ADVANCEMENT OF A 30 KW SOLAR ELECTRIC PROPULSION SYSTEM CAPABILITY FOR NASA HUMAN AND ROBOTIC EXPLORATION MISSIONS

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Solar Electric Propulsion has evolved into a demonstrated operational capability performing station keeping for geosynchronous satellites, enabling challenging deep-space science missions, and assisting in the transfer of satellites from an elliptical orbit Geostationary Transfer Orbit (GTO) to a Geostationary Earth Orbit (GEO). Advancing higher power SEP systems will enable numerous future applications for human, robotic, and commercial missions. These missions are enabled by either the increased performance of the SEP system or by the cost reductions when compared to conventional chemical propulsions systems. Higher power SEP systems that provide very high payload for robotic missions also trade favorably for the advancement of human exploration beyond low Earth orbit. Demonstrated reliable systems are required for human space flight and due to their successful present day widespread use and inherent high reliability, SEP systems have progressively become a viable entrant into these future human exploration architectures. NASA studies have identified a 30 kW-class SEP capability as the next appropriate evolutionary step, applicable to wide range of both human and robotic missions. This paper describes the planning options, mission applications, and technology investments for representative 30kW-class SEP mission concepts under consideration by NASA

I. INTRODUCTION

Electric propulsion (EP) has been recognized as one of the most efficient means of conducting large missions beyond Earth's orbit dating back to the 1950's as most famously reflected in the seminal space exploration architectures of Dr. Ernst Stuhlinger.[1] The earliest of these concepts, published in 1954 as shown in Figure 1, relied on solar power to generate electricity; an approach to EP presently referred to as solar electric propulsion (SEP). Subsequent concepts for space exploration spacecraft quickly shifted to nuclear power sources for the required electricity[2] in what is now known as nuclear electric propulsion (NEP). NEP has long shown incredible promise for future space exploration missions, as most recently exemplified by NASA's Jupiter Icy Moons Orbiter mission cancelled in 2005. However, due to a number of factors touched on by Choueiri in his excellent monograph on the early history of EP, the use of space-based nuclear power generation reached its zenith in 1987 with the flight of the Soviet Topaz reactor, and is unlikely to be revisited as the power source for EP for the foreseeable future.[3]

The use of SEP has not suffered the same difficulties as NEP and is now widely used. This has mainly been possible due to the synergy between EP and the onboard photovoltaic power systems required for the communication payloads of geostationary telecommunication satellites (geocomsats). There are currently in excess of 200 spacecraft that have successfully employed SEP systems and the vast majority of them are geocomsats.[4] The EP systems utilized for these applications are based on a number of different types of EP thrusters including resistojets, arcjets, Hall thrusters, and ion

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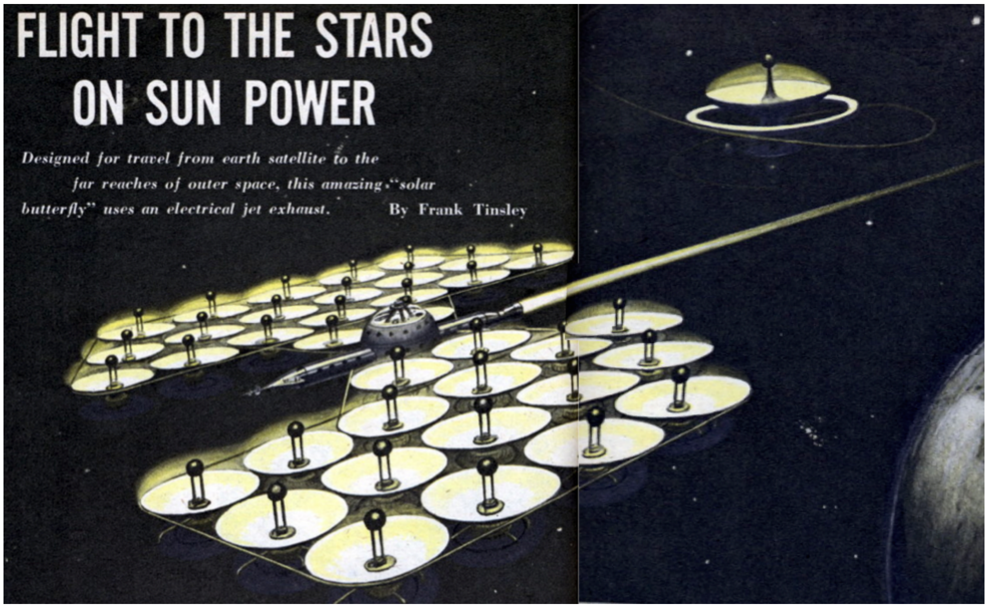


