The Importance of Electric Propulsion to Future Exploration of the Solar System

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Abstract: NASA and its international partners have identified an exciting plan for opening up cislunar space and making the first steps toward human exploration of Mars in the 2020s. 1 Aerojet Rocketdyne is working with NASA to develop higher power Electric Propulsion (EP) in support of this vision. The Advanced Electric Propulsion System (AEPS) is being developed to support a demonstration of Solar Electric Propulsion (SEP) at the 50 kW power level on the first element of the lunar Gateway – the Power and Propulsion Element (PPE). For higher power applications, such as Mars cargo or Deep Space Transport (DST) vehicles, Aerojet Rocketdyne, the University of Michigan, and NASA are working together to develop the 100 kW class XR-100 thruster system.

A key motivation for the use of SEP in the NASA Exploration architectures is the ability to transfer much larger masses over much larger distances. Comparing what is required to support these new exploration plans to what has been done historically is instructive. In the 1960s, the United States developed the Saturn V launcher to fulfill the goal of landing a human being on the Moon. This system was more powerful than any rocket that has been developed before or since. And yet it was only able to transfer about 15 mT to the lunar surface. When in 2008 NASA examined the requirements to support a larger crew (4 persons) and a longer stay time, the resultant Altair lander grew to approximately 45 mT. The Global Exploration Roadmap (GER) in 2018 identified a lunar outpost scenario that required a partially reusable lander that required delivery of 35 mT to the surface and an additional 10 mT assigned to pre-positioned pressurized rovers. NASA and US industrial teams have identified a concept for early human Mars exploration that requires landing four 20 mT cargo blocks prior to the arrival of the crew in a combined lander and Mars Ascent Vehicle (MAV) that will be at least 30 mT. Clearly, all of these scenarios go well beyond what we did during Apollo. SEP systems allow for optimal use of the new heavy lift capabilities being developed by NASA with the SLS by reducing the amount of propellant required for the in-space transfers and orbit injection maneuvers. The ability to do this enables the sustainable exploration of the Moon and Mars. It also opens up the potential to employ reusable in-space elements to transport material and resources that make commerce and in-space manufacturing feasible.

As part of our in-house architecture work, Aerojet Rocketdyne has examined the use of SEP at the 100 kW – 300 kW power level to support early Mars exploration by pre-positioning cargo elements. We have also studied the use of very high power SEP as part of a hybrid chemical-SEP DST. Each of these concepts has its pros and cons, but both show tremendous mission benefit from the use of EP systems in the 13 kW – 100 kW power range for individual thruster strings. The decision on which type of thruster to employ is mostly a system level trade based on the total power level. This paper will describe some of these trades and how the development of the AEPS and XR-100 nested Hall thruster strings will support future missions.

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1.0 Introduction

Mission architects are again looking at ways to expand human presence into the solar system. Three forms of advanced in-space propulsion are usually discussed when looking at efficient in-space transportation. Electric Propulsion (EP) refers to any form of in-space propulsion technology which uses electricity to enhance the specific impulse of the thruster. Solar Electric Propulsion (SEP) simply refers to any electric propulsion system which derives the electric power from solar cells. In contrast, Nuclear Electric Propulsion (NEP) would provide the electric power from a nuclear reactor. In Nuclear Thermal Propulsion (NTP), the propellant is heated directly by the nuclear reactor without generation of electricity.

Solar Electric Propulsion (SEP) is now a widely accepted form of satellite propulsion for functions ranging from North-South station keeping to orbit acquisition and even complete orbit transfers between GTO and GEO or too difficult-to-reach deep space objects. Approximately 1/3 of the satellites in orbit have some form of EP aboard. Since 2000 there has been over 35% growth in the number of satellites with EP. Figure 1 shows the current use of EP devices on satellites now operating in space.
SEP has achieved widespread application in large part because satellite power levels have steadily increased as the requirements for payload power has grown. The higher powers allow for quick and easier orbit transfer or orbit maneuvering. Figure 2 shows the growth in power level from the 1990’s (typical power level of 5 – 10 kW) through the 2010’s (typical power level of 15 – 20 kW).

