the electromagnet thrustor and had an outer diameter of 9.208 centimeters and a thickness of 0.16 centimeter. The screen pole piece had an 8.57-centimeter outside diameter, a 4.46-centimeter center hole, and a lip that extended axially 0.48 centimeter into the discharge chamber. The thickness of this pole piece was 0.13 centimeter. The screen pole piece (fig. 2(c)) was attached to the molybdenum screen grid used in the electromagnet thrustor, while the screen-grid pole piece (fig. 2(b)) replaced the molybdenum screen.

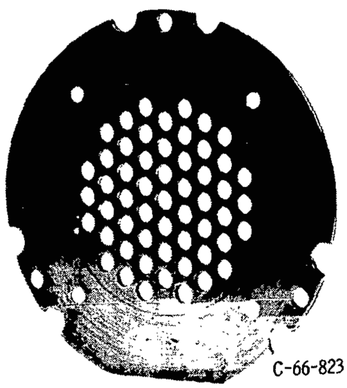
Both distributor pole pieces were of the radial type and had a thickness of 0.13 centimeter and a diameter of 7.62 centimeters with a center hole of 2.54 centimeters. One distributor pole piece had a center collar that extended 1.27 centimeters into the discharge chamber.

The rod magnets were a high-temperature type of sintered Alnico V with a diameter of 0.785 centimeter and a length of 8.25 centimeters. All magnets were cut to give a tight fit between the mild-steel pole pieces.

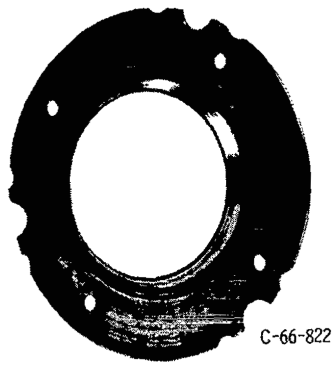
The permanent magnet thrustor configurations used in this investigation along with their associated magnetic fields are presented in figure 3 (pp. 8 to 10). Configurations 1, 2, 3, and 4 used four rod magnets along with the respective pole pieces to make up the magnetic circuits, while configuration 5 used only three rod magnets. The magnetic fields of each configuration were measured before and after each test to ensure that no change was encountered during the test. In each case, no deterioration of the magnetic field was detected. Such a change (if found) would be a result of careless handling, since permanent magnet thrustors have operated for many hundreds of hours with no change in field strength. Measurements were taken along the thrustor axial centerline. An additional measurement was made at 2.0 centimeters from the axial centerline for configuration 5.



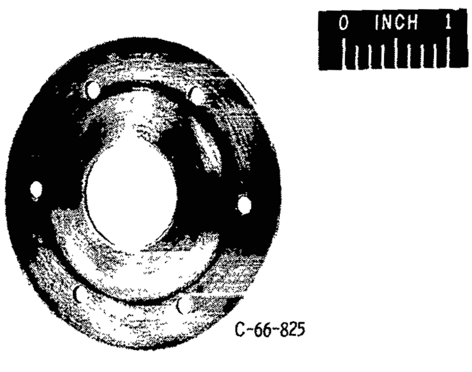

(a) Grounded shield removed.



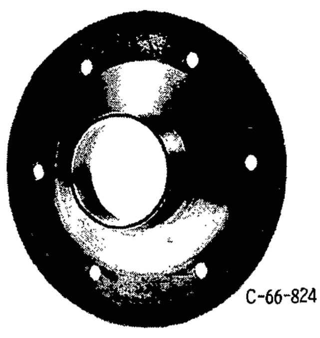

(b) Mild-steel screen-grid pole piece.




(c) Mild-steel screen pole piece with extended lip.




(d) Mild-steel distributor pole piece.




(e) Mild-steel distributor pole piece with extended center collar.

Figure 2. - Thrustor with permanent magnet field configuration.

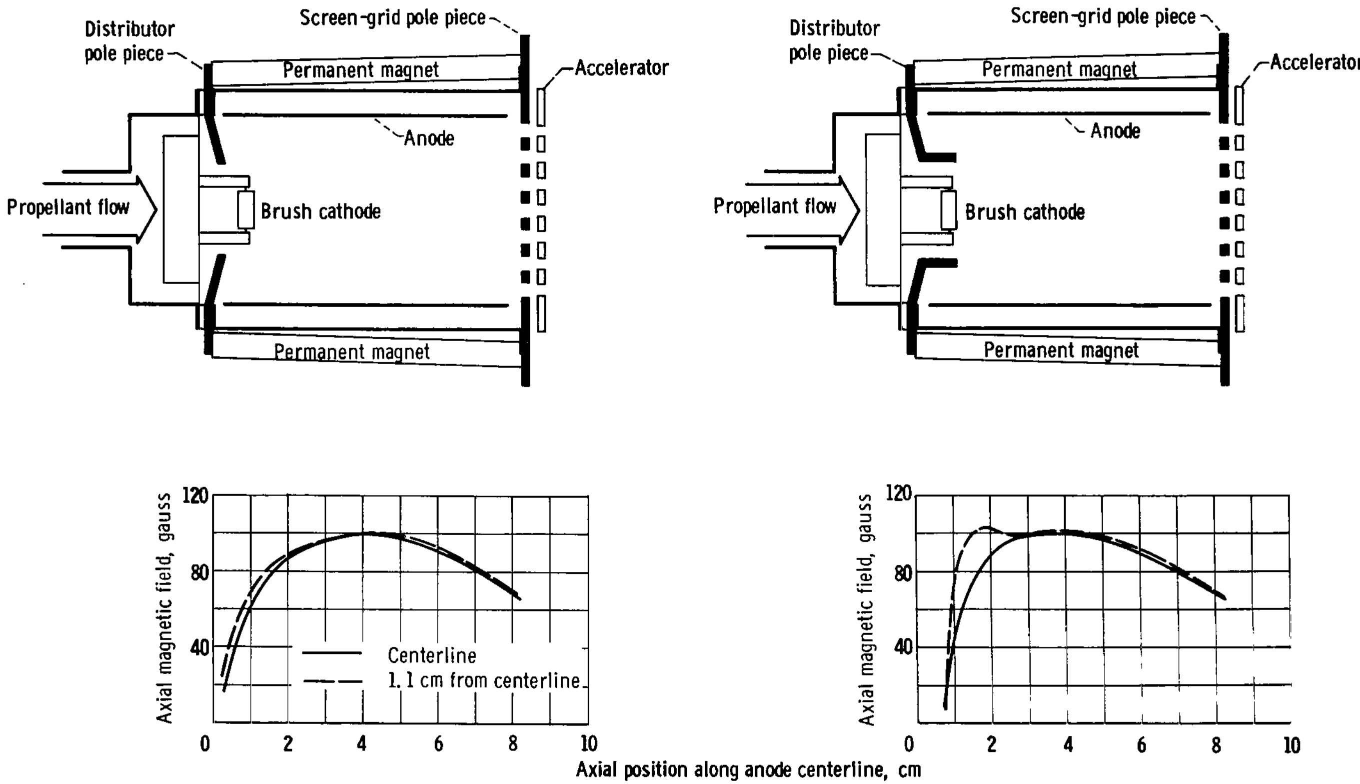
In order to obtain the best possible comparison between the electromagnet thrustor and the permanent magnet thrustor configurations, the permanent magnet thrustor components were made exactly the same except for the distributor and screen pole pieces. In addition, the same oxide cathode was used in each test in an effort to minimize any change in cathode emission characteristics that might occur by using different cathodes. The only exception was configuration 5, for which a new oxide cathode was used. Each thrustor was operated for approximately 10 hours to stabilize cathode emission before thrustor data were taken.

Configuration 1 has the screen-grid pole piece that serves to distribute the magnetic flux density across the face of the screen. The distributor pole piece is similar in design to that of the electromagnet thrustor (fig. 3(a)). The magnetic field reaches its maximum value at approximately the center of the discharge chamber but only reduces to about 60 percent of its maximum at the screen. The magnetic field at the cathode is approximately 65 percent of the maximum.

Configuration 2 has the screen-grid pole piece and the distributor pole piece with the extended center collar. This extension on the distributor pole piece tends to concentrate the magnetic flux density at the edge of the extended collar. The highest magnetic field strength was measured at this point, as indicated in figure 3(b). Thus, the highest magnetic field point is located nearer to the cathode and thereby produces a field somewhat similar to that of the electromagnet thrustor.

Configuration 3 has the screen pole piece with the lip extension into the discharge chamber (fig. 3(c)). The purpose of this pole piece was to concentrate the magnetic flux density at the outer periphery of the discharge chamber at the screen. The distributor pole piece is similar in design to that of the electromagnet thrustor. As can be seen from the magnetic field curve, the field along the centerline is highly divergent from about 2.5 centimeters from the screen and approaches a value of zero near the screen. At about the center of the discharge chamber, the field reaches a maximum and varies from 100 gauss at the axis to about 102 gauss at 1.1 centimeters from the axis centerline. The magnetic field at the cathode is approximately 65 percent of the maximum.

