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BACKGROUND GASES ON INTERNAL EROSION OF THE  
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**EFFECT OF FACILITY BACKGROUND GASES ON INTERNAL EROSION  
OF THE 30-CM HG ION THRUSTER**

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TECHNICAL PAPER to be presented at the  
Thirteenth International Electric Propulsion Conference  
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One life limiting phenomenon of mercury bombardment thrusters is sputtering erosion of the upstream side of the molybdenum screen grid by discharge chamber ions. Data were obtained which revealed that the screen grid erosion was very sensitive to the partial pressure of certain background gases in the space simulation vacuum facility. The results of tests conducted to evaluate this effect are presented. An estimate of the screen grid erosion in space was made which showed that adequate lifetime for proposed missions exists.

INTRODUCTION

The use of ion thrusters for primary space propulsion requires long operating times, usually in excess of 10 000 hours. Recently, a number of endurance tests, varying in length from about 500 to 10 000 hours, were conducted at the NASA Lewis Research Center (LeRC) and at Hughes Research Laboratories (HRL) to evaluate the lifetime of the Engineering Model 30-cm mercury ion thruster (EMT) (refs. 1 to 4). One life-limiting phenomenon identified was the sputtering erosion of the upstream side of the screen grid by discharge chamber ions. These ions, a fraction of which are multiply charged, bombard the discharge chamber boundary surfaces with energies that are approximately equal to the product of the potential of the plasma, with respect to the surface, and the charge of the ion.

Table I compares the screen grid erosion rates of the EMT (refs. 2 and 3) obtained from two tests (A and B) conducted at LeRC and a 4165-hour test (C) conducted at HRL. All of the erosion rates presented were obtained at constant thruster conditions of 2.0 ampere beam current and 36±1 volts discharge voltage. The erosion rates obtained in tests A and B, and expected in test C, predicted a thruster lifetime in excess of 25 000 hours. However, the high screen grid erosion rate measured in test C predicts a lifetime of only 8000 hours - much less than that required by most missions of interest.

Thruster tests and analyses were conducted to investigate the sensitivities of screen grid erosion to variations in the thruster operating



conditions, the power supply type, and differences between the two vacuum facilities used in obtaining the different erosion rates. An estimate was made of the expected screen grid erosion in space based on extrapolation of the data taken. The results of these tests and analyses are presented.

## APPARATUS

### Thrusters

The two 30 cm thrusters used in this test program were equivalent to the "900" series EMT described in reference 3. One of the thrusters was modified by installing a gas feed line to the mercury (Hg) vapor manifold to permit the introduction of external gases directly into the thruster discharge chamber. This allowed the effects of the addition of small amounts of various gases on screen grid erosion to be studied. The thruster also used ion optics with accelerator grid hole diameters of 1.27 mm, rather than the EMT design of 1.52 mm diameter, to allow the discharge voltage to be varied over a wide range. The screen grid was isolated from its mounts so that it could be biased with respect to the thruster body potential and net ion currents could be measured.

The thrusters, positioned next to each other were mounted from the spacecraft simulator frame used in the Multiple Thruster Array program described in reference 2.

### Power Supplies

Two types of power supplies, described below, were used for the tests presented. Both were used for long duration tests while only the laboratory supplies were used for short duration off-normal operating conditions.

Laboratory supplies. - The laboratory power supplies were 60 hertz input supplies. The screen and accelerator high-voltage supplies were a high capacity, three phase, full wave bridge rectifier design. The discharge, magnetic baffle, and two keeper supplies were full wave, single phase rectified d.c. sources. The six resistive heaters were powered with alternating current.

Series resonant inverter. - Some of the long duration tests were done with an SCR series resonant inverter power processor unit (ppu) similar to that described in reference 6. This ppu has 12 flight type power supplies. While the specific design, such as output impedance, of the resistive load supplies does not significantly affect thruster control or operation, this is not necessarily true of the plasma load supplies. Pertinent characteristics of the five plasma load supplies are given in reference 7.

## Facility

The tests were conducted in the 3.0-m diameter by 3.0-m long chamber of the 7.6-m diameter by 21.4-m long vacuum tank at NASA's Lewis Research Center (ref. 8). The facility pressure was dependent upon the levels of pumping used and ranged between  $6 \times 10^{-6}$  and  $1 \times 10^{-7}$  torr when either 5 or all 20 oil diffusion pumps were used. Convoil 20 hydrocarbon oil was used in the diffusion pumps.

## Instrumentation

Optical spectrometer. - A Jarrell-Ash, model 82-000 series 0.5 m Ebert scanning spectrometer with electric drive was used with a strip chart recorder to monitor the spectral line intensities emanating from the 30 cm thrusters. The spectrometer was located about 20 m from the thrusters at the opposite end of the facility and viewed each discharge chamber at about 9 degrees off the ion beam axis. A dual unilateral curved jaw variable slit assembly, set at 75 microns, was used in conjunction with a single fishtail type diaphragm to adjust both slit heights simultaneously to view only the central portion (about 5 percent) of the extraction area on the thruster. Wavelength resolution was 1 angstrom per 0.5 cm on the chart paper.

Mass spectrometer. - A Veeco, model SPI-10 monopole mass spectrometer was used to analyze the residual gases in the LeRC facility.

Gas flowmeter. - A gas flowmeter calibrated for nitrogen was used to measure the flow of nitrogen added to either the thruster or facility.

Electronic micrometer. - An electronic measuring machine was used to measure the screen grid thicknesses before and after long duration tests. The uncertainty of the measurement was 2.5  $\mu\text{m}$ .

## PROCEDURE

Reference 9 has successfully used optical spectroscopy to study sputtering yields of low energy ions. References 10 and 11 have shown that the use of optical spectroscopy can provide real time diagnostics of the thruster discharge chamber phenomena. Optical spectroscopy utilizes the fact that when an excited atom or ion decays to its ground level, it radiates light at a discrete wavelength. At an appropriate wavelength for a molybdenum (Mo) atom transition, the spectral line amplitude is a measure of the probability of Mo atoms being excited. This is proportional to the product of the Mo atom density, the exciting electron density, and the average value of the product of the electron velocities and the excitation cross-sections for the particular transition. The excitation cross-section is a function of the exciting electron energy

which, in thrusters, is related to the discharge voltage. At constant discharge conditions where the electron density and energy are assumed constant, changes in the Mo line amplitude are assumed to be caused by changes in the Mo atom density. The two sources of Mo in the thruster are the screen grid and accelerator grid. It was assumed that most of the Mo signal was due to Mo sputtered from the screen grid, rather than from accelerator grid impingement, and was directly related to screen grid erosion.

