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Operation of the J-Series Thruster Using Inert Gas

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OPERATION OF THE J-SERIES THRUSTER USING INERT GAS

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ABSTRACT

Electron bombardment ion thrusters using inert gases are candidates for Large Space Systems. The J-Series 30 cm diameter thruster, designed for operation up to 3 kW with mercury, has been developed to a state of technology readiness. This paper compares the characteristics of operation with xenon, krypton, and argon propellants in a J-Series thruster with that obtained with mercury. The performance of the discharge chamber, ion optics, and neutralizer; the overall efficiency as functions of input power and specific impulse; and thruster lifetime were evaluated. As expected, the discharge chamber performance with inert gases decreased with decreasing atomic mass. In addition, aspects of the J-series thruster design which would require modification to provide operation at high power with inert gases were identified.

INTRODUCTION

Electron bombardment ion thrusters using inert gases are being considered for Large Space Systems (LSS). Inert gas propellants are of interest because they: (1) provide some performance benefits (such as near instantaneous startup and simplified power processing) which are important for LSS applications; (2) they are noncontaminating and nonreactive with space system elements which should simplify integration with the Space Transportation System (STS) and LSS; and (3) they are nontoxic and nonreactive with biosphere constituents which should minimize ecological concerns relative to other space propulsion concepts.

Because thruster performance strongly impacts the trip time and power requirements of potential missions, experimental programs were intiated to investigate the operation of thrusters using inert gases. The J-Series 30 cm diameter electron bombardment ion thruster, designed for operation up to 3 kW with mercury propellant, has been developed to a state of technology readiness[1]. It has undergone extensive performance characterization, vibration, thermal, and endurance testing, and has been integrated into a propulsion module with the power processor and propellant tank. It was, therefore, of interest to determine the performance of inert gas propellants with the highly developed J-Series thruster and what modifications would be necessary to provide operation at high power with inert gases. Knowledge of that performance and those modifications will allow an assessment of the desirability of proceeding with thruster designs that promise improved performance[2,3] or lifetime.

The performance of other hollow cathode, electron bombardment ion thrusters, operated with propellants other than mercury or cesium, has been reported. A 15 cm diameter Space Electric Rocket Test (SERT) II-type thruster was tested with xenon, krypton, argon, nitrogen, neon, helium, and carbon dioxide[4] and Kaufman and his co-workers have reported results from their inert gas ion thruster technology program[5]. Operation of a divergent field 30 cm diameter ion thruster using argon and xenon was presented in reference 6. The expected propulsion system performance characteristics for LSS using ion thrusters were analyzed in references 7 and 8. Recently, Sovey[2] reported improved performance of an argon ion thruster which utilized a type of plasma containment different from that of the SERT II and J-Series thrusters. In addition, several companion papers present the operation of inert gas ion thrusters which vary in diameter from 5 cm to 30 cm (references 9-15).

This paper presents the results of a brief test program to provide performance data and information of the modifications required of the J-Series thruster operated on xenon, krypton, and argon.

APPARATUS

Thruster

The thruster used for the tests, reported herein, was a 30 cm diameter mercury ion thruster built by Hughes Research Laboratories (HRL) and designated SN-J8. The thruster was fabricated and acceptance tested at HRL, as described in reference 16, and delivered to NASA Lewis Research Center (LeRC). It was operated with mercury at LeRC[17] for about 400 hours prior to testing with inert gases.

The ion optics system is basically a pair of 0.38 mm thick molybdenum plates perforated with matching apertures over an area with a 28.3 cm diameter. The upstream or screen grid has 1.9 mm diameter holes and the downstream or accelerator grid has 1.14 mm diameter holes. The open area fractions of the screen and accelerator grids are 0.67 and 0.24, respectively. The cold grid-to-grid spacing is 0.5 mm. The thruster was modified, in several ways, for operation with inert gases. First, it was anticipated that cathode and neutralizer propellant flow rates, with inert gases, might be much higher than those with mercury. Therefore, direct lines, without the porous tungsten vaporizers, were run from the gas supply to each cathode. The main vaporizer was retained, but the isolator was not stressed with high voltage during the test. The gas supply feed lines were grounded and electrically isolated from the thruster by one meter lengths of plastic tubing. In accommodating the neutralizer gas supply line change, the neutralizer cathode was located outward one cm from its normal position. The only other modification to the thruster was the use of a single piece 4.1 cm diameter magnetic baffle for some of the tests instead of the standard three piece tantalum clad 5.6 cm diameter baffle.

Facility

The thruster was operated in a 4.6 m diameter by 19.2 m long vacuum tank. The base pressure, without

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propellant gas flow, was about 3 x 10^{-4} Pa (2 x 10^{-6} torr) after 24 hours of pumping. During thruster operation, the pressure varied between 1 and 7 x 10^{-3} Pa (1 and 5 x 10^{-5} torr).

Power Supplies

60 hertz input laboratory power supplies were used. The two cathode heaters were powered with alternating current while the discharge, magnetic baffle, and two keeper supplies had full wave, single phase, rectified outputs. The discharge supply had a 100 V-100 amp output and was operated in the current limited mode. The screen and accelerator high voltage supplies were of a high capacity, three phase, full wave bridge rectifier design.

Propellant Feed System

The inert gases used were research grade (≥ 99.99 percent purity). The main, cathode, and neutralizer flow rates are measurements of the propellant supplied to the discharge chamber volume (usually the major portion of the total flow rate), the discharge cathode, and the neutralizer cathode, respectively.

Flow rates were controlled manually with precision leak valves. Flow rates were measured with digital readout mass flow rate transducers which were calibrated using volume displacement methods.

PROCEDURE

The thruster was installed and the facility was pumped out for 24 hours. Each feed line was purged with propellant gas. Both cathode discharges were started, the flow rates were then reduced to operating values, and the ion beam was extracted. To characterize the discharge chamber performance, the flow rates were fixed at the desired values and then the discharge power was varied by adjusting the reference signal for the current limited discharge current. The magnetic baffle was varied at fixed discharge power. The performance of the ion optics was evaluated at fixed flow rate and discharge power. Finally, neutralizer information was obtained at fixed values of beam current.

Measured Value Corrections

There are numerous ways to present measured performance data. The discharge chamber performance data presented herein have been corrected to account for gas ingestion by assuming a total neutral propellant flow rate larger than the measured flow rate by an amount proportional to the facility pressure (typically 3 to 5 percent). Facility ionization gage pressure values were corrected for different sensitivities, depending on the propellant type, according to reference 18.

The discharge chamber performance presented herein, for mercury and inert gas propellants, have not been corrected to account for doubly charged ion current. The measured values of beam current were used to calculate values of discharge power per beam ampere and propellant efficiency. However, values of total thruster efficiency and specific impulse were calculated using measured values of thruster parameters and applying correction factors for doubly charged ions and non-axial ion trajectories. The thrust correction factor for doubly charged ions (α), used herein for inert gases, was assumed to be only a function of the measured discharge chamber propellant efficiency and to be the same as for mercury. It has been shown[19] that for mercury propellant, and a given thruster geometry (900 series), the doubly to singly charged ion current ratio (r) correlates well with the measured discharge propellant efficiency over a wide range of discharge parameters and propellant flow rates. As shown in figure 1, the correlation holds for the J-Series thruster which uses ion optics having a smaller hole accelerator grid (SHAG). The SHAG optics are the primary reason for the increase in propellant efficiency obtained at a given value of the doubly to singly charged ion current ratio. Figure 1 also shows the average double ion current ratio as a function of propellant efficiency for Sovey's[13] ring-cusp magnetic field ion thruster operated on xenon, krypton, and argon. These data show that, to first order, the double ion current ratio-propellant efficiency correlation is independent of propellant type, for a given thruster design. Based on these results, the propellant efficiency values measured herein with inert gases were used, with the curve from figure 1 for the J-Series thruster, to predict values of the doubly to singly charged ion current ratio (r) and thrust correction factor (α), where

