# Quantifying Facility Effects on Electric Propulsion Performance in Orbit

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**Electric Propulsion (EP) performance differs in orbit from ground testing as a result of facility effects, a difference arising from limited pumping capacity compared to the vacuum of space, confining walls of the testing facility and plume interactions with the walls themselves. Due to the limitations of testing facilities, there is an inherent overestimate of measured performance during ground testing compared to performance in space. This overestimate arises from multiple factors including a residual background pressure that results in multiple significant effects, an electrical interaction with the facility creating different electric potentials, and other miscellaneous effects that are areas of active research. This paper delves into these effects and sheds some insight into the research that has been conducted and how we may be able to develop a simple extrapolation parameter that allows for the characterization of the thruster's performance in space. Due to the inherent complexity behind facility effects and differences between facilities, it is not currently possible to create one single extrapolation parameter that accounts for facility effects for EP systems between different testing facilities.**

## I. Nomenclature

| | | |
|---|---|---|
| $I_b$ | = | Beam Current |
| $\dot{m}_i$ | = | Ion Mass Flow Rate |
| $m$ | = | Ion Mass |
| $q$ | = | Fundamental Charge |
| $P$ | = | Pressure |
| $T$ | = | Temperature |
| $R$ | = | Gas Constant |
| $k_b$ | = | Boltzmann Constant |
| $A_{ch}$ | = | Area of Channel |
| $T$ | = | Thrust |
| $V_0$ | = | Beam Voltage |
| $V_D$ | = | Discharge Voltage |
| $\theta_d$ | = | Divergence Angle |
| $\sigma_c$ | = | Cross-Sectional Collision Area |
| $V_{CC}$ | = | Cathode Voltage |

## II. Introduction

Electric Propulsion (EP) is a form of in-space propulsion that contrasts against the traditional chemical propulsion methods used since the advent of space flight. Commonly used for commercial station keeping and deep-space exploration missions, EP has benefits that shine for long-duration missions; its characteristic high specific impulse and high efficiency (for Hall effect and gridded ion thrusters) make EP thrusters much more "fuel-efficient" than chemical rockets, requiring less fuel on board a spacecraft to achieve the same increase in velocity. This in turn means either a less massive spacecraft is required (saving money in launch costs) or additional payload can be placed on board, allowing the spacecraft to have additional functionality. However, EP as a field is not completely understood as there are still gray areas in the theoretical characterization of its performance metrics. A significant example of this is the discrepancy between key performance metrics from thrusters tested in vacuum chambers on Earth's surface against thrusters operating in space.

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The purpose of this report is to perform preliminary research to determine the theoretical difference between performance in a facility and in orbit. A currently known issue from evaluating the differences of EP systems is that several poorly understood effects arise from thruster interactions with testing facilities, altering the reported system performance. These performance differences stem from limited vacuum pumping capacity, the presence of the confining walls of the facility, and other contributing factors that are actively being researched. Typically, the residual chamber pressure will result in more columnated exhaust plumes that improve the divergence efficiency of the thruster, which will, in turn, overestimate its performance. Additionally, background pressure present in testing facilities causes the acceleration region for ions in a Hall thruster to move downstream, which can lower divergence efficiency and affect other performance parameters as well. Furthermore, the presence of background pressure artificially aids cathode coupling as the cathode electrons couple more easily to the plasma ions at higher pressures; this lowers the cathode voltage and results in higher electrical efficiency performance not seen on orbit. Recently, an increased focus on understanding facility effects have come about in the sense that EP systems must be proven flight-ready, a standard called Test Like you Fly. However, many facility effects have been researched and are providing insight as to how EP systems are impacted by testing on the ground as opposed to in the environment in which they will operate. Even though much research has been conducted there remain several effects that, until recently, have not been well understood such as thermal effects and the effects of Earth's magnetic field.

This research will provide a brief overview of the theoretical performance of EP systems and how performance will differ in ground facilities and if this difference can easily be defined or quantified. Firstly, this performance difference will be estimated through theory and then compared against real-world performance metrics. Comparing the extrapolation parameter against actually measured performance metrics will allow for the validation of this parameter.

# III. Thesis

The thruster performance metrics reported from ground facility tests are an over-representation of actual performance in orbit. The performance difference comes from the fact that even the best vacuum facilities on the ground are unable to simulate true vacuum during ground testing; state-of-the-art vacuum chambers only have the capability to pump down to pressures on the order of ten-billion times higher pressure than the vacuum of space. Because of the large difference in the actual pressures of ground vacuum and the vacuum of space, it is not possible to determine the true performance of EP systems directly from reported measurements from vacuum chamber testing on the ground. Since the pressure difference is so significant, the plume exiting the thruster is more columnated which results in a higher measured thrust. This paper will delve into the characterization of the performance difference and investigate if a performance parameter can calculate the suggested performance of the EP system while in a true vacuum.