The thruster and facility were initially operated as they were for the endurance tests reported in reference 2. Then the thruster operating parameters were varied while the thruster was observed with the optical spectrometer. The results of those and additional tests are described in the next section.

## RESULTS AND DISCUSSION

The results of the program which addressed the high screen grid erosion rate of the 4165 hour EMT lifetest will be discussed. This discussion will be divided into three sections which present: (1) the spectral line amplitude characteristics, of an EMT, as functions of thruster operational and geometric parameters, and facility pressure variations due to the introduction of various background gases; (2) a description of the phenomenon believed responsible for the variation of screen grid erosion rate at constant thruster operating conditions; and (3) the results of tests conducted to increase the understanding of that phenomenon and allow an estimate to be made of screen grid erosion rates in space.

### Spectral Line Amplitude Characteristics

The spectral line amplitudes for molybdenum atoms (MoI, 379.83 nm) and for mercury atoms (HgI, 380.17 nm) and singly charged ions (HgII, 380.64 nm) were measured as the thruster operating and geometric parameters and facility pressure were varied. These lines were chosen for their closeness in value of wavelength and relative intensity. These Hg lines are weak with respect to other Hg lines while the Mo line chosen is the most sensitive which allowed observation of all three on the same instrument sensitivity range. In addition, these lines were monitored throughout several endurance (>500 hr) tests. The absolute values of line amplitudes as well as the ratios of the MoI line to HgI line were sensitive to the viewing angle through the discharge plasma when the spectrometer was moved to view a different thruster. This sensitivity was probably caused by viewing the length of the discharge where large gradients in plasma properties exist. Therefore, comparisons of absolute MoI amplitudes from identical thrusters at different locations should not be made. However, all of the trends, of line amplitude variations with

thruster and facility parameters, reported below were the same for each thruster. The sensitivities of line amplitude to thruster and facility variations are presented next.

Variation of thruster operational parameters. - The line amplitudes from an EMT were measured as the operating parameters were individually varied from the full power conditions of a 2.0-ampere beam current and discharge voltage and current of 36 volts and 13 amperes, respectively. Figure 1 shows the variations of line intensities, normalized to the full power operating point, as a function of beam current. At constant discharge losses per beam ion, the discharge current, and hence electron density available for excitation, are reduced in proportion to the beam current thereby partially contributing to the reduction of observed intensities. The HgI amplitude decreased about 36 percent as the beam current was decreased from 2.0 to 0.77 amperes, about 62 percent. Assuming that the major reasons for this line amplitude decrease were the density reductions of neutral mercury and exciting electrons, it was not surprising that the fractional change in HgI was less than that of the beam current because the propellant utilization efficiency is lower at reduced beam current. The MoI intensity variation followed the HgII intensity variation as expected because the presence of molybdenum atoms is due to sputtering of the screen grid by mercury ions. Both intensities decreased by more than 80 percent as the beam current was decreased.

Figure 2 shows the line amplitudes variation as the discharge voltage,  $V_p$ , was varied from 32 to 44 volts. The HgI line intensity decreased only slightly because the effect of the neutral flow rate decrease (due to increased discharge power) was offset by an increase in the energy of the exciting electrons as  $V_p$  was increased. The HgII line intensity increased as  $V_p$  was increased to about 39 volts but then began to decrease at higher voltages, probably because of a decrease in single ion density as the doubly charged ion density was increasing. Studies have shown that in Hg bombardment thrusters most doubly charged ions are created from singly charged ions (refs. 12 and 13). Figure 2 also shows that the MoI intensity increased with  $V_p$  but at a faster rate at higher voltages. This is due to the formation of multiply charged ions which sputter more Mo atoms than singly charged ions.

Figure 3 shows that the line intensities are much less sensitive to changes in the discharge current than those observed for changes of discharge voltage or beam current. In addition, it was found that at the nominal values of beam current, discharge voltage and discharge current, the line intensities, and thus assumed screen grid erosion, were insensitive to large changes in the net and total ion accelerating voltages, cathode flow rate, cathode keeper current, and power supply type.

Variation of accelerator grid hole diameter. - As shown in references 14 to 16, thrusters using ion optics having accelerator grid hole diameters less than the EMT design can be operated at discharge voltages less than

36 volts without suffering discharge chamber performance losses. Those studies and figure 2 suggest that reductions in discharge voltage could significantly reduce the sputter erosion of the screen grid. Figure 4 compares the MoI line intensity as a function of discharge voltage for the same thruster at the same location operated with EMT optics and ion optics with a small hole accelerator grid (SHAG). As shown, the MoI line intensity is lower with SHAG optics and, in addition, the thruster can be operated at lower discharge voltages. This grid geometry was tested for 937 hours, in the same facility as the 4165 hours test, at a discharge voltage of 32 volts and had a screen grid erosion rate of 9 nm/hr, about 3.7 times less than that of the 4165 hour test of the EMT (ref. 4).

Variation of facility pressure. - One of the major differences between the facilities used in the thruster endurance tests was that the vacuum chamber used for the 4165 hour test at HRL employed a frozen Hg ion beam collector (ref. 3). Thus, the partial pressure of Hg in that facility was probably higher than in the Lewis facility (where the lower erosion rates were measured). The MoI line intensity was observed, while the total facility pressure was increased from  $2.4 \times 10^{-7}$  to  $1.2 \times 10^{-5}$  torr by the addition of Hg vapor near the thruster, and found to be invariant with an increase of the partial pressure of Hg. Thus, the presence of the Hg target in the HRL lifetest facility was excluded as the reason for high screen grid erosion rate.

Another difference between the two facilities was the background pressure when the thruster was off. At Lewis, there was no change in pressure when the thruster was turned on. At the HRL test facility, the base pressure, without thruster operation, was  $2 \times 10^{-7}$  torr which was a factor of 10 less than the value ( $2 \times 10^{-6}$  torr) during test C. At Lewis, the MoI line intensity was observed for an EMT at the nominal operating point while the facility total pressure was reduced by increasing the number of operating oil diffusion pumps and reducing the temperature of the liquid nitrogen cooled tank liner. Increasing the number of diffusion pumps probably reduced the partial pressure of all components of the total pressure, whereas reducing the temperature of the cryogenic surface had little or no effect on the partial pressure of  $N_2$  or  $CO_2$  but did condense Hg,  $C_2$ , and  $H_2O$  vapors. The effect of tank pressure on the MoI line intensity is shown in figure 5. As the pressure decreased from  $6 \times 10^{-6}$  to  $5 \times 10^{-7}$  torr the MoI intensity increased dramatically by a factor of 2.7.

