SOLAR ELECTRIC PROPULSION VEHICLE DEMONSTRATION TO SUPPORT FUTURE SPACE EXPLORATION MISSIONS

Bryan K. Smith, Margaret L. Nazario, Cameron C. Cunningham
NASA John H. Glenn Research Center, Cleveland, OH 44135

ABSTRACT

Human and robotic exploration beyond Low Earth Orbit (LEO) will require enabling capabilities that are efficient, affordable, and reliable. Solar Electric Propulsion (SEP) is highly advantageous because of its favorable in-space mass transfer efficiency compared to traditional chemical propulsion systems. The NASA studies have demonstrated that this advantage becomes highly significant as missions progress beyond Earth orbit. Recent studies of human exploration missions and architectures evaluated the capabilities needed to perform a variety of human exploration missions including missions to Near Earth Objects (NEOs). The studies demonstrated that SEP stages have potential to be the most cost effective solution to perform beyond LEO transfers of high mass cargoes for human missions. Recognizing that these missions require power levels more than 10X greater than current electric propulsion systems, NASA embarked upon a progressive pathway to identify critical technologies needed and a plan for an incremental demonstration mission. The NASA studies identified a 30kW class demonstration mission that can serve as a meaningful demonstration of the technologies, operational challenges, and provide the appropriate scaling and modularity required. This paper describes the planning options for a representative demonstration 30kW class SEP mission.

INTRODUCTION

Recent studies performed for NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) have demonstrated that SEP is critically enabling for both near term and future architectures and science missions. SEP is also providing cost effective solutions in challenging budget environments. The increased operational use in commercial systems and the move to higher power systems, demonstrated use in satellite mission recovery, high payoff for both human and science exploration missions, and technology investment from NASA's Office of Chief Technologist (OCT), are providing the necessary convergence and impetus for a 30kW class SEP mission.

NEED FOR SEP IN EXPLORATION

The NASA's vision to explore beyond the Earth-Moon system includes both robotic precursor and human missions.[1,2] A single human mission to a destination beyond the Earth-Moon system would require multiple large launch vehicles. Many architecture studies reflect the need for these types of missions based on multiple launches from the Earth's surface to deliver the required systems and propellants to an assembly point in space. High specific impulse in-space propulsion allows the dramatic reduction of total mass-to-orbit, and hence, number of launches for such mission architectures.

SEP provides such an advantage by providing the high specific impulse transportation solution that reduces overall mass-to-orbit. For missions beyond LEO, spacecraft size and mass can be dominated by the onboard propulsion systems and propellant that may constitute more than 50 percent of the spacecraft mass. This impact can be substantially reduced through the utilization of SEP due to its substantially higher specific impulse. SEP also provides versatile propulsion operation, enhancing operational capability, and robustness. This enables “on-the-fly” mission redirection or correction. Implementing SEP onto next generation spacecraft will require high power photovoltaic power and propulsion systems. To enable SEP missions at higher power levels, an in-space demonstration of an operational SEP spacecraft at power levels greater than current state-of-art is required. This demonstration will have direct applicability to a wide range of current and future NASA missions and should be extensible to future higher power systems that may require 100kW of power or more.

CURRENT STATE OF FLIGHT SYSTEMS

Electric propulsion is currently used on over 200 commercial satellites, primarily for on-orbit station keeping, due to its efficiency and reliability. Communications satellites dominate this category, and have mission lives of 15 years or more enabled by electric propulsion. Three of the largest applications are the Space Systems Loral 1300 bus with a 1.5kW Hall thruster, the Boeing 702 bus with a 4.5kW ion thruster, and the Lockheed Martin A2100AX with a 2kW Arcjet thruster. Electric propulsion has proven a highly reliable source of secondary propulsion for these systems.

