

High-Power Solar Electric Propulsion for Future NASA Missions

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NASA has sought to utilize high-power solar electric propulsion as means of improving the affordability of in-space transportation for almost 50 years. Early efforts focused on 25 to 50 kilowatt systems that could be used with the Space Shuttle, while later efforts focused on systems nearly an order of magnitude higher power that could be used with heavy lift launch vehicles. These efforts never left the concept development phase in part because the technology required was not sufficiently mature. Since 2012 the NASA Space Technology Mission Directorate has had a coordinated plan to mature the requisite solar array and electric propulsion technology needed to implement a 30 to 50 kilowatt solar electric propulsion technology demonstration mission. Multiple solar electric propulsion technology demonstration mission concepts have been developed based on these maturing technologies with recent efforts focusing on an Asteroid Redirect Robotic Mission. If implemented, the Asteroid Redirect Vehicle will form the basis for a capability that can be cost-effectively evolved over time to provide solar electric propulsion transportation for a range of follow-on mission applications at power levels in excess of 100 kilowatts.

I. Introduction

The high specific impulse provided by solar electric propulsion (SEP) has long been recognized for the mission benefits it provides. Despite that, it wasn't until geostationary (GEO) telecommunication satellites began using SEP for North-South station keeping (NSSK) beginning in the mid 1980's that spacecraft began to routinely realize these benefits. Since that time the number of operational SEP spacecraft has grown at a rate of approximately ten per year to a high of 236 in 2013, with nearly half of all satellites currently located in GEO using some type of SEP for NSSK.

This widespread acceptance of SEP for GEO applications is entirely attributed to economic considerations. The economic benefits include reduced launch mass, increased payload mass, increased operational lifetime, or some combination of all three characteristics. The penalty paid for this benefit was increased complexity and a willingness to perform station keeping with very low thrust, relative to conventional chemical systems. The low thrust, typically measured in millinewtons, meant that regular orbit-correction maneuvers would take hours to execute. The increased complexity was mitigated somewhat by utilizing kilowatt-class SEP systems that essentially utilized the power and heat rejection systems already required for the communication payloads of these spacecraft.

Utilizing these same kilowatt-class SEP systems for orbit transfer, rather than orbit corrections, also offered the benefit of significant launch mass reduction, but the very low thrust necessitated relatively lightweight spacecraft and very long thrust periods. In 1991 with the launch of the Deep Space -1 technology demonstrator, NASA began implementing SEP for this type of application. A decade later, with the launch of the Dawn spacecraft in 2007, the use kilowatt-class SEP for orbit transfers was taken to its practical extreme for a NASA mission. Fully fueled the Dawn spacecraft had a total wet mass of just over 1200 kilograms; 450 kilograms of that mass was xenon propellant that would require over 6 years of full power operation to process. To provide an equivalent total impulse to a Dawn-sized spacecraft using a conventional bipropellant chemical system would only take a manner of hours, but would require over 66,000 kilograms of propellant.

Unfortunately not all missions can tolerate thrusting for multiple years in order to achieve huge potential mass savings. Additionally, there are certain missions that require a minimum ratio of thrust-to-spacecraft-mass such as when operating in a gravity-well. The result of these limitations is that kilowatt-class SEP has become something of a niche form of space propulsion for NASA missions that is seen as best suited for non-time-constrained, deep space missions to small-bodies. To overcome these limitations NASA would require higher power SEP systems with higher thrust that can achieve the same kind of mass savings as low power systems without the penalty of prohibitively long trip times. This is an objective that NASA has investigated multiple times since the early 1970's. With a present day mandate to once again extend human exploration beyond low Earth orbit (LEO) NASA is currently reexamining high power SEP for its ability to

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cost-effectively enable various exploration architectures.

II. Background

To overcome the thrust time limitations of implementing SEP at the kilowatt power level NASA has long sought to combine multiple thrusters onto larger, higher-power platforms to perform a wide range of crosscutting missions. In 1971, under contract to the NASA Ames Research Center, TRW completed a detailed conceptual design of a multi-mission solar electric-stage, a 17.5-kilowatt SEP vehicle designed to be launched from a Titan class booster.¹ This spacecraft was designed to have a mass of 1,590 kilograms including 462 kilograms of mercury propellant; similar in size to the previously mentioned Dawn spacecraft, but with nearly an order of magnitude higher thrust. Five different types of missions were chosen as the basis for this design. These missions included: a close solar approach (as close as 0.1 AU); a Mercury orbiter with a periapsis altitude of 500 kilometers and eccentricity of 0.9 or less; an out-of-ecliptic orbit with an orbit inclination of at least 45 degrees; a comet rendezvous; and a rendezvous with a major asteroid such as Ceres. Each of these missions was to be completed with trip times on the order of two years or less. Design highlights include six 4.5-kilowatt, 3000-second mercury ion thrusters and rollout solar arrays. This concept is shown in Figure 1.