AR has focused on SEP because currently all of the operational satellites using EP today use solar power. This trend is expected to continue as solar array designs become lighter, more robust and capable of generating more power per unit area than they did a decade ago. In fact, up to power levels of about 300 kW – 400 kW, solar power will probably be the preferred alternative. Above 500 kW, there is a tradeoff between solar and nuclear power. And that is where the use of NEP designs starts to become viable. However, for the foreseeable future, commercial satellite and robotic deep space exploration applications will remain limited to 20 kW – 40 kW, so the focus will remain on maximizing the end-to-end efficiency of SEP systems.

AR currently has and is developing a variety of EP products that span from 3 to 13 kW, using various technologies depending on the application. These include the flight XR-5 Hall thruster systems, the NEXT-C ion engine slated for flight on the NASA / APL DART mission in 2021, and the AEPS Hall thruster system planned for demonstration on the NASA Power and Propulsion Element (PPE) in 2022.

NASA Human Exploration missions are initially planning for 50 kW vehicles in cis lunar space, and ultimately 100 kW to 400 kW vehicles. This is accomplished by ganging multiple thrusters together. For deep space missions, the payoff comes when you couple SEP capability with the heavy lift launch capability of the SLS. Only SLS’s capability coupled with SEP will be able to deliver the payload mass required to support sustained human exploration missions. None of the other vehicles will be able deliver payload mass required for human exploration.
missions to the higher energy orbits (such as TLI) desired by the preferred architectures. The propellant required to fly back and land the boosters on the reusable vehicles costs performance – in both reduced payload mass and orbital energy. The argument to use reusable commercial vehicles to build sustainable exploration architecture does work because the vehicles are not capable enough to launch the amount of payload needed to the orbits required. That said, SEP coupled with reusable vehicles could provide logistics to and from the Gateway.

2.0 SEP Application for Exploration Missions

For sustained human exploration, the better solution is to use a launcher like the SLS that can deliver very high mass (and large volume) payloads to high energy orbits and then to use SEP for the in-space maneuvering of these vehicles. SEP factors in because, for a typical deep space mission, the amount of delta V that must be imparted after the launcher has placed the spacecraft into orbit is greater than or equal to the delta V to get it into orbit. In other words, launch is only half the battle. By using SEP as the in-space propulsion to accomplish the required maneuvers, the amount of propellant for the in-space maneuvers can be reduced by as much as a factor of 10. The amount of mass devoted to useful payload items such as rovers, landers, habitats and other critical exploration elements can be correspondingly increased and we make the most of each and every SLS launch.

Therefore, the industry focus on development and fielding of a 13 kW thruster string under the AEPS program supports both the potential higher power commercial satellite market that we forecast for the next 5 – 10 years, as well as NASA’s near-term plans with the launch of the PPE in 2022 and demonstration of the 50 kW-class SEP system in cislunar space. Future missions, such as a hybrid SEP/Chemical Deep Space Transport (DST) could also benefit from such higher power thruster strings, and possibly even higher power versions at 50 – 100 kW per string.

Currently, the AEPS program is embarked on a dual-track of development testing. One track is subjecting the thruster and PPU to environments testing, while the second track is focused on demonstrating component and system lifetime.

The AEPS 12.5 kW Hall thruster design and fabrication has been completed and an Engineering Test Unit (ETU) thruster is in test at NASA’s Jet Propulsion Laboratory (JPL). Initial results of the thermal vacuum testing indicate that the thruster is performing as expected. Figure 3 shows the thruster firing in the vacuum chamber at JPL.
A. Early Demonstration and Subsequent Mission Application