The largest and most recent NASA use of SEP as primary propulsion is the Dawn spacecraft launched on September 27, 2007. As a mission belonging to NASA’s Discovery Program, Dawn travelled to the asteroid belt between the orbits of Mars and Jupiter, where it orbited one member of the main asteroid belt, Vesta, before heading to gather yet more data at a second, Ceres. The mission addresses questions regarding the role of size and water in determining the evolution of these two protoplanets, providing clues on the early formation of the solar system.

The Dawn spacecraft uses SEP for primary propulsion, which provides the efficient operation and ability to alter trajectory required to meet its mission objectives. The Dawn spacecraft utilized three xenon ion thrusters, with a specific impulse of 3100s and thrust of 90 mN, which were derived from technology demonstrated on the Deep Space 1 spacecraft. The whole spacecraft, including the ion thrusters, is powered by a 10 kW (at 1 AU) triple-junction gallium arsenide photovoltaic solar array. To get to Vesta, Dawn allocated 275 kg of xenon, with another 110 kg to reach Ceres, out of a total capacity of 425 kg of on-board propellant. With the propellant it carries, it can perform a velocity change of over 10 km/s, far more than any other spacecraft has done with onboard propellant after separation from the launch rocket. Dawn is NASA’s first purely exploratory mission to use ion propulsion engines and presently has over 24,000 hours of thrusting time.

In 2003, the Japan Aerospace Exploration Agency (JAXA) launched the Hayabusa SEP spacecraft to return a sample of material from a small near-Earth asteroid named Itokawa to Earth for further analysis. Hayabusa rendezvoused with Itokawa in mid-September 2005 and remained in close proximity to study the asteroid's topography before landing on it in November 2005. The four xenon ion thrusters at 1kW provided the primary propulsion. Samples of asteroid material were collected and returned to Earth on June 13, 2010, via a small re-entry capsule.

Recently, SEP proved its operational versatility during recovery efforts for the United States Air Force’s Advanced Ultra High Frequency (AEHF) Program. Launched in August 2010, the 6090 kg Space Vehicle 1 was intended to deliver the AEHF satellite to a geosynchronous orbit 36,000 km above the Equator, providing critical communication for the military. AEHF was placed in highly elliptical transfer orbit aboard an Atlas V and would perform perigee raising primarily with a liquid apogee engine. However, the apogee engine shutdown after a few seconds due to a propellant-line blockage. Attempts to re-ignite the engine failed, and the mission appeared lost.

Four days after the failure, the team devised a strategy to utilize the xenon Hall thrusters in conjunction with its hydrazine-fueled reaction engine assemblies as the primary propulsion to complete the insertion to geosynchronous orbit. The electric propulsion system was operated as the primary propulsion system from October 2010 to August 2011. This required the solar arrays to make many more transfers through the Van Allen belts. A plan to minimize exposure time was employed and the Hall thrusters fired 10-12 hours per day at apogee until they raised the perigee from 4,800 to 36,000 km. The electric propulsion system also provided thrust for final orbit circularization.

SEP TECHNOLOGY DEMONSTRATION BACKGROUND

FTD-1 History

The NASA's recent effort to fly an SEP demonstrator began with the Flight Technology Demonstrator (FTD-1) in the Exploration Systems Mission Directorate. The program was intended to support the President's vision for human spaceflight by aggressively pursuing technology to meet future spaceflight needs. For FTD-1, this included specific objectives for advanced electric propulsion and lightweight array technology.

As NASA reorganized its exploration and technology efforts, the project was moved to the newly created OCT in 2011 and remained a SEP Technology Demonstration Mission (TDM). The SEP TDM provides a technology pathway toward a large Human Exploration Formulation Team (HEFT) 300kW SEP spacecraft that would deliver humans and equipment to/from a NEO. The SEP TDM can now be viewed as more than solely a technology demonstration but an actual capability at the 30kW-class power level that could both advance the Technology Readiness Level (TRL) of high-power SEP technologies and serve a mission function to a variety of potential customers.

