DEVELOPMENT OF 12 kW HALL THRUSTERS FOR NASA LUNAR GATEWAY POWER AND PROPULSION ELEMENT

SPACE PROPULSION 2022
ESTORIL, PORTUGAL | 09 – 13 MAY 2022

Joe Cassady (1), Brian Boyce (2), Brent Kearney (3), Dan Herman(4) , Peter Peterson(5)
(1) Aerojet Rocketdyne, Arlington, VA, USA, Email:joe.cassady@rocket.com
(2)(3) Aerojet Rocketdyne, Los Angeles, CA, USA
(4)(5) NASA Glenn Research Center, Cleveland, OH, USA

KEYWORDS: electric propulsion, Hall thrusters, high power SEP, orbit transfer

ABSTRACT:

NASA is embarking on a new and exciting era of human exploration to the Moon and its vicinity. Under the Artemis program, NASA is developing the lunar Gateway, an orbiting platform in Near Rectilinear Halo Orbit (NRHO) about the Moon. In 2024 the initial elements of the Gateway will be launched and then transferred from a high Earth orbit to the NRHO via the use of Solar Electric Propulsion (SEP). The SEP system is located on the Power and Propulsion Element (PPE), which will provide up to 60 kW of power for the lunar Gateway. Aerojet Rocketdyne is developing the 12 kW flight Hall thrusters to be used for transferring the PPE and the Habitat and Logistics Outpost (HALO) module to NRHO. Development testing is complete and the results are described in the paper. The Advanced Electric Propulsion System (AEPS) project has also recently completed its Critical Design Review (CDR) and is transitioning to the fabrication of three flight thrusters.

INTRODUCTION

On December 11, 2017 the National Space Policy of the United States was updated by the President and directed NASA to *"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."*[1] In keeping with this new Space Policy Directive, NASA is charged with landing the first American woman and next American man on the South Pole of the Moon by 2024, followed by a sustained presence on and around the Moon by 2028. The Artemis Program created to meet this challenge is divided into two Phases: Phase I is focused on the missions and systems required to achieve landing humans on the surface of the moon in 2024 and Phase II will establish a sustainable long-term presence on the lunar surface. Recent updates to the Artemis manifest have now established 2025 as the target date for Artemis III, the first landing mission.

NASA's Gateway will develop and deploy critical infrastructure required for operations on the lunar surface. NASA's Power and Propulsion Element (PPE), the first planned element of NASA's lunar Gateway, leverages prior and ongoing NASA and U.S. industry investments in high-power, long-life SEP technology investments. Since 2012 NASA has been developing a 13 kW Hall thruster electric propulsion string that can serve as the building block for a 50 kW-class SEP capability. The high-power Hall thruster system, along with flexible blanket solar array technology, provides a readily scalable technology with a clear path to much higher power systems. NASA's Gateway will leverage the benefits of high-power SEP capability provided by the Power and Propulsion Element. PPE enables the start of Gateway and crewed lunar surface operations followed by a sustainable presence in lunar orbit for expanded surface operations and extensibility for Mars exploration beyond the 2020s.

In May 2020, NASA directed a significant change to the plan for launching the initial elements of the Gateway, motivated by reducing both cost and risk. Instead of launching the first two modules, PPE and the

Habitation and Logistics Outpost (HALO), separately and docking them in lunar orbit as originally planned, the decision was made to integrate them on the ground and perform a co-manifested vehicle (CMV) launch on a single launch vehicle. The resultant significant changes to the PPE for the co-manifest launch required the roughly doubling of the required SEP total impulse to be provided by PPE during co-manifest electric orbit raise (EOR) due to the increased mass of the CMV and the correspondingly reduced launch apogee, as well as many other significant changes to the PPE spacecraft and mission. To provide the increased electric propulsion capability associated with the co-manifested launch change, the PPE electric propulsion system was required to increase in the xenon storage capacity and to add an additional 12kW Advanced Electric Propulsion System (AEPS) thruster. The three AEPS thrusters will be fabricated by Aerojet Rocketdyne and provided by NASA to Maxar as government-furnished equipment (GFE).