At maximum pumping capability of the Lewis facility, the tank pressure was increased by introducing, individually, air, nitrogen, argon, and mercury vapor into the facility while the MoI line intensity was noted. The results are shown in figure 6. The pressure variation was limited at the low end ( $2.4 \times 10^{-7}$  torr) by the facility and at the high end ( $5 \times 10^{-5}$  torr) by thruster operational instabilities and excessive high voltage arcing. Over this range it was found that the MoI line intensity decreased as air or nitrogen gas was introduced into the facility. The addition of argon or mercury vapor had no effect on the MoI line intensity.



At a given total pressure the partial pressures of the constituent gases were probably different for each of the five methods of pressure variation shown in figures 5 and 6. Thus the cause of the changing MoI intensity may be due to several contributing gases. The results presented were obtained while two EMT's were being endurance tested to verify the results previously obtained at Lewis (Tests A and B, table I). The results of the verification tests are shown in table II as tests D and E and agree, within the measurement uncertainty, with the results of tests A and B.

At this point two thrusters were tested for about 570 hours at the nominal operating point to measure the screen grid erosion rate at reduced facility pressure. Table II compares the results of those tests, F and G, with tests D and E and shows that, at constant thruster operating conditions, the screen grid erosion rate is a function of facility pressure; and that, to first order, large changes in MoI intensity, at constant thruster operating conditions, indicate large changes in screen grid erosion.

The sensitivity of line intensities to thruster operating conditions shown in figures 1 to 4 remained the same at the lower tank pressure. The thrusters used in tests F and G were different in that thruster G incorporated a "700" series type baffle mount. This type of baffle mount increased the baffle erosion rate and was believed, in reference 2, to also cause high screen grid erosion. A careful review of the Lewis facility pressure history showed that the facility pressure was lower ( $3$  to  $8 \times 10^{-7}$  torr) when the "700" series baffle mount was tested than when the "400" and "900" series baffle mounts were tested ( $2 \times 10^{-6}$  torr). On the basis of these tests it was concluded that certain constituents of the total facility pressure were the cause of the discrepancy between initial erosion rate measurements obtained at higher pressure at Lewis and those obtained in the 10 000 hour and 4165 hour endurance tests at HRL. A description of how facility pressure affects sputtering rates will be presented in the following section.

### Pressure Dependent Sputtering

The erosion rate of a surface is determined by the number and the average sputter yield of the ions impinging on that surface. It is assumed that the local pressure is sufficiently low to allow the sputtered material to escape (less than  $10^{-2}$  torr). The pressure of an operating EMT, due mostly to Hg, is sufficiently low, about  $4 \times 10^{-4}$  torr. The ion energy and arrival rate are fixed by the thruster operating conditions and should not change substantially as the facility pressure is varied from  $10^{-5}$  to  $10^{-7}$  torr. Since the erosion rate (and MoI line intensity) of the molybdenum screen grid decreased drastically when the total pressure in the facility was increased by adding air or nitrogen, it was concluded that the sputter yield of the screen grid was probably being reduced by the presence in the thruster of certain facility atmospheric gases, such as oxygen or nitrogen.

Figure 7 describes how the presence of a reactive gas could affect the net erosion rate of the screen grid. At very low facility pressures an equilibrium condition is reached between the removal rate of the surface material and the arrival rate of certain background gases. In this condition, a negligible fraction of the surface is covered and the sputtering rate of the base metal occurs. At this pressure, the base metal sputtering rate increases for greater values of ion energy and/or density. At intermediate values of facility pressure, some of the flux of background constituent gases will be adsorbed by the base metal and form a partial coverage layer which results in a net sputtering rate which is less than that of the base metal. Again, for greater values of ion energy and density the sputter yields for the base metal and protective layer will increase thereby reducing the effect of the lowered sputtering rate. The amount of surface coverage increases as the facility pressure increases, reducing the net sputtering rate, until the net erosion rate becomes insensitive to facility pressure and is at a value lower than that of the base metal. Similar phenomena have been noted (refs. 17 to 20) but at much higher sputtering rates and/or facility pressures. Simple criteria for "clean surface" sputtering by low energy and low density ions were noted in the literature and were generally satisfied for the conditions in the Lewis facility. Thus, the erosion rates obtained from the Lewis tests conducted at facility pressures of  $2 \times 10^{-6}$  torr were felt to be those of the clean base metal. It is now apparent that those criteria were inadequate for the conditions of interest in the 30 cm thruster.

Because the addition of air or nitrogen reduces the Mol line intensity it is felt that one or more oxides or nitrides of molybdenum such as  $\text{MoO}_3$ ,  $\text{MoN}$ , or  $\text{Mo}_2\text{N}$  are formed at the screen grid surface of a thruster operating in a ground based facility. It is also thought that the chemisorption of certain gases on molybdenum is enhanced in the discharge chamber where the molecular state is reduced to "chemically reactive" excited atomic states (ref. 21). For example, when the facility pressure was increased by the addition of nitrogen, strong line intensities of atomic nitrogen as well as spectra of molecular nitrogen were noted.

Protective coatings will not be present for thrusters operated in space. Careful interpretation of the results of ground based endurance tests, where the partial pressures of the contaminant gases may be sufficient to reduce the true screen grid erosion rate, is desirable. The next section will describe efforts conducted to increase our understanding of the phenomena and allow an estimate to be made of the screen grid erosion rate in space.

#### Pressure Effect Tests

In order to improve the understanding of the effect of contaminant gases on screen grid erosion, a modified EMT (as described in the APPARATUS section) was tested in the Lewis vacuum facility. Nitrogen gas was intro-

duced either into the thruster discharge chamber or into the facility about 4 meters from the thruster. The screen grid was also biased negatively to increase the sputter rates.