As a key technology for moving large amounts of cargo across the greater distances from Earth to the Moon and subsequently to Mars, early demonstration of high power SEP is of great interest. Therefore, NASA has made it a priority to fly on the Power and Propulsion Element (PPE) in 2022. This demonstration will prove the ability to operate SEP systems at up to 60 kW, with individual strings operating at the 13 kW input power of AEPS. The PPE will also demonstrate the ability to transfer xenon and refuel such a SEP system, providing the potential for future space-based systems to be refueled and reused for a variety of missions. Figure 4 shows the extensibility of the SEP system demonstrated on the PPE to future higher power Mars missions.3

One such mission application is cislunar cargo transportation. In 2012, Aerojet Rocketdyne conducted a series of studies based on a 27 kW SEP system for delivery of cargo to a NASA station in a cislunar orbit.5 NASA specified that a total amount of cargo needed to be delivered over a specified time period. The results, shown in Figure 5, illustrate that to reduce the cost per kg of cargo two factors were most important — reduce the total number of launches and reduce the cost of each individual launch.

Figure 3. AEPS ETU Thruster Firing at JPL.

Figure 4. SEP System Extensibility Building from PPE Demonstration (ref. Gates and Barrett, NASA 2019).
B. Conceptual Design of Modular SEP Transports

With the SEP system, you could influence this in two ways:

- On a given launcher you could load more useful payload than a comparable chemical transfer, thus accomplishing the total cargo mass delivery in fewer launches
- For a given cargo mass, you could move to a lower class of launch vehicle – even enabling the use of the Falcon 9 for some missions

The trade-off for using the SEP system was longer transfer time (approximately 4 – 5x) when compared to a 90 day chemical transfer. This did not affect the ability to meet the delivery requirement within the required time, only the individual payload block delivery time. The results were examined over transfer times from 1 year to 2 years with the savings in cost per kg maximized for the longest transfer times.

Now, with a total SEP system power of 60 kW being demonstrated on the PPE, it is possible to get these same results with much shorter transfer times. The increase in power is essentially an increase in the SEP system thrust, this reducing the transfer time required for a given payload mass. A notional SEP system design is shown in Figure 6.

The system employs eight AEPS thruster strings giving it a maximum power capability of over 100 kW. This would enable the efficient transfer of 10 - 15 mT payloads between the Earth and the Moon in only about 200 days.

For future missions that envision even higher power SEP systems, such as the hybrid SEP/chem Deep Space Transport (DST) with potentially as much as 400 kW –
500 kW of total power, the total number of AEPS thruster strings required would grow to 30 – 40. This begins to be a system integration issue due to the number of feed lines, power cabling, etc. If instead there were a single thruster string capable of processing 50 kW – 100 kW of power, the number of thruster strings would drop to a more manageable 4 – 10 total. An example of this concept is shown in Figure 7, where four of the AEPS strings are replaced by a single Nested Hall Thruster (NHT). AR and its teammates from University of Michigan and JPL recently completed testing of such a design at NASA Glenn Research Center.\(^5\)

![Figure 7. Potential On-Ramp of Higher Power XR-100 Thruster Strings by Replacing AEPS Strings.](image)

### 3.0 Mission Analysis of SEP

Aerojet Rocketdyne has analyzed a number of scenarios for these types of cargo transfer missions. NASA has focused their ARTEMIS efforts on having the Gateway located in a specific halo orbit known as a Near Rectilinear Halo Orbit (NRHO).\(^7\) These include transfers of material from HEO to NRHO as well as transfers within lunar orbit such as from NRHO to LLO. The tools and analytical methods employed, as well as some representative results, are described in this section.

#### A. Tools and Analysis Capability

AR uses various tools to analyze the capabilities of SEP that captures performance, power level, thrust variation, and solar array degradation. All trajectory segments are modelled with NASA’s Copernicus trajectory design and optimization system. Copernicus can create complex trajectories using low thrust finite burns under high-order gravity models and is ideally suited for the three body application. Analysis of SEP effectively requires a minimum of three body analysis.\(^10\) Planet and satellite gravity data is included in Copernicus based on NASA's Navigation and Ancillary Information Facility (NAIF) data in form of Spice Kernels and can be augmented with updates from other sources of data like the GRAIL GRGM660PRIM model for Lunar missions. Due to the solar electric nature of the technology, and frequency of eclipses in LLO, the Copernicus cylindrical shadow model was used to simulate the loss of sunlight to the solar arrays and power to the HET thrusters during operation.

