Performance Analyses of Electron Bombardment Ion Thrusters

John J. Murray[1]

The University of Alabama, Tuscaloosa, AL, 35487

Two ion bombardment thrusters are considered. The theoretical mercury ion thruster is analyzed for accelerating and accelerating-decelerating configurations; thrust, specific impulse, and output power are determined. The NASA-developed J-Series thruster is then analyzed to determine the efficiencies associated with a 5210 W xenon configuration, and calculated values are compared with experimentally determined values.

Nomenclature

ε_0	=	permittivity of free space (8.85×10^{-12} C^2/Nm^2)
η_p	=	power efficiency
η_u	=	propellant efficiency
I_{sp}	=	specific impulse
P_e	=	output power
R	=	ratio of net voltage to total voltage
V_a	=	screen potential

Equations and Methods

To find the thrust of an electron bombardment thruster, the equation

$$\frac{F}{A} = \frac{8}{9}\varepsilon_0 \left(\frac{V_a}{L}\right)^2 \tag{19-15}$$

from the notes will be used. To determine the specific impulse, the equation

$$I_{sp} = \frac{u_e}{g} = \frac{\sqrt{\left(2\left(\frac{q}{m}\right)V_a\right)}}{g} \tag{19-16}$$

is used. To round out the performance metrics, engine power can be found by

[1] M.S. Candidate, Department of Aerospace Engineering and Mechanics, The University of Alabama.

$$\frac{P_e}{A} = \frac{4}{9}\varepsilon_0\left(\frac{2q}{m}\right)^{\frac{1}{2}}\left(\frac{V_a^{\frac{5}{2}}}{L^2}\right) \tag{19-17}$$

I. Mercury Electron Bombardment Thruster

A. Acceleration Grid

Given a 30 cm diameter mercury electron bombardment thruster with a screen potential of 1400 V, a grounded accelerator grid with 7 mm spacing, the thrust can be found by Equation 19-15 to be

$$\mathrm{F} = \pi(0.15)^2\frac{8}{9}\varepsilon_0\left(\frac{1400}{0.007}\right)^2 = \mathbf{0.0222\ N}$$

The specific impulse of the engine is found to be

$$I_{sp} = \frac{\sqrt{\left(2\left(\frac{1.602x10^{-19}}{3.33x10^{-25}}\right)1400\right)}}{9.81} = \mathbf{3,740\ s}$$

and the power generated is

$$P_e = \pi(0.15)^2\frac{4}{9}\varepsilon_0\left(\frac{2(1.602x10^{-19})}{3.33x10^{-25}}\right)^{\frac{1}{2}}\left(\frac{1400^{\frac{5}{2}}}{0.007^2}\right) = \mathbf{408.2\ W}$$

B. Accel-Decel Grids

The addition of a grounded decelerator grid changes the problem—in this new scenario, the once-grounded accelerator grid now holds -500 V. Net voltage is then 1900 V, while total voltage is 900 V.

Equation 15 becomes

$$F = \pi(0.15)^2\frac{8}{9}\varepsilon_0\left(\frac{1900}{0.007}\right)^2\left(\frac{1900}{900}\right)^{-\frac{3}{2}} = \mathbf{0.0259\ N}$$

While the new forms for specific impulse and power give the following:

$$I_{sp} = \frac{\sqrt{\left(2\left(\frac{1.602x10^{-19}}{3.33x10^{-25}}\right)1900\right)}}{9.81} = \mathbf{4358\ s}$$

$$P_e = \frac{Fu_e}{2} = \frac{0.0259\left(\sqrt{\left(2\left(\frac{1.602x10^{-19}}{3.33x10^{-25}}\right)1900\right)}\right)}{2} = \mathbf{553.7\ W}$$

II. Extended Mercury Electron Bombardment Thruster

If the spacecraft in Part I experienced a solar event that charged its accelerator grid to +200 V, the performance would be as follows:

$$F = \pi(0.15)^2 \frac{8}{9}\varepsilon_0 \left(\frac{1200}{0.007}\right)^2 = \mathbf{0.01634\ N\ (26.4\%\ decrease)}$$

In the case of a similar acceleration-deceleration thruster, the thrust performance would then be

$$F = \pi(0.15)^2 \frac{8}{9}\varepsilon_0 \left(\frac{1200}{0.007}\right)^2 \left(\frac{1200}{1600}\right)^{-\frac{3}{2}} = \mathbf{0.0252\ N\ (2.7\%\ decrease)}$$

III. J-Series Thruster

Working with a 5210 W J-series thruster with xenon propellant, it is of great utility to know its operating efficiencies in various configurations. Given as background information on the thruster are the following data:

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

Source: Rawlin, Vincent K., "Operation of the J-Series Thruster Using Inert Gas," prepared for the Sixteenth International Electric Propulsion Conference, New Orleans, LA, 1982.