Partial pressures of nitrogen. - With no nitrogen added, the partial pressure of nitrogen in the facility was assumed to be the same in the thruster and was estimated by the following tests. A mass spectrometer analysis of the constituents of the facility pressure was made at the minimum facility pressure. At total pressures of about  $1 \times 10^{-7}$  torr, the fraction of nitrogen was estimated to be 25 percent or less. The partial pressure of nitrogen ( $\sim 2.5 \times 10^{-8}$  torr) was probably due to residual nitrogen from external air leaks as well as nitrogen from small internal leaks in the liquid nitrogen cryogenic surfaces. When gaseous nitrogen was leaked into the vacuum facility to raise the total pressure the partial pressure of nitrogen was calculated as the total pressure minus 75 percent of the minimum pressure ( $7.5 \times 10^{-8}$  torr).

A worst case estimate of the error, in the assumption of 25 percent nitrogen at the minimum total pressure, may be made as follows. If the A.M.U. -28 peak from the mass spectrometer was due to other gases such as CO and there was no nitrogen in the facility at the minimum pressure, then the calculated partial pressure of nitrogen, for a total pressure of  $5 \times 10^{-7}$  torr would be only 6 percent high.

The partial pressure of nitrogen in the thruster, with gas introduced into the thruster, was calculated as the sum of the partial pressure of nitrogen added to the thruster plus the partial pressure of nitrogen due to backflow from the facility. The latter contribution was calculated as previously described. The former contribution was calculated by using the measured nitrogen flow rate into the thruster and equations for free molecular flow through the accelerator grid.

Screen grid bias. - At fixed facility and thruster conditions, the screen grid was biased positive and negative with respect to thruster potential (cathode common) while the MoI line intensity was noted. Figure 8 presents those results for the normal thruster operating point with no added nitrogen. At zero bias, the screen grid is at its normal potential. With positive values of bias voltage the ions strike the screen grid with less energy producing less sputtered molybdenum and the MoI intensity is reduced. Positive polarity of bias voltage also attracts electrons to the screen grid and causes an increase in discharge power losses. With negative bias voltages the impinging ion energy increases causing strong increases in sputtering and thus MoI intensity. The saturation ion currents were found, as in reference 2, to be about 35 percent of the beam current.

Line amplitudes with added nitrogen. - Continuous recordings of line intensities for wavelengths between 3000 and 5000 Å were obtained at facility pressures of  $4 \times 10^{-7}$  and  $4 \times 10^{-6}$  torr (due to added nitrogen) for an EMT operating at nominal conditions. All of the nearly 700 line and



band intensities observed were measured and identified. One third of the spectral intensities were due to Hg while another third were identified as atomic and molecular compounds of atmospheric constituents, such as  $N_2$ ,  $O_2$ ,  $CO_2$ , CO, CN, and NH. The remainder of the spectra were from sputtered thruster discharge chamber components such as Ni, Fe, Cr, and Mo or back-sputtered flux from facility components such as Cu from the liquid nitrogen cooled liner, Ni, Fe, and Cr from the stainless steel tank wall and compounds from the hydrocarbon pump oil. For both cases the Hg and Cu line intensities were invariant with facility pressure while the strong line amplitudes for Mo, Fe, Ni, and Cr were reduced when nitrogen was added. These results agree with those of reference 22 where it was found that the chemisorption of nitrogen by metals may be categorized into three groups. Metals in these groups either: (1) chemisorb nitrogen and form a nitride, (2) do not chemisorb nitrogen but do form a nitride, or (3) do not chemisorb or form a nitride. It was found that refractory metals fall into the first group while copper, gold, and silver are in group three.

Erosion reduction with added nitrogen. - As shown earlier, the measured screen grid erosion rate, for a thruster tested in the Lewis facility, increased from 4.6 to 30 nm/hr when the facility pressure was reduced from  $2 \times 10^{-6}$  to  $5 \times 10^{-7}$  torr. Figure 9 shows the variations of the MoI line intensity for a large range of values of facility partial pressure of nitrogen while the thruster operation conditions were held constant and the screen grid bias was varied. The partial pressure of nitrogen was varied by leaking nitrogen into the facility. The thruster was operated with a high discharge voltage of 50 volts to show the two levels of near constant erosion and the transition region between them. Note that at the more negative values of bias voltage, the MoI intensity increases with nearly the sensitivity to bias voltage expected from Mo sputter yield curves. The HgI, HgII, and HgIII line intensities remained constant within  $\pm 10$  percent over the range of nitrogen partial pressures shown with the exception of the very high nitrogen partial pressures where an appreciable amount of nitrogen was ionized and extracted as beam current. At this point about 30 percent of the beam current was due to nitrogen ions. Curves similar to figure 9 were obtained when the thruster was operated at other values of discharge voltage and beam current.

The same thruster operating points shown in figure 9 were repeated while nitrogen was leaked into the thruster only. MoI line intensities were recorded as the nitrogen mass flow rate was varied from 0 to about 14.5 sccm and are shown, as a function of the calculated partial pressure of nitrogen, in figure 10. The curves are nearly identical in shape and magnitude, the major difference being that the partial pressure scale in figure 10 appears slightly expanded with respect to figure 9. This difference is probably due to the assumptions made when calculating the partial pressures for each case. Similar data were obtained for discharge voltages ranging from 32 to 60 volts with the major difference being that the normalized curves are shifted to lower values of nitrogen partial pressure as the discharge voltage was lowered. In all cases, for a given discharge voltage, the Hg line intensities were constant within  $\pm 5$  percent.

Figure 11 shows the data of figure 9 with each curve normalized to its own maximum. This was done to eliminate the changes in the MoI due to changes in bias voltage. Note that as the ion energy was decreased, a measure of the removal rate of chemisorbed nitrogen or other gases was indicated by a shift in the curves. As the bias voltage was reduced, the sputter yields of the adsorbed gases were reduced and the pressure effect occurred at lower partial pressures of nitrogen.

