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Evolved Commercial Solar Electric Propulsion: a Foundation for Major Space Exploration Missions

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ABSTRACT

Solar Electric Propulsion (SEP) has become vital in several commercial space applications and is positioned well for application in important space exploration and science missions. The commercial model provides a production base that can keep the hardware cost-effective and well-established commercial approaches are in place for scaling and tailoring SEP systems to US government missions. A notional roadmap is discussed, illustrating how these capabilities can evolve from the current commercial technology base and two applications to government exploration missions are presented. One is a possible NASA Discovery class mission to a main belt asteroid that can use current commercial SEP technologies with only minor modifications to accommodate voltage variation with solar distance. The other is the Asteroid Redirect Mission in which high-power third generation SEP derived from commercial capabilities is used to return a large asteroid mass to the Earth-Moon system. Finally, we make a case for a National SEP Testbed to support correlation between design and performance of smaller and larger systems, integrated with theoretical models describing performance and scaling relationships. Such a testbed will be of very high value once SEP systems reach a size and life that effectively prohibits full-scale system testing on the ground, and will help pave the way to low-risk major space transportation and exploration missions employing SEP.

INTRODUCTION

Second-generation Solar Electric Propulsion (SEP) systems now in commercial production are a key step forward enabling cost-effective and mass-efficient space transportation for exploration missions. As designed with 5 kW class Hall Effect thrusters, they are suitable for Discovery class missions carrying significant sensors and/or targeting faraway objects. As outcomes of a judicious methodology for scaling up prior and current SEP flight systems by a factor ~3, they provide a sound basis for similar low-risk steps toward 15-kW and then 50-kW class thrusters including essential solar array and power control equipment. The big missions supported by the latter capabilities directly benefit from US Government and commercial development of flexible solar arrays and NASA investments in very long life, high-power Hall thruster technologies.

Fielding these technologies for exploration missions can benefit from commercial space product development approaches which are strongly focused on early product configuration decisions, modularity and scalability, all anchored in design for manufacturability and rigorous qualification to an envelope of application environments. The benefits resulting from this uncompromising bottom line approach include schedule-certain development, qualification, product insertion, and cost-effectiveness of recurring production. Valuable SEP technology enhancements in work at US Government labs should be transitioned to industry for commercial development completion to further benefit the cost effectiveness of these missions.

This paper provides an overview of SEP's benefits and a notional roadmap covering enhanced commercial, smaller planetary, and large space transportation capabilities. Two examples are highlighted of exploration missions based on commercial production SEP spacecraft optimized for deep space operations. One illustrates how a JPL/SSL Discovery Class science mission proposed by Arizona State University to the main belt asteroid 16Psyche can be accomplished with nearly 100% commercial SEP hardware. The other shows how a much larger near-earth asteroid redirect and mass return mission can be performed with replication of the same, modular commercial hardware and further enhanced in capability with an additional ~3x scale up of key SEP components.

THE COMMERCIAL VALUE OF SEP

Manufacturers of large geosynchronous commercial spacecraft must carefully balance the costs of the spacecraft against the revenues enabled by the spacecraft's technologies. Over decades, the success of the commercial communication satellite industry has fueled ever more capable and diverse spacecraft capable of generating substantial incomes over their operating life. With nearly $200 Billion in annual revenues[1], the global satellite industry now includes direct to consumer services such as Direct Broadcast Television, Satellite Radio and Satellite Broadband. These direct-to-user applications have amplified the revenue leverage of each kilogram of satellite payload, and have more than ever driven a push to increase the payload mass fraction for each satellite at launch. Electric propulsion has tremendous benefit in reducing satellite propellant mass and has thus become a major enabler for increased payload mass fraction. Through careful implementation, it has now emerged as a reliable, highly successful technology and is now implemented on approximately 50% of all satellites produced by major satellite manufacturers such as SSL.

Beyond the cost of the spacecraft itself, one of the most significant underlying costs to the operators is the expense of placing the spacecraft in orbit with sufficient propellant to maintaining its position over its operating life of 15 years or more. Also, by international agreement, a spacecraft's total propellant load must include and budget reserves to move it into a non-synchronous graveyard orbit. Thus, the actual service life of a communication spacecraft is most often not determined by when its hardware fails but by when its station-keeping propellant is exhausted. SEP lowers the launch mass of a satellite by requiring much less propellant mass or conversely extends the operating life of the spacecraft. Figure 1 illustrates the major benefit derived from SEP in increasing payload mass fraction in commercial GEO communications satellite missions.

