A Review of Facility Effects on Hall Effect Thrusters

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An increasing number and variety of missions are benefiting from Hall Effect Thrusters supplied by different suppliers utilizing a variety of development processes and facilities. This situation, in part, has led to multiple recommendations for standardized approaches in all phases of thruster developments and integration. To help inform such standardization, a review was conducted to collate open-literature data on the measurement and influence of ground test facility pressures on the performance and lifetime evaluations of Hall Effect Thrusters. No flight thrust data were available, so comparisons of ground and in-space thruster performances weren't possible. The review found that pressures are obtained using a range of approaches which complicate comparisons of pressure effects in different facilities. The limited data base on the influence of pressure on thruster performance exhibited extreme variations and recent, non-invasive diagnostics efforts both provide new physical insights into the interaction of facility environments with thrusters and indicate the use of simple, ingestion correction factors are inadequate. Few data were found that directly evaluated the influence of pressure on thruster lifetime and the cited non-invasive diagnostics studies suggest that effects other than partial pressures of contaminants may be critical. No data on facility effects on swirl torques were found. Overall, the review illustrated the extremely situational nature of the effects of facility pressure and strongly supports the establishment of test standards for Hall Effect Thruster programs.

Nomenclature

C_g = gauge factor to correct for xenon
P_B = facility base pressure with no propellant flow
P_C = corrected facility pressure
P_M = measured facility pressure

I. Introduction

Hall Effect Thrusters (HETs) are being used [1-3] for in-space propulsion functions on commercial and other Western European, Russian, and United States spacecraft. The HET systems are being provided by different entities that use of a range of processes, procedures, and test facilities. This situation, in part, has led to recommendations for establishment of standards for the development and test of electric propulsion systems [4-6].

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To help inform such standardization, a review was conducted of open-literature data on the measurement and influence of ground-facility, particle environments on the performance and lifetime evaluations of HETs**.**

As pointed out by Andrenucci and Biagioni [5], it is technically appropriate to describe the ground facility particle environments in terms of densities and associated temperatures. However, in most cases only pressure data were provided and so pressures are used herein for the convenience of workers in the field. Bugrova and Morozov [7] showed that use of facilities where backsputtered facility materials are not negligible may result in phenomena such as surface coating and negative ion flows that can very strongly affect internal HET plasmas, critical material surface properties, and global performances. Therefore, to reflect present practice, the report considers only data taken in facilities that provided low levels of contamination via a combined set of characteristics including dimensions, pumping approaches, and pumping speeds. Although critical, interfaces are beyond the scope of the report as they involve many, complex issues including standard electrical, thermal, and mechanical issues and non-standard considerations such as plumes and electromagnetic interference.

Randolph et al. [8] and Kahn et al. [9]provided early information and guidance on test facility pressures required for high-fidelity evaluations of, respectively, the performance and lifetime of the Stationary Plasma Thruster-100 (SPT-100). A limited number of additional experimental and theoretical efforts were then conducted [7,10-18] which directly measured or calculated the influence of ground facility pressures on global performance characteristics and oscillatory behavior [19] of low-power HETs. Only one additional experimental study [16] of facility effects on HET lifetime was found. Recent, studies [15-19], using non-invasive diagnostics, have provided information on basic interactions of facility environments with HETs and have exposed more complex pressure-thruster interactions than previously considered. In addition to ground based efforts, two, open-literature references [20,21] were found that contrasted available ground and space data. This paper will document open-literature information germane to ground test pressure effects on HET characteristics to illuminate the present situation and inform efforts to establish test and facility standards for HET research and development.

II. Pressure Influence on HET Performance

This section will briefly review identified experimental and theoretical information on the influence of ground test facility pressures on HET performance. For convenience, the data will be provided in roughly the chronological order of publication.

Figure 1 [8] shows the variation of SPT-100 efficiency as a function of facility pressure, expressed herein in units of the 10^{-6} Torr scale, for tests at Fakel (Kaliningrad), the Jet Propulsion Laboratory (JPL), and the Lewis Research Center (LeRC). The SPT-100 data were taken at the nominal operating point of about 1.35 kW and a discharge voltage of 300V. Randolph et al. [8] provided the first, quantitative guidance on pressure requirements for high-fidelity data on

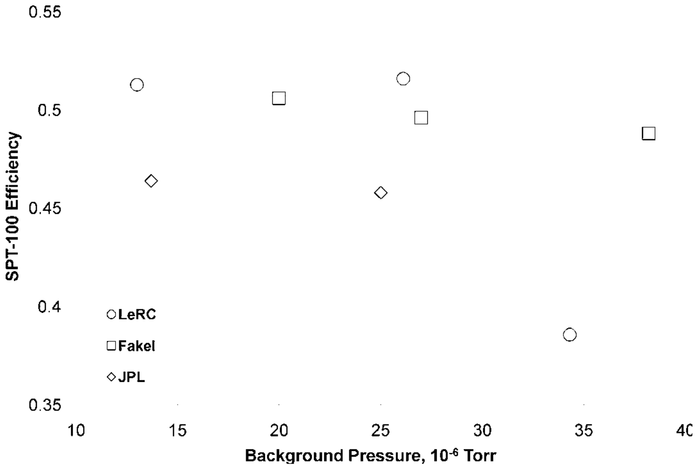
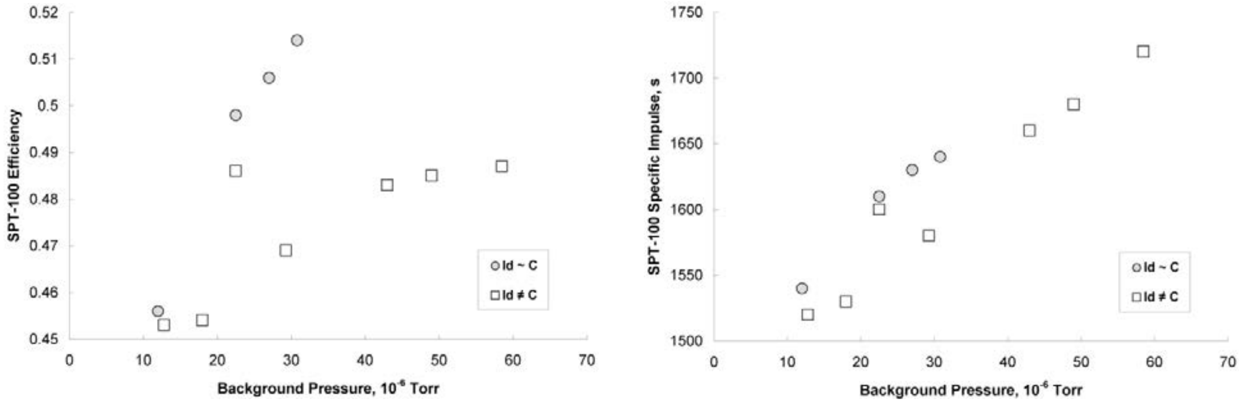