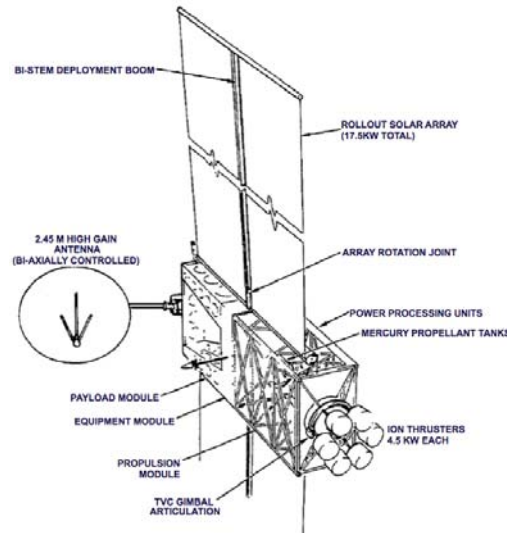


Figure 1: TRW multi-mission solar electric-stage [1971].

In 1974 parallel studies were initiated at Northrop and Boeing under contract to the Marshall Space Flight Center to design and evaluate an even more capable Solar Electric Propulsion Stage (SEPS) for use with the Space Transportation System (STS) shuttle orbiter currently under development.^{2,3} At that time the SEPS was identified as an in-space transportation element with the potential to cost-effectively augment the capability of the STS for missions beyond low Earth orbit (LEO). Some of the key constraints for the study were: assume a 25-kilowatt beginning-of-life (BOL) power level, launch via the Space Shuttle, design to perform geosynchronous missions and to be readily adaptable to planetary missions, and the ability to deliver multiple payloads to synchronous orbit, collecting spent payloads from synchronous orbit, and interchanging up-and-down payloads with a tug. The designs were also to utilize a technology cut-off date of September 1975, resulting in 3-kilowatt, 30-centimeter mercury ion engines based on current propulsion technology development efforts being conducted at what was then the NASA Lewis Research Center.

The 25-kilowatt Northrop SEPS concept shown in Figure 2 used a rollout type solar array as proposed by TRW and an array of nine ion thrusters. The Northrop SEPS had an estimated mass of 2116 kilograms including 907 kilograms of mercury propellant. Also, as part of this effort a traffic model was developed that indicated there were 121 distinct payloads that could be delivered by the vehicle over a decade starting in 1981. The majority of these were GEO payloads. Of note was the consideration of operating the solar arrays at high voltages, using a configuration that has since been known as “direct-drive.” For this application a reduction in solar array size by approximately 9% was enabled by the elimination of the inefficiencies in the thruster power conditioning units. This was seen as highly desirable as solar array costs were a significant part of the overall vehicle cost. A final note, the estimated cost for the development and delivery of the first unit was estimated at \$120 million dollars in 1975 dollars. This estimate did not include launch or mission operations. This would be the

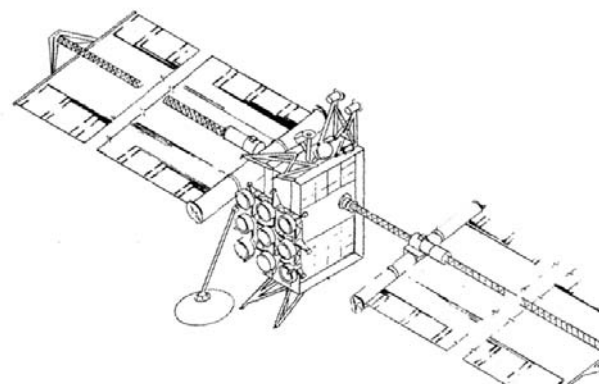


Figure 2: Northrop Solar Electric Propulsion Stage [1975].

equivalent of \$530 million dollars in 2014 based on inflation.