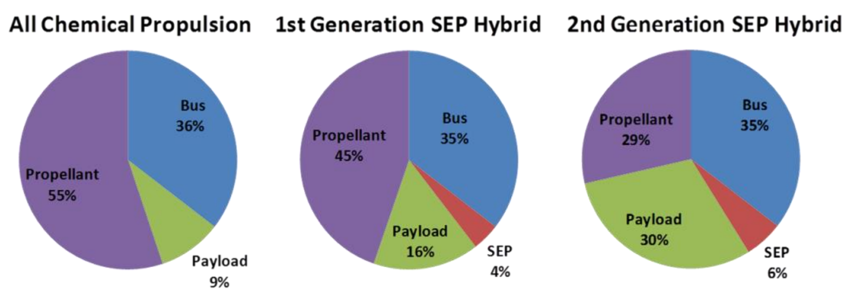

Figure 1. Beneficial Impact of SEP on GEO communications payload mass fraction

Overall, the availability of reliable SEP subsystems changes the optimization equations in the trades between payload mass, propellant mass, launch cost and operational life. While this yields slightly different solutions for different operator business plans, SEP provides compelling returns on investment in all high-end applications.

COMMERCIALLY SUCCESSFUL SEP: THE FIRST GENERATION

In 1997 the Boeing company implemented the first electric propulsion subsystem for a commercial communication satellite. The gridded ion thrusters known as XIPS operated at 0.4 kW providing 18 mN thrust and were used exclusively for north/south station-keeping[2]. In 2004, SSL started flying Russian Hall Effect thrusters manufactured by Fakel known as Stationary Plasma Thrusters or SPT-100s. Operating at 1.5 kW the SPT-100s produce 83 mN of thrust and were also employed to reduce the amount of north/south station-keeping propellant required over life. On orbit performance of these Hall thruster systems has been excellent and has proven its value to operators, and its success is well established with well over 32 SEP-equipped spacecraft placed on orbit or currently in production by SSL. Figure 2 shows a typical GEO communications satellite with SPTs positioned on deployable, steerable arms near the anti-nadir end of the spacecraft body.

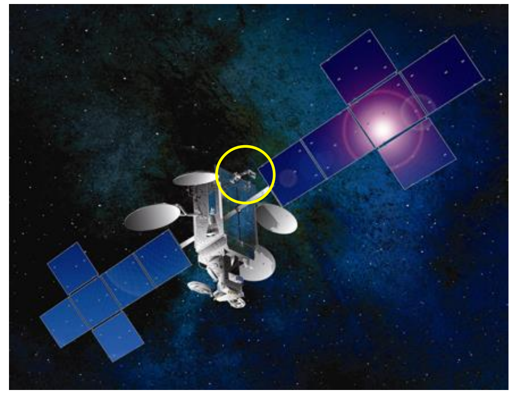

Figure 2. Typical GEO communication satellite with steerable Hall Thruster modules

ADAPTING COMMERCIAL SEP FOR GOVERNMENT MISSIONS

Government has often provided the initial funding stimulus for new space technologies, as well as the initial application demand for particularly high-leverage technologies. For SEP this is also true, even if it was the Soviet government in the case of the SPT system. But in the case of SEP, industry recognized the leverage for commercial missions and brought the technology at the proper scale to flight. Now Government is targeting applications of SEP that can benefit from this industry investment by applying the commercial products in near-term science missions and significantly scaled-up commercial hardware in future very large exploration missions.

Using commercial product development and qualification strategies and infusing recent government-developed theory and technology improvements in Hall thruster magnetic shielding provides the fastest and most cost-effective path to the science and human exploration benefits expected for large scale government missions. Industry can provide these capabilities in synergy with their existing commercial market base, yielding cost benefits via economies of scale and the inherent efficiency of competitive commercial operations.

SEP ROADMAP

Several years ago, SSL conceptualized a notional evolutionary roadmap for SEP development along three paths branching out from the original small-scale commercial GEO capabilities. This roadmap, shown in Figure 3, illustrates this with SEP technologies that SSL has a successful history of applying and with others that have high potential for future cost-effective implementation.