$$\alpha = \frac{1 + \frac{\sqrt{2}}{2} r}{1 + r} \qquad (1)$$

For all data reported herein, triply charged ions were assumed to be negligible. Measured values of discharge chamber performance presented herein may be corrected to allow comparisons with those of other thrusters by dividing the discharge power per beam ampere and multiplying the propellant efficiency by the beam ion correction factor (β) where

$$\beta = \frac{1 + \frac{1}{2} r}{1 + r} \qquad (2)$$

The measured perveance of the ion optics was reduced by the thrust correction factor for doubly charged ions (α) as discussed in reference[20]. For a given grid geometry, the correction for non-axial ion trajectories has been shown[21] to be primarily a function of the ratio of net-to-total ion accelerating voltage. Because that ratio was maintained at a near constant value of 0.7, a beam divergence thrust correction factor of 0.98 was utilized for all calculations. Values of total efficiency, presented herein, are only for the thruster. Total system efficiency values would require inclusion of efficiency factors for the power processor and cabling as indicated in reference 22.

RESULTS AND DISCUSSIONS

The test results will be presented in separate discussions of discharge initiation, discharge chamber performance, ion optics performance, neutralizer performance, overall thruster performance, and thruster lifetime. The effects of propellant type variation will be discussed in each subsection.

Discharge Initiation

The cathodes and electron emitting inserts were J-Series hardware. The normal insert conditioning and cathode heating procedures[16] were initially

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used. Open circuit keeper voltages of 350 v were used to ignite the keeper discharges at inert gas propellant flow rates of about 2 equivalent amperes (each atom is assumed to be singly charged). The main cathode discharge could also be initiated by applying a 3 KV-3 microsecond pulse between the keeper electrode and the heated cathode using approximately 15 eq. amp of propellant. For all three inert gas propellants, both cathode discharges could be reliably initiated with unheated cathodes, 350 v on the keeper electrodes, and very high propellant flow rates through the cathodes. The neutralizer required about 15 eq. amp while the main cathode required about 35 eq. amp. This difference was probably due to the fact that the neutralizer orifice diameter is half that of the main cathode so that the internal gas pressure is higher at a lower propellant flow rate. This latter method of cathode starting was usually used to expedite testing. Regardless of cathode starting technique, the main discharge always started simultaneously with the cathode discharge initiation. The anode open circuit voltage was always 100 volts. Main propellant flow rates were always maintained at values nearly equal to the desired beam current.

Discharge Chamber Performance

As discussed earlier, the discharge chamber performance reported herein was not corrected for doubly charged ion content. Typical maximum β connections for xenon, krypton, and argon would be about 10, 6, and 2 percent, respectively.

Mercury - Figure 2 shows the discharge chamber performance of thruster J-8, tested at LeRC[17], for three values of beam current and at a constant discharge voltage (V_D) of 32 volts (acceptance test conditions). Thruster acceptance test procedures and power processor limitations precluded testing at other than near-nominal operating conditions or at those which allow a measurement of the minimum discharge power per beam ampere (E_I). Thus, the shapes of the curves shown in figure 2 were estimated from previous J-Series-like thruster data[23]. At a constant discharge voltage, the maximum discharge propellant efficiency (N_{UD}) increased and the minimum E_I decreased as the beam current (J_B) was increased.

The discharge chamber performance and lifetime of the J-Series thruster, operated with mercury (Hg) propellant, were optimized by using ion optics with a small hole accelerator grid and operating the discharge at 32 v. The E_I and magnetic baffle current (J_{MB}) are adjusted, over the power throttle range, to maximize thruster performance and stability.

Xenon - As reported in reference 4, the discharge chamber performance with Xenon (Xe) is quite similar to that of Hg. To expedite testing with the inert gases, the propellant flow rates were fixed and the discharge power was varied to produce discharge chamber performance data. Thus, the beam current and V_D increase with N_{UD}. Figure 3 shows the discharge chamber performance for several values of main propellant flow rate. The cathode flow rate and J_{MB} were held constant at 0.147 amp and zero, respectively. Calculated values of neutral propellant, ingested from the facility, are included in the main flow rates shown and were typically 3 to 5 percent of the total flow rate for all 3 inert gases. The numbers next to the data points are values of V_D. For values of E_I greater than 200, N_{UD} increased as the main flow was increased from 1.3 to 4.4 eq. amp. The discharge current (J_D), required for high values of E_I and N_{UD} at 3-4 eq. amp. of main flow, was in excess of 20 amp. Because the thruster was thermally designed to operate at a maximum J_D of 14 amp., extended operation at high values of J_D was limited in the amount of data taken and the length of time at any given point (approximately 10 min maximum). The discharge voltage, beam current, and N_{UD} all increased as the cathode flow rate was reduced at a constant value of main flow and J_D. Both the trend of increased performance with decreased cathode flow rate and the minimum cathode flow rate which permits a stable discharge are similar to results obtained with Hg[24]. The ratios of minimum cathode to main propellant flow rates are between 0.03 and 0.12 for both Hg (figure 2) and Xe (figure 3). The magnetic baffle current could be increased, at any value of cathode flow, to increase V_D, J_B, and N_{UD}. This implies that it may be possible to reduce the baffle diameter and use the magnetic baffle current to vary the cathode flow rate, as with Hg, to optimize the discharge chamber performance at values of V_D consistent with acceptable thruster lifetime. Figure 4 shows the effect of J_{MB} and baffle diameter on discharge chamber performance. The magnetic baffle current was increased from zero to two amp at constant flows. At any value of E_I, the propellant efficiency and discharge voltage increased. To avoid high values of V_D, the baffle diameter was decreased and the cathode flow rate was increased. The discharge voltage was reduced, but could be increased to 32 or 33 volts by increasing J_{MB}. The performance was unchanged when compared to that with the larger baffle and a fixed J_{MB} of 2 amps, even though V_D was lower by 4 or 5 volts. The main conclusion of figure 4 is that the behavior and performance of the J-Series discharge chamber operated with Xe are nearly identical to those with Hg. It is likely that the relatively large values of electron impact ionization cross sections (both total and multiply charged) for Xenon offset any performance degradation relative to Hg due to its lighter atomic mass. The values of total and doubly charged ionization cross sections, for the test gases and in the energy range of interest (30 to 50 eV), increase with increasing atomic mass, except for those of Xenon which are greater than those of Hg by about 10 and 50 to 170 percent, respectively.

Krypton - Krypton (Kr) was used in the thruster for tests only with the smaller 4.1 cm diameter baffle. The discharge chamber performance for several values of cathode and main flow rates and no active magnetic baffle is shown in figure 5. Values of N_{UD} of about 0.87 (or 0.04 less than with Xe) were obtained with E_I of 180 w/amp. Minimum values of E_I are similar to those of Xe and Hg.