The Boeing SEPS design, shown in Figure 3, utilized a similar approach with 10 rather than 9 thrusters, a difference deemed necessary to meet vehicle reliability requirements. The 25-kilowatt Boeing concept had a mass of 2117 kilograms including 907 kilograms of mercury propellant. The design included the use of flexible-membrane solar array wings with Z-fold panels and a central deployable mast under development by Lockheed at that time, a configuration similar to that eventually used on the International Space Station. The concept was based on thrusters with 10,000-hour (~14 month) operational lifetimes. The executive summary of this report included the following statement: “a vehicle employing solar electric propulsion technology is a cost-effective method for boosting massive payloads to the higher Earth orbits” – the same rationale for NASA reexamining SEP for beyond LEO human exploration missions today.

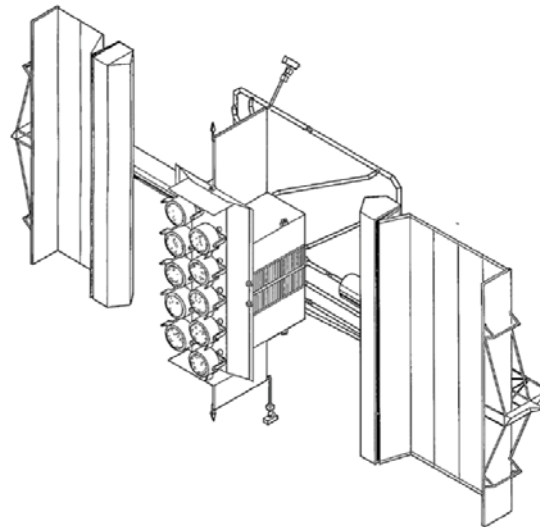


Figure 3 Boeing Solar Electric Propulsion Stage [1975].

One of the significant technical challenges for both these concepts was the large deployable structure associated with the solar arrays. Both concepts were based on what was a then state-of-art 10-11% efficient silicon solar cell. The result was a requirement for a pair of solar array on the order of 4 meters wide by 32 meters long, this at a time when the largest solar array flow to date was an order of magnitude smaller. In total there was approximately \$30 million dollars invested in the development of the SEPS mission capability and required technology, but by the early 1980's NASA efforts to develop and utilize high power SEP were greatly curtailed, in part due to a renewed interest in using nuclear electric propulsion (NEP) for high power electric propulsion applications due to its advantages relative to SEP for outer planetary missions. In retrospect, it wasn't really until the middle of the last decade with the release of the “Vision for U.S. Space Exploration” in 2004 and the cancellation of the Jupiter Icy Moons Observer mission in 2005

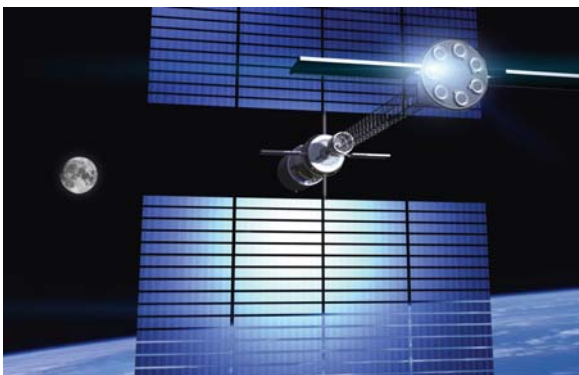


Figure 4: OASIS 500-kilowatt SEP vehicle concept [2002].

the that NASA began to again make significant investments in high power SEP for the types of space transportation applications that were the focus of the SEPS effort of the 1970's. The focus from approximately 2000 until the early 2010's was much larger 500 kilowatt-class SEP cargo delivery vehicle concepts as part of overall human-crewed mission architectures with either the explorations of the Moon and or Mars as their ultimate objective. An example is the SEP vehicle concept developed for the study, led by the NASA Langley Research Center, called Orbital Aggregation & Space Infrastructure Systems (OASIS) that looked at crewed missions to the Earth-Moon L1 Lagrange point as a staging point for follow-on missions.⁴ This 584-kilowatt SEP vehicle, shown in Figure 4, had a mass of 32,800 kilograms including 21,500 kilograms of xenon propellant with propulsion provided by 50-kilowatt gridded ion thrusters operating at 3,300 seconds of specific impulse.⁵ Increasing power level by more than an order of magnitude relative to SEPS was done to maximize the SEP payload delivery capability based on a shuttle-derived launch vehicle with a 60,000-kilogram lift capability to LEO. The resulting payload capacity was approximately 36,500 kilograms. It should be noted, that like in the case of SEPS, it is launch vehicle lift capability, payload mass, destination, and maximum allowable trip time that drive the selection of SEP vehicle power level and the electric propulsion system specific impulse.

