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A 30-CM DIAMETER BOMBARDMENT THRUSTER WITH A VARIABLE MAGNETIC BAFFLE

by Robert T. Bechtel
Lewis Research Center
Cleveland, Ohio

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A 30-CM DIAMETER BOMBARDMENT THRUSTER WITH A VARIABLE MAGNETIC BAFFLE

Robert T. Bechtel
Aerospace Research Engineer
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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Abstract

Thruster performance and stability over a range of beam currents is a function of the hollow cathode propellant flow which depends in part on the baffle geometry. Variable magnetic baffles have been used to allow a change in baffle geometry to improve thruster performance and stability. Test results of a 30-cm thruster with magnetic baffle are presented. Thruster performance characteristics are analyzed to show how the magnetic baffle field strength can improve performance at a fixed beam current, as well as increase the range of ion beam current for throttling.

Introduction

Mercury bombardment thrusters which use a hollow cathode require a baffle located in the discharge chamber to control the impedance to electron current from the cathode to the main discharge and anode. In addition, thruster performance and stability of operation is a function of the amount of propellant flow introduced into the discharge through the hollow cathode. In order to improve discharge performance and stability, magnetic baffles have been used to vary the baffle impedance and thus minimize dependence on cathode propellant flow rate.(1,2,3) Tests are described in which a 30-centimeter diameter thruster was equipped with a magnetic baffle and operated at a fixed flow rate to determine discharge chamber performance and running modes both with and without the magnetic baffle.

Because some missions require that the thruster power throttled to match available solar cell array power,(4,5) the tests were also extended to cover other main propellant flow rates and beam currents. The magnetic baffle can be used to reduce the range of cathode flow rate variation required to vary the beam current over a given throttling ratio (ratio of high to low beam current). This increases the throttling ratio for a given thruster geometry. The magnetic baffle can also be used to optimize thruster performance at a fixed beam current level.

Apparatus

Discharge Chamber

The 30-centimeter diameter thruster described in Refs. 6 and 7 was used. The only modification to the discharge chamber was to the distributor pole piece-baffle area. The baffle was mounted from four mild steel legs which were connected through a mild steel cylinder and flange to one face of 8 parallel electromagnets (Fig. 1). The other faces of the magnets were in contact with the standard distributor pole piece. The baffle was 0.25 mm (10 mil) thick tantalum and was mounted to the annular ring at the end of the four legs. Each solenoid core was wrapped with 12 turns of magnet wire (96 turns total) connected in series. The same system was used for tests with no magnetic baffle by disconnecting the solenoid.

Extraction System

A two-grid extraction system similar to that described in Ref. 8 was used. The grids were dished downstream (convex side downstream) to a depth of 2.54 cm. The spacing at the edge was set at 0.87 mm (34 mil). This spacing remained fixed during operation, but the spacing in the center is estimated in Ref. 8 to be 0.60 mm (24 mils) due to differential thermal expansion of the two grids. Both screen grid and accelerator grid apertures were 1.25 mm (50 mil).

Neutralizer and Cathode

A hollow cathode neutralizer was used to provide space-change beam neutralization of a fraction of the beam for all tests. The remainder of the neutralizing electrons were acquired from the facility walls. Both neutralizer and thruster cathodes were the same type described in Refs. 6 and 7.

Procedure

The thruster was operated by setting propellant vaporizer temperatures to provide the desired flow rates. These temperatures were held constant by means of proportional controllers. The flow rates were measured by measuring the rate of change of a height of a mercury column in a small bore glass tube reservoir. The emission current was varied at each of several magnet currents and pertinent data recorded. The magnet currents were set by first raising the power supply current to maximum and then reducing the current to the desired value in order to avoid hysteresis problems. Extraction system voltages were typically held at +1000 and -500 volts throughout the tests.

Results and Discussion

Fixed Configuration Performance

Effect of discharge voltage. In general, the performance of a hollow-cathode thruster with a fixed baffle and pole piece configuration improves as the discharge chamber voltage is increased.(9) This improvement is reflected by a shift in the discharge chamber losses (eV/ion) versus propellant utilization efficiency curve to lower losses and/or higher utilization. For a fixed baffle configuration a fixed main propellant flow rate, and a fixed discharge voltage, this curve is generated by changing both cathode propellant flow rate and emission current. Figure 2 shows a family of eV/ion, utilization curves for three different discharge chamber voltages.