PPE will utilize 60 kW arrays, two large xenon tanks, and a combined 48 kW electric propulsion system spread over seven Hall thrusters. The xenon feed system provides up to 2770 kg of xenon at launch and can be refuelable while in-orbit around the moon.[2] The seven Hall Thrusters, in addition to 24 bipropellant chemical thrusters are designed to supply all propulsion needs for the entire lunar Gateway. The high efficiency SEP system will provide the primary source of ΔV capability for initial CMV lunar transit and insertion, orbital maneuvers to maintain the Gateway in the Near Rectilinear Halo Orbit (NRHO) for 15 years, as well as for performing orbit transfers and the eventual disposal of the entire Gateway stack. The PPE mission depicted in Figure 1 begins in 2024 with a launch on a Falcon Heavy launch vehicle placing the CMV in a highly elliptical transfer orbit. After separation from the launch vehicle, PPE will perform a series of bus equipment checkouts. PPE will then begin a period of long duration autonomous Electric Orbit Raise (EOR) utilizing the SEP system to transfer to the target NRHO. The PPE spacecraft is currently heading into the CDR, with the qualification and flight electric propulsion hardware fabrication already initiated and significant progress being made toward planned qualifications in support of the planned PPE spacecraft co-manifest launch in 2024.

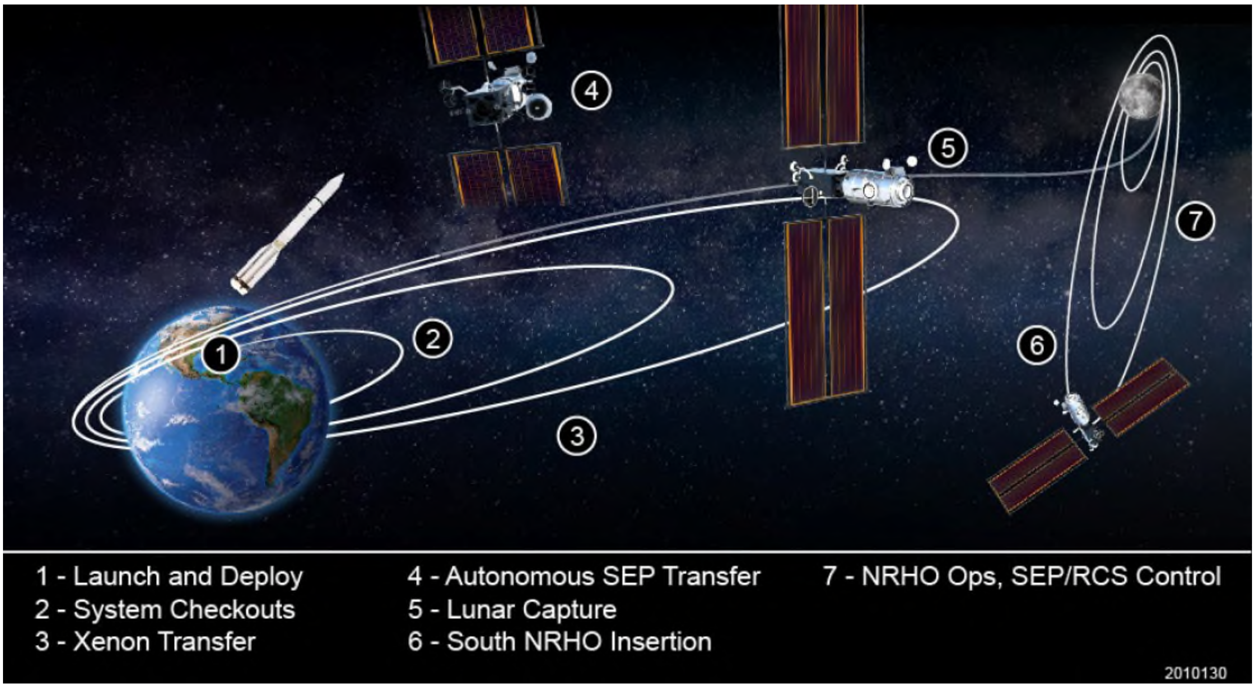


Figure 1 - PPE Concept Demonstration Mission Overview.