Figure 1. SPT-100 efficiency vs. background pressure. [8]

Table 1. Details of referenced measurements.

Reference	P_{guage} Location from Thruster exit Radial (m)	Axial (m)[a]	Corrected for Xenon	Gauge Sensitivity Factor[b]	Plasma Shielding	Comments
8	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	
10	0.5	-0.6	Yes	2.81 - Ref. 32, Table1	Yes	Pressure varied by xenon injection
11	0.2	-0.7	Yes	3.2	Yes	
12	Not Specified	Not Specified	Yes	3.2	Not Specified	Smaller facility used
12	0.2	-0.7	Yes	3.2	Yes	Larger acility used
14	3	-0.5	Yes	2.87	Not Specified	Pressure taken as average of two hot ionization gauges of different design
14	3	3	Yes	2.87	No	
15	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	
16	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	
17	Not Specified	Not Specified	Yes	Not Specified	Not Specified	Cold cathode gauge used
18	Not Specified	Not Specified	Yes	Not Specified	Not Specified	Cold cathode gauge used

[a]Negative value denotes location upstream of the thruster exit plane, [b]Factor C in equation 1



(a) **(b)**

Figure 2. SPT-100 efficiency (a) and specific impulse (b) vs. background pressure. [10]

HET performances, lifetimes, and interfaces such as plumes and radiated electromagnetic interference (EMI). Soon after, analyses of pressure effects on HET discharge currents, thrusts, and efficiencies were published [7]. As indicated in Table 1, no details regarding the pressure measurements in Randolph et al. were provided. At all three facilities the measured efficiencies were nearly insensitive to pressure from the lowest values of about 12×10^{-6} Torr up to around 25×10^{-6} Torr where the efficiency decreased, sometimes in the presence of increasing discharge current instabilities. The facility background gas ingested by the SPT-100 was calculated [8], where the plan area of the discharge chamber annulus was taken as the entrance area for ingested flow and free molecular flows were assumed. This was the generic approach used to estimate ingested gas in all references cited herein. It was concluded [8] that to assure the ratio of ingested to injected propellant flow was less than about 0.03, the background pressure should be held below 50×10^{-6} Torr. That pressure has since been often cited as the maximum appropriate for high-fidelity performance testing of HETs.

Additional early data [10] on SPT-100 efficiency and specific impulse versus facility pressure are shown in Figs. 2 (a) and 2 (b), respectively. The Fig. 2 data were obtained in a one-meter diameter bell jar attached to a facility 4.6 m in diameter by 19 m long with a pumping speed of 0.15 Ml/s on xenon (all pumping speeds cited herein will be for xenon unless otherwise specified) and were not corrected for ingestion of facility gases. Available data on the measurements are shown in Table 1. No information was provided in Sankovic et al. [10], or in other references cited herein, that correlated the listed pressures to the pressures, or associated particle number densities and temperatures, near the thruster exit. The two data sets shown in Fig. 2 were taken at a constant discharge voltage of 300V with slightly different anode propellant mass flows. The cathode flow for both data sets was fixed about 0.05 of the total flow which was lower than usual for the nominal operating point of the SPT-100. For the circled data the discharge current was nearly constant (4.53 ± 0.02A); but for the data shown in squares, the discharge current increased from 4.25 to over 5A as the pressure was increased.

Figure 2 shows that for pressures above about 10×10^{-6} Torr, the minimum pressures tested, significant increases in both SPT-100 efficiency and specific impulse occurred as the facility pressure increased. Sankovic et al. [10] indicated that the observed performance changes were larger than estimated on the basis of ingested flows. The sensitivity of performance to pressure shown in Fig. 2 was stated elsewhere [8] to be partially due to the lower-than-normal cathode flows used. At a given facility pressure, the efficiency and specific impulse differed for the two data sets and the sensitivity of both parameters, especially efficiency, to pressure was also different. This behavior was not discussed [10], but may have been partially due to the fact that the measured performance, including regions of stability, continued to vary during the entire test program. Regardless, the different responses to facility pressure indicates the prudence of assuring that the intended thruster interfaces with the flow control and power processor units are appropriately simulated while facility effects are evaluated.

The D-55, which is a Thruster with Anode Layer (TAL) that operates at about the same flow rates and power levels as the SPT-100, was also tested [11] over a range of facility pressures at fixed values of discharge voltage and anode and cathode propellant flows. The pressure data were corrected for xenon via use of a formula of the form:

$$P_C = (P_M - P_B)/C_g + P_B \tag{1}$$

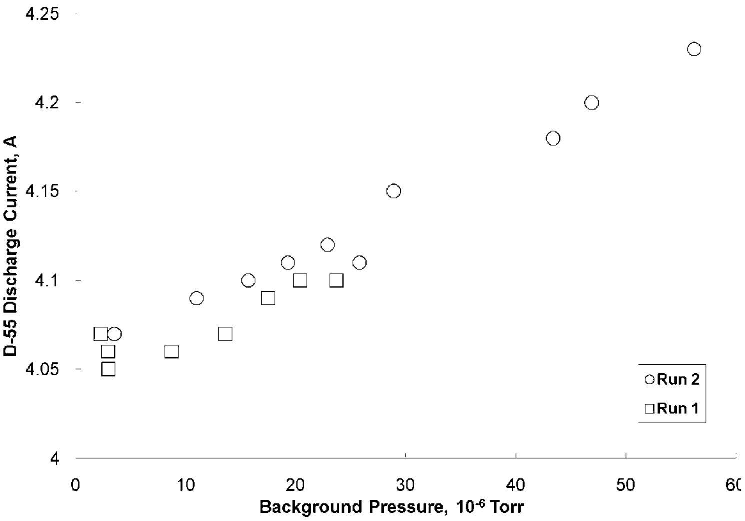
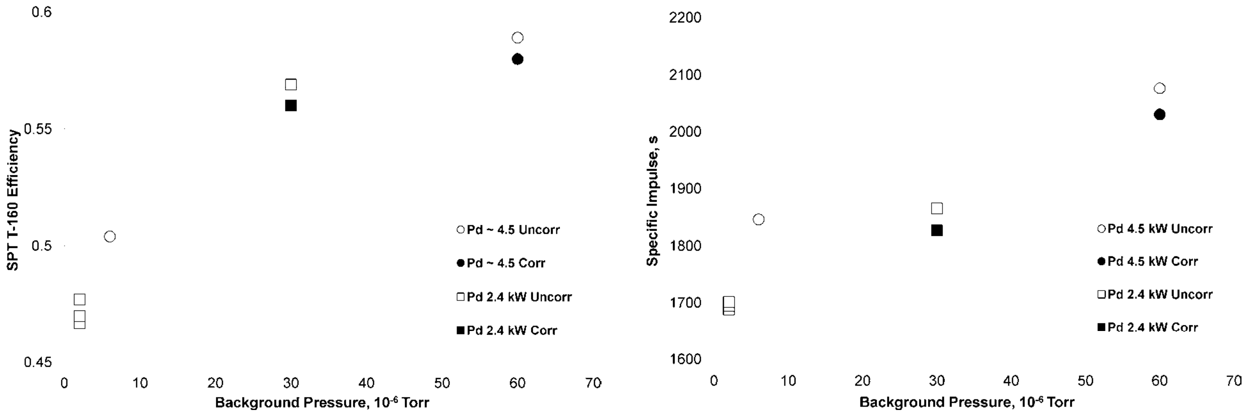


Figure 3. D-55 Discharge current vs. background pressure. [11]

Tests were run with cathode flows of about 18 and 10% of the total flow. The tests were performed in a 5 m-diameter by 20 m-long facility with a pumping speed of 0.32 Ml/s with both 20 diffusion pumps and the helium cryogenic pumps operating. At a fixed operating point, the pressure was varied by first turning off the diffusion pumps and then bleeding xenon into the facility. The pressure readings were corrected for xenon with a gauge factor of 3.2, in contrast to values used in other references. Other details of pressure measurements are in Table 1. Sankovic et al. [11] provided the only the variation of discharge current with facility pressure during two test runs and those data are shown in Fig. 3. The three datums of Run 1 at the lowest pressures reflect the pressure difference with and without diffusion pumps. The small increase in pressure from about 2 to 3.2×10^{-6} Torr caused the discharge current to decrease with no change in thrust. For larger increases in background pressure to over 50×10^{-6} Torr, the discharge current increased about 4 % and the text indicated the thrust increased by only 2 %. Basically the same results were obtained with both cathode flow rates and calculation of the discharge current increase, based on known sensitivities to injected anode propellant and estimated ingested gas, underpredicted the current change by a factor of two. Overall, the D-55 sensitivity to background pressure was in crude agreement with and markedly less, respectively, than the SPT-100 sensitivities shown in Randolph et al. [8] and Sankovic et al. [10]. It is not known if the different sensitivities of performance to pressure were affected by the pressure variation techniques or reflected other sources such as the different range of facility pressures available in the different test programs.

The pressure sensitivity was evaluated for the nominal 4.5 kW SPT T-160 [12]; which, with the data of Hofer et al. [14], was the highest power HET for which such data were found. Pressure variations were obtained by operating the T-160 in two facilities of very different size and pumping speed. The larger facility was that used by Sankovic et al. [11], described above and in Table 1. The smaller facility was 1.5 m-diameter by 5 m-long with an unspecified pumping speed achieved with four-0.08m-diameter diffusion pumps. Pressures were corrected using the procedure of Sankovic et al. [11]. Figures 4 (a) and (b) show the variation of, respectively, T-160 efficiency and specific impulse with pressure. In both figures, data taken in the 10^{-6} and 10^{-5} Torr ranges were obtained, respectively, in the large and small test chambers. For clarity, data at only the nominal power level and one lower power are shown in Fig. 4. The data taken in the small facility were corrected for gas ingestion and the corrected values of efficiency and specific impulse are shown as the filled-in datums in Fig. 4.



(a) **(b)**

Figure 4. SPT-160 efficiency (a) and specific impulse (b) vs. background pressure. [12]

Figure 4 shows that the T-160 efficiency and specific impulse at both nominal and half power increased significantly for pressure increases from the low-mid 10^{-6} Torr scale to the mid 10^{-5} Torr range. Also, if data taken at low pressures are arbitrarily assumed to be correct, corrections of efficiency and specific impulse, based on propellant ingestions calculated as discussed above, represented, respectively, only about ten and twenty percent of the errors at higher pressures experienced with both power levels. These data clearly indicate the inadequacy of simple corrections of facility effects via estimates of ingested flow that use the discharge annular open area and free molecular flow assumptions.

Early analytical evaluations of the effect of facility pressures on HET discharge currents, thrusts, and efficiencies were presented by Bugrova and Morosov [7]. The analyses indicated that ingestion of facility particles could increase or decrease HET efficiency, dependent on the electrical potentials at which the ingested ions were ionized. Ingestion was found to decrease or increase HET efficiencies if the mean potential at which the ingested ions was ionized was, respectively, less or greater than one-fourth the mean potential at which the nominal propellant was ionized. Bugrova and Morosov [7] also pointed out that ingested facility neutrals affected the onset of discharge plasma oscillations and could alter key features, such as the electric fields, of discharge chamber plasmas.