The optimum operating point is the "knee" of this curve, or that operating point which maximizes the total efficiency by trading off utilization efficiency and discharge losses (eV/ion). The total efficiency is given by

$$\eta_T = \eta_u \times \eta_\rho$$

$$\eta_T = \frac{\eta_u V_I}{(V_I + \varepsilon_I + V_G) + \frac{P_K}{\eta_u J_0}} \tag{1}$$

where

η_T total efficiency

η_ρ power efficiency

η_u thruster propellant utilization efficiency

V_I net accelerating potential

ε_I discharge losses

V_G neutralizer to beam voltage

P_K fixed power losses (independent of beam current)

J_0 total neutral propellant flow rate (beam current = $\eta_u J_0$)

A breakdown of the values of these parameters is given in Table 1. The calculated total efficiency is indicated on the curves of Fig. 2. As the utilization efficiency is increased at constant discharge voltage, the total efficiency increases to a maximum at the knee and then decreases due to an increasing eV/ion. At any point along the curves of Fig. 2, the higher discharge voltage results in a higher total efficiency. Thus it is desirable to operate at the highest permissible discharge chamber voltage possible for all beam current levels.

The major constraints on maximum discharge voltage are adverse effect on cathode lifetime and possibility of introducing doubly ionized mercury into the beam. For these reasons voltages in excess of 40 volts are not considered, and a typical operating value of 37.5 volts is used. By fixing the discharge voltage and main propellant flow rates, the eV/ion versus utilization curve (Fig. 2) is uniquely defined which in turn defines single values of utilization efficiency, eV/ion, cathode flow rate, and beam current to provide the maximum total efficiency.

Throttling. If the thruster is to be operated efficiently over a range of beam currents, the main propellant flow rate must be varied. An increase in main flow rate causes a decrease in discharge chamber voltage. Three methods of restoring the voltage to its original value are available for a fixed geometry thruster. The emission current can be increased, the cathode flow rate can be decreased, or a combination of both. It is desirable to maintain the ratio of emission current to beam current in order to keep constant eV/ion near the point of maximum total efficiency. Table 2(a) gives two data points at low and high beam current, illustrating throttling. The data point for low beam current is near the maximum total efficiency point for a discharge voltage of 37.5 V. To maintain a constant discharge voltage and near constant eV/ion, the cathode flow rate must be reduced from 133 to 51 equivalent mA. The performance at both points is acceptable, but a cathode flow rate of 51 equivalent mA is the minimum value required for cathode operating stability. Any further increase in main flow rate and beam current would result in a decrease in discharge voltage and, as a result, a decrease in total efficiency. This is the major disadvantage of throttling with a fixed discharge chamber geometry.

Magnetic Baffle

Magnetic field strength. Any baffle presents a physical and electrical impedance to both neutrals and electrons. Reference 9 shows that the electrical impedance determined by the baffle has a different effect than the physical impedance. The magnetic baffle system superimposes a radial magnetic field across the annulus between the baffle and the distributor pole piece (Fig. 3). The magnet used was not optimized for power losses, but generally required less than 50 watts. An estimated magnet power of 35 watts was used for power efficiency calculations. The $\overline{v} \times \overline{B}$ force effectively increases the impedance of the discharge. Figure 3 shows that the radial magnetic field in the annulus $\overline{B}_r$ increases from 12.9 gauss for zero magnetic baffle current to 24.5 gauss for a magnetic baffle current of 15A. The axial component, B_z, is essentially unchanged. Figure 3 also shows the change in radial and axial magnetic field strength at a position 0.63 cm downstream of the baffle. The radial component due to the magnetic baffle is significantly reduced from the upstream position over the same range of magnet current. The axial component remains essentially independent of magnet current, although the base level is higher than at the upstream position.

