

Development Status of the 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS)

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The Hall Effect Rocket with Magnetic Shielding (HERMeS) is a 12.5 kW Hall thruster being co-developed by NASA Glenn Research Center and the Jet Propulsion Laboratory. HERMeS incorporates magnetic shielding to eliminate discharge channel erosion in order to reach its design lifetime of 50 kh at specific impulses up to 3000 s. The capabilities of a HERMeS-based Ion Propulsion System are described. The thruster design was recently transferred to Aerojet Rocketdyne under the Advanced Electric Propulsion System (AEPS) contract. HERMeS hardware is being used by NASA to conduct risk reduction and life qualification tasks in support of AEPS. These includes a series of progressively longer wear tests, plasma characterization and modeling for life qualification, environmental testing, cathode testing, material investigations, diagnostic development, and EMI testing.

I. Introduction

SINCE 2012 NASA has been developing a 14 kW Hall thruster electric propulsion (EP) string that can serve as the building block for realizing a 40 kW-class propulsion system capability [1]. NASA continues to evolve a human exploration approach for beyond low-Earth orbit and to do so, where practical, in a manner involving international, academic, and industry partners [2]. A reference exploration concept was publicly presented at the HEOMD Committee of the NASA Advisory Council meeting on March 28, 2017 [3]. The concept is based on an evolutionary human exploration architecture, depicted in Figure 1, expanding into the solar system with cis-lunar flight testing that will validate exploration capabilities before launching crewed missions beyond the earth-moon system towards Mars. One of the key objectives is to achieve human exploration of Mars through a stepping stone approach that prioritizes technologies and capabilities best suited for such missions [4]. High-power solar electric propulsion (SEP) is a key technology that has been prioritized because of its exploration benefits. A high-power, 40 kW-class Hall thruster propulsion system provides significant capability and represents, along with flexible blanket solar array technology, a readily scalable technology with a clear path to much higher power systems [5-8].

The 14 kW Hall thruster system development, led by the NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL), began with in-house maturation of the high-power Hall thruster and power processing unit (PPU). The technology development work has transitioned to Aerojet Rocketdyne (AR) via a competitive procurement selection for the Advanced Electric Propulsion System (AEPS) contract [9]. The AEPS contract includes deliveries of engineering, qualification, and flight hardware. The AEPS EP string consists of the Hall thruster, PPU, xenon flow controller (XFC), and harnesses. Figure 2 shows the progress from the NASA HERMeS thruster design (left) to an early concept of the EDU thruster (middle) to the present EDU design (right). NASA continues to support the AEPS development leveraging in-house expertise, plasma modeling capability, and world-class test facilities. Additional information on the development of the AEPS system can be found in Ref. [1,9].

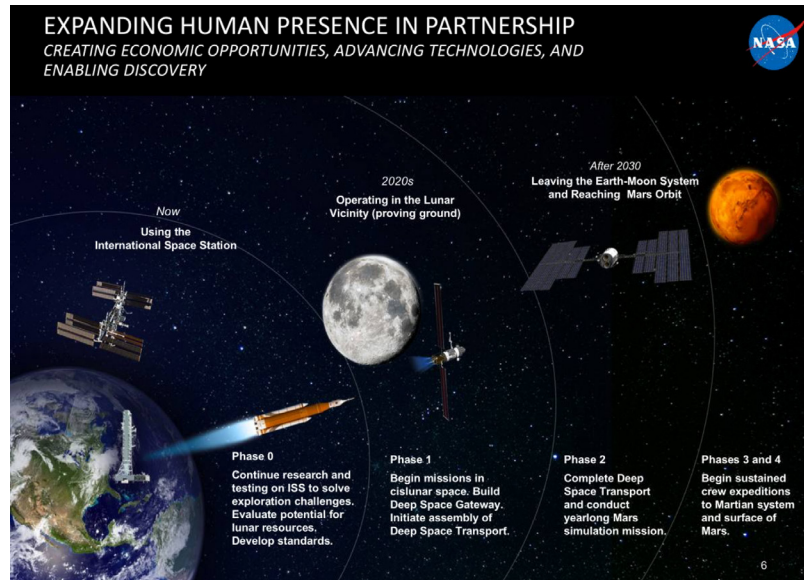


Figure 1 NASA Human Exploration Vision including Deep Space Gateway (DSG) and Deep Space Transport (DST).

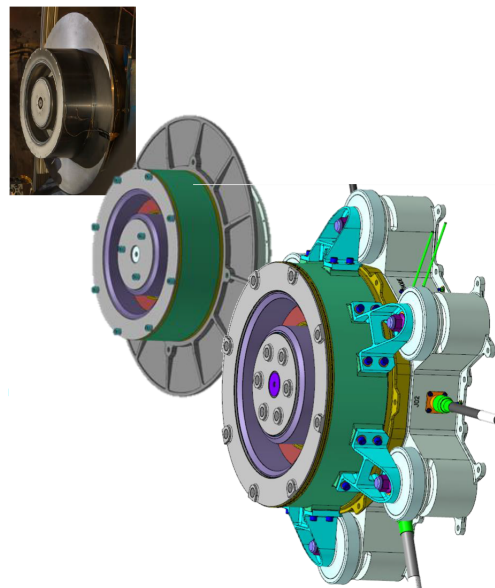


Figure 2 AEPS EDU thruster design improves upon NASA HERMeS development investments [1].

This paper provides an overview of the tasks that NASA has executed over the past year in order to reduce risk and support life qualification of the AEPS thruster. Several related papers provide additional detail on these and other topics [1,9-25]. In the next section, the system specification and thruster capabilities are summarized. This is followed by a discussion of recent NASA risk reduction and life qualification activities supporting AEPS.

II. Ion Propulsion System Capabilities

The Ion Propulsion System (IPS) was originally developed to meet the requirements of the now cancelled Asteroid Redirect Mission (ARM) [26]. As a potential first use of the IPS, and described in greater detail in Ref. [1], NASA is now investigating an in-house Power and Propulsion Element (PPE) conceptual design. The PPE leverages in-house mission concepts and vehicle designs from the SEP Technology Demonstration Mission project and Asteroid Redirect Robotic Mission (ARRM) [5,6,26,27].

Table 1 lists the key capabilities of the IPS. The 40 kW-class system is built around three operating strings consisting of a thruster, PPU, and XFC. Single string fault tolerance is provided bringing the total number of strings to four. Each string, which nominally processes 13.3 kW of input power to the PPU, includes a 5% contingency for a maximum capability of 14 kW input power. Each thruster must be capable of providing at least 2600 s specific impulse and processing at least 1770 kg of xenon. The PPU input voltage of 95-140 V and solar range of 0.8-1.7 AU provides for a flexible system that is extensible to a wide range of potential missions in robotic and human spaceflight [5-8,28].

Table 1. Key capabilities of the Ion Propulsion System.

Capability	Value
Total system power	40 kW
Maximum specific impulse	2600 s
Xenon throughput	5,300 kg
String fault tolerance	Single
Solar range	0.8 – 1.7 AU
PPU input voltage range	95 – 140 V

The IPS thruster is the Hall Effect Rocket with Magnetic Shielding (HERMeS). Shown in Figure 3, HERMeS is designed to operate at 12.5 kW discharge power and up to 3000 s specific impulse with a service life of 50 kh. Hall thrusters are now capable of meeting such extraordinary throughput requirements due to the breakthrough advances enabled by magnetic shielding [29-33], a technology that decreases discharge chamber erosion by orders of magnitude. Magnetic shielding physics were first identified through numerical simulations performed by JPL of AR's XR-5 Hall thruster [29,30], subsequently validated through simulations and experiments on the magnetically shielded H6MS Hall thruster [32-34], and then extended to high-specific impulse [35,36] and high-power [37]. HERMeS is the first Hall thruster designed with magnetic shielding over its entire service life and brings together advances in thruster performance and lifetime from NASA research since the turn of the century [38]. To achieve its design goals, HERMeS uses an integrated magnetic and thermal design, graphite pole piece covers, a graphite cathode keeper, a cathode-tied electrical configuration, an internally mounted cathode, and a downstream-plenum gas distributor.