The key notion is that second generation SEP now being inserted into commercial space becomes a branch point for three different but interconnected types of missions. The center branch is the further evolution of commercial GEO systems which will likely stay close to the scale of current second generation technologies but may see occasional beneficial use of third generation SEP components. Power levels for GEO missions are not expected to grow as dramatically as in the 1990s and 2000s, and therefore second generation SEP remains a mainstay, with product improvements based on developments for other applications. The lower branch represents application of second generation commercial SEP to low- and medium-power science missions, especially in deep space. The third, top branch pushes development of third and fourth generation SEP in the service of large scale space exploration as well as derived commercial in-space transportation applications, with dramatically higher power and scaled-up and replicated hardware.

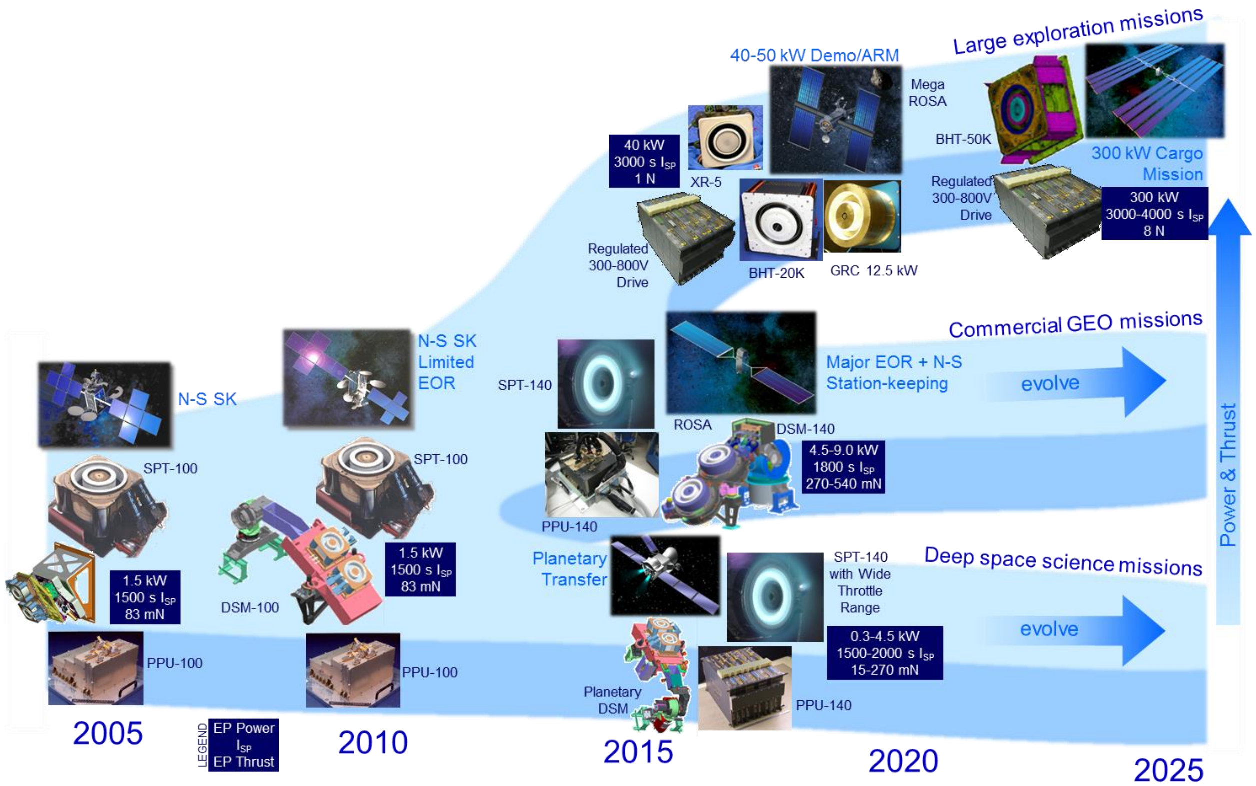

Figure 3. Notional SEP Roadmap showing three major application classes

In subsequent sections, we describe examples of government applications along the lower and upper branches and how they benefit from the commercial base at the branch point, the commercial infrastructure that is in place, and the commercial methodologies and practices that ensure performance and cost-effectiveness. Continued cross-infusion of technology improvements between these branches is an important goal to ensure that government and commercial applications stay at their most competitive and highest bang-for-the-buck levels. We will comment on one approach to keeping these technologies in synch via theoretical models, a testbed, and performance correlation, with the objective of making optimal scaling and design of these advanced SEP systems more of a science than an art.

