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OPERATION OF AN ELECTRON-BOMBARDMENT ION SOURCE USING VARIOUS GASES

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16. Abstract

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SUMMARY

A electron-bombardment ion thruster of the SERT II (Space Electric Rocket Test) type 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. Mass spectrometer data indicated that the xenon contained 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 because the basic thruster designed was optimized for operation with mercury. Some future performance improvements may be realizable with thruster modifications directed specifically toward low molecular weight gas operation.

INTRODUCTION

The electron-bombardment ion thruster (refs. 1 and 2) has been the object of a research and development program (ref. 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 (refs. 4 and 5). This ion source has been operated in excess of 7000 hours in ground tests (ref. 5). Thrusters 5 to 150 centimeters (ref. 3) in diameter have been operated and net ion energies from 10 volts (ref. 6) to 70 kV (ref. 7) have been produced. 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 thruster with a refractory-metal cathode was operated with several gases (ref. 8) and more recently a hollow-cathode thruster was operated with argon (ref. 9). Operation with gases other than mercury and cesium is of interest for a number of ground-based applications (ref. 10). In addition, some flight applications such as biowaste expulsion (ref. 11) or simulation of ionospheric conditions (ref. 6) may be of interest. This report 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

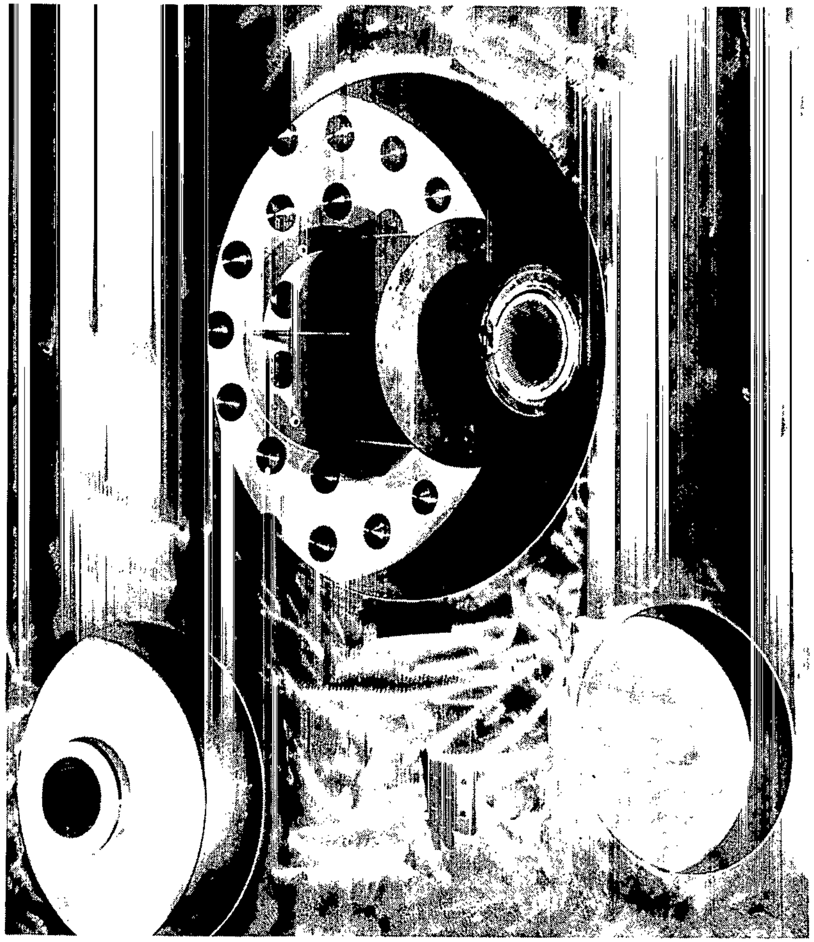
The basic 15-centimeter-diameter thruster used in this investigation has been described previously (ref. 9). The thruster was a modification of the SERT II thruster (ref. 12) and is shown installed in the vacuum facility in figure 1(a) and in cross section in figure 1(b). Two modifications were made to the thruster of reference 9 for some of these tests. The orifice in the hollow cathode tip was enlarged from 0.4 to 0.75 millimeter. Other experiments (ref. 13) 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 (ref. 8) to increase the neutral density in the discharge chamber with the low molecular weight gases. This increased density permitted stable discharges to be obtained with the light gases. The thruster operated with the masked screen will be referred to herein as the modified thruster.

Usually the discharge of a hollow cathode thruster is initiated with the aid of a high starting voltage (~300) between the cathode and the cathode keeper. However, with the light gases it was often difficult to initiate the keeper discharge. The 300-volt starting potential was also applied between the cathode and the anode in these cases. The thruster discharge would then 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 presumably closer to the Paschen minimum for the breakdown than that of the keeper region.

