Summary of Gateway Power and Propulsion Element (PPE) Studies

David Irimies
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
216-433-5979
david.p.irimies@nasa.gov

David Manzella
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
216-977-7432
david.manzella@nasa.gov

Timothy Ferlin
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
216-433-6297
timothy.j.ferlin@nasa.gov

***Abstract*— NASA's Power and Propulsion Element (PPE) is based on a joint industry/NASA demonstration of an advanced solar electric propulsion powered spacecraft to meet commercial and NASA objectives. The PPE can establish the initial presence in cislunar space for the Gateway through initial operations and the subsequent deployment of additional partner-provided elements for the cislunar platform. Five commercial vendors were selected to conduct PPE studies which addressed key drivers for PPE development and support for the Gateway concept formulation. The study vendors focused on their performance trades and assessing their strategic capabilities, leveraging their existing and planned capabilities for PPE development. The industry studies examined differences between prior Solar Electric Propulsion (SEP) mission concepts, expected industry capabilities, and potential needs supporting NASA's Gateway concept. These studies provided data on commercial capabilities relevant to NASA's exploration needs and reduced risk for a new, powerful, and efficient SEP-based PPE spacecraft.**

TABLE OF CONTENTS

1. INTRODUCTION

In support of Space Policy Directive-1, NASA's human exploration focus is on the Moon and lunar vicinity. The policy calls on 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 [1]." The development of the Lunar Orbital Platform, or Gateway, directly supports this directive. The Power and Propulsion Element (PPE) is under development as a foundational element.

NASA's approach is through partnership for research and development of a PPE with U.S. commercial industry. Through one or more partnerships with U.S. commercial companies, NASA intends to demonstrate advanced solar electric propulsion (SEP) technology that leverages commercially-available, U.S. spacecraft systems aligning with anticipated industry needs. The approach includes a spacecraft demonstration phase which will begin at PPE launch and end after insertion of PPE into a target orbit. NASA is targeting PPE launch in 2022. The PPE will be fully owned and operated by an industry partner through completion of combined demonstration objectives. After successful completion of the in-space demonstration, NASA will have the option to acquire the PPE for NASA use, specifically, as the first element of the Gateway.

In this approach, the PPE will provide the foundational capabilities for the Gateway, including power, propulsion, and communications. The Gateway will provide NASA with a strategic presence and critical infrastructure in near lunar orbit. The Gateway will provide core capabilities at the Moon, including crew habitation, science and technology utilization, logistics resupply, crew and science airlocks, and robotics. From there, NASA and its partners will conduct missions to the lunar surface, ground-breaking science and technology demonstrations, and gain key operational experience for deep space missions. NASA demonstration objectives are crafted to demonstrate advanced 50 kilowatt (kW)-class SEP which is extensible for future deep space NASA missions. Work on PPE is progressing rapidly with

NASA targeting launch in 2022 on a partner-provided commercial launch vehicle [2].

In November 2017, five companies selected through the Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA) were awarded contracts for studies to investigate the feasibility of developing a PPE based on a commercial spacecraft through a public-private partnership. In March 2018, the studies were completed. The results of these studies informed the approach NASA adopted for the PPE BAA initially released on June 21, 2018.

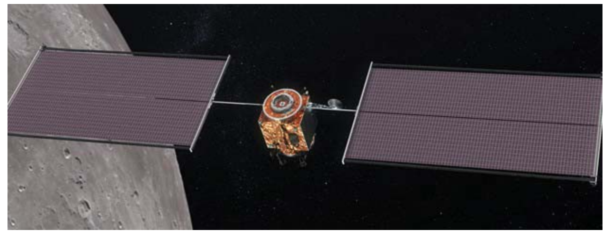

Figure 1. A notional Power and Propulsion Element in flight

2. PPE OVERVIEW

The Spaceflight Demonstration of a PPE will be an industry/NASA partnership for the development and spaceflight demonstration of a PPE [2, 3]. An image of a notional PPE is provided in Figure 1.