Figure 6 shows the effect of cathode flow rate and J_{MB} on N_{UD} and V_D. J_{MB} was varied from 0 to 5 amp in 1 amp steps. Again, the numbers by the data points are values of V_D. At higher values of cathode flow rate V_D and N_{UD} increased, as expected, as J_{MB} was increased. As the cathode flow rate was reduced, for constant values of J_{MB}, V_D increased yielding more efficient generation of ions and a N_{UD} increase. When compared to Xe

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(figure 4) the maximum values of N_{UD} obtained for Kr are about 8 percent lower than those for Xe in spite of the fact that the values of V_D for Kr are 10 to 20 volts greater than those of Xe. The reduced values of N_{UD} are probably due to the combined effects of the reduced ionization cross sections of Kr and the lighter mass of Kr and relatively short length of the thruster which yiel shorter neutral atom residence times. The length of the thruster used in reference 13 is about 8 cm longer than that of J8 which probably contributes to the ability of that thruster to achieve higher values of N_{UD} at lower values of V_D with Xe, Kr, and argon. It is also noted from figures 5 and 6 that the range of the ratio of cathode to main flow rate is 0.10 to 0.20 for Kr as compared to .03 to 0.12 for Hg and Xe. Cathode modifications, which would allow lower cathode flow rates, might lead to improved thruster performance as with Hg and Xe. Also shown in figure 6 is the variation of V_D and N_{UD} for a higher value of J_D at the lowest value of cathode flow rate. As J_{MB} was increased, from zero to two amp, V_D initially decreased with a corresponding reduction of E_I and N_{UD}. A further increase in J_{MB}, from 2 to 4 amp, resulted in increases in V_D, E_I, and N_{UD}. Thus, there appears to be performance advantages of using values of J_{MB} above two amp. As with Xe, the best performance obtained was with the use of the magnetic baffle.

Argon - The discharge chamber performance using argon (Ar) is shown, in figure 7, for a variety of main and cathode propellant flow rates. The minimum values of V_D are about 6 volts greater than those for Kr. The data points are with J_{MB} set equal to zero. The performance is seen to improve, as with the other propellants, as the cathode to main flow rate ratio was decreased. Without J_{MB}, the maximum N_{UD} is about 0.7 and the minimum E_I is about 170. The minimum flow ratio was about 0.44 which was about 4 times greater than Kr and 14 times greater than Hg. Perhaps thruster performance would improve with cathode modifications which would permit low cathode flow rates at low values of V_D. As with Xe, there was little difference in performance for operation with two different baffle sizes. Figure 7 also shows the performance, for a range of main flows at constant cathode flow, as J_{MB} was varied from 0 to 5 amp. All of the data fell in a band in which V_D increased from about 40 to 48 volts as N_{UD} increased from 0.55 to 0.77 at a near constant E_I value of 160 watt per beam ampere. At comparable values of E_I, the N_{UD} for Ar is about 0.16 less than that for Xe. Again, the discharge current was limited by thermal and wire insulation considerations to values under 30 amp thereby limiting values of N_{UD} and E_I to those shown. In general, as J_{MB} was increased, V_D also increased, which led to increases in N_{UD} at near constant E_I. At low values of J_{MB} the discharge was less stable and prone to abrupt changes in V_D at constant flow rates and J_D. Reference 19 has shown that with Hg propellant the onset of discharge instabilities was related to the magnitude and direction of the magnetic field near the cathode orifice. Other inert gas thrusters (references 2, 3, 10, 12, and 13) with different discharge chamber magnetic field geometries, have found it beneficial to use permanent magnets to adjust the magnitude and direction of the field in the vicinity of the cathode. Thus, modifications in the cathode pole piece region may allow stable operation at lower values of V_D and cathode flow rate.

Ion Optics Performance - The perveance of the ion optics was evaluated for the three inert gas propellants and compared to that of Hg. Values of beam current and minimum total accelerating voltage were varied from 0.785 to 6.4 amp. and 0.73 to 1.56 kilovolt, respectively. Figure 8 shows the product of the J_B, α, and the square root of the propellant atomic mass (M) plotted as a function of the minimum total accelerating voltage (V_T). Over the range of values tested, the beam current was found to satisfy equation 3:

$$J_B \alpha \sqrt{M} = 17.5 V_T^{2.2} \pm 25 \text{ percent} \tag{3}$$

where J_B is in amps, M is in a.m.u., and V_T is in kilovolts. The results for Hg and Ar fell toward the lower end of range of data while those of Xe and Kr gave above average values of the beam current parameter. The spread of the data was reduced by correcting for multiply charged ions. The smallest correction factor used was 0.973 for Xe. The cause of the remaining data spread is not known, but may be experimental or partially due to larger fractions of multiply charged ions than have been assumed. The faster than classical increase of J_B with V_T is likely to be caused by deviations from Child's law, such as variation of the ion accelerating distance, variations in the location of the current limiting regions of the grids, and non-zero initial ion velocities. In the range of interest (V_T = 1.0 to 1.5 kilovolts) the values of J_B obtained from this expression are about 25 percent higher than those calculated from the expression given by Sovey[16]. This is probably due to the closer, more uniform inter-electrode spacing of the J-Series grids used herein.

Neutralizer Performance

The open keeper design of the J-Series neutralizer allows efficient operation with Hg propellant, but will require major modifications for efficient operation with inert gases. As with the main cathode, the minimum neutralizer flow rate increases with decreasing gas atomic mass. With the exception of the value of flow rate, the neutralizer performance was similar to that of Hg. Figure 9 shows how the neutralizer keeper voltage (V_{NK}) (with respect to neutralizer common) and thruster floating voltage (V_G)(neutralizer common with respect to ground) varied with neutralizer flow rate for the four gases tested. In all cases, V_{NK} increased as the flow rate was reduced. The minimum values of V_{NK} were 2-4 v. greater for inert gases than for Hg which might be due to the increased radial position of the neutralizer cathode. The major differences in performance were the very large increases in minimum neutralizer flow rate as the atomic mass was decreased. It should be noted that the magnitude of V_G did not increase with decreasing flow rate as with Hg indicating that the neturalizer to beam coupling was not limited at the minimum flow rates as the neutralizer to keeper coupling indicated. As with Hg, there were secondary effects on V_{NK} and V_G as J_B or the neutralizer keeper current (J_{NK}) were increased. In either case, the minimum flow rate decreased slightly prior to the rapid rise in V_{NK}. Values of V_G were unaffected. At a fixed neutralizer flow rate, V_{NK} decreased when J_B was increased. This effect was probably due to an increase in cathode temperature. The V_{NK} increased whenever J_{NK} was increased. Recently, work by others using enclosed keeper designs (references 10 and 12), have indicated lower required neutralizer flow rates with inert gases than have been presented here. However, their designs, using argon, still impose a rather severe penalty on total efficiency when compared to neutralizer performance with Hg. Perhaps the neutralizer could use a different gas than the thruster or a thrust system using inert gas could benefit from a spacecraft or system neutralizer rather than individual thruster neutralizers.

Overall Thruster Performance

The overall thruster performance of J8, based on some selected data points using Hg and inert gases, is presented in Tables I-V. Performance values of a J-Series-like thruster, beyond those values of the J-Series acceptance test, were obtained from reference 26 and are presented in Table II. Tables III, IV, and V contain performance results for Xe, Kr, and Ar, respectively. The correction factors for doubly charged ions and beam divergence were discussed earlier. Total propellant flow rates are those values measured and corrected for background gas ingestion with the exception of the inert gas neutralizer flow rate which was assumed to be 0.1 eq. amp. or approximately 3 times that for Hg. Values of total input power are those measured with the exception of the inert gas neutralizer, for which an assumed value of 40 watts was used. The Tables show that values of thrust of about 0.2N were obtained, with inert gases, at values of input power from 5 to 9 kw. As expected, the power required for a given thrust increased as the propellant atomic mass decreased.

Figure 10 shows the thruster efficiency as a function of specific impulse normalized by α and the square root of the atomic mass. The efficiency varied nearly linearly from 0.49 to 0.75 as the normalized specific impulse was increased nearly a factor of two. The cause of linearity is that the thruster was operated at near constant values of beam voltage and E_I. The major reason for increasing efficiency is the increase of N_{UD} with increasing M and beam current. Assuming an efficient neutralizer, the overall thruster efficiency increased from a range of 0.5 to 0.6 for argon, to approximately 0.7 for krypton, 0.73 for xenon, and about 0.75 for high power operation with mercury. The only way to greatly increase the thruster efficiency at a given value of the specific impulse parameter is to operate at lower values of E_I.