Figure 1: January 1956, "Designed for travel from Earth satellite to the far reaches of outer space, this amazing "solar butterfly" uses an electrical jet exhaust."[5]

thrusters, but all operate at kilowatt-class power levels. The very modest amounts of thrust produced by these kilowatt-class EP systems are typically measured in milliNewtons. The low thrust produced by these systems has made kilowatt-class SEP most well suited for station-keeping applications with a few significant exceptions. The exceptions have all been science missions that have used the EP systems analogous to what is commercially used on geocomsats for primary propulsion. These missions accommodated the use of low thrust primary propulsion in order to enable high Delta-V-transfers to be accomplished using only a very modest amount of propellant. This has proven to be enabling from a cost standpoint by allowing what would be a stand-alone mission to be conducted as a secondary payload as in the case of SMART-1 or by allowing what would be a large flagship-class mission to be conducted for a fraction of that cost as in the case of Dawn. Several of these SEP science missions are summarized in Table 1.

The challenge of utilizing kilowatt-class SEP for primary propulsion, even for the

Table 1 SEP science missions

Mission	DEEP SPACE 1	SMART 1	HAYABUSA	Dawn
Year Launched	*1998*	*2003*	*2003*	*2007*
Dry Mass	*400 kg*	*280 kg*	*465 kg*	*780 kg*
Xe Propellant Mass	*82 kg*	*80 kg*	*65 kg*	*450 kg*
Spacecraft Power	*2.5 kW @ 1 AU*	*1.8 KW @ 1 AU*	*2.6 kW @ 1 AU*	*10 kW @ 1 AU*
EP power	*2.1 kW*	*1.2 kW*	*1.2 kW*	*2.3 kW*
Delta V	*2.7 km/s*	*2.7 km/s*	*1.4 km/s*	*10 km/s*

small to intermediate-sized spacecraft shown in Table 1, is the long time required to process the EP propellant, resulting in long trip times. The rate at which the propellant is processed for SEP missions is directly dependent upon the amount of power provided to the EP system. This illustrates one of the inexorable truths of SEP: trip time depends on power. In order to address this, higher power EP systems have been or are being developed. There are two 5kW Hall thruster systems: one developed by Aerojet[6] and a second under development by Space Systems/Loral[7] and a 7kW gridded ion thruster system under development by NASA.[8] The impact that higher power EP systems can have when used for primary propulsion was clearly demonstrated when an SEP system utilizing two 5kW Aerojet Hall thrusters was used for orbit insertion of a large geocomsat when its liquid apogee engine failed.[9] This, in addition to other economic reasons, has in turn led to at least one major satellite manufacturer offering an "all electric" small geocomsat that utilizes high-specific impulse EP for all primary and secondary propulsion functions, including insertion from GTO to GEO.[10]

The idea of utilizing SEP as the primary propulsion for transporting very large payloads (up to 50mT) has most recently been revisited by NASA in 2010 with the announcement of their "capability driven framework" investigation of human-crewed exploration architectures.[11] In a desire to extend human-crewed exploration beyond Low Earth Orbit (LEO) to destinations including a near-Earth asteroid (NEA), a 300kw-class SEP architecture element was envisioned. This element, described in detail by Brophy et. al.[12] and shown in Figure 2, builds upon prior large-scale SEP vehicle concepts developed in support of human-crewed exploration architectures.[13,14,15] This concept also utilizes a large modular flexible-substrate photovoltaic solar array similar in concept to the system employed on the International Space Station.