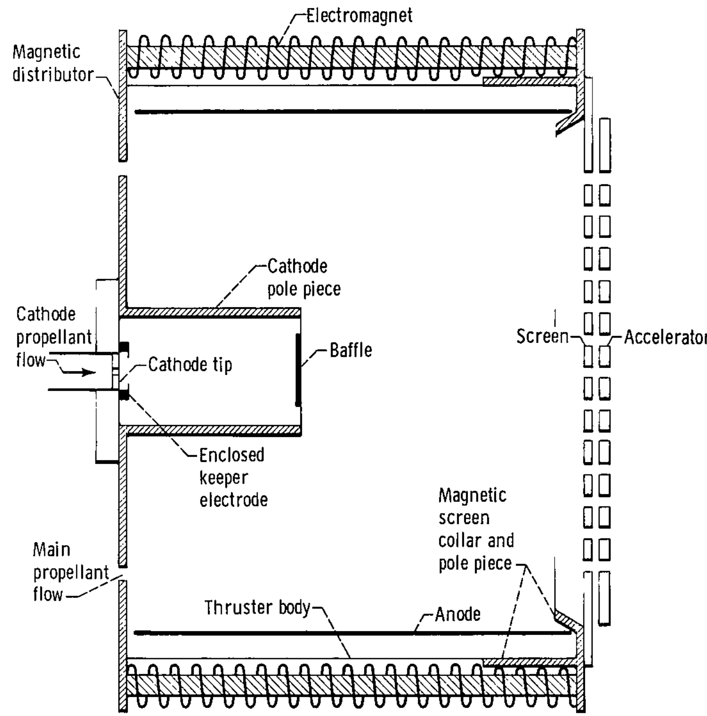
The magnetic field strength could be varied with the eight electromagnets described in reference 9. The magnetic field strengths quoted herein were measured 2 millimeters downstream of the cathode pole piece baffle.

The gases used as propellants were from commercially available stock. No attempts were made to purify or dry the gases previous to introduction into the thruster. Some physical properties of the test gases (refs. 14 and 15) are listed in table I.

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



(a) Thruster in vacuum facility.



(b) 15-Centimeter-diameter.

Figure 1. - Test thruster.

TABLE I. - PROPERTIES OF TEST GASES

Gas	Molecular weight	Ionization potentials, V		Maximum total ionization cross section		Ratio of double to total ionization cross section[a]
		Single	Double	Cross section m^2	Electron energy, V	
Mercury	200.6	10.39	18.65	5.42×10^{20} to 7.1×10^{20}	80	0.096
Xenon	131.3	12.08	21.1	5.51 to 7.9	100	.136
Krypton	83.8	13.93	26.4	4.2 to 5.52	80	.12
Argon	39.9	15.68	27.76	2.89 to 3.59	91	.08
Nitrogen (N_2)	28.0	15.51	-----	2.5 to 2.98	112	------
(N)	14	14.48	29.47	3.08	100	------
Neon	20.2	21.47	40.9	.79 to .87	181	.04
Helium	4.0	24.46	54.14	0.38	128	.0023
Carbon dioxide	44.0	14.4	-----	--------------------	---	------

[a]At electron energy for maximum total ionization cross section.

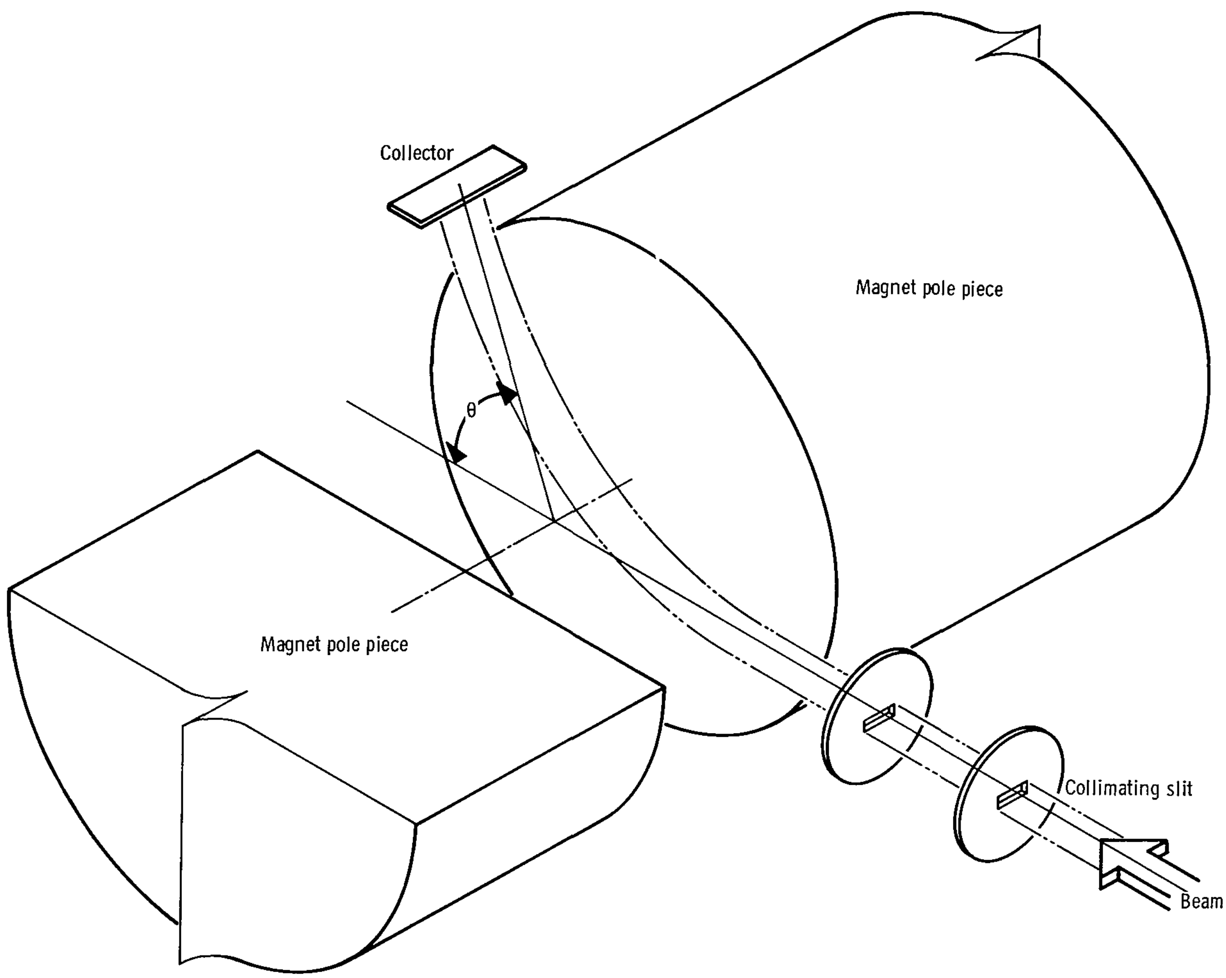


Figure 2. - Magnetic spectrometer.