Solar panel systems are degraded as they encounter high energy electrons when passing through the Van Allen radiation Belts (VAB). AR modeling accounts for this in our analysis of SEP system spiraling out from lower Earth orbits. AR mission analysis will typically include degradation losses between 8 to 20% as a function of the starting orbit above 900 km and how long the trajectory takes which is highly dependent on the power input and Isp of the EP system. AR used NASA JPL tools like Solar Electric Control Knob Setting Program by Optimal Trajectories (SECKSPOT) to examine and correlate our degradation factors that we have used in our analysis with Copernicus for Earth orbit transfers that pass through the VAB. The trajectories are then patched using a process of matching the backwards integrated trajectory from Copernicus to the drop-off conditions analyzed with SECKSPOT.\(^11,12\)

Using the AR SEPM to deploy Earth orbiting satellites – or transfer habitats in the case of Gateway – required developing a concept of operations (ConOps) for low thrust maneuvering in different orbital regimes and an
understanding of the associated astrodynamics challenges. By understanding the physics of the operation, the SEPM design elements could be traded and sized within engineering constraints. AR has explored the impact of many SEP-only trajectory methods on near-Earth mission requirements (TOF, V, etc.) to assist in the development of SEP spacecraft concepts. Additionally, as a parallel activity, AR has performed studies looking at LEO constellation deployment and the implications on the trajectory design and the performance requirements it sets for the SEP system.\textsuperscript{13}

AR SEP spacecraft concepts under development have been based around the idea of a modular and scalable design that can be used across multiple markets and for multiple missions. While future deep space exploration will need SEP vehicles in the 100-200 kW range, AR’s focus has been on the design of a 12 kW – 50 kW SEP stages that can be “stacked” with additional stages to provide increased power and xenon capacity for higher power cargo missions to cislunar or interplanetary space. Stacking SEPMs for extensibility across missions is discussed and illustrated in Cassady et al.\textsuperscript{14}

Figure 8 illustrates the approach that can be used to address multiple mission opportunities using a scalable power system and power processing unit (PPU) capability that can perform at low to high voltage levels to ensure the optimum performance (i.e., low or high thrust while optimizing on delivered Isp). A mission payload is typically attached on the docking collar opposite of the thruster assembly.

String efficiencies of the AEPS thruster and PPU, based on the AEPS and HERMeS thruster specifications detailed in Jackson et al. and Herman et al., were accounted for in the low thrust engine modeling used by AR in the mission studies. To simply the attitude control algorithm, the thrust vector can be fixed in ascension and declination for a given thrust segment of the trajectory.\textsuperscript{15, 16} A similar command and control approach was successfully flown on the ion-propulsion Dawn spacecraft between mapping orbits of Vesta and Ceres.\textsuperscript{17}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Modular Scaling of SEP Vehicle from 50 kW to 100 kW.}
\end{figure}

B. Missions Examined

AR has assessed missions for maneuvering within orbits around the Earth, moon and Mars as well as transferring from medium Earth orbits to higher orbits like GEO and performing planetary missions with Earth escape. AR SEP mission analysis has examined low power systems in the 10 to 50 kWe and systems with power levels in the hundreds of kWe using NASA AEPS type 13 kWe per thruster designs. Many of these have already been mentioned in the earlier section (e.g., Earth orbital and orbital maneuvering cited in Ref. 13).

Most recently AR has been involved analyzing the capability to use SEP for efficiently transporting cargo from Earth orbit to the NHRO being considered for the NASA Gateway orbital research facility and space docking
node. These studies are showing that designing for a SEP spacecraft that performs as a cis-lunar tug provides opportunities for scaling the power system to create more capable higher power tugs or lunar Gateway propulsion for multiple mission needs. See Figure 8 above illustrating the scalability of a 50 kWe type SEP system up to a 100 kWe spacecraft to be used for a cis-lunar tug or a power resource for in-orbit systems.

