The Importance of Utilizing and Developing Radioisotope Electric Propulsion for Missions Beyond Saturn

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Abstract

While numerous scientifically compelling missions have visited the outer solar system during the past four decades, the science return has been limited partly by contemporary power and propulsion technologies that limit a spacecraft's ability to carry heavy or high power demand payloads to its destination in a timely manner. Recent studies have endorsed radioisotope electric propulsion (REP) as a strong candidate for enhancing those capabilities. REP mission possibilities include Cassini level science at Neptune or Dawn-like coverage of a Kuiper Belt Object (KBO). This report will discuss the science benefits associated with the use of REP, a trade space analysis of mission architectures, and case studies of REP missions to regions beyond Saturn, with specific distinction to giant planet and small body targets. In addition to these, necessary REP flight qualification developments will be outlined.

Overview

The destinations available to and the science payloads carried by outer planet missions are typically limited by both power and propulsion technologies. A solution to this dilemma is to leverage spacecraft subsystems that have robust propulsion capabilities and consistent power performance at deep space distances. Such a solution lies within the use of REP technology. REP is borne from the combination of two flight proven technologies: radioisotope power systems (RPS) and electric propulsion (EP).

RPS technology has very high heritage and has been used on approximately 26 NASA missions, including Voyager, Cassini, and New Horizons. This technology converts the heat output by a radioisotope, such as Plutonium 238, into electrical energy. Currently this conversion is achieved through the use of thermoelectrics or the Stirling cycle[1] (only thermoelectric RPSs have been flown to date, while the Stirling cycle RPS is under current development). RPSs are specifically beneficial when solar power is not readily available.

EP technology has been successfully flown by a variety of missions, including Dawn, Deep Space 1, and Hayabusa. This technology creates milli-Newton thrust levels by accelerating a collimated beam of ions to high velocities. Although EP technology has high power requirements, it is ideal for missions that require very high velocity changes, such as rendezvous, multi-orbit survey, satellite tour, sample return, and campaigns to the outer solar system. Low thrust trajectories allow large velocity changes while increasing efficiency and decreasing propellant mass. At these distances solar panels become too inefficient; however, solar flux independent RPSs can provide near constant power to the EP system.

REP leverages the long lifetimes and high heritage of both technologies, as well as the advantages of EP's high specific impulse and RPS's solar independence. Due to the advantages of coupling EP and RPS, REP use primarily has two far reaching benefits for in-depth exploration beyond Saturn: excess power available to the instrument payload and continued EP capabilities upon arrival to the target body. These benefits allow for missions that can conduct Cassini-type science at Uranus or Neptune[2] and detailed in-situ analysis of the Pluto system[3] or other KBO's[4].

Science Benefits

The 2003 Solar System Exploration Decadal survey outlined the importance of nuclear-electric technologies, noting the significant advantages they provide over other power-propulsion technologies. Without REP, full-fledged science investigation of the outer solar system is very constrained. Moreover, there are numerous key distinctions to using an REP system for exploration. Due to the high power (> 1 kW) required by the EP system, power constraints usually levied on other spacecraft subsystems are relieved when EP is not engaged. This abundant power available to the spacecraft subsystems enhances mission operations and greatly increases science return. The excess power and presence of an EP system at the target body also allows for the continued use of EP which enables new types of missions and new methods of science investigation. Table 1 displays the science benefits of having ample power and continual use of EP in regions beyond Saturn. Additionally, specific science opportunities enabled by the use of REP are discussed in R. Noble's 2009 SSE Decadal Survey whitepaper: *New Opportunities for Outer Solar System Science Using Radioisotope Electric Propulsion*.

REP Science Benefits Associated with RPS Use

The availability of extra power has three positive consequences for the breadth of science investigation, regardless of the target body type:

1. Instrument payloads are less power constrained - Missions that formerly relied on RPS power for ~500 W are no longer power-constrained, but mass constrained. REP missions will now be able to carry more power-intensive instruments (e.g. >150 W imaging radars and LIDAR) as well as more capable versions of other instruments (e.g. spectrometers with more channels). This enables missions to have greater observing capabilities, increasing the breadth of the science investigation in the range of observed wavelengths and particle sizes.