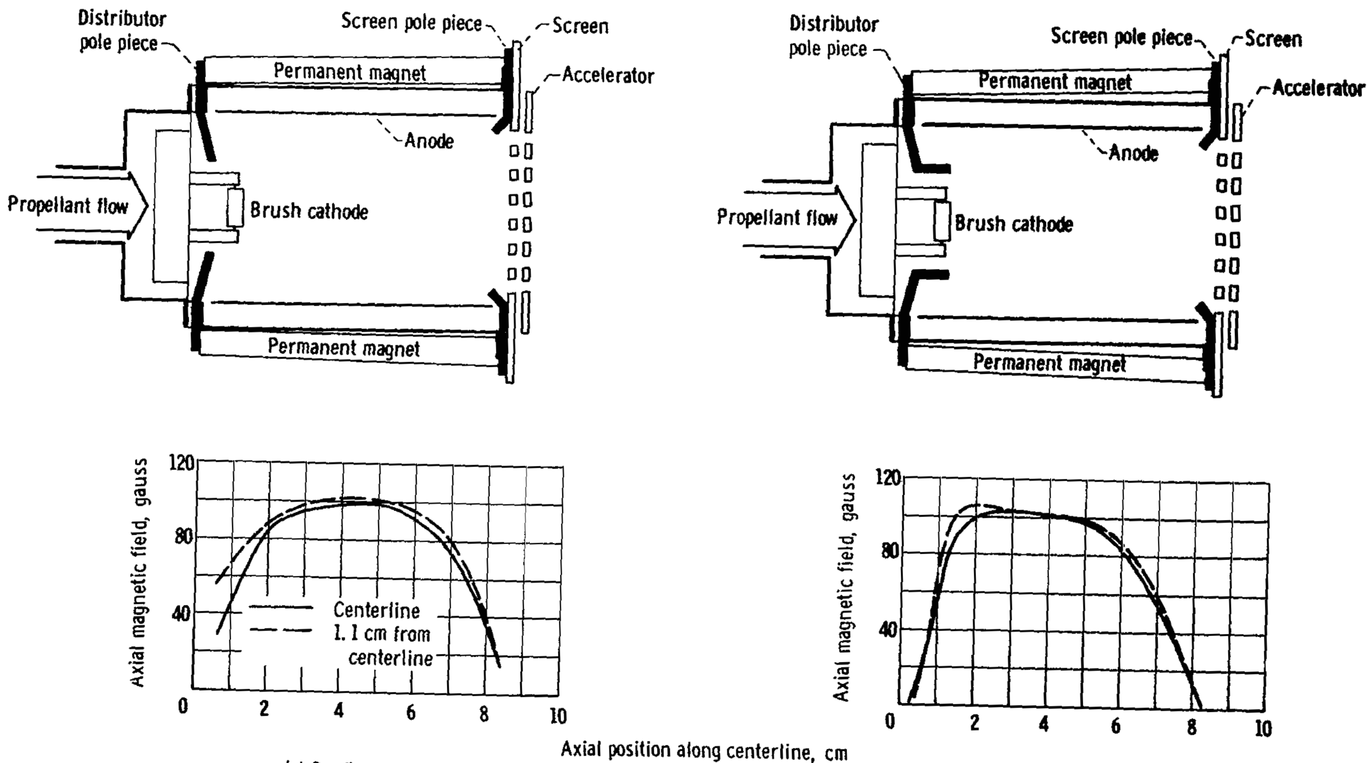
Configuration 4 employs both the extended collar distributor pole piece and the screen pole piece with extended lip (fig. 3(d)). This configuration produces highly concentrated fields near the centerline at the distributor pole piece and at the outer periphery of the discharge chamber at the screen pole piece. Configuration 5 employs the same pole pieces as configuration 4 but uses only three rod magnets instead of four to reduce the magnetic field strength in the discharge chamber (fig. 3(e)). Configuration 5 approximates the electromagnet thrustor magnetic field better than any of the other configurations.




(a) Configuration 1.

(b) Configuration 2.

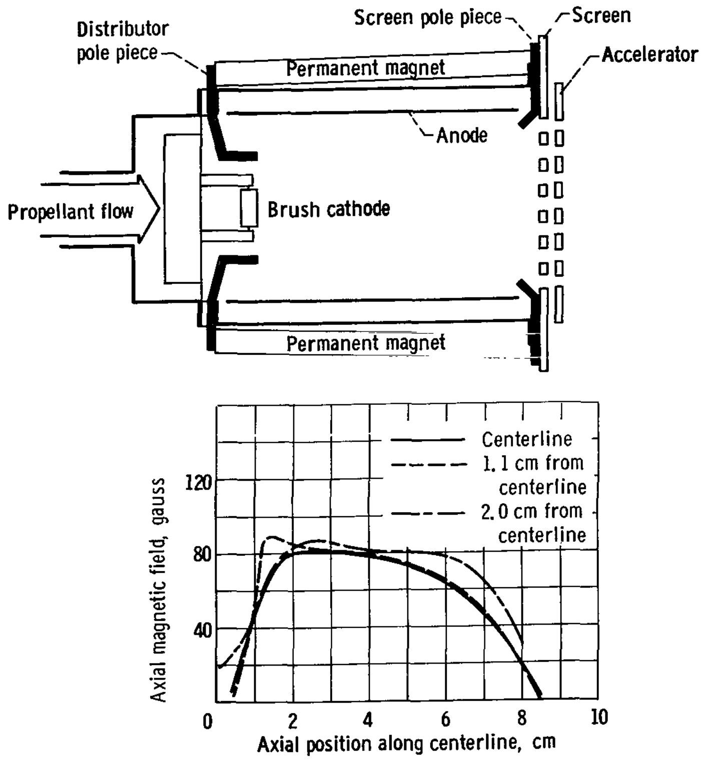
Figure 3. - Schematic view of permanent magnetic thrustors and associated magnetic fields.




(c) Configuration 3.

(d) Configuration 4.

Figure 3. - Continued.




(e) Configuration 5.

Figure 3. - Concluded.

## Cathode

The chamber cathode was a tantalum brush (0.5 cm in diam and 1.2 cm long) coated with Radio Mix No. 3 (57 percent $BaCO_3$, 42 percent $SrCO_3$, and 1 percent $CaCO_3$) and had a surface area of 1.8 square centimeters. The cathode was supported between two copper rods and was centrally located in front of and parallel to the plane of the distributor. The cathode was approximately 1 centimeter from the distributor. Further details about this cathode may be obtained in references 3 and 5.

## Vaporizer

Mercury vapor was supplied to both the electromagnet and permanent magnet thrustors by a steam-heated vaporizer. A sharp-edged orifice was used to control the propellant flow rate from the vaporizer. A range of orifice sizes was used to obtain equivalent propellant flow rates corresponding to values from 0.025 to 0.075 equivalent ampere of singly charged mercury ions.

## Facility

The ion thrustors used in this investigation were mounted in a metal bell jar connected by a 0.9-meter gate valve to a 1.5-meter-diameter, 4.5-meter-long vacuum tank. It was pumped by four 0.8-meter-diameter oil-diffusion pumps with liquid-nitrogen-cooled baffles. The tank pressure varied from $1.0\times10^{-6}$ to $3.0\times10^{-6}$ torr and bell jar pressure from $3.0\times10^{-6}$ to $5.0\times10^{-6}$ torr during thrustor operation.

# RESULTS AND DISCUSSION

Presentation of the results will be made in the following order: (1) a presentation of the average experimental results from a number of tests conducted with the electromagnet thrustor, (2) a comparison of the electrical parameters affecting thrustor performance with ion-chamber performance for the electromagnet thrustor and the various permanent magnet thrustor configurations, (3) a comparison of ion-chamber performance over a range of propellant flow rates between the best permanent magnet thrustor and the electromagnet thrustor, and (4) a comparison of the power to thrust ratio for a range of thrust values between the best permanent magnet thrustor and the electromagnet thrustor.

## Electromagnet Thrustor Performance

Several tests were conducted with the electromagnet thrustor in an effort to determine reproducibility of thrustor performance. For each test, the same physical thrustor was used with the exception that a new oxide-coated brush cathode was used each time. For each new cathode, preliminary activation and aging were performed before each test as prescribed in reference 5. For each test, the thrustor was operated for at least 10 hours to age the oxide cathode further before thrustor data were taken. The neutral propellant flow rate for these tests was maintained constant at 0.050 equivalent ampere.

Data were then obtained for all electrical parameters affecting thrustor performance. Data from these tests showed that thrustor performance could vary by as much as 150 electron volts per ion. Since all physical parameters were unchanged, with the exception of the oxide cathode, and data were taken over the same range of electrical parameters, it is not unreasonable to assume that the emission characteristics of each cathode were not identical, resulting in the variation of ion-chamber performance. An arithmetic average for the data was obtained and is presented in figures 4 to 7 (p. 13) as the average thrustor performance for the electromagnet thrustor performance.

Figure 4 shows the variation of ion-chamber performance with magnetic field strength. The ion-chamber potential difference was 30 volts, the ion-chamber potential was 4000 volts, the accelerator potential was -1000 volts, and the ion-beam current was maintained constant at 0.0225 ampere. The magnetic field strength at the distributor is 2.5 times the value at the screen. The optimum magnetic field strength is the point at which the sum of the chamber losses and magnetic field losses is minimized. For the electromagnet thrustor, this condition was realized for a field of about 60 gauss at the distributor and about 24 gauss at the screen (fig. 1(e), p. 4). This magnetic field was then used for the remainder of the test program.

Figure 5 shows the effect of ion-chamber potential difference on ion-chamber performance at various values of propellant utilization efficiencies. The data indicate that the ion-chamber performance is only slightly affected over the potential difference range investigated. A potential difference value of 30 volts was selected as the typical operating voltage for this thrustor.

Figure 6 shows the effect of varying net accelerating voltage on ion-chamber performance and accelerator impingement current. The ion-beam current was constant at 0.0225 ampere. The ratio of net to total accelerating voltage was maintained constant at 0.8 so that electron backstreaming would not occur. The net accelerating voltage was varied from 2100 to 6000 volts. The ion-chamber performance varied from about 600 electron volts per ion at 2300 volts to about 430 electron volts per ion at 6000 volts, while the accelerator impingement remained at about 1 percent of the ion-beam current over most of this voltage range. Below about 2300 volts, the impingement current and ion-chamber losses rapidly increase with decreasing voltage.

Figure 7 shows the dependence of ion-chamber performance on propellant utilization efficiency. The ratio of net to total accelerating voltage was again maintained constant at 0.8 with the ion-chamber potential at 4000 volts and the accelerator voltage at -1000 volts. The ion-chamber discharge energy per ion gradually decreases at lower utilizations and rapidly increases at propellant utilization efficiencies higher than about 0.60.

## Permanent Magnet Thrustor Comparison

The data presented in the figures for the comparison of the permanent magnet thrustor configurations are given in table I. The variation of ion-chamber performance with ion-chamber potential difference for the thrustor configurations investigated is presented in figure 8 (p. 14). Data were obtained for three propellant utilization efficiencies of 0.33, 0.45, and 0.60. The ion-chamber potential was 4000 volts and the accelerator potential was -1000 volts. A propellant flow rate of 0.050 equivalent ampere was used. Configurations 4 and 5 compared quite well with the electromagnet thrustor at each

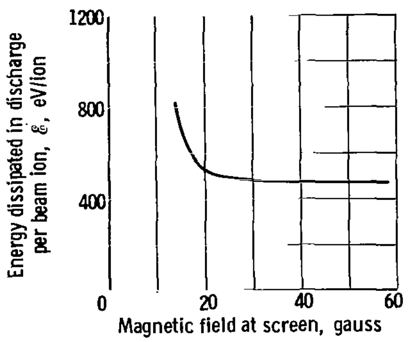



Figure 4. - Effect of varying magnetic field on average ion-chamber performance for electromagnet thrustor (distributor magnet field larger by factor of 2.5). Ion-beam current (constant), 0.0225 ampere; propellant utilization efficiency, 0.45; ion-chamber potential, 4000 volts; accelerator potential, -1000 volts; ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

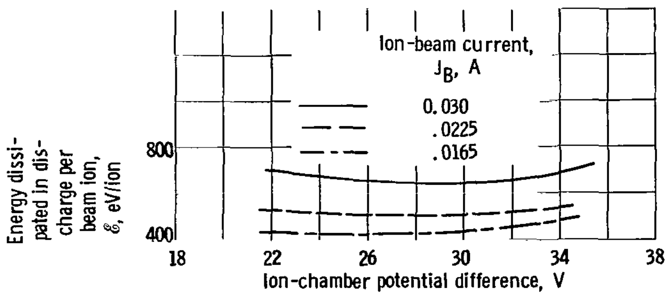



Figure 5. - Effect of ion-chamber potential difference on average ion-chamber, performance for electromagnet thrustor. Ion-chamber potential, 4000 volts; accelerator potential, -1000 volts; magnetic field strength at screen and distributor 24 and 60 gauss, respectively; neutral propellant flow rate, 0.050 equivalent ampere.