Even though the background pressure is the largest contributor to the increased thrust, multiple facility effects alter the performance of the EP systems on the ground. There are additional effects on the electrical configuration that alter thruster performance that occur only during on-ground testing. An area of research that has recently been considered is the variety of effects that the Earth's magnetic field can have on thruster performance. More recently, there has been an increased interest in thermal effects, and how environmental temperature differences can alter performance and lifetime. This paper will analyze these effects, and provide key insight to these facility effects.

# IV. Theory

To determine the extent of the impact that facility effects have on thruster performance, we must first look at which differences arise from testing in a vacuum chamber compared to in orbit. These differences include but are not limited to: the residual background pressure; electrical configurations and cathode coupling; and other miscellaneous effects. By applying first-order principles and basic knowledge of the physics of electric propulsion, we will attempt to build a simple and straightforward model to understand the performance differences on Earth versus the performance on orbit.

## A. Facility Effect Overview

These facility effects can be further simplified into their direct contribution to the overestimation of the performance metrics of thrusters. The experiments analyzed mainly focus on Hall Effect Thrusters (HET) and their performance on the ground and in orbit.

- **Background pressure:** The background pressure arising from the facility's limited pumping capability will be considered since an idealized thruster operating in space will experience vacuum pressure at the exit plane of the thruster, but this is not feasibly reproducible for on-ground testing. This background pressure affects the location of the acceleration region which can affect the divergence angle of the plume. Furthermore, the background pressure columnates the plume as well, leading to measurements that underestimate the divergence losses that would be experienced on orbit. The background pressure additionally allows for additional neutrals to be ingested which increases the effective mass flow rate of the system. Furthermore, a model has been developed relating cathode coupling to background pressure. As the background pressure increases, cathode coupling decreases and therefore results in better thrust performance [1].

- **Electrical Configuration:** The electrical configuration will be analyzed since in space there is no true "ground" that the thruster can reference. This lack of common ground results in differing electrical efficiencies that is still not well understood. However, there are three electrical configuration types that this paper explores; grounded thruster, grounded cathode, and a floating thruster configuration.
- **Miscellaneous Effects:** Background pressure and the electrical configuration have been characterized as large contributors to the performance difference arising from facility effects; however, there has been increased interest in researching the performance effects from thermal contributions and also the effects of Earth's magnetic field.

### B. Background Neutrals Model

A theoretical approach to the effect of background neutrals can be considered, utilized in the Background Pressure - Mass Flow section. For a typical Hall effect thruster, the beam current, or current of ions exiting the thruster, can be represented as,

$$I_B = \frac{\dot{m}_i q}{m_i}, \tag{1}$$

Where $q$ is the fundamental charge, $m_i$ is the mass of the ions being used, and $\dot{m}_i$ is the mass flow rate of ions.

When there is additional pressure in the chamber from an imperfect vacuum, this results in some ambient gas that can drift into the thruster discharge. This additional gas flow will affect the beam current by implementing an additional contribution to the mass flow from the extra neutral particles in the chamber. This is shown by the total mass flow term, $\bar{\dot{m}}_i$, containing this additional ambient pressure term,

$$\bar{\dot{m}}_i = \dot{m}_i + \frac{P_\infty}{RT_\infty}\sqrt{\frac{k_b T_\infty}{m_i}} A_{ch}, \tag{2}$$

Where $P_\infty$ is the ambient pressure, $T_\infty$ is the ambient temperature in the chamber, and $A_{ch}$ is the thruster channel area. Therefore, we can see this additional mass flow boost that the thruster gains from background neutrals in the facility. Since the thrust of a Hall effect thruster can be represented as,

$$T = I_B\sqrt{\frac{2m_i V_0}{q}}\cos\theta_d, \tag{3}$$

It is possible to quantify this additional thrust that the thruster experiences during on-ground facility tests as compared to in-space thrust. This beam current will be larger due to the additional mass flow term in on-ground facilities. Thus, if a given Hall thruster were to operate at the same mass flow rate on-orbit as on-ground, the thrust can be overestimated by a measurable amount.

## V. Experiments

There has been an extensive amount of research conducted to determine how the performance differs between on-Earth and in-flight performance. From this research, it has been determined that the most significant factor altering thruster performance is the background pressure caused by neutral flows. The next most significant performance altering condition is the electrical configuration of the thruster since the floating ground can add electrical biases to the thruster and alter performance.

There has been a large amount of research conducted studying facility effects, specifically over the past several years to determine and possibly quantify the expected performance in space. During spacecraft integration and testing, engineers attempt to achieve the best-case testing environment to ensure that the spacecraft performs nominally throughout its mission. The concept of verifying a thruster's performance to ensure the operation of it in space is called Test Like You Fly.