HAT/HEFT

Starting in 2010 under the direction of the HEOMD, the HEFT and later Human Spaceflight Architecture Team (HAT) both identified SEP as key to reducing mission cost and providing unique operational capabilities for human exploration. Missions to geostationary orbit (GEO), the Moon, Mars, and other NEOs were studied to determine architecture drivers, and thus allow NASA to address technical deficiencies. The study concluded that a SEP vehicle on the order of 300kW was a key enabler, reducing heavy lift mass by 50 percent and mass growth sensitivity by 60 percent.

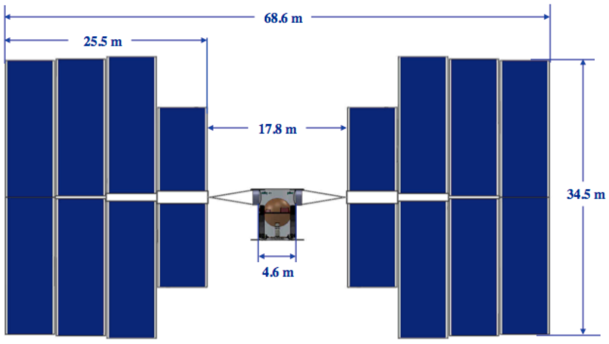

Figure 1. HAT nominal design for a 300kW SEP sized array

Waypoint

Recently, NASA embarked on a "Waypoint" study to examine the architectures required to place humans at Earth-Moon Lagrange point 2. This mission is considered one of the most challenging in cis-lunar space, and if demonstrated, would allow NASA to venture to other points and/or objects such as Earth-Sun Lagrange points or Martian Moons. Initially SEP systems of 2.8kW, 9kW, and 18kW were included in the trade space, constrained to existing capabilities. Preliminary results show that SEP is highly advantageous to meet launch mass constraints and provide affordable solutions for operations. Expanding the trade space to 30-70kW SEP systems are under consideration and have initially proven to be highly enabling.

EMERGING COMMERCIAL INTERESTS FOR HIGHER POWER SEP

At least one commercial satellite manufacturer has recently announced their intent to produce an all-electric vehicle capable of performing orbit raising from a GEO transfer orbit to a final GEO orbit. This marks a significant departure for commercial satellites from using electric propulsion for only station keeping operations to a wider range of primary propulsion operational capabilities. The resulting mass savings from eliminating chemical propellant mass can be traded for reduced launch vehicle class, greater payload capability, increased lifetime, or an optimized mix. The payoffs realized by an all-electric system offset the additional time to position the asset into its operational orbital position. Future higher power systems will further reduce the time to on-orbit operations, but will require higher power thrusters, power processing units, and solar arrays.

TECHNICAL CHALLENGES

Risk Assessment

The SEP TDM team performed a technology risk assessment for a high power (100kW+) SEP vehicle concept, to define the risk areas that could be addressed by a flight demonstration of a 30kW-class system or through ground tests. The top risks included lightweight deployable arrays, integration and operation of a high-power SEP system, power management, and high-power EP system. From this, technology maturation efforts in OCT were defined in the areas of array structures, power management, and electric propulsion for utilization on the SEP TDM.[3, 4]

Demo Sizing

The 30kW-class was selected for the SEP TDM based on several factors. First, this size provides logical progression to SEP vehicles in the 100kW+ range, and a 10-fold increase over Dawn. Second, the development of the technology for a 30kW class mission is achievable such that it does not prohibit a near-term flight demonstration. Third, and maybe most important, the 30kW-class provides a vehicle size that intersects the needs of future science missions, human missions (exploration, cargo delivery), commercial operations (larger all electric communication satellites) and military applications.[5] Once demonstrated, the TDM will provide the confidence to utilize SEP vehicles in this power regime, a design that can transition directly to other uses, and the completion of the first major step in higher SEP systems.