Figure 3 The 12.5 kW HERMeS Technology Development Unit 3 (TDU-3).

Figure 4 depicts the operating envelope of HERMeS that has been refined during development testing [15,39-41]. Several Reference Firing Conditions (RFCs) are used to benchmark performance between different thrusters and facilities. The primary throttle curve of the IPS spans 300-600 V at a constant discharge current of 20.8 A. A low-thrust branch extending from 9 to 20.8 A is also shown at 300 V. This branch is used after system startup at 300 V, ~9 A until 20.8 A is reached and then the voltage is throttled to as high as 600 V.

Figure 5 shows the approximate thrust and specific impulse over the throttle curve and HERMeS operating envelope as a function of thruster discharge power. Table 2 lists the minimum required performance of the AEPS string as a function of PPU input power. The operating conditions roughly correspond to the throttle curve, depicted in Figure 4, which spans 300-600 V.

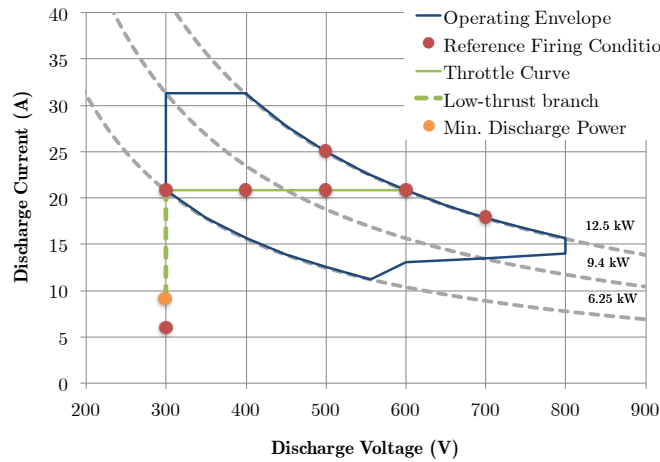


Figure 4 The HERMeS operating envelope spans 300-800 V and discharge power up to 12.5 kW. Also shown are the Reference Firing Conditions used during development testing, the primary throttle curve, a low-thrust branch at 300 V, and the minimum discharge power that is used at system startup.

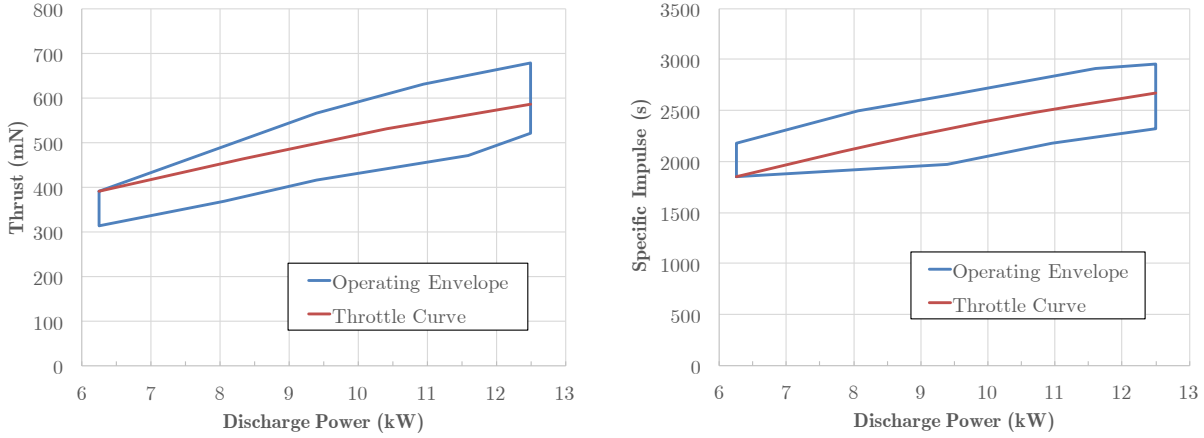


Figure 5 Approximate thrust and specific impulse capability of a HERMeS thruster versus thruster discharge power.

Table 2 Minimum required AEPS string performance corresponding to the throttle curve depicted in Figure 4.

EP String Total Input Power (kW)	Discharge Voltage (V)	Thrust (mN)	Mass Flow Rate (mg/s)	System Efficiency
13.3	600	589	22.9	0.57
11.1	500	519	22.0	0.55
8.9	400	462	22.1	0.54
6.7	300	386	21.7	0.52

III. Risk Reduction and Life Qualification Activities

NASA is utilizing HERMeS thrusters and cathodes to perform life qualification and risk reduction testing in support of the AEPS contract and potential mission implementation. This activity began with transition of the HERMeS thruster design and completed test results at the beginning of the AEPS contract. This section describes major elements of the risk reduction and life qualification activities supporting AEPS.

A. Wear testing

Magnetic shielding essentially eliminates discharge chamber erosion as the primary failure mode in Hall thrusters. This greatly extends the service life of Hall thrusters, but other components are subject to wear out failure modes that also must be accounted for. Among these include pole erosion [42-46], several cathode failure modes (insert depletion or evaporation, keeper erosion, cathode orifice erosion, heater failure), electromagnet insulation failures, and other failure modes related to high-temperature operation and thermal cycling (e.g., propellant isolator or anode structural failures).

In order to assess these wearout failure modes and also to prepare for the planned 23 kh life qualification test of the AEPS EDU thruster, wear tests with durations ranging as short as 10 h to as long as 3 kh are being conducted with HERMeS. The approach is similar to the one taken with the development of the NSTAR ion thruster, which also included a series of progressively longer wear tests as confidence grew in the thruster design and testing methods [47]. HERMeS wear testing has focused on quantifying known and potentially unknown erosion modes of the discharge chamber, pole covers, and cathode. Plasma simulations are used concurrently to predict and interpret wear tests outcomes. Facility effects encountered during wear testing have also been a focus of these investigations. In particular, the effects of carbon deposition in the discharge chamber on thruster performance and stability are being closely studied. Finally, the wear tests are building the expertise with the thruster, diagnostics, and vacuum facility prior to starting the 23 kh life qualification test. In the remainder of this section, we summarize the objectives and major results from these wear tests.

1. 1.7 kh TDU-1 wear test

The longest wear test to date of a NASA magnetically shielded Hall thruster was completed in the Fall of 2016 in VF5 at NASA GRC [14,44,48]. The wear test accumulated 1.7 kh of operation on the HERMeS TDU-1 thruster. Analytical and numerical models of the pumping and carbon backscatter environment were also developed in support of wear testing [49,50]. Results from the wear test are a critical element of validating plasma simulations used as part of the life qualification process [17,18,42,51].

