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OVERVIEW OF THE DEVELOPMENT OF THE ADVANCED ELECTRIC PROPULSION SYSTEM (AEPS)

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NASA is committed to the demonstration and application of high-power solar electric propulsion to meet its future mission needs. It is continuing to develop the 14 kW Advanced Electric Propulsion System (AEPS) under a project that recently completed an Early Integrated System Test (EIST) and System Preliminary Design Review (PDR). In addition, NASA is pursuing external partnerships in order to demonstrate Solar Electric Propulsion (SEP) technology and the advantages of high-power electric propulsion-based spacecraft. The recent announcement of a Power and Propulsion Element (PPE) as the first major piece of an evolvable human architecture to Mars has replaced the Asteroid Redirect Robotic Mission (ARRM) as the most likely first application of the AEPS Hall thruster system. This high-power SEP capability, or an extensible derivative of it, has been recognized as a critical part of a new, affordable human exploration architecture for missions beyond-low-Earth-orbit. This paper presents the status of AEPS development activities, and describes how AEPS hardware will be integrated into the PPE ion propulsion system.

I. INTRODUCTION

For missions beyond low Earth orbit, spacecraft using chemical propulsion suffer from having to carry a large amount of propellant, which can constitute more than 50 percent of the total vehicle's mass. This impact can be significantly reduced through use of Solar Electric Propulsion (SEP) which can offer at least an order of magnitude improvement in specific impulse over chemical systems. Recent studies conducted for NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) show that a 40 kW-class SEP capability can be enabling for many human exploration architectures and robotic science missions.[1]

Since 2012, NASA has been developing a 14 kW Hall thruster electric propulsion (EP) string that can serve as the building block for a 40 kW-class SEP vehicle. NASA presented a new reference exploration architecture at the HEOMD Committee of the NASA Advisory Council meeting on March 28, 2017.[2] This approach is based on an evolutionary human exploration strategy that focuses on flight testing and validation of exploration capabilities in cislunar space prior to conducting missions to Mars. An important aspect in achieving this goal is prioritizing the technologies best suited for such missions based on this stepping stone approach to exploration.[3] High-power solar electric propulsion is one of those key technologies. A high-power, 40 kW-class Hall thruster propulsion system represents, along with flexible blanket solar array technology, a readily scalable technology with a clear path to much higher power systems.

The 14 kW Hall thruster system development, led by NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL), began with maturation of the high-power Hall thruster and power processing unit (PPU). The technology development work has transitioned to Aerojet Rocketdyne via a competitive procurement selection for the Advanced Electric Propulsion System (AEPS) contract. The AEPS contract includes the development, qualification and delivery of multiple flight-qualified electric propulsion strings. Each string consists of a 14 kW Hall thruster, PPU, Xenon Flow Controller (XFC), and associated intra-string harnesses. NASA supports the AEPS development through in-house EP expertise, plasma modeling capabilities, and unique world-class test facilities. NASA also conducts risk reduction activities in support of AEPS development and mission applications.

II. NASA EXPLORATION ARCHITECTURE

Phase 1 of the reference exploration architecture involves cislunar demonstration of exploration systems and buildup of a Deep Space Gateway (DSG), which is conceptually shown in Fig. 1. The DSG, when docked with an Orion vehicle, supports a crew of four for up to 42 days, providing the ability to support multiple cislunar mission options in Phase 1 and beyond. The first deployed Phase 1 element is the 50 kW-class Power and Propulsion Element (PPE), which is highlighted in Fig. 1. The PPE could be a co-manifested payload on Space Launch Systems (SLS) Exploration Mission-2 (EM-2) in the 2023 timeframe.[3] A major HEOMD architecture guideline is to use the Space Technology Mission Directorate (STMD) developed 40 kW SEP system that is being delivered through the AEPS contract.[4]

Phase 2 entails cislunar validation of exploration systems and buildup of a Deep Space Transport (DST) that provides habitation and transportation of crew into deep space, including supporting human Mars missions. The DST is designed to be reused for three Mars-class missions with minimal resupply and maintenance, and could be readied for a shakedown cruise by 2029.[3]