Fife [13] analyzed the influence of facility pressure on the performance and operating characteristics of an SPT-70, which operates at a nominal power of about 650W. The thruster discharge and near-exit plasmas were numerically simulated using a model “HPHall”. The effect of pressure was estimated by consideration of ingested flow calculated via the usual methodology. The calculated change in SPT-70 efficiency, neglecting cathode propellant flow, is presented in Fig. 5. Fife [13] noted that the calculated increase of efficiency with pressure was much less than that measured by Sankovic et al. [10] and that difference was stated as likely due to mechanisms not identified and modeled in the analyses. To the authors’ knowledge, no subsequent analyses of the effect of facility pressure on HET performance have been performed that employ numerical simulations of thruster plasmas.

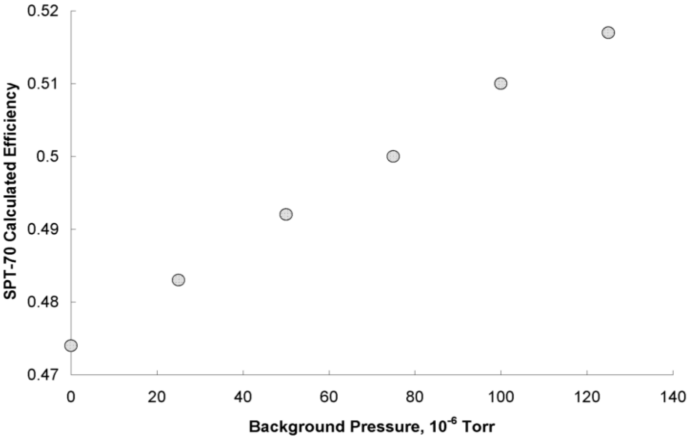
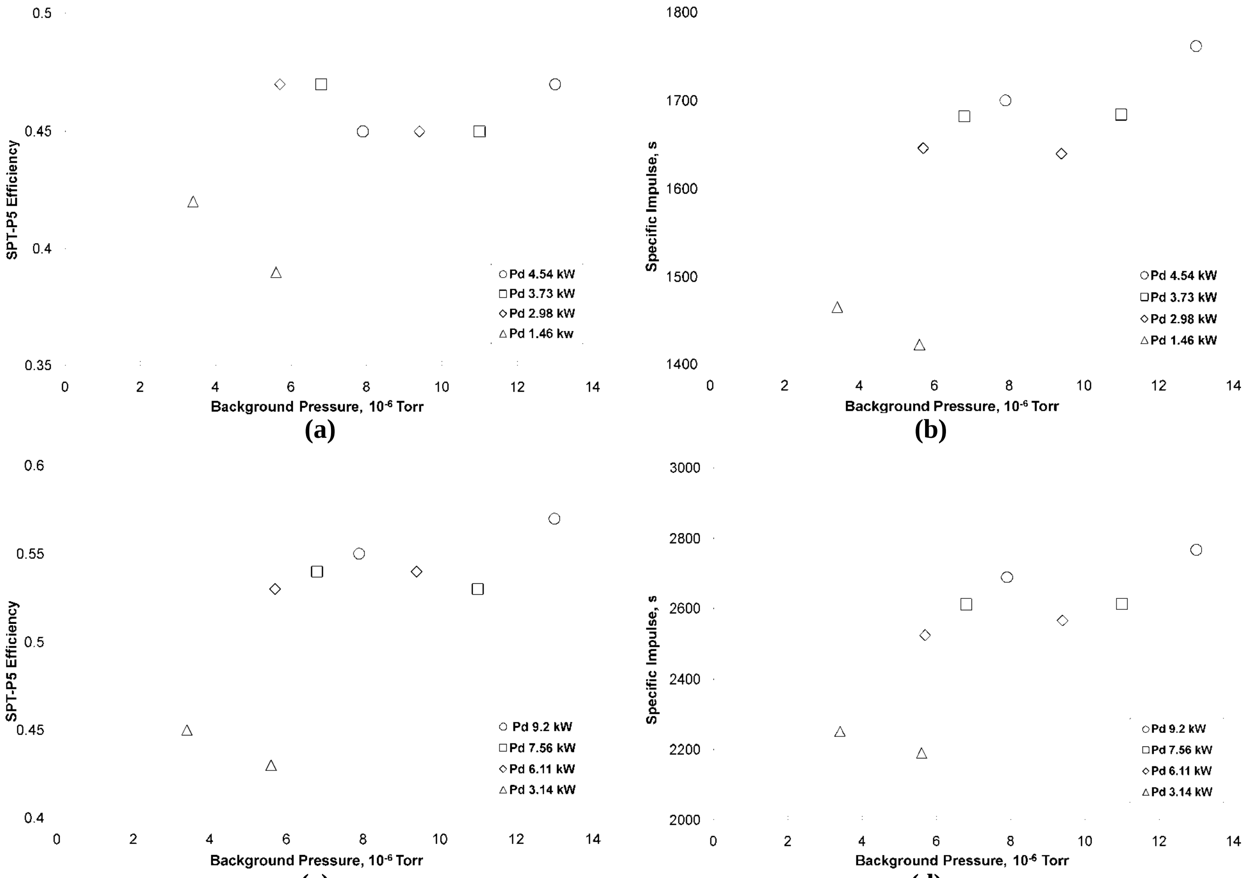


Figure 5. SPT-70 efficiency vs. background pressure. [13]

Facility pressure effects on the performance of SPT P5, which operates at a nominal power of 5 kW, were presented by Hofer et al. [14]. For these tests the SPT P5 was on the center line of a large 6 m-diameter by 9 m-long facility that had pumping speeds of 0.24 and 0.14 Ml/s with, respectively, seven and four cryopumps in operation. The pressure readings were the averages of two hot ionization gauges, upstream and downstream of the thruster, on the tank wall (Table 1). The facility pressure was varied between two levels by changing facility pumping speed by increasing the number of operating cryopumps from four to seven. This approach was selected rather than introduction of xenon with a fixed pumping speed as it was stated to result in lower xenon losses and elimination of some potential effects of xenon injection into the facility. The SPT P5 efficiencies and specific impulses versus facility pressure are shown in Fig. 6 for operation at different discharges powers at discharge voltage of 300 and 600V and a fixed cathode propellant flow. At a given discharge voltage, the discharge power was varied by changing the discharge current and anode propellant flow rate. When the pumping speed was increased from 0.14 to 0.24 Ml/s, which lowered the facility pressure, the discharge voltage and power were maintained at constant levels by slight increases, always less than 2%, in anode propellant flows.