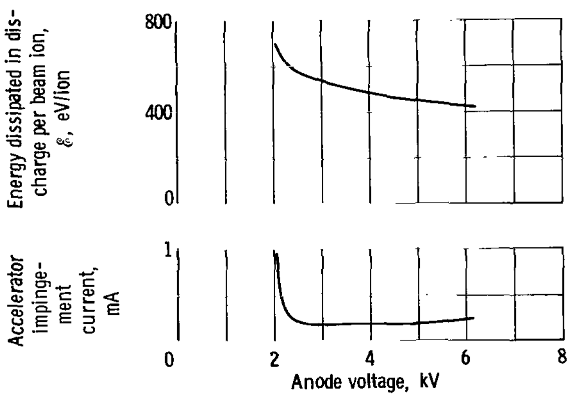



Figure 6. - Effect of varying net accelerating voltage on ion-chamber performance and accelerator impingement current for electromagnet thrustor (average values presented). Ion-beam current (constant), 0.0225 ampere; propellant utilization efficiency, 0.45; ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

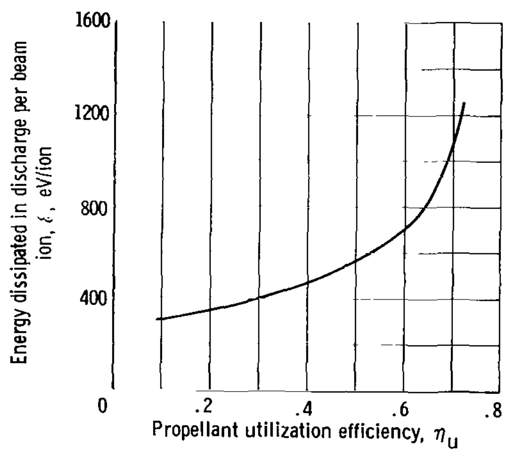
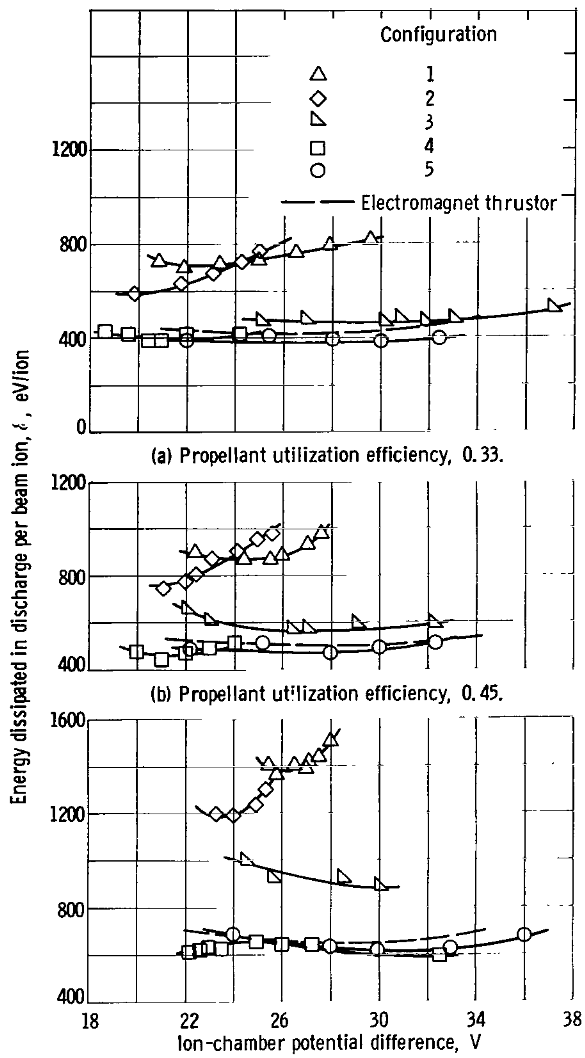



Figure 7. - Average values of propellant utilization efficiency for electromagnet thrustor. Ion-chamber potential, 4000 volts; accelerator potential, -1000 volts; ion-chamber potential difference, 30.0 volts; magnetic field strength at screen and distributor, 24 to 60 gauss, respectively; neutral propellant flow rate, 0.050 equivalent ampere.




(a) Propellant utilization efficiency, 0.33.

(b) Propellant utilization efficiency, 0.45.

(c) Propellant utilization efficiency, 0.60.

Figure 8. - Ion-chamber performance for various thrustor configurations; ion-chamber potential, 4000 volts; accelerator potential, -1000 volts; neutral propellant flow rate, 0.050 equivalent ampere.

propellant utilization. The ion-chamber discharge power loss of configuration 3 is higher at a propellant utilization of 0.6 but compares fairly well with the performance of configurations 4 and 5 at the lower propellant utilizations. In general, for configurations 4 and 5, the ion-chamber performance varies only slightly over the ion-chamber potential range considered with a slight minimum value at about 30 volts for configuration 5 and a minimum value usually several volts lower for configuration 4 (see fig. 8(a)).

Configurations 1 and 2 exhibited the poorest performance of the permanent magnet configurations considered. At a propellant utilization of 0.6, well-defined minimums in ion-chamber performance were obtained at 24 and 26 volts for configurations 2 and 1, respectively. At the lower utilizations, ion-chamber loss per ion was not as large but was still higher than the loss in the other configurations tested. Since the only significant differences among the configurations are in the distribution of the magnetic field, these differences may be assumed to be responsible for the large changes in efficiency. Both configurations 1 and 2 have higher field strengths at the screen than at the distributor, which is contrary to the variation found desirable in reference 6. Configurations 3, 4, and 5 come closer to the variation desirable in reference 6 by having lower field strength at the screen than at the distributor. What is unusual about these latter configurations, though, is that the axial field at the center of the screen is approximately zero. It should be noted, however, that the low magnetic field at the center of the screen does not necessarily mean (as it would in an electro-

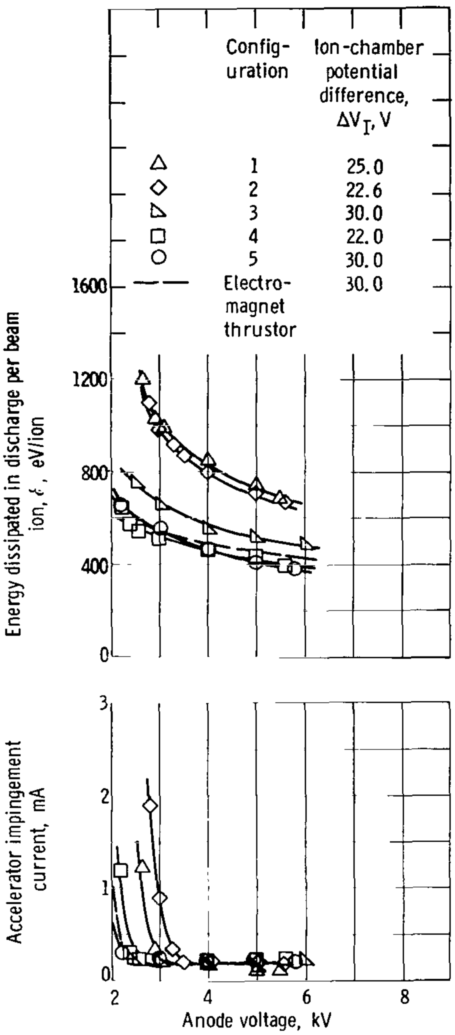



Figure 9. - Comparison of effect of net accelerating voltage on ion-chamber performance and accelerator impingement current for various thrustor configurations. Beam current (constant), 0.0225 ampere; propellant utilization efficiency, 0.45; neutral propellant flow rate, 0.050 equivalent ampere.

magnet model) that the path emitted electrons use to reach the anode is an easy one. In fact, the field is locally quite high near the screen pole piece, so that electrons must pass through the magnetic field in this region before reaching the anode. Thus, permanent magnet configurations 3, 4, and 5 can operate efficiently with field strengths at the screen that would correspond to very poor performance in the electromagnet version (see fig. 4, p. 13).

The effect of net accelerating voltage on ion-chamber performance and accelerator impingement current for the various thrustor configurations is compared in figure 9. The propellant utilization efficiency was maintained constant at 0.45. The ion-chamber potential differences were held constant for each configuration and are shown in figure 9. Configurations 4 and 5 are again comparable to the electromagnet thrustor with ion-chamber performance varying from about 600 electron volts per ion at 2500 volts to about 400 electron volts per ion at 6000 volts. Configuration 3 gave performance values of about 100 electron volts per ion higher than configurations 4 and 5. The ion-chamber performance for configurations 1 and 2 was 1.5 to 2.0 times higher than that of configurations 4 and 5 over the range of net accelerating voltage considered.

The accelerator impingement current was about 1 percent of the ion-beam current when the accelerator grids were not operative near maximum perveance, which was considered to be the region where the impingement rises. Configurations 1 and 2 exhibit increased impingement at voltages higher than the other configurations. The accelerator grid spacing for each of these configurations was maintained within the limits stated in the APPARATUS AND PROCEDURE section. A probable explanation is that the high magnetic field at the screen results in a more nonuniform ion current profile in the beam, hence maximum perveance is reached at the center

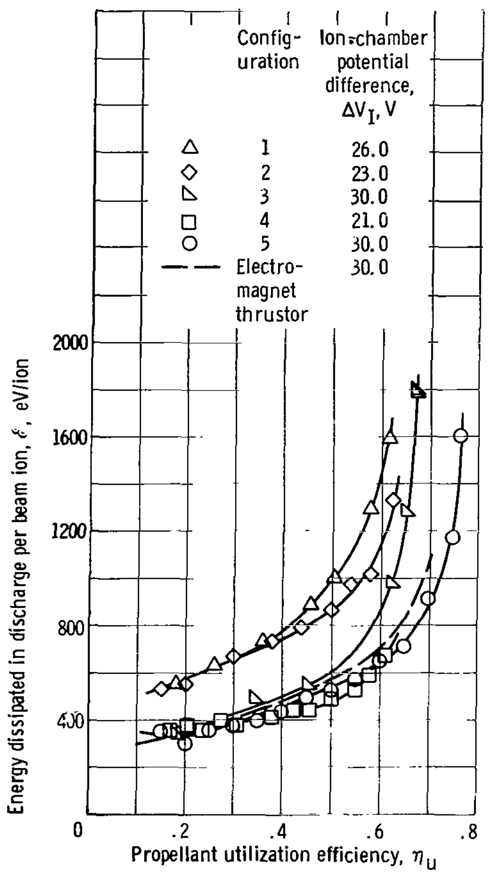



Figure 10. - Comparison of thrustor configurations over range of propellant utilization efficiency. Ion-chamber potential, 4000 volts; accelerator potential, -1000 volts; neutral propellant flow rate, 0.050 equivalent ampere.

