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ELECTRON-BOMBARDMENT ION SOURCE OPERATION USING VARIOUS GASES

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INTRODUCTION

The electron-bombardment ion thruster[1,2] has been the object of a research and development program[3] at the Lewis Research Center and elsewhere for over a decade. The primary interest in this ion source has rested on application to advanced space propulsion systems. Two experimental space flights have been conducted with the mercury electron bombardment ion source.[4,5] This ion source has been operated in excess of 6000 hours in ground tests.[5] Thrusters 5 cm to 150 cm[3] in diameter have been operated and net ion energies from 0.4 kV to 70 kV[3,6] have been utilized. Mercury and cesium have been the propellants used for most tests because their large atomic mass is attractive for propulsion applications. The electron-bombardment ion source can be operated with a variety of gases. An early refractory cathode thruster was operated with several gases[7] and more recently a hollow-cathode thruster was operated with argon.[8] Operation with materials other than mercury and cesium is of interest for a number of ground based applications.[9] In addition, some flight applications such as biowaste expulsion[10] may be of interest. This paper presents the operation of a flight type (Space Electric Rocket Test (SERT II)) thruster with xenon, krypton, argon, neon, nitrogen, helium, and carbon dioxide. Magnetic spectrometer data were taken with some of these gases to determine the ion species ejected from the source.

APPARATUS AND PROCEDURE

The basic 15-cm diameter thruster used in this investigation has been described previously.[8] The thruster was a modification of the SERT II thruster[5] and is shown in cross section in figure 1. The details of construction and operation have been adequately described elsewhere.[11] Two additional modifications were made to the thruster[8] for some of these tests. The orifice in the hollow cathode end cap was enlarged from 0.4 mm to 0.75 mm. Other experiments[12] indicate that cathode erosion rates should be reduced by as much as two orders of magnitude by this enlargement. For some tests the screen grid was masked down to half radius (i.e., 7.5 cm beam diameter). This last modification had been done in an earlier experiment[7] to increase the neutral density in the discharge chamber and had allowed a wider range of operaion with the low molecular weight gases. The thruster operated with the masked screen will be referred to herein as the modified thruster.

The thruster startup procedure was nearly identical to that described by Schertler.[8] A high starting voltage was applied, however, to both the cathode keeper and the anode rather than to the cathode keeper alone. With the low molecular weight (less than 50 amu) gases the thruster discharge would often initiate directly between the cathode and anode followed by ignition of the keeper discharge. In these cases the product of pressure and distance between the cathode and the anode was closer to the Paschen minimum for the breakdown than that of the keeper region.

The magnetic field strength could be varied with the eight electromagnets described in reference 8. The magnetic field strengths quoted herein were measured a few millimeters downstream of the cathode pole piece baffle.

After determining the performance on various gases with the basic and modified thruster, a simple mass spectrometer was installed in the facility in order to determine the ion species in the thruster beam. All of the spectrometer data were obtained with the modified thruster. The spectrometer consisted of a set of collimating slits positioned on the beam axis, a uniform variable magnetic field region, and an ion current collector which could be biased negatively to prevent electron collection. The magnetic field was varied so that beam ions of different charge-to-mass ratios would strike the collector located at an angle of 60° with respect to the axis of the collimating slits.

RESULTS AND DISCUSSION

Data are presented on the performance of xenon, krypton, argon, neon, nitrogen, helium and carbon dioxide. The performance is defined in terms of discharge power dissipated per beam ion produced (eV/ion) and propellant utilization. The propellant utilization is the ratio of the ion beam current to the total inlet neutral flow rate. All neutral flow rates are expressed in equivalent amperes. The presence of multiply ionized or fractionated ions in the beam impacts both of these performance parameters. For simplicity, the graphically presented data are shown with the assumption of singly charged parent ions in the beam. Use of the magnetic spectrometer allowed evaluation of the assumption of single charge. Data are presented for the basic thruster[8] and/or the modified thruster for the various gases. Other parameters which affect thruster lifetime or stability (for example, chamber or keeper discharges) are also discussed. The screen and accelerator extraction voltages were +3 and -2 kV respectively for all data presented herein.

