REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 18-08-2009	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE

Hall Effect Thruster Ground Testing Challenges

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

33SP0706

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZST
4 Draco Drive
Edwards AFB CA 93524-7160

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-RZ-ED-TP-2009-316

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

AFRL-RZ-ED-TP-2009-316

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (PA #09382).

13. SUPPLEMENTARY NOTES

For the American Testing Society to be held in Huntington Beach, CA from 13-15 October 2009.

14. ABSTRACT

This paper presents the challenges in the ground testing of Hall effect thrusters for plasma spacecraft propulsion applications. Hall effect thrusters by virtue of their high specific impulse can reduce spacecraft station-keeping propulsion mass by as much as an order of magnitude. However, testing and qualifying such plasma propulsion systems for use on spacecraft has a number of challenges. These challenges include the need for simulating the space environment, measuring very low thrust levels, determining lifetime, and under-standing the interaction of the energetic plume with spacecraft surfaces. Overcoming these challenges requires the use of both measurements and simulations of the complex plasma- surface interactions. It is only through the combined use of test and measurement resources that these plasma thrusters can be adequately characterized for on orbit qualification.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. William A. Hargus Jr
a. REPORT **Unclassified**	**b. ABSTRACT** **Unclassified**	**c. THIS PAGE** **Unclassified**	SAR	23	**19b. TELEPHONE NUMBER** *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Hall Effect Thruster Ground Testing Challenges

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This paper presents the challenges in the ground testing of Hall effect thrusters for plasma spacecraft propulsion applications. Hall effect thrusters by virtue of their high specific impulse can reduce spacecraft station-keeping propulsion mass by as much as an order of magnitude. However, testing and qualifying such plasma propulsion systems for use on spacecraft has a number of challenges. These challenges include the need for simulating the space environment, measuring very low thrust levels, determining lifetime, and understanding the interaction of the energetic plume with spacecraft surfaces. Overcoming these challenges requires the use of both measurements and simulations of the complex plasma-surface interactions. It is only through the combined use of test and measurement resources that these plasma thrusters can be adequately characterized for on orbit qualification.

I. Introduction

Electric propulsion in its most general sense can be defined as; *The acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces.*[1] While this definition appears relatively straight forward, the are many methods by which electricity and propellants may be combined to create propulsive devices.

Thrust levels for electric thrusters are limited. First, the available electrical power P limits the energy input available to accelerate the propellant. Second, the thrust T is inversely proportional to the I_{sp}. So for a constant propellent flow and energy conversion efficiency, the thrust is proportional to P and inversely proportional to specific impulse I_{sp}. This results in long firings in order to effect measurable changes in the vehicle's orbit. Firings of an hour or more may be required for station-keeping while orbit repositioning or raising operations may require months.

$$T \propto \frac{P}{I_{sp}} \tag{1}$$

In addition to increasing payload mass fractions, electric propulsion is capable of providing several unique capabilities. In situations where the available propellent mass is fixed, a low thrust, high I_{sp} electric thruster may be capable of repositioning a satellite in a particular circular orbit more quickly than an impulsive high thrust, low I_{sp} chemical thruster. This is possible since the spacecraft with electric propulsion will be constantly thrusting throughout the entire maneuver and will enter a more effective rephasing orbit. The use of low thrust, high I_{sp} propulsion also presents several unique orbital possibilities. Due to the efficient use of propellent mass, it is possible to place spacecraft in relatively low altitude, high drag orbits that are short lived except for continuous thrusting. Should there be sufficient electrical power, it is also possible to place spacecraft into non-Keplarian orbits.

A. Hall Thrusters

Hall effect thrusters are a form of electrostatic propulsion where the propellant is first ionized and the resulting ions are subsequently accelerated by direct application of electric body forces. Neutralization of the ion beam is provided by an external electron source, typically a hollow cathode. The resulting I_{sp} can vary from 1,000 s to greater than 3,000 s. For Hall effect thrusters, the electrical conversion efficiency

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Figure 1. Photograph of Busek Co., Inc. circular BHT-600 Hall thruster. Photograph courtesy of the Busek Company, Natick, MA.

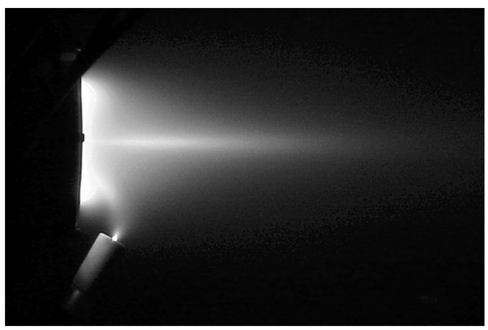

Figure 2. Photograph of Busek Co., Inc. circular BHT-600 Hall thruster in operation within a vacuum chamber at AFRL Edwards AFB, CA.

typically rises with power levels and can reach 70-80% above 5 kW, particularly at high I_{sp} (3000+ s). Low I_{sp} (<1200 s) operations are typically much less efficient since various energy losses (such that required to ionize the propellent, and the electrode potential falls) are approximately constant.

Unlike the gridded ion engine which supports its applied electric field using closely spaced grids, the Hall effect thruster, does not use grids, but rather a magnetic field to produce the electric field which accelerates the ionized propellant. A major advantage of the Hall effect thruster is that unlike gridded electrostatic thrusters, this device contains a neutral plasma and hence the thrust density is not charge limited. In order to produce significant thrust, all presently flying electrostatic thrusters use high atomic weight propellants, typically xenon (131.3 amu), but krypton (83.8 amu) has been considered for higher I_{sp} missions. Early Hall effect and ion engine testing used cesium (132.9 amu) and mercury (200.6 amu), but these efforts were abandoned due to the cost and dangers associated with ground testing. Recently Hall thrusters researchers are investigating the use of bismuth (209 amu) which offers several advantages as well as disadvantages as a propellant.[2] Figures 1 and 2 show a typical hall effect thruster and the same Hall effect thruster viewed during operation.

Comparing the I_{sp} of Hall effect thrusters to spacecraft chemical propulsion systems which vary from approximately 200 s for monopropellants such to 280-400 s for various bipropellants, it is immediately obvious that the propulsion system mass of spacecraft can be reduced significantly ($\approx 10\times$) by replacing existing chemical propulsion systems with newly developed Hall effect thrusters. Commercial spacecraft operators have recently begun to take advantage of these economics by increasing their payload mass while reducing

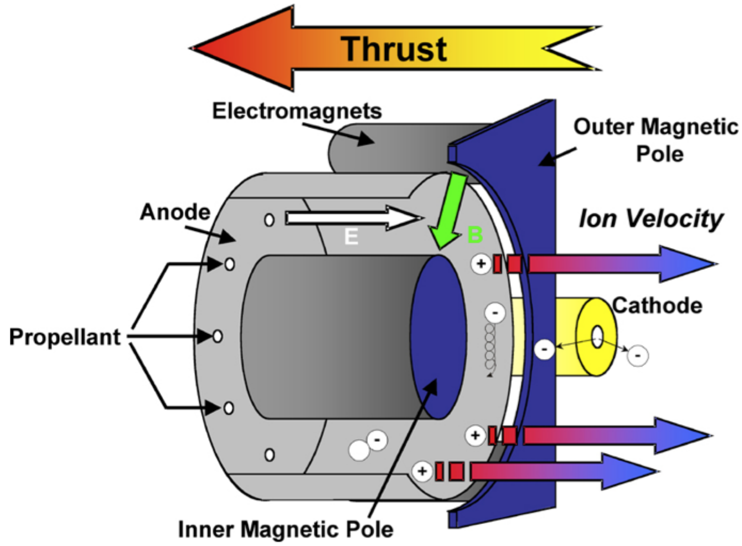

Figure 3. Diagram of basic Hall effect thruster operation with the propellant distribution, anode, cathode, two magnetic poles, and resultant ion flow direction shown.

their overhead propulsion system mass with significant economic net gain.

B. Theory of Operation

Although originated in the U.S. in the late 1960's, much of the development of Hall effect thrusters occurred in the former Soviet Union between 1970 and 1995. It was only later than the technology was transfered the Europe and the U.S., which in the intervening years have developed organic capabilities. The efforts since 1995 have concentrated on the re-qualification of these devices to western standards and the replacement of Soviet era power processing with more efficient electronics. Considerable development and measurements have occured on Hall thrusters in the past 15 years. As is the case for ion engines, most of the efforts have gone into characterizing the plume dynamics to avoid the effect of ion impact on spacecraft surfaces.