BACKGROUND

High-power solar electric propulsion is one of the key technologies that has been prioritized because of its significant exploration benefits, specifically for missions beyond low Earth orbit. Studies performed for NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) have demonstrated that 40-kW-class SEP provides the necessary capabilities that would enable near term and future architectures, and science missions[3]. Accordingly, NASA has been developing a 12 kW Hall thruster electric propulsion thruster that can serve as the building block for a 40-kW-class SEP capability. The 12 kW thruster development, led by the NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL), began with the maturation of the high-power Hall Effect Rocket with Magnetic Shielding (HERMeS). The technology development work transitioned to AR via a competitive procurement selection for the AEPS contract in May 2016. Management of the AEPS contract is being led by NASA GRC with funding from NASA's Science Technology Mission Directorate (STMD) under the Technology Demonstration Missions (TDM) program. NASA continues to support the AEPS development leveraging in-house expertise, plasma modeling capability, and world-class test facilities. Originally, the target mission for the high power SEP spacecraft was the Asteroid Retrieval Robotic Mission (ARRM) which would have returned a sample of an asteroid and demonstrated SEP capabilities necessary for human exploration of asteroids and Mars. As efforts shifted more toward lunar exploration and the Artemis program, it was evident that high power SEP could be effectively demonstrated as the primary propulsion for the Gateway PPE.

The NASA HERMeS, shown in Figure , is designed to operate at 12.5 kW discharge power and up to 3000 s specific impulse with a service life of 50 kh[4] [5]. At the 600 V maximum operating voltage required for the AEPS flight system, HERMeS produces more than 2800 s specific impulse and a thrust efficiency of 67% (not including Power Processing Unit). A design life capability of up to 50 kh is achieved using magnetic shielding that eliminates discharge chamber erosion as a wear out failure mode. 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[6789]. To achieve its design goals, HERMeS uses an integrated magnetic and thermal design, graphite pole piece covers, a cathode-tied electrical configuration, an internally mounted cathode with a graphite keeper, and a downstream-plenum gas distributor. The HERMeS thruster was design to span operational power from 6.25-12.5 kW for use in a 40-kW Ion Propulsion System for missions extending as far as 2.45 AU. The HERMeS Technology Development Unit 3 (TDU-3) thruster has accumulated over 4,500 hours of total operation with over 7,000 hours demonstrated cumulatively with all TDUs[10].

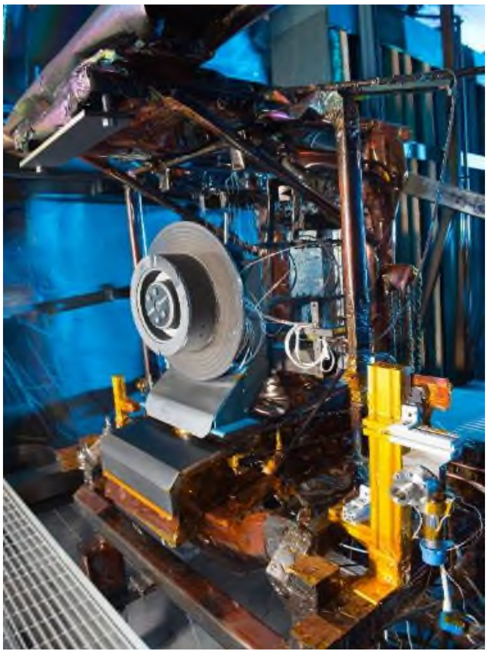


Figure 2 - The 12.5 kW HERMeS Technology Development Unit 3 (TDU-3).

Under the AEPS contract, AR has built upon the HERMeS thruster development investments to produce the thruster design with improved structural capability, a modified thermal management approach that allows for elimination of the HERMeS thruster radiator, and improvements to manufacturability, including incorporation of a flight-qualified electromagnetic coil process. The AEPS thruster is designed to operate at input discharge powers up to 12 kW, while providing a specific impulse over 2600 seconds at an input voltage of 600 volts. The AEPS flight thruster will require only 23 kh of operation (equivalent to 1700 kg of xenon throughput), but this still represents more than a factor of two greater operating time than previous Hall thruster flight systems such as the Aerojet Rocketdyne XR-5 or the Fakel SPT-140[11]. Figure 3 illustrates the design progression that the AEPS Hall Current Thruster (HCT) has gone through to reach the final configuration that successfully completed CDR in March 2022 and one of the two Engineering Test Units (ETU) that were used to demonstrate that the AEPS thruster can meet all the qualification requirements for the PPE mission.