The overarching objective of the TDU-1 wear test was to operate the thruster more than ten times longer than previous wear test experience of any NASA magnetically shielded Hall thruster as a pathfinder to the planned 23 kh EDU life qualification test. Specifically, the TDU-1 wear test objectives were to: 1) Quantify performance and wear trends over an extended period of operation to identify unknown failure modes and support validation of service-life models, 2) Quantify the deposition rate of backscattered facility material to identify the impact of deposition on thruster surfaces, to validate facility modeling, and to inform facility configuration for future tests, and 3) Provide guidance for future long-duration testing by identifying best practices and unknown issues associated with facility operation and configuration.

The first parts of the wear testing aimed to determine which combination of pole cover material and thruster electrical configuration were necessary to achieve the HERMeS throughput requirements (1770 kg, which is equivalent to 23 kh operation). To reduce risk to TDU-1, the H6MS was first tested at JPL to characterize the effects of a proposed cathode-tied electrical configuration that connects the thruster chassis to cathode common [39,43,52,53]. The cathode-tied configuration regulates the energy of ions that erode the pole covers while eliminating parasitic electron currents that would otherwise circulate through the vacuum facility. After the H6MS tests, a series of test segments with TDU-1 at GRC were started that lasted between 0.1-0.4 kh each and totaled 0.7 kh duration. Different combinations of pole cover material and electrical configuration were used during these early test segments. This testing demonstrated that graphite pole covers and the cathode-tied electrical configuration would enable HERMeS to meet the throughput requirement [41,44,48,54,55]. Using this thruster configuration, TDU-1 was fired for 1 kh, reaching 1.7 kh over all testing. Consistent with earlier performance and wear testing of magnetically shielded Hall thrusters [32,35,37,45,56], erosion of the discharge chamber was not detected and thruster performance was essentially constant with time. The measured erosion

rates on the inner front pole were found to be consistent with meeting the 23 kh life requirement with at least 50% margin (i.e., >35 kh).

2. Surface Layer Activation TDU-2 wear test

For the past several years, wear tests with durations of 100-200 h have been used with the H6MS and TDU thrusters to characterize component erosion rates [24,35,44,45]. These tests were successful in first identifying pole erosion as the likely first failure mode of magnetically shielded Hall thrusters. While these 100-200 h tests are short compared to the 23 kh service life requirement of the thruster, they are still relatively expensive and time consuming, which limits the number of operating conditions that can be characterized.

Surface Layer Activation (SLA) is an erosion diagnostic technique that can reduce the firing times to just 8-12 h, which greatly expands the number of conditions that can be interrogated over a fixed test period [21,57]. For SLA testing with TDU-2, a front pole cover fabricated from molybdenum was first bombarded with an 11-MeV proton beam to produce a thin layer (~ 100 μm) containing a small amount of gamma emitting $^{95\text{m}}\text{Tc}$. Then, the thruster was operated with the activated cover and the erosion depth was computed after the test based on the fraction of remaining radioactivity using a calibration curve.

The objective of the SLA test at JPL was to quantify the erosion rates of the inner front pole cover over a broad range of operating conditions that would provide insight on the sensitivity to voltage and current, magnetic field strength, discharge voltage ripple, and chamber pressure. Thirteen different combinations of discharge current and discharge voltage were tested that spanned 300-600 V, 10-31 A. Representative results are shown in Figure 6, which depicts the molybdenum erosion rates of the inner front pole cover over 300-600 V, 20.8 A. Graphite erosion rates are at least five times lower, depending on the ion energy.

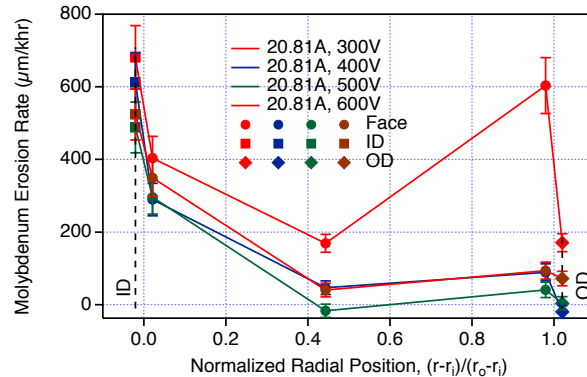


Figure 6 Molybdenum erosion rates measured over the inner front pole cover on TDU-2 via Surface Layer Activation at JPL. Graphite erosion rates are at least five times lower, depending on the ion energy.

SLA testing significantly advanced our understanding of the primary drivers to the erosion of the inner front pole cover, which include:

- Low current and low voltage conditions (worst case)
- Structure and motion of acceleration zone (particularly divergent ions at beam edge)
- Magnetic field magnitude
- Chamber pressure (at inner radii)

- Multiply-charged ions in cathode plume (may not be a concern with graphite)

Additionally, it was revealed that the discharge voltage oscillations were not a significant driver. Over a broad range of operation, SLA risk reduction tests identified primary drivers of pole erosion and worst-case conditions, which are key inputs for thruster life assessment and wear test planning. Additional detail on can be found in Ref. [21].

3. *TDU-3 & TDU-1 short duration wear test*

The SLA testing with TDU-2 described in the previous section provided new insights on the drivers of inner front pole cover (IFPC) erosion. Described in detail in Ref. [24], these insights motivated deferring a planned long-duration wear test of TDU-3 (see Section III.A.5) so that a series of short-duration wear tests could be conducted. These short-duration tests used a graphite pole cover with added molybdenum strips for masking and secondary measurements of erosion rates in order to verify and explore with greater fidelity some of the trends observed in the SLA TDU-2 testing that used a molybdenum IFPC. Besides assessing the IFPC, the testing also monitored the outer front pole cover (OFPC), the cathode keeper, and the discharge chamber. The overall objectives of the test remained the same as those described in Section III.A.1, with the added focus of assessing design changes in TDU-3.

Seven short duration wear tests lasting about 200 h each were conducted using two thrusters (TDU-1 and TDU-3) in two vacuum chambers (VF-5 and VF-6 at GRC). The TDU-1 thruster was used in the 1.7 kh wear test (Section III.A.1) while the TDU-3 thruster was recently fabricated incorporating some design changes that reflect the AEPS EDU thruster, including a discharge chamber fabricated from a BN-SiO₂ blend (see Section III.E and Ref. [15]) and a change in the axial position of the cathode keeper. VF-6, which was recently prepared for high-power Hall thruster testing [19], has about half the pumping speed of VF-5, which afforded the opportunity to assess pressure effects.

Operating conditions were selected that would provide the first direct measurements of graphite IFPC erosion over the throttle curve shown in Figure 4. This included TDU-3 operation in VF-5 at 300, 400, and 500 V and 20.8 A and one condition at 600 V, 20.8 A and 125% of the nominal magnetic field strength. TDU-1 was tested at 300 and 600 V and 20.8 A in VF-6.

Performance over more than 900 h of TDU-3 operation showed no significant variations (Figure 7-left). Due to the use of magnetic shielding, the discharge chamber became coated in backspattered carbon. Spalling of carbon deposited on the anode was observed during chamber venting. Erosion of the OFPC was measured, but the erosion rates were near the detection threshold of the measurement. Plasma simulations are suggesting that OFPC erosion may be enhanced with changes in the magnetic field, which may motivate further investigation [17].

Unexpectedly, high erosion rates in the cathode keeper were measured in TDU-3. Net deposition was measured on the TDU-1 cathode keeper, which was consistent with the 1.7 kh TDU-1 wear test. The TDU-1 keeper is recessed axially upstream from the IFPC plasma facing surface. Plasma simulations have captured the dependence of keeper erosion on its axial location [18]. Going forward, the EDU thruster is expected to use the upstream keeper location and additional testing is planned to further explore the drivers of keeper erosion.