Thruster Lifetime

The life limiting phenomenon of the 30 cm dia. Hg thruster has been identified as erosion of discharge chamber components, specifically the screen grid, due to sputtering by ions from the discharge plasma (reference 27). Models, which predict the erosion rates of discharge chamber components as functions of J_B, propellant type, target type, density, and sputter yield, and the ratio of doubly to singly charged ions, were presented in references 27 and 28. Assuming that the conditions of the J-Series Hg thruster (J_B = 2 amp and V_D = 32 volts) will give 15 000 hours lifetime, comparisons may be made for operation with other gases in the same thruster as functions of discharge chamber parameters. First, it will be assumed, as discussed earlier, that the doubly to singly charged ion current ratio is only a function of the measured N_{UD} and independent of propellant type. For Hg, the nominal operating point gives a doubly charged current ratio of 0.153 at a N_{UD} of 0.975. Assuming that the same thrust per thruster is required, the J_B for Xe, Kr, and Ar would scale inversely with the square root of the atomic mass to be about 2.5, 3.1, and 4.5 amp, respectively, if the beam voltage remained constant. From data taken with J8 values of N_{UD}, for several values of V_D, were used with figure 1 to obtain ratios of doubly to singly charged ion current for each of the three inert gases. The average screen grid erosion rate for an inert gas, relative to that of Hg, was calculated from equation 4:

$$\frac{F_{gas}}{F_{Hg}} = \frac{J_{Bg}\left[y_+ + \frac{r}{2(1+r)}\left(y_{++} - 2y_+\right)\right]}{0.626 \times 10^{-3}} \tag{4}$$

where F is proportional to the sputtering rate of the screen grid, J_{Bg} is the beam current of the gas in amperes, y_+ is the sputter yield of molybdenum in atoms per incident gas ion at energy eV_D, y_{++} is the yield for a doubly charged ion with energy 2 eV_D, and r is the doubly to singly charged ion current ratio. The denominator of equation 4 was evaluated for a mercury ion beam current of two amperes, values of 2×10^{-4} and 2.5×10^{-3} for the sputter yields due to singly and doubly charged mercury ions, incident on molybdenum, with energies of 32 and 64 electron volts, respectively, and a doubly to singly charged ion current ratio of 0.153. For ions incident on tungsten it was found[29] that the sputter yields for Xe, Kr, and Ar ions are approximately 2, 3, and 4 times that of Hg ions at a given energy up to about 100 eV. The sputter yeilds for Hg ions on molybdenum were taken from reference 30 and assumed to increase for inert gases by the same factors given above for tungsten. While the absolute values of ion energies and putter yields may be uncertain the trends obtained form the use of equation 4 should be useful. The calculated values of screen grid erosion rate for inert gases relative to those for Hg are shown in figure 11 and approach unity only for xenon. Although the values of r for the gases are lower than those of Hg, they are offset by the increased values of J_B and the increased values of y. These results would also be expected for the relative sputter erosion of other discharge chamber components.

For conventional thrusters, operated on inert gases. to have lifetimes equivalent to those with Hg, values of V_D equal to or less than those with Hg are required. Another possible way of reducing erosion would be to operate components or the entire discharge chamber above cathode potential to reduce the energy of ions incident on discharge chamber surfaces[31]. Other thruster designs[13] may be required to allow operation at reduced discharge voltage or with flatter beam current profiles than are possible with a J-series thruster.
Upon post-test inspection of J8, it was observed that some of the wiring insulation was melted, indicating the thruster had been heated beyond the

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design point. Values of thruster discharge power used with inert gases were nearly three times the maximum used with Hg in J8. Wire size and location as well as insulation type will require re-evaluation for higher power operation.

CONCLUDING REMARKS

The J-Series 30 cm diameter ion thruster, developed for operation up to 3 kw with mercury propellant, was operated with xenon, krypton, and argon. The results were compared with those of mercury and modifications required to provide operation a high power with inert gases were identified.

Cathode discharges could be initiated with hot or cold cathodes at high propellant flow rates with normal keeper and anode voltages. The minimum values of discharge power per beam ampere were nearly the same for all propellants at about 160 watts per ampere. The propellant efficiency and discharge voltage for mercury and xenon were nearly identical as expected from past reported results. At comparable values of discharge power per beam ampere, the propellant efficiency for krypton and argon were less than that of xenon by about 0.04 and 0.16, respectively. An increase in discharge chamber length would lead to higher values of propellant efficiency for the lighter gases, although some increase in ion production energy costs would probably occur.

The trend of increased performance at the minimum cathode flow rate that permits a stable discharge, which was observed for Hg, also existed for operation with Xe. However, for operation with Kr and Ar, the discharge voltage increased rapidly when attempts were made to reduce the cathode flow rate to levels achieved with Hg and Xe. Overall, the minimum cathode flow rate increased with decreasing gas atomic mass. The use of the magnetic baffle usually caused an increase in discharge voltage and propellant efficiency, often at near constant discharge losses.

For nearly a factor of 9 variation in beam current, the product of the beam current, the correction factor for doubly charged ion current (α), and the square root of the propellant atomic mass was found to be proportional to the 2.2 power of the total ion accelerating voltage.

Neutralizer performance curves with inert gases were similar to that of mercury, except that with inert gases the minimum neutralizer flow rate, required to maintain reasonable values of neutralizer keeper voltage, increased as the propellant atomic mass decreased. Neutralizer design modifications, possibly an enclosed keeper, will be required to avoid large propellant penalties.

The nominal 3 kw thruster was operated with input powers up to 9 kw. With an efficient neutralizer assumed, the overall thruster efficiency increased from a range of 0.5 to 0.6 for argon, to approximately 0.7 for krypton, 0.73 for xenon, and about 0.75 for high power operation with mercury.

Screen grid erosion rates, due to sputtering by discharge plasma ions, for inert gases relative to those for Hg, were estimated and found to be several times greater for Xe and Kr, and very much higher for Ar. A major cause of expected increased erosion was the fact that minimum values of discharge voltage, and refractory metal sputter yields, tended to increase with decreasing atomic mass. A secondary effect which lowered the erosion rates was the decrease in doubly charged ion content with decreasing atomic mass. This was partially offset by the need for increased beam current to maintain constant thrust at constant beam voltage. For conventional thrusters, operated on inert gases, to have lifetimes equivalent to those with Hg reductions decreases in the energy of incident ions or flatter beam profiles will be required.

Operation at higher beam current required higher discharge power. Thus, the thruster ran hotter and caused some wiring insulation melting. Thermal analyses and some redesign would be required for reliable operation at high power.

Overall, the J-Series thruster can be operated with inert gases and have high discharge chamber performance. Some modifications will be required to avoid large penalties due to high neutralizer propellant flow rates and to shortened thruster lifetimes from expected increased discharge chamber component erosion, especially as the gas atomic mass decreases.