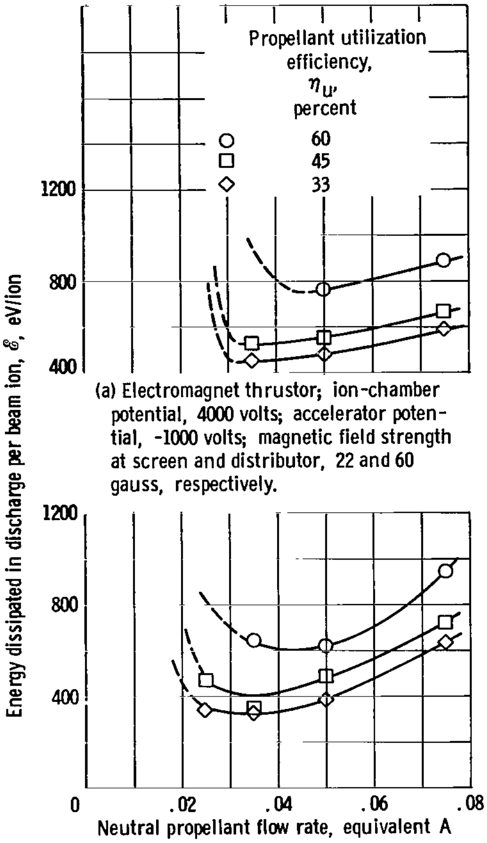
of the grid system at higher voltages with these configurations.

Comparison of the thrustor configurations over a range of propellant utilization efficiencies is presented in figure 10. The net to total accelerating voltage was again held constant at 0.8 with the ion-chamber potential at 4000 volts and the accelerator grid at -1000 volts. The ion-chamber potential difference was held constant for each configuration, as shown in figure 10. As indicated in figures 5 (p. 13) and 8 (p. 14), the differences in ion-chamber potential difference should not be significant, at least for the better performing configurations. The neutral propellant flow rate was constant at 0.050 equivalent ampere. Configurations 4 and 5 were again comparable to the electromagnet thrustor with about 350 electron volts per ion at the low utilizations to about 650 electron volts per ion at a utilization of 0.6. Ion-chamber losses rose sharply at propellant utilizations greater than 0.6. Configuration 3 had comparable performance with configurations 4 and 5 up to a 0.5 propellant utilization at which point the losses increased sharply. Configurations 1 and 2 again exhibited ion-chamber losses that were 1.5 to 2.0 times higher than the other configurations considered.

Based on the comparison of ion-chamber performance for the electrical parameters considered, configurations 4 and 5 appear to give the best comparison with the electromagnet thrustor. Configuration 5 was selected as the optimum permanent magnet thrustor for further comparisons with the electromagnet thrustor since the elimination of one rod magnet in the permanent magnet thrustor had little effect on chamber performance and because the permanent magnet thrustor has a magnetic field that closely matched the magnetic field of the electromagnet thrustor, at least for the upstream half of the ionization chamber.

## Effects of Propellant Flow Rate

For both the electromagnet thrustor and the permanent magnet thrustor (configuration 5), the only change made for the data in this section was in the orifice used to




(a) Electromagnet thrustor; ion-chamber potential, 4000 volts; accelerator potential, -1000 volts; magnetic field strength at screen and distributor, 22 and 60 gauss, respectively.

(b) Permanent magnet thrustor; ion-chamber potential, 4000 volts; accelerator potential, -1000 volts.

Figure 11. - Effect of varying neutral propellant flow rate.

control the neutral propellant flow rate. The electromagnet thrustor used in this portion of the investigation exhibited slightly higher losses than the average ion-chamber losses for this thrustor presented earlier. All data presented in this section are given in table II.

Figure 11 shows the ion-chamber performance at a given propellant utilization efficiency for the electromagnet and permanent magnet thrustors over a range of neutral propellant flow rates. Both thrustors were operated at a net accelerating voltage of 4000 volts. The ion-chamber potential difference of the thrustors at each neutral propellant flow rate is given in the following table:

| Neutral propellant flow rate, equivalent A | Ion-chamber potential difference, $\Delta V_I$, V |
|---|---|
| 0.075 | 20 |
| .050 | 30 |
| .035 | 28 |
| .025 | 30 |

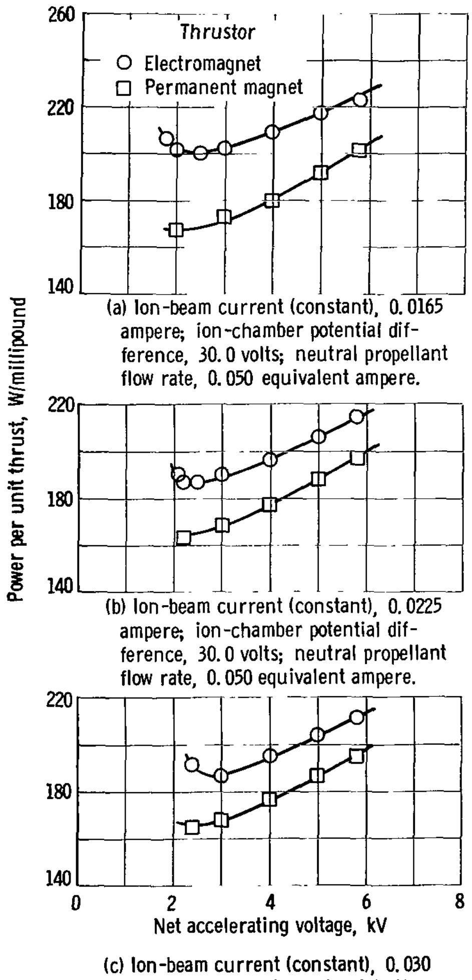
For both thrustors, the ion-chamber losses increased with increasing propellant flow rate. The potential difference at a neutral propellant flow rate of 0.075 equivalent ampere was 20 volts, which gave the best ion-chamber performance for each thrustor at that neutral flow. The increased losses per ion at high neutral flow rates appear somewhat contradictory with previous experience (refs. 2, 7, and 8), but it should be kept in mind that this thrustor design, particularly the distributor, was optimized at a neutral flow rate of 0.050 equivalent ampere. Hence, minimum losses near this condition might be expected.

A definite lower limit in neutral propellant flow rate does exist for each thrustor. For the electromagnet thrustor, the data indicate that a neutral propellant flow rate of 0.035 equivalent ampere is the lower limit for efficient thrustor operation but only at the lower propellant utilization efficiencies (fig. 11(a)). For the permanent magnet thrustor, the lower limit on neutral propellant flow rate was 0.025 equivalent ampere, again only for the lower propellant utilizations. In general, though, propellant flow rates of 0.035

to 0.050 equivalent ampere resulted in best ion-chamber performance for both thrustors.

## Power To Thrust Ratio Comparison

In order to evaluate the applicability of the thrustors to practical systems, a comparison is made of the total power input per unit thrust between the electromagnet and permanent magnet thrustors over a range of net accelerating voltages and thrust values. The total input power for the thrustors is obtained from the sum of the ion-beam power, discharge power, cathode heating power, and the power loss resulting from accelerator impingement. For the electromagnet thrustor, the power necessary to operate the electromagnet was included in the total input power. Throughout the investigation no neutralizer was used, and neutralization of the ion-beam was accomplished by electrons from the tank wall. The vaporization of the mercury propellant was accomplished by use of a steam boiler. Therefore, the total input power considered herein does not include the power that would be necessary to operate the propellant vaporizer or the ion-beam neutralizer.




(a) Ion-beam current (constant), 0.0165 ampere; ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

(b) Ion-beam current (constant), 0.0225 ampere; ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

(c) Ion-beam current (constant), 0.030 ampere; ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

Figure 12. - Comparison of power to thrust ratio for electromagnet and permanent magnet thrustors over range of accelerating voltages.

A comparison of the power to thrust ratio for the electromagnet and permanent magnet thrustors over a range of net accelerating voltages and propellant utilization efficiencies is presented in figure 12. For this series of data, the ion-chamber potential difference was set at 30 volts and the neutral propellant flow rate was 0.050 equivalent ampere for both thrustors. The data presented in the figures are also presented in table III(a).

Examination of figure 12 indicates that, for either the electromagnet or permanent magnet thrustor at each propellant utilization, minimum values of power to thrust ratio occurred at net accelerating voltages that were at or near maximum perveance conditions for the accelerator system (see fig. 9, p. 15). In each case, increasing the net accelerating voltage also increased the power to thrust ratio. In general, the electromagnet thrustor operated at power to

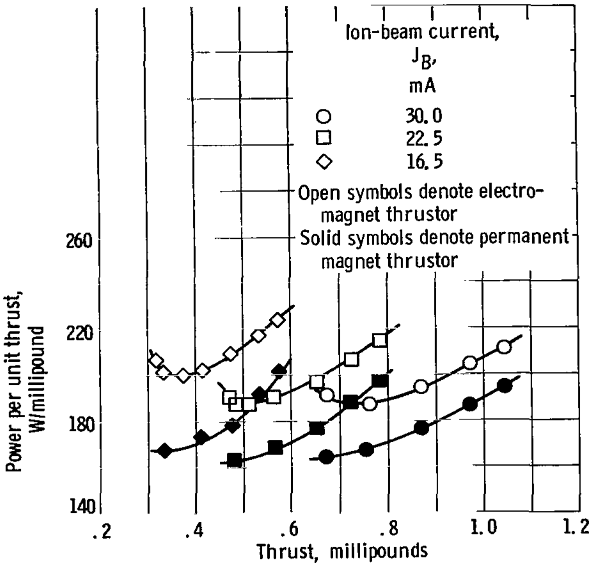



Figure 13. - Comparison of power to thrust ratio for permanent magnet and electromagnet thrustors at constant ion beam values of 20.0, 22.5, and 16.5 milliamperes. Ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

thrust ratios of 16 to 35 watts per millipound higher than the permanent magnet thrustor over the range of net accelerating voltages and utilization efficiencies. This represents a performance advantage of 11 to 12 percent for the permanent magnet thrustor when compared on the basis of the power to thrust ratio.

Figure 13 shows the power to thrust ratio comparison for the thrustors over a range of thrust values for the same data presented in figure 12 (p. 18). The minimum values of power to thrust ratio for each thrustor were obtained at approximately the same net accelerating voltage but at different propellant utilizations. For the electromagnet thrustor, minimum values of power to thrust ratio of 186, 187, and 200 watts per millipound were obtained at thrust values of 0.76, 0.48, and 0.38 millipound, respectively. The corresponding values of net accelerating voltage were 3000, 2500, and 2500 volts. For the permanent magnet thrustor, minimum values of power to thrust ratio of 164, 163, and 167 watts per millipound were obtained at thrust values of 0.67, 0.48, and 0.34 millipound, respectively. Here, the corresponding net accelerating voltages were 2400, 2200, and 2000 volts, respectively. From figure 13, data indicate that a range of thrust would be available for values of power to thrust ratio that vary slightly from the minimum value by maintaining a constant net accelerating voltage and varying the ion-beam current. Varying the ion-beam current while keeping the neutral flow rate constant means, of course, poor utilization at the lower thrust levels. Many applications for small thrustors, though, are relatively insensitive to propellant utilization.