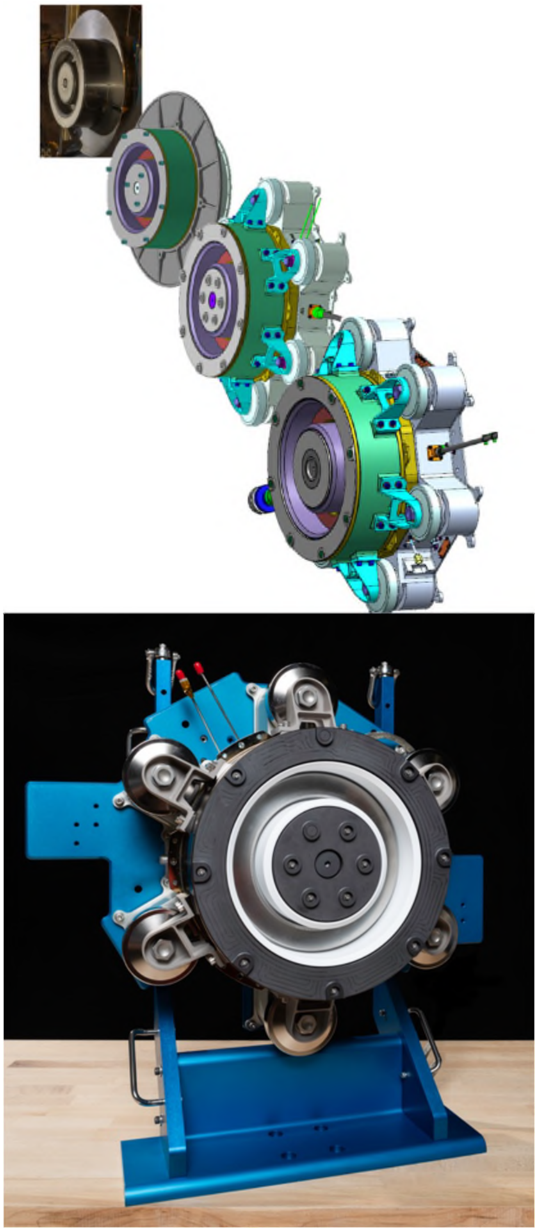


Figure 3 - AEPS Progression from HERMeS to the Flight AEPS thruster (Photograph of the ETU-1 included)

TECHNICAL APPROACH AND RESULTS

As part of the AEPS program, AR built two Engineering Test Unit (ETU) Hall thrusters based on the NASA HERMeS magnetically shielded Hall thruster and conducted a series of tests to validate the design. One series of tests focused on environments and functional testing, while the other series was primarily focused on long duration wear test blocks to characterize erosion rates. Results from these both of these test series were compared with NASA data from the HERMeS thruster. Testing of the two thrusters took place in Redmond, at NASA GRC, at JPL, and at the Aerospace Corporation. One ETU thruster (ETU-1) was designated to undergo hot fire performance, dynamic and thermal qualification level environmental testing, and the other (ETU-2) to undergo hot fire performance, plasma characterization, and wear testing at NASA GRC.

The key objective of the development testing leading up to the AEPS CDR was to establish the capability of the AR thruster design to meet the mission requirements. Owing to some requirements being modified, as the primary mission for the AEPS demonstration evolved from the ARRM to the PPE mission, a technical assessment of the updated requirements was made and the criteria for development tests adjusted accordingly. The most notable changes were reduction of shock requirement at 100 Hz and relaxation of the thrust vector alignment requirement to allow the use of shock isolators. Figure 4 shows a Computer Aided Design (CAD) rendering of the ETU thruster and associated cabling. One other change made to facilitate the PPE spacecraft pointing mechanism requirements was to break the power input cables up into three separate assemblies – one for discharge power, one for heater power and one for auxiliary power.

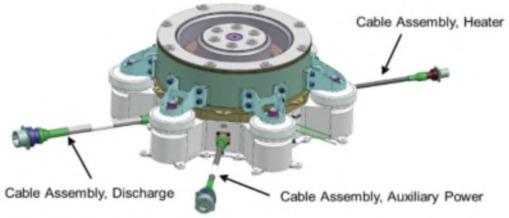


Figure 4 – Engineering Test Unit (ETU) Thruster Design

ETU-1 was used to demonstrate compliance with the environments defined for the PPE mission. ETU-1 completed an environmental test series at JPL and AR's Redmond, WA facility. Figure 5 shows this thruster in the process of being assembled at Aerojet Rocketdyne prior to being shipped to JPL.

The JPL Owens Vacuum Chamber employs a water cooled inverted pendulum thrust stand to measure the thrust of the thrusters. The thrust stand was calibrated before and after each operation of the ETU-1 thruster in order to assess the impacts of thermal drift on the recorded thrust data.