It is important to note that there are two major variants of Hall effect thrusters. The first, and much more common, is the device with insulating walls. This variant is sometimes called the *stationary plasma thruster* (SPT), or more often is simply referred to by the generic term *Hall effect thruster.* The second is the variant with an isolated conducting wall (typically graphite or molybdenum). This variant is referred to as the *thruster with anode layer* (TAL), or *anode layer thruster* (ALT). The difference between the two variants is subtile.[3] The presence of an insulator in the discharge chamber cools the electrons confined within the short circuited Hall current via high energy electron collisions with the wall producing substantial low energy secondary electron emission. This extends the electrostatic potential fall in the ion acceleration zone within the Hall effect thruster. The conducting wall in an anode layer thruster suppresses the creation of low energy secondary electrons when high energy electrons penetrate the wall sheath and strike the wall. This increases the electron temperature dramatically within the anode layer thruster and produces a very short potential fall region for ion acceleration. This very short potential fall is commonly known as the *anode layer*.[3]

Figure 3 shows a schematic of a typical Hall type thruster. Hall thrusters function by use of perpendicular electric and magnetic fields. The radial magnetic field acts to impede the flow of electrons from cathode to anode. The electrons are trapped near the exit of a coaxial acceleration channel. The crossed fields produce a net Hall electron current in the Θ direction. The trapped electrons act as a volumetric zone of ionization for neutral propellant atoms. Electrons collide with the slow moving neutrals producing ions and more electrons to both support the discharge and ionize additional neutrals. The positive ions are not signicantly affected by the magnetic field due to their larger Larmor radii, which are on the order of meters. The ions are accelerated through the electric field produced by the impedance of the magnetic field on the plasma. The resulting high speed ion beam is subsequently neutralized with an external electron source.

C. Mitigating Spacecraft Interactions

High energy ions exiting Hall effect thrusters may erode via sputtering spacecraft surfaces on which they impinge. Furthermore, the sputtered materials may be redeposited on other spacecraft surfaces. These issues, and others, such as electromagnetic interference and spacecraft charging, cause concern for spacecraft integrators who desire the advantages that Hall effect thrusters offer, but are adverse to any increased risk.

The role of ground testing is therefore vital to the mitigation of these concerns and enabling the benefits of the Hall effect thrusters to be realized by the spacecraft operator. Due to the complexities of the plasma, Hall effect thruster ground testing consists not only of measurements, but is rather a combined effort measurements integrated strongly with modeling and simulation. This combination of experimental and numerical efforts is necessary since the ground test facilities can only approximate the vacuum of space. However, the models of the plasma and plumes are themselves reliant on measurements for verification and calibration. As such, these two prongs of ground test and investigation are very closely linked in the ground testing of Hall effect thrusters.

II. Testing Strategies

Hall effect thrusters, relying as they do on low density plasmas, require large vacuum facilities for ground test operations. The critical plasma acceleration process relies on mechanisms that occur only in the free molecular flow regime. As such, ground testing is reliant on high quality vacuum systems capable of high gas through throughput. Pumping speeds of useful vacuum test facilities typically range from 25,000 L/s to several facilities in excess of 1,000,000 L/s. Typically these space simulation chambers are preferred to be to cryogenically pumped since deposits on electrodes from back streaming diffusion pump oil have been shown to interfere with thruster operation. These large, expensive test resources are limited in quantity and have encouraged the development of computational tools to aid ground testing activities. In most cases, these tools are required to predict the far plumes since chamber background pressures of 1×10^{-6} torr are insufficient to adequately simulate the space enviroment.

A. Performance

Since a Hall thruster is first and foremost a propulsive device, thrust is the most important measure of performance. Without thrust measurements, the fundamental performance of the device is unknown. Thrust measurements do not provide detailed information on the physics of thruster operation, but rather, a temporally and spatially averaged global performance parameter. From a thrust measurement, mean propellant exit velocity $\bar{v}$, specic impulse I_{sp}, and thrust efciency η may be computed.[4]

$$\bar{v} = \frac{T}{\dot{m}} \tag{2}$$

$$I_{sp} = \frac{T}{\dot{m}g} \tag{3}$$

$$\eta = \frac{2P}{T\bar{v}} \tag{4}$$

Where I_{sp} is the specic impulse, g is Earth's gravitational constant, η is the thrust efficiency, $\dot{m}$ is the propellant mass flow rate through the thruster, and P is the electrical power dissipated by the thruster. In order to provide a system η, P is the total system power including power dissipated in supporting the hollow cathode discharge and magnetic field. Although, thrust measurements only directly provide information on the efficiency of the thruster as a whole, values of I_{sp}, or $\bar{v}$, are valuable as comparisons with more advanced spatially resolved measurements.

Due to the low levels of thrust, typically ranging between 10 mN and 400 mN, a displacement type measurement of the thrust is preferred. Load cells are not used since they lack sufcient resolution. The most commonly used thrust stand design for electric thrusters is an inverted pendulum thrust stand.

Figure 4 shows a schematic of the general form of the typical inverted pendulum thrust stand used for Hall effect thruster performance measurements. The inverted pendulum thrust stand consists of two main parts. These are the lower portion which is fixed to the test facility and the upper pendulum portion upon which the thruster is mounted. These two parts are connected by several flexures, a restoring spring, and the

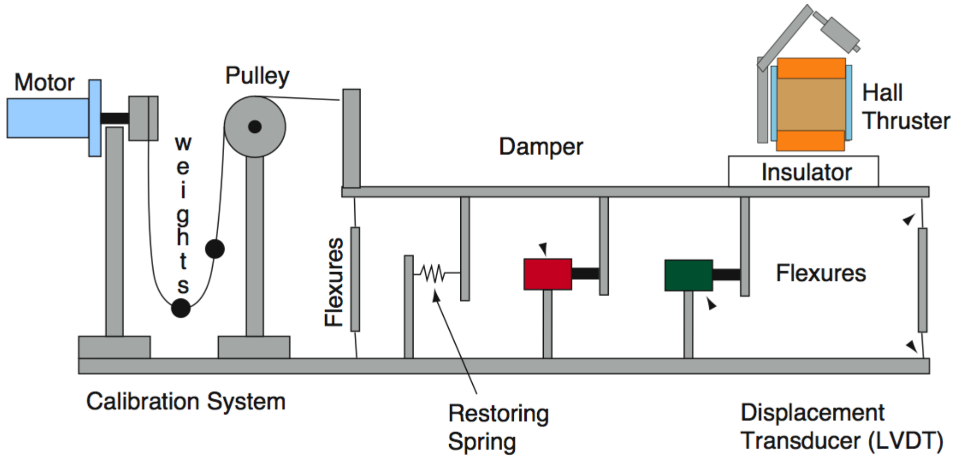

Figure 4. Diagram of the displacement style inverted pendulum thruster suitable for Hall effect thruster performance measurements. Note that the use of a LVDT as the displacement sensor is typical, but laser displacement sensors are presently being used on newer thrust stand. Furthermore, newer thrust stands use the damper coil to produce net zero displacement and thusly measure the restoring force directly.

propellant feed lines (not shown). The flexures in concert with the restoring spring and the propellant feed lines form a composite spring with an effective spring constant of K. The thruster displaces the inverted pendulum a distance x, and the thrust stand produces a restoring force $F = Kx$. Similar to a simple pendulum, gravitational force has a component along the displacement axis given by Mgx/h. Where h is the pendulum length and Mg is the gravitational force acting on the pendulum. In this case, Mg is not a restoring force, but rather a destabilizing force as shown in Eqn. 5.

$$x = \frac{T}{K - \frac{Mg}{h}} \tag{5}$$

The effective spring constant is adjusted such that the unstable condition of $K = Mg/h$ is avoided, but still provides sufcient displacement for high measurement sensitivity. If the denominator of Eqn. 5 is too small, slight variations in the force due to minor disturbances such as thrust stand tilt, or hanging cable perturbations, will have a signicant inuence on the measurements. Ultimately, the conditional stability of the inverted pendulum thrust stand provides improved measurement sensitivity.[5]

With the displacement of the inverted pendulum proportional to the thrust, it must be measured accurately, often with a linear variable differential transformer (LVDT) which measures the change of impedance associated with the relative positions of a stationary coil and an iron core. In this way, T is measured without contact between the inverted pendulum and stationary base. A similar electromagnetic damper restrains oscillations that couple into the thrust stand from the test environment. Stiction, a combination of friction and sticking of thrust stand spring components and exures, often masks small thrust variations and is overcome by using the damper circuit to induce oscillations between thrust measurements. Another technique used to improve measurement accuracy is to use the damper circuit to null the displacement x of the thrust stand. This variation is known as a null balance inverted pendulum thrust stand and uses a feed back loop using the LVDT to ensure $x = 0$. Instead of monitoring the displacement, the current to the restoring electromagnetic coil is monitored.

Calibration of the thrust stand is performed using an electric motor and pulley system. Weights are suspended from the pulley attached to the inverted pendulum. The electric motor then lowers, or raises, several weights of known mass. The response of the thrust stand for a known calibration weight yields a linear calibrated force curve.

A number of relatively complex models exist that attempt to simulate the performance of Hall effect thrusters. Due to the complexities of the thrusters and the resultant plasmas, the models have encountered difficulties in the *a priori* prediction of significant global properties. Most notably among these is the discharge current which is the sum of the recycled electron current that shorts between the anode and the cathode as well as the ion current which is the primary charge carrier between the anode and cathode.

Predictions of thrust can be performed analytically by assuming nearly complete ionization of the neutral propellant and its subsequent acceleration to potentials approximating the applied anode potential less a sheath loss of between 15-40 V. As a result, the models, as well as backs of envelopes, can predict the thrust levels, but efficiencies are nearly never predicted correctly since the fraction of recycled electrons has proven difficult to estimate.