Ground vs. Flight testing

Many components and subsystems can achieve high TRLs through a comprehensive ground testing. Individually, the power systems and propulsion systems are good examples of this. However, retiring system level and operational risks via ground testing is a challenge for high power SEP vehicles due to the environmental effects and system interactions which cannot be fully replicated, if even understood, in ground facilities. Risks that can be addressed by flight-testing include the following:

- Operating of a large SEP vehicle through LEO, with the associated challenges of vehicle control, stability and dynamics

- Assessing effects of multiple passes through the Van Allen belts and Sun/shadow transitions

- Sustaining operability of the heat rejection system in vacuum, particularly for a high-power processing unit

- Assessing effects of low energy ions scattered from the thruster plume onto the solar array and radiators

- Interaction effects of multiple-engine operation

- Effects on new materials and systems in deep space

- Array pointing, degradation, and performance

FACILITY CONSIDERATIONS

The development and testing of higher power electric propulsion systems will necessitate investment in the ground-test facility infrastructure to accommodate the higher propellant flow rates of higher power thrusters and higher power systems of clustered thrusters. For a single thruster in the 10kW range, operating at 2000 seconds specific impulse would correspond to a flow rate on the order of 40 mg/s. Similar total flow rates could be realized when testing a cluster of thrusters of lower power levels. Based upon research performed on Hall-effect thrusters operating at ≤ 1.4kW in the 90's, a background pressure of ≤ 5x10^{-5} Torr has often been cited as the maximum for high-fidelity performance testing of Hall thrusters.[6] Since then, research and development of multiple Hall thruster systems has led to the conclusion that there is a lack of understanding of the interactions between the Hall thruster and facility pressure because of its complex nature and dependence upon the specifics of the Hall thruster design, operating condition, and facility characteristics. Facility pressures are seen to affect Hall thruster performance at pressure levels as low as 5x10^{-6} Torr and result in different global thruster characteristics, influence the onset of discharge plasma oscillations, and alter key features of the discharge plasma such as the electric fields.[6] To reduce the risk to future flight programs, it is critical that the vacuum chamber best simulate the anticipated space environment (i.e., test as you fly). There are few vacuum facilities within the United States that are suitable for high power electric propulsion testing; several of them are located within NASA Glenn Research Center (GRC) at Lewis Field and Plum Brook Station.[7] For accurate characterization of Hall effect thrusters, background pressures less than 1x10^{-5} Torr would be desired. Figure 2 depicts one of the GRC's unique vacuum facilities that will be undergoing facility modifications to increase the effective pumping speed in order to accommodate higher flow rates.

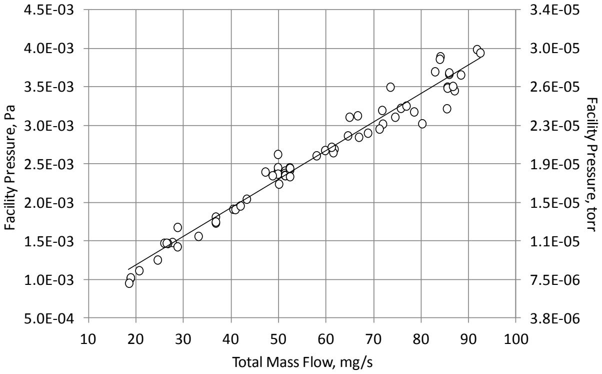

Figure 2: Facility pressure near thruster as a function of total flow rate for VF5 at Glenn Research Center.

CURRENT SEP DEMO PROJECT

Project Planning

The SEP TDM project resides at the NASA's GRC and currently reports to the NASA OCT. This project utilizes personnel and resources from GRC, the Jet Propulsion Laboratory (JPL), and the Air Force Research Laboratory (AFRL). Primary stakeholders for the SEP TDM are the OCT, HEOMD, and SMD. Potential non-NASA stakeholders include the Department of Defense and commercial companies. The project is presently in Pre-Phase A formulation with a launch planned for the 2018 timeframe.

Project Goals

The goal of the demonstration is the operation of a 30kW class SEP spacecraft performing a 1-year (nominal), high-energy orbit transfer mission to address the major risks associated with using SEP as primary propulsion for applications where chemical systems have traditionally been used. To support this goal, four objectives were identified:

- Perform an in-space demonstration that validates the technology readiness of advanced high-power electric propulsion and an autonomously deployed high-power flexible-substrate solar array.