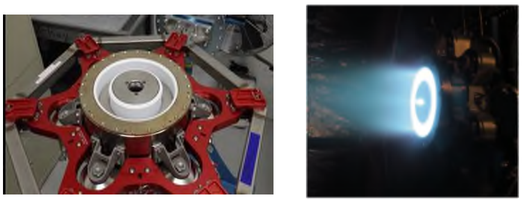
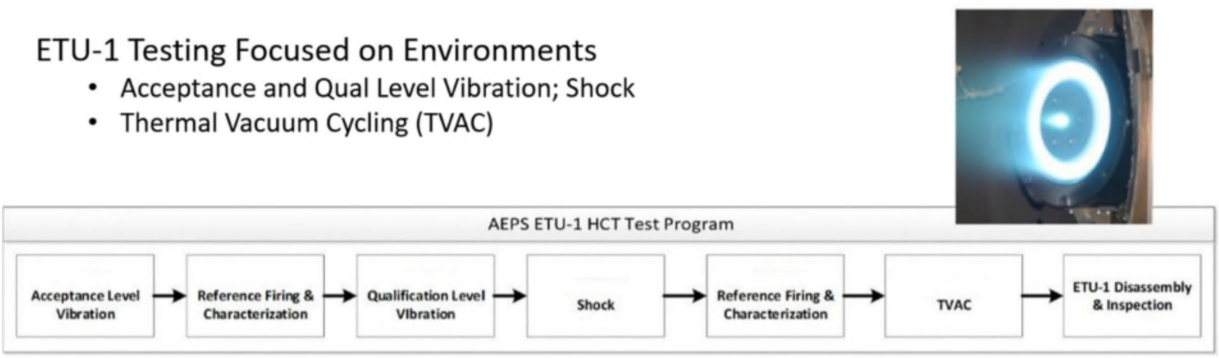


Figure 5 – AEPS ETU-1 Thruster in Assembly and in Hot Fire Testing at JPL

The ETU -1 thruster was first functionally tested, then was subjected to acceptance test level vibration. Following that it was again fired to ensure no changes to performance or functional behavior. After this, the ETU-1 thruster was subjected to qualification level vibration testing and shock tests, then again fired to demonstrate no changes to performance or function. Finally, the ETU-1 thruster was run through a full thermal vacuum test to hot bias and cold bias conditions. ETU-1 completed all environmental tests successfully with no major design updates required.

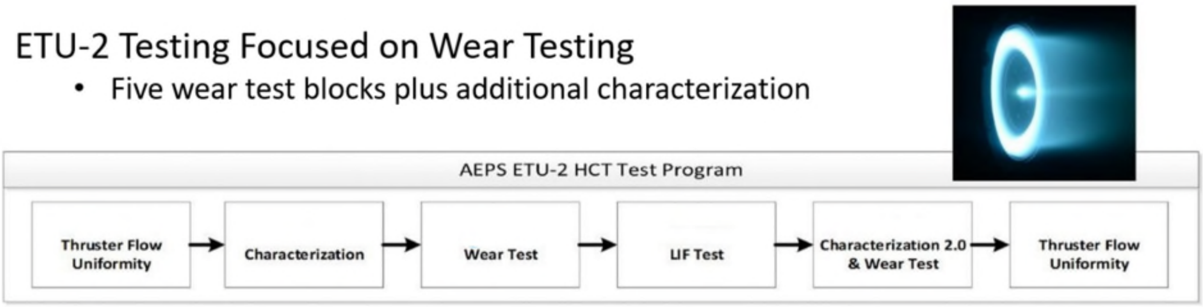
ETU-2 was tested to provide thruster wear data and plasma characterization after completing initial hot fire and flow uniformity testing. These tests were conducted in the NASA VF-5 facility at GRC to allow for direct comparison with the earlier data gathered on the NASA TDU thrusters. The ETU-1 and ETU-2 development test sequences are shown in Figure 6.