B. Lifetime

Measuring lifetime is an important issue for Hall effect thrusters since their operational lifetime can extend to 10,000 hours, or more. This requirement is levied by Eqn. 1 which limits the thrust to a quotient of the thruster power P and the specific impulse I_{sp}. Therefore, high impulse maneuvers require extended firing periods to achieve. For example, commercial geosynchronous communication satellites presently require approximately 1 hour per day to for north-south station-keeping. More ambitious concepts for Hall thruster orbital transfer vehicles propose trip times of 60 to 90 days. As a result, moderate power (∼1-5 kW) Hall effect thrusters appear to require qualification to lifetimes approaching 10,000 hours. It is conceivable that future high power Hall effect thrusters will require qualification for significantly longer lifetimes if they are developed for routine repeated orbital transfer applications.

The life limiting process for Hall effect thrusters is the erosion of the acceleration channel by divergent accelerated ions. These ion sputtering events will eventually result in the complete erosion of the dielectric channel walls. Once the dielectric sleeve has eroded away, the magnetic circuit is exposed to the plasma. This point has generally been arbitrarily chosen to be defined as the end of thruster life. However, it has been demonstrated that the thruster can often be operated for significantly longer periods of time. The final end of life that results in thruster destruction occurs when the magnetic circuit is eroded to an extent that the electromagnet coils producing the magnetic field are interrupted. Once the magnetic field can no longer be generated, the thruster discharge is converted from an efficient momentum transfer device to a very bright glow discharge.

As it would be expected, the highest thrust efficiency η operating point is often the longest lived. This is due the efficiency being a measure of the thruster's ability to convert electrical power to useful momentum transfer as shown in Eqn. 4. Ions that impact the acceleration channel walls resulting in sputter induced erosion can not produce useful thrust.

1. Measurements

Measurements of lifetime are reasonably straight forward, but expensive propositions. The thruster is placed in a vacuum chamber and operated for the expected lifetime of several thousand hours. Erosion of the acceleration channel insulator is monitored remotely via an optical viewport to provide feed back on test progress. The most well documented of these tests is the lifetime qualification of the Russian SPT-100 Hall effect thruster (1.35 kW) which was operated for 7,500 hours at JPL to verify the manufacturers claims. Several years later, the test article was placed in a chamber again and operated for an additional 7,500 hours until the magnetic circuit was irrevocably breached.[6]

The erosion process itself appears to occur in two stages. In the first 10% of thruster lifetime, the erosion rate can be very high exceeding 10-20 μm/hr. Following this initial high erosion period, the erosion rate decreases to 1-3 μm/hr, or less. The accepted theory for the initial high erosion rate is that the ions following the norm's of the divergent magnetic fields impact the intersection dielectric walls, thus eroding them. Anecdotal references have suggested that when the outermost portions of the dielectric channel insulators are beveled, the erosion rates remain at the low rate through out the thruster lifetime, but that the bevels ultimately reduced thruster lifetime by the equivalent period of high erosion and no net benefit was realized.

Hall effect thruster life testing has a number of other special considerations. The thrusters are operated for a variety of duty cycles during the life tests. There are several reasons for this. First, it better simulates the actual operational profile of the thrusters during their missions. Second, the start up sequence is the most harsh interval on the thruster, hollow cathode, and power processing unit (if this is being tested with the thruster since often thruster life tests are operated using laboratory power supplies). The hollow cathode is the most sensitive portion of the Hall effect thruster. Its requirement for very high purity propellent to eliminate the risk of oxidation poisoning the thermionically emitting electron/neutralizer source drive the entire Hall effect propulsion system to use 99.9995% pure propellant with the oxygen and water as the two most dangerous potential sources of contamination leading to failure of the hollow cathodes and hence the thruster. Interestingly, Russian Hall effect thrusters typically fly with a spare hollow cathode, while US Hall effect thrusters fly with only one hollow cathode.

There is one final facility consideration. The surfaces on which the plume impacts also sputter following impact of approximately 300 eV ions and must be protected. Low sputter rate conductive materials are preferred to prevent charging of chamber surfaces. Typically, graphite is used since it has a low sputter yield and the redeposited materials are easily removed. Carbon-carbon sheets and woven cloth are also used to protect surfaces, but due to their high cost, these are typically reserved for special purposes. The redeposition of sputtered chamber materials also can affect thruster operation. Due to the free molecular flow regime in which these thrusters operate, it is not uncommon for materials to redeposit within the Hall effect thruster and disrupt normal thruster following extended operation. Good design of beam stops can reduce the likelihood of this occurrence, but it is not uncommon to see Hall effect thrusters eject luminous sparks, presumably of redeposited graphite, following several hundred hours of continuous operation.

2. Predictive Capabilities

Computational predictions have been attempted to determine the lifetime of various thrusters. These simulations have been frustrated by four issues. First, the internal models of the plasma conditions within the thruster are not particularly accurate. The models therefore have poor fidelity in the prediction of the likelihood of any given ion striking a wall. Second, the sputtering of dielectric materials (and molecular materials in general) are poorly understood and there are very few measurements of sputter yields for the relatively low ion energies involved. This deficiency also includes substantial uncertainties as to the minimum energy required to sputter the dielectric wall materials. Third, plasma simulations in present use are limited to two dimensions for ease of application and to minimize computational requirements. These two dimensional models appear to account for a the $E \times B$ shear that may be responsible for critical electron transport and hence determines the ion energy distributions within the Hall effect thruster. Fourth, there is little lifetime data for validation purposes.

What thruster lifetime data have been measured are usually not publicly made available due to its proprietary nature. The primary source of lifetime/erosion data is the JPL life test of the Russian SPT-100 Hall effect thruster.[6] These data have been fit by several efforts; however, at present there are no SPT-100 Hall effect thrusters undergoing active test in the US. Cheng has published the most complete end to end testing and modeling effort for two Hall effect thrusters.[7] This effort produced reasonable predictive agreement, but the models relied on empirical estimates of the $E \times B$ shear. Ultimately, the shear models are very immature and life tests of several thousand hours remain necessary.

Modeling of Hall effect thruster lifetime has been accomplished using two methods. The most common method involves using 2-D axisymmetric (r-Z) hybrid particle in a cell (hybrid-PIC) models of the plasma where the ions are modeled using representative macroparticles each representing a large number of neutrals or ions immersed in a electron fluid.[8] This modeling effort requires an *a priori* estimate of the 3-D electron cross field mobility. Measuring and understanding the 3-D electron cross field electron mobility is the major focus of Hall effect thruster basic research. With the model of the plasma within the thruster defined, the ion flux density, impact angle, and energies are recorded and averaged over a suitable number of time steps. At this point, the computational grid is remeshed using a linear estimate of the erosion of the computation domain. Smoothing or fitting may be required depending on relative erosion rates between adjacent mesh volumes. The process is repeated until the end of life criterion is met.

There are several issues associated with hybrid-PIC models of Hall effect thruster lifetime. First, the process is expensive, a single test condition might require as long as 10 hours on a single processor to converge. This can be mitigated by modifying the code to operate in parallel, but significant computational cost remains. Second, the requirement to remesh the computational to account for the life limiting erosion between runs may requires considerable user inputs. There are judgement calls required to determine the timing of the remeshing events, and the remeshing itself may produce or enhance existing numerical instabilities especially those due to unequal erosion across adjacent surfaces. Third, validation data of the interior plasma is usually limited to particular portions of the thruster lifetime, and particular point of the lifetime is unknown, although generally the data corresponds to the beginning of thruster lifetime. Finally, this technique requires significant time and artistry to produce an estimate of lifetime.

The second method used to model Hall effect thruster lifetime is a relatively new technique pioneered by the University of Michigan.[9] This method uses fluid based plasma equations such as the magneto-hydro-

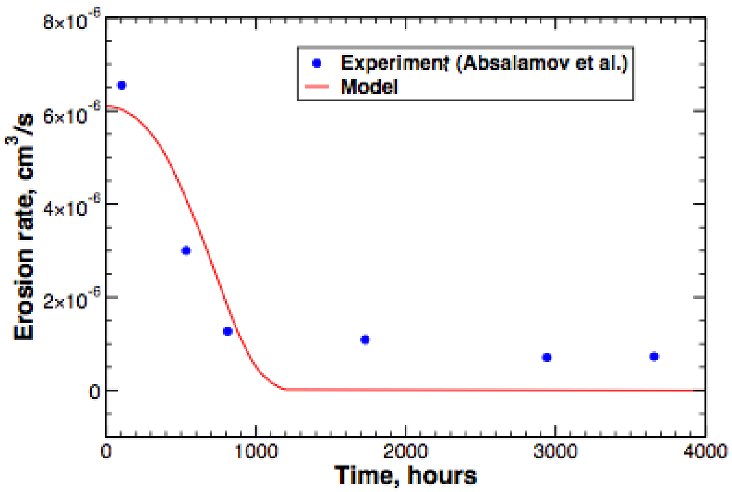

Figure 5. Results of Yim and Boyd's hydrodynamic mode of Hall effect thruster erosion compared to data from the Russian SPT-100 as measured by Absalomov et al.

dynamic (MHD) equations to model the flow. Although the flow within a Hall effect thrust is technically in the transition to or in the free molecular flow regime, Yim and Boyd discovered that the 2-D MHD equations produce reasonable approximations to the flow within the thruster. Again, accounting for the ion flux density, impact angle, and energies the erosion rates can be calculated using a suitable model of the sputter yield. The advantage of this method is that a complete erosion lifetime of a Hall effect thruster can be computed in less than 5 minutes.