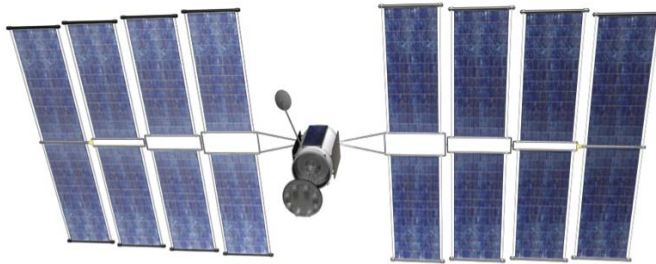


Figure 5: HEFT 300-kilowatt SEP vehicle concept [2011].

HEFT (shown in Figure 5) had a total mass of 49,700 kilograms including 39,000 kilograms of xenon propellant. The propulsion system was comprised of seven 43-kilowatt Hall thrusters operating at 2000 seconds of specific impulse in a direct drive configuration similar to that proposed for the SEPS over 35 years earlier.⁷ This concept is also based on a roll out type solar array similar in concept to what TRW proposed back in 1971. The focus of the HEFT architecture study on functional capabilities also highlighted the need to develop certain critical technologies. The technologies requiring development for the 300-kilowatt SEP vehicle were solar arrays and electric propulsion.

The most recent relevant past human-crewed mission architecture was that developed by NASA’s Human Exploration Framework Team (HEFT) in 2011.⁶ This study introduced a “capability driven framework” approach that enables multiple destinations. One again, electric propulsion was identified as an architecture enabler from an affordability perspective. The 300-kilowatt SEP vehicle concept developed by

III. Technology Maturation

SEP vehicle concepts at power levels of hundreds of kilowatts require significant technical advancements in both solar arrays and electric propulsion system to become a reality. The current state-of-art for high-power solar arrays are the rigid panels being used by high-power geostationary communication satellites with total powers in the 25-kilowatt range. The current state-of-art for electric propulsion is 5-kilowatt systems capable of processing 100’s of kilograms of xenon propellant. In 2010 NASA Space Technology Mission Directorate (STMD) began addressing these technology shortfalls with technology maturation efforts in each of these two areas. These efforts are described below.

A. Solar Arrays

In April of 2012 NASA released a solicitation for the development of the technology needed for mass and volume efficient, large-area solar array systems (SAS) with total power levels of 30-50 kilowatts that allows extensibility to power levels of 250 kilowatts or greater for the high power SEP cargo applications described previously.⁸ Mass and stowed volume efficiency were specifically targeted for advancements relative to state-of-art systems because improvements in these area will enable high power SEP vehicles to fit within the lift capability and fairing constraints of current launch vehicles such as the family of Evolved Expendable Launch Vehicles (EELVs) including the Atlas V and the Delta IV. In August 2012 NASA STMD selected two companies for SAS development efforts: Deployable Space Systems (DSS) of Goleta, California and ATK Space Systems Inc., of Commerce, California.⁹ In 2014, under contract to NASA Glenn Research Center, each of these contracted efforts demonstrated engineering development unit (EDU) 20-kilowatt-class solar array wings. These demonstrations resulted in advanced solar arrays for SEP applications up to 50 kilowatts with a technology readiness level of at least 5.

Deployable Space System (DSS) designed, manufactured, and tested an EDU Roll Out Solar Array (ROSA) wing 6.2-meters wide and 13.6-meters long that was sized to produce approximately 20 kilowatts. ROSA employs a pair of composite booms that serve as both the primary structure for the wing and the deployment actuator. The use of two booms, rather than a single boom as utilized by the solar arrays concepts employed by the TRW and Northrop SEP vehicle concepts presented previously, provides a level of strength and stiffness approximately an order of magnitude greater than state-of-art high rigid solar



Figure 6: DSS Engineering development unit roll out solar array

arrays. The photovoltaic blanket consists of standard solar cells bonded to a flexible substrate that is rolled onto a mandrel in the stowed configuration. Testing of the ROSA EDU included hot and cold thermal vacuum deployment testing at temperature extremes of $\pm 60^\circ$ Celsius. Vacuum deployed structural dynamics testing was also conducted validate to the ROSA EDU design. The deployed ROSA EDU is shown in Figure 6 along with the horizontal gravity off-loader developed for deployment testing.