ETU-1 Testing Focused on Environments

- Acceptance and Qual Level Vibration; Shock
- Thermal Vacuum Cycling (TVAC)

Figure 6 – Test Sequence for ETU-1 Development Thruster



ETU-2 Testing Focused on Wear Testing

- Five wear test blocks plus additional characterization

Figure 7 – Test Sequence for ETU-2 Development Thruster

The ETU-2 reference firing and characterization test was performed at the NASA Glenn Research Center (GRC) Vacuum Facility 5 (VF-5) chamber in Cleveland, OH. The vacuum chamber is approximately 4.6m in diameter and 18.3m in length, and is lined with graphite panels to minimize ion sputtering of chamber surfaces. An additional graphite structure at the downstream end of the chamber protects the chamber walls from erosion and can be electrically biased with respect to the chamber ground. The facility has a pumping speed of 700,000 L/s on Xenon at 10^{-6} Torr and a base pressure of 10^{-7} Torr. During the test campaign, the chamber pressure on all ion gauges remained below 6×10^{-6} Torr while pumping on Xenon at the maximum nominal HCT propellant flow rate. The testing sequence for ETU-2 is shown in Figure 7. ETU-2 testing began flow uniformity tests, and baseline performance characterization. This was followed by plume measurements with Laser Induced Fluorescence (LIF) to characterize the plume. Plume characteristics measurements were repeated over the duration of the test. It was then set up in the VF-5 facility at NASA GRC for the first block of wear testing. VF-5 was used for the wear testing to ensure the highest fidelity measurements of thruster erosion and to provide traceablity to the HERMeS thruster data. ETU-2 accumulated a total of 2500 hours over five separate wear test blocks. The demonstrated wear rates support the mission requirement of 1770 kg of xenon throughput with a 1.5 times margin.

ETU-1 testing at JPL established the performance and impact of environments (such as launch load, shock and thermal) on performance. FASTCAM data was acquired approximately every 30 minutes throughout the sequence, Faraday probe data was taken at least 5 minutes before shutdown, while thrust measurements were taken during the run and after shutdown of each cycle. Thrust calibration was performed at the very end of the reference firings to provide accurate end of run calibration. Table 1 provides the ETU-1 pre- and post-shock thrust and specific impulse measurements compared to data taken with the HERMeS TDU-2 thruster. Faraday probe data were taken at three different axial locations downstream from the thruster at each voltage operating point, and are shown in Figure 8. The plume data show minimal changes in current density at all voltage conditions between the pre- and post- qualification vibration and shock.

	Thrust (mN)			Isp (sec)		
	NASA HERMeS (TDU)	ETU-1 (Pre-shock)	ETU-1 (Post-shock)	NASA HERMeS (TDU)	ETU-1 (Pre-shock)	ETU-1 (Post-shock)
300V	398	398	390	2021	2019	1981
400V	478	477	474	2366	2364	2355
500V	544	548	544	2568	2635	2623
600V	608	613	608	2883	2896	2882

Table 1 – Performance Comparison of ETU-1 (Pre- and Post-Shock) to NASA HERMeS

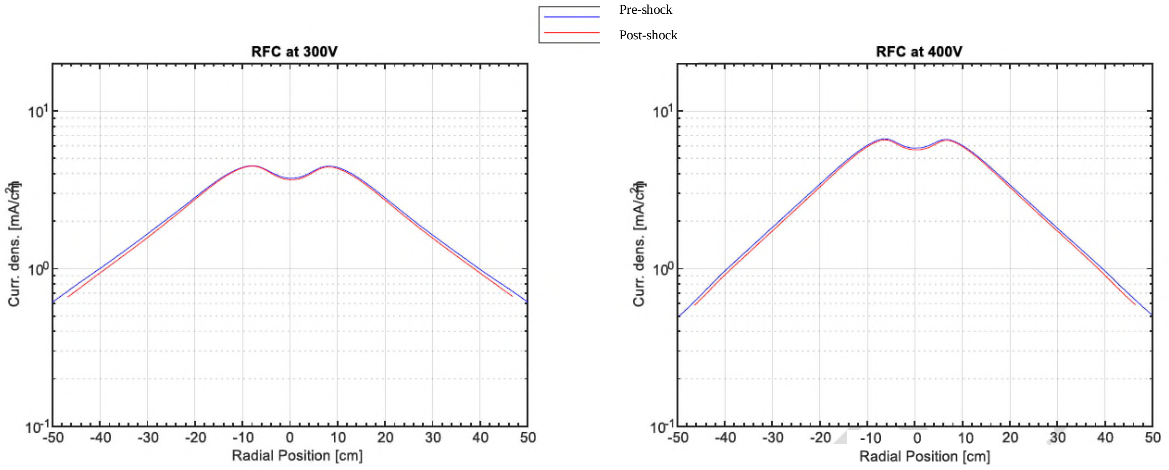


Figure 8 – Pre- and Post-shock Faraday Probe Plume Profiles

The primary objectives of the ETU-1 acceptance and characterization test were to: 1) verify the thruster's functionality and its ability to sustain operation; 2) meet the expected performance against requirements; 3) characterize the risks of demonstrating compliance for qualification and flight units; 4) gather thermal data to support thermal modeling and evaluate thermal risks; gain a better understanding of the minimum ignition characteristics of the cathode. The ETU-1 demonstrated that it met specified performance and that environments did not statistically affect either performance or functionality of the thruster operation.