REFERENCES

1. Schnelker, D. E., Collet, C. R., Kami, S., and Poeschel, R. L., "Characteristics of the NASA/Hughes J-Series 30-cm Engineering Model Thruster," AIAA Paper 79-2077, Oct. 1979.
2. Sovey, J. S., "Performance of a Magnetic Multipole Line Cusp Argon Ion Thruster," AIAA Paper 81-0745, Apr. 1981.
3. Ramsey, W. D., "12-cm Argon/Xenon Ion Source," Journal of Spacecraft and Rockets, Vol. 16, No. 4, July-Aug. 1979, pp. 252-257.
4. Byers, D. C., and Reader, P. D., "Operation of an Electron-Bombardment Ion Source Using Various Gases," NASA TN D-6620, 1971.
5. Kaufman, H. R., Robinson, R. S, and Trock, D. C., "Inert-Gas Thruster Technology," AIAA Paper 81-0721, Apr. 1981.
6. Sovey, J. S., "Characteristics of a 30-cm Diameter Argon Ion Source," AIAA Paper 76-1017, Nov. 1976.
7. Byers, D. C. and Rawlin, V. K., "Electron Bombardment Propulsion System Characteristics for Large Space Systems," AIAA Paper 76-1039, Nov. 1976.
8. Kaufman, H. R., "Performance of Large Inert Gas Thrusters," AIAA Paper 81-0720, Apr. 1981.
9. Nakamura, Y., Miyazaki, K., and Suzuki, E., "Operations and Performances of a 5 cm Diameter Ion Thrust by Using Inert Gases," AIAA Paper 82-1924, Nov. 1982.
10. Ramsey, W., "Inert Gas Tests of Two 12 cm Magneto-Static Thrusters," AIAA Paper 82-1925, Nov. 1982.
11. Carpenter, R. T., Boardsen, S. A., and Daniels, S. W., "Plasma Characteristics of a 17-cm

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Diameter Line-Cusp Ion Thruster," AIAA Paper 82-1926, Nov. 1982.

12. Steiner, G., "Development of a Large Inert Gas Ion Thruster," AIAA Paper 82-1927, Nov. 1982.

13. Sovey, J. S., "Improved Ion Containment Using a Ring-Cusp Ion Thruster", AIAA Paper 82-1928, Nov. 1982.

14. Frisa, L. E., Robinson, R. S., and Kaufman, H. R., "Plasma Experiments in a Multipole Discharge Chamber", AIAA Paper 82-1930, Nov. 1982.

15. Arakawa, Y., and Kawasaki, Y., "A Discharge Plasma in a Multipole Ion Thruster," AIAA Paper 82-1931, Nov. 1982.

16. Dugeroff, C. R., and Poeschel, R. L., "Retrofit and Verification Test of 30 cm Ion Thruster," Hughes Research Labs, Malibu, CA, Dec. 1980. (NASA CR-165233).

17. Gooder, S. T., Private Communication.

18. Holanda, R., "Sensitivity of Hot-Cathode Ionization Vacuum Gages in Several Gases," NASA TN D-6815, July 1972.

19. Poeschel, R. L., "2.5 KW Advanced Technology Ion Thruster," Hughes Research Labs, Malibu, CA, Apr. 1976 (NASA CR-135076).

20. Beattie, J. R. and Kami, S., "High Thrust and Low-Power Operation of a 30-cm-Diameter Mercury Ion Thruster," AIAA Paper 81-0718, Apr. 1981.

21. Danilowicz, R. L., Rawlin, V. K., Banks, B. A., and Wintucky, E. G., "Measurement of Beam Divergence of 30-Centimeter Dished Grids," AIAA Paper 73-1051 Oct. 1973.

22. Byers, D. C., "Characteristics of Primary Electric Propulsion Systems." AIAA Paper 79-2041, Oct. 1979.

23. Rawlin, V. K., and Hawkins, C. E., "Increased Capabilities of the 30-Cm Diamater Hg Ion Thruster," AIAA Paper 79-0910, May 1979.

24. Rawlin, V. K., "Performance of 30-cm Ion Thrusters with Dished Accelerator Grids," AIAA Paper 73-1053, Oct. 1973.

25. Kieffer, L. J., and Dunn, G. H., "Electron Impact Ionization Cross Section Data for Atoms, Atomic Ions and Diatomic Molecules," Reviews of Modern Physics, Vol. 38, No. 1, Jan. 1966, pp. 1-35.

26. Rawlin, V. K., "Extended Operating Range of the 30 cm Ion Thruster with Simplified Power Processor Requirements," AIAA Paper 81-0692, Apr. 1981.

27. Mantenieks, M. A. and Rawlin, V. K., "Sputtering in Mercury Ion Thrusters," AIAA Paper 79-2061, Oct. 1979.

28. Beattie, J. R., "A Model for Predicting the Wearout Lifetime of the LeRC/Hughes 30 cm Mercury Ion Thruster," AIAA Paper 79-2079, Oct. 1979.

29. Stuart, R. V., and Wehner, G. K., "Sputtering Yields at Very Low Bombarding Ion Energies," Journal of Applied Physics, Vol. 33, No. 7, July 1962, pp. 2345-2352.

30. Askerov, Sh. G., and Sena, L. A., "Cathode Supttering of Metals by Slow Mercury Ions," Soviet Physics - Solid State, Volume 11, No. 6 Dec. 1969, pp. 1288-1293.

31. Williamson, W. S., and Hyman, J., Jr., "Discharge Chamber Sputtering in Mercury Ion Thrusters," Journal of Spacecraft and Rockets, Vol. 15, No. 6, Nov.-Dec. 1978, pp. 375-380.

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TABLE I. - THRUSTER PERFORMANCE MERCURY PROPELLANT (REF. 17)

Beam voltage, V	Beam current, A	Discharge voltage, V	Discharge power per beam ampere, W/A	Measured propellant efficiency	Thrust loss factor	Thruster input power, W	Thrust, N	Specific impulse, sec	Thruster efficiency
1100	2.00	32	192	0.960	0.933	2650	0.126	2970	0.694
820	1.30	32	209	.899	.943	1400	.0716	2430	.612
600	0.75	32	246	.831	.946	694	.0354	1930	.485

TABLE II. - THRUSTER PERFORMANCE MERCURY PROPELLANT (REF. 26)

Beam voltage, V	Beam current, A	Discharge voltage, V	Discharge power per beam ampere, W/A	Measured propellant efficiency	Thrust loss factor	Thruster input power, W	Thrust, N	Specific impulse, sec	Thruster efficiency
1100	2.0	32	194	0.920	0.960	2660	0.130	2940	0.705
1300	3.0	28	224	.920	.971	4650	.213	3210	.728
1450	4.0	28	220	.958	.952	6770	.294	3460	.743
1570	5.0	28	232	1.04	.927	9910	.374	3830	.767

TABLE III. - THRUSTER PERFORMANCE XENON PROPELLANT

Beam voltage, V	Beam current, A	Discharge voltage, V	Discharge power per beam ampere, W/A	Measured propellant efficiency	Thrust loss factor	Thruster input power, W	Thrust, N	Specific impulse, sec	Thruster efficiency
1020	1.35	38.4	209	0.875	0.954	1710	0.069	3290	0.646
1030	1.44	45.2	228	.933	.941	1850	.072	3480	.662
1110	2.55	36.1	158	.905	.954	3280	.134	3560	.716
1110	2.69	38.1	166	.954	.943	3490	.140	3710	.734
1110	2.87	42.9	190	1.019	.916	3790	.145	3850	.727
1200	3.75	27.9	177	.915	.954	5210	.204	3740	.724
1200	3.88	28.7	190	.947	.947	5440	.210	3840	.731
1200	4.06	31.2	196	.991	.934	5730	.217	3970	.741
1200	4.16	33.5	205	1.016	.923	5920	.220	4030	.738

[a]Assumes neutralizer flow rate of 0.1 eq. amp.
[b]Assumes neutralizer power of 40 watts