IFPC erosion was only weakly dependent on discharge voltage, except at 300 V where higher rates were measured (Figure 7-right). The result is consistent with SLA testing, plume measurements showing high energy ions at high angles, and measurements of ion velocities showing larger plume divergence at lower voltages [10,14,21]. However, plasma simulations do not

currently capture these dependencies, which remains a focus of efforts to improve the physics used to capture pole erosion in the code.

The short duration wear testing has reduced risk to the EDU thruster by providing a wealth of data and new understanding of erosion modes over the throttling curve. These data are now being used for validation of service life models and are informing the EDU design prior to the start of the planned 23 kh life qualification test.

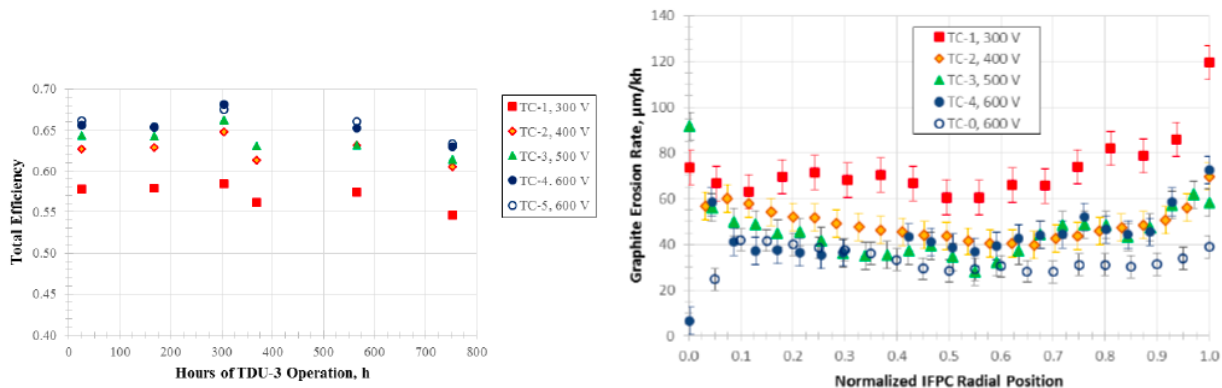


Figure 7 Efficiency of TDU-3 (left) and erosion rate of the inner front pole cover (IFPC) during short duration wear testing in VF-5 at GRC (see Ref. [24] for full details). TC-0: TDU-1 from 2016 testing at 20.8 A; TC-1 to TC-4: TDU-3 at 20.8 A; TC-5: TDU-3 at 20.8 A and 125% nominal magnetic field.

4. H6MS Accelerated Carbon Deposition Campaign

In order to assess the impact of backspattered carbon on the EDU thruster operation throughout the planned 23 kh qualification wear test and identify potential failure mechanisms related to ground testing, the Accelerated Carbon Deposition Campaign (AC/DC) was performed using the H6MS, a similar magnetically shielded 6-kW Hall thruster. Based on measured backsputter rates in VF-5 at GRC [49], where the planned qualification test will occur, approximately 40-μm of carbon is expected to coat all downstream facing surfaces. Measurements of thrust, thruster insulation resistances, carbon deposition, and other telemetry were recorded as the H6MS thruster was coated with 40-μm of carbon over 410 h of thruster operation. The carbon backsputter rate was accelerated by placing a 1-m×1-m graphite plate 0.5 m downstream from the thruster (see Figure 8). The complete details of the AC/DC test setup and results are being compiled for publication in a future work, however, the end results show no significant variations in any operating parameters or performance as demonstrated in Figure 8. The result is consistent with previous short duration wear tests [35,44,45]. The AC/DC reduces the risk of performing the planned 23 kh EDU wear test by demonstrating negligible performance/stability effects and robustness against shorting events.

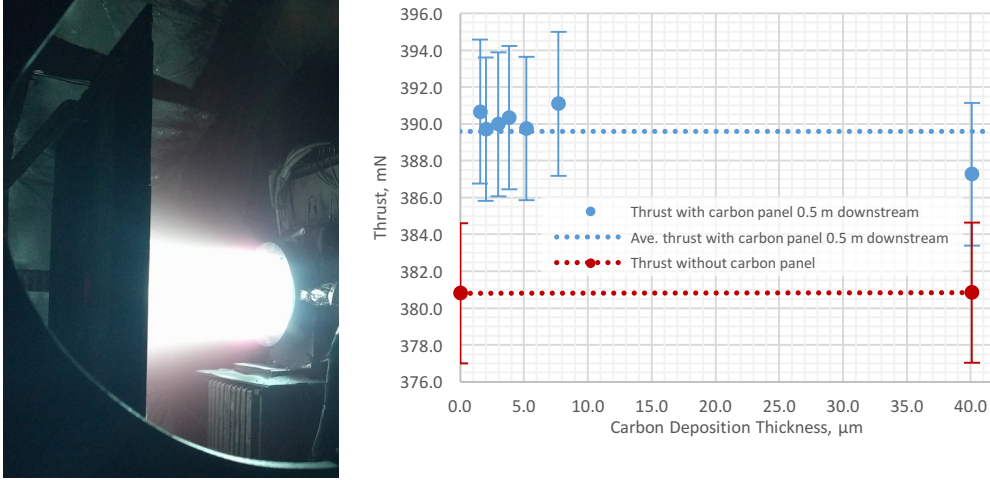


Figure 8 Left: photograph of H6MS firing at JPL in to a 1-m×1-m graphite target 0.5-m downstream to accelerate carbon backsputter rate. Right: Thrust as a function of carbon deposition measured during the AC/DC.

5. TDU-3 long duration wear test

The knowledge and experience gained during each of the TDU wear tests has progressively reduced risk for the planned 23 kh wear test of the EDU thruster. Preparations are now underway to begin a final TDU-3 long duration wear test in VF-5 at GRC. This wear test aims to complete 3 kh of operation on the thruster, which will extend further the operational experience of wear testing magnetically shielded Hall thrusters. The wear test is expected to extend until the EDU thruster is delivered next year under AEPS. The overall objectives of the test remain the same as those described in Section III.A.1, with particular focus on the development of effective procedures for conducting long duration tests in VF-5 and the demonstration of new diagnostics.

The wear test will demonstrate two new diagnostics in VF5. The first is an optical profilometer, similar to the one used in previous wear tests [24,44,48], but adapted for use in the vacuum chamber environment. Critically, the TDU-3 wear test is an opportunity to demonstrate the efficacy of the profilometer as well as its reliability over thousands of hours of thruster operation. The second diagnostic is a thrust vector probe that will use a series of Faraday probes mounted to a rotating boom. The probe will provide a means to monitor changes in the thrust vector during start-up transients and over many thousands of hours of thruster operation.

B. Plasma characterization and modeling supporting life qualification

1. Non-invasive, internal plasma measurements

The first measurements of the ion velocity distribution function (IVDF) using laser-induced fluorescence (LIF) on HERMeS were recently completed on TDU-2 at JPL [10]. These non-invasive measurements are a critical component of thruster life qualification, providing the empirical inputs necessary to determine the anomalous cross-field transport profile for hydrodynamic simulations using JPL's Hall2De code. The experiment provided time-averaged maps of the radial and axial ion velocities in the discharge chamber and near-field plume of the thruster.