Throttling. Increasing the magnetic baffle current has the same effect on discharge performance as decreasing the cathode propellant flow rate. Figure 4 shows the discharge chamber volt-ampere characteristics for a fixed main propellant flow rate. An increase in the magnetic baffle current from 0 to 2.5 amperes has the same qualitative effect as decreasing the cathode flow rate from 133 to 113 equivalent mA (Fig. 4), namely an increase in discharge chamber voltage at a given emission current. Thus an increase in magnetic baffle current can be used in place of a decrease in cathode propellant flow rate. The application of this result ot throttling is shown in Fig. 5. The main propellant flow rate was increased from 857 to 1805 equivalent mA and the cathode propellant flow reduced from 133 to 103 equivalent mA (Fig. 5(a)). The eV/ion utilization characteristics shifted significantly to lower values of utilization. Operation at discharge voltages greater than 35 volts could not be obtained at the higher main flow rate without a large increase in eV/ion and total efficiencies at this higher main flow rate were estimated to be much less than 0.60. As mentioned previously, a further reduction in cathode flow rate to the minimum required for stability (51 equivalent mA) raised performance to an acceptable level. Figure 5(b) shows that the same can be achieved by increasing the magnetic baffle current to 10 amperes. The throttling data points with a magnetic baffle are given in Table 2(b). Comparison of Table 2(a) and (b) shows that the use of the magnetic baffle has increased the throttling ratio from 1.84 to 2.03 while reducing the cathode flow rate change from 82 to 20 equivalent mA. A further increase in the throttling ratio could be realized before the minimum cathode flow rate for stability is encountered.

Thruster performance. The magnetic baffle can also be used to optimize thruster performance at a fixed main propellant flow rate. This method provides greater operating flexibility than varying the size of a fixed baffle. To determine the magnet current providing optimum thruster performance, the eV/ion-utilization curves are plotted at a discharge voltage of 37.5 v for different magnet currents in Fig. 6. The best performance occurs at a magnet current of 5.0 and possibly 7.5 amps. An anomaly in general trends occurs for a cathode flow rate of 180 equivalent mA as the magnet current is increased from 5.0 to 7.5 A. The utilization efficiency is increased but at an eV/ion which locates the operating point well above the knee. All data points at higher magnet currents and cathode flow rates show discharge losses above the knee with only slight changes in utilization efficiencies (data points 7 through 11). It was not possible to reduce the discharge losses by reducing the emission current in these regions of operation. This was because the discharge voltage actually increased with decreasing emission current at magnetic baffle currents of 7.5 amperes and greater. Therefore, if the emission current was reduced to reduce the eV/ion, the cathode flow rate had to be raised, rather than lowered, to restore the discharge voltage to 37.5 volts. The increase in cathode flow rate generally reduced the beam current, thus increasing the eV/ion.

Thus the optimum magnet current is the highest current which does not force operation in a region of increasing discharge voltage with decreasing emission current. In this case, the optimum magnet current is 5A. This result is consistent with results of other investigations that have shown optimum performance for single point operation is obtained with the minimum permissible cathode flow.

Conclusion

It is desirable to operate a thruster at the maximum possible discharge voltage to maximize the total efficiency. An increase in main propellant flow rate to increase the beam current significantly reduces the discharge voltage. This necessitates a decrease in cathode propellant flow rate. For a fixed geometry thruster without a magnetic baffle, a reduction in cathode flow rate from 133 to 51 equivalent mA resulted in a beam current throttling ratio of 1.84. This represents the minimum cathode flow rate for stable cathode operation.

An increase in magnetic baffle field strength has the same general effect on discharge chamber performance as a reduction in cathode flow rate. When the magnetic baffle current was increased to 10 amperes at the high beam current operating point, a reduction in the cathode flow rate to only 103 equivalent mA resulted in a throttling ratio to 2.03. Thus the use of the magnetic baffle significantly increased to throttling range.

The magnetic baffle can also be used to optimize thruster performance at a fixed beam current level in the same manner as a change in diameter of a fixed baffle. An optimum magnetic baffle current was found which maximized the total efficiency. A further increase in magnetic baffle current resulted in high discharge chamber losses causing a decrease in total efficiency.