In an effort to examine this aspect further, both thrustors were operated at several constant net accelerating voltages with the net to total accelerating voltage ratio held constant at 0.8. The ion-beam current was then varied to obtain a range in thrust values. Shown in figures 14(a) to (c) (p. 20) are the results of varying the ion-beam current of the thrustors at net accelerating voltages of 3000, 4000, and 5000 volts, respectively. The potential difference of both thrustors was maintained at 30 volts and the neutral propellant flow rate at 0.050 equivalent ampere. The ion-beam current was varied by small adjustments to the filament emission control.

Here again, the permanent magnet thrustor has lower values of power to thrust ratio

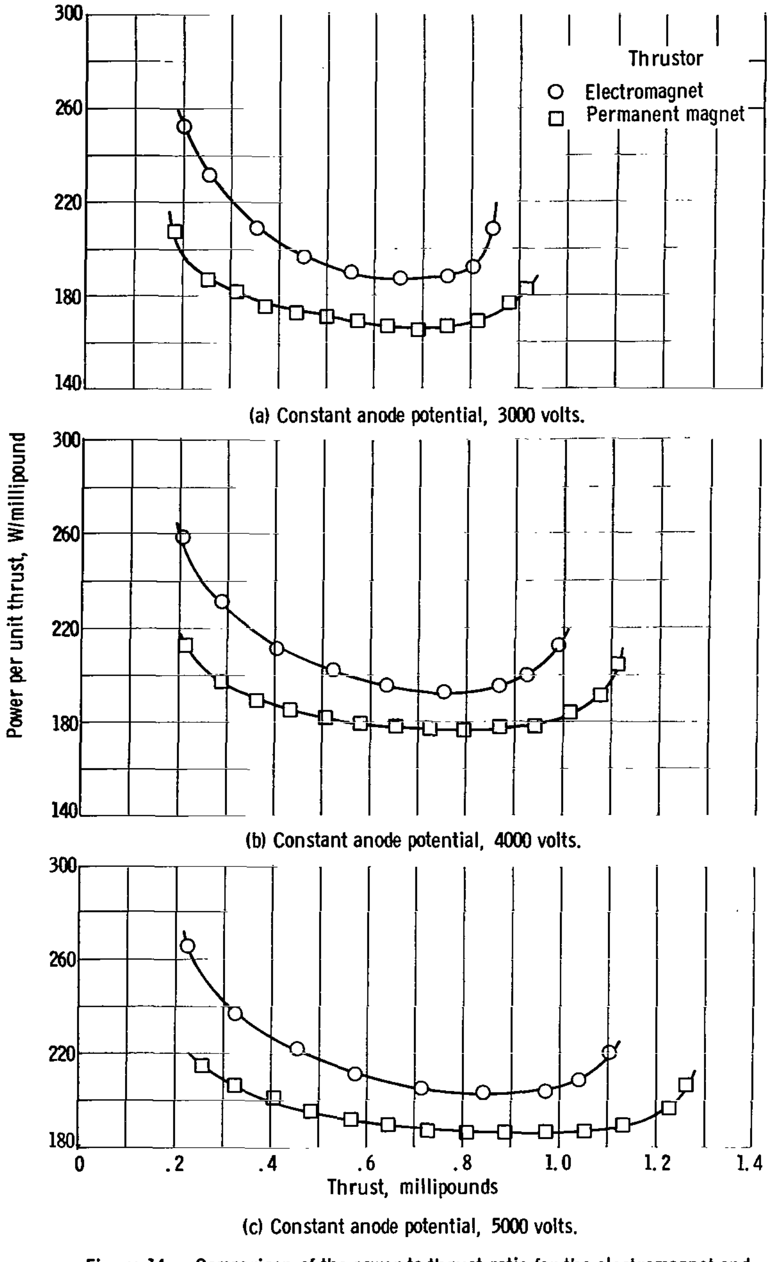



Figure 14. - Comparison of the power to thrust ratio for the electromagnet and permanent magnet thrustors over a range of thrust values. Ion-chamber potential difference, 30.0 volts; neutral propellant flow rate, 0.050 equivalent ampere.

than the electromagnet thrustor. In addition, the permanent magnet thrustor has a larger range of thrust values for minimum values of power to thrust ratio than the electromagnet thrustor. In an effort to define this range, minimum power to thrust ratio values are defined here as a variation of 5 watts per millipound from the lowest value recorded at each net accelerating voltage. For the permanent magnet thrustor, minimum values of power to thrust ratio vary from a thrust of 0.53 to 0.83 millipound with 165 watts per millipound as the lowest value at a net accelerating voltage of 3000 volts. At a net accelerating voltage of 5000 volts, the minimum range is extended from a thrust of 0.56 to 1.17 millipounds with 186 watts per millipound as the lowest value.

In reference 3, the power needed for the vaporizer and neutralizer was 8.7 and 15.5 watts, respectively. If these values were added to the power losses for the permanent magnet thrustor, values of 200 watts per millipound at 0.69 millipound and 3000 volts net accelerating voltage; and 216 watts per millipound at 0.81 millipound and 5000 volts net accelerating voltage would be obtained for an overall power to thrust ratio for the thrustor.

## CONCLUDING REMARKS

Throughout the investigation an effort was made to optimize a permanent magnet thrustor version of an optimum electromagnet ion thrustor suitable for station keeping and attitude control of a synchronous earth satellite. Several permanent magnet electron bombardment ion thrustor configurations were investigated and compared with the reference electromagnet ion thrustor. Results from the investigation showed that a permanent magnet version of the electromagnet thrustor gave ion-chamber performance comparable or slightly better than the electromagnet thrustor for all electrical parameters investigated. The only condition necessary was that the permanent magnet field strength along the axis of the ion chamber be similar to that of the magnetic field of the electromagnet thrustor.

Comparison of chamber performance over a range of propellant flow rates for the electromagnet thrustor and the optimized permanent magnet thrustor showed that the best ion-chamber performance for both thrustors was obtained for propellant flow rates from 0.035 to 0.050 equivalent ampere.

Comparison of both thrustors on the basis of the power to thrust ratio showed that the permanent magnet thrustor had a performance improvement of approximately 12 percent over that of the electromagnet thrustor, with the difference almost entirely accounted for by the electromagnet power of the latter. A power to thrust ratio of 165 watts per millipound was obtained at a thrust of 0.69 millipound and a net accelerating voltage of 3000 volts for the permanent magnet thrustor when the neutralizer and vaporizer power losses were neglected. Consideration of reasonable estimates of the vaporizer and neutralizer power losses gave an overall power to thrust ratio of 200 watts per millipound at 0.69 millipound ($3\times10^{-3}$ newton) of thrust for the permanent magnet thrustor.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 3, 1966,
120-26-02-05-22.

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TABLE I. - PERMANENT MAGNET THRUSTOR DATA

(a) Ion-chamber potential difference comparison of thrustor performance; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor, $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Configuration 1 | | | | | |
| 4000 | -1000 | 0.030 | 28.0 | 1.65 | ------ | 0.00018 | 1.59 | 7.0 | 1510 | 0.60 |
| | | | 27.5 | 1.60 | ------ | .00019 | 2.29 | 9.4 | 1435 | |
| | | | 27.1 | 1.60 | ------ | .00019 | 2.55 | 10.3 | 1420 | |
| | | | 27.0 | 1.58 | ------ | .00015 | 2.49 | 10.0 | 1390 | |
| | | | 26.5 | 1.62 | ------ | .00019 | 2.88 | 11.3 | 1400 | |
| | | | 25.8 | 1.62 | ------ | .00019 | 3.05 | 11.9 | 1365 | |
| | | | 25.5 | 1.68 | ------ | .00019 | 3.0 | 11.9 | 1400 | |
| | | 0.0225 | 27.6 | 0.82 | ------ | 0.00018 | 2.08 | 8.8 | 979 | 0.45 |
| | | | 27.0 | .80 | ------ | .00019 | 2.44 | 10.1 | 934 | |
| | | | 26.0 | .79 | ------ | .00018 | 2.71 | 11.0 | 888 | |
| | | | 25.5 | .80 | ------ | .00018 | 2.71 | 11.0 | 864 | |
| | | | 24.4 | .82 | ------ | .00018 | 2.86 | 11.5 | 865 | |
| | | | 22.4 | .92 | ------ | .00019 | 3.02 | 12.1 | 892 | |
| | | 0.0165 | 29.6 | 0.47 | ------ | 0.00017 | 2.05 | 9.0 | 813 | 0.33 |
| | | | 27.9 | .49 | ------ | .00018 | 2.29 | 9.8 | 795 | |
| | | | 26.5 | .49 | ------ | | 2.4 | 10.2 | 760 | |
| | | | 25.0 | .50 | ------ | | 2.5 | 10.5 | 732 | |
| | | | 23.4 | .52 | ------ | | 2.6 | 10.9 | 714 | |
| | | | 21.9 | .55 | ------ | | 2.71 | 11.25 | 705 | |
| | | | 20.9 | .59 | ------ | | 2.82 | 11.5 | 728 | |
| | | | | | Configuration 2 | | | | | |
| 4000 | -1000 | 0.030 | 25.3 | 1.58 | ------ | 0.00028 | 2.32 | 9.6 | 1305 | 0.60 |
| | | | 24.9 | 1.52 | ------ | .00023 | 2.74 | 10.9 | 1235 | |
| | | | 24.0 | 1.52 | ------ | .00023 | 3.02 | 11.7 | 1192 | |
| | | | 23.3 | 1.57 | ------ | .00038 | 3.12 | 12.0 | 1195 | |
| | | 0.0225 | 25.6 | 0.88 | ------ | 0.00019 | (a) | (a) | 976 | 0.45 |
| | | | 25.0 | .88 | ------ | .00019 | 1.0 | 4.5 | 952 | |
| | | | 24.2 | .86 | ------ | .0002 | 1.59 | 7.0 | 901 | |
| | | | 23.1 | .87 | ------ | .00019 | 2.08 | 8.6 | 869 | |
| | | | 22.4 | .83 | ------ | .00019 | 2.44 | 9.9 | 804 | |
| | | | 22.0 | .81 | ------ | .00019 | 2.68 | 10.5 | 771 | |
| | | | 21.1 | .82 | ------ | .0002 | 2.90 | 11.2 | 750 | |
| | | 0.0165 | 25.0 | 0.52 | ------ | 0.00019 | 2.20 | 9.3 | 762 | 0.33 |
| | | | 24.3 | .51 | ------ | | 2.41 | 10.0 | 725 | |
| | | | 23.1 | .50 | ------ | | 2.56 | 10.2 | 675 | |
| | | | 21.8 | .50 | ------ | | 2.71 | 10.7 | 639 | |
| | | | 19.8 | .51 | ------ | | 2.9 | 11.3 | 591 | |

[a]Autocathode.