The resulting demonstrated SEP system is intended to support both NASA and U.S. commercial future applications. NASA-specific objectives for the spaceflight demonstration include the following:

• Demonstrate high-power, 50kW-class solar array and electric propulsion (EP) technology in relevant space environments,

• Demonstrate continuous, long-term electric propulsion operation sufficient to predict the xenon throughput capability and lifetime of high-power systems,

• Demonstrate the deployment and successful long-term, deep-space operation of high-power solar array systems with applicability to future higher power missions,

• Characterize in-space operation of a next-generation electric propulsion string,

• Demonstrate integrated SEP end-to-end system performance in relevant space environments,

• Observe and characterize performance of integral high-power SEP system including thrusters, arrays, bus, and payloads as they operate as an integrated system and as they respond to the natural and induced in-space environments,

• Demonstrate extended, autonomous high-power SEP operations in deep space,

• Demonstrate a high-data throughput uplink and downlink communication system using internationally-coordinated interoperability standards,

• Demonstrate PPE insertion into a crew-accessible Near Rectilinear Halo Orbit, and

• Obtain design, development, and flight demonstration data to determine acceptability of the PPE for the Gateway.

The spacecraft demonstration phase will also include TBD partner demonstration objectives. The spacecraft demonstration phase ends after insertion of PPE into a target orbit, which is to take place no longer than one year after targeted launch. After successful completion of the in-space demonstration, NASA will have the option to acquire the power and propulsion element for use. NASA's plan is to use the PPE as the first element of the Gateway. In this role, key PPE functionality is anticipated to include:

• Provide power to the Gateway,

• Provide transportation for the Gateway between cislunar orbits and perform any needed orbital maintenance,

• Provide attitude control for the Gateway in multiple configurations with and without visiting vehicles such as Orion,

• Provide Gateway communications with Earth, visiting vehicles, and the lunar surface, as well as act as a relay with Earth for visiting vehicles and lunar surface operations, and

• Support utilization experiments and technology demonstrations provided by NASA, international, or commercial partners.

Over its life, PPE is planned to support a number of Gateway configurations. Gateway is expected to be built up over time via a set of supporting elements. For all anticipated Gateway configurations, PPE plans to provide the same basic set of key functions.

The PPE is a partnership, and, as such, NASA developed a minimum set of requirements unique to NASA's needs [3]; the spacecraft developer will complete the full set of spacecraft requirements. This is intended to allow the industry partner to add the remainder of the spacecraft requirements to encompass their own unique commercial spacecraft and future applications. Therefore, the actual PPE design configuration is not yet known. However, based on the NASA-unique requirements and the overall functionality needed for the Gateway, it is anticipated that the PPE will utilize high-power, 50kW-class SEP to perform low-thrust propulsive functions. The PPE solar arrays will supply power to Gateway elements as well as to the electric propulsion system. A chemical reaction control system (RCS) will perform small translation maneuvers and attitude control along with momentum exchange devices. The PPE will have a forward docking port to support integration with Gateway and accept both SEP and RCS propellants in refueling from the adjacent Gateway element. The PPE will be refuelable (both SEP and RCS propellants) from the aft using a commercially-defined interface. The PPE will provide communications to Earth using X-Band and Ka-band systems as well as vehicle-to-vehicle communications via S-band links. PPE will also have external interfaces for science packages or robotic manipulators which would allow it to host demonstration packages.

The advancements in SEP that NASA wants to stimulate represent a power level three times the current state-of-the-art. The continual engagement with U.S. industry ensures smart steps are taken to advance the technologies in a way that mutually benefits both government and the private sector.

3. Study Overview, Objectives, Scope, and Topics

Study Overview

In November 2017, NASA awarded five PPE studies contracts solicited under the NextSTEP BAA Appendix C [4]. These studies investigated several key drivers for PPE development and support of the Gateway concept. The five commercial vendors selected for these studies focused on performance trades, assessing strategic capabilities, and leveraging their existing and planned capabilities for PPE development. Figure 2 provides notional concepts for these studies. The industry studies concentrated on examining differences between prior SEP mission concepts, expected industry capabilities, and potential needs supporting NASA's Gateway concept. The study vendors provided data on commercial capabilities relevant to NASA's exploration needs and reduced risk for a new, powerful, and efficient SEP-based PPE spacecraft. The studies completed March 2018.