NASA is investigating a PPE conceptual design leveraging in-house mission concepts and vehicle designs for the SEP Technology Demonstration Missions and recently cancelled Asteroid Redirect Robotic Mission (ARRM).[5-8] The PPE relies on several key technologies including high-efficiency, high-power solar arrays and high-power, high-throughput EP. Functions for the PPE include: providing power to other DSG elements; serving as the DSG's main propulsion system; providing passive and active attitude control for the DSG; and providing communications with Earth, visiting vehicles and crew on extravehicular activities. The PPE acquisition strategy is still being formulated, and options are being evaluated. On July 17, 2017, there was a dual release of a Request for Information (RFI) to solicit information and ideas for possible use in a cost-effective development of the DSG PPE and a release of a synopsis for PPE studies.[10,11] The PPE study synopsis serves to inform industry that NASA intends to release a solicitation to seek proposals for studies of a PPE targeted for release in the September to October, 2017 timeframe.[10]

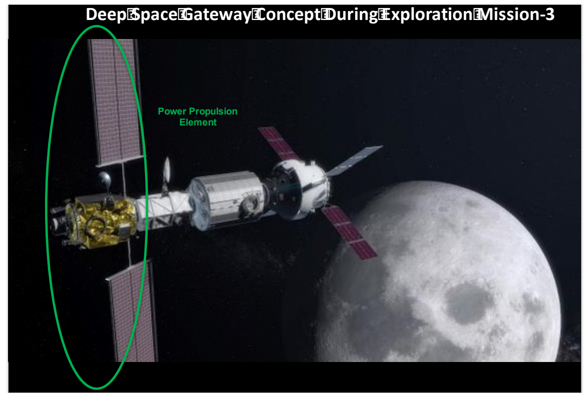

Figure 1: Conceptual design of the Power and Propulsion Element (PPE) integrated into the Deep Space Gateway (DSG).

III. ION PROPULSION SYSTEM (IPS) DESCRIPTION

The IPS features four identical AEPS Electric Propulsion (EP) strings with the overall performance capabilities shown in Table 1.

Table 1: Key Ion Propulsion System Capabilities.

Capability	Value
Total system power	40 kW
Maximum specific impulse	2600 s
Xenon throughput	5,000 kg
String fault tolerance	Single
Solar range	0.8 – 1.7 AU
Input voltage range	95 – 140 V

A key capability is that the IPS will be single fault tolerant while processing up to 5,000 kg of xenon over an input power range of 6.67 to 40 kW with input voltages ranging from 95 to 140 V. For nominal operation of three strings, the propellant throughput of 5,000 kg translates to 1,700 kg per thruster, by far the largest propellant throughput processed by any electric propulsion system.

Each string is composed of a Flight Thruster (FT), PPU, Xenon Flow Controller (XFC), and interconnecting cable harnesses. The IPS also includes the high-pressure portion of the xenon feed system, and mechanical integration hardware, including cabling. The xenon feed system consists of the xenon tanks, a propellant management assembly, and the AEPS xenon flow controllers. Each EP string is operated independently of the others by the spacecraft. Single fault tolerance is achieved through block-redundancy at the EP string level with internal redundancy for the xenon feed system components outside of the EP strings. The PPE conceptual design includes a 2-axis thruster gimbal assembly that is considered part of the Structures and Mechanisms Subsystem.

The PPE IPS design includes four metal-lined, composite-overwrapped pressure vessels capable of storing more than five tons of xenon propellant. The PPUs are mounted directly to heat-pipes on the same sides of the spacecraft as the solar arrays to minimize direct solar flux. The thrusters are mounted on individual deployable booms that reduce the impact of thruster plume interactions with the solar arrays and the docking mechanisms on the aft end of the spacecraft. The SEP thrusters also provide pitch, yaw, and roll control during ion thruster operation.

IV. AEPS DEVELOPMENT

In 2010, NASA STMD began developing large, deployable photovoltaic solar array structures for high-power electrical power generation and high-power EP technologies.[6,11-15] The maturation of the critical technologies required for the high-power SEP vehicle has made mission concepts utilizing high-power SEP viable.[16] The high-power electric propulsion investments were in areas having high technical risks and/or long-lead times.

IV.I NASA IN-HOUSE DEVELOPMENT

NASA in-house development of the 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS) thruster, shown in Fig. 2, and the HP-120V/800V power processing unit (PPU) have yielded three high-fidelity development model thrusters and a brass-board PPU that have been extensively tested and characterized separately, as well as demonstrated as an integrated system. The HERMeS development plan was formulated from a set of technical risks that could impact mission success.[17,18] Each element of the development plan is traceable to these risks. The comprehensive Technology Development Unit (TDU) test campaign that started in 2015 included: (1) performance, stability, thermal, and wear characterizations; (2) demonstrated thruster performance, verified magnetically shielded operation at high specific impulse, and affirmation that the internally mounted cathode minimizes the effects of facility pressure on performance; and (3) demonstrated TDU thruster compliance to qualification-level environments.[18-27]