Figure 12 shows an effect similar to figure 11 but here the discharge voltage was varied with no screen grid bias. Again at lower ion energies the curves shift to lower values of nitrogen partial pressure. The shift in pressure per volt of ion energy change was greater for figure 12 than figure 11 because the multiply charged ion content was less at lower values of discharge voltage. The shift in pressure was about a factor of two for a ten volt reduction in discharge voltage. For lower values of discharge voltage the upper plateau of near constant base metal erosion could not be found. But, from figure 12 it can be estimated that at a discharge voltage of 32 volts (the nominal EMT operating point with SHAG optics) the upper plateau should be in the  $10^{-8}$  torr range of nitrogen partial pressure. Unfortunately, that condition occurs near the minimum facility pressure with no gas added. Thus, the results of ground based endurance tests with low values of discharge voltage, conducted at the conditions of the Lewis facility or lower total pressures, should be representative of operation in space. This conclusion is strengthened by noting that the sputter yields of oxides and nitrides are relatively insensitive to changes in ion energy (refs. 9, 22 to 24). Thus, even at the low value of discharge voltage of 32 volts, needed to reduce the erosion of the screen grid, the mercury singly and doubly charged ions have sufficient energy to maintain a clean surface, free of chemisorbed gases, provided the arrival rate is sufficiently low.

Nitrogen was added to the tank when the thruster was operated with a discharge voltage of 50 volts and the ion beam current was varied from 1.0 to 3.0 amperes. Figure 13 shows the MoI line intensities for each beam current, normalized to the maximum value for each curve. Even though the ion energy was nearly constant for each case, the ion density was probably much higher at a beam current of 3.0 ampere than it was at 1.0 ampere. Thus, again it appears that the effect is dominated by the arrival rate of contaminant gases while the erosion rate of those adsorbed gases plays a lesser role.

The previously described tests were conducted by adding nitrogen to the tank and thruster to show the consequences of contaminant gases on the screen grid erosion. Air, oxygen, or other reactive gases could have been used, probably with similar results, since it is the arrival rate of the contaminant gases, or tank pressure, which is important. Figure 14 shows many measured screen grid erosion rates, from reference 2, contractors endurance tests, and this program, plotted as a function of tank pressure for several values of discharge voltage. The error bars for each value of erosion rate arise from the fixed measurement uncertainty divided

by the time of each test. These shorter tests have larger error bars. Lines drawn through the data points, at constant discharge voltages of 36 and 32 volts, are the estimates of the authors. Accounting for the reduction of multiply charged ions when the discharge voltage is reduced from 36 to 32 volts, the sputter yield of pure Mo should be reduced by a factor of nearly 2.8 (refs. 25 and 26). Assuming the maximum erosion rate of 33 nm/hr was obtained at 36 volts, a maximum erosion rate of 12 nm/hr is expected at a discharge voltage of 32 volts. The erosion rate, measured for the EMT with SHAG optics and operated at 32 volts, of 9 nm/hr is felt to be about 30 percent less than the maximum rate expected in space.

### CONCLUSIONS

The discrepancy between the 30 centimeter Hg thruster screen grid erosion rate expected from Lewis tests and experienced in the 4165 hour test at HRL was investigated. Real time data related to screen grid erosion were obtained through the use of an optical spectrometer which related spectral line intensities to screen grid erosion rates. The variation of all thruster parameters indicated that the screen grid erosion rate was most sensitive to the discharge voltage and beam current. Because of the high partial pressure of mercury in the HRL facility (from the frozen Hg target) the operating facility pressure was the same as tests conducted at Lewis, but the pressure due to atmospheric constituents was 10 times less than at Lewis. When the facility pressure, due to atmospheric constituents, was reduced at Lewis the molybdenum spectral line intensity increased dramatically. Two 570 hour endurance tests of EMT's were conducted at Lewis, at lower facility pressure, and had screen grid erosion rates comparable to the HRL endurance test. These tests verified that the erosion rate discrepancy was due to facility pressure. A 980-hour endurance test, conducted at HRL using an EMT equipped with ion optics having smaller accelerator grid holes which allowed operation at a reduced discharge voltage, resulted in a low pressure erosion rate which is commensurate with the long lifetimes required of thrusters. Other tests conducted at Lewis have provided information leading to the estimate that screen grid erosion rate measured at HRL is about 30 percent less than that expected in space. This fact implies that the space erosion of the screen grid is too small to be of concern for any proposed mission for the 30-centimeter mercury bombardment thruster.

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TABLE I. - "900" SERIES EMT TEST RESULTS

Test	A	B	C
Reference	2	2	3
Duration, hr	976	605	4165
Facility	Lewis	Lewis	HRL
Discharge voltage, V	35	37	36
Maximum erosion rate, nm/hr	4.3±2.3	10.4±4.3	33±1.3

TABLE II. - EMT RECENT TEST RESULTS

(Beam current, 2.0 A, discharge voltage, 36 V)

Test	C	D	E	F	G
Duration, hr	4165	545	548	568	573
Facility	HRL	Lewis	Lewis	Lewis	Lewis
Facility total pressure, torr					
Thruster off	2×10 <sup>-7</sup>	2×10 <sup>-6</sup>	2×10 <sup>-6</sup>	5×10 <sup>-7</sup>	5×10 <sup>-7</sup>
Thruster on	2×10 <sup>-6</sup>	2×10 <sup>-6</sup>	2×10 <sup>-6</sup>	5×10 <sup>-7</sup>	5×10 <sup>-7</sup>
Maximum erosion rate, nm/hr	33±1.3	4.6±4.6	4.6±4.6	30±4	30±4

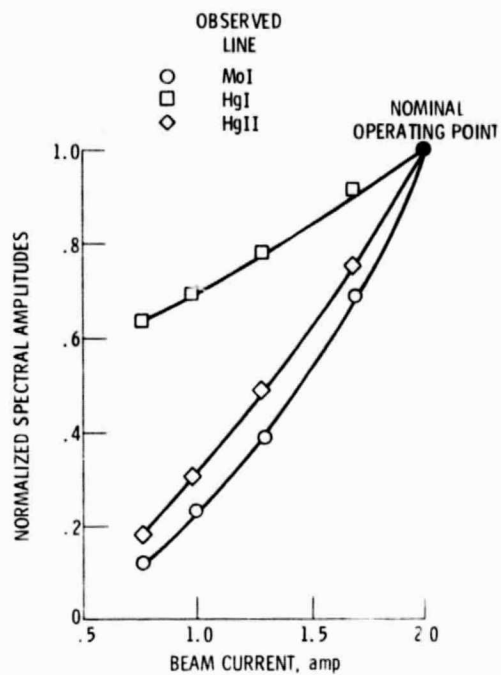


Figure 1. - Normalized spectral line amplitudes as a function of beam current. (Discharge voltage 36 V, discharge losses 198 eV/ion.)