ATK Space Systems designed, manufactured and tested a 9.7-meter diameter EDU MegaFlex solar array wing sized to provide approximately 17-kilowatts. MegaFlex is an evolution of ATK's heritage UltraFlex solar array that was successfully flown on the NASA Mars Phoenix lander and has been flight qualified for on the Orbital Sciences Corporation's Cygnus commercial resupply spacecraft. Megaflex improves upon the fan-fold, tensioned membrane design of UltraFlex that stows with a characteristic length equal to the radius of the deployed wing by introducing an additional hinge in the radial structural elements to further reduce the size of the stowed solar array wing. Megaflex employs a photovoltaic blanket consisting of individual triangular gores supported by radial composite spars. The individual gores consist of conventional solar cells bonded to a flexible substrate that fold in half in the stowed configuration. Testing of the MegaFlex EDU also included hot and cold thermal vacuum deployment testing at temperature extremes of $\pm 60^\circ$ Celsius and vacuum deployed structural dynamics testing. The circular design of the MegaFlex is particularly attractive to high power SEP applications because of the low moment of inertia associated with this geometric configuration. The deployed MegaFlex EDU and gravity off-loader as configured for thermal vacuum deployment testing is shown in Figure 7.



Figure 7: ATK Engineering development unit MegaFlex solar

B. Electric Propulsion

In the Fall of 2011, while planning the SAS procurement, STMD made the decision to focus technology development efforts addressing Hall thruster and power processing unit (PPU) technology to be compatible with the solar arrays then slated for development. This was done in order to enable a 30-50 kilowatt SEP transportation capability with the type of crosscutting applicability that has been desired for decades. The thruster technology development was based on recent advancements in long-life Hall thrusters utilizing the concept of magnetic shielding as previously demonstrated with 5-kilowatt class thrusters^{10,11,12} The objective was to develop a 15-kilowatt class Hall thruster incorporating these innovations to a technology readiness level of 5. A design point corresponding to 12.5 kilowatts of input power, 3000 seconds of specific impulse, and an operational lifetime of up to 50,000 hours were targeted as was the ability to throttle to lower powers and lower specific impulses. A technology demonstration unit (TDU) thruster, shown in Figure 8 without the center-mount cathode, has been designed and fabricated to these specifications and is currently waiting performance testing and lifetime evaluation.

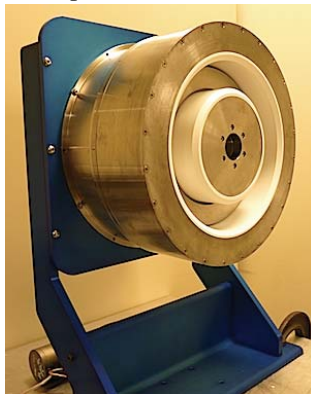


Figure 8: TDU Hall Thruster

The PPU development targeted two separate approaches: developing a conventional 15-kilowatt class transformer-isolated PPU and developing the technology to enable direct drive. The conventional PPU development has produced two breadboard-model PPUs: a unit with a 300 Volt input and a 400 Volt output that would enable high voltage power bus without the challenges of direct drive and a unit with a 120 Volt input and a 800 Volt output as required to achieve specific impulses up to 3000 seconds. The direct drive technology development activity has investigated using the solar array output directly to power a Hall thruster as previously demonstrated in a prior investigation.¹³ These efforts have focused on the challenges of integrating and operating Hall thrusters from a solar array with output voltages from 300 to 600 Volts.

The result of these activities have indicated that direct drive may offer an extremely attractive approach for future high-power SEP applications requiring specific impulses closer to 2000 seconds.¹⁴

IV. Technology Demonstration Mission

Overcoming the barrier to inclusion of new SEP technologies on future NASA missions, a challenge that historically has been very difficult to overcome, is the objective of the Technology Demonstration Missions (TDM) Program. Over the last several years, as the SAS and electric propulsion technology developments were ongoing, there has been a companion activity seeking to define an SEP TDM for NASA to implement in 2017-2019 timeframe. The focus of this mission has been free-flying SEP spacecraft with between 30 and 50 kilowatts of power. 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 geostationary communication satellite currently available, and it enables acceptable trip times for missions delivering even multiple tons of payload due to an ability to process many hundreds of kilograms of EP propellant in months rather than years with this size system. Since 2012 a number of mission concepts have been explored to satisfy the objectives of an SEP TDM.