the ion species in the thruster beam. The spectrometer is shown schematically in figure 2 and consisted of a set of collimating slits positioned on the beam axis, a variable magnetic field region, and an ion current collector.

The collimating system was identical to that described in reference 16. The slits were 12.7 millimeters long, 1.02 millimeters wide, and were spaced 28.6 millimeters apart. Ions with velocity vectors at angles larger than about 2° from the axis of the slit system were intercepted and did not pass through the slit system into the magnetic spectrometer. Therefore, the maximum spread in velocity vector for ions entering the magnet region was about 4°. The magnet consisted of two circular pole pieces 10 centimeters in diameter spaced 5.0 centimeters apart. The spectrometer magnetic field strength was varied by an external power supply. The collector could be biased negatively with respect to ground to prevent electron collection.

Ions which passed through the collimating slits and entered the magnetic field region traversed a circular path of radius R_I (the ion cyclotron radius) and exited the field region at a position corresponding to the angle θ shown in figure 2. For an ion entering on the slit axis, the relation between the spectrometer magnetic field strength and the exit location was

$$B = \left(\frac{\sin \theta}{1 + \cos \theta}\right) \frac{\sqrt{\frac{2m}{q} V_I}}{R_m} \tag{1}$$

where

B magnetic field strength, T

m ion mass, kg

q ion electronic charge, C

R_m magnet radius, m

V_I ion energy, V

Information concerning the degree of fractionation and multiple ionization was obtained by setting the thruster at a constant condition and varying the magnetic field strength. At the appropriate field strength (eq. (1)) the ions would strike the collector which was fixed at 60°.

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 the 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. Multiple ionization or fractionation in the discharge chamber would affect the 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. Data are presented for the basic thruster and/or the modified thruster for the various gases. The basic thruster was designed for operation with mercury. Operation of the basic thruster with both mercury and argon was reported in reference 9. Other parameters which affected thruster lifetime or stability (for example, chamber or keeper discharges) are also discussed. The screen and accelerator extraction voltages were +3 and -2 kilovolts, respectively, for all data presented herein.

Xenon

The thruster was operated over a wide range of cathode propellant flow rate J_{OK} and main propellant flow rate J_{OM}. The total inlet flow rate J_O is the sum of the cathode and main propellant flow rates. With xenon, as with all propellant gases, both an upper and lower limit on flow rate existed for proper thruster operation. The upper limit on total flow rate resulted because of the space charge limited current of the accelerator grid system. Operation at high propellant utilization was not possible at total flow rates in excess of the space charge limited current. Operation at low values of propellant utilization can lead to excessive production of charge-exchange ions in the grid acceleration region which can result in accelerator grid damage (ref. 17). The lower limit on total flow rate was the minimum flow through the cathode required for stable discharge operation. For xenon, the upper and lower limits on flow rate were about 0.6 and 0.3 ampere, respectively.

Figure 3 shows the thruster performance with xenon for the four combinations of cathode and main propellant flow rate for which the best discharge chamber performance was attained. The discharge voltages were between 29 and 42 volts for all the data of figure 3. (Table II contains most of the thruster data obtained in this investigation.)

As the inlet flow rates were varied, the performance shifted and was best at the conditions of figure 3(c) and (d), near the minimum cathode flow rate for that total flow rate. At optimum conditions, the discharge losses were similar to those for mercury