The results of the fluid based models appear to resemble experimental results. The models predict with good fidelity the high initial erosion rate with the following period of reduced erosion rate as shown in Fig. 5. However, the fluid models predict that that period of near steady erosion will eventually cease. This contradicts the limited available experimental erosion data which instead shows a near constant erosion rate in the neighborhood of 1-3 μm/hr. The reasons for this discrepancy are not precisely known; however, it can be assumed that the fluid nature of the models does not account for the outlier particles of the population which likely are responsible for the erosion in this period of life.

There are several issues with the fluid continuum models of Hall effect thruster lifetime. First, the models also rely on empirical electron cross field mobility models that themselves rely on often conflicting experimental measurements. Second, the models of the ion sputter yield are the same as those used by the hybrid-PIC models with their poor understanding of minimum energy for sputtering to occur as well as poor data and models for molecular sputtering in general.

3. Future Efforts

There are several exciting possibilities for future Hall effect thruster lifetime models and their associated measurements. New improved methods of measuring erosion have been developed. These include *in situ* laser interferometry and chromatic aberration non-contact techniques which are replacing commonly used contact measurements which presently require removal of the Hall effect thruster from the test chamber for erosion measurements. Several researchers have demonstrated using emission from boron to predict the instantaneous erosion rates of the BN Hall effect thruster dielectric insulator.[10,11]

It has been informally proposed that the two previously lifetime modeling techniques could be combined to maximize predicative capability while minimizing computational resources. This combination of capabilities would play to the strengths of both numerical techniques, but has yet to be implemented.

Another proposal is to combine numerical and experimental techniques. It may be possible to use one of the aforementioned models to predict sputter erosion at a particular lifetime and then subsequently operate the thruster to verify the model prediction fidelity. The thruster insulator may then be machined to the predicted profile and the process repeated. This would allow for the *boot-strapping* of accelerated lifetime

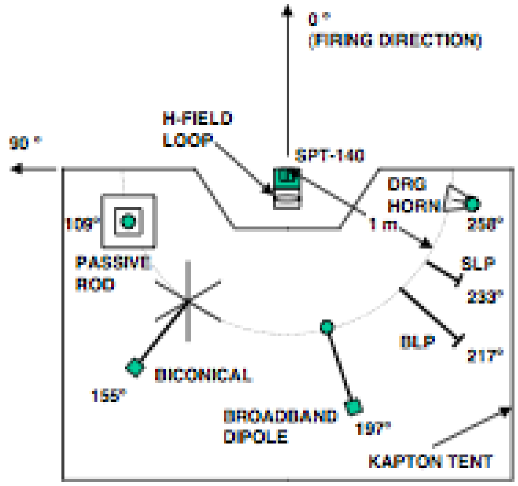

Figure 6. NASA GRC EMI test setup and need a reference.

tests of Hall effect thrusters using a hybrid of self consistent modeling, extrapolated short term erosion predictions, and limited validation periods.

Of course, ultimately the goal is predictive capability of Hall effect thrust lifetime. Unfortunately this does not exist yet due to limits of the models and as well as limited availability of experimental data for validation. As such, this remains one of most active regions of Hall effect thruster research.

C. ElectroMagnetic Interference

One concern for spacecraft integrators is the effects of electromagnetic interference (EMI) from the Hall effect thruster discharge on the host spacecraft. Hall effect thruster EMI is routinely examined using a wide variety of passive receiving antennae within a suitable vacuum chamber. Typically radiated EMI emissions are compared to those specified within MIL-STD-462 with modifications specific to spacecraft operations.[12]

As an example, EMI emissions test apparatus used for testiing the 5 kW SPT-140 Hall effect thruster at NASA Glenn Research Center[13] are shown in Fig. 6. In this apparatus, a portable EMI test pallet[12] was positioned near the middle of 10 m diameter vacuum chamber. It served as a base upon which supports for the thruster and measurement antennas were fixed, as shown in Fig. 6.

In this particular case, E-field sensing antennas were arrayed in a 1 m radius semicircle behind the thruster exit plane. Each antenna was mounted using fiberglass supports to minimize scattering. A Kapton tent was erected to enclose the array but exclude the thruster, so that plasma environment effects on the antenna properties were mitigated. A 14 cm diameter loop antenna for the H-field emission measurement was fixed coaxial to the thruster centerline 7 cm behind the back face of the thruster. Residing outside the main Kapton tent, the H-field loop was enclosed by a separate Kapton envelope to likewise prevent plasma impingement.

All thruster power supplies were located outside the vacuum chamber and fed through via twisted pair, shielded cables. Antennas were connected via low-loss coaxial cable to EMI receiving equipment located immediately outside the tank feedthrough. Wide frequency ranges were assembled from a composite of many individual sweeps covering smaller frequency spans. To provide background emission references, full E-field (MIL-STD-461C, RE02) and H-field (MIL-STD-461D, RE101) sweeps were performed at vacuum with the Hall effect thruster in an unpowered off state.

Alternatively, mid-sized vacuum chambers or sub-chambers on larger facilities have been constructed from a suitable dielectric, most usually fiberglass. The advantage of such a configuration is that the antennae can then be placed in ambient laboratory conditions so long as the background EMI is mitigated. Chambers of this type are in use, but the size of such vacuum facilities is limited as is their availability. As such, larger metallic tanks with the EMI test apparatus co-located within the vacuum facility are likely to continue to be the norm.

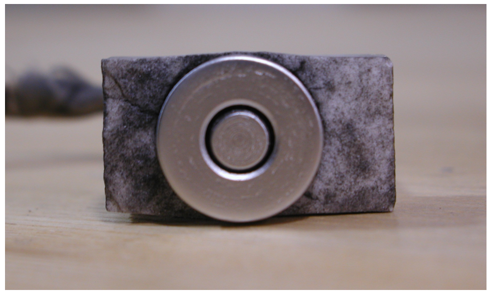

Figure 7. Photograph of a typical guarded Faraday probe used to measure ion flux at a set radial distance from a Hall thruster.

D. Common Plume Measurements

Plume measurements are vital for qualification of Hall effect thrusters since high energy ions emitted by the devices are capable of damaging sensitive spacecraft surfaces. The damage may consist of erosion due to sputtering, redeposition of previously sputtered materials, and/or arcing due to the presence of a free charges from the ionized plume. Fortunately, this is one research area where the models are reasonably accurate so long as the source simulation is itself accurate. This can can be a problem as previously noted. However, even the existing Hall effect source models do produce reasonably accurate plume propagations.[14]

The models have to take into account the effects of the vacuum chambers and their relatively high background pressures. As such it appears that the simulations must not only model the effects of the Hall effect thruster on a spacecraft in orbit, but the same simulations must be made of the ground test facility in order to fully understand the measurements. Ultimately, it appears that some measurements in orbit are required to fully validate placement of a Hall effect thruster on a spacecraft.

The issues that remain to be resolved in are the evolution of high angle plume, including back flow. This back flow is due to two similar mechanisms. First, elastic scattering of plume ions can cause a small number of the colliding ions to scatter at highly oblique angles. The second mechanism is charge exchange which is the tunneling exchange of an electron (or exchange of identity) between an ion and a neutral. This produces a high energy neutral and low energy ion which can be greatly affected by the fringing magnetic and electric fields in the near plume. Understanding these processes and their likelihood remains a large driver of Hall effect thruster plume testing.