An example of the data obtained is provided in Figure 9, which shows the mean axial ion velocity and estimated plasma potential on channel centerline during operation at 20.83 A discharge current over 300-600 V discharge voltage. The experiment also measured the effects of magnetic field strength, background pressure, and harness inductance (i.e., discharge voltage oscillations). A key finding was the measurement of bimodal velocity distributions, consistent with breathing mode oscillations of the acceleration zone location, that were observed at 500-600 V. Accounting for these oscillations in simulations has been found to be necessary in order to predict the correct inner pole cover erosion rate [17].

The TDU-2 measurements have also motivated the implementation of a time-resolved LIF diagnostic capability at JPL. The technique has recently been demonstrated on a hollow cathode with driven current oscillations and will soon be deployed on the thruster. Additionally, LIF diagnostics are being deployed at GRC that will be used to collect data on the EDU thruster when it is delivered next year. The combined efforts of JPL and GRC to conduct non-invasive LIF measurements of the thruster plasma are reducing risk by improving our understanding of the ion dynamics and providing the validation data necessary for Hall2De simulations used for life qualification.

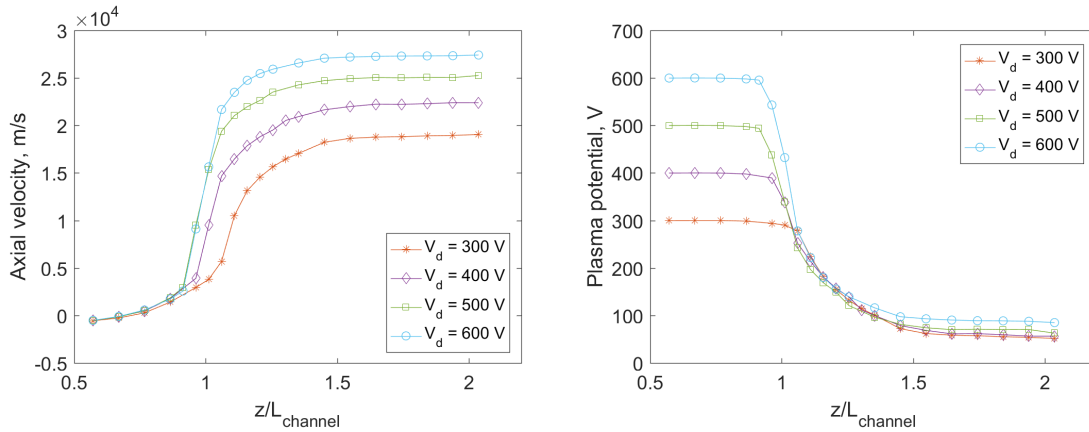


Figure 9 Left: Mean axial ion velocities along channel centerline of TDU-2 at 20.83 A discharge current from testing at JPL. Right: Plasma potentials estimated from the mean velocity profiles using conservation of energy. [10]

2. Plasma modeling

The 2-D axisymmetric codes Hall2De [58-60] and OrCa2D [61-64] developed at JPL to enable simulations of the partially ionized gas in Hall thrusters and hollow cathodes respectively, are employed to support the wear tests and to provide life assessments for HERMeS. The full throttling envelope of thruster was investigated with Hall2De, consisting mostly of operation at the nominal discharge current of 20.8 A and discharge voltage range of 300-600 V. One of the primary objectives of the simulations was to assess potential failure of the thruster due to erosion of the graphite pole piece covers. To assess the sensitivity of the erosion to the strength of the magnetic field, simulations at 75% and 125% of the nominal value also were performed. The plasma modeling work with Hall2De employed the multi-fluid and particle-in-cell (PIC) capabilities of the code and is reported in more detail in Ref. [17]. OrCa2D was employed to perform numerical analyses of the LaB₆ and BaO cathodes proposed for HERMeS, with the

objectives to assess depletion/vaporization of the emitter material and erosion of the cathode plate and keeper electrodes. The OrCa2D simulations were supported by Hall2De to determine the contribution of ions from the thruster to the erosion of the keeper. The results of the cathode simulations with OrCa2D are reported in Ref. [18]. Typical results are shown in Figure 10 for the plasma density in the Hall thruster (top) and hollow cathode (bottom) operating with a BaO emitter.

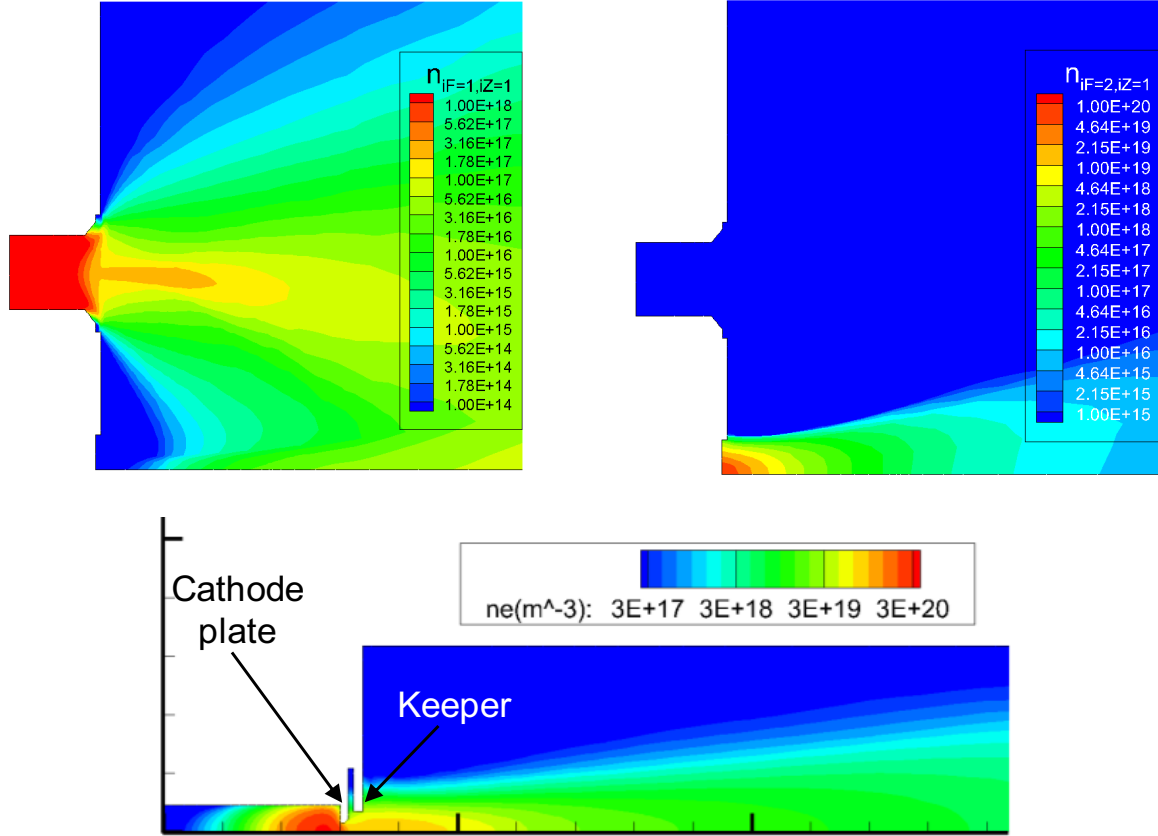


Figure 10 Top: JPL Hall2De simulation results of the ion number density (m⁻³) of singly-charged ions in HERMeS at a discharge current of 20.8 A and nominal magnetic field. Left-top: ions generated in the acceleration channel (Fluid #1). Right-top: ions generated in the cathode plume (Fluid #2). Bottom: JPL OrCa2D simulation result for the electron number density in the HERMeS cathode operating with a BaO emitter at 20.8 A and nominal applied magnetic field.