Figures 6 (a) and (b) show that at a discharge voltage of 300V, the sensitivities of SPT P5 efficiency and specific impulse to pressure significantly changed as the discharge powers, and associated facility pressures, increased. At the lowest discharge powers and facility pressures both the efficiency and specific impulse decreased with increasing pressure. As the discharge powers increased, efficiencies and specific impulses became less sensitive to pressure and at the highest discharge power both parameters increased with increasing pressure. Also, facility pressures are seen to affect HET performance at pressure levels down to at least 5×10^{-6} Torr. The same general behavior occurred at a discharge voltage of 600V when the discharge power varied from about 6.1 to 9.2 kW. These data with a single HET clearly show the interactions of facility pressure with HETs are complex and, dependent on conditions, may lead to quite different behavior of global thruster characteristics. As discussed above, Bugrova and Morozov [7] provided criteria, which require knowledge of internal HET plasma conditions, to determine the



(a) (b)

(c) (d)

Figure 6. SPT-P5 efficiency (a) and specific impulse (b) vs. background pressure for 300 V discharge and efficiency (c) and specific impulse (d) vs. background pressure for 600 V discharge. [14]

direction (sign) of change in efficiency with increasing pressure. Hofer et al. [14] indicated that the potential effects of the changing facility environment on internal thruster mechanisms, such as ionization and acceleration, were unknown but could be especially important in HETs where those processes occur downstream of the exit plane. As noted later, this situation exists with many HETs.

Mazouffre et al. [15] provided information on facility pressure effects on global performance characteristics and internal and external plasma properties of a laboratory model SPT-100. No data on the test facility or pressure measurements were provided in Refs. 15 or 16. Pressure variations were produced by bleeding xenon into the facility at a fixed pumping speed. The discharge voltage (300 V) and propellant flows were held constant for data from Ref. 15 presented herein. Figure 7 shows the efficiency and specific impulse, both derived from other data in Ref. 15, as a function of facility pressure. As the pressure increased by about an order of magnitude from the low 10^{-5} Torr level, the efficiency decreased slightly, the specific impulse increased by about 75 seconds, and, not shown, the discharge current and thrust, respectively, increased by about 15 and 5%. Reference 15 indicated that the thrust increase was likely due to the ingested gas, the increase in discharge

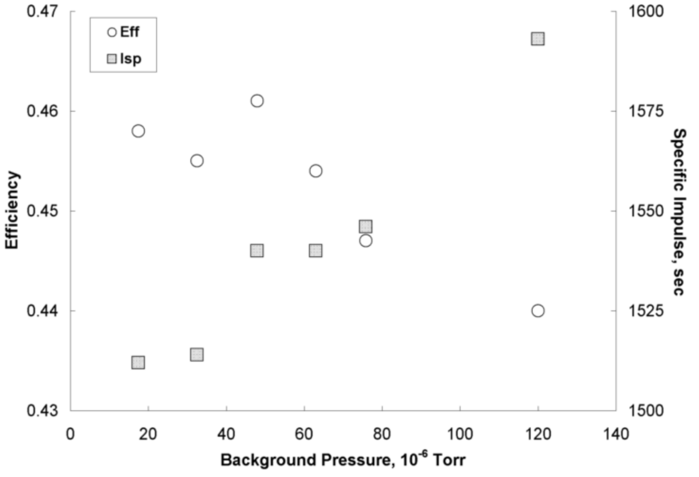


Figure 7. SPT performance vs. background pressure. [15]

current, and decreased ion beam divergence at increased facility pressures. While the thrust growth resulted in larger specific impulses, the efficiency decreased due to the power growth associated with increased facility pressures.

Table 2. Ion velocity vs. distance and pressure. [15, 16]

Measurement Type	FPI	FPI	LIF	LIF
Distance from HET exit, mm	2	2	2	32
Facility Pressure, Torr	15×10^{-6}	120×10^{-6}	15×10^{-6}	15×10^{-6}
Axial ion velocity, km/s	14	19.3	15	19.5

Details of the xenon ion flow fields of the SPT-100 obtained via Fabry-Pérot interferometry (FPI) were also presented [15]. It was stated that while FPI offered lower spatial and spectral resolutions than laser induced fluorescence (LIF), it was somewhat more convenient to use in standard HET test facilities. Axial, xenon ion velocities measured by FPI and LIF were presented in Ref. 15 as a function of position from about 13 mm upstream to 25 mm downstream of the thruster exit and were in good agreement. Table 2 shows FPI measurements of the axial, xenon ion velocity 2mm downstream of the exit of the SPT-100 at two facility pressures. LIF data from Ref. 16 on axial, xenon ion velocities at 2 and 32 mm downstream positions are also shown in Table 2. The FPI data show that that as the pressure was increased from 15×10^{-6} Torr to 120×10^{-6} Torr, the ion velocity increased by 5.3 km/s, a 38% increase. Reference 15 indicated that this could have been due to an upstream shift and/or narrowing of the acceleration zone. The LIF data [16] indicate, however, that the final axial ion velocity was about the same at both pressures. These data show that measurements of global performance characteristics may not fully reflect some key interactions of facility pressure environments with HET plasmas.

LIF was used [17] to evaluate axial ion velocity distributions of a BHT-HD-600, which is a small SPT with a nominal operating power of about 0.6 kW. Both most probable and mean axial ion velocities were obtained from the LIF diagnostic. Data were taken for factor of two variations of both facility pressures and thruster magnetic fields. The measurements were conducted in a 1.8 m-diameter by 3 m-long facility with a pumping speed of 0.032 Ml/s that enabled background pressures of about 15×10^{-6} Torr at nominal thruster operating conditions. Pressure readings were taken with a cold cathode gauge and corrected for xenon. No other details of pressure measurements were provided in Ref. 17.