1. Faraday Probes

Plume ion current flux (A/m^2, or A/m^2/Str) may be measured using a Faraday probe. Figure 7 shows a probe typically used in experimental measurements of plume ion flux. The electrodes are constructed from molybdenum, or another low sputter yield material. Ion current is collected by negatively biasing the collection surfaces into the ion saturation regime of the I-V characteristic (typically 20 to 30 V below the chamber ground) of both the inner disk and outer guard ring. The current collected on the inner ring is due to ion impact and accommodation is equal to the ion net charge flux to the surface. Since the majority of the ions (85-90%) are singly charged, the current flux follows closely the actually ion flux. The fraction of multiply charged ions (xenon ions with charge of +5 have be identified in the plume) does add complexity to the analysis of the data from a Faraday probe, but a recent effort has shown that this can be used to better understand the thruster efficiency.[15] The effects of secondary electron emission due to ion impact can be neglected for xenon since the ion energies (typically 300 V, or less) are sufficiently low to result in uncertainties of less than a few percent. For lighter propellant gases such as krypton, this assumption may require further investigation. Figure 8 shows a results of a series of ion flux scans for a Hall effect thruster.[14]

2. Double Langmuir Probe

A double Langmuir probe may be used measure plasma density. A double probe consists of two electrodes that float with respect to the plasma. Voltage is swept between the two electrodes while current collected by the electrodes is measured. Because the mean probe potential must remain at plasma floating potential, an equal amount electron and ion current is collected by the electrodes. The main advantage of a double probe

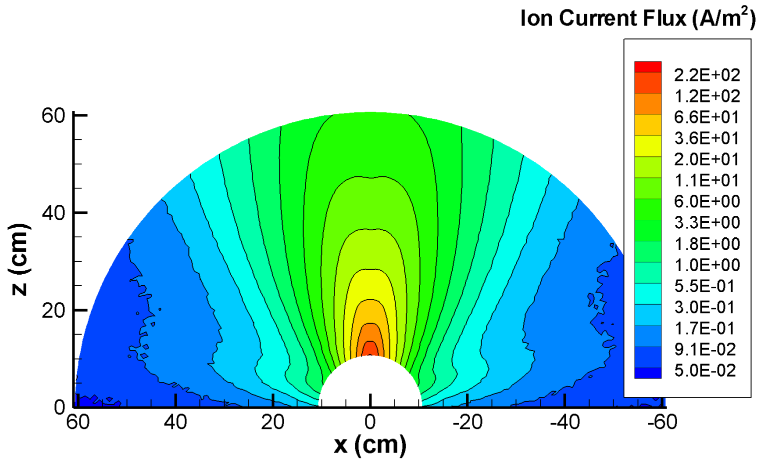

Figure 8. A two dimensional sweep of a Faraday probe to measure ion flux for a low power Hall effect thruster.

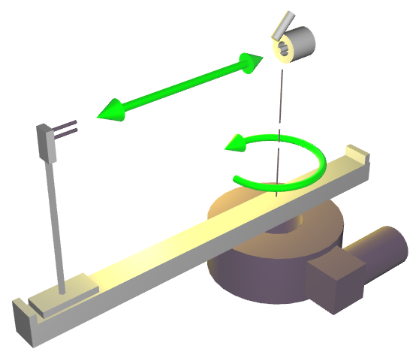

Figure 9. A schematic of a double probe mounted on a two dimensional sweep translation system similar to that that used to measure the ion flux data in Fig. 8.

is that it never draws a current from the plasma that exceeds the ion-saturation current, thus preventing excessive probe heating, or excessive current draw from the plasma.[16] Figure 9 shows a schematic of a double probe used to probe a Hall effect thruster plume.

Analysis of the double probe current-voltage characteristic relationship provides measurements of electron temperature T_e, plasma density n_e, and Debye length λ_d. The electrodes are generally constructed of tungsten or another suitable low sputter yield conductor. The probe must be sized so that plasma sheath thickness is small compared to the diameter of the probe and planar sheath theory can be applied.

The current-voltage $(I - V)$ characteristic trace for a double probe is analyzed to find ion saturation current and electron temperature. The analytical characteristic trace for electrodes with equal areas can be described as[17]

$$I = I_i \tanh\left(\frac{V}{2T_e}\right) \tag{6}$$

where I is current, I_i is ion saturation current, and V is the applied probe potential. In practice however, the $I - V$ trace exhibits the effects of sheath expansion and plasma non-uniformities. Therefore the experimental data is generally fit to a function similar to that below which captures the linear growth of the sheath with applied probe potential.[14]

$$I = I_i \tanh\left(\frac{V + V_0}{2T_e}\right) + A1\,(V + V_0) + A2 \tag{7}$$

where V_0 is a fit parameter to account for probe potential offsets, $A1$ is a coefficient that accounts for sheath

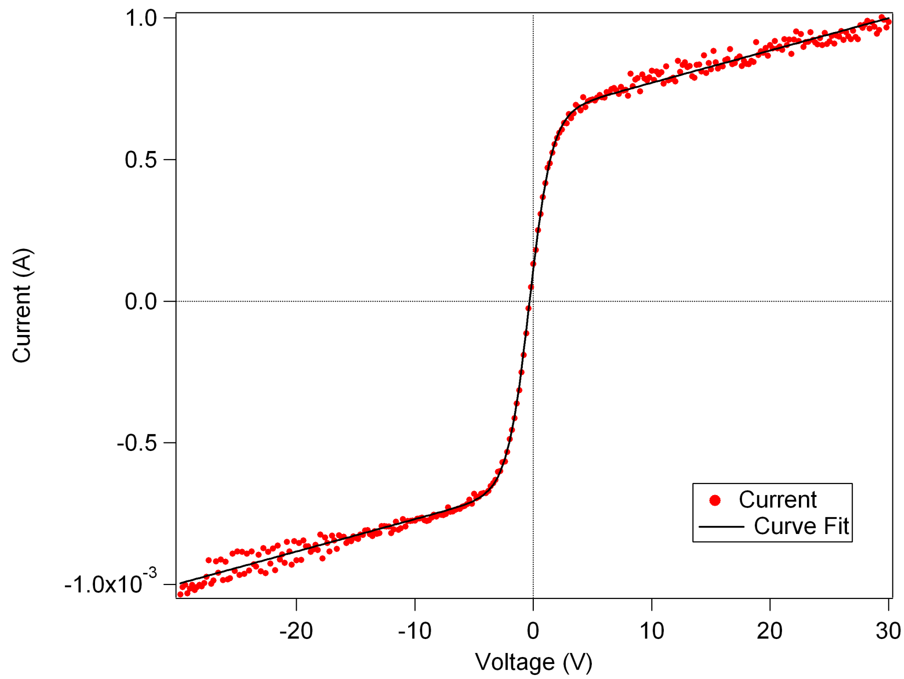

Figure 10. A typical current vs. voltage trace from the double probe. The experimental data is shown in red dots. The data was fitted with Eqn. 7. The curve fit is shown by the black line.

expansion, and coefficient $A2$ accounts for plasma non-uniformities. A typical sample of double probe data[14] is shown in Fig. 10.

Analysis of the double probe data is a multi-step procedure. First, a function of the form of Eqn. 7 is fit to the data using a curve fitting routine. The functional fit provides values for I_{sat} and T_e. Next plasma density is calculated from the Bohm velocity approximation.

$$n_e = \frac{I_i}{Ae}\sqrt{\frac{m_i}{kT_e}} \tag{8}$$

Where n_e is the plasma density, A is the collection area of the electrode, e is the elementary charge, m_i is the ion mass, and k is the Boltzmann constant. In this initial calculation, the probe surface area is considered to be the collection area of the electrode. However, the actual collection area of the electrode depends on the sheath thickness. An iterative method must be then be used to solve for both sheath thickness and plasma density.[18]

3. Retarding Potential Analyzers

The retarding potential analyzer (RPA) is a simple energy filtered Faraday probe. The energy filtering is accomplished using a series of biased grids in front of the current collector. The total current collected for a single species is as follows.[16]

$$\Gamma(\Phi_0) = \int_0^\infty f(\phi)\phi \, \mathrm{d}\phi \tag{9}$$

Which can be rewritten.

$$\Gamma(\Phi_0) = \int_{-\infty}^{\Phi_\infty} f_\infty(\phi_\infty)\phi_\infty \, \mathrm{d}\phi_\infty \tag{10}$$

Where Φ_∞ is the critical applied potential given by the following.

$$v_\infty = -\sqrt{|2qeV_0/m|} \tag{11}$$

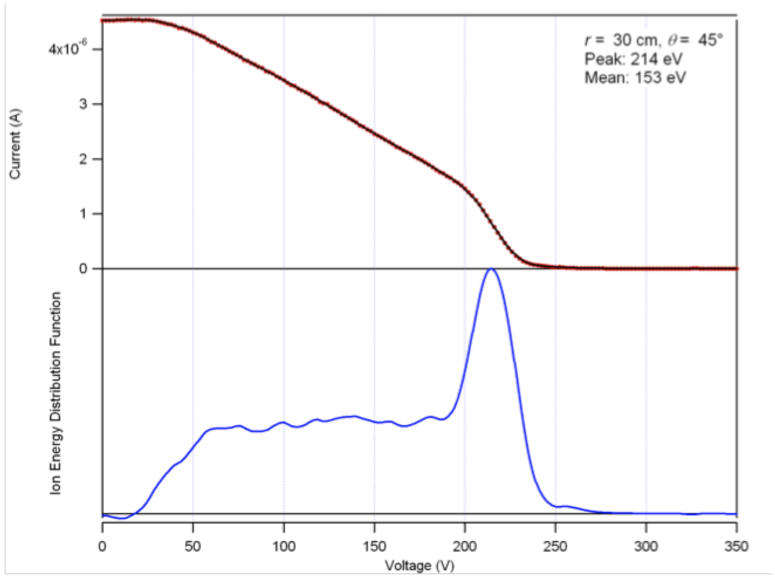

Figure 11. Retarding potential analyzer raw trace and ion energy distribution following differentiation.

Upon differentiation, Eqn. 11 demonstrates the following.

$$\frac{d\Gamma(\Phi_0)}{dV_0} = \sqrt{\frac{2qe}{m}} \frac{1}{2|V_0|^{1/2}} f_\infty(\phi_\infty)\phi_\infty = \frac{qe}{m} f_\infty(\phi_\infty) \tag{12}$$

The RPA filters ions based on energy to charge ratio only allowing the ions with energy greater than v_∞ to pass through to the collector. The trace of the energy passed through to the collector can be used to generate an ion energy distribution f_∞ via Eqn. 12.