Any of these prior multi-hundred kilowatt-class SEP vehicle concepts, including the early version from Stuhlinger, illustrates the primary challenge of implementing SEP on such a large scale: incorporating a large-lightweight system for electric power generation. The most straightforward way of meeting this challenge using present day technology is through the use of photovoltaic (PV) solar arrays. This is a result of the dramatic improvements in solar array technology that has occurred since its first application in 1958 onboard the Vanguard I spacecraft to the present day.[16] During this time PV solar cells have improved in efficiency from approximately 10% to over 30% for some emerging technologies and solar array wing sizes have

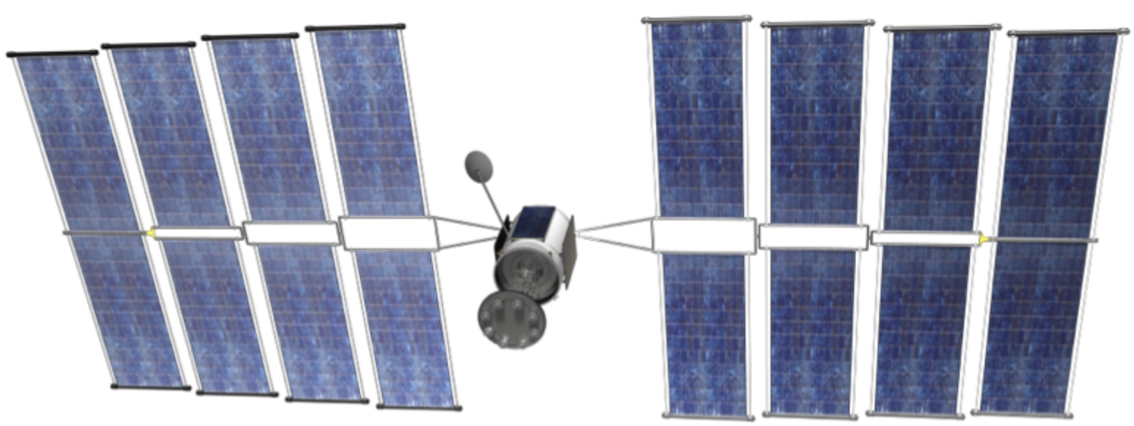


Figure 2: 300kw-Class SEP architecture element from NASA's capability driven framework

grown from small body mounted panels to large deployed structures such as those utilized on the International Space station. It is the development of large solar array systems that can be compactly stowed along with their SEP spacecraft within a single launch vehicle shroud, reliably deployed once in orbit, while still meeting all the additional mission constraints that is the primary technology challenge to the implementation of SEP at these power levels.

This paper will describe the development efforts that NASA has initiated to eventually enable multi-hundred kilowatt-class SEP vehicles for space exploration. These efforts are focused on an integrated SEP system at the 30kW-class power level. This power level was chosen for a number of reasons: it reflects a significant increase in the power level over present-day, kilowatt-class electric propulsion systems, it exceeds the power level of even the largest commercial geocomsats currently available, and it enables the quick transit of even multi-ton payloads due to an ability to process many hundreds of kilograms of EP propellant in months rather than years. Subsequent sections of this paper will review both NASA's ongoing solar array and electric propulsion development activities in support of these applications along with the formulation of an SEP technology demonstration mission utilizing these technologies.

II. SOLAR ARRAY DEVELOPMENT ACTIVITIES

The development of the technology needed for mass and volume efficient, large-area solar array systems (SAS) is critical for enabling high-power SEP. As a result, in April of 2012 NASA released a solicitation for SAS development activities to enable near-term SEP applications with total power levels of 30-50kW in a fashion that allows extensibility to power levels of 250kW or greater for future applications.[17] Mass and volume efficiency were specifically identified as critical technology needs because the benefits of SEP can only be realized if these systems fit within the lift capability and fairing constraints of launch vehicles significantly smaller than those required when using conventional propulsion systems. It was also specified that the SAS technology developed must enable systems capable of providing high reliability autonomous deployment while simultaneously providing compatibility with extended duration operations in a range of operating environments including those found in low Earth orbit and the Van Allen Radiation Belts.