This paper references experiments from Diamant and Corey for the SPT-100 performance measurements [2]. It also looks into experiments from Peterson, Kamahawi, and Hofer for the NASA HERMeS configuration characterization[3]. Korsun, et. al. also discuss the effects of the geomagnetic field and use experiments for multiple thruster types to quantify their results [4]. In addition to these experiments, the discussion references certain models for these facility effects, such as the Cathode Coupling model from Cusson, Jorns, and Gallimore [5]. Finally, work done by Georgia Tech, Lockheed Martin, and Aerojet Rocketdyne on electron termination pathways is analyzed when looking at the electrical configuration [6].

## VI. Results & Analysis

### A. Model Selection

The following section outlines the models that were selected from previous experiments in addition to the theoretical model presented for background neutral ingestion.

*Background Pressure - Acceleration Region*

Byrne and Jorns conducted substantial research into the effects of background pressure and its impact on plume divergence. They discovered that the residual back-pressure in testing facilities results in the acceleration region of the Hall effect thruster moving downstream, resulting in a larger increase in divergence angle. However, determining the divergence angle requires removing Charge-Exchange Collision (CEX) wings, as these ions have different velocities than the ions originating from the beam. These CEX's can be shown in Figures 1,2 represented by the low-energy ions. Quantifying the new angle requires the formulation of a definition on a weighted divergence angle that was provided in Huang et. al. [7] shown in Equation 4.

$$\langle \cos\delta \rangle = \frac{2\pi R_{FP}^2 \int_0^{\pi/2} j(\theta)\cos\theta\sin\theta d\theta}{2\pi R_{FP}^2 \int_0^{\pi/2} j(\theta)\sin\theta d\theta} \tag{4}$$

Where $\delta$ is the charge weighted divergence angle, $\theta$ is the angle with respect to the thrusters centerline, and finally $j(\theta)$ is the ion current density that is dependent upon the angle from centerline.

*Background Pressure - Mass Flow*

The effect of neutral ingestion on the mass flow of the thruster is analyzed using the equations presented in Section IV, Theory. In addition to this model, the values are compared against the results from Diamant and Corey for the effects of background pressure on the SPT-100 thrust performance [2]. Overall, the model utilized in this analysis, consists of the following relationship between thrust and background pressure,

$$T = \frac{(\dot{m}_i + \frac{P_\infty}{RT_\infty}\sqrt{\frac{k_b T_\infty}{m_i}} A_{ch})q}{m_i}\sqrt{\frac{2m_i V_0}{q}}\cos\theta_d. \tag{5}$$

*Background Pressure - Cathode Coupling*

Cusson, Jorns, and Gallimore explore the effects of the cathode voltage coupling with background pressure. They discover that increasing background pressure decreases the coupling voltage such that, $T \propto \sqrt{V_D - V_{CC}}$. This simple model shows that the cathode voltage decreasing results in an increase in thrust. The model used for this cathode coupling voltage is provided by the equation $\Delta V_{PC} = (\frac{\delta\alpha m_e V_e \omega_{pe}}{\langle k_i \rangle q})\exp(\langle k_i \rangle (x - x_0))$. This $\Delta V_{PC}$ is the cathode coupling voltage in the plume of the cathode which is related to the background pressure by the average wave growth number $\langle k_i \rangle$. This model provides a direct relationship between increasing background pressure and increasing thrust performance through the mechanism of cathode coupling [5].

*Electrical Configuration*

Walker et. al. look into the existence of electrical facility effects by analyzing the termination paths of electrons used to neutralize the plasma discharge of Hall effect thrusters. They conclude that, by biasing an electrode downstream of the plume at a voltage above chamber ground, net electron collection on grounded chamber surfaces as well as thruster surfaces can be eliminated; another conclusion they found is that global changes in the plasma potential can affect cathode coupling efficiencies [6]. We see this in the model they developed for calculating electron current lost to the chamber walls and biased electrode plate as a function of plasma potential:

$$I_e = \begin{cases} \frac{1}{4} n_e e A \sqrt{\frac{8 k_B T_e}{\pi m_e}} \exp\left(\frac{e(\phi_w) - \phi}{k_B T_e}\right) & \text{if } \phi_w < \phi \\ \frac{1}{4} n_e e A \sqrt{\frac{8 k_B T_e}{\pi m_e}} & \text{if } \phi_w \geq \phi \end{cases}$$

where $n_e$ is the neutral density, $e$ is the fundamental charge, $A$ is the thruster channel area, $T_e$ is the electron temperature, $m_e$ is the electron mass, $\phi$ is the plasma potential at any given point, and $\phi_w$ is the potential at the wall. This equation shows that electrons will be lost to the walls if the potential of the walls is higher than the potential of the plasma, which can happen in certain electrical setups and connections to ground in facility testing, causing an efficiency hit not seen in on-orbit operation.