Figure 9. Typical SEP Transfer Mission Trajectory for Delivery to NRHO.

Those studies involved analysis of many aspects of the SEP trajectory for the Earth to lunar mission as shown in Figure 9. The mission depicted in Figure 9 had the SEP spacecraft tug dropped off by a commercial launch system (e.g., New Glenn, Falcon Heavy, or Vulcan) in a highly elliptical Earth orbit (HEO) and then the SEP system propelled the spacecraft to the Gateway NHRO. The lower power SEP using four AEPS thrusters could typically deliver greater than 2,000 kg of payload within 300 days with the addition of a lunar gravity assist. Higher power SEP using eight AEPS thrusters could deliver greater than 12,000 kg in less than 300 days. These SEP systems would be like the two solar panel and six solar panel spacecraft shown previously in Figure 8. Varying the power level using the modular SEP spacecraft approach based on using the AEPS thruster design provides for a highly robust capability depending on the mission payload and time of flight requirements.

C. Mission Analysis of Mars Missions

AR Mars mission architecture analysis has examined mid to high power approaches for both cargo and crew delivery. AR architecture studies have shown the preferred approach to minimize risk to the astronaut crew if considering power capabilities for SEP in the next two decades would be to send crew quickly and large cargo more slowly with SEP.

Studies AR performed from 2015 to 2016 examined the optimum power, voltage, and Isp performance that would maximize Mars cargo payload capability when launched off a NASA Space Launch System (SLS). The goal was to try to keep the total SEP power low to keep the system mass low and maximize the payload fraction of the NASA SLS payload capability while reducing any direct injection spiral escape time of flight. Figure 10 illustrates some of the findings from that Mars cargo study.
AR studies on the Mars cargo systems have shown that a split architecture enables use of smaller crewed vehicles providing a path for more affordable and robust transportation. Modular propulsive stages optimize launched mass and mission flexibility compared to large monolithic stages and enable commonality between missions. The SEP cargo vehicles leverage recent advances in solar electric power and propulsion such as the ROSA arrays and the AEPS thruster strings. Hall thruster based systems designed for propulsion modules at moderate power levels (100 – 300 kW) can perform Mars cargo missions with the timeframe that aligns with the crew mission that follows in later years. For instance, cargo missions could be launched during the 2033 opportunity for a crew mission in 2037. Vehicle level trades have shown that getting payloads exceeding 55 mT to Mars for the surface mission needs further analysis since time of flight is exceeding five years. What is more realistic is to examine what is required to get the Mars lander masses below 45 mT since for that payload mass a high power SEP cargo vehicle operating at a nominal 200 kW and 800 volts has a time of flight of around four years. The lower voltage, lower power 150 kW SEP cargo vehicle can also deliver 45 mT with only one year additional transfer time. The 400 volt/150 kW SEP system may be attractive in regards to cost per SEP vehicle and longer thruster life (mission margin) as Mars architecture planning evolves to see if 45 mT is a good lander design and a five year time of flight can match launch system capability within the cadence required for a Mars mission series.

Another concept that has been studied is a hybrid SEP/chemical stage with power levels near 400 kWe to the EP system. The hybrid concept can be used to deliver an all-up human Mars mission (crew + cargo) in a single transfer. AR studies are showing that this SEP trajectory can perform a typical Earth-Mars-Earth Conjunction class mission within 1,100 days with a Mars vicinity stay time around 300 days.