- Demonstrate the orbit transfer capability of a high-power SEP spacecraft by performing extended duration operations in space environments including LEO to heliocentric space.

- Demonstrate electric propulsion, solar arrays, and power system technologies that can be adapted for use in next-generation, higher power SEP systems in an evolutionary fashion.

- Demonstrate a SEP-based, in-space transportation operational capability that provides significant performance advancement over previously demonstrated missions with respect to either change in velocity, net delivered mass, or some combination of the two.

Advanced lightweight arrays and high power electric propulsion systems are required to achieve this capability. Technology maturation efforts are focused on providing these systems for a flight in the 2018 timeframe. Since capability and technology demonstration are the key drivers, the mission profile and duration are flexible. The TDM would prefer to demonstrate at least 1 year of SEP operations to better understand system life issues.

Many firsts would be achieved by flying and operating a 30kW SEP stage from LEO to HEO with the combined balance of a relatively small bus, large Xe tanks, large solar arrays, high power management, and large electric propulsion thrusters.

Science Missions

As part of the TDM mission concept studies, JPL and GRC investigated SEP demonstration missions that would benefit NASA's science missions. Utilizing SEP systems of 15-50kW range, the team investigated 33 missions with various destinations and objectives and ranked them based on value criteria. Six missions were selected that were significantly enabled by SEP either by reduced cost or increased velocity. These included a Trojan asteroid rendezvous, a NEO surveyor mission, a Europa orbiter, a Jupiter multi-moon orbiter, and Uranus orbiter, and a Mars mission. A recent study completed for the Keck Institute for Space Studies to retrieve a NEO indicates that it would be possible to return a ~500,000-kg NEO to high lunar orbit by around 2025. Notable in the study is that the transportation capability is enabled by a ~40kW solar electric propulsion system with a specific impulse of 3,000 s.[16]

Technology Advancement in OCT

The SEP TDM requires technology maturation activities prior to flight. These technologies are identified on a SEP TDM roadmap as lightweight array structures and high power electric propulsion. The TDM team is also addressing system-level and operational risks through NASA-internal and contracted architecture studies and model development, specifically in the areas of trajectory analysis, control, and dynamics.

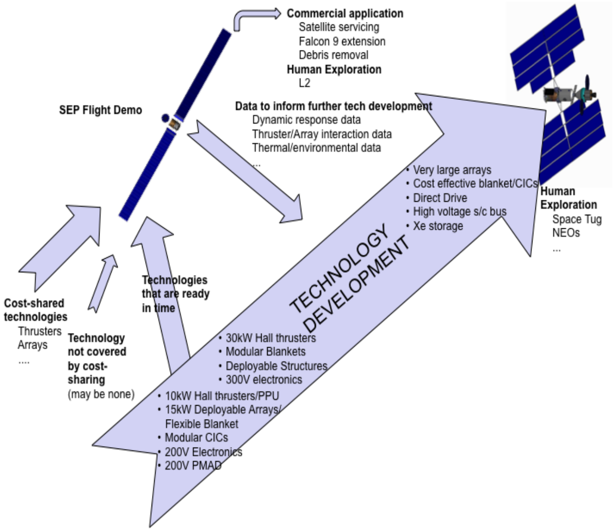

Figure 3. Technology Development Path for SEP

The large arrays required by the high power SEP offer unique challenges that require maturation investment. Current rigid panel arrays are limited to less than 30kW due to packaging requirements, structural designs and deployment schemes. To remove this barrier, flexible substrate arrays with novel deployment structures are required. These lightweight designs present their own challenges, including reliable deployment, natural frequency, and overall rigidity.[8] Because the arrays are massive compared to the rest of the vehicle, they must have a natural frequency high enough to not impact the vehicle's control system. Designing extremely large, low-mass, deployable arrays that are rigid has proven to be difficult. In May, 2012, NASA released a NASA Research Announcement titled, "Technology Development for Solar Array Systems in Support of Electric Propulsion", targeted at the 30-50kW class vehicle and future high power SEP.