*Earth's Magnetic Field*

Korsun et. al. conducted a study on the effect of the geomagnetic field on plasma plumes. These effects can be related to the plasma plumes in hall-effect thrusters and therefore impact the performance of these thrusters. Certain zones of the plasma plume are affected by the geomagnetic field. The model presented by Korsun is $x_B \approx (\frac{NTk^2}{\sigma_c u_c^2 B^2 \pi})^{1/3}$ and $r_B \approx (\frac{NT\sqrt{k}}{\sigma_c u_c^2 B^2 \pi})^{1/3}$. These $x_B$ and $r_B$ represent the cylindrical coordinate locations of the plasma plume [4].

*Thermal Effects*

There is no analytical model for expressing thermal effects within a vacuum chamber as many of the effects that the thermal gradients have on thruster performance are second-order and not well-characterized. Further research into mapping the temperature field throughout the testing facility can enable data-driven modeling of the temperature to provide insight into the impacts of thermal effects.

## B. Impacts on Performance

Testing to prove that an electric propulsion system is flight ready proves difficult due to the impact of facility effects on the performance of the system. Each small effect may cause small variations in thrust, lifetime, or efficiency that when not considered can propagate into major differences in measured thruster performance. From the presence of residual background pressure, resultant effects of plume columnation, movement of the acceleration region, additional ingested mass flow, and cathode coupling have significant impacts on performance. The electrical configuration of the system regarding the grounding of the thruster and chamber can also alter performance. Additionally, miscellaneous factors such as the Earth's magnetic field or the thermal conditions within the facility can affect performance.

*1. Background Pressure - Acceleration Region*

A current major challenge to testing EP systems in vacuum facilities is the residual pressure that remains in even some of the best facilities. This background pressure results in the background neutrals making their way into the thruster and undergoing ionization, resulting in more generated thrust. This, in turn, moves the acceleration region within the Hall thruster[1]. This shifting the acceleration region results in the exhaust exiting the thruster with a larger divergence angle. However, while the diverging plume will lower the performance, the background pressure will also columnate the plume resulting in a plume with a lower overall divergence angle. These two effects of the shifting acceleration region paired with the columnation from the background pressure create a non-linear relationship that is difficult to model empirically. An analysis of the exhaust plumes shows that operating in space will result in an exhaust plume with a greater divergence angle than the angle measured during facility testing. Figures 1 and 2 visualize the difference in the exhaust plume profile with the ground test having a more columnated exhaust profile. This columnation of the exhaust is attributed to the lower pressure when operating in space causing the exhaust to expand when in a vacuum.

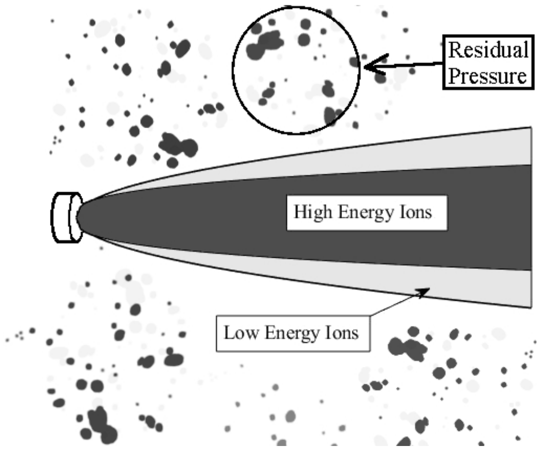


**Fig. 1 Ground test with visualization of background effect on the exhaust plume.**

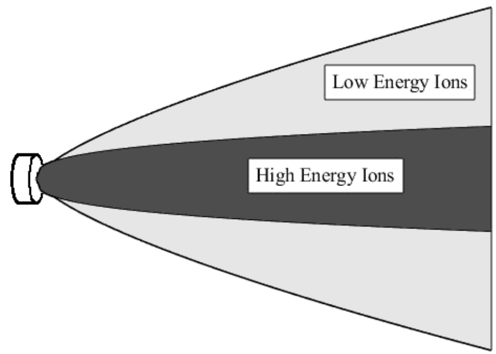


**Fig. 2 Space performance emphasizing the uncolumnated exhaust plume.**

Extensive research has been conducted and a consensus has reached that increasing the background pressure results in an exponential increase in thrust [2]. This background pressure caused by the residual neutrals in the vacuum chamber decreases the divergence angle of the plume and as a result increases the thrust generated by the thruster, even though through experimentation we have found that the acceleration region shifts down-stream.

*2. Background Pressure - Mass Flow*

Figure 3 shows real lab data as collected from two separate facilities operated by L-3 Communications Electron Technologies, Inc. (L-3) and the Aerospace Corporation (Aerospace), respectively [2]. The SPT-100 in both configurations was run off a constant discharge voltage of 300 V, constant power of 1.35 kW, constant discharge current of 4.50 A, and a magnet current of 6.0 A. Using these settings and other values for the SPT-100, it is possible to generate an analytical curve of thrust performance varying with pressures. Figure 4 demonstrates this curve using the theoretical approach outlined in the Theory section, showing thrust in mN as a function of pressure in Torr as would be expected based on theory.