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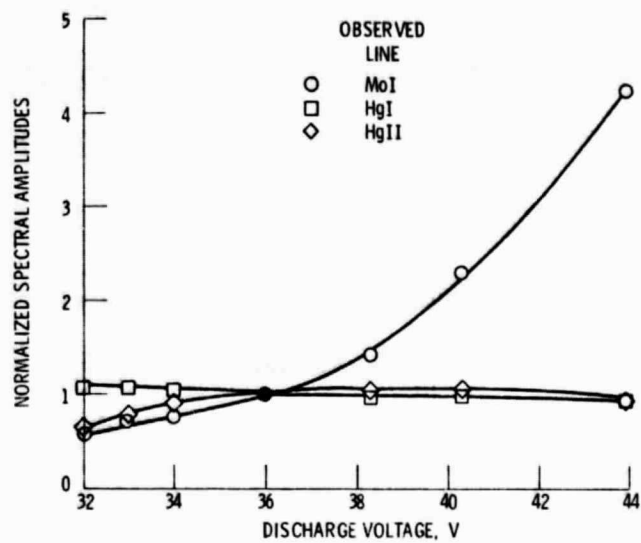


Figure 2. - Normalized spectral line amplitudes as a function of discharge voltage. (Discharge current, 13 A, beam current, 2.6 A.)



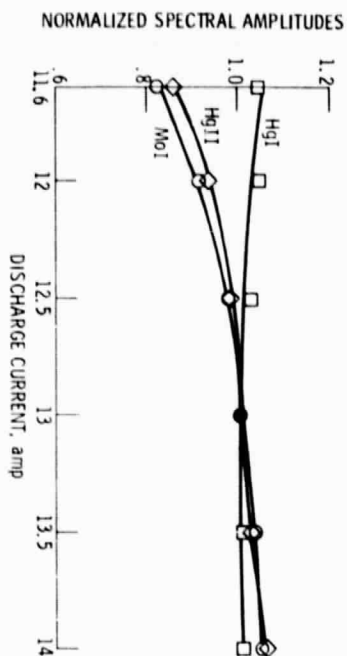


Figure 3. - Normalized spectral line amplitudes as a function of discharge current. (Discharge voltage, 36 V. Beam current, 2.0 A.)

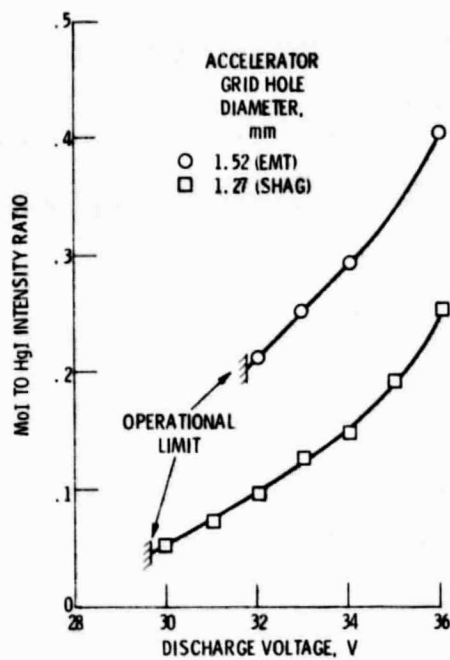


Figure 4. - Line intensity ratio as a function of discharge voltage. (Beam current, 2.0 A, discharge losses, 198 eV/ion.)

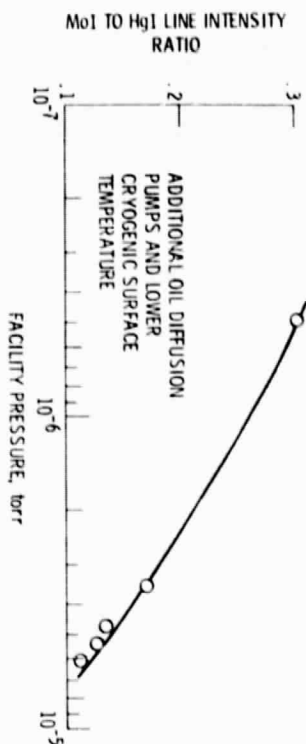


Figure 5. - Line intensity ratio as a function of facility pressure. (Beam current, 2 A, discharge voltage, 36 V, discharge current, 13 A.)

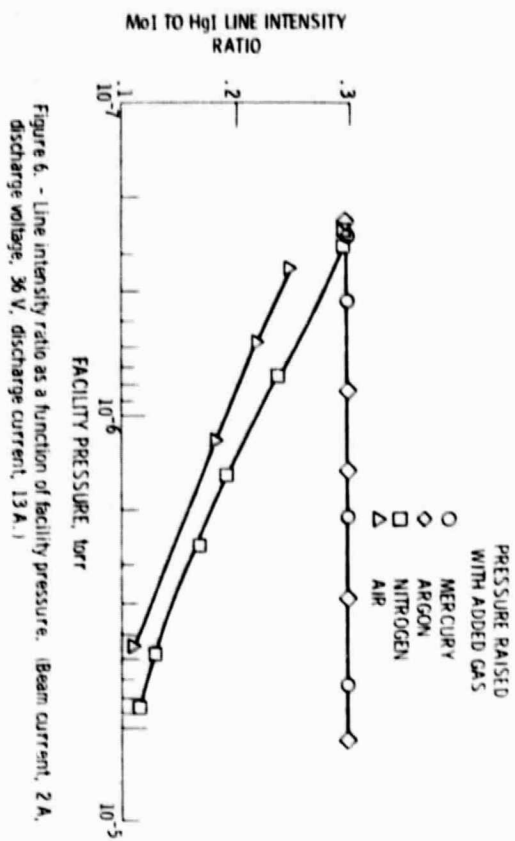


Figure 6. - Line intensity ratio as a function of facility pressure. (Beam current, 2 A, discharge voltage, 36 V, discharge current, 13 A.)