Several stand-alone mission concepts were developed both by NASA and by industry via study contracts performed in 2012. A review of several of these concepts illustrates the range ideas considered for an SEP TDM. The first of these concepts, developed by Analytical Mechanics Associates (AMA), Inc., was a 38-kilowatt spacecraft with a mass of 5,400 kilograms including 2,900 kilograms of xenon propellant.¹⁵ This concept, which utilized MegaFlex solar arrays, would initially be launched to LEO via a SpaceX Falcon 9. The demonstration mission would then take up to 17 months transit to an Earth-Moon libration point demonstrating a number of operational modes including the demonstration of direct drive. This concept, shown in Figure 9, is representative of several large SEP TDM concepts that sought to fully demonstrate the new technology and capability that could be provided using this technology. These concepts confirmed that a SEP TDM approaching 50 kilowatts would likely have a total lifecycle cost in excess of \$500 million dollars.

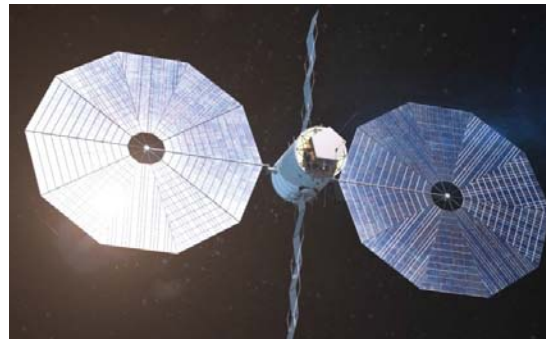


Figure 9: AMA SEP TDM concept [2012].

Multiple concepts attempted to strike a balance between the size of the flight system, the extent to which the new technology was being exercised, and total lifecycle cost. The concept developed by Lockheed Martin typical of this type was a 25-kilowatt spacecraft with a mass of 1570 kilograms including 590 kilograms of xenon propellant.¹⁶ This concept, shown in Figure 10, utilizing the DSS ROSA solar arrays could be launched on a small launch vehicle such as Athena II and perform a spiral out from LEO to low lunar orbit. Interestingly, a spacecraft in this class would essentially duplicate the capability that was sought by the SEPS concepts developed in the 1970s utilizing technology finally being developed for a near-term demonstration mission. While this class of SEP demonstrator was more affordable, a total life cycle cost in excess of \$300 million dollars was estimated for concepts approaching 30 kilowatts.



Figure 10: LM SEP TDM concept [2012].

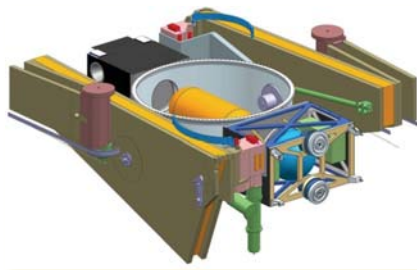


Figure 11: Design-to-cost concept [2013].

The last concept that should be mentioned was a design-to-cost SEP TDM spacecraft developed by the NASA Jet Propulsion Laboratory.¹⁷ This concept illustrated that utilizing either ROSA or MegaFlex solar arrays a SEP spacecraft with powers up to 30 kilowatts could be incorporated into an EELV secondary payload adapter (ESPA). The 30-kilowatt spacecraft concept, shown in the stowed configuration in Figure 11, had a total mass of 1350 kilograms including 220 kilograms of xenon propellant. While the capability of this concept was less than that of the other class of SEP TDM missions, the reduced size of

the spacecraft along with cost savings achieved as result of launching as a secondary payload resulted in an estimated total life cycle cost in the range of \$200 to \$250 million dollars.

The completion of these SEP TDM concepts studies illustrated that even the smallest, least expensive spacecraft were capable of providing considerable transportation capabilities. The synergy of this transportation capability with a wide range of applications enables the potential for implementing a demonstration mission in collaboration with a cost-sharing partner with a compatible payload. Over the past year NASA began investigating the potential of this type of cost-sharing partnership as the basis for an SEP TDM with industry. There has been a favorable response to initial cost sharing discussions as the geostationary telecommunication satellite user community has begun to accept the time penalty of performing a portion of the orbit raising to GEO using SEP providing there is a significant financial benefit, such as dramatically reducing launch costs Boeing has shown with their all-electric 702SP platform dual manifested on a Falcon 9.¹⁸ Additionally the reduced mass and modular nature of the SAS flex-blanket solar arrays represent a cost savings opportunity for these applications. Unfortunately these applications do not require high power electric propulsion systems of the type NASA is developing. Their missions can be accomplished using existing 5-kilowatt systems. Despite this, in late 2012 an alternate partner-based mission concept designed specifically to utilize the full SEP capability envisioned by NASA at the 50-kilowatt power level was identified for further study, the Asteroid Redirect Robotic Mission.