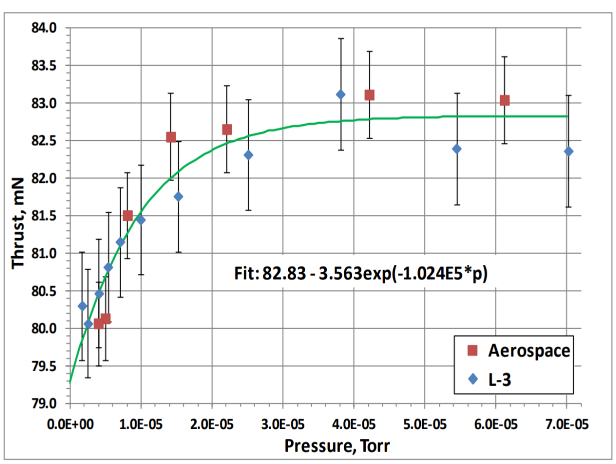


**Fig. 3 SPT-100 performance as a function of pressure shows a steady increase in thrust in the presence of background pressure [2].**

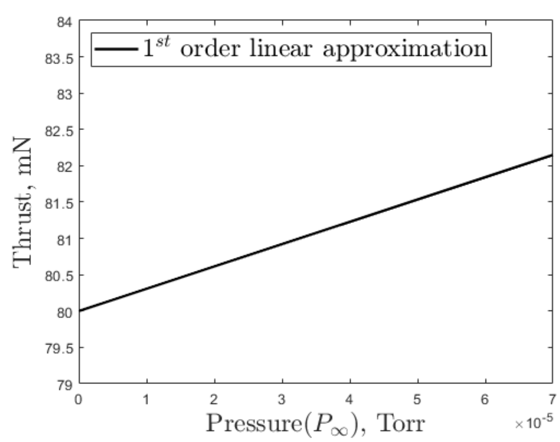


**Fig. 4 SPT-100 performance as calculated from theoretical equations relating background pressure to an increase in thrust.**

From these two figures, it is possible to directly compare the effect of background neutrals in a facility to the thrust generated from the SPT-100. The theoretical values follow a very linear trend using equations 1-3, generating a linear relationship between thrust $T$ and background pressure $P_\infty$. The actual data from Aerospace and L-3 are more logarithmic in shape. This shows that the earlier equations relating the background neutrals to an additional boost in thrust are not entirely accurate with regards to real system operation. This inherent difference in the relationship between pressure and thrust makes it impossible to develop a single extrapolation parameter to explain the difference between lab data and theory; from this data, it is possible to conclude that there are more factors than simply the background pressure contributing to additional mass flow that affects the thrust parameter. Thus, these additional effects influence the thruster performance in such a way that a single parameter cannot be used to quantify the difference.

Overall, the results from both the linear model and the SPT-100 performance results show that as pressure increases by only about 6 x $10^{-5}$ Torr, the resulting thrust increases by 2 mN or 2.5% increase. The background pressure therefore results in neutral ingestion that can overestimate the thrust performance of a hall thruster by about 1-3%, which is a significant increase.

*3. Background Pressure - Cathode Coupling*

There is significant research published looking into the effect of cathode coupling on thruster performance as a result of background pressure. From the University of Michigan, a simplified model for cathode coupling voltage versus background pressure was generated for the SPT-100 Hall thruster [5]. This study discusses the proportionality between thrust and cathode coupling voltage and how this voltage depends on background pressure. The thrust $T$ scales following the relation: $T \propto \sqrt{V_D - V_{CC}}$.

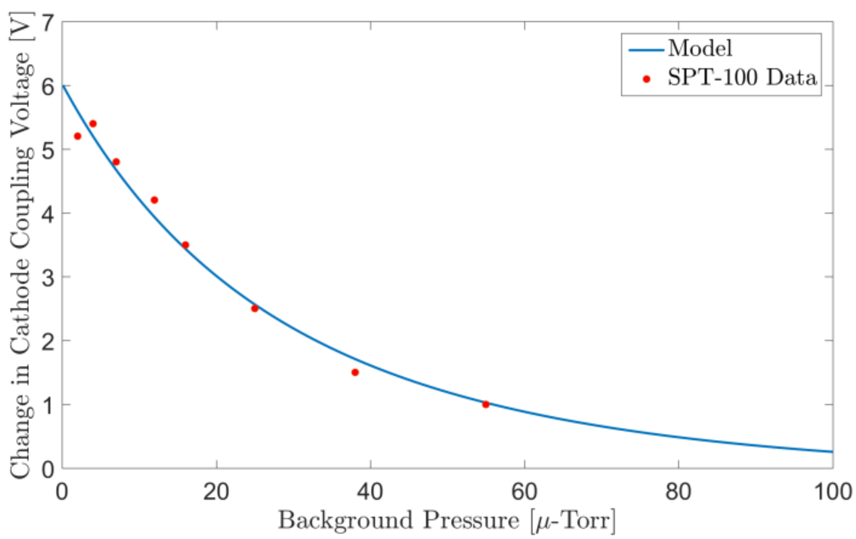


**Fig. 5 Change in cathode coupling voltage as a function of background pressure for SPT-100 Data and the simplified model [5].**