The first, power efficiency, is determined by

$$\eta_p = \frac{\frac{1}{2}mu_e^2}{\left(\frac{1}{2}\right)mu_e^2 + e_i + e_L}$$

Knowing that exit velocity is related to beam voltage by

$$u_e = \sqrt{2\frac{q}{m}V_a} = \sqrt{\frac{2(1.602x10^{-19})}{2.18x10^{-25}}(1200)} = 42.0\ km/s$$

and the energy loss per ion is given as 116 eV (1.859 x10^{-17} J), and the ionization energy of xenon is 12.13 eV (1.943 x 10^{-18} J, *source: WolframAlpha*), it can be determined that, for single ionization,

$$\eta_p = \frac{\frac{1}{2}(2.18x10^{-25})(4.2x10^{4})^2}{\frac{1}{2}(2.18x10^{-25})(4.2x10^{4})^2+1.859\,x10^{-17}+1.943\,x\,10^{-18}} = \mathbf{0.904}$$

Given a case of a second ionization, an additional 116 eV would be lost and the transition energy of xenon from its first to second ionization state would have to be considered (2nd state is 21.21 eV, or 3.398 x 10^{-18} J), the power efficiency would then become

$$\eta_p = \frac{\frac{1}{2}(2.18x10^{-25})(4.2x10^{4})^2}{\frac{1}{2}(2.18x10^{-25})(4.2x10^{4})^2+2(1.859\,x10^{-17})+(3.398-1.943)\,x\,10^{-18}} = \mathbf{0.833}$$

Propellant efficiency is nominally found as the ratio of beam current to total current

$$\eta_u = \frac{J_B}{J_{TOT}}$$

where total current is (using values from Table III)

$$\left(\frac{P}{V_a}\right) = \frac{5210}{1200} = 4.34\ A$$

propellant efficiency is then found to be

$$\eta_u = \frac{3.75}{4.34} = 0.86$$

This is only for a single ionization case, however. To account for a second ionization, the ion current ratio must be accounted for, given by consulting Figure 7 from the lecture notes, below.

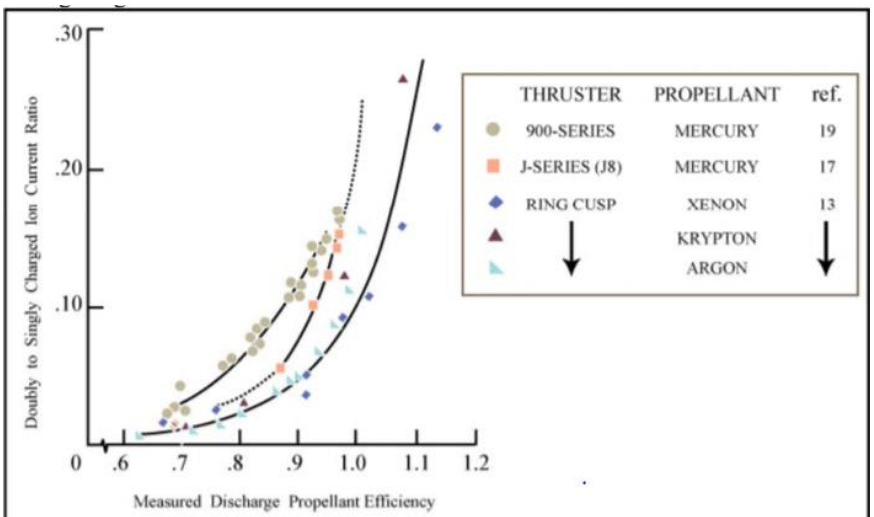

Figure 7 - Doubly to singly charged ion current ratios as functions of measured discharge propellant efficiencies

At a xenon propellant efficiency of 0.86, the ratio is found to be approximately 0.4. Using this to find the correction factor for propellant efficiency,

$$\beta = \frac{1+\frac{0.4}{2}}{1+0.4} = 0.857 \rightarrow \boldsymbol{\eta_u = 0.737}$$

Finally, this allows for the calculation of overall efficiency

$$\eta_t = \eta_p \eta_u = \mathbf{0.614}$$

Compared to the NASA technical report values:

	Calculated	**Experimental (Rawlin)**
$\boldsymbol{\eta_u}$	0.737	0.724
$\boldsymbol{\eta_p}$	0.860	0.915
$\boldsymbol{\eta_t}$	0.614	0.662