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Radioisotope Electric Propulsion Missions Utilizing a Common Spacecraft Design

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RADIOISOTOPE ELECTRIC PROPULSION MISSIONS UTILIZING A COMMON SPACECRAFT DESIGN

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A study was conducted that shows how a single Radioisotope Electric Propulsion (REP) spacecraft design could be used for various missions throughout the solar system. This spacecraft design is based on a REP feasibility design from a study performed by NASA Glenn Research Center and the Johns Hopkins University Applied Physics Laboratory. The study also identifies technologies that need development to enable these missions. The mission baseline for the REP feasibility design study is a Trojan asteroid orbiter. This mission sends an REP spacecraft to Jupiter's leading Lagrange point where it would orbit and examine several Trojan asteroids. The spacecraft design from the REP feasibility study would also be applicable to missions to the Centaurs, and through some change of payload configuration, could accommodate a comet sample-return mission. Missions to small bodies throughout the outer solar system are also within reach of this spacecraft design. This set of missions, utilizing the common REP spacecraft design, is examined and required design modifications for specific missions are outlined.

INTRODUCTION

Various authors have studied the use of electric propulsion powered by radioisotope power sources for science missions beyond earth orbit.[1-7] More recent work has shown that such radioisotope electric propulsion (REP) spacecraft can *orbit or co-orbit* various large and small science targets beyond Mars with transit times comparable to large fission-based nuclear electric propulsion (NEP) vehicles, but deliver less science payload with proportionately less power available for science instruments. Although REP vehicles would be much smaller and have less on-board power available for science instruments than fission-based NEP, REP vehicles, like those using NEP, could conduct missions that are not accessible to chemical, solar electric or aerocapture vehicles.[6] This recent work discovered that using a medium class launch vehicle with an upper stage can reduce the REP trip times 50 percent from past estimates by using the launch vehicle to provide the Earth escape and acceleration while the REP (generally) only has to decelerate and shape the trajectory to capture at the target.

REP is particularly well suited for missions to small bodies throughout the outer solar system. To obtain the shorter trip times, high excess escape energy launches are used.[8] Because of the very low thrust available to the spacecraft (electric propulsion at up to approximately 1 kW_e); the orbit nearest to Earth that an REP spacecraft can achieve is that equivalent to Jupiter's orbit about the Sun. However, beyond Jupiter's orbit, the spacecraft can perform missions to many outer planetary bodies. The low thrust available also is better suited to small bodies with weak gravity.

Spiraling around a body with a large gravity well can add much time to the mission because of the very low thrust available.

The Vision for Space Exploration[9] calls for "robotic explorers [to] visit new worlds first, to obtain scientific data, assess risks to our astronauts, demonstrate breakthrough technologies, identify space resources, and send tantalizing imagery back to Earth." Advanced radioisotope power and electric propulsion are technologies that can enable many of these goals in locations where conventional power and propulsion are not practical.

The combination of these technologies has the potential to offer many benefits to the robotic explorers of the next decades.

This paper explores the applicability of a single REP spacecraft design for multiple missions to small bodies throughout the outer solar system. The two challenges inherent in this study are the design of a small spacecraft and the application of the design to multiple missions. Because the launch mass (approximately 500 kg) is limited, the total impulse and spacecraft dry mass are limited. Thus, innovative approaches are required to design a mass-constrained spacecraft. Science is restricted to approximately 50 kg, power and propulsion systems to approximately 200 kg, leaving approximately 150 kg allocated to all other necessary spacecraft systems (communications, attitude control, structures, thermal, etc.). These mass allocations require creative approaches to the spacecraft design to meet the mass goals required by the mission design. Applying this spacecraft design to several missions can also affect the design. Ignoring the science payload, the spacecraft design is required to change for a sample-return mission as opposed to an orbiter, and it is also required to change for a mission to a more distant target because of life issues. The nominal spacecraft design and any modifications required to successfully complete the mission are outlined herein.