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Table 1 - Operating parameters for 30 cm diameter thruster

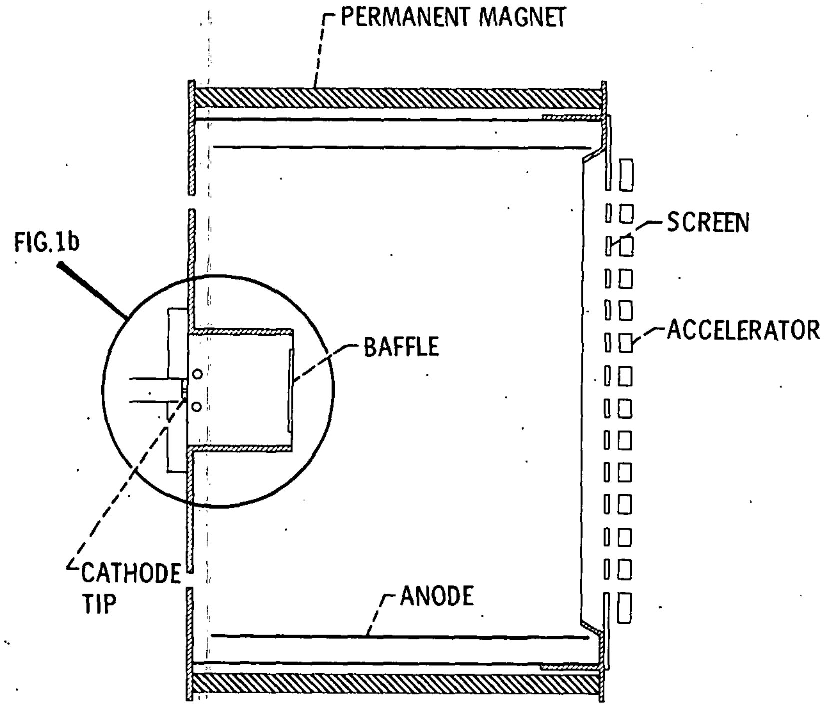
	Power, watts
Cathode	8
(Keeper and vaporizer)	
(Tip heater not used for steady state operation)	
Neutralizer	22
(Keeper, vaporizer, tip heater)	
Other	50
(Accel, main vaporizer, magnet)	
Fixed power losses, P_F	80
Other operating parameters	
Net accelerating potential, V_I,	1000 volts
Neutralizer to beam coupling voltage, V_G,	20 volts

$$\eta_T = \frac{\eta_u \, 1000}{(1020 + \varepsilon_I) + \frac{80}{\eta_u J_0}}$$

(See text for symbol definitions.)

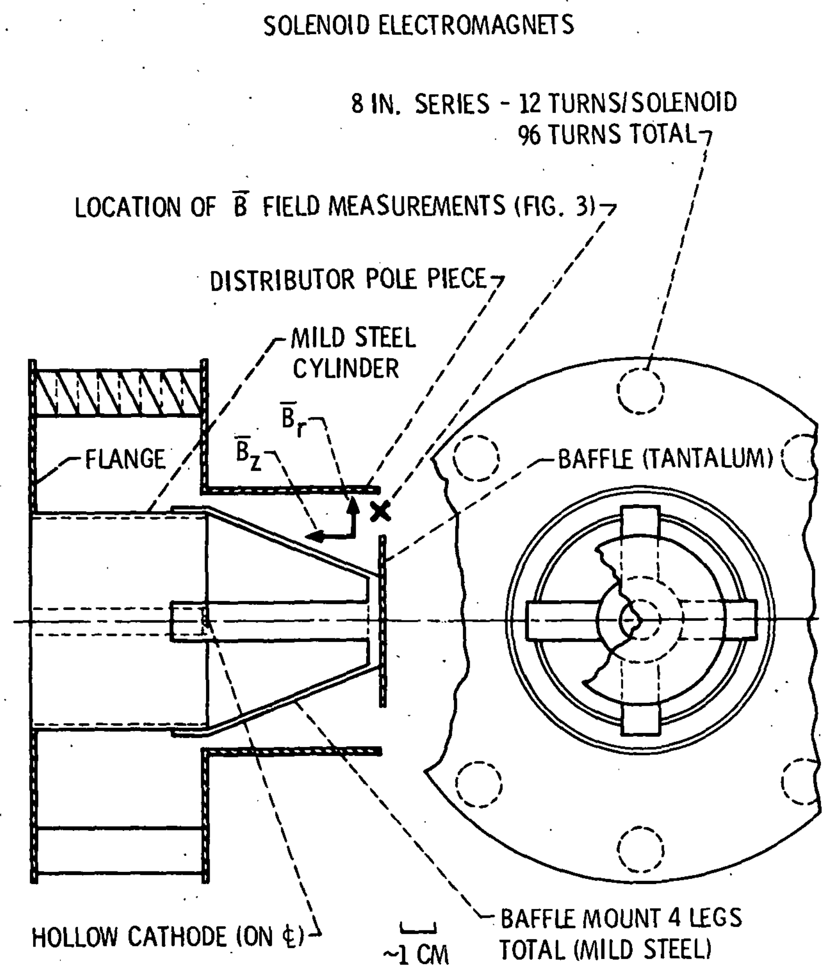
Table 2 - Throttling at discharge voltage of 37.5 volts (data shown in Fig. 5)