The Asteroid Redirect Robotic Mission (ARRM) is a SEP TDM concept based on a partnership between three different mission directorates with NASA: the Science Mission Directorate, the Space Technology Mission Directorate, and the Human Exploration Mission Directorate. The concept is based on utilizing a SEP spacecraft to rendezvous and return a small asteroid, or a boulder from the surface of a larger asteroid, to orbit around the Moon for subsequent access by a human crewed mission. During the past year this concept has been studied extensively. The ARRM spacecraft would utilize a 50-kilowatt spacecraft having a total mass of 15,180 kilograms including 10,000 kilograms of xenon propellant. Both ROSA and MegaFlex solar arrays could be accommodated and the mission requires the performance of the 12.5-kilowatt magnetically shielded Hall thrusters operating at 3000 seconds in combination with a 13-kilowatt PPU. This concept, as shown in Figure 12, would satisfy the SEP TDM objectives while simultaneously providing a transportation capability with the potential for follow-on NASA applications either as is or with further modifications.

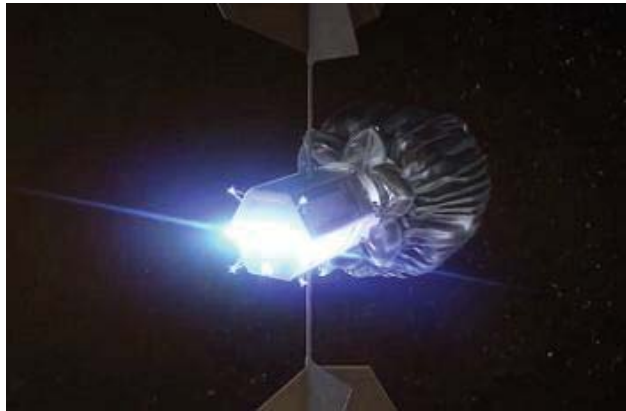


Figure 12: Asteroid Redirect Robotic Mission concept [2014].

V. Extensibility

If NASA was to perform the ARRM, the resulting SEP vehicle and capability should have direct applicability to other follow-on missions to maximize the value of the development. Furthermore, this vehicle should have the capability of being evolved over time with minimal additional investments to support even more challenging future NASA applications. This reflects a “stepping stone” type of approach based on a high-power SEP capability that can be modified to perform increasingly more challenging mission by incorporating incremental improvements without the need for additional new technologies. Mission applications that may follow the initial ARRM demonstration could include those utilizing a second identical SEP spacecraft or a copy of the initial spacecraft with small modifications. An example of this type of modification would be adding the capability for power transfer from the SEP spacecraft to other exploration vehicles. This could potentially enhance or enable longer-duration follow-on missions including those to the returned asteroid involving new exploration elements.

The stepping-stone approach to SEP capability evolution can provide a progression of increasingly higher power SEP spacecraft, referred to as “blocks”, each conceived to meet specific NASA mission needs. The initial spacecraft, *block 1*, would be the SEP vehicle configuration used on ARRM with 50 kilowatts of power at the beginning of life, 40 kilowatts of electric propulsion, and 10,000 kilograms of xenon propellant. The capability of *block 1* will be sufficient not only for ARRM, but it could be used for

deep-space science missions and follow-on Earth-orbital missions in support of human exploration moving logistics payloads and positioning in-space assets such as habitation modules. This vehicle level extensibility is in addition to the extensibility achieved at the subsystem level with the SEP technology having direct applicability to other non-NASA vehicles and missions, such as the advanced deployable, large-area, lightweight, solar array systems already under consideration for commercial applications due to potential cost improvements over state-of-the-art.

There is a set of later NASA mission requiring a SEP capability beyond the *block 1* configuration where the same vehicle bus can be used with upgrades to specific subsystems. This configuration, referred to as *block 1a*, would utilize larger solar arrays directly evolved from those used for ARRM and a higher power electric propulsion system achieved by simply adding additional thruster/PPU strings. *Block 1a* would therefore leverage the same set of technology maturation activities described earlier, taking full advantage of the SEP technologies and systems proven on ARRM. If *block 1* is designed to accommodate this future growth there will be little or no changes to the bus structure and propellant storage systems. This *block 1a* configuration would provide additional capability due to the higher power arrays and electric propulsion but without any additional propellant storage requirements or structural/configuration changes. This eliminates the need to perform a new vehicle development and qualification. The *block 1a* SEP vehicle could support additional missions leading towards a long-term goal of sending crew to the surface of Mars such as those in the "proving ground" or Mars moons. Proving ground missions would be the set of missions on the way to Mars surface where other systems, elements, and habitats would be demonstrated.