As the background pressure in the facility increases, the cathode coupling voltage decreases and the overall thrust increases. Since on-ground facilities generally have pressures in the $\mu$Torr range while the pressure in space is around $10^{-12}$ Torr, six orders of magnitude smaller, this cathode voltage can be an order of magnitude higher in space than on the ground. The simplified model comes from treating the cathode coupling voltage as a sum of the voltage drop from the cathode emitter to the cathode exit plane, $V_{int}$, and the voltage drop from the cathode exit to the thruster plume $V_{PC}$. By assuming that $V_{int}$ is insensitive to facility neutral density, it is possible to observe the effect on cathode coupling from the effect of background neutrals on $V_{PC}$.

From this simplified model, the researchers found that the plume cathode voltage is coupled with the background pressure. So, an increase in pressure results in damping of the ion-acoustic waves which then reduces the coupling voltage, therefore increasing the observed thrust [5]. For the SPT-100, this observed thrust increase can be quantified to a value of about 1% across a 100 $\mu$Torr increase assuming a discharge voltage of 300 V.

*4. Electrical Configurations*

Another proposed facility effect that alters performance is the electrical configuration of the testing facility and thruster. Multiple configurations have been tested to determine how varying the electrical connections affect the thruster's performance. The configurations are as follows; thruster grounded to vacuum ground, thruster with a floating ground, thruster grounded to cathode common.

Figures 6, 7, and 8 show the configurations that to date have been tested to determine how they influence the performance of the thrusters. This effect has only recently been identified as a concern that needs to be considered in the development and qualification of Hall effect thrusters. Generally, three primary configurations have been traditionally used throughout Hall effect thruster testing which is: 1) the thruster body and the facility share the same ground as shown in Figure 6; 2) the thruster has a "floating" ground as shown in Figure 7; and 3) where the thruster body is isolated from the facility ground and is electrically tied to the floating cathode common as shown in Figure 8 [3].

The electrical configuration is shown in Figure 6 is the most common configuration traditionally used in a majority of Hall effect thruster development and qualification tests. This configuration has shown that the electrons can travel with the ion beam or instead follow an alternate path to the thruster body and any other grounded structure in close proximity to the thruster, namely the testing facility itself. The electrons traveling through the lower resistance path of the chamber walls meet with the ions in the beam, and/or charge-exchange (CEX) ions, on the walls of the chamber or the grounded, often carbon-based beam dump.

However, Hall effect thrusters in space will have a minimal chance of interaction between the plasma plume and the spacecraft. This lower interaction of the plume with the spacecraft acts similarly to a "floating" Hall effect thruster body in a conducting vacuum chamber. This electrical environment more closely matches the expected environment seen in space where the electrons will travel with the beam ions rather than conducting through the vacuum chamber as there simply is no confining facility to conduct to when in space.

Although a seemingly minor detail, the electrical configuration has shown that it can alter the measured performance of Hall effect thrusters during on-ground tests. From the research conducted on NASA's HERMeS, Peterson et. al. found that the overall efficiency would change up to approximately 4% depending on the electrical configuration used [3]. These small but significant effects are highlighted in Table 1 and show that the electrical configuration used in testing is just one of many effects that need to be considered when adapting data from ground testing to predicting in-space performance.