TABLE I. - Continued. PERMANENT MAGNET THRUSTOR DATA

(a) Continued. Ion-chamber potential difference comparison of thrustor performance; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor, $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Configuration 3 | | | | | |
| 4000 | -1000 | 0.030 | 30.0 | 0.92 | -0.05 | 0.00015 | 2.1 | 10.5 | 890 | 0.60 |
| | | | 28.5 | 1.00 | -.03 | .00014 | 2.2 | 11.0 | 920 | |
| | | | 25.6 | 1.11 | ------ | .00014 | 2.35 | 11.6 | 920 | |
| | | | 24.5 | 1.25 | .02 | .00015 | 2.5 | 12.1 | 995 | |
| | | 0.0225 | 32.2 | 0.45 | 0.04 | 0.00018 | 2.25 | 11.4 | 606 | 0.45 |
| | | | 29.0 | .49 | -.04 | .00019 | 2.25 | 11.4 | 600 | |
| | | | 26.4 | .51 | -.04 | | 2.3 | 11.6 | 570 | |
| | | | 25.0 | .54 | -.035 | | 2.4 | 11.9 | 575 | |
| | | | 23.0 | .61 | -.03 | | 2.4 | 12.0 | 603 | |
| | | | 22.0 | .69 | -.02 | | 2.5 | 12.2 | 652 | |
| | | 0.0164 | 37.1 | 0.25 | -0.03 | 0.00018 | 2.1 | 10.8 | 521 | 0.33 |
| | | .0166 | 33.0 | .26 | -.03 | | 2.2 | 11.1 | 483 | |
| | | .0166 | 31.8 | .26 | -.03 | | 2.15 | 11.1 | 465 | |
| | | .0166 | 30.8 | .28 | -.03 | | 2.2 | 11.2 | 487 | |
| | | .0164 | 30.1 | .27 | -.03 | | 2.2 | 11.1 | 465 | |
| | | .0165 | 26.9 | .31 | -.02 | .00019 | 2.25 | 11.4 | 478 | |
| | | .0166 | 25.0 | .33 | -.02 | .00019 | 2.25 | 11.5 | 472 | |
| | | | | | Configuration 4 | | | | | |
| 4000 | -1000 | 0.030 | 32.5 | 0.58 | ------ | 0.0002 | 2.95 | 11.2 | 595 | 0.60 |
| | | | 29.5 | .66 | ------ | | 3.0 | 11.4 | 620 | |
| | | | 27.2 | .74 | ------ | | 3.05 | 11.6 | 642 | |
| | | | 26.0 | .78 | ------ | | 3.1 | 11.8 | 650 | |
| | | | 24.9 | .82 | ------ | | 3.15 | 12.0 | 658 | |
| | | | 23.5 | .83 | ------ | | 3.21 | 12.3 | 625 | |
| | | | 23.0 | .85 | ------ | | 3.27 | 12.5 | 627 | |
| | | | 22.6 | .85 | ------ | | 3.3 | 12.6 | 620 | |
| | | | 22.2 | .86 | ------ | | 3.34 | 12.8 | 610 | |
| | | 0.0225 | 24.0 | 0.50 | ------ | 0.00022 | 2.95 | 11.2 | 510 | 0.45 |
| | | | 23.0 | | ------ | | 3.00 | 11.4 | 487 | |
| | | | 22.0 | | ------ | | 3.1 | 11.6 | 466 | |
| | | | 21.0 | | ------ | | 3.2 | 12.0 | 445 | |
| | | | 20.0 | .56 | ------ | | 3.34 | 12.6 | 476 | |
| | | 0.0165 | 24.2 | 0.30 | ------ | 0.0002 | 2.85 | 10.5 | 416 | 0.33 |
| | | | 22.0 | .32 | ------ | .00022 | 2.90 | 10.7 | 405 | |
| | | | 21.0 | .32 | ------ | | 2.97 | 11.0 | 386 | |
| | | | 20.4 | .33 | ------ | | 3.02 | 11.2 | 389 | |
| | | | 19.6 | .37 | ------ | | 3.12 | 11.5 | 420 | |
| | | | 18.6 | .40 | ------ | | 3.25 | 12.1 | 432 | |

TABLE I. - Continued. PERMANENT MAGNET THRUSTOR DATA

(a) Concluded. Ion-chamber potential difference comparison of thrustor performance; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor, $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Configuration 5 | | | | | | | | | | |
| 4000 | -1000 | 0.030 | 36.0 | 0.59 | 0.08 | 0.0002 | 2.05 | 10.2 | 673 | 0.60 |
| | | | 33.0 | .60 | .07 | .00022 | 2.2 | 10.8 | 628 | |
| | | | 30.0 | .65 | .065 | | 2.3 | 11.3 | 620 | |
| | | | 28.0 | .71 | .045 | | 2.4 | 11.5 | 635 | |
| | | | 24.0 | .85 | .030 | | 2.45 | 11.7 | 685 | |
| | | 0.0225 | 32.3 | 0.38 | 0.04 | 0.00022 | 2.2 | 10.9 | 512 | 0.45 |
| | | | 30.0 | .39 | .035 | | 2.25 | 11.0 | 490 | |
| | | | 28.0 | .41 | .035 | | 2.3 | 11.2 | 471 | |
| | | | 25.2 | .48 | .030 | | 2.35 | 11.4 | 512 | |
| | | | 22.2 | .51 | .020 | | 2.45 | 11.9 | 480 | |
| | | 0.0165 | 32.4 | 0.22 | 0.02 | 0.0002 | 2.2 | 10.9 | 397 | 0.33 |
| | | | 30.0 | .23 | .02 | .0002 | 2.25 | 11.2 | 388 | |
| | | | 28.0 | .25 | .02 | .0002 | 2.35 | 11.4 | 395 | |
| | | | 24.7 | .29 | .015 | .00022 | 2.4 | 11.7 | 410 | |
| | | | 22.0 | .31 | .01 | .0002 | 2.45 | 12.0 | 391 | |

TABLE I. - Continued. PERMANENT MAGNET THRUSTOR DATA

(b) Variation of net accelerating voltage with thrustor performance and accelerator impingement current; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Configuration 1 | | | | | | | | | | |
| 2650 | -665 | 0.0225 | 24.8 | 1.11 | ------ | 0.00122 | 2.6 | 10.5 | 1205 | 0.45 |
| 2900 | -725 | ↓ | 25.0 | .95 | ------ | .00035 | 2.8 | 11.3 | 1030 | ↓ |
| 3100 | -775 | ↓ | 25.0 | .92 | ------ | .0002 | 2.82 | 11.4 | 994 | ↓ |
| 4000 | -1000 | ↓ | 25.2 | .79 | ------ | .00015 | 2.88 | 11.6 | 854 | ↓ |
| 5000 | -1250 | ↓ | 25.0 | .69 | ------ | .00012 | 2.95 | 11.8 | 741 | ↓ |
| 5500 | -1375 | ↓ | 25.0 | .64 | ------ | .00012 | 2.95 | 11.8 | 687 | ↓ |
| Configuration 2 | | | | | | | | | | |
| 2800 | -700 | 0.0225 | 22.1 | 1.14 | ------ | 0.0019 | 2.5 | 10.2 | 1100 | 0.45 |
| 3000 | -750 | ↓ | 22.5 | 1.01 | ------ | .0009 | 2.5 | 10.2 | 987 | ↓ |
| 3300 | -825 | ↓ | 22.6 | .94 | ------ | .00035 | 2.61 | 10.5 | 920 | ↓ |
| 3500 | -875 | ↓ | ↓ | .89 | ------ | .0002 | 2.74 | 10.8 | 870 | ↓ |
| 4000 | -1000 | ↓ | ↓ | .82 | ------ | .0002 | 2.80 | 11.0 | 800 | ↓ |
| 5000 | -1250 | ↓ | ↓ | .73 | ------ | .00019 | 2.84 | 11.1 | 710 | ↓ |
| 5600 | -1400 | ↓ | ↓ | .69 | ------ | .00019 | 2.89 | 11.2 | 670 | ↓ |
| Configuration 3 | | | | | | | | | | |
| 2500 | -625 | 0.0225 | 29.9 | 0.59 | ------ | 0.00019 | 2.35 | 11.8 | 753 | 0.45 |
| 3000 | -750 | ↓ | 29.9 | .52 | ------ | .00017 | 2.3 | 11.5 | 660 | ↓ |
| 4000 | -1000 | ↓ | 30.0 | .44 | ------ | .00019 | 2.25 | 11.4 | 556 | ↓ |
| 5000 | -1250 | ↓ | 30.0 | .41 | ------ | .00014 | 2.45 | 12.2 | 515 | ↓ |
| 6000 | -1500 | ↓ | 30.0 | .39 | ------ | .00021 | 2.25 | 11.4 | 490 | ↓ |
| Configuration 4 | | | | | | | | | | |
| 2200 | -550 | 0.0225 | 22.0 | 0.68 | ------ | 0.0012 | 3.25 | 12.0 | 643 | 0.45 |
| 2400 | -600 | ↓ | ↓ | .61 | ------ | .0003 | 3.26 | 11.9 | 575 | ↓ |
| 2600 | -650 | ↓ | ↓ | .58 | ------ | .00022 | 3.28 | 12.0 | 545 | ↓ |
| 3000 | -750 | ↓ | ↓ | .55 | ------ | ↓ | 3.2 | 11.9 | 516 | ↓ |
| 4000 | -1000 | ↓ | ↓ | .50 | ------ | ↓ | 3.15 | 11.8 | 467 | ↓ |
| 5000 | -1250 | ↓ | ↓ | .47 | ------ | ↓ | 3.1 | 11.6 | 437 | ↓ |
| 5600 | -1400 | ↓ | ↓ | .43 | ------ | ↓ | 3.1 | 11.7 | 398 | ↓ |
| Configuration 5 | | | | | | | | | | |
| 2200 | -550 | 0.0225 | 30.0 | 0.51 | 0.05 | 0.0003 | 2.4 | 11.7 | 650 | 0.45 |
| 3000 | -750 | ↓ | ↓ | .44 | .045 | .00025 | ↓ | ↓ | 557 | ↓ |
| 4000 | -1000 | ↓ | ↓ | .38 | .035 | .00022 | ↓ | ↓ | 476 | ↓ |
| 5000 | -1250 | ↓ | ↓ | .33 | .025 | .00022 | ↓ | ↓ | 410 | ↓ |
| 5800 | -1450 | ↓ | ↓ | .31 | .025 | .00022 | ↓ | ↓ | 383 | ↓ |