Xenon

Figure 2 shows the performance of the basic thruster with xenon for several values of cathode propellant flow rate, J_{ok}, and main propellant flow rate, J_m. The total inlet flow rates, J_o (where $J_o = J_{ok} + J_m$), were varied over a larger range than shown in figure 2 but the flow rates shown gave the best performance. The upper limit on total flow rate resulted because the space-charge-limited current of the ion extraction system with xenon was about 0.6A. At higher total flow rates it was not possible to operate at high propellant utilization. The lower limit on total flow rate for stable discharge operation was a cathode flow rate of about 0.3A. The discharge voltages were between 29 and 40 volts for all of the data of figure 2.

As the inlet flow rates were varied the performance shifted and was best at the conditions of figure 2(c), near the minimum cathode flow rate for that total flow rate. At optimum conditions the discharge losses were similar to those for mercury. The eV/ion generally decreased with increasing magnetic field at constant propellant utilization efficiency. At optimum flow conditions, however, the sensitivity of discharge losses to magnetic field variations was small. The magnetic field also affected thruster stability in that as the field strength increased the stable range of discharge current decreased. The crosshatched areas on the figures represent regions of thruster instability.

Magnetic spectrometer data were obtained with xenon after the basic thurster had been masked down. The data are shown in figure 3. Data obtained with argon are also shown in figure 3 and will be discussed later. The ratio of the ion current due to doubly charged ions to the total ion current is shown as a function of discharge voltage. The ratio of twice the double ionization cross-section to the total ionization cross-section[13] as a function of electron energy is shown as a dashed line. This ratio yields the relative ion current when electron-ion-inelastic collisions are neglected.[14] For xenon no doubly ionized atoms were observed at discharge voltages less than 40 volts. The measured amount of double ionization was, however, somewhat less than indicated from the cross-section data. Because all the data of figure 2 were at discharge voltages less than 40 volts, the values of discharge loss and propellant utilization are essentially those for singly charged ions.

Krypton

The performance of krypton is shown on figure 4 over a range of inlet flow rates. The upper and lower limits on flow rate due to ion extraction limits and discharge instability with krypton and were about 0.9A and 0.45 respectively. The optimum flow rate for krypton is difficult to specify. At the lower magnet field strength the performance degraded as the cathode flow decreased. At the high magnetic field the range of discharge stability increased with decreasing cathode flow and allowed higher propellant utilizations to be achieved. At magnetic fields slightly higher than those shown, the thruster exhibited instabilities at nearly all values of discharge current.

No mass spectrometer data were taken with krypton. All the data of figure 4 were taken at discharge voltages between 31 and 38 volts. The ratio of double to total ionization cross-section at 40 volts is less than one percent[13] so that no significant double ionization should have resulted.

Argon

Argon was tested with the modified thruster to determine if the range of propellant flow and stability could be improved over previously published data for the basic thruster. Operation with argon is of particular interest because the gas is relatively inexpensive and easily pumped. These considerations would be of importance for several ground based gas ion source applications.

Figure 5 shows the performance of the modified thruster with argon. The best performance obtained with argon in the basic thruster is shown by the dashed line for comparison. Masking the screen grid caused about a factor of three increase in the eV/ion. Such an increase might be expected because the discharge losses of this thruster type are quite sensitive to the open area of the screen grid.[15] Figure 5 also shows that the modified thruster could be operated at considerably lower discharge voltage than the basic thruster. The low discharge voltages are of interest because the cathode lifetime increases with decreasing discharge voltage.

The performance of the modified thruster was quite sensitive to magnetic field strength. An increase in the magnetic field strength generally caused an increase in the discharge voltage and propellant utilization and a decrease in the discharge losses.

The strong dependence of discharge performance on cathode keeper power noted with the basic thruster was sharply reduced with the modified thruster. For example, a variation of 8 to 34 watts keeper power caused less than a 5 percent change in discharge losses and less than a 2 percent change in propellant utilization. Such a keeper power increase with the basic thruster caused about a 50 percent increase in eV/ion at a fixed propellant utilization efficiency.

Mass spectrometer data were taken with argon operated with the modified thruster and are shown in figure 3. Double ionization was detected at a discharge voltage of 35 volts. In the range of discharge voltage from 50 to 70 volts, where most of the argon data of reference 8 were obtained, the ratio of double to total ion current varied from 5 to 9 percent. Operation of the modified thruster was possible, however, at discharge voltages where the fraction of doubly ionized ions were negligible (i.e., below 40 volts).