SECOND GENERATION SEP: INITIAL TRANSPORATION CAPABILITIES

Commercial Development of Second Generation SEP

Expanding the role of SEP beyond low thrust station-keeping is being made possible by second generation 5-kW class Hall Effect Thrusters and gridded Ion Engines providing significantly more thrust (240 mN and 167 mN respectively)[3] enabling them to be utilized during the orbit raising phase when excess power is available. Despite the dramatic 3x and 10x performance enhancement, the second generation system provide orders of magnitude less thrust than traditional chemical propulsion systems. Second generation SEP still provides only a fraction of a Newton of thrust, and takes several months to perform orbit raising maneuvers that can be completed in days with 100-500 N class bi-propellant Main Satellite Thrusters (MST). However, with specific impulse (I_{SP}) in the thousands of seconds, SEP is almost an order of magnitude more mass-efficient in terms of propellant usage. This substantially lowers the propellant mass required to raise the satellite into its final orbit. The result is a tradeoff between the economics of time of flight and the expense of launch mass. For large operators of commercial fleets, with the ability to plan for and manage when new spacecraft are required on orbit, trading time of flight for lower launch mass or more payload is an attractive option. In the US, both Boeing and SSL have developed all electric spacecraft optimized for low launch mass, and configured to support low-cost shared launch on SpaceX's Falcon 9.

The second generation of SEP is now in commercial production and is poised to become a commercially successful technology based primarily on the transportation value it provides. SSL, working with Fakel, has qualified the second generation SPT-140 thrusters along with associated PPU-140 Power Processing Units and DSM-140 Deployable SPT Modules designed to position and steer the thrusters in both orbit raising and station-keeping operations. SSL is now applying this technology on spacecraft for launch in 2017. The cost-effective technology is expected to be widely applied and is interestingly already being considered for valuable spin-off applications in deep-space science missions as discussed in the next subsection.

Leverage for Discovery Class Missions

By starting with the capabilities and performance of the second generation SPT-140, Arizona State University's (ASU) proposed Discovery Class Mission to the asteroid 16 Psyche (Figure 4) exemplifies a capabilities-based approach to adapting commercial SEP for government applications. The Psyche Spacecraft's architecture was jointly engineered by JPL and SSL to achieve a significant milestone in the evolution of commercial SEP. It is unique in that, for the first time, a production line commercial SEP system dominates the power demand of the overall spacecraft architecture. Instead of powering a communications payload, SSL's high power production line solar arrays power a Hall thruster system designed to reach 3.3 Astronomical Units into the solar system carrying a cargo of highly sensitive instruments to survey a metallic world. The Psyche mission would for the first time explore the solar system's only exposed planetary core – directly measuring what is deep inside all planets to reveal how they accrete, differentiate and collisionally re-form.

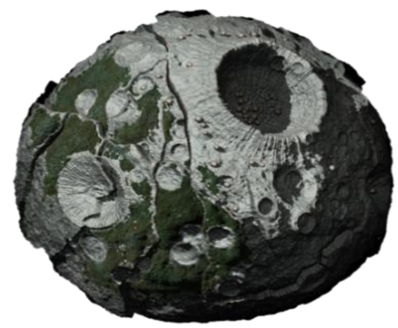

Figure 4. Metallic asteroid Psyche, proposed for exploration with a commercial-based SEP vehicle

As Discovery class missions are cost capped and required to demonstrate low technical risk through high technology readiness, they benefit significantly from the use of existing commercial technologies. Adapting those technologies to a different class of mission is easily achieved as most commercial space products are developed based on the commercial strategies emphasizing scalability, manufacturability, modularity, and covering a broad envelope of requirements.

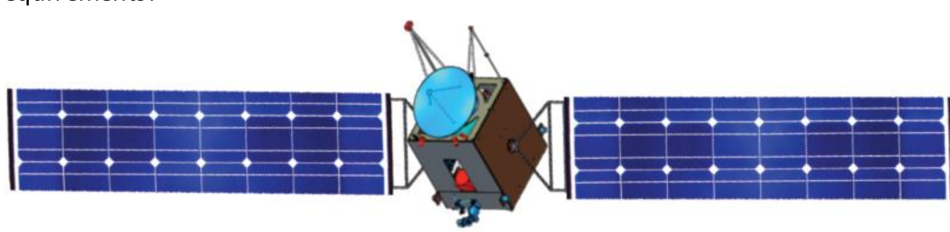

Figure 5. Concept of a small exploration vehicle with commercially derived bus features, including SEP