Science Benefits Associated With REP Utilization	
Science Benefit	**Mission Regime**
> 1 kW available power at target	
Instrument payloads are less power constrained	Giant Planets, Small Bodies
Power sharing no longer required for science operations	Giant Planets, Small Bodies
Increased data rate and data return	Giant Planets, Small Bodies
Continued use of electric propulsion at target	
Rendezvous capability	Small Bodies
Planetary system tour assistance	Giant Planets

Table 1 – The two main radioisotope electric propulsion (REP) benefits are shown with their respective benefits for science. All mission regimes are beyond Saturn.

2. Power sharing no longer required for science operations - In the same way that the selection of a science payload is no longer power constrained with REP use, the science operations are no longer power constrained as well. This enables all of the science instruments to be operated at crucial events, such as flybys or in observing transient phenomenon, providing full spectrum coverage and maximizing science yield. Moreover, the freedom of running instruments concurrently may help meet operational requirements, providing more freedom in the planning of activities to reduce risk, lower cost, and increase science yield.

3. *Increased data rate and data return* - To offset the increased data volume from running instruments concurrently, more power is made available to the communications subsystem which can increase the transmitted power through the radio system. Allowing more data to be sent down to Earth can also result in less required on board memory for data storage and shorter data latency time.

REP Science Benefits Associated with EP Use

REP utilization also enables the continued use of EP at the target body, which has distinct benefits for giant planet (e.g. Neptune) and small body (e.g. KBO) missions:

1. *Rendezvous capability* - For small body missions beyond Saturn, it is difficult to use conventional chemical propulsion methods to perform a rendezvous (e.g. ballistic orbit capture) at small bodies with shallow potential wells. Conventional methods, like SEP or chemical propulsion, that could enable rendezvous missions to the outer solar system have transit times that are prohibitively long or utilize propulsive mass fractions that are infeasible to engineer. Conversely, REP systems can use their high specific impulse thrusting to alter a spacecraft's velocity during cruise such that orbit about small bodies can be achieved. REP is an enabling technology for science involving long-duration analysis of small bodies beyond Saturn.

2. *Planetary system tour assistance* - Some particular orbital maneuvers, namely orbit insertion, may require a large, short impulse while others, like tours of giant planet systems, can be handled by utilizing the low thrust EP systems[5]. Transfers between moons in the Neptunian and Uranian systems can be done with low enough velocity changes and over long enough duration that EP will provide an efficient means of propulsion. This will aid in decreasing the propulsion subsystem mass.

The cumulative effects of these REP advantages are that new solar system missions may be enabled and existing feasible outer solar system missions can be enhanced by increased science data return, specifically in the ability to support more instruments and concurrent observation with higher data rates. REP is an enabling technology for long duration small body science, while also being able to enhance the science tours of giant planet systems. With these enhancements in mind, the following sections will discuss mission architecture trade space comparisons and REP case studies at regions beyond Saturn, with distinctions between applications at giant planets (e.g. Neptune and Uranus systems) and small bodies (e.g. Centaur, KBO).

Giant Planet Applications

Outer solar system missions to target bodies with deep gravity wells will gain many benefits from the use of REP. Table 2 compares the main types of mission architectures for giant bodies in regions beyond Saturn.

Trade Space for Giant Planet Missions (e.g. Neptune, Uranus)				
Transfer type	**SEP**	**REP**	**NEP**	**Chemical**
Power source	Solar Panels	RPS	Fission Reactor	Any
Orbit insertion methods available	Aerocapture, Chemical	EP rendezvous, Chemical	EP rendezvous	Chemical
Most advantageous orbit insertion method	Aerocapture	Chemical	EP rendezvous	Chemical
Power available at target	~ 1kW	> 1kW	>> 1kW	~ 1kW
Instrument mass fraction	> 10%	~ 10%	< 10%	<< 10%
Mission risk	High (AC)	Medium	Medium	High
Technology heritage	Low (AC)	High	Low	High
Technology development cost	$$$ (AC)	$	$$$	$
SEP = Solar Electric Propulsion, REP = Radisotope Electric Propulsion, NEP = Nuclear Electric Propulsion, RPS = Radioisotope Power System, EP = Electric Propulsion, AC = Aerocapture				

Table 2 – Comparison of spacecraft architectures for giant planet missions beyond Saturn. Each metric is good if green, adequate if yellow, and worrisome if red. SEP mission risk, technology heritage, and development cost are driven by aerocapture technology considerations only.