As described within this solicitation the current state-of-the-art for solar power generation are systems capable of generating on the order of 20-30kW at beginning of life, however these systems are generally designed for operation over a narrow range of orbital altitudes and require either medium class or larger launch vehicles to accommodate their stowed size. As a result these systems are not readily extensible to the higher power SEP future applications as discussed above. The resulting SEP SAS development effort is anticipated to occur in two phases. For the first phase development to a minimum technology readiness level[18] (TRL) of 5 within 18 months in duration is required. In August 2012 NASA selected two companies for phase I development efforts: Deployable Space Systems (DSS) of Goleta, California and ATK Space Systems Inc., of Commerce, California.[19] Subsequently, it is anticipated that a Phase II effort will demonstrate the most promising of the selected SEP SAS concepts in space and that the in-space demonstration will be conducted as part of the flight demonstration of a 30kW-class advanced SEP spacecraft. A demonstration as a hosted payload onboard the International Space Station (ISS) or on a free-flying vehicle (e.g. ISS cargo delivery vehicle during the post ISS departure stage) may also be considered.

III. ELECTRIC PROPULSION DEVELOPMENT ACTIVITIES

The electric propulsion technology needed to ultimately propel multi-hundred kilowatt-class SEP vehicles is the long-term goal of NASA's current electric propulsion technology development activities. However, the near-term unavailability of power systems of this class has dictated that these efforts focus on extending the power level of individual thruster strings from the 5kW power level of existing state-of-the-art Hall thrusters to an intermediate power level of approximately 15kW. This represents a "stepping stone" type approach where the focus is on an intermediate power level that can be directly utilized in concert with the 30kW-class PV systems being developed in parallel.

The primary emphasis of these technology efforts is power processing and thruster technology. The thruster technology is based on recent developments in long-life Hall thrusters have focused on the concept of magnetic shielding as previously demonstrated with 5kW-class thrusters[20,21,22] Initial activities for this two-year development activity will focus on developing a 15kW-class Hall thruster incorporating these innovations to a TRL of 5.

In addition to thruster development there is a companion development of power processing. This two-year development activity has identified two separate approaches: the development of higher-input voltage conventional power processing unit (PPU) technology and the development of the technology required to implement a "direct drive" configuration. The PPU approach is investigating developing existing PPU technology sufficiently for possible inclusion as part of a 30kW-class advanced SEP spacecraft. The direct drive technology development activity is developing the technology to minimize the PPU by utilizing a high voltage PV system to directly power a Hall thruster as previously demonstrated in a prior investigation.[23] These efforts have focused on the challenges of integrating and operating Hall thrusters from a high-voltage PV array. Recent results of these activities have indicated that direct drive may offer an extremely attractive approach for future high-power SEP applications.[24]

IV. SEP TECHNOLOGY DEMONSTRATION MISSION DEVELOPMENT ACTIVITIES

In addition to solar array and electric propulsion technology maturation activities NASA is investigating mission concepts for a SEP technology demonstration mission (TDM) that addresses vehicle level integrated system issues while simultaneously retiring technology risks that cannot be adequately simulated on the ground. The goal of such a mission would be to demonstrate the operation of a 30-kW class SEP spacecraft performing a high-energy orbit transfer mission using EP for an application where chemical propulsion systems are traditionally used. An example of high interest would be an orbit-raising mission beginning in low Earth orbit at an altitude of approximately 400km (circular) to a final destination at the Earth-Moon L2 libration point. This initial orbit (or a similar orbit) is attractive for an SEP TDM because it is low enough to enable the SEP system to perform substantial orbit raising through the widest range of operational environments, including transit of the Van Allen Radiation Belts, while still being a sufficiently high altitude to mitigate atmospheric drag, which could lead to premature vehicle re-entry if initial EP operations are delayed. The initial and final orbits are also attractive because they coincide with the assumptions made for the development of reference mission architectures in support of human-crewed exploration missions to a NEA.[12]