To achieve these benefits, the "sun to thrust" SEP system was carefully configured to maximally preserve the commercial off-the-shelf cost advantages of the existing commercial product. This capabilities-focused system optimization included accommodating the wider operating voltage range of the solar array over the range of solar distances with a revised cell string layout compatible with the four-panel mechanical design which SSL has been flying for decades. SSL's existing Solar Array Drive Assembly (SADA) is compatible as-is and existing Power Control

Unit (PCU) battery power converters are used to boost the solar array voltage over all mission conditions to the standard regulated bus voltage for input to SSL's PPUs. The deployable SPT-140 modules, providing two axes of mechanical steering, are used intact from the SSL production line. SSL's standard composites spacecraft structure provides the chassis for this SEP transportation bus, supporting seven heritage xenon tanks arranged in a modular fashion to provide the system propellant load. A key need was demonstrating the performance of the SPT-140 at a highly throttled-down operating point which is required as the spacecraft gradually approaches Psyche (Figure 6), a low thrust point well below that of the SSL commercial application. Hall thrusters have been shown to support a wide throttling range, but in a voltage-regulated mode, throttling must be accomplished through regulating the xenon flow. The JPL/SSL engineering team successfully demonstrated that a simple change to the existing flight-ready xenon flow controller electronics is capable of throttling the thruster to very low rates.

It is no longer true that only government developed solutions are capable of meeting government mission requirements. The vast majority of commercial environmental qualification requirements exceed those of point-design deep space missions such as the mission to Psyche. The harsh electromagnetic environment of the geosynchronous orbit, the typical 15+ year operational design point for GEO communications satellites, plus the additional radiation exposure when passing through the Van Allen belts in the course of orbit raising, together establish a radiation hardness design envelope that supports most deep space mission requirements. Acoustic, vibration, and shock dynamic environments are all dominated by the launch vehicle and commercial spacecraft are designed for a wide envelope of launchers well beyond those used by the U.S. government. While the nature of the thermal environments of deep space is clearly different than that of Earth's geosynchronous orbit, on close examination they are found to be functionally equivalent. Over the more than hour-long earth eclipses experience in geosynchronous orbit external spacecraft elements experience cold temperature extremes similar to the low solar illumination environment deep into the solar system.

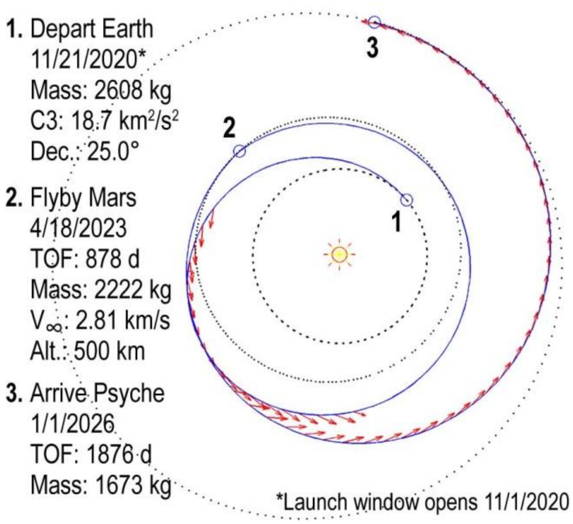

Figure 6. Psyche Mission Trajectory Arrows indicate thrust

The result of the JPL/SSL engineering team's capabilities-based approach to requirements definition, focused on using existing commercial space hardware, is a qualified system which is based substantially on existing current production technologies. In the few areas where modifications are required, the relevant performance specifications and requirements have been fully characterized such that they can be implemented by SSL via a low-risk protoflight test campaign. By eliminating the need for dedicated qualification campaigns through rigorous adherence to capabilities-based system optimization, the resulting "Psyche SEP Chassis" can be extracted from SSL's commercial production line on commercial firm fixed price contract terms where any remaining development risks are borne entirely by SSL. The adoption of commercial production line SEP technology by the ASU Principal Investigator represents a paradigm shift in very cost-effective, cutting-edge deep space exploration missions through judicious application of commercial technologies.

THIRD GENERATION SEP: MAJOR SPACE TRANSPORTATION CAPABILITIES

The Psyche spacecraft transports a mere 30 kg of scientific instruments into deep space, but tens of tons of equipment will need to be carried for major exploration missions, requiring a third generation of SEP capabilities. In looking forward toward that third generation we can anticipate achieving a similar 3x increase in component power, resulting in 15 kW class Hall thrusters with far greater capabilities and possibly another 3x increase to 50 kW class thrusters. As in the previous developments, the thruster's aperture will be scaled up and the power supply requirement achieved by increasing the number of 1.5 kW PPU modules again by a factor of three. Such SEP systems, producing nearly an order of magnitude more thrust than the first generation, will be able to perform major deep space transportation missions.