Neon, Nitrogen, and Helium

The discharge performance for neon and nitrogen are shown on figure 6 (note the scale break on figure 6(b)). These gases are presented together because the performance was extremely poor for both. The total inlet flow rate was through the cathode for the data of figure 6 and was 12.5 and 7.0 equivalent amperes for nitrogen and neon, respectively. Operation at slightly lower neutral flow rates caused unstable operation with both gases. The 0.04 to 0.05 propellant utilizations shown on figure 6 are substantially lower than the 0.1 and 0.2 values obtained in an earlier study.[7] This difference was most probably due to the characteristics of the present hollow cathode operating on low molecular weight gases when compared with the thermionic refractory emitters used in that study.

Because the space-charge-limited ion beam current for either gas was less than 1 ampere it was impossible to obtain high propellant utilizations with stable operation. Magnetic spectrometer data were taken with both gases. No double ionization of neon was detected at discharge voltages up to 80 volts, which is in agreement with available cross-section data.[13] Figure 7 shows the spectrometer data taken with nitrogen at a discharge potential of 60 volts. Relative percentages of peak ion currents were 78, 15, and 7 percent for charge-to-mass ratios corresponding to 28, 14, and 7 amu for singly charged ions. The peak at 7 amu equivalent was probably doubly charge atomic nitrogen. Because a magnetic spectrometer was used, the relative fractions of doubly charged diatomic and singly charged atomic nitrogen at 14 amu equivalent could not be assessed.

Helium was also operated briefly during one test. The neutral flow rates required to initiate the discharge with helium were such as to raise the vacuum tank pressure to approximately 10^{-3} torr. Operation with helium was not possible at values of discharge voltage and current below approximately 100 volts and 10 amperes, respectively. Very limited testing was done with helium because operation at the required discharge parameters would probably result in very short cathode lifetime. Again, operation on helium with the hollow cathode was more difficult than with the refractory thermionic emitter of reference 7.

Carbon Dioxide

The modified thruster was operated with carbon dioxide, a possible biowaste propellant[10] as the main flow propellant (fig. 1) and argon as the cathode flow propellant. Carbon dioxide was not introduced through the cathode because of the possibility of cathode-material oxidation. Some results are shown in figure 8. For these data the argon flow rate was held nearly constant at 0.1 equivalent ampere. With no carbon dioxide flow the argon flow rate was 0.27 ampere. The 0.1 ampere argon cathode flow was the lowest that allowed stable thruster operation at any carbon dioxide flow rate. The discharge voltage was between 52 and 64 volts for the data of figure 8. The addition of carbon dioxide first caused the ion beam current to increase to 0.3 ampere and then decrease monotonically with increasing carbon dioxide flow rate. The measured currents indicated propellant utilizations from about 0.8 at about a 2.5:1 carbon dioxide to argon flow ratio to less than 0.01 at a 50:1 flow ratio. Magnetic spectrometer data were also taken during the argon-carbon dioxide test. The resolution of the spectrometer did not allow clear separation of the ion currents corresponding to singly changed particles of amu 28 to 44. This range would include CO^+, A^+, and CO_2^+. As the carbon dioxide flow was increased to 1.9 ampere, however, the ion current at amu 16 increased to about 30 percent of the total ion current. In addition, it was noted that the peak ion current occurred at a slightly lower spectrometer magnetic field as the carbon dioxide flow increased. This indicated that CO^+ was formed in substantial quantities in the discharge.

CONCLUDING REMARKS

A modified SERT II ion thruster was operated with xenon, krypton, argon, neon, nitrogen, helium, and carbon dioxide. The discharge performance with xenon, krypton, and argon was similar to that obtained previously with mercury.[8] Mass spectrometer data indicated that xenon could be operated efficiently with no significant multiple ionization. Restriction of the beam area, with an associated decrease in discharge potential, was necessary to reduce multiple ionization with argon to a negligible level. This modification also resulted in more stable operation of the thruster. Performance with the remaining gases was poor, but some future performance improvements may be realizable with modifications directed specifically toward low molecular weight gas operation.