TABLE I. - Continued. PERMANENT MAGNET THRUSTOR DATA

(c) Variation of propellant utilization efficiency with thrustor performance; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathscr{E}$, eV/ion | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Configuration 1 | | | | | | | | | | |
| 4000 | -1000 | 0.0309 | 26.0 | 1.93 | ------ | 0.00015 | 3.0 | 11.8 | 1590 | 0.618 |
| | | .029 | | 1.47 | ------ | .00012 | 2.75 | 11.0 | 1290 | .58 |
| | | .0254 | | 1.00 | ------ | .00015 | 2.80 | 11.2 | 998 | .508 |
| | | .0229 | | .80 | ------ | .00015 | 2.81 | 11.4 | 882 | .458 |
| | | .018 | | .52 | ------ | .00015 | 2.81 | 11.4 | 727 | .36 |
| | | .0131 | | .33 | ------ | .00011 | 2.7 | 11.2 | 629 | .262 |
| | | .009 | | .20 | ------ | .0001 | 2.55 | 10.7 | 552 | .180 |
| Configuration 2 | | | | | | | | | | |
| 4000 | -1000 | 0.0312 | 23.3 | 1.81 | ------ | 0.0004 | 2.94 | 11.5 | 1330 | 0.624 |
| | | .029 | 23.0 | 1.32 | ------ | .00021 | 2.9 | 11.3 | 1022 | .58 |
| | | .027 | 23.1 | 1.16 | ------ | .00019 | 2.93 | 11.3 | 975 | .54 |
| | | .025 | 23.1 | .96 | ------ | | 2.82 | 11.4 | 864 | .50 |
| | | .022 | 22.9 | .78 | ------ | | 2.8 | 11.3 | 790 | .44 |
| | | .019 | 23.0 | .62 | ------ | | 2.75 | 11.0 | 727 | .38 |
| | | .015 | 23.0 | .45 | ------ | | 2.63 | 10.7 | 668 | .30 |
| | | .010 | 23.0 | .25 | ------ | .00015 | 2.45 | 10.2 | 551 | .20 |
| | | .0075 | 23.0 | .18 | ------ | .0001 | 2.35 | 10.0 | 530 | .15 |
| Configuration 3 | | | | | | | | | | |
| 4000 | -1000 | 0.033 | 30.0 | 2.02 | 0.08 | 0.00011 | 2.5 | 12.1 | 1805 | 0.67 |
| | | .0325 | 30.0 | 1.42 | .01 | .00011 | 2.4 | 11.6 | 1280 | .65 |
| | | .031 | 29.8 | 1.05 | ------ | .00015 | 2.25 | 11.3 | 977 | .62 |
| | | .0225 | 30.0 | .43 | ------ | .00019 | 2.3 | 11.55 | 540 | .45 |
| | | .0169 | 30.0 | .28 | ------ | .00019 | 2.25 | 11.5 | 482 | .338 |
| | | .009 | 30.0 | .11 | ------ | .00012 | 2.1 | 11.0 | 337 | .180 |

TABLE I. - Concluded. PERMANENT MAGNET THRUSTOR DATA

(c) Concluded. Variation of propellant utilization efficiency with thrustor performance; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor, $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Configuration 4 | | | | | | | | | | |
| 4000 | -1000 | 0.0305 | 21.5 | 0.94 | ------ | 0.0002 | 3.50 | 13.0 | 644 | 0.61 |
| | | .029 | 21.0 | .84 | ------ | .0002 | 3.50 | 13.0 | 589 | .58 |
| | | .0275 | | .72 | ------ | .00021 | 3.40 | 12.5 | 529 | .55 |
| | | .025 | | .60 | ------ | .00025 | 3.29 | 12.2 | 482 | .50 |
| | | .0229 | | .50 | ------ | .00022 | 3.22 | 12.0 | 437 | .458 |
| | | .0212 | | .46 | ------ | .00021 | 3.18 | 11.8 | 433 | .424 |
| | | .019 | | .39 | ------ | .00021 | 3.08 | 11.5 | 410 | .38 |
| | | .0158 | | .30 | ------ | .0002 | 3.00 | 11.0 | 376 | .308 |
| | | .0138 | | .27 | ------ | | 2.91 | 10.7 | 390 | .276 |
| | | .0119 | | .21 | ------ | | 2.84 | 10.5 | 352 | .238 |
| | | .0102 | | .19 | ------ | | 2.77 | 10.2 | 378 | .204 |
| | | .0085 | | .15 | ------ | | 2.7 | 9.9 | 350 | .17 |
| Configuration 5 | | | | | | | | | | |
| 4000 | -1000 | 0.0382 | 30.0 | 2.08 | 0.04 | 0.00019 | 2.35 | 11.2 | 1605 | 0.764 |
| | | .0375 | | 1.50 | .055 | .0002 | 2.35 | 11.2 | 1170 | .75 |
| | | .035 | | 1.10 | .065 | .00022 | 2.4 | 11.5 | 912 | .70 |
| | | .0325 | | .80 | .070 | | | 11.9 | 708 | .65 |
| | | .030 | | .68 | .055 | | | | 650 | .60 |
| | | .0275 | | .55 | .045 | | | | 570 | .55 |
| | | .0250 | | .46 | .04 | | | | 522 | .50 |
| | | .0225 | | .39 | .03 | | | 11.8 | 490 | .45 |
| | | .020 | | .31 | .03 | | | 11.8 | 434 | .40 |
| | | .0175 | | .25 | .02 | .0002 | | 11.8 | 399 | .35 |
| | | .015 | | .20 | .015 | .0002 | 2.4 | 11.7 | 370 | .30 |
| | | .0125 | | .16 | .01 | .00019 | 2.3 | 11.6 | 353 | .25 |
| | | .010 | | .11 | .005 | .00018 | 2.3 | 11.5 | 300 | .20 |
| | | .0075 | | .095 | 0 | .00015 | 2.3 | 11.2 | 350 | .15 |

TABLE II. - NEUTRAL PROPELLANT FLOW DATA

[Ion-chamber potential, 4000 V; accelerator potential, -1000 V.]

| Ion-beam current (common ground), $J_B$, A | Ion-chamber potential difference, $\Delta V_I$, V | Current collected by anode, $J_I$, A | Current collected by screen and distributor, $J_{SD}$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Neutral propellant flow equivalent, A | Propellant utilization efficiency, $\eta_u$ |
|---|---|---|---|---|---|---|---|---|---|
| Electromagnet thrustor[a] | | | | | | | | | |
| 0.045 | 20.2 | 2.02 | 0.045 | 0.00045 | 2.85 | 12.5 | 888 | 0.075 | 0.60 |
| .0337 | 20.0 | 1.15 | .045 | .00045 | 2.8 | 12.5 | 662 | .075 | .45 |
| .0248 | 20.2 | .75 | .035 | .00045 | 2.6 | 11.7 | 591 | .075 | .33 |
| .030 | 29.9 | .80 | .025 | .00015 | 2.7 | 11.5 | 766 | .050 | .60 |
| .0225 | 30.0 | .44 | .025 | .00018 | 2.4 | 10.8 | 556 | .050 | .45 |
| .0165 | 30.0 | .29 | .015 | .00018 | 2.65 | 11.4 | 496 | .050 | .33 |
| .0157 | 28.0 | .31 | .005 | .00005 | 2.95 | 12.9 | 526 | .035 | .45 |
| .0115 | 28.0 | .20 | .005 | .00005 | 2.65 | 12.0 | 457 | .035 | .33 |
| Permanent magnet thrustor (configuration 5) | | | | | | | | | |
| 0.045 | 19.8 | 2.19 | 0.010 | 0.0006 | 2.85 | 12.7 | 944 | 0.075 | 0.60 |
| .0337 | 20.5 | 1.22 | .050 | .0006 | 2.20 | 11.2 | 720 | .075 | .45 |
| .0248 | 20.0 | .81 | 030 | .00055 | 2.45 | 11.5 | 634 | .075 | .33 |
| .030 | 30.0 | .65 | .065 | .00022 | 2.3 | 11.3 | 620 | .050 | .60 |
| .0225 | 30.0 | .39 | .035 | .00022 | 2.25 | 11.0 | 490 | .050 | .45 |
| .0165 | 30.0 | .23 | .020 | .0002 | 2.25 | 11.2 | 388 | .050 | .33 |
| .021 | 28.7 | .49 | ----- | .0001 | 3.35 | 14.4 | 641 | .035 | .60 |
| .0157 | 28.0 | .21 | .01 | .0001 | 2.65 | 12.3 | 346 | .035 | .45 |
| .0115 | 28.2 | .15 | .01 | .0001 | 2.50 | 11.9 | 340 | .035 | .33 |
| .0112 | 30.0 | .19 | ----- | .00005 | 2.9 | 13.7 | 477 | .025 | .448 |
| .0088 | 30.0 | .10 | ----- | .00005 | 2.6 | 12.6 | 311 | .025 | .352 |

[a]Magnetic field strength at screen and distributor; 24 and 60 gauss, respectively.

TABLE III. - OVERALL THRUSTOR PERFORMANCE

[Ion-chamber potential difference, 30.0 V.]