SYSTEMS ANALYSES

Radioisotope Electric Propulsion Spacecraft

The baseline REP spacecraft was developed as part of an REP concept study led by the Advanced Concepts Branch at the NASA Glenn Research Center in cooperation with the Johns Hopkins University Applied Physics Laboratory.[10] This concept (see fig. 1) included all necessary components to successfully accomplish a New Frontiers class mission to the Trojan Asteroids at the Jupiter L4 point. The craft includes an advanced radioisotope power system (ARPS), an ion thruster system for primary propulsion, pulsed plasma thruster (PPT) system for attitude control, communications system, and small (20-50 kg) science payload. The design uses a truss structure to help minimize the mass of the spacecraft. The spacecraft mass equipment list is shown in Table 1.

The ARPS in its baseline configuration provides 750 W_e of power for propulsion and approximately 60 W_e for housekeeping functions. However, the full 828 W_e of power is available for housekeeping, science, and communications during non-thrusting periods of the mission. The ARPS system is assumed to have a specific power of 8 W_e/kg.[11, 12]

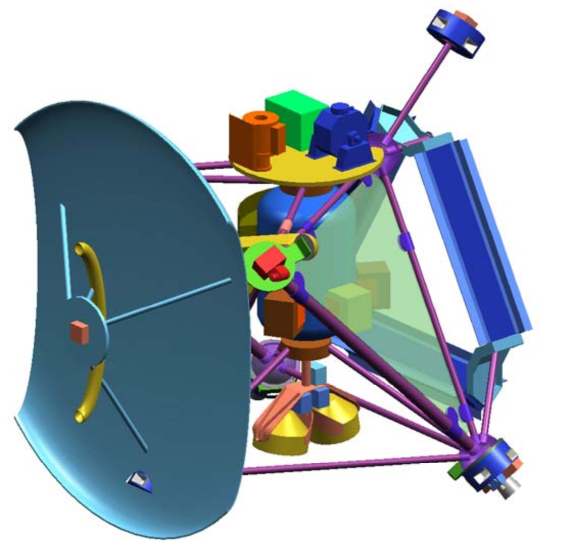

Figure 1.—NASA GRC REP Concept Study Spacecraft.

The ion propulsion system includes a mix of existing and in-development hardware designs. The two thrusters included in this configuration are 20 cm diameter thrusters, which currently exist only as a lab model design at NASA GRC. The two power processing units (PPUs) and the digital control and interface unit (DCIU) are based on the design of the NEXT PPU and DCIU. The ion thruster xenon feed system is a design developed by VACCO under a contract from NASA. A composite over-wrapped tank with a titanium liner and capacity of approximately 350 kg of xenon completes the electric propulsion system. I_{SP}s for the ion system are 3000 to 5000 seconds and were optimized for the analyses in this paper.

The PPT system is needed to provide attitude control for the spacecraft over long periods of time. The Teflon® fueled PPTs and their PPU are based on components developed under a NASA contract with Unison Industries that are presently undergoing life evaluation at NASA Glenn.[13] The PPTs provide roll-control during periods of ion engine thrusting and three-axis control during coast and science periods.

The communications system is mostly composed of components that are fully developed or will be by the time they are needed for a flight program. These include a 2.1 m high-gain antenna under development for the New Horizons mission to Pluto and the Kuiper Belt, three low-gain antennas, Ka-band traveling wave tube, and X-band solid-state amplifier among other pertinent communications equipment.

Table 1.—REP Concept Study Mass Equipment List.