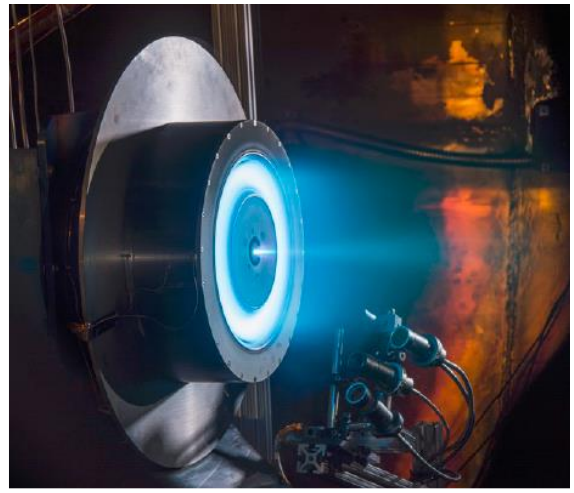

Figure 2: 12.5kW Hall-Effect Rocket with Magnetic Shielding (HERMeS) operating in VF5 at NASA GRC.

There was no direct development work for the XFC because it is low-risk and does not require a long development as a result of multiple options available utilizing flight qualified components. The NASA development work validated subsystem design methodologies, developed critical diagnostics, demonstrated performance that meets current mission requirements, made significant strides in life qualification, developed and validated an array of models, and provided the basis for the AEPS requirements. While the focus of the work is now on the AEPS contract and hardware designs, NASA continues to utilize the TDU thrusters for AEPS and risk reduction testing, as well as for AEPS-specific tests such as the Early Integrated System Test (EIST).

IV.II AEPS CONTRACT

The AEPS acquisition was initiated for engineering development and subsequent system qualification and flight unit fabrication in order to meet the required flight hardware delivery dates for ARRM. Although the ARRM mission has been cancelled, NASA is committed to developing the AEPS hardware to meet the needs of PPE and other potential missions. Given the lead times required for the development and fabrication of the EP strings, the AEPS contract was initiated on May 5, 2015 with the draft RFP release. The competitively-selected cost-plus fixed fee including an incentives contract focuses on development of an Engineering Development Unit (EDU) EP string and optional Qualification Model (QM) and Flight Model (FM) hardware delivery within three years.[28] This contract includes the thrusters, PPUs, xenon flow controllers, and electric harnesses between the subsystems. The contract was awarded to Aerojet Rocketdyne as the prime with major subcontractors ZIN Technologies and VACCO Industries. Management of the contract is being led by NASA GRC. Authorization to proceed for the contract was on May 16, 2016. In addition to the use of the AEPS development and hardware for PPE, the system is being considered for other mission applications.[29]

Aerojet Rocketdyne held the system PDR in August 2017.[30] Driving design challenges to the EP string system are the high-power and high-specific impulse system performance, flow rate control and measurement accuracy, immature vehicle interface definition, and the high thrust accuracy required for deep-space mission operations utilizing EP for primary propulsion and attitude control during EP thrusting.

Aerojet has built upon the HERMeS thruster development investments with the AEPS thruster design with improved structural capability to survive launch environments, a modified thermal management approach that allows for elimination of the HERMeS thruster radiator, and improvements to manufacturability including incorporation of flight-qualified electromagnet manufacturing process.

The driving PPU design challenges are the dynamic (input and output) operating range including high-power, high-voltage operation, mass, efficiency, the inclusion of the system digital control and interface capability in a high-noise environment, low conducted and radiated emissions to minimize impacts to the vehicle communications while thrusting, and challenges associated with the thermal and mechanical design of a complex, high-voltage, and high-power electronics box that is driving a dynamic thruster load. The AEPS EDU PPU mechanical packaging is shown in Fig. 3.

The AEPS Xenon Flow Controller (XFC) is a derivative of the Xenon Flow Control Module (XFCM) that was previously developed under a NASA contract by VACCO.[31] The design maturity of the XFC was furthest ahead of all of the AEPS components. Driving requirements for the XFC design are: mass flow rate control precision that feeds into system-level thrust precision accuracy; total flow telemetry accuracy that is important to accurately determine xenon propellant usage throughout the mission; propellant throughput; and off-nominal operation at up to 3000 psia inlet pressure (in an upstream regulation failure scenario).