A comparison of the front pole erosion rate from ETU-2 wear test block 1 and TDU-3 prior test data is shown in Figure 9.

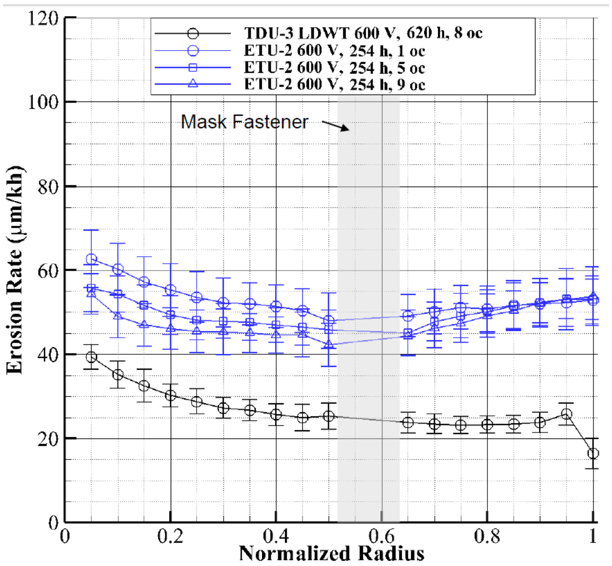


Figure 9 – Inner Front Pole Cover Erosion Rate Measurements from Wear Test Block 1

Thruster erosion measurements included laser profilometer and laser induced fluorescence (LIF) data. The laser profilometer data was taken after 250 hours at each of three operating points – 9kW, 11kW, and 12kW. These data were used to anchor the JPL pole erosion model which has been described in previous papers.[12] The results of the model predictions show adequate margin at 35,000 hours, which is equivalent to PPE mission life with a 1.5x margin.

The development test campaign with the ETU-1 and ETU-2 thrusters was completed in 2021, in spite of having to deal with issues related to COVID-19 limitations. Results showed that the AEPS thruster design was capable of meeting the PPE mission requirements and that design modifications to the thruster for flight did not adversely affect either performance or lifetime compared with the NASA HERMeS design, thus clearing the way for the design to proceed to CDR. In addition, the development test series provided valuable insights into the facility procedures to support qualification and flight thruster acceptance testing.

MISSION ARCHITECTURE IMPLICATIONS OF HIGH POWER SEP

The use of the AEPS thrusters on the PPE spacecraft will provide the first true demonstration of the capability of SEP to transfer larger payloads (greater than 10 t) out of Earth orbit and insert them into orbit around another celestial body. This is important for the Artemis program because it sets the stage for efficient transportation of equipment and supplies to the Moon, but it also proves the concept for use of SEP to pre-position payloads at Mars.

As an example, we examined the utility of an SEP cargo tug in combination with the co-manifested payload capability (10 t) of the SLS Block 1b launcher. Figure 10 shows a typical orbit transfer using the high power SEP to deliver a large payload to lunar orbit (NRHO). The assumption is that SEP system will initiate the transfer after drop off by SLS at TLI. The initial payload was sized to fit within the SLS Block 1b co-manifest constraints of 10 t delivered to TLI on every Orion launch.

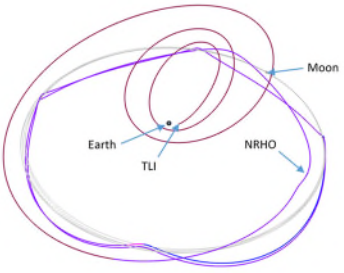


Figure 10 – Low-thrust Trajectory Analysis of SEP System Transfer

Table 2 shows the payload delivery capability and transfer time required for two different systems – one with two AEPS thrusters and another with three AEPS thrusters. The result of this analysis showed that a trip time savings of approximately 82 days can be gained with only a small loss of payload (< 500 kg) if additional power can be provided to enable use of three AEPS strings. This result shows the importance for lunar transport of having a higher power SEP capability. The savings over a lunar logistics campaign to deliver 26 t of supplies would be nearly one full year.