When the EP engine becomes the dominant user of spacecraft power, the solar array and power processing electronics can be optimized as was done for the proposed Psyche mission as an integrated sun-to-thrust system based on the overall economics of transportation efficiency. With the advent of magnetically shielded Hall thruster technology this third generation has the potential to dramatically lower the cost of in-space transportation to the point of enabling entirely new commercial applications to become viable. Infusion of government SEP technology expertise into development of the third generation of SEP systems could catalyze major space transportation capabilities available on terms similar to those so valuable to the global commercial satellite industry.

Government Investments

The US Government has conducted valuable technology work in-house and with contractors to advance key solar array and thruster technologies at power levels that support 50+ kW class missions. As summarized below, these technologies have major leverage for space transportation objectives. They are being or should be transitioned to industry so they can be produced cost-effectively for government and commercial applications alike to realize economies of scale.

Solar Arrays

Government investments in SBIR contracts are recognized as providing high levels of innovation for relatively modest investments. The weak point of these developments is that they are rarely transitioned into full scale production, especially for commercial use. In the area of SEP one of the most notable exceptions to this is the Roll Out Solar Array (ROSA) technology from Deployable Space Systems (DSS). The unique scalability advantages of ROSA technology have led to its adoption by SSL as a high-leverage commercially viable technology for its communications satellite product line. As a result of SSL's commercialization, ROSA and its inherent scalability will be available to the benefit of the future government applications. From the perspective of providing solar power for SEP propelled spacecraft, ROSA's inherent scalability makes it relatively straightforward to extend to the scale of 25 kW wings. MegaROSA deployable backbone structure technology can then be combined with these 25 kW building blocks to produce 75 kW and 150 kW wings.

Thrusters: The Promise of Magnetic Shielding

As dedicated SEP systems are implemented into large scale mission, thruster life and propellant throughput become paramount. Wear tests performed in NASA labs at Glenn and JPL have identified a phenomenon termed "magnetic shielding" in which the electromagnetic design of the Hall thruster is implemented in such a way as to protect the thruster's insulator walls from erosion. Through laboratory demonstration, the design principles and test validation methodology have been established. Currently, Hall thruster technology requires qualification through test with hundreds of kg of xenon throughput over a period of multiple years. With carefully coordinated design and verification, the next generation of Hall thrusters can be rigorously qualified for as many as 50,000 hours of operation and several tons of xenon throughput through limited testing and measurements combined with analysis. Qualification by analysis of thrusters with such significant capability will dramatically lower the development and implementation costs for large scale SEP systems, with qualification requiring months as opposed to years. This is a valuable result of great benefit to both government and commercial SEP applications.

These valuable government-developed capabilities are ready for immediate insertion into the next generation of Hall thrusters at contained costs following the pattern of two generations of successful SEP commercialization.

Test Facilities

Dedicated test facilities capable of large vacuum pumping rates are essential to testing of high capacity ion thrust EP systems. Electric propulsion systems have been shown to be sensitive to residual test chamber back pressure, a problem that only becomes more acute as larger amounts of xenon are flowed into the test chamber by the thruster. The government's large capacity vacuum test facilities are a valuable asset in the development and qualification of high power thrusters as are specialized thruster characterization facilities capable of evaluating thrusters life limiting wear mechanisms under operating conditions. NASA has provided services to commercial SEP developers, including SSL, for thruster and subsystem validation testing. These capabilities could be extended into a national testbed as will be recommended in a later section of this paper.

Asteroid Redirect Mission (ARM) Study

The purpose of the asteroid redirect mission study recently completed for NASA by SSL was to evaluate the adaptation of SSL's commercial spacecraft to meet the requirements of the Asteroid Redirect Mission. NASA provided performance objectives for the ARM mission at ~50 kW as well as for two evolutionary capability blocks beyond that at ~150 and 300 kW, based on which the Asteroid Redirect Vehicle architecture, development plan and costs were developed. The study emphasized the recognition of breakpoints in the ability to extend commercial performance capabilities to reach each of the designated performance blocks. SSL elected to define an additional Block 0 at 50 kW in which the approach developed for Psyche, using current and near term commercial hardware, was extended to maximum performance without stretching the basic existing bus configuration. By this definition, Block 0 constitutes the highest performance SEP transportation bus currently available from a commercial production line without the need for extensive qualification and major investment.