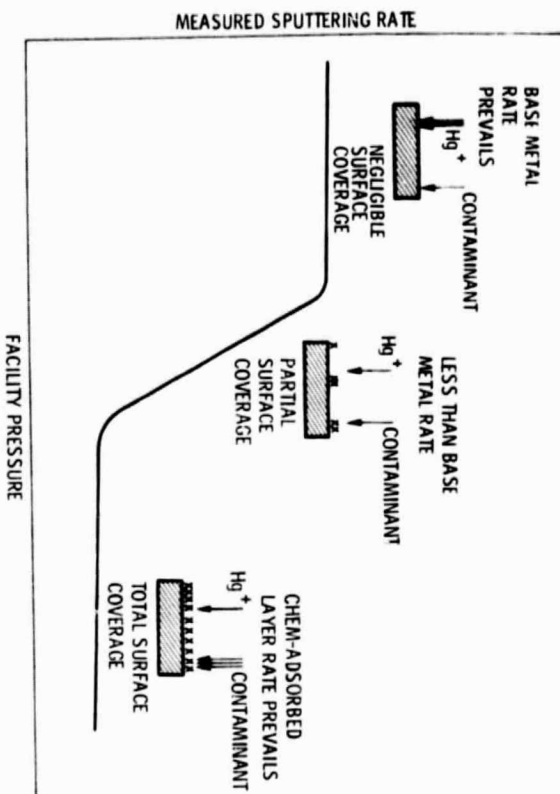


Figure 7. - Measured sputtering rate as a function of facility pressure.

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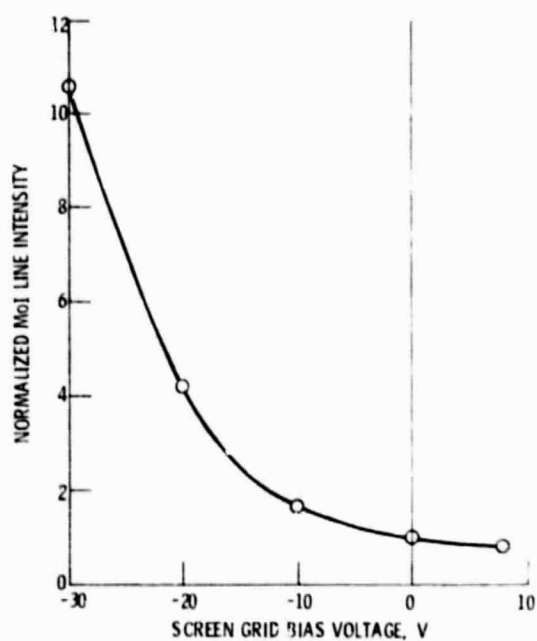
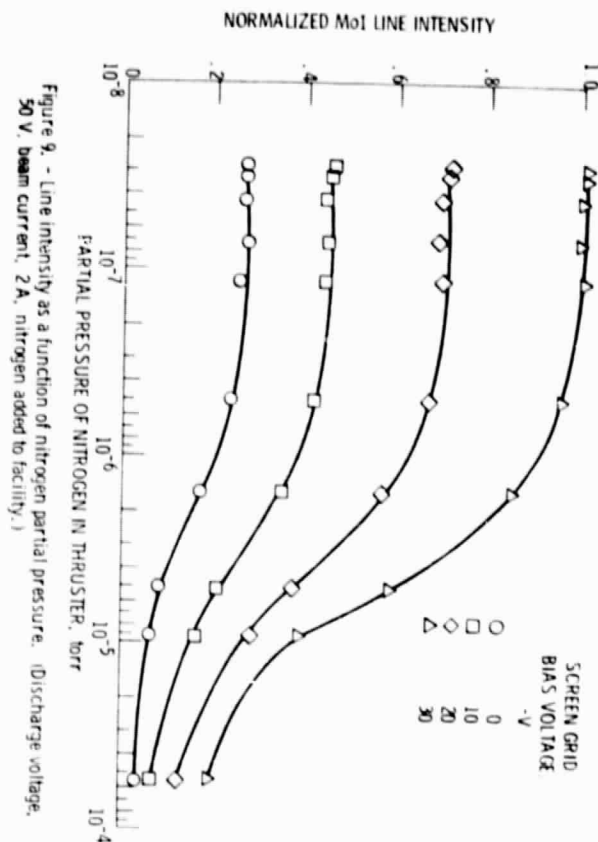


Figure 8. - Normalized line intensity as a function of screen grid bias. (Beam current, 2 A, discharge voltage, 32 V, discharge current, 14 A.)



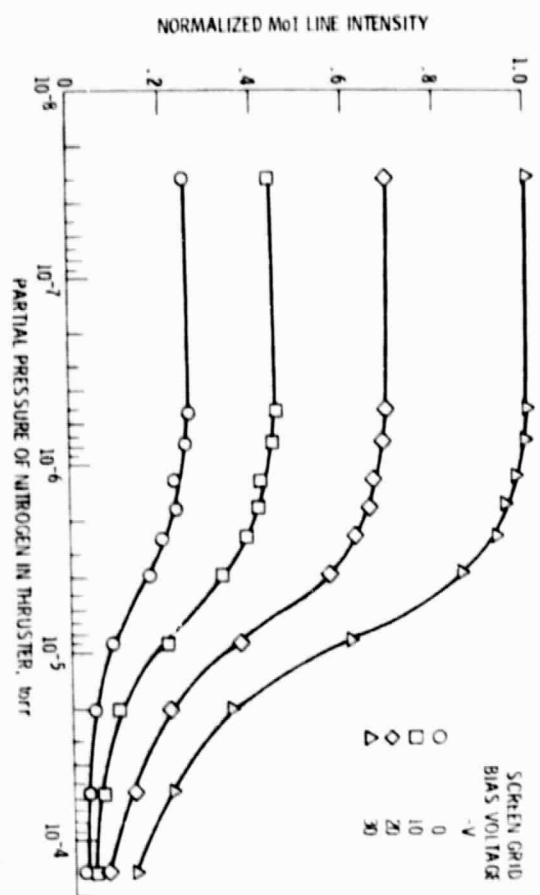


Figure 10. - Line intensity as a function of nitrogen partial pressure. (Discharge voltage, 50 V, beam current, 2 A, nitrogen added to thruster.)