The simulation results were compared with a wide range of measurements produced through a series of tests involving the thruster as well as the two cathodes in standalone configurations that employed a cylindrical anode [39,65]. The Hall2De modeling work for example was guided by non-invasive LIF measurements (see Section III.B.1) of the average ion velocity at multiple points in the acceleration channel. These were the first non-invasive measurements that allowed comparisons with simulation results away from the channel centerline, and led to improvements in our understanding of both the anomalous collision frequency and the erosion of the thruster's pole covers. An example of the measured and computed velocity fields of singly-charged (Xe) ions overlaid on computed plasma potential contours is provided in Figure 11-left. Referring to the

LIF data in Figure 11-left, it should be noted that only those unit vectors that lie in regions where the potential is noticeably changing carry any appreciable speed; ions residing in the fully-red colored contour region carry energy of only a few volts and hence the comparison with the computed streamlines reveals little information. A comparison of the axial ion velocities along the channel centerline is provided in Figure 11-right at different strengths of the magnetic field.

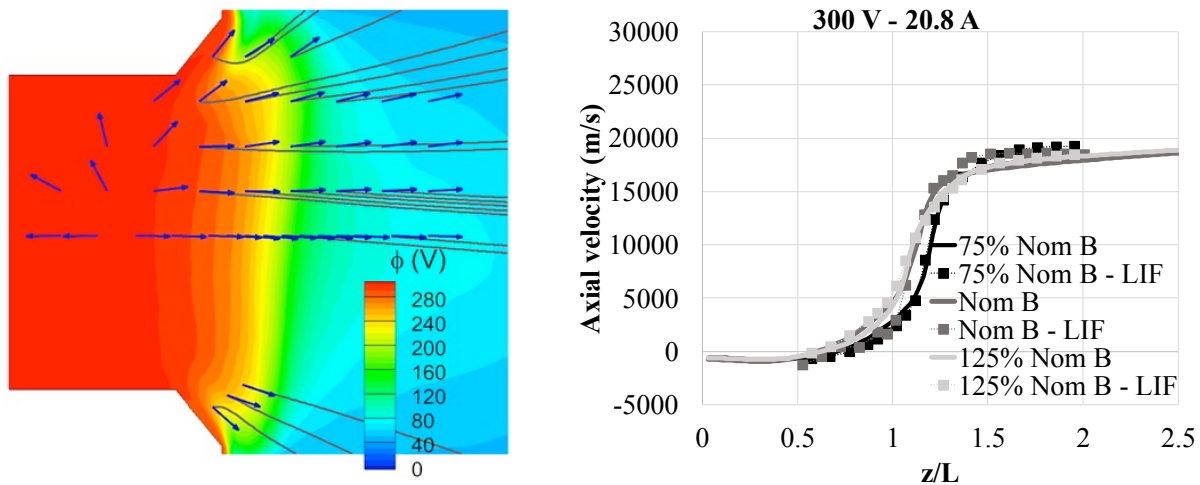


Figure 11 Left: 2-D comparison between singly charged ion streamlines from JPL's Hall2De and unit vectors of the ion velocity field from LIF measurements at nominal magnetic field strength. The velocity fields are overlaid on the computed contours of the plasma potential. Right. Comparison of the LIF and computed axial ion velocities along the channel centerline at different strengths of the magnetic field.

Regarding erosion of critical thruster surfaces the simulations revealed that the global oscillations, occurring naturally in the discharge due to the breathing mode, lead to increased erosion rates along the thruster pole covers with the increase being proportional to the amplitude of the oscillations. In fact, at 500 V and 600 V (20.8 A), the measured erosion rates are only captured in the simulations when global oscillations are accounted for. These operating conditions exhibit discharge current oscillations of approximately 40% of the nominal discharge current. This mechanism was found to be insignificant at the 300- and 400-V operating conditions as their oscillations are considerably smaller. The contribution to the erosion of the pole cover by ions associated with the cathode plume was found to be negligible. Magnetic shielding was found to prevent erosion of the channel walls, as expected, while moderate erosion rates were computed at the pole covers of the thruster with maximum values on the order of 60 $\mu\text{m}/\text{kh}$. The predicted erosion rates are low enough such that the inner pole cover will prevent erosion of the magnetic poles after 34.5 kh of operation. The simulations also capture qualitatively most of the erosion trends along the outer pole cover observed during the 2017 wear tests [24] though most of the comparisons are based on computed graphite erosion and measured molybdenum rates. However, quantitatively, these simulations carry much greater uncertainty compared to the inner pole cover predictions because the computed erosion rates are found to be highly sensitive to very small changes in the location of the acceleration region. As such, more detailed assessments of the erosion along the outer pole cover are being considered in the plans for the next HERMeS long

duration wear test, including, possibly, measurements at 600 V and 75% lower-than-nominal magnetic field for which the simulations showed high erosion rates and less sensitivity.

The OrCa2D simulations showed that the range of emitter temperatures found in the operating envelope of the hollow cathode yields emitter life that greatly exceeds the requirement of 34.5 kh of operation, for both the LaB₆ and BaO emitters. For the baseline (BaO) cathode emitter, life is expected to exceed 4,500 kh. Erosion of the cathode plate orifice was found to be extremely small, with erosion depths not exceeding 0.1 mm for all cases simulated. Sputtering rates along the keeper electrode however were not as low. It was determined that in a configuration where the cathode keeper exit is in the same plane as the pole cover, erosion of the keeper is large enough that it does not meet the life requirement plus margin. The erosion is due, largely, to sputtering by thruster ions as determined by supporting simulations with Hall2De. These ions are generated inside the acceleration channel and/or in the thruster plume and erode the keeper in the same manner they erode the inner front pole cover of the thruster. In response to these results and direct measurements that confirm the trends found in the simulations [24], the HERMeS development team has taken the action to increase the keeper thickness, and place the cathode upstream of the pole cover surface (facing the plasma) in a way that the latter shields partially the keeper from thruster ions.

Beyond the main objectives associated with the thruster and cathode life assessments outlined above, the plasma modeling work has also undertaken a few key risk reduction activities this year. Specifically, last year's efforts to eliminate any reliance of the electron transport coefficients on plasma measurements continued through attempts to develop a first-principles model of the anomalous resistivity. The lack of such a model prohibits fully predictive numerical simulations of Hall thrusters and remains today one of the longest standing problems in electric propulsion. Progress on this work is reported in Ref. [16]. Finally, efforts have also been undertaken to optimize the magnetic shielding topology in HERMeS by relaxing the protection of the channel walls by the magnetic field with the intent to reduce erosion of the poles. The premise behind this activity is that the complete elimination of the erosion along the chamfered channel walls, which has traditionally driven the design of magnetically shielded thrusters thus far, may not be necessary considering the finite life requirements of any given mission. Since unshielded thrusters have typically not suffered from pole erosion, it has been postulated since the inception of magnetic shielding [30-32] that an optimized magnetic shielding topology can be constructed such that erosion of both the channel and pole surfaces meet the mission requirements, with margin.

C. TDU-2 environmental test campaign

Environmental testing is being conducted at JPL for the expected launch and deep-space environments that includes random vibration and thermal cycling. The objectives of the environmental test campaign are to subject TDU-2 to dynamic and thermal environments in order to:

1. Evaluate the thruster design and look for possible inherent issues with the design, and, in particular, demonstrate that the monolithic, large-diameter, BN-SiO₂ ceramic discharge chamber can survive qualification environments
2. Path find the execution of environmental tests for the AEPS engineering, qualification, and flight model thrusters, and
3. Gather data to validate and/or improve structural and thermal models.