Block 0 - 50 kW Based on Current Technology

The Block 0 ARM architecture, illustrated in Figure 7, applies current second generation thruster and power management technologies along with near-term ROSA. For xenon storage, it uses replication of currently available, relatively small tanks. This design can return a near Earth asteroid mass up to 6,400 kg depending on the asteroid orbit and mission trajectory. The limiting factor for this is not the capability of the SEP system, but the mass of xenon that can be supported by the current spacecraft primary structure. Beyond that point, an upgraded, enlarged structural interface to the launch vehicle is required to achieve the performance objectives of the mission. It is interesting though that a limited asteroid mass return mission can in fact be executed with current commercial space hardware.

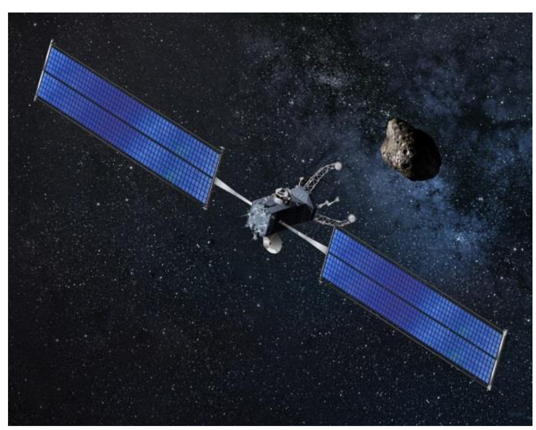

Figure 7. Block 0 50-kW Asteroid Redirect Vehicle with 3,600 kg Xe using current technologies

Block 1 - 50 kW Based on Second and Third Generation Technology

The Block 1 study results are founded on an enlarged spacecraft interface capable of supporting the very large xenon propellant loads envisioned. The system, illustrated in Figure 8, takes advantage of the scale-up extension of current Hall thrusters in the 5 kW class into the 15 kW class. It should be noted that it is possible to leverage the modularity principle to simply use heavy replication of 4.5 kW thrusters to achieve the same performance, as in Block 0. However, there is a point at which a very large number of thrusters and resulting complexity make the system more expensive to produce and unwieldy to integrate. In addition, advancing Hall thruster size and technology is a necessary evolutionary step to set the stage for extremely large scale, 150-300 kW SEP. Similarly, while large propellant loads could be contained within a multitude of smaller existing propellant tanks as in Block 0, the number of small tanks would become very difficult to accommodate for the Block 1 xenon load of 10,000 kg, and the cost of developing very large xenon tanks becomes worthwhile. Development and qualification of large thrusters and tanks are readily achievable at acceptable risk and cost under a well-structured fixed-price procurements. For ROSA, much of the risk of realizing the increased scale of hardware has already been retired through ground development and demonstration by DSS at the 25 kW ROSA level, and the MegaROSA deployable backbone structure has been demonstrated on engineering development hardware as well.

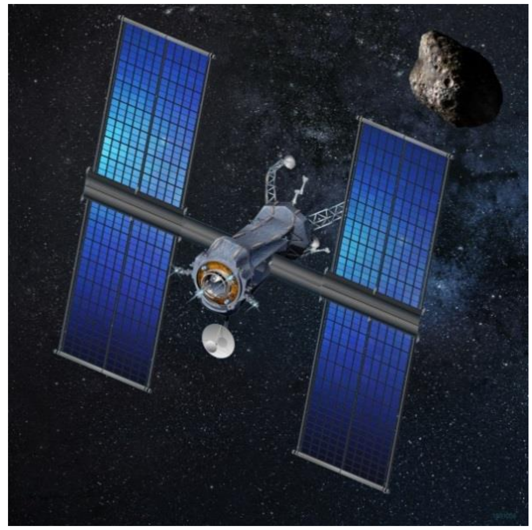

Figure 8. Block 1 50-kW Asteroid Redirect Vehicle with 10,000 kg Xe and extensibility to Block 1A

More than any other factor, the implementation of a dedicated high-power, high-voltage power train combined with the next generation of magnetically shielded 15 kW class thrusters provides a tremendous increase in propulsion effectiveness as quantified by the I_{SP} of the SEP System. One of the key findings of the study was that the only major technology breakpoint in extending SSL commercial capabilities to the asteroid mission is the spacecraft structure and interface to the launch vehicle.