Figure 2. PPE Industry Study Participants

Study Objectives

The first, and most significant, objective of the studies was to identify and understand significant potential synergies between PPE-specific capabilities and current and/or future commercially-available capabilities. This objective was multi-faceted, including: identification of PPE-specific capabilities which may be beyond current and/or future planned commercial capabilities; use of advanced SEP; innovative ideas for partnership business models including intellectual property, asset ownership, and timing of delivery of the asset and/or services to the Government.

The second objective of the studies was to evaluate and understand driving technical differences and implications between prior concepts and approaches developed under the Asteroid Redirect Robotic Mission (ARRM) and the vendors' proposed concepts for PPE. This objective also examined implications of meeting reference technical requirements and drivers for validating a concept of operations for PPE.

The third objective was to obtain data that supports NASA's ability to define, derive, and validate the PPE requirements and a baseline mission concept. This objective included identification of options and approaches to meeting PPE-specific capabilities, as described in Appendix C at the time of the studies solicitation [5], and for contributing reliability and verification/validation data for a PPE approach that supports a human-rated, integrated Gateway and Orion system.

Scope and Expectations of the Studies

The purpose of the PPE Studies fundamentally was to learn industry practices and desires of their trade spaces for PPE. NASA gained significant industry perspectives on the range of possibilities and recommendations for the PPE. The studies were not a typical, full, comparative assessment across vendors' work products, nor a Pre-Phase A or Phase A point design solution for NASA to evaluate feasibility. The studies were not expected to generate the solutions, nor did NASA dictate the solutions.

A key example of learning industry trade spaces was in understanding industry breakpoints in terms of meeting PPE capabilities and industry characterizing those breakpoints as hard breakpoints or soft breakpoints. Hard breakpoints were defined as new design or major modifications, in other words, fundamental architecture changes to a vendor's platform. For example, a hard breakpoint would result in a new design that is PPE unique. A hard breakpoint would also be defined as something derived from an earlier design with substantial modifications to design, fabrication, procedures, parts, and/or materials. Another example would be a vendor having to perform a new analysis. A final example would be a vendor having to perform a full set of proto-qualification tests, or life tests. Soft breakpoints were defined as minor modifications that still utilized vendor heritage designs or modifications which represented extensions to a vendor's platform. For example, a soft breakpoint would result in a minor modification to design, fabrication, procedures, parts, and/or materials. Another example is a vendor having to update pre-existing analyses. A final example would be a vendor having to perform a sub-set of proto-qualification tests.

Finally, NASA embraced the notion that industry had different answers in a given study topic or set of topics. For example, on controllability of PPE and the integrated Gateway stack, as well as approaches for station keeping and momentum management, vendors had different perspectives and approaches due to their differences in assumptions, their understanding of the technical issues and challenges, and their inherent performance capability.

Study Topics

The studies topics covered various use cases, technical and programmatic themes, and represented a broadened trade space from ARRM. Study topics included identifying approaches for PPE design and verification; meeting a 15-year lifetime for the PPE; minimizing the probability of the occurrence of failure modes; orbit maintenance; uncrewed autonomous orbit transfer; attitude control of the Gateway stack; power generation and transfer capability; managing battery charge/discharge during eclipse durations; accommodating International Docking System Standard Interfaces; rendezvous and docking of visiting vehicles; long-term, autonomous operations; high-reliability communications; accommodations for hosting hardware, including an optical communication demonstration; assessment of NASA Standards for a PPE in a human-rated Gateway/Orion system; extensibility to current and future commercial capabilities, as well as extensibility to future exploration; impacts of acquiring electric propulsion strings as part of the commercial bus; conceptual layout, potential clearance and blockage issues; and, PPE assembly, integration and test approach.

4. KEY STUDY FINDINGS

Synergies of PPE and Commercial Capabilities

All study vendors actively developed PPE-related commercial applications and business models that could form the basis of a public-private-partnership with NASA. Multiple commercial applications were also identified that are enabled or enhanced by PPE. Examples include incremental upgrades to existing capabilities and product lines, such as Electric Orbit Raising (EOR), and power systems upgrades; extensibility to and development of new applications, such as satellite servicing and space and servicing logistics (e.g. fluid transfer); and, emerging markets for commercialization of cislunar space, such as communication relay services (e.g. long-term service agreement in exchange for hardware development) and payload delivery.