To accomplish these objectives, TDU-2 is being subjected to qualification level dynamic and thermal environments with periodic external physical inspections, magnetic field mappings and functional tests to verify operation or identify anomalies. The test flow for the environmental campaign is depicted in Figure 12. All dynamic and thermal testing is being conducted at JPL. Figure 13 shows TDU-2 during the random vibration and thermal cycling testing. Random vibration testing has now completed and the thermal cycling testing is now in progress. Additional details will be the subject of a future publication after the campaign completes.

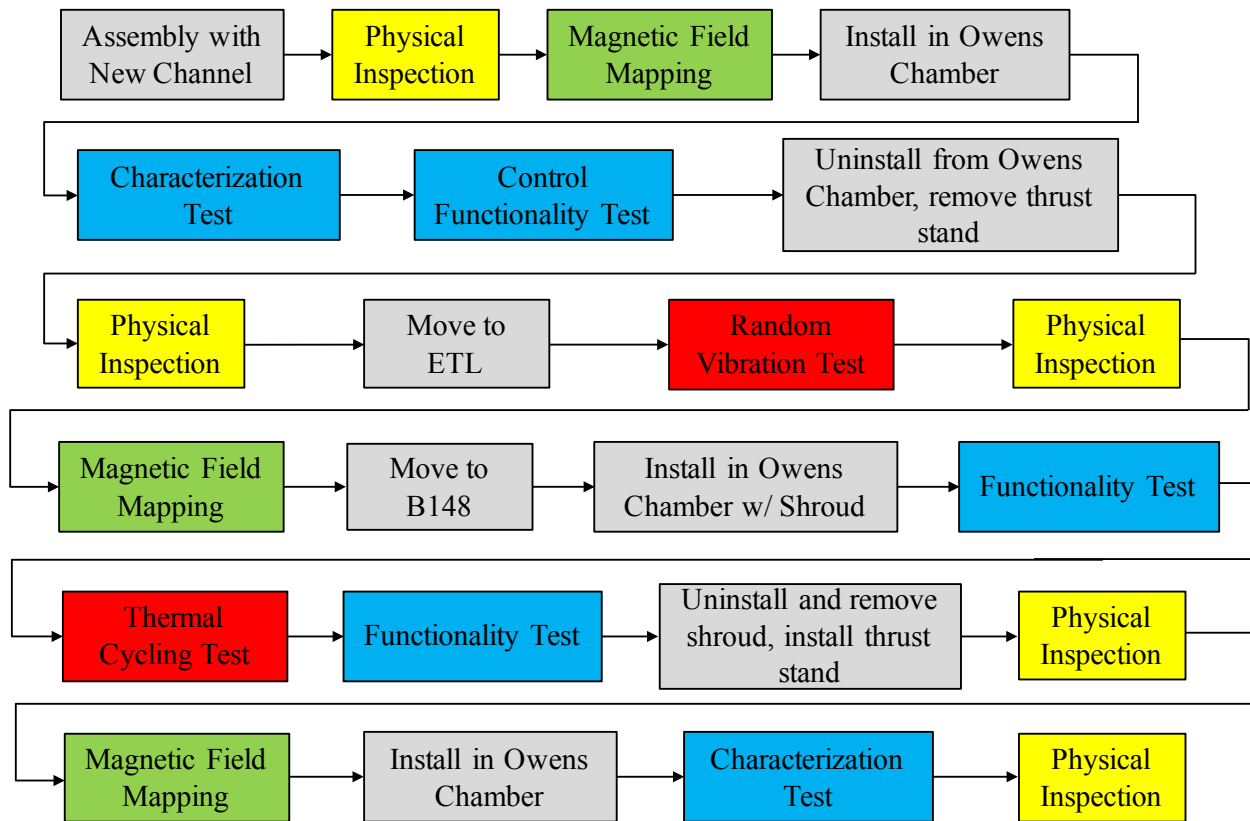


Figure 12 Test flow for the TDU-2 Environmental Test Campaign at JPL.

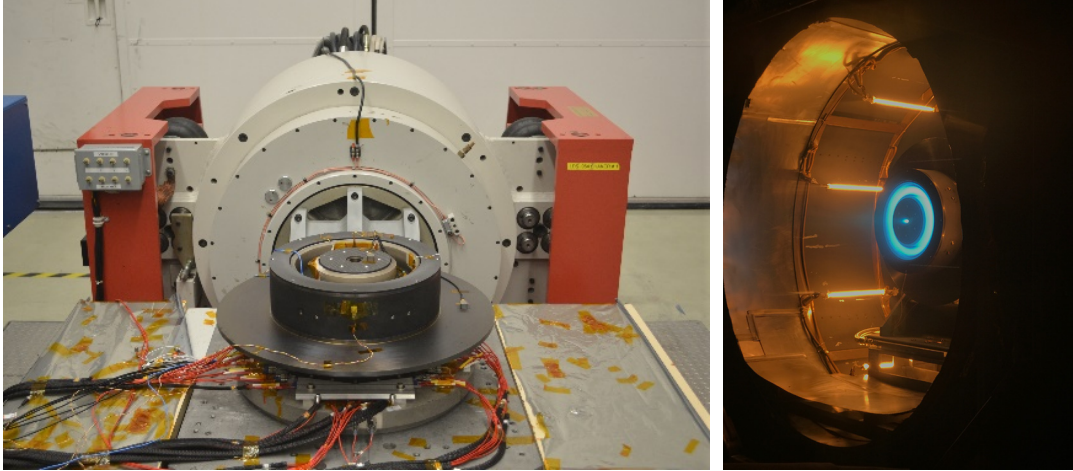


Figure 13 Left: TDU-2 installed on the shaker table in the Environmental Test Laboratory at JPL. Right: TDU-2 firing at 12.5 kW, 600 V during thermal cycling testing.

D. Cathode testing

Candidate BaO and LaB₆ hollow cathode technologies have been under development for HERMeS [12,13,39,66-69]. BaO cathodes have extensive heritage in US electric thrusters and can have larger current throttling ratios [29,70], but LaB₆ cathodes are much more resistant to propellant impurities and more extensible to high-current operation [65,71-73]. Recently, the BaO cathode was selected for use in the AEPS thruster for a variety of reasons, but chiefly since the aggressive development schedule for AEPS made selecting the BaO cathode a lower risk approach, due to its higher flight heritage in the United States and technical maturity of the BaO cathode heater technology.

Development activities in the last year have included: the design and analysis of BaO and LaB₆ cathodes with brazed joints, hollow cathode testing for evaluation of keeper configuration updates, the development of more efficient radiation shields, testing to quantify the effects of oscillating currents on the emitter temperature, and activities related to heaters, which are described below in more detail. Finally, preparations are underway to design tests and prepare facilities for component testing of the AEPS heaters and cathodes.

1. MgO-insulated heaters

The transfer of NASA MgO-insulated heater fabrication processes is being conducted in order to enhance AR's capability to fabricate reliable, reproducible, long-life heaters for AEPS. NASA cathode heaters were qualified for flight under the International Space Station plasma contractor program resulting in their successful use on-orbit starting in 1999. Subsequently, they were flown in space on the Deep Space One and Dawn missions that used the 2.3 kW NSTAR ion thruster and are now being implemented in the 7 kW NEXT-C program [23]. After the BaO cathode was selected for AEPS, an effort was started to transfer NASA's flight hollow cathode fabrication processes. In support of this effort, a series of technical interchange meetings were held with AR to review the NASA heritage fabrication processes. These included a NASA heater fabrication workshop to demonstrate the end-to-end process, the transfer of heater documentation, the production of a video demonstrating the fabrication process, and review of AR's heater fabrication

approach. Lastly, NASA is providing insight/oversight during the AEPS heater fabrication and will verify the heater capability through thermal cycling testing at JPL.