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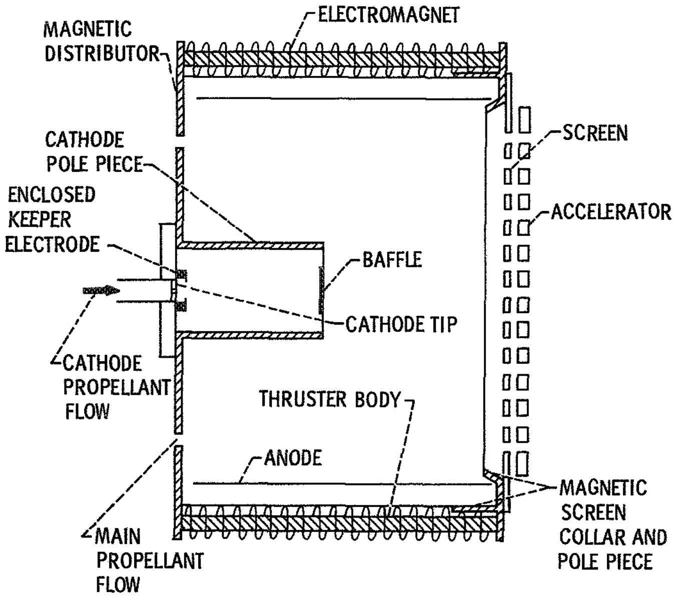

Figure 1. - Sketch of 15-cm. diameter electron bombardment thruster.

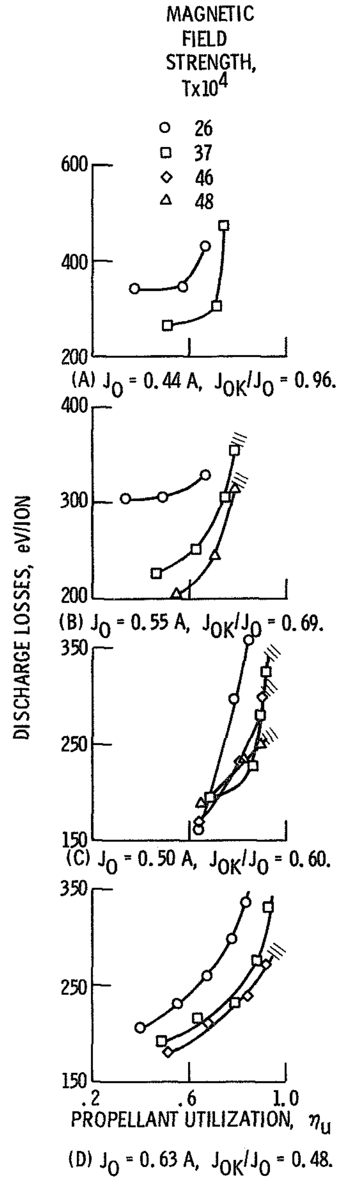

Figure 2. - Discharge chamber performance for xenon.

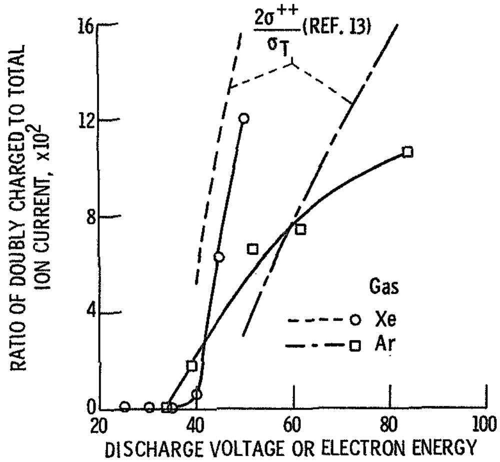

Figure 3. - Ratio of doubly charged to total ion current for xenon and argon. Modified thruster.