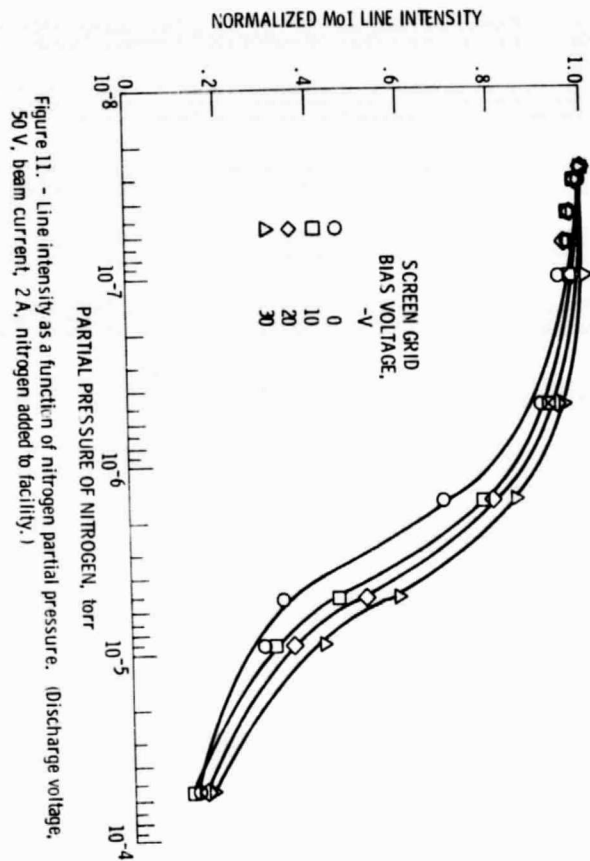
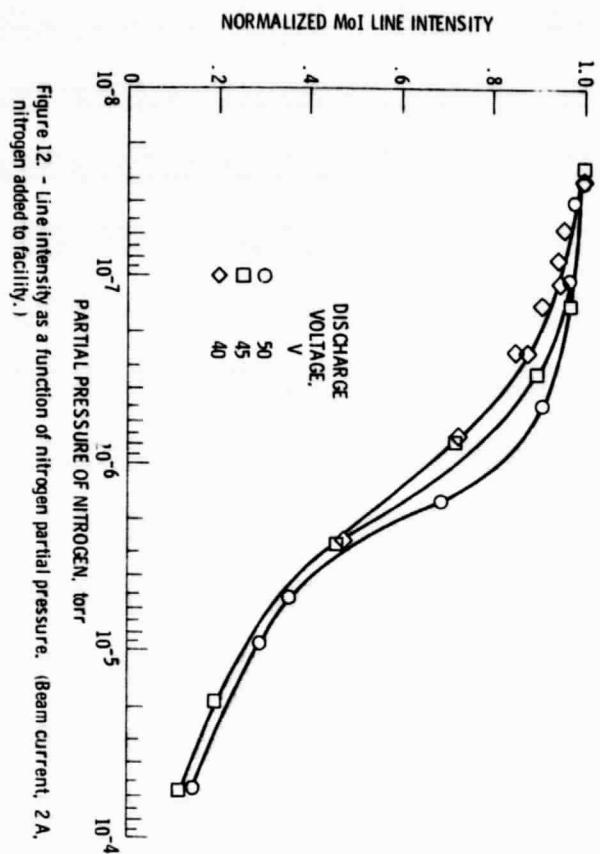


Figure 11. - Line intensity as a function of nitrogen partial pressure. (Discharge voltage, 50 V, beam current, 2 A, nitrogen added to facility.)

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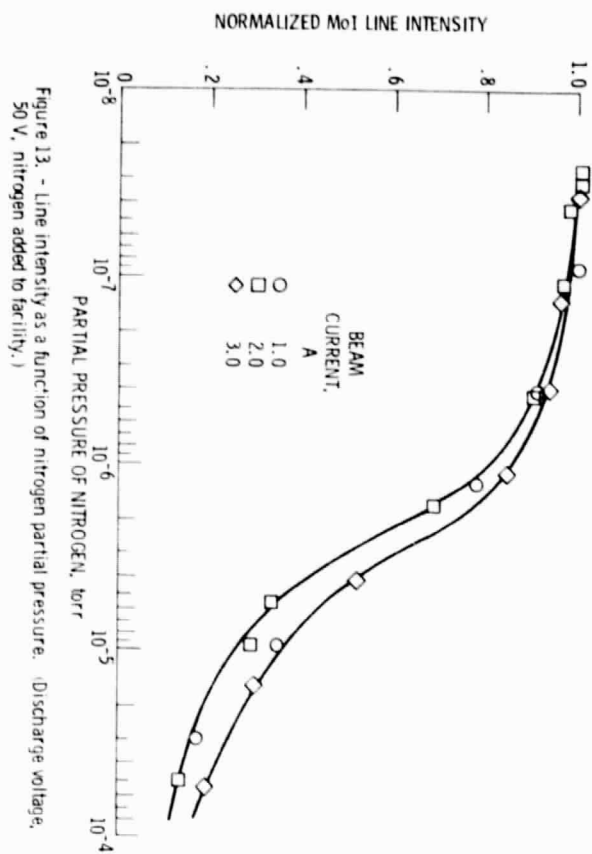


Figure 13. - Line intensity as a function of nitrogen partial pressure. (Discharge voltage, 50 V, nitrogen added to facility.)

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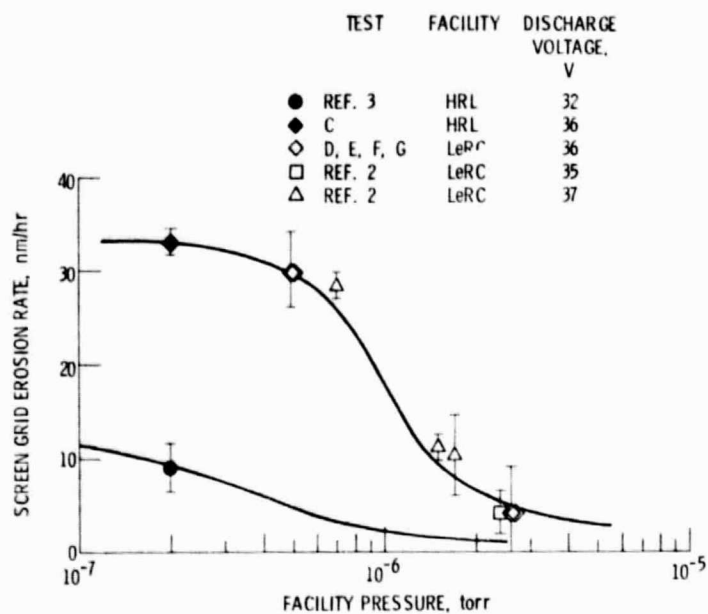


Figure 14. - Screen grid erosion rate as a function of facility pressure.  
(Beam current, 2 A.)