Nuclear electric propulsion (NEP) and chemical based architectures are problematic for giant planet missions. The complexity and scale of NEP architecture forces a dramatic reduction of payload mass fraction. Similarly, a mission utilizing chemical propulsion will either require exorbitant amounts of propellant or not be able to support missions other than flybys. Due to these limitations, these architectures are either not practical for use or cannot meet basic science return requirements.

REP and SEP based architectures are favorably suited for giant planet missions. SEP based missions coupled with aerocapture maximize the instrument payload mass fraction. However this architecture is constrained by the immaturity of using aerocapture for orbit insertion. REP based architectures utilizing chemical propulsion orbit insertions may not deliver quite as high instrument mass fractions as SEP with aerocapture, but have significantly less risk and cost issues. REP is able to leverage the flight proven histories of EP and RPS, which minimizes mission risks and technology development issues.

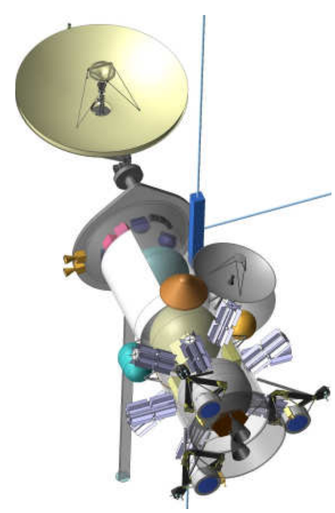

Figure 1 – NSE configuration

The use of REP based architecture was investigated in the Neptune Systems Explorer (NSE)[2], which was a joint study between NASA's JPL and GRC. The study, which was performed by JPL's Team X, confirmed that a flagship level mission could conduct remote sensing, subsurface radar, multispectral mapping, and atmospheric probe science in the Neptunian system. A 15 year REP low thrust trajectory would deliver the spacecraft to Neptune, where a chemical insertion burn would place it into orbit. Once properly in orbit, three years of science operations would commence.

A competing architecture to NSE was studied in the Vision Mission study[6], which utilized SEP for transfer and aerocapture for orbit insertion. Both studies returned results similar to those listed in Table 2, with the biggest distinctions being the delivered instrument mass fraction and technology development. Both studies are equally important because they show that a sizable payload mass fraction (≥ 10%) can be delivered to Neptune, which greatly increases the likelihood of an excellent science return. It is prudent to recommend that both architectures continue to be developed because they are the main methods of delivering adequate sized instrument mass fractions to giant planet systems in deep space. Although, REP has a quicker return on its investment since it only requires engineering development of existing RPS and EP technology. Whereas SEP with aerocapture requires a more costly technology development that cannot leverage an existing design.

Small Body Applications

Small body missions beyond Saturn gain many advantages through the use of REP. Most notable is the ability to make rendezvous with a small body target, like a Centaur asteroid or a KBO. Table 3 analyzes the trade space for mission architectures that are able to orbit a small body.

Trade Space for Small Body Missions (e.g. Centaur, KBO)		
Transfer type	**REP**	**NEP**
Power source	RPS	Fission Reactor
Orbit insertion methods available	EP rendezvous	EP rendezvous
Power available at target	~ 1 kW	>> 1 kW
Instrument mass fraction	~ 5%	< 5%
Mission Risk	Low	High
Technology Heritage	High	Low
Technology Development Cost	$	$$$
REP = Radioisotope Electric Propulsion, NEP = Nuclear Electric Propulsion, RPS = Radioisotope Power System, EP = Electric Propulsion		

Table 3 - Comparison of spacecraft architectures for small body missions beyond Saturn. Each metric is good if green, adequate if yellow, and worrisome if red.

The two enabling methods of achieving orbit about a small body are the use of NEP and REP. Orbits are achieved as a rendezvous with the target, which enables Dawn and Hayabusa-like analysis of distant, small bodies. Of the two enabling methods, NEP is heavily limited by development constraints and high mission risk due to immature, undeveloped technology and complicated integration issues between subsystems and an in-space fission reactor. This essentially qualifies REP as the only viable solution for orbit capture of a small body. As is the case for giant planet missions, REP is most beneficial due to its ability to deliver a relatively high payload mass fraction and not suffer from any major development issues. The use of EP trajectories minimizes the mission risk by providing sufficient time for trajectory error mitigation. However, the main advantage from REP remains the ability to enable orbits of small body targets.