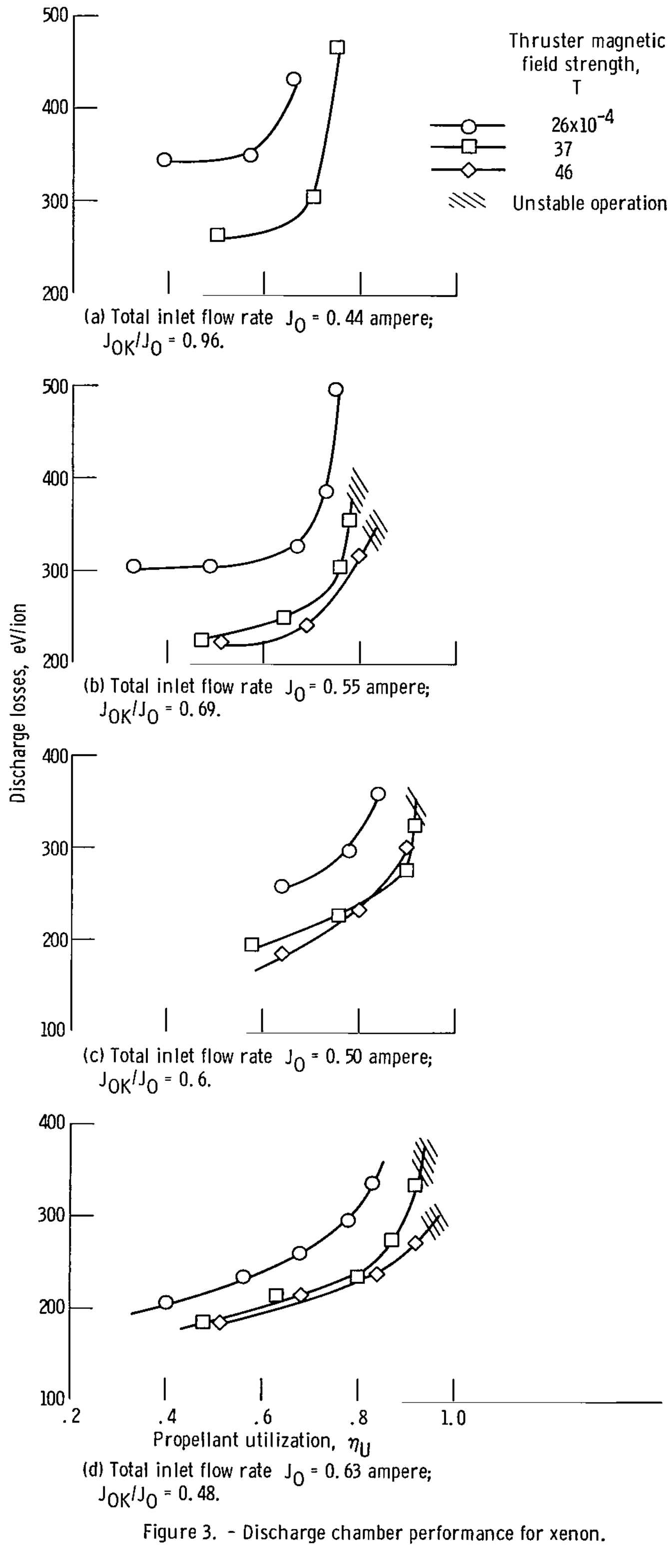


Figure 3. - Discharge chamber performance for xenon.

TABLE II. - THRUSTER OPERATION WITH VARIOUS GASES

Gas	Thruster	Flow rate, equivalent A		Thruster magnetic field strength, T	Ion beam current, A	Discharge voltage, V	Discharge current, A	Discharge losses, eV/ion	Propellant utilization, η_u
		Cathode	Main						
Xenon	Basic	0.54	0	26×10^{-4}	0.20	30	3.0	420	0.37
					.25	29	4.0	435	.46
					.30	31	5.0	483	.55
				37×10^{-4}	0.27	31	3.0	319	0.50
					.33	32	4.0	352	.61
					.35	34	5.0	450	.65
				46×10^{-4}	0.20	38	2.0	376	0.37
					.30	33	3.0	298	.55
					.35	36	4.0	375	.65
		0.42	0.02	26×10^{-4}	0.17	31	2.0	345	0.39
					.25	32	3.0	348	.57
					.29	34	4.0	430	.66
					.30	39	5.0	607	.68
				37×10^{-4}	0.22	33	2.0	265	0.50
					.31	35	3.0	303	.70
					.33	42	4.0	470	.75
		0.38	0.17	26×10^{-4}	0.18	30	2.0	301	0.33
					.27	30	3.0	304	.49
					.37	33	4.0	326	.67
					.40	33	5.0	384	.73
					.41	36	6.0	495	.75
				37×10^{-4}	0.26	33	2.0	226	0.47
					.35	33	3.0	250	.64
					.42	35	4.0	304	.76
					.43	36	4.7	355	.78
				46×10^{-4}	0.28	36	2.0	222	0.51
					.38	35	3.0	240	.69
					.43	37	4.0	308	.78
					.44	37	4.2	317	.80
		0.30	0.20	26×10^{-4}	0.32	31	3.0	258	0.64
					.39	32	4.0	295	.78
					.42	33	5.0	359	.84
					.44	35	6.0	448	.88
				37×10^{-4}	0.29	33	2.0	195	0.58
					.38	33	3.0	227	.76
					.45	35	4.0	279	.90
					.46	36	4.6	326	.92
				46×10^{-4}	0.32	35	2.0	185	0.64
					.40	36	3.0	233	.80
					.45	38	4.0	300	.90
				48×10^{-4}	0.32	36	2.0	187	0.64
					.41	37	3.0	234	.82
					.45	37	3.6	248	.90
		0.30	0.33	26×10^{-4}	0.25	24	2.0	205	0.40
					.35	30	3.0	231	.56
					.43	31	4.0	260	.68
					.49	32	5.0	298	.78
					.52	32	6.0	337	.83
				37×10^{-4}	0.30	33	2.0	183	0.48
					.40	33	3.0	217	.63
					.50	33	4.0	231	.80
					.55	34	5.0	275	.87
					.58	36	6.0	337	.92
				46×10^{-4}	0.32	35	2.0	183	0.51
					.43	35	3.0	212	.68
					.53	36	4.0	238	.84
					.58	37	4.8	271	.92