Table 2: Solar Electric Propulsion Technology Demonstration Mission Objectives

Technology Mission Objective:	***Integrated System Mission Objective:***
Perform an in-space demonstration that advances the maturity of high-power electric propulsion technology and high-power solar array power system technology in relevant space environments and operational regimes.	*Demonstrate integrated SEP spacecraft design, fabrication and test as well as operational modes associated with orbit transfer.*
Extensibility Mission Objective:	***Capability Mission Objective:***
Demonstrate extensible high-power electric propulsion and solar array power system technologies and integrated SEP spacecraft operational modes that can be adapted for use in next-generation, higher power SEP systems.	*Provide a SEP-based transportation capability with performance advancements over those previously demonstrated.*

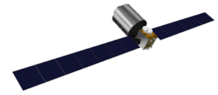
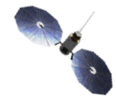
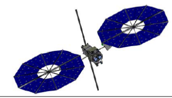
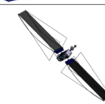
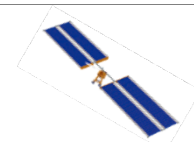
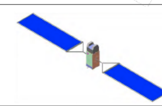
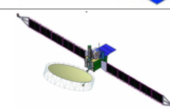
To date SEP TDM formulation activities have focused on establishing mission objectives and developing initial mission concepts that attempt to fully address these objectives. The four separate top-level objectives for this mission are presented in Table 2.

While the ideal SEP TDM concept would address each of these objectives equally well, there is a tension between the technology and extensibility objectives, and the integrated system and capability objectives. This is because it is possible to envision a SEP TDM concept based entirely on existing technologies that could address many of the integrated system and capability objectives. An example of this would be the LEO-to-GEO insertion of a SEP spacecraft utilizing off-the-shelf technology. Similarly, there are SEP TDM concepts that could be envisioned that would demonstrate particular technologies including those extensible to multi-hundred kilowatt-class SEP applications without addressing the integrated system and capability objectives. An example of this might be hosted payload demonstration of a high power EP system or advanced high-voltage solar array wing. The challenge of the SEP TDM formulation activity is to develop mission concepts that meaningfully address each of these objectives in a self-consistent manner.

Seven initial mission concepts designed to address each of these objectives have been developed over the past year through Glenn Research Center contracts with industry. A summary of each of these seven mission concepts is shown in Table 3.

To assess the technical value of these mission concepts twelve separate measures of effectiveness (MOEs) were developed to reflect how well the concepts addressed the individual mission objectives. Individual MOEs were then evaluated for each concept and aggregated and normalized to provide a zero to five score, with a score of zero reflecting that a concept did not address an objective at all and a score of five reflecting a concept that completely addresses an objective. The results from this assessment were then plotted on a radar plot as shown in Figure 3.

Table 3: Initial SEP TDM concepts

	Mission	*Power*	*Mass*	*New Technologies*	
1	*LEO to E-M L2 payload delivery*	*40kW*	*5900kg*	*none*	
2	*LEO to heliocentric space (asteroid rendezvous)*	*38kW*	*5400kg*	*Advanced high voltage solar arrays, high-power direct-drive EP*	
3	*LEO to GEO to LEO*	*22kW*	*2100kg*	*Advanced solar arrays*	
4	*GTO to LEO*	*30kW*	*1600kg*	*2 different advanced high voltage solar arrays, high power EP*	
5	*LEO to low lunar orbit (LLO)*	*25kW*	*1600kg*	*Advanced high voltage solar arrays, high-power direct-drive EP, advanced Xe storage*	
6	*LEO to GEO*	*40kW*	*6000kg*	*Advanced high voltage solar arrays, high-power direct-drive EP*	
7	*LEO to GEO*	*12kW*	*3000kg*	*Advanced power generation, advanced thermal control system*	