More demanding missions and those requiring more propellant than *block 1a* would require *block 2* SEP vehicles. *Block 2* could support human missions beyond cis-lunar space all the way to supporting Mars surface missions through further increases in solar array size and electric propulsion power.⁷ There would also be a requirement for more xenon propellant storage capacity on *block 2*, but the SEP technologies and sub-systems could be directly derived from that demonstrated on ARRM.

The different evolutionary steps in this block approach are shown in Figure 13 including a concept of how the solar arrays could be scaled. The left-hand

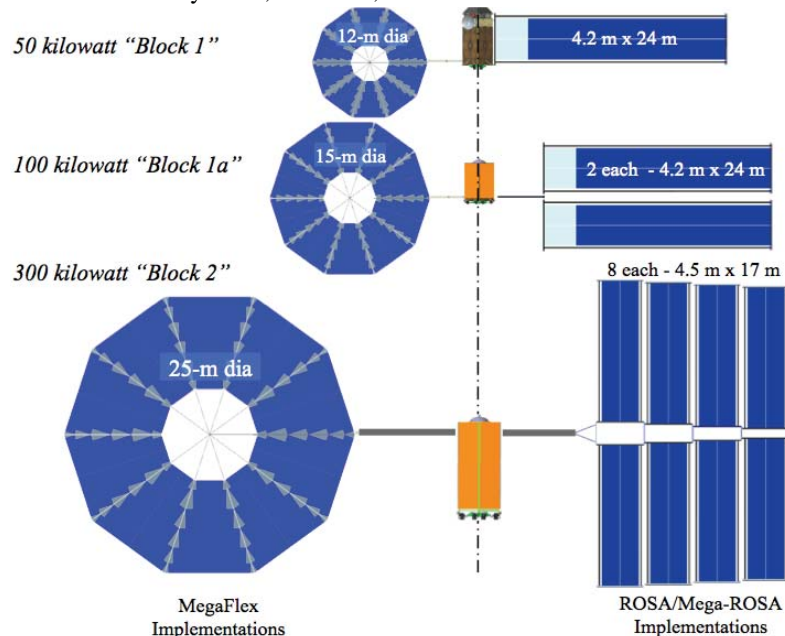


Figure 13: Evolutionary block approach based on SAS developed wings

side in the figure shows how the ATK MegaFlex array concept could grow the wing diameter sufficiently to achieve total power levels of up to 300 kilowatts with a pair of wings, each of which could be tested in existing thermal vacuum test facilities. The right-hand side in the figure shows how the DSS ROSA concept could evolve to 300 kilowatts by utilizing winglet modules similar in size to those used for the ARRM solar array wings in conjunction with a structural backbone in a configuration known as Mega-ROSA. There may be other combinations of scalability, modularity and block upgrades that could yield an even better evolution from a cost perspective, but mission specifics and the human Mars surface mission architecture will need to be better defined to permit further optimization. It will be desirable to retain some degree of design flexibility for SEP blocks beyond *block 1* to best address NASA mission extensibility until these specific follow-on missions and overall mission architecture are determined .

VI. Concluding Remarks

NASA has sought to utilize high-power SEP as means of improving the affordability of beyond-LEO in-space transportation for almost 50 years. Early efforts focused on 25 to 50 kilowatt systems that could be used with the Space Shuttle, while later efforts have focused on systems nearly an order of magnitude

higher in power that could be used with large EELVs or heavy lift Space Shuttle-derived vehicle concepts. These efforts never progressed significantly beyond the concept development phase in part because the technology required was not sufficiently mature. Since 2012 the NASA Space Technology Mission Directorate has had a coordinated plan to mature the requisite solar array and electric propulsion technology needed to implement a 30 to 50 kilowatt SEP capability. Efforts to develop concepts for demonstrating these maturing technologies have investigated a range of demonstration mission with recent efforts focusing on an Asteroid Redirect Robotic Mission. If implemented, the Asteroid Redirect Vehicle will form the basis for a capability that can be cost-effectively evolved over time to provide solar electric propulsion transportation for a range of follow-on mission applications at power levels in excess of 100 kilowatts.

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