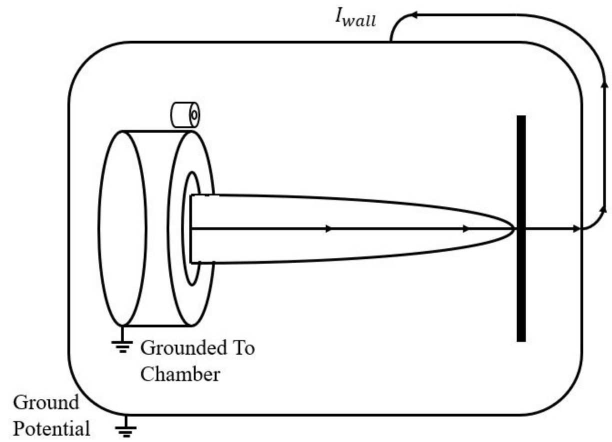


**Fig. 6 The electrical configuration where the thruster shares the same ground as the chamber.**

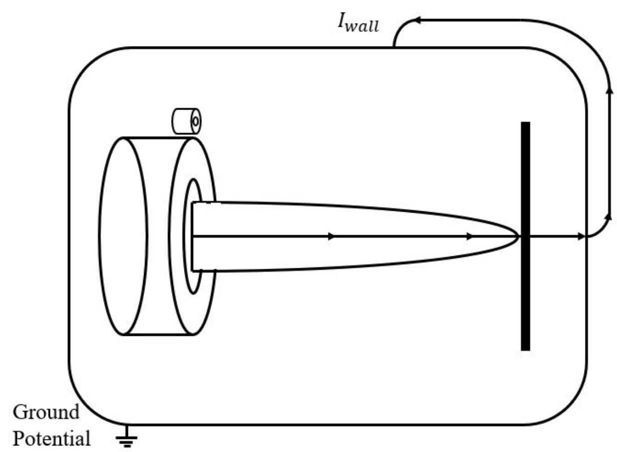


**Fig. 7 The electrical configuration where the thruster has a floating ground, where the chamber and thruster are grounded independently.**

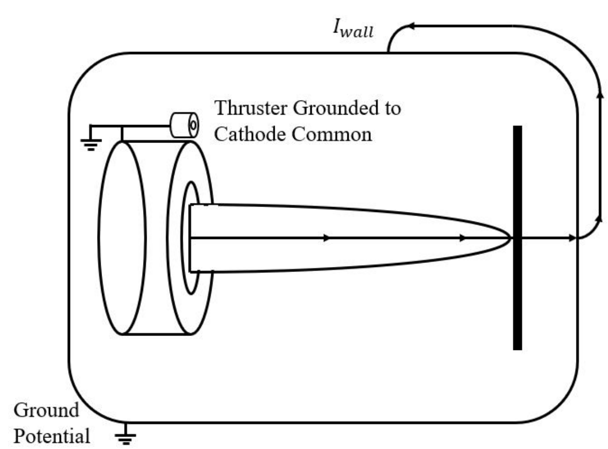


**Fig. 8 The electrical configuration where the thruster is grounded to the cathode common.**

**Table 1 NASA HERMeS Hall Effect thruster TD-1 Testing differing electrical configurations[3].**

| | Thruster Configuration | Electrical Configuration | Thrust, $mN$ | Total Efficiency | Divergence Angle |
|---|---|---|---|---|---|
| $600V$ $12.5kW$ | Graphite | Grounded | 613 | 68.2% | 19.3° |
| | | Floating | 590 | 64.5% | 19.2° |
| | | Cathode | 611 | 67.8% | 19.3° |
| | Dielectric | Grounded | 599 | 66.7% | 19.5° |
| | | Floating | 589 | 64.8% | 19.8° |
| | | Cathode | 589 | 64.6% | 19.6° |

*5. Earth's Magnetic Field*

Earth's magnetic field could also alter the performance of the thruster since some of the exiting electrons and ions can travel about the earth's magnetic field lines. However, the performance difference arising from this is small to negligible but is still an area of active research.

Under the geomagnetic field, plasma jets can become elongated along the field lines. These result in the expansion of electric thruster plumes that are significant on high orbits and less significant on lower and medium Earth orbits [4]. From the study by Korsun et. al. on Earth's Magnetic Field effects, the authors came to this conclusion on the height of the orbit affecting the plume properties. Overall, the geomagnetic field has small effects on the performance but can still affect the plume expansion depending on the orbit radius. Therefore, it is increasingly difficult to quantify this effect with a single model since the geomagnetic effect varies with orbital radius.

*6. Thermal Effects*

Another proposed area of research is the potential range of effects caused by the varying thermal conditions in a testing facility and how they do not match the conditions experienced in space. The temperature conditions vary significantly comparing the environments from Earth to space. Both environments vary in temperature but distinctly different ways. In space, the sun-facing side of the thruster absorbs the heat from the light that impinges on its surface, creating a temperature imbalance compared to the parts of the thruster that do not face the sun; however, in a facility on the ground, the ambient temperature cannot reach almost absolute zero like in space, creating an inherent difference between testing and operational environments. Furthermore, the temperature in a testing facility is not uniform as the cryogenic vacuum pumps are colder than their surrounding components and the walls themselves vary in temperature based on distance from the hot thruster plume. As referenced in Frieman's dissertation on background neutrals, there are organized background flow fields of these neutrals within each testing facility he studied [8]; these neutrals can, therefore, be affected by the uneven temperature of the different regions within the testing facility, and contribute to higher-order effects on the previously mentioned ingestion of neutrals mentioned in the Mass Flow subsection. Thermal effects can, therefore, contribute to additional complexity when looking at the neutral ingestion facility effect and have small but potentially significant contributions to how neutral ingestion leads to an overestimation of thruster performance. The effects of temperature gradients within the testing facility and their impacts on thruster performance are not yet well understood as this is an area of active research that could greatly benefit from studies conducted specifically to characterize these effects.