(a) Comparison of power to thrust ratio by varying accelerating voltage; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Current collected by anode, $J_I$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Thrust, millipound | Power per unit thrust, W/millipound |
|---|---|---|---|---|---|---|---|---|---|
| Electromagnet thrustor[a] | | | | | | | | | |
| 2400 | -600 | 0.030 | 1.00 | 0.0004 | 2.8 | 11.7 | 970 | 0.672 | 191.51 |
| 2500 | -625 | ↓ | .98 | .00025 | 2.7 | 11.4 | 950 | .685 | 203.91 |
| 3000 | -750 | ↓ | .92 | .00018 | 2.7 | 11.6 | 890 | .767 | 186.47 |
| 4000 | -1000 | ↓ | .83 | .00015 | 2.6 | 11.3 | 800 | .870 | 194.77 |
| 5000 | -1250 | ↓ | .79 | .00015 | 2.65 | 11.3 | 760 | .972 | 204.46 |
| 5800 | -1450 | ↓ | .78 | .00015 | 2.5 | 10.8 | 750 | 1.045 | 211.56 |
| 2100 | -525 | .0225 | .59 | .00035 | 2.6 | 11.3 | 759 | .473 | 190.10 |
| 2200 | -550 | ↓ | .53 | .00019 | 2.7 | 11.4 | 677 | .484 | 187.23 |
| 2500 | -625 | ↓ | .50 | .00019 | ↓ | 11.4 | 636 | .515 | 187.36 |
| 3000 | -750 | ↓ | .48 | .0002 | ↓ | 11.4 | 610 | .565 | 190.00 |
| 4000 | -1000 | ↓ | .42 | .00018 | ↓ | 11.5 | 530 | .653 | 196.47 |
| 5000 | -1250 | ↓ | .40 | .00015 | ↓ | 11.5 | 503 | .729 | 206.09 |
| 5800 | -1450 | ↓ | .40 | .00018 | ↓ | 11.55 | 503 | .786 | 214.63 |
| 1800 | -450 | .0165 | .38 | .00022 | 2.65 | 11.4 | 660 | .320 | 206.86 |
| 2000 | -500 | ↓ | .34 | .00019 | ↓ | ↓ | 589 | .338 | 201.99 |
| 2500 | -625 | ↓ | .31 | .0002 | ↓ | ↓ | 533 | .378 | 200.33 |
| 3000 | -750 | ↓ | .30 | .00018 | ↓ | ↓ | 515 | .414 | 202.35 |
| 4000 | -1000 | ↓ | .29 | .00018 | ↓ | ↓ | 496 | .478 | 209.62 |
| 5000 | -1250 | ↓ | .28 | .00018 | 2.6 | 11.3 | 479 | .534 | 217.65 |
| 5800 | -1450 | ↓ | .26 | .00019 | 2.6 | 11.3 | 443 | .576 | 223.91 |
| Permanent magnet thrustor (configuration 5) | | | | | | | | | |
| 2400 | -600 | 0.030 | 0.83 | 0.00035 | 2.4 | 11.6 | 800 | 0.674 | 164.61 |
| 3000 | -750 | ↓ | .75 | .00022 | ↓ | ↓ | 720 | .752 | 167.98 |
| 4000 | -1000 | ↓ | .64 | .00022 | ↓ | ↓ | 610 | .870 | 176.20 |
| 5000 | -1250 | ↓ | .58 | .00022 | ↓ | ↓ | 550 | .973 | 186.81 |
| 5800 | -1450 | ↓ | .52 | .0002 | ↓ | ↓ | 490 | 1.048 | 194.84 |
| 2200 | -550 | .0225 | .51 | .0003 | 2.4 | 11.7 | 650 | .484 | 163.17 |
| 3000 | -750 | ↓ | .44 | .00025 | ↓ | ↓ | 557 | .565 | 168.21 |
| 4000 | -1000 | ↓ | .38 | .00022 | ↓ | ↓ | 476 | .652 | 177.70 |
| 5000 | -1250 | ↓ | .33 | .00022 | ↓ | ↓ | 410 | .729 | 188.12 |
| 5800 | -1450 | ↓ | .31 | .00022 | ↓ | ↓ | 383 | .785 | 197.12 |
| 2000 | -500 | .0165 | .33 | .00025 | 2.35 | 11.5 | 570 | .338 | 167.38 |
| 3000 | -750 | ↓ | .27 | .0002 | 2.35 | 11.5 | 460 | .414 | 172.46 |
| 4000 | -1000 | ↓ | .22 | ↓ | 2.3 | 11.4 | 370 | .479 | 179.95 |
| 5000 | -1250 | ↓ | .21 | ↓ | 2.3 | 11.4 | 351 | .535 | 191.87 |
| 5800 | -1450 | ↓ | .20 | ↓ | 2.3 | 11.4 | 334 | .576 | 201.14 |

[a]Magnet power, 10 W.

TABLE III. - Continued. OVERALL THRUSTOR PERFORMANCE

[Ion-chamber potential difference, 30.0 V.]

(b) Comparison of power to thrust ratio by varying ion-beam current; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Current collected by anode, $J_I$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Thrust, millipound | Power per unit thrust, W/millipound |
|---|---|---|---|---|---|---|---|---|---|
| Electromagnet thrustor[a] | | | | | | | | | |
| 3000 | -750 | 0.008 | 0.11 | 0.0001 | 2.45 | 10.8 | 386 | 0.201 | 252.16 |
| | | .010 | .16 | .0001 | 2.55 | 11.0 | 450 | .255 | 231.08 |
| | | .014 | .22 | .00015 | 2.6 | 11.3 | 440 | .352 | 208.58 |
| | | .018 | .34 | .00018 | | | 536 | .452 | 196.95 |
| | | .022 | .48 | .00020 | | | 623 | .553 | 190.14 |
| | | .026 | .66 | .00018 | | | 730 | .653 | 187.40 |
| | | .030 | .92 | .00017 | | | 890 | .754 | 188.42 |
| | | .032 | 1.13 | .00015 | 2.8 | 10.9 | 1030 | .805 | 192.31 |
| | | .0335 | 1.46 | .00018 | 3.3 | 13.5 | 1260 | .842 | 208.58 |
| 4000 | -1000 | 0.0072 | 0.10 | 0.0001 | 2.3 | 10.5 | 386 | 0.209 | 258.99 |
| | | .010 | .13 | .0001 | 2.4 | 10.8 | 360 | .290 | 231.20 |
| | | .014 | .21 | .00015 | 2.45 | 11.0 | 420 | .406 | 212.04 |
| | | .018 | .31 | .00018 | 2.5 | 11.1 | 486 | .522 | 202.10 |
| | | .022 | .42 | .00015 | | 11.1 | 543 | .638 | 195.21 |
| | | .026 | .61 | .00018 | | 11.0 | 674 | .754 | 193.83 |
| | | .030 | .89 | .00015 | | 11.0 | 860 | .870 | 195.74 |
| | | .032 | 1.08 | .00015 | 2.7 | 11.7 | 980 | .928 | 200.27 |
| | | .0341 | 1.46 | .0001 | 3.25 | 13.5 | 1250 | .990 | 213.43 |
| 5000 | -1250 | 0.007 | 0.10 | 0.00015 | 2.25 | 10.4 | 398 | 0.227 | 266.19 |
| | | .010 | .13 | .00015 | 2.35 | 10.6 | 360 | .324 | 237.77 |
| | | .014 | .21 | .00018 | 2.5 | 11.0 | 420 | .453 | 222.21 |
| | | .018 | .30 | | 2.5 | | 470 | .583 | 211.55 |
| | | .022 | .40 | | 2.5 | | 515 | .712 | 205.30 |
| | | .026 | .57 | | 2.55 | | 627 | .841 | 203.89 |
| | | .030 | .81 | .00015 | 2.55 | | 780 | .970 | 204.52 |
| | | .0322 | 1.02 | .00015 | 2.75 | 11.8 | 920 | 1.042 | 209.01 |
| | | .0341 | 1.39 | .00015 | 3.25 | 13.5 | 1190 | 1.105 | 220.75 |

[a]Magnet power, 10 W.

TABLE III. - Concluded. OVERALL THRUSTOR PERFORMANCE

[Ion-chamber potential difference, 30.0 V.]

(b) Concluded. Comparison of power to thrust ratio by varying ion-beam current; neutral propellant flow rate, 0.050 equivalent ampere

| Ion-chamber potential, $V_I$, V | Accelerator potential, $V_A$, V | Ion-beam current (common ground), $J_B$, A | Current collected by anode, $J_I$, A | Current collected by accelerator, $J_A$, A | Filament heating potential difference, $\Delta V_F$, V | Filament heating current, $J_F$, A | Energy dissipated in discharge per beam ion, $\mathcal{E}$, eV/ion | Thrust, millipound | Power per unit thrust, W/millipound |
|---|---|---|---|---|---|---|---|---|---|
| Permanent magnet thrustor (configuration 5) | | | | | | | | | |
| 3000 | -750 | 0.0075 | 0.10 | 0.00015 | 2.30 | 11.3 | 370 | 0.188 | 206.57 |
| | | .010 | .12 | .00019 | 2.35 | 11.5 | 330 | .255 | 186.32 |
| | | .0125 | .19 | .0002 | 2.35 | 11.5 | 426 | .314 | 181.75 |
| | | .015 | .23 | .0002 | 2.4 | 11.6 | 431 | .377 | 175.49 |
| | | .0175 | .30 | .00022 | | | 485 | .440 | 172.21 |
| | | .020 | .38 | | | | 540 | .502 | 170.46 |
| | | .0225 | .45 | | | | 571 | .565 | 168.36 |
| | | .025 | .52 | | | | 594 | .628 | 166.60 |
| | | .0275 | .61 | | 2.35 | 11.5 | 635 | .691 | 165.36 |
| | | .030 | .74 | | 2.35 | 11.5 | 710 | .754 | 166.61 |
| | | .0325 | .92 | .0002 | 2.35 | 11.4 | 820 | .817 | 169.21 |
| | | .035 | 1.25 | .0002 | 2.3 | 11.3 | 1040 | .880 | 176.30 |
| | | .0364 | 1.52 | .0002 | 2.3 | 11.3 | 1222 | .915 | 182.78 |
| 4000 | -1000 | 0.0075 | 0.095 | 0.00015 | 2.3 | 11.2 | 350 | 0.217 | 212.50 |
| | | .010 | .11 | .00018 | 2.3 | 11.5 | 300 | .290 | 196.93 |
| | | .0125 | .16 | .00019 | 2.3 | 11.6 | 353 | .362 | 189.80 |
| | | .015 | .20 | .0002 | 2.4 | 11.7 | 370 | .435 | 185.28 |
| | | .0175 | .25 | .0002 | | 11.8 | 399 | .507 | 181.75 |
| | | .020 | .31 | .00022 | | 11.8 | 434 | .580 | 179.20 |
| | | .0225 | .39 | .00022 | | 11.8 | 490 | .653 | 178.10 |
| | | .025 | .46 | | | 11.9 | 522 | .725 | 177.17 |
| | | .0275 | .55 | | | | 570 | .797 | 177.02 |
| | | .030 | .68 | | | | 650 | .870 | 178.04 |
| | | .0325 | .80 | | | | 708 | .944 | 178.39 |
| | | .035 | 1.10 | | | 11.5 | 912 | 1.015 | 184.04 |
| | | .0375 | 1.50 | .0002 | 2.35 | 11.2 | 1170 | 1.087 | 191.40 |
| | | .0382 | 2.08 | .00019 | 2.35 | 11.2 | 1605 | 1.113 | 205.21 |
| 5000 | -1250 | 0.008 | 0.10 | 0.00015 | 2.2 | 10.9 | 345 | 0.259 | 215.18 |
| | | .010 | .12 | .00018 | 2.25 | 11.1 | 330 | .324 | 206.55 |
| | | .0125 | .17 | .0002 | 2.3 | 11.3 | 377 | .405 | 201.16 |
| | | .015 | .20 | | 2.35 | 11.4 | 370 | .486 | 195.88 |
| | | .0175 | .24 | | 2.35 | 11.5 | 382 | .567 | 192.13 |
| | | .020 | .29 | | 2.35 | | 405 | .647 | 189.87 |
| | | .0225 | .34 | | 2.4 | | 423 | .729 | 187.65 |
| | | .025 | .40 | .00022 | | | 450 | .810 | 186.94 |
| | | .0275 | .49 | .0002 | | | 505 | .890 | 187.02 |
| | | .030 | .58 | .0002 | | | 550 | .971 | 186.97 |
| | | .0325 | .70 | .00019 | | | 616 | 1.055 | 187.19 |
| | | .035 | .90 | | | | 732 | 1.132 | 190.44 |
| | | .0379 | 1.32 | | | | 1015 | 1.229 | 197.26 |
| | | .039 | 1.71 | | | | 1285 | 1.262 | 206.16 |



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