Item	Qty	Comments	Est. Unit Mass, kg	Contingency, %	Total Est Mass, kg
Bus Science & non power/propulsion					258.1
Science					48.1
MDIS	1	Mercury dual imaging system	6.8	30	8.8
MASCS	1	Surface Comp Spectrometer	3.1	5	3.3
DPU	2	Data Prcoessing Units	3.3	5	6.9
Misc.	1	Harness, etc	6.8	30	8.8
GRNS	1	Gamma-ray & neutron spectrometer	13.4	10	14.7
Mapping Optics	1	Added Item to account for Special Optics needed for mapping. Work with MDIS.	2	30	2.6
EPPS	1	Energetic particle and plasma spectrometer	2.6	10	2.86
Attitude Control System					46.3
Star Tracker	3	Mini star tracker	0.3	30	1.2
PPT	4	Mass estimate based on advanced PPT components developed under contract with Unison Industries.	5	30	26.0
PPU-ACS	1	Power Conditioning and controls for PPTs	2.5	30	3.3
Inter stellar compas	2		2.9	30	7.5
Attitude Processing Electronics	2	2 sets, TBD (Estimate is under 4 kg each, and under 5 Watts)	3	30	7.8
Passive sun sensor	4		0.1	30	0.5
Communications etc.					71.3
S/C Main Computer	2	S603 Rad Hard version	5.5	30	14.3
High Gain Antenna	1	2.1-m high gain antenna (New Horizon)	9.47	30	12.3
Low Gain Antenna	3	X-band quadrifilar	0.16	30	0.624
Low Noise Amp (LNA)	3		0.01	30	0.039
USO 2030	2	Ultra Stable Oscillators	0.55	30	1.43
X-band SSA	2	Solid State Amp	1.1	30	2.86
TWTA	1	Ka Band	2.2	30	2.86
Ultra-Caps	2	Power Conditioning	5.2	30	13.52
Data Storage Unit	2	60 gbytes	1	30	2.6
Transponder	2	SDST	3	30	7.8
Cabling	1	Includes passive devices	10	30	13.0
Structures					67.5
RPS Radiation Shield	1	Aluminum	10	30	13
IPS Support Structure	1	Supporting Thrusters, Xe Feed System, & related hardware.	29.6	30	38.5
Spacecraft Bus	1	Based on dual tetrahedron, Titanium nodes, struts made from Cyanate Ester w Ti inserts	12.3	30	16.0
Thermal					24.96
Radiator #1	1	Main S/C radiator for avionics & shunt, assuming approx 3kg/m^2, 1.2m^2	3.6	30	4.68
Radiator #2	1	PPU waste heat, 0.2 m^2	0.6	30	0.78
Misc.	1	MLI, resistance heaters, temp sensors	15	30	19.5
Power & Propulsion System					215.6
Propulsion System					93.6
Thruster	2	20cm-ion Engine	5.1	30	13.3
Xenon Storage Tank	1	Volume of 213 liters based on 357 kg propellant	16	30	20.8
Xe Pressure Isolation Module	1	Smart Module VACCO	1	30	1.3
Xenon Flow Control Module	2	Vacco	1.1	30	2.9
Xe Feed System Misc.	1	Tubing and wiring	3.0	30	3.9
Residual Propellant	1	Treated as Dry Mass - Assumes 100 psia end pressure	7	15	8.1
2-axis Gimbal & Tri-Pod support	1	Guessed to be about 70% of DS-1mass.	15.4	30	20.0
PPU	2	Estimate - advanced low power PPU.	9	30	23.4
Power System					122.0
Advanced RPS	6	Assuming 8.0 W/kg specific power	17.3	5	109.0
Power Conversion & Distribution Box	1	28VDC conversion & integration box - including switches and relays not counted in specific power value	10	30	13.0

Total Spacecraft Estimated (DRY) Mass = 474 kg

The science package chosen for the REP concept study includes instruments important for studies of the Trojan Asteroids, but can be modified within the same range of mass and power for other interplanetary science missions. The instruments included in the REP concept study are the Mercury Dual Imaging System, Surface Composition Spectrometer, Gamma Ray and Neutron Spectrometer, and an Energetic Particle and Plasma Spectrometer.

Modifications to this design are suggested in following sections to improve the spacecraft's performance. One such suggestion is the increase of spacecraft power from 828 W_e to 1104 W_e. This change will increase the mass of the spacecraft subsystems accordingly (see Table 2). One other modification, not explicitly mentioned in the following sections, is that because of the lifetime required of the propulsion system for the longer missions, additional thrusters may be required. Each additional thruster will add between 8 and 10 kg to the spacecraft's dry mass.