Block 1A - 150 kW Based on Third/Fourth Generation Technology

Extending the architecture into the large capacity system envisioned for the 150-kW Block 1A, shown in Figure 9, is relatively straightforward to accomplish by incrementally scaling the system up and replicating large building blocks. In many ways this is made possible through the MegaROSA, thruster, power, tank and spacecraft structural configurations having been configured up-front with extensibility to Block 1A in mind. While scaling the 15 kW thruster into a fourth generation 50 kW class thruster is envisioned, Block 1A could also be implemented using the 15 kW class thrusters in larger numbers on a modular basis. Solar array scaling is again straightforward based on the modular, scalable ROSA and MegaROSA architectures from DSS, and for Block 1A is accomplished by adding four then-heritage 25 kW ROSA winglets. Xenon tanks are scaled by stretching the five Block 1

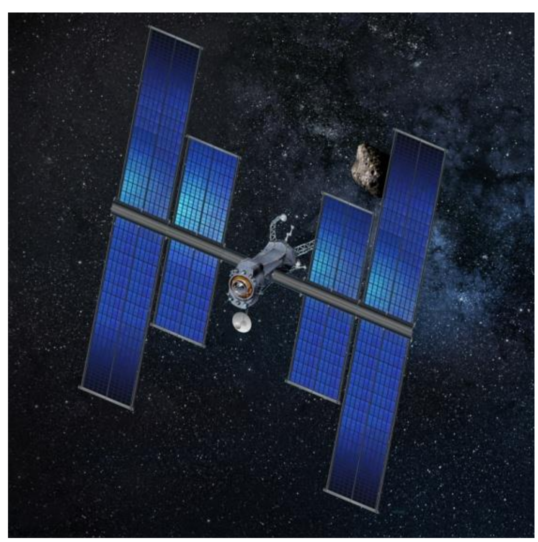

Figure 9. Block 1A 150-kW Asteroid Redirect Vehicle with 16,000 kg Xe and extensible to300kW Block 2

tanks to support 16,000 kg of xenon. Some of these capabilities could be seen as fourth generation SEP technologies, evolutionarily derived from the third generation at very modest risk.

SSL's Block 1A architecture illustrates one potential path forward in the adaptation of commercial approaches to achieve the development of major space transportation capabilities. Because they are grounded in existing commercial practices and production technologies they require relatively modest investments to dramatically advance the successful evolution of SEP for space exploration and commercial space applications.

A NATIONAL TEST BED

The next generations of Hall thruster technology will reach levels of power and long life that they will be increasingly difficult if not impossible to fully test as a complete end-to-end system prior to flight. Reliable system performance models to accurately simulate behaviors, along with physics-based techniques for analytically demonstrating high thruster throughput as a function of geometry and operational modes, will need to be developed and adopted by both industry and government. Validating these models and the scaling relationships requires a testbed where performance, both measured and analytically derived, can be correlated. Much of the knowledge and science required to accomplish this already exist in government, especially NASA's Glenn Research Center and the Jet Propulsion Laboratory, and industry also has significant expertise and practical design knowledge which should be utilized. Since SEP is the essential space exploration leverage technology, bringing all of this to bear on it appears valuable and necessary, and therefore SSL recommends establishment of a national SEP testbed at, for example, NASA Glenn and/or JPL.

This testbed will help validate scaling laws so that future, ever larger SEP systems can be credibly simulated at lower power levels. Correlation of, for example, 5 kW and 15 kW end-to-end SEP system performance via test and theory can then be extended to scaling up to 50 kW largely on theory supported by component-level test data. In addition, extreme, transient and contingency operating conditions and failure response can be tested at a feasible scale and analytically extended to larger and larger systems. Establishing these scaling and analytical performance laws on a recognized national testbed will lay the groundwork for subsequent confident leaps to larger, more capable systems. The implementation of such a national capability would significantly reduce the cost and risk of introducing new Hall thruster and EP system designs.

CONCLUSION

Solar electric propulsion has emerged as a commercially valuable technology by dramatically changing the distribution of spacecraft mass in favor of revenue-producing payloads. Building on a decade of experience, reliable and economical second generation commercial SEP systems can be leveraged to provide even greater returns to the global satellite industry and government-sponsored space exploration. Infusion of Government-developed expertise and technologies into SEP production by industry enables a high-power, high-performance third-generation of commercial SEP to emerge as the basis for major space exploration and transportation missions. It is recommended that this is supported by a national SEP testbed to reduce the cost of progressive insertion of ever more capable hardware at low risk.

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