The Kuiper Belt Object Orbiter (KBOO) case study[4] is a good example of an REP mission to a small body. This study demonstrated that a spacecraft using REP could orbit a KBO at distances of 30 – 35 AU (e.g. 2001-QT322) with an adequate payload mass fraction. The study, which was performed by GRC's COMPASS Team, confirmed that a flagship level mission could conduct remote sensing, subsurface radar, and multispectral mapping of a KBO during a 1 year science campaign. The mission design utilized a REP low thrust trajectory to rendezvous with the KBO. Primary results for the mission are the same as those shown in Table 3.

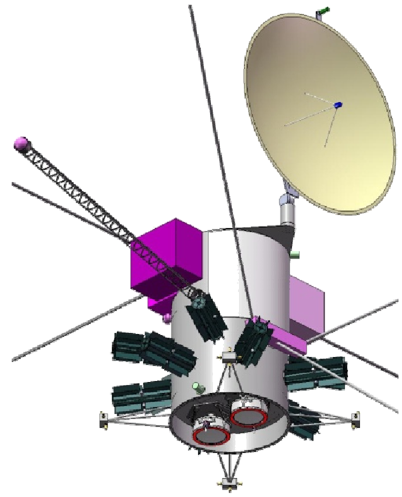

Figure 2 – KBOO configuration

REP Technology Development

Combining RPS and EP has many advantages and applications, as has been discussed. These REP capabilities do not require technology development, but rather engineering development. RPS and EP technologies currently exist and have been flight proven; however mating these technologies would require an upgrade of existing technology. Table 4 outlines the RPS and EP requirements that must be met in order to support New Frontiers through Flagship class REP missions to regions beyond Saturn. Table 4 is based on REP mission studies to Neptune[2], Pluto[3], KBOs[4], Centaur asteroids[7], and interstellar space[8].

Radioisotope Electric Propulsion (REP) Technology Development			
Parameter	**Current Capability**	**REP Requirement**	**Development Tasks**
Radioisotope Power System (RPS)			
RPS block power output [W]	140 - 150	400 – 500	Design larger heat source configurations
Specific power [W/kg]	7-8	10 – 11	Enhance conversion efficiencies
Lifetime [yrs]	14	15 – 18	Verify if existing design can handle extended life
Electric Propulsion (EP)			
Operating power [kW]	up to 5	2 – 3	Within existing capability
Thruster efficiency [%]	up to 60	65 – 75	Improve power conversion
Mass throughput [kg]	up to 500kg	≥ 600	Research beneficial grid materials

Table 4: Current RPS and EP capabilities are listed in comparison to necessary engineering developments needed and the type of work that must be done to achieve REP requirements. RPS current capability values listed are based on Advanced Stirling Radioisotope Generator specifications, which are currently in development and do not have any flight experience[9]. Actual RPS flight specifications are based on the performance of the thermoelectric based GPHS-RTG[9], which has RPS block power output = 285 W, specific power = 5.1 W/kg, and lifetime = 14 years.

REP development funding is needed to develop higher output power conversion systems, higher specific power, and longer lifetimes per unit. Research into heat source configurations and conversion technology efficiencies will lead to enhanced power output and specific power from a single RPS source. Additionally, RPS systems require validation for use in missions longer than 14 years. The main goal of these enhancements is to enable sufficient power for EP operations from a reasonable number of RPS units on a spacecraft.

REP development funding will also drive EP enhancements by looking into higher thruster efficiencies and mass throughput (e.g. EP engine lifetime) at the 2 – 3 kW operating range. Studies have shown that this operating power range is a niche area for REP that balances trajectory considerations and power subsystem mass and configuration. Less massive propulsion systems are achieved and most deep solar system trajectories are satisfied by increasing thruster efficiencies and mass throughput. This enhancement requires research into improving EP system power conversion and the use of more beneficial grid material. Developments driven by REP funding will have far reaching benefits beyond REP, possibly leading to higher power RPS units for in-situ robotic exploration and EP enhancements for SEP missions.

In conclusion, the use of REP technology would enable new missions in regions beyond Saturn as well as increasing science data return and augmenting operational capability in existing missions. At giant planets REP may reduce the propulsive mass required for orbit insertion; at small bodies it will make rendezvous possible. Both target types benefit from abundant power that can support more instruments and higher data rates to earth. The existing systems and heritage provide a strong basis for further development and refinement. With this additional development, these advances will allow for unprecedented deep space science discoveries in the near future.

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