The mission profile breaks down as follows. The SEP (700 kW solar array power levels with chemical propulsion assistance) can take 4 to 40 days to depart the cislunar environment using a combination of chemical propulsion and lunar gravity assist. Figure 11 illustrates this with a nominal design that is a 13 day time of flight to leave the cislunar orbital state (e.g., -2.11 km²/sec²) toward Earth escape conditions. Figure 11 has two perspectives shown: Earth polar top view (top half) and Earth ecliptic view (bottom half).
Once the SEP-Chemical stage achieves a positive escape velocity the SEP propulsion system performs a powered segment, then a coast, then the SEP system performs a powered segment again to adjust the spacecraft’s velocity for capture at Mars. This mission example for a 2039 round trip mission required an AEPS thruster scaled from the 13.3 kWe design to provide 2,000 to 2,500 seconds of Isp running at 400 kWe to the thruster(s) and a solar array system with a maximum power capability near 700 kWe output.

This mission has a 300 day stay in Mars vicinity and returns using a similar burn, coast, burn optimization to minimize the required Xenon propellant load. Total SEP thruster operating time could approach 550 days at full power and at a minimum Isp around 2,000 seconds.

This example Earth-Mars mission started with a SEP/Chemical concept around 130 mT gross mass using between 20 to 30 mT of Xenon depending on the burn, coast, burn optimizations for 2000 to 2,800 seconds of Isp delivery. The efficiency of the SEP propulsion reduces the propellant to levels that can be delivered with fewer Earth to orbit launches.
4.0 Conclusions

NASA is embarking on a course of exploration that is unprecedented in its history. More ambitious robotic missions such as Mars Sample Return and small body sample returns require the capability of higher power SEP. Human exploration of deep space can also benefit greatly from the efficient transfer of larger mass systems over greater distances. The Dawn mission showed what is possible with the use of SEP by performing more delta V with its ion engines than was provided by the Delta II launch vehicle to get it into space. This is the new reality of deep space exploration.

Now the challenge is to scale up the successful application of EP on commercial satellites and with interplanetary missions such as Dawn to much higher powered SEP systems that can transport much heavier payloads over much larger distances. Just as was the case in the Dawn mission, there is as much delta V required after the spacecraft is launched as it took to get it into orbit. This puts a premium on the efficient in-space transportation and SEP is an ideal solution for this critical function. These missions span the range from robotic precursor missions such as the Mars Sample Return to full Mars cargo missions of up to 50 mT. SEP systems of 50 kW, such as the PPE demonstration, can provide a useful building block that enables a modular approach to achieving the required SEP total systems power levels of 150 kW – 400 kW. Thruster development under the AEPS and NEXTSTEP programs is keeping pace with the needs of higher powered SEP systems by providing thruster strings capable of 13 kW – 100 kW per string.

The use of high-power and highly efficient SEP technology can bring affordability to NASA’s near-term lunar surface exploration and provide a sustainable path to future solar system exploration. A three-stage approach for the lunar activities, using an intermediary solar electric “tug derived from a developed system (i.e., the Gateway’s PPE) can provide a reduction in lander launch mass (enables commercial launch options) and can eliminate performance driven complexity (due to a desire to reduce mass in a single stage or two stage lander approach). The trajectory sensitivities and trades presented here can be used for feasibility assessments during NASA’s down select of their future lunar mission architecture. Future work going forward is to investigate a three
burn, or more, approach to targeting specific lunar inclinations and optimizing the trajectory using advanced control algorithms (e.g., variable thrust vectoring).

For longer term Mars plans, SEP systems of up to 400 kW can provide either efficient cargo transport to pre-position all the necessary hardware and supplies for astronauts. AR has shown that these SEP systems can be built up from subsystem modules derived from the technologies demonstrated on the NASA PPE at the lunar Gateway in 2023. Using this approach, and with potential on-ramps for higher power thruster strings derived from the XR-100, large cargo vehicles capable of carrying up to 55 mT to Mars can be ready by the early 2030s.

The testing that is now underway and the planned in-space demonstration of a 50 kW-class SEP system on the PPE will put in place the required elements to support many future deep space exploration missions. As these capabilities come on line, we plan to continue to evolve our mission design to better utilize the SEP vehicles in the overall lunar and Mars campaign. As we move outward from low Earth orbit, it is clear that efficient in-space propulsion will be a key factor in supporting and sustaining exploration of the solar system.
5.0 References


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