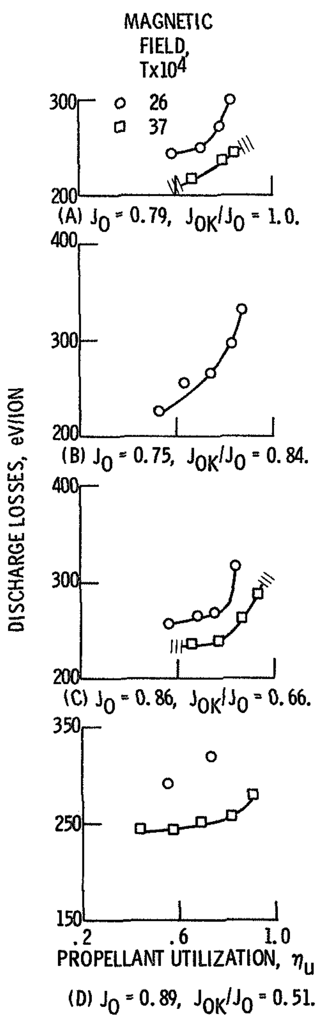

Figure 4. - Discharge chamber performance for krypton.

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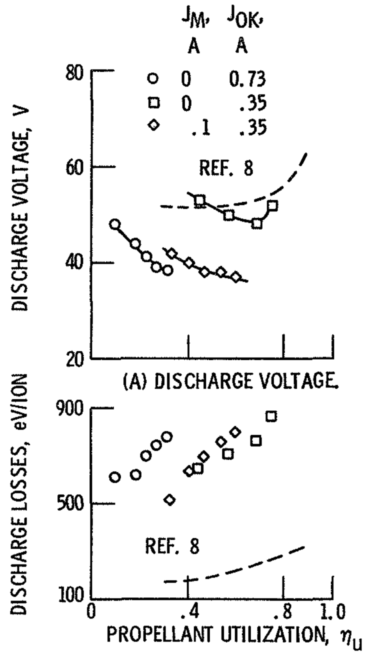
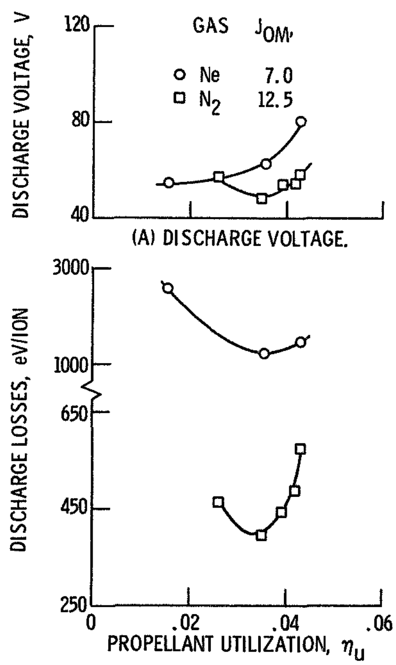


(B) DISCHARGE LOSSES.

Figure 5. - Discharge chamber performance with argon. Modified thruster. Magnetic field strength, 26×10^{-4} T.



(B) DISCHARGE LOSSES.

Figure 6. - Discharge chamber performance with nitrogen and neon. Modified thruster.

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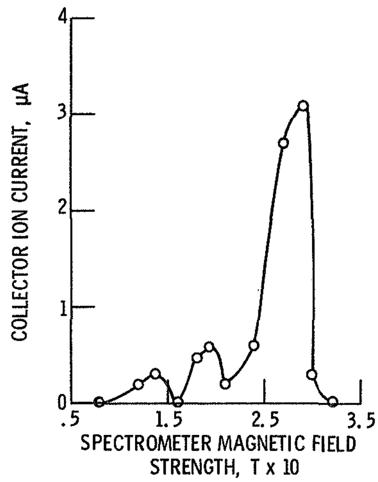

Figure 7. - Collected ion current as a function of spectrometer magnetic field strength with nitrogen. Modified thruster; discharge voltage, 60 V.

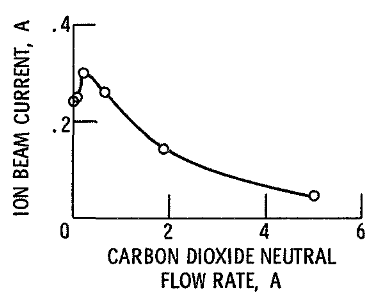

Figure 8. - Effect of carbon dioxide flow rate on ion beam current cathode flow, argon, modified thruster.

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