TABLE II. - Continued. THRUSTER OPERATION WITH VARIOUS GASES

Gas	Thruster	Flow rate, equivalent A		Thruster magnetic field strength, T	Ion beam current, A	Discharge voltage, V	Discharge current, A	Discharge losses, eV/ion	Propellant utilization, η_u
		Cathode	Main						
Krypton	Basic	0.79	0	26×10^{-4}	0.47	32	4.0	242	0.59
					.56	31	5.0	248	.70
					.62	31	6.0	270	.78
					.66	31	7.0	297	.84
				37×10^{-4}	0.53	33	4.0	216	0.67
					.63	34	5.0	236	.80
					.67	33	5.6	244	.85
		0.63	0.12	21×10^{-4}	0.53	33	5.0	277	0.72
				26×10^{-4}	0.39	35	3.0	225	0.53
					.47	34	4.0	255	.64
					.56	33	5.0	265	.76
					.62	34	6.0	295	.84
					.65	34	7.0	331	.88
				33×10^{-4}	0.62	36	5.0	255	0.84
		0.56	0.30	26×10^{-4}	0.48	35	4.0	255	0.56
					.58	34	5.1	264	.67
					.64	32	6.0	267	.74
					.69	31	7.0	283	.80
				37×10^{-4}	0.56	38	4.0	235	0.65
					.66	36	5.0	238	.77
					.74	37	6.0	263	.86
					.80	37	7.0	286	.93
		0.45	0.44	26×10^{-4}	0.50	32	5.0	290	0.56
					.57	34	6.0	323	.65
					.66	33	7.0	319	.74
				37×10^{-4}	0.39	36	3.0	241	0.44
					.51	35	4.0	240	.57
					.61	35	5.0	251	.69
					.72	35	6.0	257	.81
					.80	36	7.0	279	.90
Argon	Modified	0.73	0	15×10^{-4}	0.13	36	4.0	1080	0.18
				26×10^{-4}	0.07	48	1.0	612	0.0
					.14	44	2.0	609	.19
					.17	41	3.0	690	.23
					.2	39	4.0	735	.28
					.23	38	5.0	777	.32
					.24	38	5.4	823	.33
				37×10^{-4}	0.24	43	4.0	678	0.33
				42×10^{-4}	0.24	44	4.0	679	0.33
		0.35	0	15×10^{-4}	0.20	48	4.0	900	0.58
				26×10^{-4}	0.16	53	2.0	625	0.45
					.20	50	3.0	700	.57
					.24	48	4.0	750	.69
					.26	52	4.6	855	.76
				37×10^{-4}	0.24	53	3.0	611	0.68
					.28	51	4.0	678	.78
					.32	52	5.0	761	.92
		0.35	0.10	15×10^{-4}	0.15	36	4.0	922	0.33
				26×10^{-4}	0.15	42	2.0	516	0.33
					.18	40	3.0	621	.41
					.21	38	4.0	685	.47
					.24	38	5.0	750	.54
					.27	37	6.0	785	.60

TABLE II. - Concluded. THRUSTER OPERATION WITH VARIOUS GASES

Gas	Thruster	Flow rate, equivalent A		Thruster magnetic field strength, T	Ion beam current, A	Discharge voltage, V	Discharge current, A	Discharge losses, eV/ion	Propellant utilization, η_u
		Cathode	Main						
Argon	Modified	0.35	0.10	37×10^{-4}	0.27	41	4.0	567	0.6
				46×10^{-4}	0.31	46	4.0	548	0.69
		0.21	0.33	15×10^{-4}	0.13	38	3.0	840	0.24
					.16	38	4.0	915	.3
					.17	34	5.0	1000	.31
					.20	33	6.0	995	.36
				23×10^{-4}	0.21	42	4.0	758	0.39
Nitrogen	Modified	12.5	0	26×10^{-4}	0.44	49	4.0	395	0.035
					.49	54	4.5	441	.039
					.52	55	5.0	485	.042
					.55	58	6.0	577	.043
Neon	Modified	7.0	0	15×10^{-4}	0.11	55	5.2	2540	0.016
				26.5	.25	63	5.2	1240	.036
				30	.24	75	4.0	2080	.034
				41	.30	80	5.7	1440	.043
Helium	Modified	----	0	30×10^{-4}	0.20	100	7.0	3400	-----

(ref. 9). The eV/ion generally decreased with increasing magnetic field at constant propellant utilization. At optimum flow conditions, however, the sensitivity of discharge losses to magnetic field variation was small. This effect was noted in reference 8 with a thruster which used a thermionic emitter. The magnetic field also affected thruster stability in that, as the field strength increased, the stable range of discharge current decreased. The cross-hatched areas in the figures represent regions of thruster instability.

Magnetic spectrometer data were obtained with xenon with the modified thruster and are shown in figure 4.

Data obtained with argon are also shown in figure 4 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 discharge voltage was varied by changing of both the thruster magnetic field strength and the cathode flow rate. The ratio of twice the double ionization cross section to the total ionization cross section (ref. 14) as a function of electron energy is shown as a dashed line. This ratio would yield the relative ion current if single electron-atom collisions were the dominant ionization process in the discharge chamber. For xenon the measured amount of double ionization at a given discharge voltage was somewhat less than that for an equal electron energy as given in reference 14. The exact cause of this difference is not known; however, several items

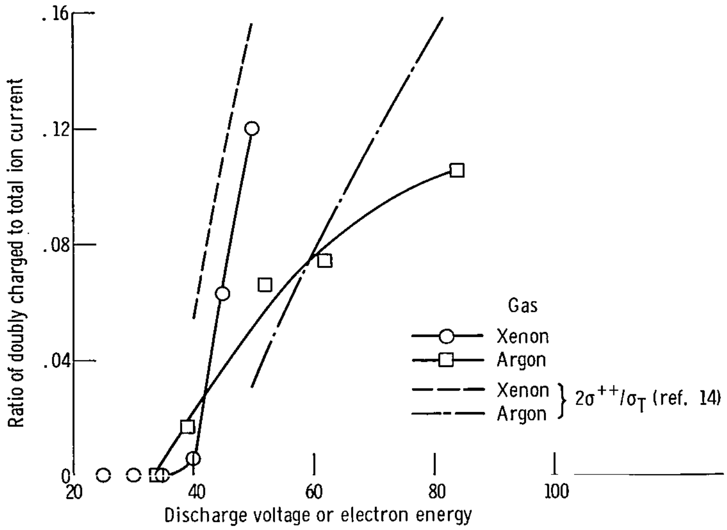


Figure 4. - Ratio of doubly charged to total ion current for xenon and argon. Modified thruster.

that could contribute are:

(1) It is likely that the maximum electron energy in the discharge chamber is somewhat less than that corresponding to the discharge voltage (refs. 18 and 19).