	(a) Without magnetic baffle		(b) With magnetic baffle	
Magnet current, A	0	0	0	10
Cathode flow rate, eq. mA	133	51	133	103
Discharge losses, eV/ion	250	235	250	265
Utilization efficiency	0.868	0.855	0.868	0.912
Beam current, A	0.859	1.58	0.859	1.74
Total efficiency	0.637	0.654	0.637	0.685
Throttling ratio	1.84		2.03	



(a) Section view of thruster

Figure 1 - 30 cm diameter thruster.



(b) SKETCH OF MAGNETIC BAFFLE AND DISTRIBUTOR POLE PIECE.

Figure 1. - Concluded.

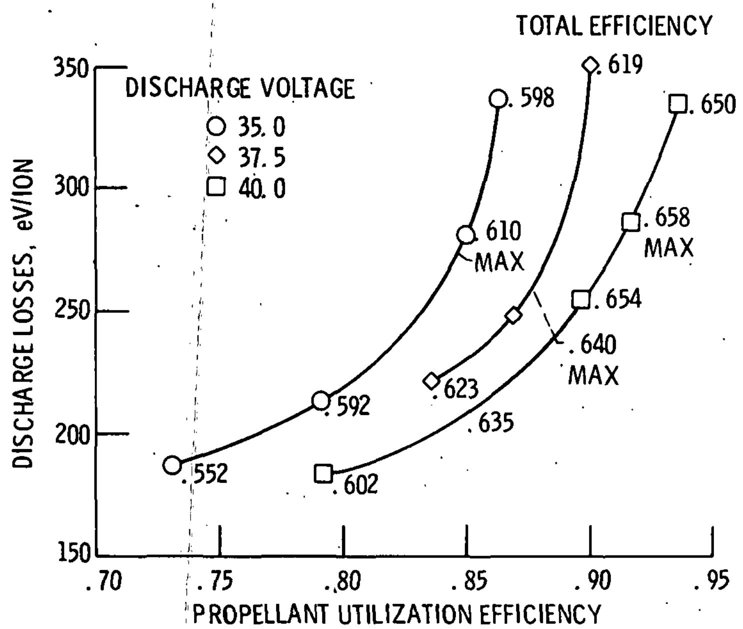


Figure 2. - Thruster performance at constant discharge voltage main propellant flow rate 857 equivalent mA.