A typical RPA used to interrogate the plume ion energy distribution of a Hall effect thruster consists of three grids separated by insulators. The first grid acts as an aperture and is allowed to float at the local plasma floating potential. The second grid, biased negatively (e.g. -30 V), repels incoming electrons within the plasma while allowing ions to pass through. The final grid is swept from zero to high positive potentials and retards ions based on their incipient energy. On occasion, a fourth grid is placed in front of the collector to suppress ion impact induced secondary electron emission. Since the ions in Hall effect thruster plumes are usually below a 1 keV in energy, the inclusion of this grid is often omitted.

The RPA is able to approximately determine the energy distribution function f_∞ with the caveat that it is actually measuring the energy per charge (E/q) distribution. Some ambiguity is created by the presence of multiply-charged ions. Those created within the thruster will be indistinguishable from singly-charged ions since they will have passed through the same potential drop as the majority of the singly-charged ions and will consequently have the same E/q ratio. Ions created outside the main discharge whether by charge exchange or electron bombardment will have energies that may be different than ions created within the thruster. Identification and complete characterization of these non-standard ion populations is challenging and generally requires use of additional diagnostics to remove measurement ambiguities.

Figure 11 shows a raw current trace from a RPA sweep as well as the differentiated ion energy distribution for a low power Hall effect thruster. This trace near the thruster exit shows a high fraction of low energy ions with a peak distribution at a potential of approximately 214 eV. The value to the spacecraft integrator is that the energies of the potentially damaging ions can be measured and their flux quantified. In fact, should the transperancy of the grids be known with sufficient accuracy, it is possible to use the fully integrated current of the RPA signal (i.e. $\Phi = 0$) to replace the functionality of the Faraday probe.

4. E×B Probles

The Lorentz equation in Eqn. 13 illustrates the deflecting force $\vec{F}$ acting on a charged particle with charge qe moving at velocity $\vec{u}$ within electric field $\vec{E}$ and magnetic field $\vec{B}$. If a passage for transiting charged particles

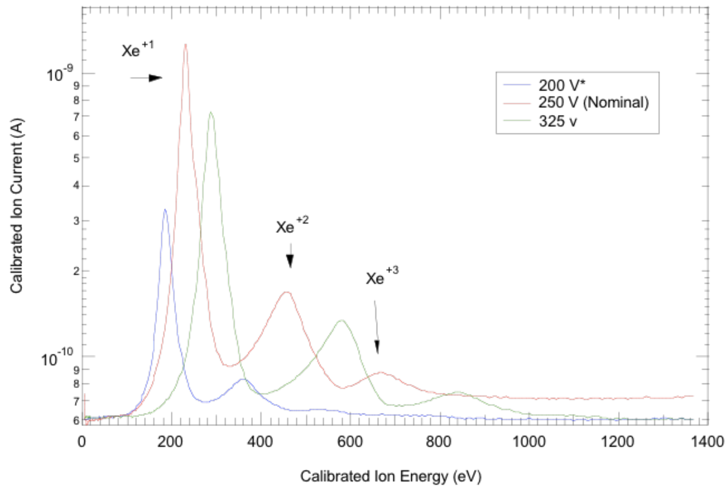

Figure 12. E×B probe data for a low power Hall effect thruster operated at 200, 250, and 300 V discharges showing the relative signals of Xe^{+}, Xe^{2+}, and Xe^{3+}.

is constructed with orthogonal electric and magnetic fields as well as suitable geometrical apertures, only a particular velocity class $u + \delta u$ where $\vec{F} = 0$ will be able to transit through the resulting sensor. Sensors of this type which use the Lorentz force thusly to separate ions according to their velocity class are also known as a Wein filters, and can be traced to some of Maxwell's original research on proton mass and charge.[19,20]

$$\vec{F} = qe(\vec{E} + \vec{u} \times \vec{B}) \tag{13}$$

Typically the instruments have fixed magnetic fields of several tenths of Tesla produced using permanent magnets. The electric field required is produced using up to several thousand volts on parallel plate conductors which can be scanned to vary the transmitted velocity increment. Once the ions pass through the velocity selection process, they are collected on a grounded conductor and the low level current is measured with a suitable instrument such as a current amplifier.

By scanning the electric field, it is possible to generate the velocity profile of the ion stream at a particular plume location; however, the accuracy of the calculated ion velocities and derived ion energies is limited by the accuracy of the alignment of the probe fields and geometrical collimation.

For Hall effect thruster testing, the primary use of the $E \times B$ probe is in the identification of various ionic charge states created within the thruster. Since Hall effect thrusters use a single atomic species as their propellant, the mass and identity of the ions collected is unambiguous. Therefore, the energy of the ions can be calculated by squaring $\vec{u}$ in Eqn. 13 and the $E \times B$ probe is able to distinguish between the various ionic charge states (e.g. Xe^{+}, Xe^{2+}, etc.) so long as they are created in the same region and pass through the same potential fall. For example those ions created within the Hall thruster where the various ions are all accelerated to the same energy, Vq. However, ions created, or which have modified their charge state in the plume, are more difficult to unambiguously identify. Figure 12 shows sample data traces of three accelerating potentials and the resulting distinct populations of singly, doubly, and triply charged ions.

From the resulting velocity distribution functions such as that shown in Fig. 12, it is possible to calculate the species fractions of the various ion charge states by solving the following equation.[20]

$$\Omega_i = \frac{q^{3/2}(1+\gamma_i)\zeta_i}{\sum_i q^{3/2}(1+\gamma_i)\zeta_i} \tag{14}$$

Where the relative peak height I_i of the i_{th} charge state is defined as follows.

$$\sum_i \Omega_i = \frac{I_i}{\sum_i I_i} \tag{15}$$

From conservation, the total species fractions ζ_i must sum to unity.

$$\sum_i \zeta_i = 0 \tag{16}$$

Where γ_i is the secondary electron emission coefficient for ion impact which can be neglected for lower energies, but should be accounted for ions with energies above several hundred electron volts (eV). The analysis in Eqns. 14, 15, and 16 assumes that the ion component distributions are broaden uniformly in velocity space. If this is not the case, a more substantiative analysis of the areas under each peak must be undertaken to determine the relative ion charge state fractions.

5. *Chamber Effects*

One of the most significant challenges in ground testing electric propulsion devices is characterizing the effects of background chamber pressure on measured plasma properties. Alteration of the plume due to ion collisions with background gas and thruster ingestion of these neutrals hinders efforts to compare ground test data to numerical simulations and finally to predict flight characteristics of the thruster.

Background gas ingested by the thruster affects thruster performance, plume properties, and thruster lifetime. Randolph, et al.,[21] performed the most comprehenisive study on the relationship between these thruster characteristics and background pressure for the Russian SPT-100 Hall effect thruster. Notably, he found that a background pressure of less than 1.3×10^{-5} torr was necessary for accurate charge flux measurements taken within 1.2 m of the thruster due to diffusion of the beam from charge exchange collisions. He also observed that when the background pressure reached a certain threshold (between 3×10^{-5} and 8×10^{-5} torr), the discharge current oscillations became large in amplitude, causing a significant decrease in thruster performance. Randolph attributed these discharge current oscillations to plasma potential instabilities in the near-cathode region or ionization instabilities from increased neutral density in the discharge channel.

Various other experiments have documented facility effects on Hall thruster. Walker, et al.,[22] used electrostatic probes 1 m downstream to study background pressure effects on the plume. Hofer, et al.,[23] examined performance using a thrust stand for various background pressures. However, no experimental data exist concerning background pressure effects on the internal ion acceleration of a Hall thruster.

Background vacuum quality can also affect the operation of the Hall effect thruster itself. Non-intrusive measurements of the internal ion velocity distributions taken using laser induced fluorescence have been recently performed,[24,25] and showed that increasing background pressure shifted the ion acceleration region upstream and led to broadening of the ion velocity and energy distributions particularly at locations inside the acceleration channel. In addition, increased background pressure led to increased discharge oscillations. This is likely an enhancement of the thruster naturally occuring breathing mode which produces a dithering of the local plasma potential and thus affects the local instantaneous ion velocities. Increasing the background pressure seems to increase the magnitude of this oscillation within the thruster. The magnification of the thruster oscillations moves the time averaged peak electric field downstream. It is not yet known what the trade-off is with respect to lifetime between moving the peak electric field downstream and producing higher energy ions deep within the acceleration channel due to the oscillations in the local plasma potential, but there are reasons to belive that lifetime is detrimentally affected by the introduction of high energy ions deep within the Hall effect thruster.

Background pressure effects on thruster operation appear to be a complex issue and are not simply an addition to the discharge current due to ingestion. The effect of background pressure changes the acceleration profile and the oscillatory behavior of the thruster. This has serious implications for the understanding of ground based testing of Hall thrusters. Randolph, et al.,[21] proposed background pressure criteria for far-field ion flux and performance measurements. Recent measurements suggest that background pressure criteria should also be established for internal and near-field plasma measurements of Hall effect thrusters. However, the required background pressure for adequately minimizing chamber effects within the Hall effect thruster is still unknown and remains an active research area.