(2) It is probable that the electron energy distribution varies with position in the discharge chamber. Complete analysis of the degree of double ionization would require that the collimating slit system be pointed to accept ions from various portions of the discharge.

(3) The technique used to vary the discharge voltage could have affected the results (i.e., flow rate and thruster magnetic field changes).

Because all the data of figure 3 were at discharge voltages less than 42 volts, the values of discharge losses and propellant utilization should be essentially those for singly charged ions.

Krypton

The performance of krypton is shown in figure 5 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 0.9 and 0.45 ampere, respectively. The optimum flow rate for krypton is difficult to specify. At the lower magnetic 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. At magnetic fields slightly higher than those shown, the thruster exhibited instabilities at nearly all values of discharge current.

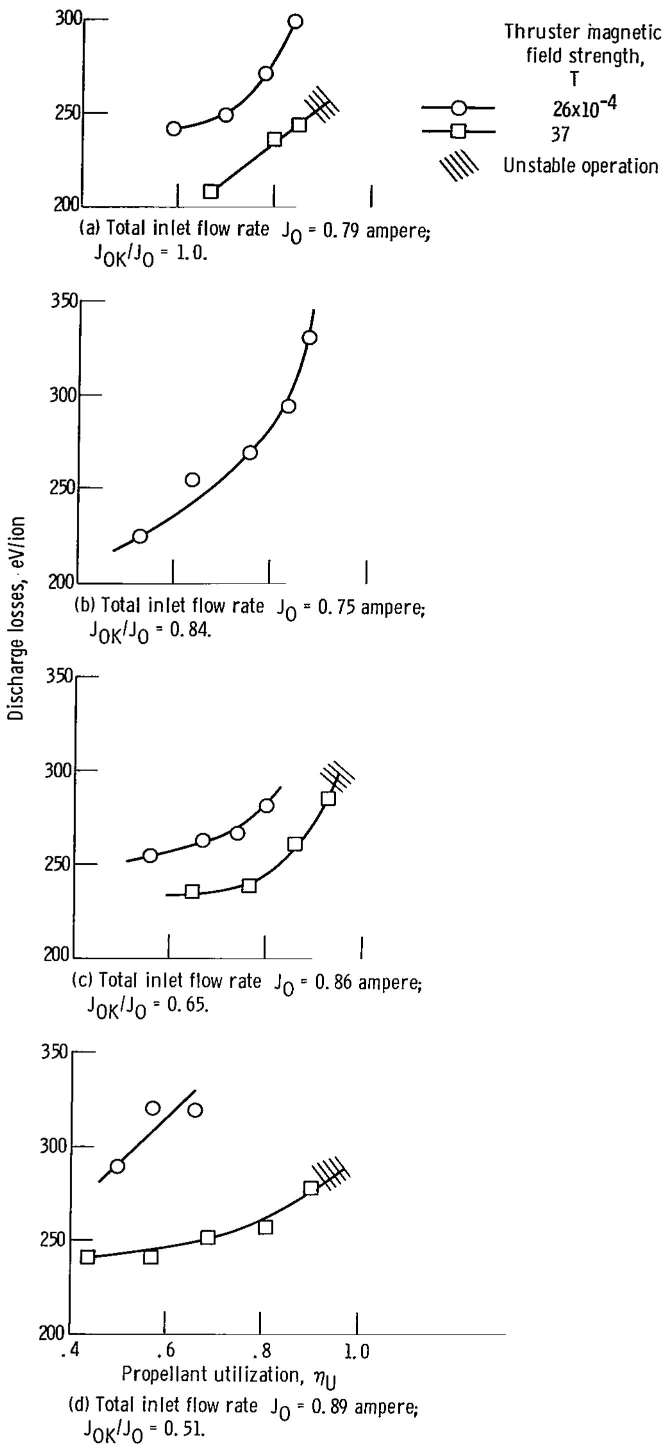


Figure 5. - Discharge chamber performance with krypton.

No mass spectrometer data were taken with krypton. All the data of figure 5 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 1 percent (ref. 14) so that probably no significant double ionization resulted.

Argon

Argon was tested with the modified thruster to determine if the range of propellant flow and/or stability could be improved over previously published data (ref. 9) 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 6 shows the performance of the modified thruster with argon. The best per-