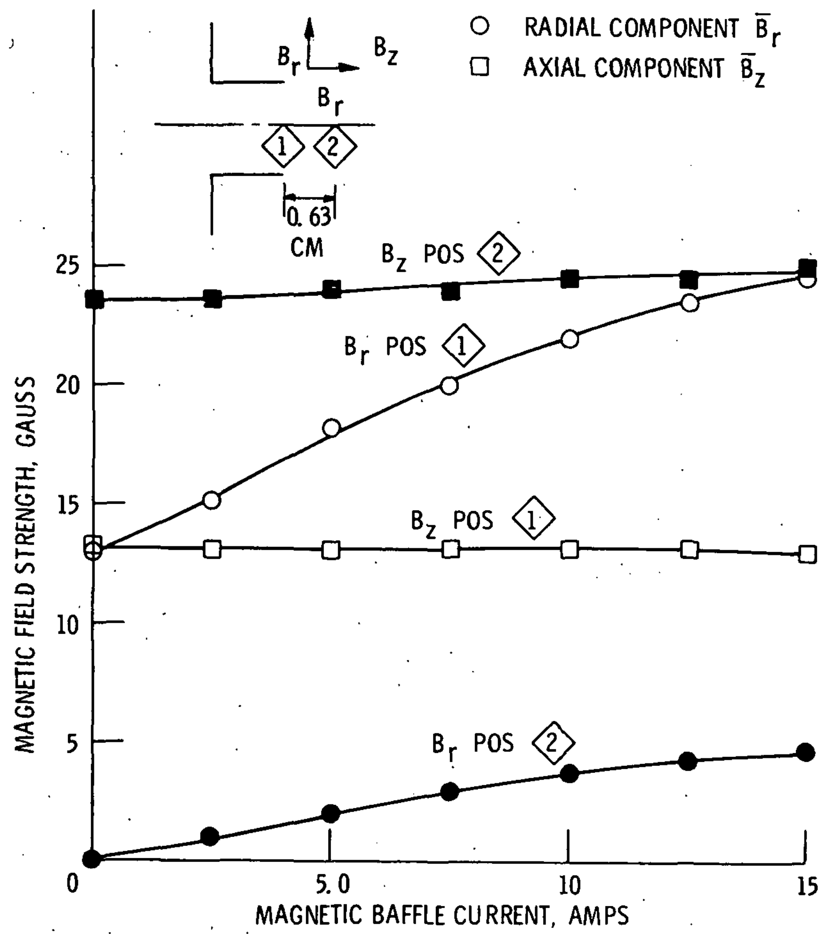


Figure 3. - Effect of magnetic baffle current on discharge chamber magnetic field.

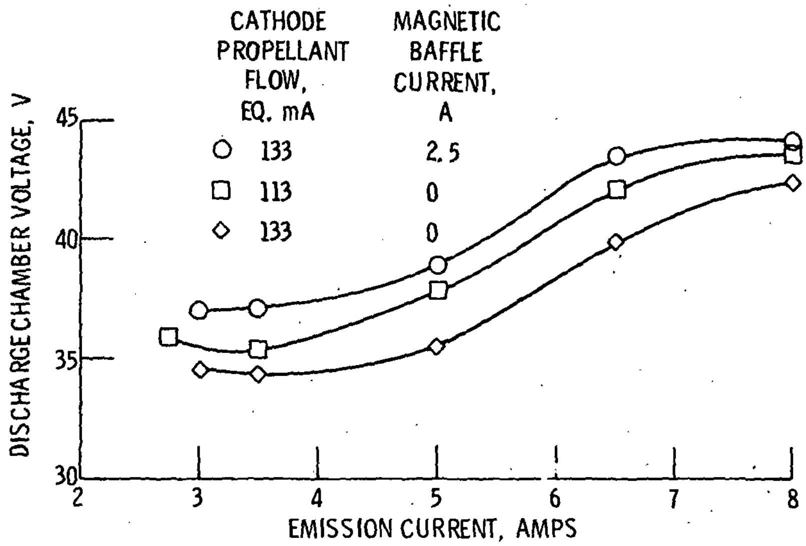


Figure 4. - Discharge volt-ampere characterisics. Main propellant flow rate, 857 equivalent mA.