E. Exotic Measurements

There are a large number of Hall effect thruster measurements that are less routinely taken that those discussed above. These include laser, interferometric, and emission spectroscopy. These measurements typically require considerable expertise and are only maintained in a few laboratories around the world. For example, laser induced fluorescence of ion velocities is only known to be available at four locations.

Nonetheless, these techniques represent an outgrowth of real needs primaily driven by the requirement for accurate validation of numerical models the Hall effect thruster plasma. The needs of model and simulation verification has driven ground test diagnostics to examine ever more minute charaacteristics of the Hall effect thruster plasma discharge and its plume.

1. Laser Induced Fluorescence

Laser induced fluorescence is a convenient diagnostic for the investigation of ionic and atomic velocities as it does not perturb the plasma as do other common diagnostic techniques, most notably electrostatic probes. Manzella was the first to use the the $5d[4]_{7/2} - 6p[3]_{5/2}$ xenon ion transition at 834.72 nm to make velocity measurements in a Hall thruster plume and it has been extensively developed since.[26–28] While the diagnostic techniques is not routine, there are at least four active laboratories capable of performing these measurements on xenon Hall effect thrusters.

Laser induced flourescence (LIF) functions by using a laser to excite an accessible optical transition in a species of interest (in this case xenon ions). The fluorescence of the excited state is collected as the laser is scanned across the optical transition. The local velocity is then determined by the spatially resolved measurement of the Doppler shift of the absorbing ions.[29]

LIF studies of Hall effect thrusters have been able to quantify the near field (between the exit and cathode planes) ion acceleration. It is interesting to note that approximately a third the energy deposition on the ionized xenon propellant occurs outside the Hall effect thruster body. Thereby reinforcing the concerns with chamber effects as previously noted. Not only is LIF able to measure axial velocities (on the order of 12 to 18 km/s), but LIF is also able to measure the near plume radial velocities to provide an indication of the effect of near field magnetic and induced electric fields on the propellant acceleration. Uniquely, LIF is able to measure the azimuthal ion velocity of a Hall thruster (on the order of 500 m/s) due to either collisions with Hall current trapped electrons, or partial magnetization of the ion flow.

An important issue is that the concept of a single velocity, or even several distinct ion velocities in the plume of a Hall effect thruster, is entirely inadequate, particularly in regions where significant interactions between various velocity populations occur. Although the concept of a single ion velocity remains useful for the presentation and interpretation of LIF data, it is also possible to view the resulting fluorescence line shapes as an indication of the velocity distribution.[30] A more accurate analysis of the true plume ion dynamics would be to extract velocity distribution functions from fluorescence traces. This would provide valuable data for comparison with various existing Hall thruster device models and simulations. Signal processing techniques have been developed to deconvolve the transition lineshape out of the LIF signal and produce a fair approximate measure of the ion velocity distribution function. The ion velocity distribution function is a vital verification tool since it allows the modelers and experimentalists to compare results precisely without the approximations inherent in probe based techniques that require fuzzy concepts such as temperature, or equilibrium, in this dynamic and spatially challenging plasma source.

In order to fully characterize a Hall effect thruster plasma acceleration using LIF, the interior of the plasma source must be characterized. This has been been demonstrated to be relatively simple by a slight modification of the typical scheme for the collection optics whereby the fluorescence is collected at angles other than 90°. Figure 13 shows an LIF apparatus developed that can measure ion, or neutral, xenon velocities within a Hall effect thruster. This additional functionality is make possible by the 60° angle between the probe beam and collection optics rather than using the 90° orientation that had been typical until this development.[31]

2. Interferometry

Microwave interferometry provides a method for measuring electron density that is both nonintrusive and easily interpreted. No part of the interferometer is required to be present in the plume. As such, direct effects on the plasma are avoided. Furthermore, the interferometer can easily measure time resolved electron densities. These advantages are offset to some degree by the complication that the interferometer can only directly measure the line averaged electron density across the test leg. Mathematical techniques such as *onion peeling* and Abel inversions can be used to produce spatially resolved data from a number of measurements across the plume, especially for cylindrically symmetric flows.

Interferometry provides a non-intrusive alternative to electrostatic probes when measuring plasma density. Interferometry for Hall effect thrusters functions by monotoring the transmission of electromagnetic radiation

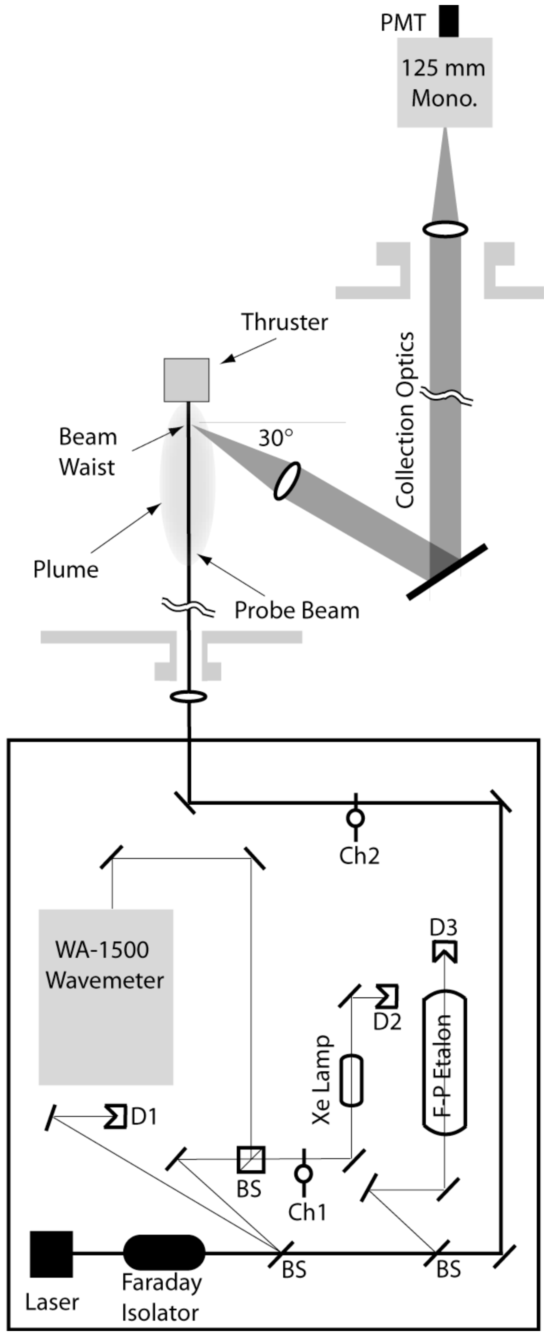

Figure 13. Laser induced fluorescence apparatus that can be used to probe within the thruster acceleration channels to measure ion and neutral velocities of xenon.

through a Hall effect thruster plasma plume. The phase shift $\Delta\phi$ of the EM radiation of wavelength λ_0 due to the plasma can be measured reasonably accurately and from this the plasma density n_e of the plasma may be calculated.

$$\bar{n_e}l = \frac{4\pi m_e \epsilon_0 c^2}{e^2 \lambda_0}\Delta\phi \tag{17}$$

Where $\bar{n_e}l$ is the path length plasma density averaged over path length l, m_e is the electron mass, c is the speed of light, e is the elementary charge, and ϵ_0 is the permittivity of free space. One immediate issue is that the measured quantity $\bar{n_e}l$ requires either multiple measurements to extract a spatially resolved plasma density n_e for data inversion techniques, or it requires the assumption of plasma density uniformity. Both add complexity to the interpretation of interferometric data. In addition, the resolution of the instrument is limited by the ability to discern the phase shift $\Delta\phi$ and have it remain unambiguous (e.g. less that one wavelength). This has the practical limitation requiring visible wavelengths for very high density arc discharges, and microwave frequencies (e.g. 30-90 GHz) for more diffuse plasmas. The quandary that this produces is that the spatial resolution of the measurements is based on the focus of the apparatus which is fundamentally limited by Gaussian beam optics to approximately 3-10λ_0. For small Hall thruster plumes, this can cause difficulties registering the extent of the measurement volume.

One significant issue with this measurement technique is that the actual measurement is a path length averaged plasma density. As such, there is often a requirement for multiple measurements in order to deconvolve spatially resolved plasma measurements. Alternatively, if one is willing to accept the path length as the sample volume, it is possible to measure time resolved fluctuations in the plasma density into the MHz time scales without much difficultly.

3. Emission Spectroscopy

Emission spectroscopy has been used with some success in the diagnosis of Hall effect plasmas for various plasma temperatures.[32] However, there are several issues that preclude direct implementation of the technique as used for denser plasmas. Most fundamentally, the Hall effect thruster plume is in a high state of thermodynamic disequilibrium due to the low low heavy particle densities (peaking at number densities of 10^{18} m^{-1}) and the rapid acceleration of the ions upon ionization (300 m/s to 20 km/s within 5-10 mm). As such, the ions and neutrals do not have clearly defined temperatures and there is little quantitative result in searching for such. Density measurements suffer from similar difficulties. Plasma density measurements based on Stark broadening are stymied by the high mass of the atomic propellant which masks the electron impact broadening.