## VII. Discussion

Facility effects are a current area of research and there is still much left to know and understand as research continues. We found that background neutrals and electrical configurations impact the on-ground performance of thrusters the most; however, there are still more considerations that need to be researched and characterized. As the University of Michigan Associate Professor Benjamin Jorns* explained, *"We must break the paradigm and enable future deep-space missions with electric propulsion."* This paradigm can be shattered with further investigation into these facility effects that result in a comprehensive model for electric propulsion.

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However, there are certain limitations to the work discussed in this paper in terms of expanding it to include all categories of EP. Most of the literature reviewed and referenced in this paper tested and characterized Hall thrusters with little consideration for the other main forms of EP, like gridded ion thrusters (GIT) or electrothermal rockets (ER). The variance of facility effects for GITs and ERs makes it exceedingly difficult to create a single extrapolation parameter to account for facility effects for *all* forms of EP, as the three technologies all differ greatly in how the facility affects their performance. Therefore, due to the complexity of EP and the myriad effects, the facility has on thruster operation, this paper does not recommend the creation of a single extrapolation parameter used to scale between on-ground testing and in-orbit performance.

Furthermore, several of the papers utilized in this report that focus on Hall thruster technology specifically analyze the SPT-100 thruster with minimal consideration given to other thruster designs or power levels. This can lead to data that explains facility effects for specifically that one thruster or power level but may not extrapolate well to other thruster geometries or power levels. As the state of the art pushes into higher and lower power values outside of the canonical 1 kW - 12.5 kW power range, this fact may be detrimental to understanding facility effects on the newest wave of EP thrusters. At the very least, it means that additional studies will have to be conducted to verify that thruster geometry and power level do not significantly impact the measurable facility effects. Additionally, the assumptions made by each paper and the corresponding limitations to their work are not all identical across the board, making it difficult to compare results directly and combine them into one extrapolation parameter.

## VIII. Conclusion

The current inability of testing facilities to accurately and reliably model in-space performance of electric propulsion thrusters is a significant problem in the field at large; as such, considerable research has been and continues to be conducted to understand and characterize these facility effects. The largest contributors to changes in measured performance metrics determined so far are the presence of background neutrals at a pressure multiple orders of magnitude higher than what is found in space as well as variance in the overall thruster efficiency due to different electrical configurations between the thruster and facility walls allowing for different electron termination pathways. Also considered are smaller effects like the presence of the Earth's magnetic field and thermal gradients within the testing facility itself. Development of more accurate and complete models of all the facility effects that can impact thruster performance enables facility-independent, apples-to-apples comparisons between thrusters, significantly simplifying validation and qualification testing while giving mission planners greater confidence in the in-space performance of electric propulsion thrusters. At the time being, however, it is not possible to create one single extrapolation parameter that covers facility effects for all thruster kinds or even one kind of thruster between different testing facilities as the variety of facility effects present have too much complexity to be represented by a single parameter.

- **Background pressure:** On-ground facilities have a background pressure of about $10^{-5}$ Torr, whereas in-space conditions are closer to $10^{-12}$ Torr. This increased pressure on the ground can result in a more columnated exhaust plume from shifting the acceleration region, increased thrust from increased neutral ingestion, and increased thrust from decreased cathode coupling voltage. The results of combining these studies show that shifting the acceleration region can affect the overall efficiency by about 4% which results in 2% thrust performance overestimations on the ground. The increased neutrals ingestion can increase thrust performance by up to about 3% on the ground for the SPT-100 thruster. Finally, the decreased cathode coupling results show that for the SPT-100 the thrust performance can increase by about 1% from in-facility effects. Overall, the background pressure has a significant impact on efficiency and thrust performance for electric propulsion systems. It is important to account for these effects when qualifying systems for in-space flight as they could impact the overall success of a mission.
- **Electrical Configuration:** The confining walls of a testing facility present a challenge in terms of an electrical configuration of the testing setup. Depending on how the facility walls are grounded, they can potentially provide a conducting path for electrons to follow as opposed to following the plume ions. This effect causes discrepancies in overall efficiency measurements of up to 4% between different electrical configurations. In the tests done on the HERMeS, the grounded configuration led to higher total efficiency than for the floating and cathode configurations for both the graphite and dielectric thruster configurations. This shows that the choice of electrical configuration has important effects on the potential overestimation of thruster efficiency and thrust.
- **Miscellaneous Effects:** Beyond the main two considerations of background pressure and electrical configuration are multiple other facility effects that have not yet been rigorously characterized. The presence of Earth's geomagnetic field causes plasma jet elongation along field lines; this effect contributes to plume expansion of varying magnitude depending on orbit radius, meaning there currently is no single model that can account for this

effect. Additionally, thermal effects are present as the thermal environment within a testing facility inherently cannot match the conditions experienced in space. The temperature gradients present in a testing facility can have second-order effects on background neutral ingestion as well as potentially distort thrust measurements by distorting the waterfall wires on the thrust stand itself. This is another field of study under active investigation in order to characterize the small but potentially significant impacts that thermal considerations can have on thruster performance.

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