These data indicate that virtually all these initial concepts addressed the integrated system and capability objectives to a substantial extent. This confirms the efficacy of a free-flying SEP demonstrator as high-payoff approach for addressing these objectives. The extent to which the technology and extensibility objectives were addressed varied to a much greater extent between the various concepts. Concept 1, which essentially had no new technology offers very little benefit in these areas while Concepts 2, 5, and 6 address the technology and extensibility objectives to a much greater extent. This approach to evaluating mission concepts and mapping their

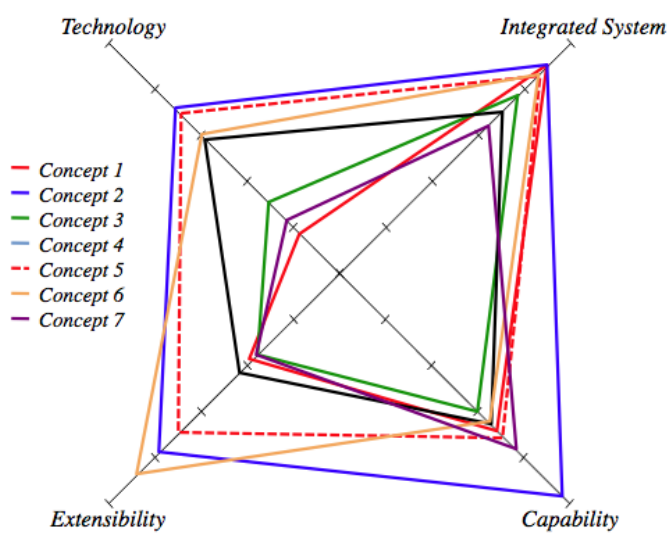


Figure 3: Technical Evaluation of Initial SEP TDM Concepts

"technical value" onto a four-quadrant radar plot is being adopted as a tool to evaluate future SEP TDM mission concepts.

The final ongoing activity that is part of the SEP TDM formulation activity is the identification of additional mission concepts that further define options for implementation. The seven initial concepts were conceived as standalone or rideshare mission concepts optimized for meeting NASA's objectives. In order to explore mission concepts that provide the best overall value to NASA, future mission concepts will consider cost sharing partnering as their basis. This is because it is believed that the crosscutting nature of a SEP TDM makes it useful for applications other than enabling future multi-hundred kilowatt-class human crewed exploration missions beyond LEO. These additional applications may be related to other government interests such as Department of Defense operational needs and NASA deep-space science mission needs. Commercial interests including the possibility of launch vehicle step down through SEP orbit insertion, as well as emerging concepts such as satellite servicing are also being considered as the basis for the development of future SEP TDM mission concepts.

V. CONCLUDING REMARKS

NASA has identified solar electric propulsion as providing an enabling capability for human-crewed exploration beyond low Earth based on multi-hundred kilowatt-class systems. Despite the widespread use of kilowatt-class solar electric propulsion systems for both commercial and robotic exploration applications, significant challenges remain to implementing solar electric propulsion at these higher power levels. To address these challenges technology development activities investigating photovoltaic solar array systems and electric propulsion have been initiated. These developments are focused on applications at the 30kW-class power level.

A 30kW-class power level was selected because it provides a significant increase in capability over present-day solar electric propulsion systems, it exceeds the power level of even the largest present-day geostationary communication satellites, and will enable the efficient in-space transportation of even multi-ton payloads. Developments at this power level would serve as an intermediate goal on the path towards higher power systems. It is also believed that solar electric propulsion systems at this power level can provide significant operational benefits for present day applications.

To more fully address the challenges of implementing operational solar electric propulsion spacecraft at this power level a solar electric propulsion technology demonstration mission is being considered by NASA. Formulation activities related to the solar electric propulsion technology demonstration mission have focused on defining the objectives of such a mission and developing and evaluating mission concepts designed to meet those objectives. Follow-on activities will focus on developing additional mission concepts based on potential partnership applications. Upon development of a suitable stand-alone or partnership based mission concept that meets the projects technical objectives while satisfying the anticipated project constraints it is anticipated that the solar electric propulsion technology demonstration mission formulation activity will transition to an actual flight project. Based on current NASA plans this would happen by 2015.

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