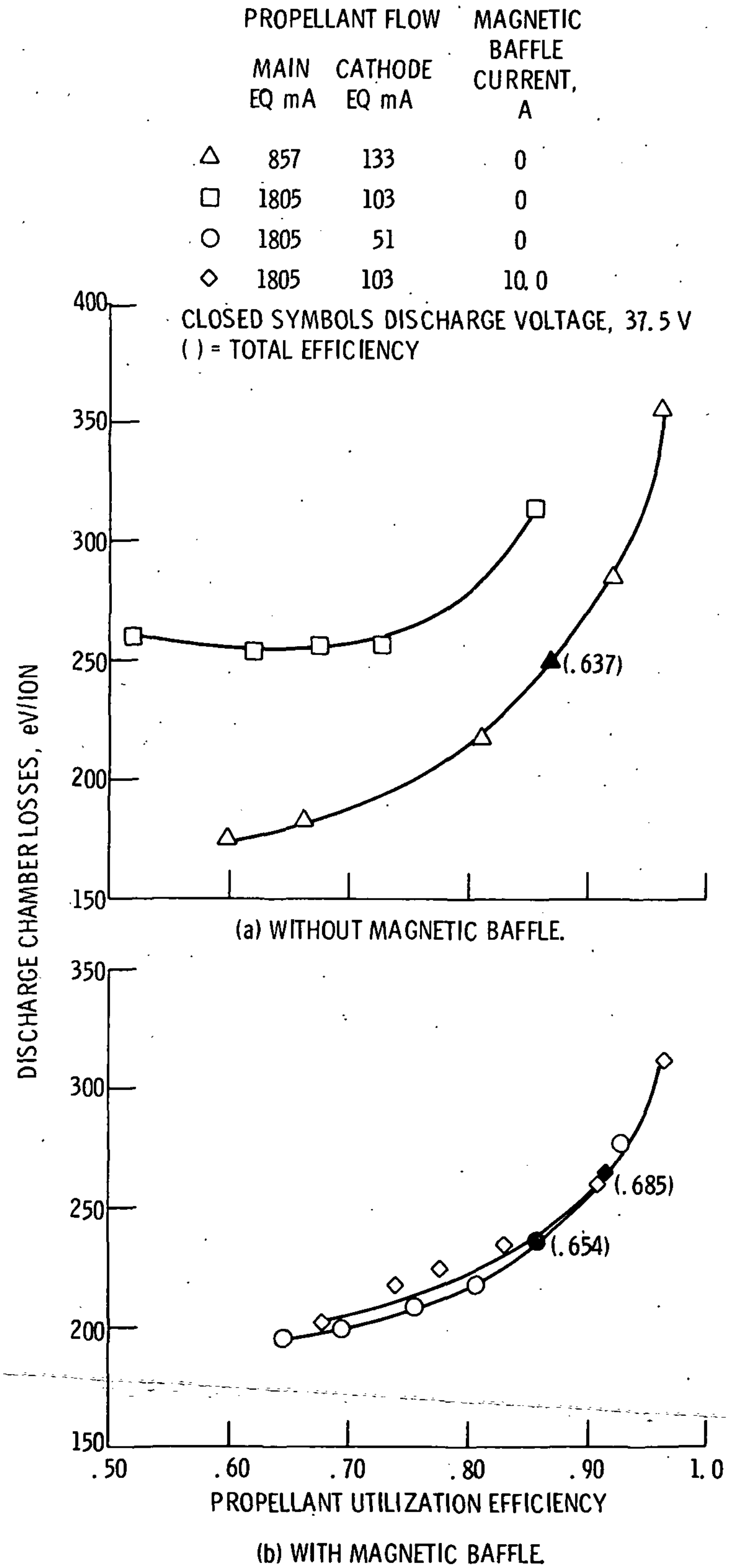


Figure 5. - Operating characteristics at high and low beam current.

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DATA POINT	MAGNETIC BAFFLE CURRENT, AMP	CATHODE FLOW EQ, AMP
1	0	113
2	0	133
3	2.5	133
4	0	180
5	2.5	180
6	5.0	180
7	7.5	180
7a*	0	208
8	2.5	208
9	5.0	208
10	7.5	208
11	10.0	208

*MAXIMUM DISCH. VOLTAGE 34 V
POINT ESTIMATED TO BE >350 eV/ION
UTILIZATION ~.92 AT VOLTAGE = 37.5 V

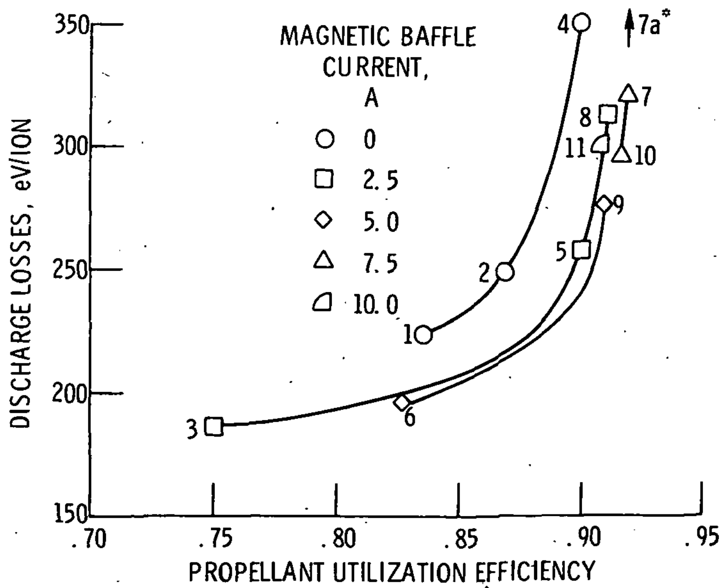

Figure 6. - eV/ion - Utilization curves for various magnetic baffle currents. Discharge voltage, 37.5 V; main propellant flow rate 857 equivalent mA.