Another finding is that while revenue generating payloads are trending to be a larger proportion of mass to commercial satellites, the paradigm of payload power dictating SEP capability may be shifting to focus instead on overall vehicle performance. The EOR duration is determined by EP power and spacecraft mass, and a higher power EP system enables the time-constrained EOR of large satellites, and furthermore, a PPE capability enables commercial high-power EOR.

The SEP system used by the PPE will rely on technologies developed by NASA specifically for this type of application: low-mass, flexible-blanket solar arrays that are extensible to power levels as high as 300kW and a magnetically-shielded Hall thruster propulsion system that operates at power levels more than twice that of existing systems. The development and demonstration of these technologies not only provide PPE an enabling SEP capability, they also enable a SEP primary propulsion capability which benefits future commercial and government spacecraft and missions.

The lower thrust and power level of current state-of-art SEP systems make them well suited for station-keeping applications, but the low thrust level has limited primary propulsion applications due to long orbit transfer durations. Over the last several years this limitation has been partially overcome by a new type of geostationary communication satellite designed as an "all-electric" spacecraft. By eliminating all chemical propulsion systems, including that used for the geostationary transfer orbit (GTO) to geostationary orbit (GEO) transfer, satellite mass can be cut in half, enabling launch vehicle insert into a more energetic "super-GTO" initial orbit. This lessens the orbit transfer burden placed on the SEP system and reduces the geo insertion time to several months. This approach was first used by Boeing with the launch of ABS-3A and Eutelsat 115 West B launched in March of 2015 but has since been adopted by other providers, including Airbus's Eutelsat 172B launched in June of 2017, and OHB-System AG's first Electra spacecraft launched in January 2017 [6].

The high-power SEP demonstrated by the PPE will allow the benefits demonstrated by these smaller all-electric satellites to be realized by spacecraft with wet masses two and three times larger. Shown graphically in Figure 3 with data provided by Tadros [7], it is possible to nearly double payload mass fraction by using an all-electric satellite configuration. Current all-electric satellites operate at 10 kilowatts or less with wet masses of 2,000 - 3500 kilograms. The SEP technology demonstrated by the PPE will enable all-electric spacecraft to accommodate payloads nearly twice the largest present-day satellites and allow dual-manifesting two spacecraft, each with a payload equivalent to that of the largest present-day satellites, on a single launch vehicle. The ability of a spacecraft to carry a payload that previously required two spacecraft and/or reduced launch costs resulting from dual manifest is believed over time to have a significant impact on the satellite industry.

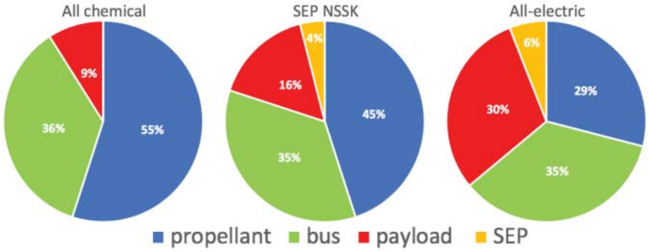

Figure 3. Geostationary Satellite's Mass Fractions
(All Chemical, SEP for North-South Station Keeping (NSSK), All-Electric)

The study also revealed the potential advantages of a commercial system approach by including implementation of proven techniques and technologies, and using existing vendor process standards and procedures to the fullest extent possible. The use of commercial standards, process, and specifications will maximize commercial synergy and minimize the PPE development cost. The degree of NASA engagement in the commercial approach may drive PPE cost and schedule.

The PPE schedule, while aggressive, is feasible if commonality with commercial platforms can be maintained, with managed changes and taking advantage of commercial experience. Commercial vendors have the ability to adapt to a fast-changing market with current procurement schedules in a 24-36 month order-to-deliver period.

Commercial launch vehicles open the possibilities in the PPE insertion point, demonstration durations, and capability demonstrated. Commercial launch vehicles also enable lightweight launch vehicle interface adapter and attachment fitting solutions. In addition, the PPE size and mass are within the demonstrated manufacturing capabilities of the study vendors, and the study vendors would be able to reuse a majority of their GEO platform hardware.