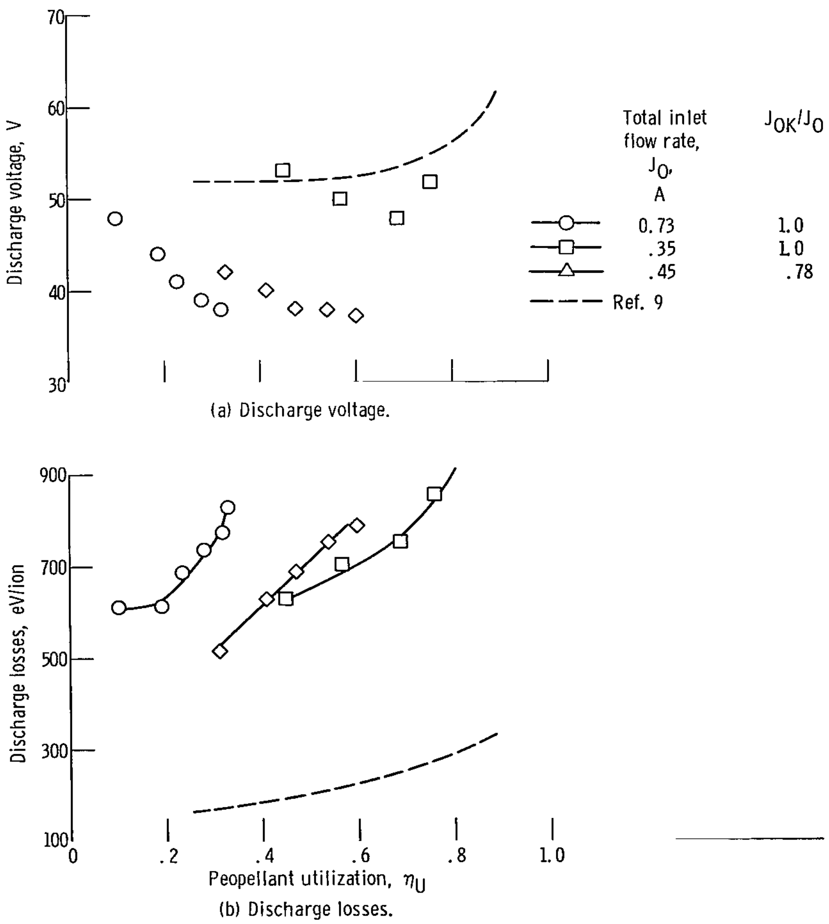
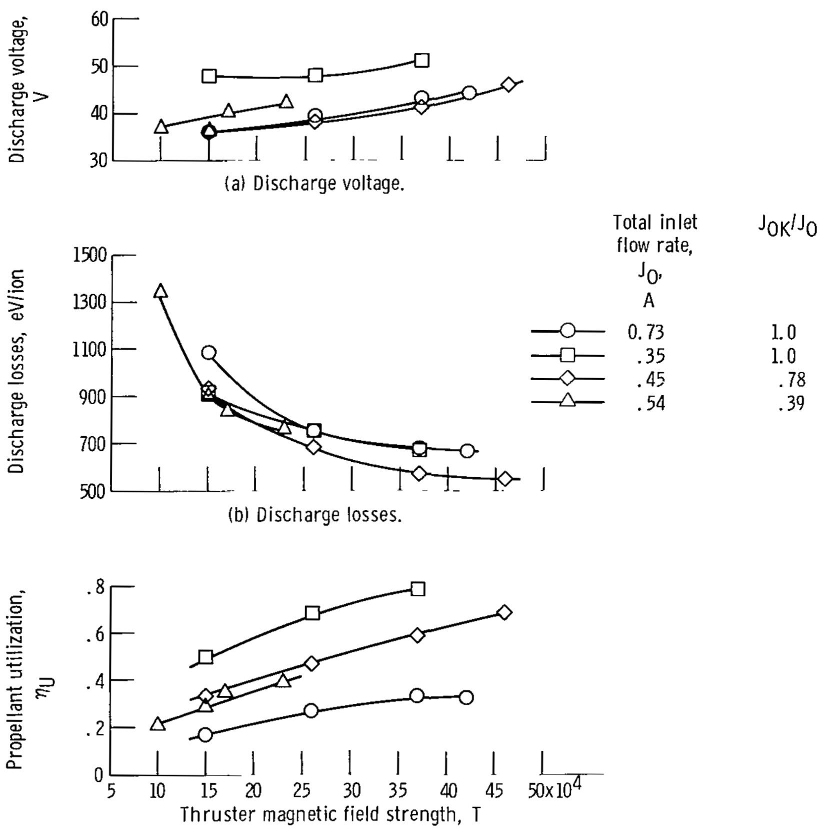


Figure 6. - Discharge chamber performance with argon. Modified thruster.

formance 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 (refs. 20 and 21). Figure 6 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 to avoid double ionization and to extend cathode lifetime.

The performance of the modified thruster was quite sensitive to magnetic field strength. The discharge voltage, discharge losses, and propellant utilization as a function of magnetic field strength are shown in figure 7 at several values of cathode and propellant flow ratio. An increase in magnetic field strength generally increased the discharge voltage and propellant utilization and decreased the discharge losses. As with xenon and krypton, an increase in magnetic field strength decreased the range of discharge current for which the thruster operated stably.

The strong dependence of discharge performance on cathode keeper power noted with the basic thruster was sharply reduced with the modified thruster. For example,



(c) Propellant utilization.

Figure 7. - Effect of magnetic field strength on performance with argon. Modified thruster; discharge current, 4.0 amperes.

a variation of 8 to 34 watts keeper power caused less than a 5 percent change in discharge losses. Such a keeper power increase with the basic thruster caused a 50 percent increase in discharge losses.