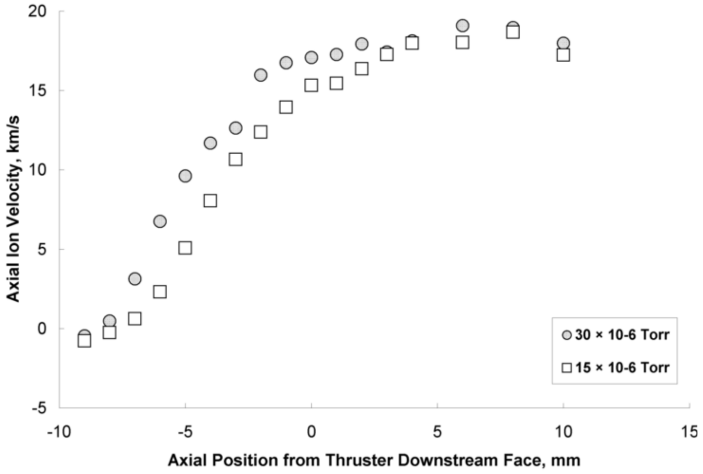


Figure 8. BHT-600 axial ion velocity vs. position. [17]

Figure 8 shows mean axial ion velocities in the BHT-HD-600 at facility pressures of 15 and 30×10^{-6} Torr at axial positions from 9 mm upstream of the downstream face of the thruster to 10 mm downstream. Arbitrarily, mean ion velocity data are shown for the higher magnetic field configuration of the thruster. It is seen that, similar to the behavior of the SPT-100 with pressure described above, higher pressures resulted in higher axial ion velocities inside the discharge chamber; but the final velocities were not changed by pressure variation over the range tested. It was also noted that discharge chamber current oscillations increased with pressure for both magnetic fields. Also not shown is the additional result that the ion velocity distributions widened at the higher pressure. The data of Fig. 8 suggest that the acceleration zone may have shifted upstream by about 2 mm when the pressure increased from 15 to 30×10^{-6} Torr. Reference 17 indicated that shift may have been in part due to changes in collision frequencies caused by gas ingestion and that the change in ion distribution width could have resulted from overlap between the ionization and acceleration regions in the discharge chamber. As discussed below, the shift in acceleration zone may be important to interpretation of lifetime tests of HETs. A key finding of Ref. 17 was that effects of pressure variation below 50×10^{-6} Torr remain a serious issue.

Axial ion velocity distribution were presented versus axial position in Ref. 18 for the BHT-200-X3, a SPT that operates at a nominal power of 0.2 kW, for corrected facility background pressures of 4.4, 15, and 26×10^{-6} Torr. The higher pressures were achieved by bleeding xenon into the facility during thruster operation. To the authors' knowledge, the background pressures for some of the data of Refs. 18 and 19 were at the lowest values at which facility pressure effects on HETs have been evaluated. The data were obtained in the same facility as used in Ref. 17, and similar details on pressure measurements were provided. Figure 9 shows the mean axial ion velocities as a

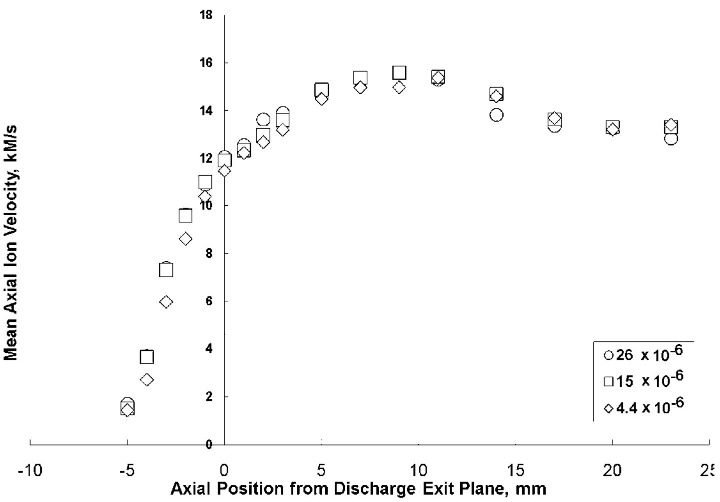


Figure 9. BHT-200-X3 mean axial ion velocity vs. position. [18]

function of distance from the thruster exit plane. The mean ion velocities and the spread in velocities of the 0.2 kW BHT-200-X3 exhibited the same general sensitivity to facility pressure as the 0.6 kW BHT-HD-600. When the facility pressure increased, the mean ion velocities, and the spread in velocities increased in the upstream and near-exit plane regions. However, the background pressure didn't significantly affect ion velocities downstream of the exit plane. The cause of the variation in mean velocities was felt due to a shift in the acceleration zone; which was estimated to be a maximum of about 0.5 mm. This shift is about a quarter of that noted in Ref. 17 and it is unknown if the difference is due to the levels of background pressure evaluated and/or the different discharge plasma characteristics of the two HETs. Reference 18 also indicated that the decrease in ion velocities with increasing distance from the exit plane may be due to collisions in the plume.

The effect of facility pressure on HET plasma oscillations was evaluated in Ref. 19 for the BHT-200 and BHT-200-X4 HETs. The BHT-200-X4 is a flight version of the BHT-200-X3 with magnetic field modifications that resulted in a shift of the ion acceleration region a few millimeters downstream and an efficiency increase of about 0.05. The oscillations were evaluated by measurements of both discharge current and singly charged ion emission spectra which provided generally similar results The data were taken in the same facility as used for Ref. 18 and the facility pressure at nominal operating conditions was 4×10^{-6} Torr. The facility pressure was increased by bleeding xenon into the tank. The peak oscillation frequency was not strongly affected by pressure for either HET. However, pressure increases caused strong increases in the magnitudes of oscillations of the BHT-200-X3 but didn't significantly affect the oscillation magnitudes in the flight model HET. The authors noted that the lack of sensitivity of the flight model HET to pressure variations relative to the BHT-200-X3 was counterintuitive, given the locations of the ion acceleration regions of the two HETs and that the behavior of the thrusters indicated the complex nature of the interaction of facility pressure with HETs.