	2x AEPS System	**3x AEPS System**
Total ΔV	3420 m/s	3330 m/s
Initial Mass (10 t)	9750 kg	
Power to Thrusters (kW)	25	37.5
Final P/W	3.167 W/kg	4.734 W/kg
Transfer Time	363.1 days	281.5 day
Payload Mass	**6940 kg**	**6460 kg**

Table 2 – Mission Results for SEP Cargo Mission to NRHO

CONCLUSIONS

The successful completion of the AEPS thruster development testing provides a good starting point to initiate qualification and flight thruster manufacturing. Results showed that we have a robust design that provides performance equal to the HERMeS laboratory thruster, while meeting all flight design requirements. Environmental testing such as thermal vacuum and launch loads including shock and vibration were all successfully completed. Preliminary short duration wear test data also indicates that the lifetime goals are in line with those expected from a magnetically shielded thruster design.

AEPS has completed development and is moving into the qualification and flight phase of the program. Good progress is being made toward delivery of the three flight thrusters for the planned launch of the combined PPE/HALO stack in late 2024. The use of SEP to transfer the first elements of Gateway to the NRHO destination orbit represents a significant milestone in the history of EP, as it represents operational reliance on an SEP system to deliver critical elements of the Artemis program to the Moon.

REFERENCES

---

[1] https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/

[2] Herman, et. al., “The Application of Advanced Electric Propulsion on the NASA Power and Propulsion Element (PPE),” IEPC-2019-651, 35th International Electric Propulsion Conference, Vienna, Austria, Sept. 15 – 20, 2019.

[3] B. K. Smith, M. L. Nazario, and C. C. Cunningham, "Solar Electric Propulsion Vehicle Demonstration to Support Future Space Exploration Missions," presented at the Space Propulsion 2012, Bordeaux, France, May 7-10, 2012.

[4] R. R. Hofer *et al.*, "Development Approach and Status of the 12.5 kW HERMeS Hall Thruster for the Solar Electric Propulsion Technology Demonstration Mission," in *34th International Electric Propulsion Conference*, Kobe, Hyogo, Japan, July 4 - 10, 2015.

[5] R. R. Hofer *et al.*, "Design Methodology and Scaling of the 12.5 kW HERMeS Hall Thruster for the Solar Electric Propulsion Technology Demonstration Mission," presented at the Presented at the 62nd JANNAF Propulsion Meeting, Nashville, TN, June 1-5, 2015.

[6] I. Mikellides, I. Katz, R. R. Hofer, D. M. Goebel, K. De Grys, and A. Mathers, "Magnetic Shielding of the Channel Walls in a Hall Plasma Accelerator," *Physics of Plasmas,* vol. 18, no. 3, p. 033501, March 8, 2011 2011, doi: 10.1063/1.3551583.

[7] I. G. Mikellides, I. Katz, R. R. Hofer, and D. M. Goebel, "Magnetic shielding of a laboratory Hall thruster. I. Theory and validation," (in English), *Journal of Applied Physics,* vol. 115, no. 4, Jan 28 2014, doi: Artn 043303 Doi 10.1063/1.4862313.

[8] W. H. Rohit Shastry, Thomas W. Haag, and Hani Kamhawi, "Langmuir Probe Measurements within the Discharge Channel of the 20-kW NASA-300M and NASA-300MS Hall Thrusters," in *33rd International Electric Propulsion Conference*, The George Washington University, USA, 2013: IEPC.

[9] R. Hofer *et al.*, "Development Status of the 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS)," presented at the 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 8 - 12, 2017, 2017.

[10] J. D. Frieman *et al.*, "Completion of the Long Duration Wear Test of the NASA HERMeS Hall Thruster," presented at the 2019 Joint Propulsion Conference, Indianapolis, IN, Aug 19-22, 2019.

[11] K. de Grys, A. Mathers, B. Welander, and V. Khayms, "Demonstration of 10,400 Hours of Operations on a 4.5 kW Qualification Model Hall Thruster," in *Joint Propulsion Conference, AIAA-10-6698*, Nashville, Tennessee, 2010.

[12] Lopez Ortega, A. and Mikellides, J., “Investigations of Pole Erosion Mechanisms in the 12.5 kW HERMeS Hall Thruster Using Numerical Simulations and Ion Velocity Measurements,” presented at the 2018 Propulsion and Energy Forum, Cincinnati, OH, 2018.