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TABLE IV. - THRUSTER PERFORMANCE KRYPTON PROPELLANT

Beam voltage, V	Beam current, A	Discharge voltage, V	Discharge power per beam ampere, W/A	Measured propellant efficiency	Thrust loss factor	Thruster input power, W	Thrust, N	Specific impulse, sec	Thruster efficiency
1210	2.61	42.8	141	0.834	0.965	3570	0.115	4330	0.684
1210	2.72	46.4	145	.868	.960	3740	.120	4490	.706
1210	2.78	49.4	150	.888	.957	3840	.122	4580	.714
1210	2.79	44.3	162	.891	.956	3880	.122	4590	.708
1210	2.84	46.6	178	.906	.954	4000	.124	4660	.708
1220	2.91	50.5	187	.926	.951	4130	.127	4750	.716
1150	3.91	40.5	203	.895	.957	5330	.167	4490	.690
1150	4.02	43.7	212	.920	.953	5530	.171	4600	.699
1150	4.16	48.1	224	.953	.946	5780	.176	4740	.708
1280	4.78	35.6	181	.853	.965	6300	.204	4280	.679
1130	4.96	37.3	182	.886	.960	6550	.211	4420	.699
1130	5.25	41.1	187	.938	.951	6980	.211	4650	.722
1140	5.47	45.4	196	.977	.941	7340	.229	4800	.734

[a]Assumes neutralizer flow rate of 0.1 eq. amp.
[b]Assumes neutralizer power of 40 watts

TABLE V. - THRUSTER PERFORMANCE ARGON PROPELLANT

Beam voltage, V	Beam current, A	Discharge voltage, V	Discharge power per beam ampere, W/A	Measured propellant efficiency	Thrust loss factor	Thruster input power, W	Thrust, N	Specific impulse, sec	Thruster efficiency
1230	3.11	47	166	0.608	0.979	4400	0.098	4680	0.508
1230	3.47	47	184	.678	.976	4970	.108	5200	.554
1230	3.59	46	203	.701	.975	5200	.112	5370	.567
1230	3.64	47	238	.711	.935	5400	.109	5220	.517
1060	3.20	47	188	.692	.976	4040	.093	4920	.553
1260	3.43	41	182	.542	.980	5000	.109	4220	.451
1390	4.76	45	223	.673	.976	6920	.141	5480	.549
1380	4.70	47	154	.687	.975	7260	.155	5570	.583
1380	4.97	47	160	.726	.974	7710	.164	5880	.613
1380	5.15	46	149	.641	.978	7940	.171	5210	.551
1380	5.36	45	160	.668	.976	8320	.177	5420	.566
1380	5.92	49	145	.681	.975	8980	.194	5550	.588

[a]Assumes neutralizer flow rate of 0.1 eq.amp.
[b]Assumes neutralizer power of 40 watts

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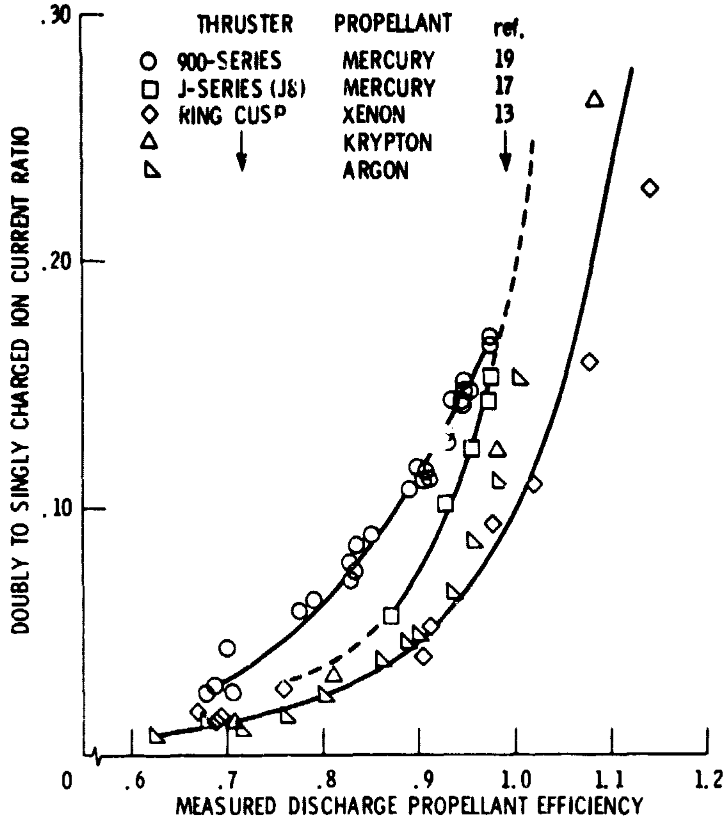

Figure 1. - Doubly to singly charged ion current ratios as functions of measured discharge propellant efficiencies.

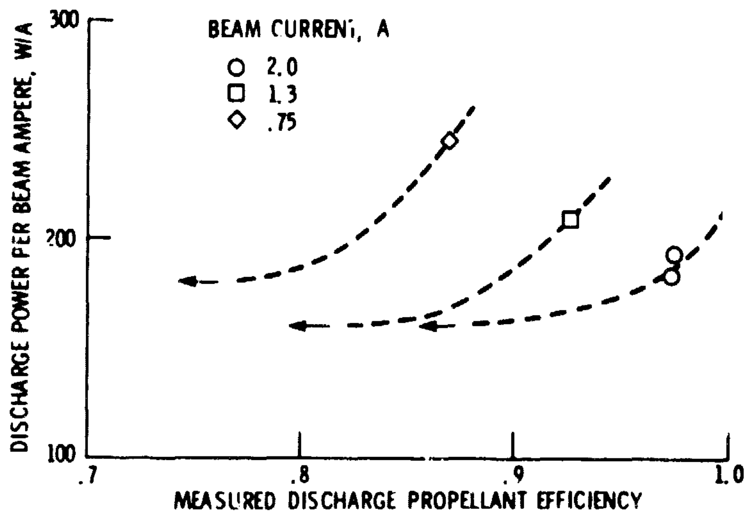

Figure 2. - Discharge perfurmace for thruster J8 operated with mercury propellant. (discharge voltage of 32 V)

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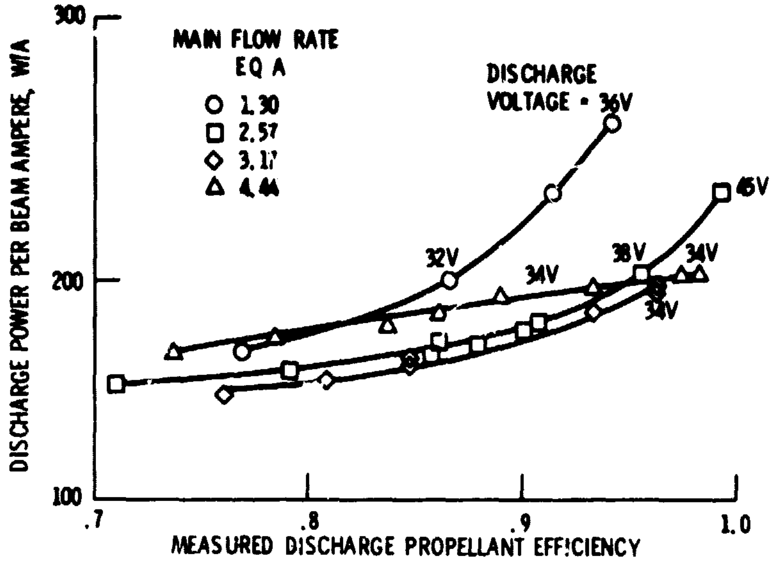

Figure 3. - Discharge performance for thruster J8 operated with xenon (cathode flow rate of 0.147 eq A, no magnetic baffle current).