Comparison of ground and in-space data can provide a relevant evaluation of ground facility test results. A search identified only two, open-literature, documented comparisons [20,21] of HET ground and in-space performance. References 20 and 21 presented, respectively, for the Intelsat 10 and Inmarsat 4F1 satellites the specific impulses and thrusts obtained during ground acceptance tests and as derived from thruster subsystem telemetry during initial, in-space operations. Unfortunately, no directly-measured flight data were yet available so appropriate comparisons of ground and flight performance data are not possible. It should be mentioned that direct, in-space measurements of thrust are extremely difficult, especially for thruster configurations used by electric, stationkeeping thrusters. Accurate comparisons of ground and in-space thrusts require significant efforts as they must consider a large number of uncertainties, including those associated with telemetry, thruster pointing, plume impingement effects, and time variations of thruster subsystem performances.

III. Pressure Influence on HET Erosion Rates

Only one direct experimental evaluation [9] of HET erosion rates as a function of ground facility background gases was found. Kahn et al. [9] provided measurements of erosion rates of insulator samples with and without background contaminant gases. Borosil samples, 3.5 to 4.0 mm square and from 0.2 to 0.7 mm thick, were attached near the exit plane on both the inner and outer insulators of a SPT-100 and mass losses were measured after tests of 3 to 6 hours in length. At the time of the tests the SPT-100 had been operated for less than 125 hours. Tests were run with no introduced gases at a pressure of 70×10^{-6} Torr and with introduced partial pressures of nitrogen and oxygen of 5×10^{-6} and 10×10^{-6} Torr. The base, no-load pressure was 0.25×10^{-6} Torr and was assumed to be air. The test facility was 1.4 m in diameter and 3.05 m long and the SPT-100 was mounted on an end plate and aligned with the facility axis. Pressures were corrected for xenon; but no other information on pressure measurements was provided.

Figures 10 shows sample erosion rates [9] versus sample thickness for operation with no contaminant gas and for two added partial pressures of nitrogen and oxygen. Unlike the erosion of molybdenum ion optics [22], the sample erosion rates didn't decrease with added contaminants but were nominally insensitive to added nitrogen and oxygen except for the case of 10×10^{-6} Torr oxygen where the erosion increased in two separate tests. Kahn et al. [9] interpreted the results shown in Fig. 10 to mean that contaminant air pressures less than about 10×10^{-6} Torr would have negligible effect on erosion of a SPT-100 with about 100 hours of operating exposure. Erosion rates of the SPT-100 drop about an order of magnitude over the life of the thruster [9]. This led to the conclusion that background facility air contamination levels less than 1×10^{-6} Torr should be adequate for high-fidelity life tests of the SPT-100. This criterion has since been often used for life tests of HETs. It is important to note that the conclusions of Ref. 9 referred to contamination levels that exist as part of the base pressure of a facility. The paper didn't evaluate the effect of xenon background pressures of erosion rates. Based on data presented above, it is likely, due to the rather high pressure of 70×10^{-6} during thruster operation, that the acceleration region was affected during the erosion tests.

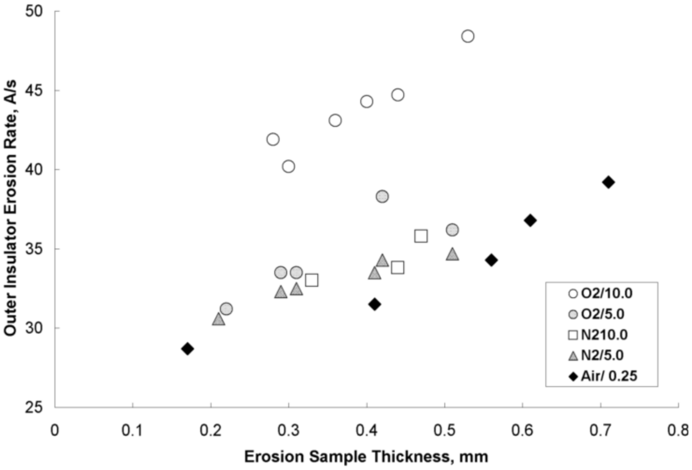


Figure 10. SPT-100 outer insulator erosion rates vs. sample thickness. [9]

Pagnon et al. [16] provided data on erosion of a SPT-100 via use of optical emission spectroscopy (OES) which, with supporting assumptions, directly determined the ceramic erosion rates from intensities of optical emission lines from boron and xenon atoms. Figure 11 shows that erosion rates determined via OES increased strongly with increasing facility pressure, which was achieved by feeding xenon into the facility. Reference 16 associated the increasing erosion with increasing energy of ions which struck the ceramic which was felt largely due to a decrease in potential losses downstream of the exit plane with increasing facility pressure. The OES technique provided signals that reflect overall erosion of the discharge channel but not the influence of facility pressure on the spatial distribution of erosion. The data of Ref. 16 show that erosion of HETs may be rather sensitive to facility pressures dominated by propellant neutrals; but, at this time, no direct measurements of erosion versus pressure are available that quantify that relationship. As discussed above, facility pressures can affect the location of the ion acceleration region and, therefore, may influence local erosion rates of chamber materials, especially near the thruster exit, which are generally used to specify the useful life of HETs.

A large number of publications have provided analyses germane to erosion of HET discharge channel walls (see, for example, Refs. 23 and 24 and references contained therein). However, no theoretical studies were identified that directly addressed the effects of facility particle environments on global or local erosion of HET chambers.