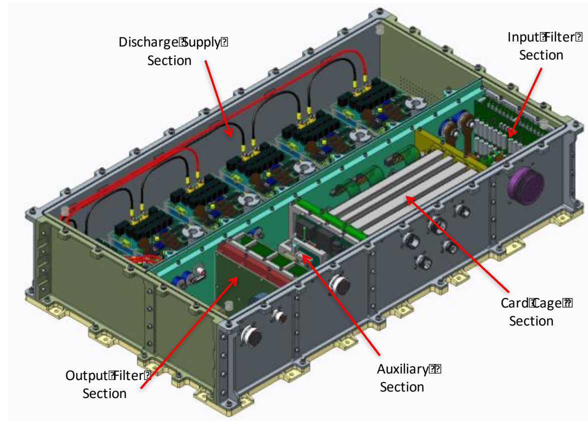

Figure 3: AEPS EDU PPU Design.

An AEPS EIST was completed in June 2017 to obtain an early characterization of system behavior, inform the design of EDU components, and reduce risk for the EDU integrated system test.[30] The EIST included the integration of the AEPS breadboard discharge supply unit, system flow controller card, xenon flow controller, and the HERMeS TDU-1 thruster. The AEPS EIST successfully demonstrated the discharge supply unit functionality while operating the TDU thruster. The test demonstrated closed-loop system operation during various startup scenarios and across the operating range, characterized oscillation at various points in the system, and characterized flow rate stability under closed-loop control providing data to improve closed-loop stability and performance.

VI. CONCLUSIONS

NASA is committed to the development and application of high power solar electric propulsion as a key element of its human exploration strategy. The recent announcement of a Power and Propulsion Element (PPE) as the first element of an evolvable human architecture to Mars has replaced ARRM as the most likely first application of the AEPS Hall thruster system. The AEPS contract development represents a continuation of STMD-funded efforts first initiated in the in-house development of the HERMeS thruster and HP-120V PPU conducted by NASA GRC and JPL. Ongoing advanced technology development work is being performed by Aerojet Rocketdyne under the AEPS contract that is managed by NASA GRC. Under the AEPS contract, Aerojet Rocketdyne is currently designing the engineering-model EP string and has recently completed an early integrated system test and held a system PDR. Fabrication of the EDU EP string components (Hall thruster, PPU, xenon flow controller, and high-voltage harness) began with planned EDU hardware and string testing planned in 2018. The AEPS contract has an option phase that can be exercised after CDR for qualification of flight strings that will meet the PPE's operational requirements and target launch date.

VII. REFERENCES

1. Smith, B. K., Nazario, M. L., and Cunningham, C. C., "Solar Electric Propulsion Vehicle Demonstration to Support Future Space Exploration Missions," Space Propulsion 2012, Bordeaux, France, May 7-10, 2012.
2. HQ, N., "Meeting Agenda and Minutes," NASA Advisory Council Human Exploration and Operations Committee Meeting, https://www.nasa.gov/sites/default/files/atoms/files/nac_heoc_march_2017_public_agenda_revb.pdf, [cited March 28, 2017].
3. Gerstenmaier, W., "Progress in Defining the Deep Space Gateway and Transport Plan," NASA Advisory Council Human Exploration and Operations Committee Meeting, https://www.nasa.gov/sites/default/files/atoms/files/nss_chart_v23.pdf, [cited March 28, 2017].
4. Free, J., "Architecture Status," NASA Advisory Council Human Exploration and Operations Committee Meeting, https://www.nasa.gov/sites/default/files/atoms/files/march_2017_nac_charts_architecturejmf_rev_3.pdf, [cited March 28, 2017].
5. McGuire, M., Hack, K., Manzella, D. H., and Herman, D. A., "Concept Designs for NASA's Solar Electric Propulsion Technology Demonstration Mission," AIAA-2014-3717, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.
6. Manzella, D. H. and Hack, K., "High-Power Solar Electric Propulsion for Future NASA Missions," AIAA-2014-3718, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2015.
7. Muirhead, B. and Brophy, J. R., "Asteroid Redirect Robotic Mission Feasibility Study," *2014 IEEE Aerospace Conference*, Big Sky, MT, March 1-8, 2014.
8. Brophy, J. and Randolph, T. M., "Status of the Asteroid Redirect Robotic Mission (ARRM)," IEPC-2017-031, 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 8 - 12, 2017.
9. NASA, "NASA Synopsis for NextSTEP BAA Appendix-C: Power and Propulsion Element Studies," Solicitation NNH17ZCQ006L-S, https://www.fbo.gov/notices/4a9a70d396472e75e5ad5bca8f6af881, [cited July 17, 2017].
10. NASA, "NASA Deep Space Gateway (DSG) Concept Power and Propulsion Element (PPE) Request for Information," Solicitation NNH17ZCQ006L, https://www.fbo.gov/notices/33368e53181a28d9fb7d9e8582aff8c7, [cited July 17, 2017].
11. Kamhawi, H., *et al.*, "Overview of the Development of the Solar Electric Propulsion Technology Demonstration Mission 12.5-kW Hall Thruster," AIAA-2014-3898, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.
12. Spence, B., *et al.*, "Technology Maturation and Advancement Update of the ROSA/MegaROSA Solar Array " Huntington Beach, CA, May 7, 2014.
13. Mercer, C. R. and et. al., "Solar Array Technology Development for Electric Propulsion," Huntington Beach, CA, May 11-14, 2015.
14. Murphy, D., *et al.*, "MegaFlex Solar Array Development and Test – Results from Phase 1 of the NASA Game Changing Development (GCD) Program for Solar Electric Propulsion (SEP) Solar Array Systems (SAS) Program," Huntington Beach, CA, May 7, 2014.
15. Kerslake, T. W., "Advanced Solar Arrays for NASA Electric Propulsion Missions," *SciTech 2015*, Kissimmee, FL, January 5-9, 2015.
16. Brophy, J. R., "Technology for a Robotic Asteroid Redirect Mission," *2014 IEEE Aerospace Conference*, Big Sky, MT, March 1-8, 2014.
17. Herman, D. A., *et al.*, "The Ion Propulsion System for the Solar Electric Propulsion Technology Demonstration Mission," IEPC-2015-008, 30th International Electric Propulsion Conference, Kobe, Hyogo, Japan, July 4 - 10, 2015.
18. Hofer, R. R., *et al.*, "Development Approach and Status of the 12.5 kW HERMeS Hall Thruster for the Solar Electric Propulsion Technology Demonstration Mission," *30th International Electric Propulsion Conference*, Kobe, Hyogo, Japan, July 4 - 10, 2015.
19. Hofer, R. R., *et al.*, "The 12.5 kW HERMeS Hall thruster for the Asteroid Redirect Robotic Mission," AIAA-2016-4825, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
20. Kamhawi, H., *et al.*, "Performance, Stability, and Pressure Effects Characterization Tests of NASA's 12.5-kW Hall Effect Rocket with Magnetic Shielding (HERMeS) Thruster,"