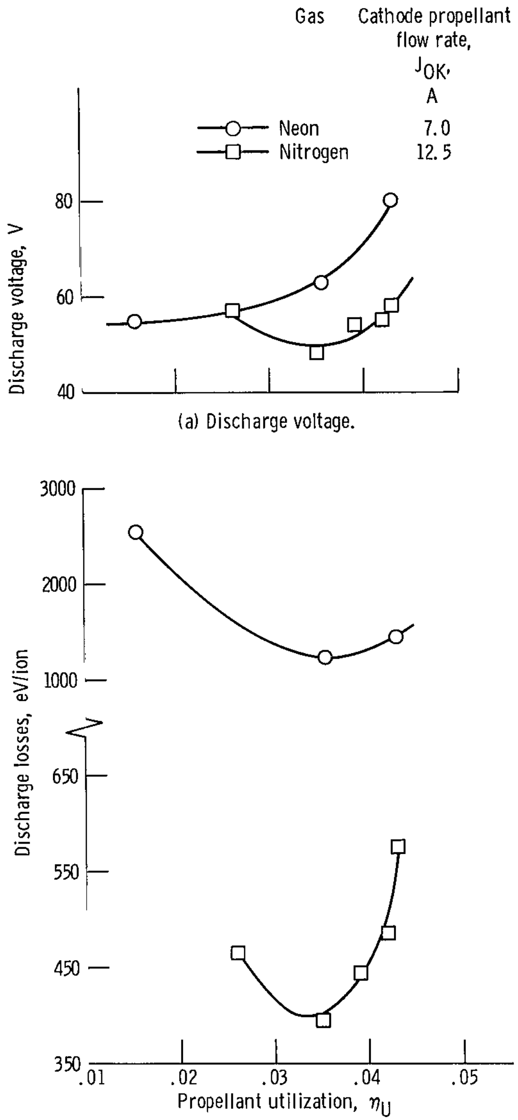
Mass spectrometer data were taken with argon operated with the modified thruster and are shown in figure 4. Double ionization was detected at a discharge voltage of 35 volts. The measured degree of double ionization was greater than that predicted by the cross section ratio for discharge voltages up to about 60 volts. Electron-distributions have been measured in the discharge chamber of a bombardment thruster operated on argon (ref. 19). In reference 19 it was found that a two temperature distribution existed. One was a Maxwellian distribution at low energy and the other was a peaked distribution located at an energy between 15 to 5 volts below the discharge voltage. It is unlikely that the onset of double ionization was due to the existence of electrons with energies in excess of the discharge voltage. Possibly the production of double ions at energies below about 60 volts was due to electron-ion or electron-excited neutral atom interactions.

In the range of discharge voltage from 50 to 70 volts, where most of the argon data of reference 9 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 V).

Nitrogen, Neon, and Helium

The discharge performance for neon and nitrogen is shown in figure 8 (note the scale break on fig. 8(b)). These gases are presented together because the performance was extremely poor for both and does not justify a more detailed exposition. The total inlet flow rate was through the cathode for the data of figure 8 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 and 0.05 propellant utilizations shown in figure 8 are substantially lower than the 0.1 and 0.2 values obtained in an earlier study (ref. 8). 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.

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 (ref. 14). Figure 9 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



(b) Discharge losses.

Figure 8. - Discharge chamber performance with nitrogen and neon. Modified thruster.

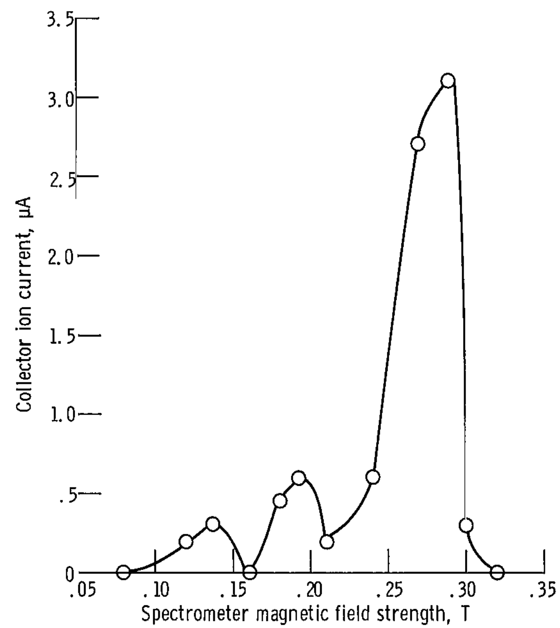


Figure 9. - Collected ion current as a function of spectrometer magnetic field strength with nitrogen. Modified thruster; discharge voltage, 60 volts.

charged 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 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 8.

Carbon Dioxide

The modified thruster was operated with carbon dioxide, a possible biowaste propellant (ref. 11) 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 10. 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 a carbon dioxide to argon flow ratio of about 2.5 to 1 to less than 0.01 at a flow ratio of 50 to 1. Magnetic spectrom-

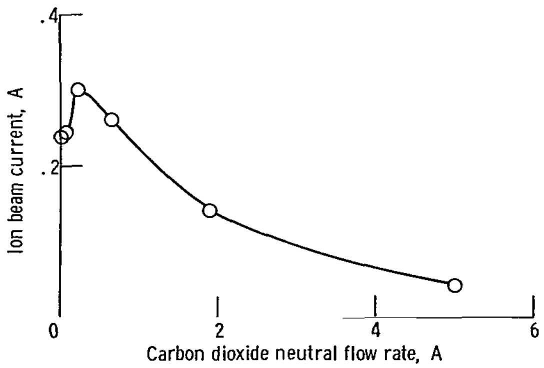


Figure 10. - Effect of carbon dioxide flow rate on ion beam current cathode flow for argon. Modified thruster.

eter 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 charged 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 amperes, the major ion peak became broadened and maximized at about 0.2 teslas less than for argon alone. In addition, a secondary peak occurred at a magnetic field corresponding to an amu of 12. These facts indicate that both carbon monoxide and carbon ions were being produced in the discharge.

CONCLUDING REMARKS

An electron-bombardment ion thruster of the SERT II type (Space Electric Rocket Test) 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 (ref. 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 because the basic thruster designed was optimized for operation with mercury. Some future performance improvements may be realizable with thruster modifications directed specifically toward low molecular weight gas operation.

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Cleveland, Ohio, October 4, 1971,
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