Implications to Meeting Reference Technical Requirements and Validating Concept of Operations for PPE

The study also found that existing regulated power systems can be utilized preserving heritage, whereas for some vendors, development of a new power system adds cost and risk. Also, power transfer from the PPE to Gateway is analogous to the criticality of reliably powering communications payloads: it is common for vendors to simultaneously use batteries (on the order of 10kW) with their power generation capability to manage peak loads e.g. orbit raising, providing additional power to payload(s).

Another key study finding is the PPE control of the Gateway is viable with commercially-derived guidance, navigation, and control systems and methodologies. For example, momentum wheels augmented with a reaction control system (RCS) eliminates the need for Control Moment Gyroscopes, thereby preserving heritage. The location of PPE at the end of the Gateway stack provides a large moment arm, which also facilitates a heritage approach. The larger control uncertainty is the overall inertia of the stack, as opposed to the moment arm. Nonetheless, control of even the maximum open architecture total mass is viable. Vendors also largely identified that a rapid slew capability is needed for orbit maintenance with Orion due to its tail-to-sun duration requirement, which can be met with RCS. Multiple attitude control implementations include momentum desaturation as frequently as every day, and such implementations are similar and in-family to the GEO communications satellite approach of momentum management. Finally, vendors largely indicate a preference for using RCS over SEP for orbital maintenance during crewed phases.

A Reliability-Driven Approach to Support the Gateway and Orion System

A final, key study finding is the insight NASA gained of the mission assurance and reliability ranges from the industry approaches and implementations. In order to promote commercial partnerships, NASA is intentionally pursuing a commercial-based approach using proven-reliable systems.

The PPE requirements for reliability are a direct flow down of requirements from Gateway in order to meet the overall Gateway system reliability. The PPE allocated hardware reliability supports Gateway compliance with program-level Loss of Crew and Loss of Mission requirements which support the human-rated Gateway-Orion System. NASA generated two reliability requirements for the PPE: one at one year after launch and another for the end of the on-orbit operational lifetime of 15 years. The first reliability requirement is part of the government acceptance of the PPE on orbit.

The mission assurance and reliability approaches and datasets received in the study addressed commercial operations and failure histories for achieving a 15-year PPE lifetime, ensuring crew-safety, and benchmarking industry best practices. The study vendors provided reliability data and verification and validation data for a PPE approach that supports a human-rated Gateway-Orion System. The study showed that developing a commercially-based PPE using an industry mission assurance and reliability-based approach can potentially satisfy the required PPE reliability requirements. This would be achieved using existing vendor tools and methods and is based upon extensive databases of greater than 15-year observed spacecraft-level, subsystem-level, and box-level reliability. In order to meet the PPE reliability requirements, changes, such as additional selective redundancy, would need to be made, particularly in newer technologies.

All study contract vendors agreed that the PPE reliability requirements (1 year and 15 year) are achievable, in a design-to fashion similar to their existing customer approach.

Of note, there are several factors which may impact the vendor's ability to meet the PPE reliability requirements by using commercially-based systems. The PPE Flight System includes Government-Furnished Equipment (GFE), such as the NASA Docking System. A commercial PPE provider will have to determine how to take reliability of GFE into account for future work. Any deviations from a proven reliable approach, either to accommodate GFE, NASA-unique functions, or other preferred processes or activities, may invalidate heritage reliability. These deviations have the potential to negatively impact both the predicted performance and resulting benefit to the commercial provider. These deviations, when necessary, must be based upon a thorough risk assessment.

5. SUMMARY

The PPE, as the first element to Gateway, will offer extensive functionality to the Gateway stack in cislunar space. The advantages of PPE in the Gateway facilitate numerous opportunities for technology development and demonstration and far-reaching scientific gains. The industry studies conducted for PPE over the last year have been critical in further innovation of PPE capabilities and development.

PPE is currently targeting launch on a partner-provided commercial launch vehicle in 2022. After the in-space demonstration of the PPE to complete industry and NASA functionality objectives, NASA will have the option to purchase the PPE for its use. The industry-provided PPE is an example of partnerships that continue to be an important element of NASA's strategy to innovate and further develop human exploration capabilities.

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