The electric propulsion system presents another a development challenge due to the schedule needed for adequate life testing. In addition, maturity of either a new power processing unit (PPU) or a direct drive alternative will require rigorous and lengthy development projects. While existing Hall-effect and ion thrusters could be utilized in a clustered arrangement, increased propulsion capability is more enabling.[3, 9]

Voltage selection also plays a major role in power system architecture and potentially development needs.[10] While many flight ready components are available in sub-100V class electronics, utilizing a high voltage (300V+) electrical power system can reduce electrical mass by up to 40 percent. This would also impact the power transfer through the solar array gimbal and interface requirements for the propulsion system. In April 2012, NASA GRC released a Request for Information with the objective to develop an integrated electric propulsion system to TRL 6 that demonstrates the combination of thrust, specific impulse, and efficiency required for human exploration architectures and a possible technology demonstration mission to begin as early as 2018.

BAA, SAA AND GOVERNMENT STUDIES

Five Broad Agency Announcement (BAA) and two Space Act Agreement (SAA) contracts have been awarded to perform 135-day SEP concept studies to assist NASA in SEP project formulation. Each study will provide a TDM mission concept which is extensible to a larger future SEP system. The focus of these contracts is to define a TDM concept that retires major SEP system risks within a $200 – 300M cost constraint, including launch vehicle. The NASA also requested input on opportunities for cost sharing to enable a fully capable demonstration and potentially utilize the SEP vehicle for payload delivery for a partner in the science, discovery, exploration, military, or commercial community.

The awardees of the BAA contracts were Analytical Mechanics Associates, Inc, (Hampton, VA), Ball Aerospace and Technologies Corp. (Boulder, CO), The Boeing Company (Huntington Beach, CA), Lockheed Martin Space Systems Company (Littleton, CO), and Northrop Grumman Systems Corp. (Redondo Beach, CA). The two SAA studies will be provided by Aerojet (Redmond, WA) and Space Systems Loral (Palo Alto, CA). The BAAs and SAAs will be used to refine the SEP mission concept point of departure, identifying driving requirements, key risks, and long lead technology insertion needs. Cost and schedule will also be assessed to aid NASA in project planning. The studies are slated for completion with the final report and presentation in June 2012.

In parallel to BAA and SAA studies, the SEP TDM conducted an NASA-internal mission concept design to better understand the operational and system level risks. A configuration was selected that includes technologies that would be at Technology Readiness Level 5 or higher by the end of the projected preliminary design phase. The NASA-internal study mission begins with a launch on a low-cost expendable launch vehicle to LEO. The vehicle would deploy its arrays, perform a series of functional tests, and begin spiraling outward to GEO and then on to Earth-Moon Lagrange 2. This mission provides a challenging environment for a SEP demonstration, since it forces the vehicle to accommodate frequent shadowing and radiation belt exposure. It would also demonstrate a robust capability that can be used for numerous missions that are less rigorous. The mission would last a minimum of 180 days to test system operation in spiral out, propulsion system life, and array degradation.

Once all of the studies are complete, the results will be evaluated against Measure of Effectiveness (MoE), such as delivered payload delivery, change in velocity, and extensibility to higher power systems to develop a final Mission Concept. From this, top-level mission requirements will be established for a Government-led Mission Concept Review.

CONCLUSION

The economic advantages of higher power commercial vehicles along with NASA's need for capability driven missions for science and human exploration will continue to drive the evolution in high power SEP systems. It is anticipated that the operational experience gained through increased commercial use, coupled with NASA's investments in solar arrays, higher power electronics, and higher power thrusters, and ultimately the 30kW demonstration, will allow for the emergence of a new class of higher power SEP vehicles. Partnerships will accelerate the development and demonstration of the 30kW SEP capability for numerous applications in science and exploration.

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