More advanced techniques can be used to to construct species dependent collisional radiative models to determine the electron temperature from either the neutral or ionic spectra. This is possible since the electrons due to their small mass and higher energies (as high as 30 eV, or 330,000 K) are able to equilibrate among themselves. Karabadzhak, et al,[33,34] have developed one such model examining the relationships between 9 different xenon neutral transitions. However, usage of this technique has proven to be to somewhat difficult due to experimental complexities and model limitations.[35]

Perhaps the most common use of emission spectroscopy for Hall effect thrusters is the realtime measurement of emission of trace materials produced by life limiting erosion of the dielectric insulator. The complexity of these measurements vary from relative emission measurements of boron emission to measurements of boron emission combined with collisional radiative models of xenon to account for changes in the electron temperature which affect the emission of the newly freed boron atoms.[10,11] Figure 14 shows vacuum ultraviolet emission of atomic boron from a Hall effect thruster for a sequential set of discharge potentials starting with a glow discharge and terminating with a discharge potential of 350 V. The step increase correspondences between the discharge potential and the boron emission shows that this diagnostic has the potential to monitor erosion and hence life limiting processes in real time.[11]

4. Thermography

Thermography with commercial cameras has a been reported on various Hall effect thrusters by research groups in both the US and France.[36–38] These measurements typically use mid or far infrared commercially available cameras. The primary experimental difficulties center on the acquisition of suitable (diameter and spectral passthrough) vacuum view ports. Various materials such as zinc selenide and germanium are

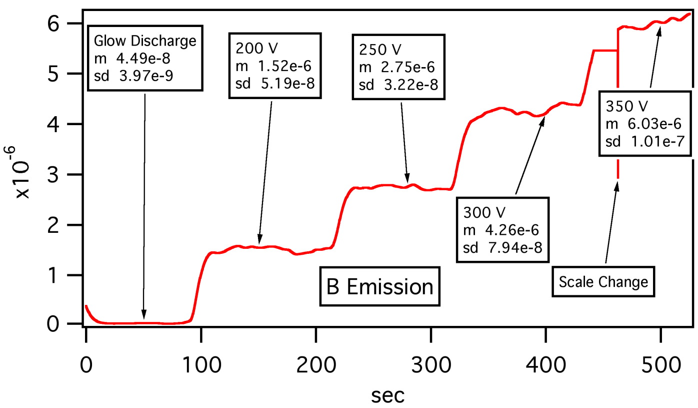

Figure 14. Boron emission for a low power Hall effect thruster for varying discharge potentials which correspond directly to the ion energies striking the walls. The annotations provide thrust discharge potential and the resulting relative emission mean (m) and its standard deviation (sd).

suitable for various wavelength windows. However in each case, the transmissivity and reflectivity of the window must be accounted for in order to ensure a suitable calibration. In addition, a wide array of Hall effect thruster materials and surface conditions result in difficult measurements and increases uncertainties substantially. As a result, optical thermography is useful in visualizing the overall thermal state of a Hall effect thruster, but there may are considerable uncertainties in the temperature measurement due to the uncertainties of the assumed emissivities. As a result, most temperature measurements reported are spot measurements taken with vacuum compatible thermocouples. Still, although there are locations such as the anode and locations in contact with the plasma where thermocouple measurements are invasive, or not convenient, and optical techniques are required.

Temperature measurements are important for a number of reasons. First the spacecraft integrator requires estimates of the heat load from the thruster body to the thruster gimbal/mount. Second, the magnetic circuit of a Hall effect thruster is subject to collapse if the magnetic circuit exceeds the Curie temperature of the ferromagnetic materials. There may also be issues with thruster temperatures should the electromagnetic coils exceed the rated temperature of the coil insulation. The temperature of various parts of the thruster may also provide insights into the thruster function and potential methods by which the efficiency of the device may be improved. Another concern with temperature is due to a study by Raneev, et al.,[39] that has shown that the sputtering of Borosil (BN-SiO_2 used in Russian Hall effect thrusters as the dielectric insulator) doubling when the temperature is varied from 450 °C to 590 °C.

Figure 15 shows a medium power Hall thruster firing within a vacuum chamber.[37] The plume is not visible since emission from xenon and various xenon ion charge states is concentrated in the blue and near infrared away from the medium infrared portion of the spectrum used in these data. The image in Fig. 15 shows the hottest potions of the thruster to be those in contact with the plasma where high energy ions are impacting and recombining. Interestingly, the cathode is the hottest portion of the thruster. The hollow cathode neutralizer's lifetime is very much dependent on its peak temperature. High temperature influences cathode lifetime by enhancing diffusion of the low work function materials away from the cathode insert. Once this effect occurs in full, the hollow cathode will no longer function nor will the Hall effect thruster.

III. Summary

This paper has attempted to briefly summarize some of the more common measurement techniques used to diagnose Hall effect thrusters. This paper is by no means a complete comprehensive summary of the literature on the topic of Hall effect thrusters and their plumes. Rather, this work seeks to introduce the topic to measurement engineers who have not yet been introduced to electric plasma thrusters in general and the Hall effect thruster in particular. The paper should therefore be viewed a brief introduction to the subject and jumping off point to those interested in the topic.

One unique feature of the Hall effect thruster for US engineers is that although the Hall effect thruster

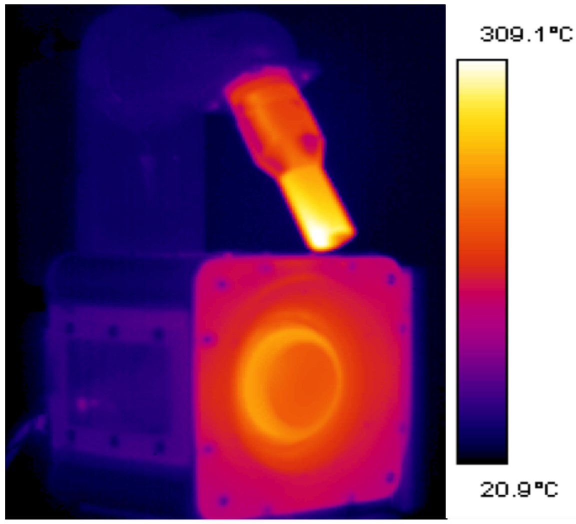

Figure 15. Thermographic Image of a medium power Hall effect thruster during operation. Note the plume emission in the visible and near infrared is not visible in the mid IR range of the detector used to acquire this image.

concept originated in the US, the primary development occurred in the former Soviet Union. Subsequent US development occurred to a large degree due to NASA and USAF sponsorship of a large number of universities as well as several corporations, most notably Aerojet and Busek. This has resulted in a very broadly distributed technology and measurement base with a considerable body of knowledge conserved in the technical literature.

This development model has its strengths and successes. Its wide diversity and breadth has made it one of the best documented development efforts for spacecraft propulsion. As a result, there a large number highly educated engineers with significant knowledge in the field of Hall effect plasmas. In addition, Hall effect thruster diagnostics are highly developed and extend from elementary thrust measurements to esoteric measurements of phase velocity of various plasma instabilities. The models and simulations are similarly arrayed from numerical calculations of thruster performance to extended models of spacecraft-plume interactions which calculate the sputtering from various spacecraft surfaces as well as the redeposition of those sputtered materials and their resputtering once they are again on a surface exposed to high energy ions from the Hall effect thruster plume.

However, there are some cautions that should be heeded. A number of complex diagnostics have been developed and not maintained. Large portions of the technical literature are not peer reviewed and contain contradictory data. Many numerical models have been used to fit experimental data later found to be incorrect and it is becoming evident to the community that validation data is difficult to extract from the multitude of available measurements and measurement techniques. As a result of the dependence of the Hall effect thruster field on widely separated and often very competitive academic institutions, the technical base is eroding as government funding begins to pursue new research topics, or completely change the course of their institutions as did NASA several years ago.

The Hall effect research topics that are currently being most actively pursued appear to be those most closely connected with the development and validation of improved numerical models of Hall effect thruster operation. This appears to be advancing the field into time resolved diagnostics to better understand the plasma turbulence that are fundamental to these turbulent plasma devices. That has begun to change the nature of the plasma diagnostics development away from engineering tools that can also be of use to engineers seeking to validate performance or the effect on spacecraft to more pure scientific measurements of electron transport due to plasma turbulence and how these physical phenomena can be efficiently numerically simulated. Ultimately, these experimental forays into more esoteric plasma physics will produce the desired product of useful, predictive numerical models useful to the spacecraft integrator.

Acknowledgments

The authors would like to thank Dr. J. Koo and Dr. M. Scharfe of the AFRL spacecraft propulsion modeling and simulation team for a series of very insightful conversations. There are several portions of this paper that owe a great deal to these illuminating conversations. We would also like to thank Dr. C. W. Larson for a series of very insightful comments and suggestions regarding Hall thruster life processes and near plume plasma dynamics. This paper also owes a debt of gratitude to Dr. J. M. Fife, G. Reed, T. Matlock, and J. Ekholm for their technical forays into many of the topics discussed in this manuscript.

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