AIAA-2016-4826, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.

21. Williams, G. J., *et al.*, "Wear Testing of the HERMeS Thruster," AIAA-2016-5025, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
22. Peterson, P. Y., Kamhawi, H., Williams, G. J., and Gilland, J. H., "NASA's HERMeS Hall Thruster Electrical Configuration Characterization," AIAA-2016-5027, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
23. Katz, I., *et al.*, "Effect of Solar Array Plume Interactions on Hall Thruster Cathode Common Potentials," *14th Spacecraft Charging Technology Conference*, Noordwijk, Netherlands, April 2016.
24. Huang, W., Kamhawi, H., and Haag, T. W., "Plasma Oscillation Characterization of NASA's HERMeS Hall Thruster via High Speed Imaging," AIAA-2016-4829, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
25. Huang, W., Kamhawi, H., and Haag, T. W., "Facility Effect Characterization Test of NASA's HERMeS Hall Thruster," AIAA-2016-4828, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
26. Gilland, J. H., Williams, G. J., Burt, J. M., and Yim, J., "Carbon Back Sputter Modeling for Hall Thruster Testing," AIAA-2016-4941, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
27. Conversano, R., Sekerak, M., Hofer, R. R., and Kamhawi, H., "Performance Comparison of the 12.5 kW HERMeS Hall Thruster Technology Demonstration Units," AIAA-2016-4827, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 25-27, 2016.
28. "Thruster and Power Processing Unit Development for an Advanced Electric Propulsion System Acquisition," Solicitation Number: NNC15ZCH014R, https://www.fbo.gov/index?s=opportunity&mode=form&id=8f06bbacbbd8c3d2d6c1108d9b0c70ef&tab=core&_cview=1, [cited May 21, 2015].
29. Snyder, J. S., *et al.*, "Additional Mission Applications for NASA's 13.3-kW Ion Propulsion System," *2016 IEEE Aerospace Conference*, Big Sky, MT, March 5-12, 2016.
30. Jackson, J., *et al.*, "13 kW Advanced Electric Propulsion Flight System Development and Qualification," IEPC-2017-223, 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 8 - 12, 2017.
31. Cardin, J. M., Cook, W., and Bhandari, R., "Qualification of an Advanced Xenon Flow Control Module," IEPC-2013-382, 33rd International Electric Propulsion Conference, Washington, DC, Oct. 6 - 10, 2013.