2. Alumina-insulated heaters

The higher operating temperatures of a LaB₆ emitter is unsuited for the MgO-insulated swaged heater typically used in BaO cathodes. Instead, an alumina(Al₂O₃)-insulated swaged heater design has been under development at JPL in collaboration with Idaho Labs for the past several years [65]. Alumina heaters have demonstrated hundreds of cycles in cathodes used for thousands of hours on several Hall thrusters, including a 20 A cathode that has been used in the laboratory for over a decade in the 6 kW H6MS and a 300 A cathode used in the 100 kW X3. BaO cathodes could also potentially use alumina heaters as a means to increase temperature margin.

In order to further the development of alumina heaters, two types of testing are being conducted: time-at-temperature (TaT) and thermal cycling. The TaT tests consists of three heaters being operated continuously at 1500 C, which is the temperature necessary to ignite a LaB₆ emitter. Thermal cycling tests are being conducted between approximately -10 to 1500 C. Table 3 summarizes the status of the alumina heater TaT and cyclic testing. More than 7,252 hours have been accumulated in TaT testing and one heater has nearly accumulated 11,000 cycles.

Table 3 Status of alumina heater time-at-temperature and cyclic testing at JPL.

Test Article	Type of Test	Duration as of 9/26/17	Status
E3	Time at Temperature	7,252 h	Hot resistance variation <0.06 Ohms; Time at temperature equivalent to ~86,907 starts
E5	Time at Temperature	7,252 h	Hot resistance variation <0.06 Ohms; Time at temperature equivalent to ~86,907 starts
D7	Time at Temperature	7,252 h	Hot resistance variation <0.045 Ohms; Time at temperature equivalent to ~86,907 starts
D1	Cycled	10,970 cycles	Hot resistance variation <0.08 Ohms
E6	Cycled	7,862 cycles	Hot resistance variation <0.1 Ohms

E. Discharge chamber material investigations

Magnetic shielding radically reduces plasma-wall interactions, allowing for the possibility of selecting discharge chamber materials based on structural and thermal considerations, rather than being dominated by plasma-specific properties such as secondary electron emission or sputtering yield [32,74]. Accordingly, NASA is investigating alternative discharge chamber materials as well as characterizing heritage materials in order to better understand possible failure mechanisms [75]. NASA heritage boron nitride, various blends of BN-SiO₂ (sometimes referred to as borosil in the Hall thruster literature), and alumina nitride are being characterized in terms of their microstructure, moisture sensitivity, and electrical, mechanical, and thermal properties.

An initial downselect to a BN-SiO₂ blend was made after early material characterizations. Discharge chambers fabricated from this material are now being tested in HERMeS. More detailed characterizations of the other materials are continuing in parallel to provide options to the AEPS thruster development should the initial selection have deficiencies requiring a change. HERMeS

testing includes detailed performance, stability, thermal, and wear characterizations in TDU-3 at GRC [15,24] as well as environmental testing to assess survivability to qualification level random vibration and thermal cycling in TDU-2 at JPL (see Section III.C). Relative to the heritage boron nitride material, these investigations have shown modest changes during thruster operation, less indication of moisture sensitivity, and successfully passed random vibration. Thermal cycling testing is in progress at the time of this writing, with positive results thus far.

F. Thrust vector measurements

Following prior works with the NSTAR and T6 ion thrusters [76,77], an array of 16 horizontal and 16 vertical graphite rods several meters downstream of the thruster provide a measurement of the HERMeS thrust vector angle during testing at JPL. The rods are biased -20 V below the facility ground to collect ions and fits to the current profiles determine the location of the ion beam centroid that is assumed coincident with the propellant momentum centroid. Figure 14 shows the variation of the thrust vector components during the first thermal vacuum (TVAC) test cycle of TDU-2. The thrust vector angles in Figure 14 are relative to the normal of the front pole surface of the thruster (within about $\approx \pm 0.04^\circ$ overall accuracy), and exhibit peak variation within $\pm 1^\circ$ throughout the thermal cycle. Further details of the setup, theory, and analysis as well as additional results are presently being prepared for publication in a future work.

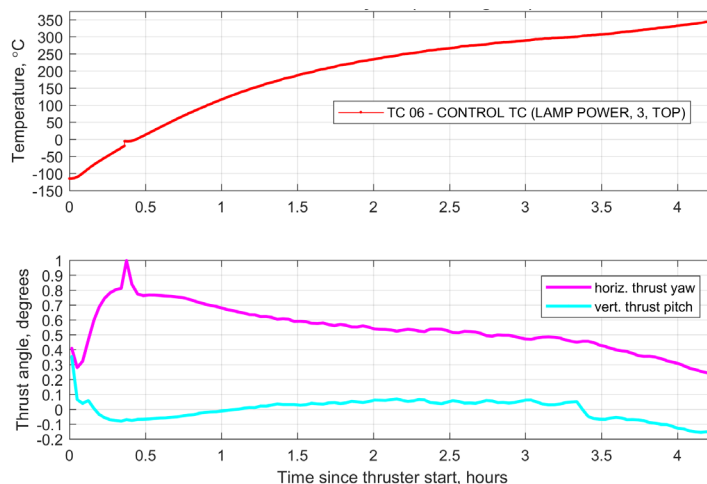


Figure 14 Thrust vector variation during TVAC cycle at JPL with TDU-2 operation at 600-V 12.5-kW from -121°C to +360°C.

G. TDU-1 Electromagnetic Interference Testing

A pathfinder electromagnetic interference (EMI) test was conducted with the TDU-1 thruster at The Aerospace Corporation (TAC) inside the anechoic room in the dielectric EMI chamber [78]. EMI characterization is part of the qualification program of the AEPS thruster, as such a checkout test of the TDU-1 thruster was conducted as part of a risk-reduction effort to characterize radiated emissions from the HERMeS TDU-1 thruster and to assess TAC EMI chamber capability for testing at power levels up to 12.5 kW. The TDU-1 thruster was operated in the TAC EMI chamber while data regarding facility health, thruster operation, and baseline sets of EMI measurements following the MIL-STD-461 RE102 standard were collected. While useful

data were obtained with this testing, the operating time of the thruster was limited to reduce heating of the dielectric chamber side wall and high operating pressure contributed to larger than normal discharge current oscillations and possibly to uncharacteristic plume behavior. Facility improvements in terms of pumping speed and thermal capability may be needed to allow nominal, sustained operation of the TDU-1 at 12.5 kW, 600 V. Such improvements are presently being planned at TAC.

IV. Conclusion

The EDU thruster design continues to be advanced by AR under the AEPS contract. NASA is supporting the EDU thruster design with insight/oversight, plasma simulations for life qualification, and world-class test facilities. HERMeS hardware is used by NASA to conduct risk reduction and life qualification tasks. These includes a series of progressively longer wear tests, plasma characterization and modeling for life qualification, environmental testing, cathode testing, material investigations, diagnostic development, and EMI testing. With the EDU thruster scheduled for delivery next year, the knowledge and experience gained through these tasks positions the program to begin the planned 23 kh wear test with well understood risks and a credible plan to execute the life qualification.

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