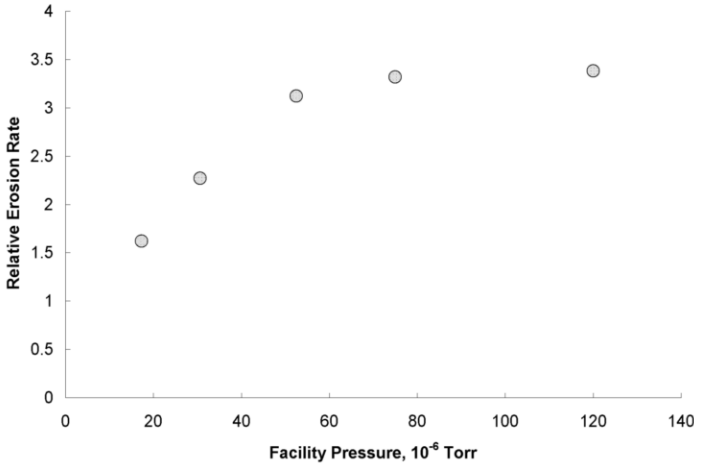


Figure 11. Relative erosion vs. facility pressure. [15]

IV. Swirl Torques

Swirl torques, around the thrust axis, may be an issue for some missions using electric propulsion as they cannot be addressed via usual thruster gimbal designs and have design, operational, and performance implications for the spacecraft. For example, gridded-ion thruster swirl torques were noted on Deep Space mission (Ref. 25) and were measured during both ground-test [25] and in-space [26] phases of the Dawn mission. For reference, at the maximum power levels of about 2.5 kW, the swirl torques of the three ion thrusters on Dawn [25] varied from about 20 to 50×10^{-6} N-m and the primary cause was given as rotational misalignment of the ion optics.

Swirl torques are also of interest with HETs, in particular due to their use of relatively high radial magnetic fields and discharge currents. Mitigation techniques, such as changing the directions of HET discharge currents [27], may be available; but knowledge of swirl torque magnitudes is important to size spacecraft subsystems. However, no direct measurements of HET swirl torque were found in the literature. One indirect, experimental evaluation found of HET swirl torques was found [28]; which presented azimuthal ion velocities, via LIF, in the plume of a 1.5 kW SPT-100 and estimated the swirl torque at about 50×10^{-6} N-m. No data were provided on the facility characteristics during the tests. The value of 50×10^{-6} N-m was similar to the torque obtained by using the maximum values calculated in Kozubsky et al. [29]. Ashkenazy et al. [27] estimated, via analyses and use of measured magnetic fields and discharge currents, that the swirl torque of a sub-kilowatt thruster was $20\text{-}40\times10^{-6}$ N-m. Swirl torques are directly proportional to the radial magnetic flux and the ion velocities which indicates they may be quite sensitive to conditions near the exit of HETs where facility pressures may strongly affect conditions. Accurate ground evaluations of swirl torques may, therefore, potentially be rather sensitive to facility characteristics.

V. Pressure Measurements

Available information on the measurements used in cited references are shown in Table 1. It is first seen that details of the measurements are often not cited. The available data indicate use of a wide variety of approaches which include differences in gauge types, locations, calibrations, and other details. The range of approaches adds uncertainty to comparisons of test results from different facilities. There is also general uncertainty regarding the relationship between the cited pressures and the facility particle environments near the exits of the HETs that are important to facility pressure-HET interactions that affect performance and lifetime. Such relationships may vary with test location as, among other issues [30], the location of vacuum pumps can have an important influence on facility pressure distributions. Analytical tools now appear capable of modeling facility environments [30,31]; but results are quite sensitive to assumptions regarding beam properties, cold-wall sticking coefficients, and other facility characteristics.

VI. Conclusion

Open data regarding the influence of ground facility pressures on the performance and erosion rates of Hall Effect Thrusters were reviewed to evaluate both the approaches used in relevant ground test programs and the present level of understanding of the influence of facility pressure on HETs. The influence of facility pressures on HET performance and erosion rates was presented in a limited number of experimental and theoretical evaluations. No data were found on the facility effects on swirl torques. Most data were obtained with HETs that operated at or less than about 1.4 kW and two reports discussed results at higher HET power levels.

Comparison of facility interaction data from different facilities is problematic because (Table 1) important aspects of the pressure measurements were frequently missing, different approaches to evaluations of pressures were often used in different facilities, and significant differences in facility designs existed. Pressure evaluations included different gauge types, locations, entrance conditions, and calibration details. Characteristics of the test facilities which varied included dimensions, pumping speeds, and locations of pumping surfaces with respect to the thruster and thruster plumes. Analyses now appear to be able to produce detailed maps of facility pressures. However, such analyses are quite sensitive to assumptions regarding HET exhausts and facilities and it is unclear if a standard set of assumptions are available or appropriate for calculations of facility pressure fields.

The effects of facility pressures on HET performance were experimentally assessed in a limited number of studies and theoretically analyzed in two reports. The overall finding was that pressure effects on HET performance were situational and quite dependent on specifics such as the design and operating condition of the HET and facility characteristics. This general behavior was well illustrated by the data of Hofer et al. [14], where, in a given facility with a given HET, increased facility pressures resulted in decreased, unmodified, and increased HET performance as the HET power, and associated flow rates and facility pressures, increased. Recent tests with non-invasive diagnostics have shown that facility pressure interactions with HETs are considerably more complex than initially assumed and may, for example, result in changes in the location of ion acceleration regions that are not detectable via measurements of global HET performance characteristics. An early analytic, analysis [7] discussed multiple influences of facility environments on HET performance and provided a criterion to determine if facility pressures would increase or decrease measured HET performance. However, use of the criterion requires detailed knowledge of the interior HET plasma. A subsequent detailed, numerical study [13] strongly underestimated pressure interactions. Also, due to the lack of in-flight thrust data, no comparisons of HET flight and ground performances were possible.

Two references were identified that experimentally evaluated the effects of facility pressures on HET erosion. It was found [9] that, different from the experiences with ion thrusters, partial pressures of reactive gases had either negligible influence or increased erosion rates. Pagnon et al. [16] found, via use of emission spectroscopy, that increased xenon pressures strongly increased HET erosion rates; but it is presently not known the degree to which that dependence is due to the influence of facility pressures or locations of HET ion acceleration zones. No experimental data or theoretical analyses were found that directly quantified sensitivity of the magnitudes and/or spatial dependences of erosion rates with facility propellant pressures. In addition, no studies were available that documented any relationships between HET swirl torques and facility pressures.

Overall, the review showed the broad range of test procedures and conditions extant for HET testing and the extremely situational, and sometimes counterintuitive, nature of the effects of facility pressure. The findings support the establishment of experimental and analytic test standards for Hall Effect Thruster programs in particular and electric propulsion devices in general.

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