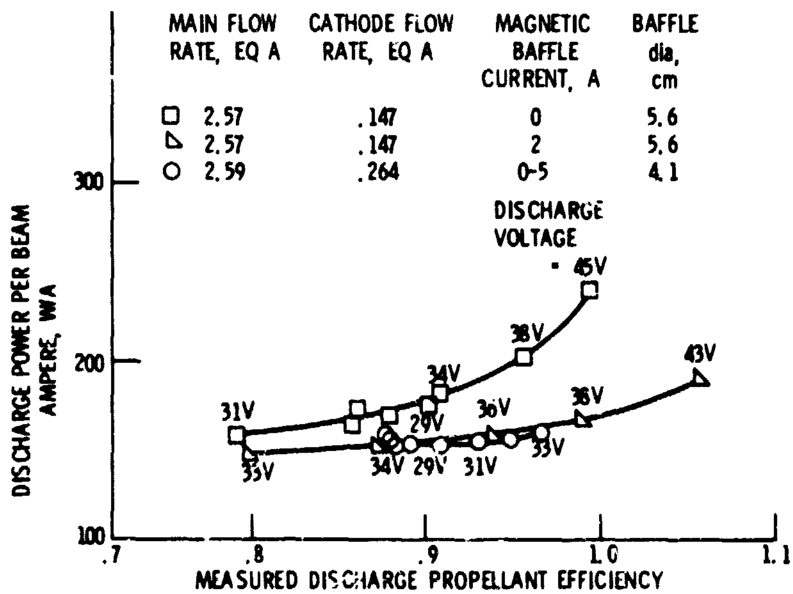

Figure 4. - Discharge performance for thruster J8 operated with xenon and physical and magnetic baffle current variations.

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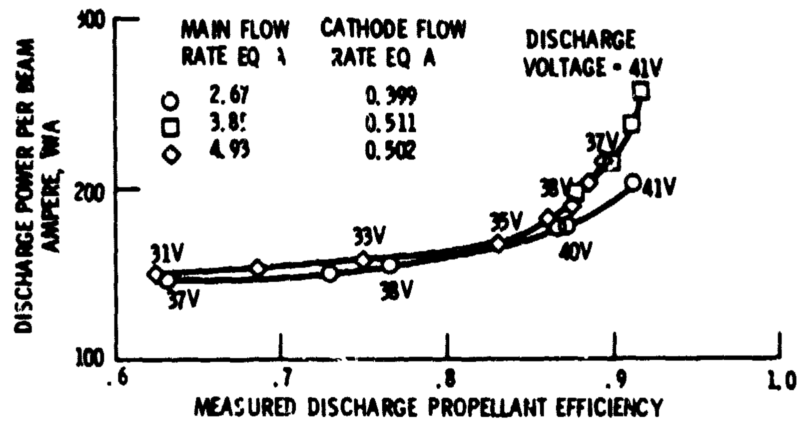

Figure 5. - Discharge performance for thruster J8 operated with krypton (baffle dia. of 4.1 cm and no magnetic baffle current).

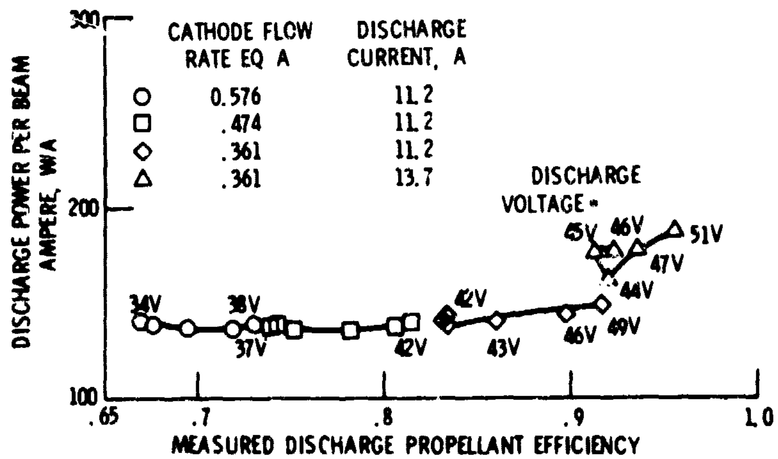

Figure 6. - Discharge performance for thruster J8 operated with krypton (main flow rate of 2.67 eq A and magnetic baffle current varied from zero to five A).

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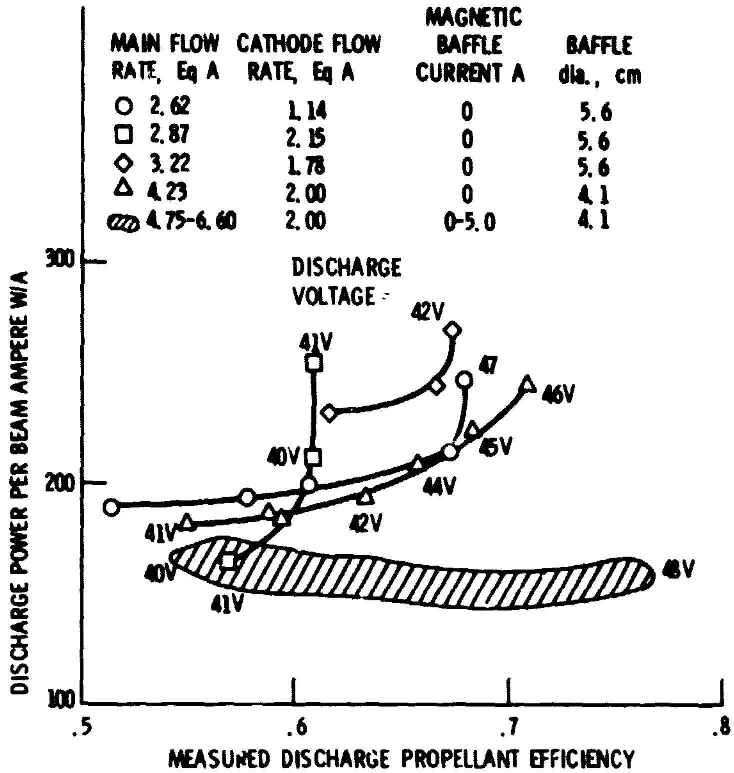

Figure 7. - Discharge performance of thruster JB operated with argon and physical and magnetic baffle current variations.

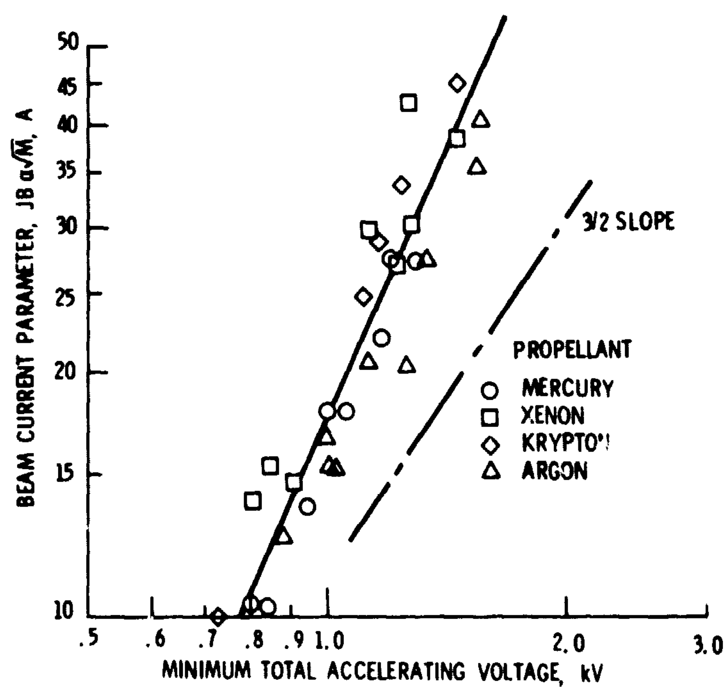

Figure 8. - Beam current parameter as a function of minimum total accelerating voltage.

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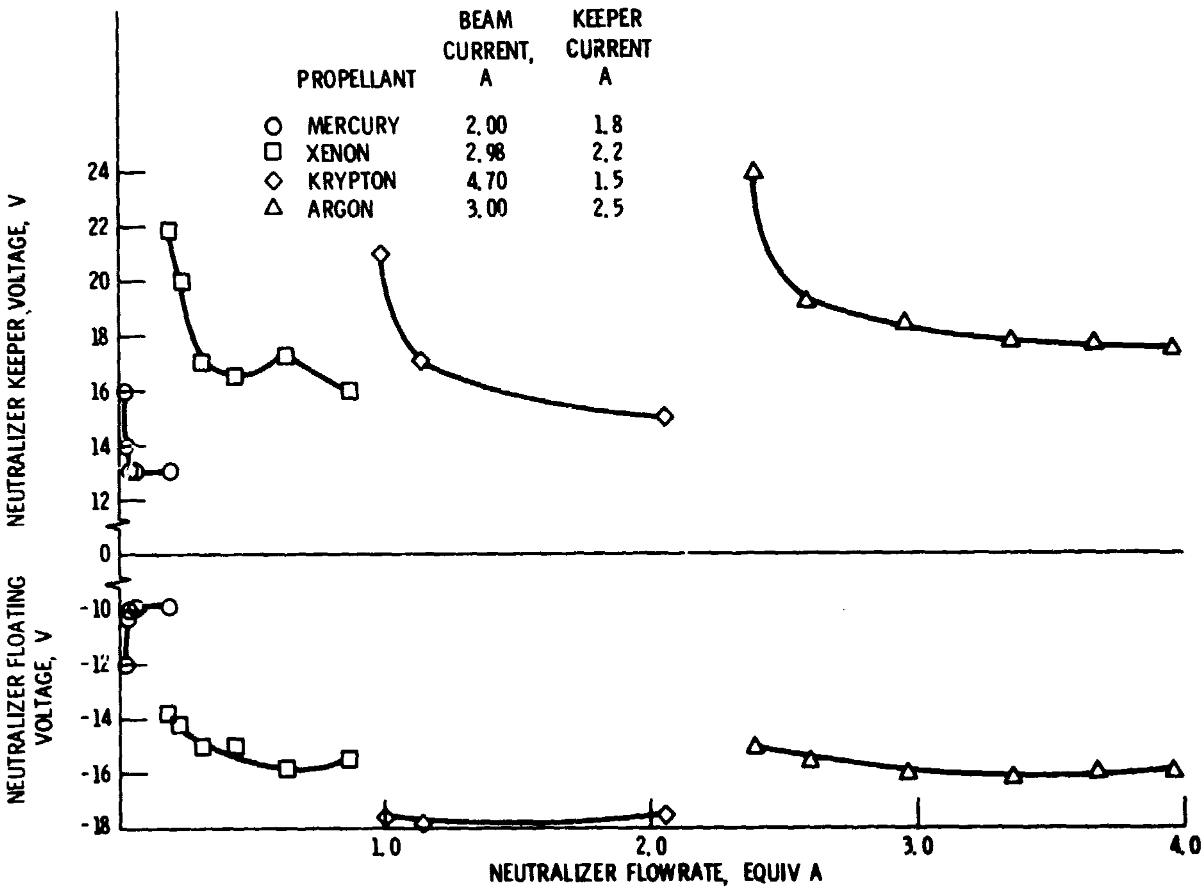

Figure 9. - Performance of the J series neutralizer for various propellants and values of beam current and keeper current.

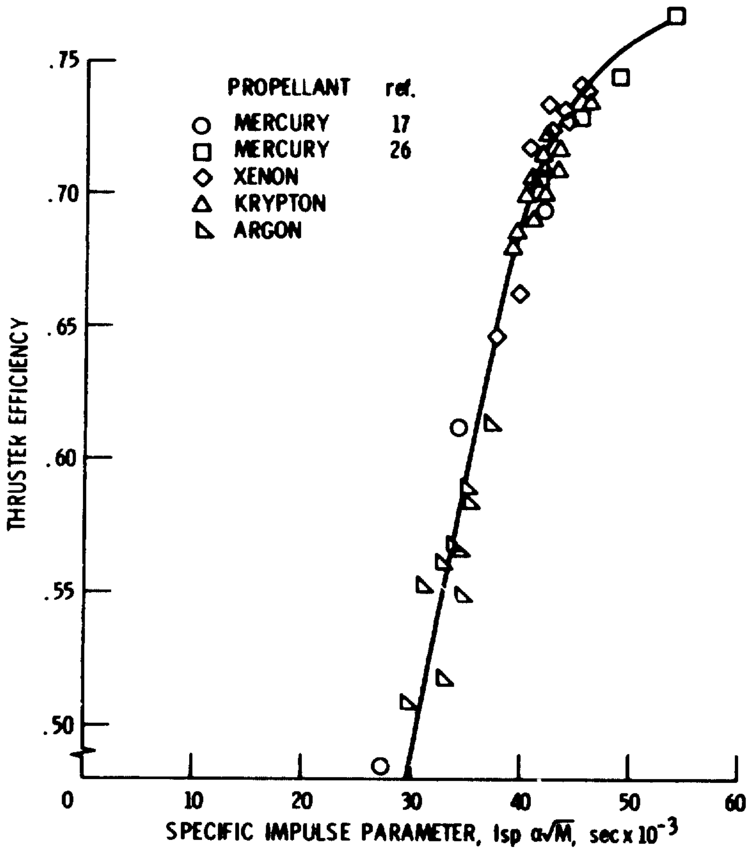

Figure 10. - Thruster efficiency as a function the specific impulse parameter for various propellants. Assumed neutralizer flow rate of 0.1 eq A and neutralizer fixed losses of 40 W.

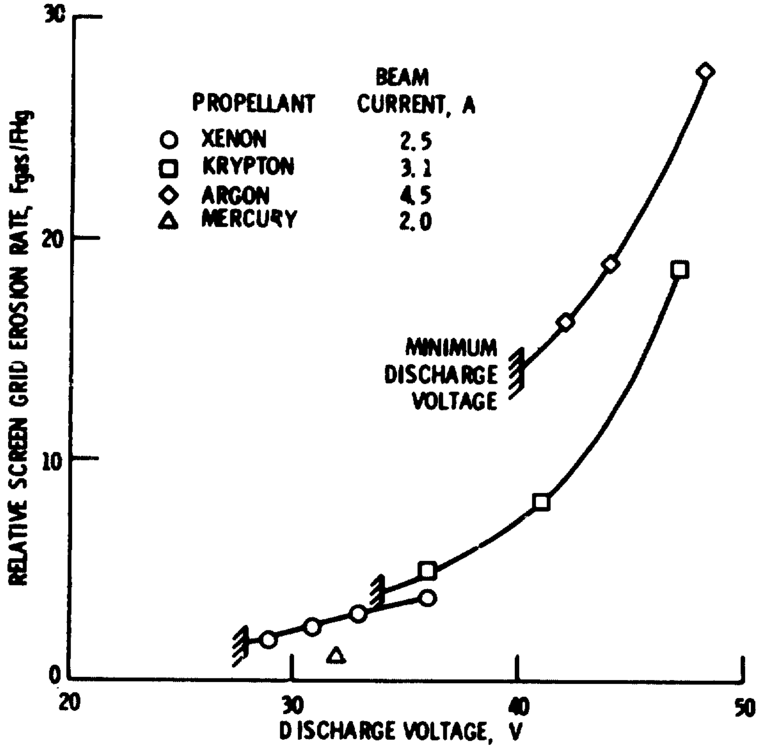

Figure 11. - Calculated screen grid erosion rates for inert gas propellant relative to those with mercury as a function of discharge voltage (constant thrust).