Table 2.—Mass Change Associated with Increased Spacecraft Power.

Spacecraft Power	828 W_e	1104 W_e
Science	48 kg	48 kg
ACS	46 kg	46 kg
Communication, Control, Data Handling	71 kg	71 kg
Structures	68 kg	72 kg
Thermal	25 kg	25 kg
Power & Propulsion	216 kg	247 kg
	474 kg	509 kg

Launch Vehicles

The Atlas V 551 with a Star 48 upper stage is used as the baseline launch vehicle for these analyses. This launch vehicle/upper stage combination was chosen because of the high excess escape energies (C_3) required for these missions (120-150 km^2/s^2). The performance of these vehicles with and without the Star motors can be seen in Figure 2. The Star 48 stage provides minimal benefit at low C_3, however it extends the useful C_3 range of the launch vehicle to beyond 150 km^2/s^2.

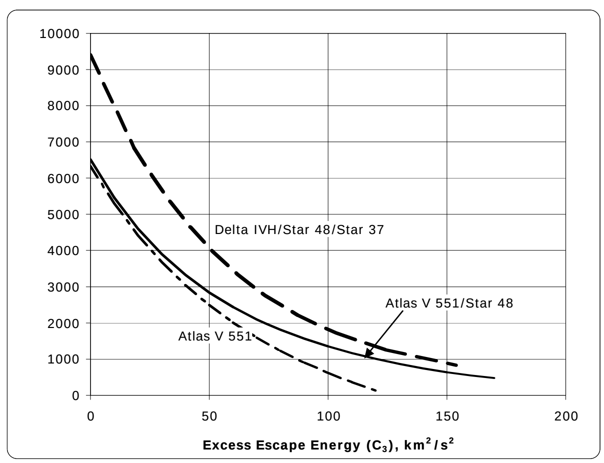

Figure 2.—Atlas V 551 Launch Vehicle Performance with and without the Star 48 Upper Stage, and Delta IV Heavy Performance with the Star 48 and Star 37 Upper Stages.[14-17]

For the more difficult missions examined, an identified modification to improve the mission performance is to use a larger staged launch vehicle. In these cases, a Delta IV Heavy staged with a Star 48 followed by a Star 37 is used (performance included in Fig. 2). This launch vehicle/upper stage combination provides more mass at the high C_3 required for these missions.

MISSION ANALYSES

Trajectory Optimization and Analysis

Trajectory design and optimization was completed using the Direct Trajectory Optimization Method (DTOM) code. As the name suggests, the DTOM is a direct method for obtaining optimal, low-thrust, interplanetary trajectories.[18] The DTOM numerically integrates the three-dimensional equations of motion using modified equinoctial orbital elements to accommodate circular orbits (eccentricity of 0).[19] The parameterized continuous-time control, thrust and coast lengths, launch date scaling factor, and Earth-escape parameters define the generic design space. More specialized problems can be defined with planetary gravity assists, loiter periods at the target body (used for sample-return missions), optimization of power level and specific impulse (either single value or parameterized continuous-time profile), and specialized thruster system models. Previous REP trajectories have been verified with the more widely used VARITOP trajectory optimization code.[20]

Mission Performance

Five missions were chosen to demonstrate the capabilities of the REP spacecraft. These missions to the outer solar system and beyond range in difficulty from 5 AU to more than 100 AU from the Sun. In order of difficulty, these missions are a Trojan Asteroid rendezvous, Centaur body rendezvous, Comet Sample-Return, Kuiper Belt rendezvous, and an Interstellar Explorer mission. All of these missions, except for the Interstellar Explorer mission, involve long-term science by means of orbiting the target body or co-orbiting the Sun near the target body. The Interstellar Explorer mission is a long-term science gathering spacecraft that will collect science from launch until end of spacecraft life (possibly more than 50 years). One similarity for all of the missions analyzed is that most of the energy required for the spacecraft to reach its destination is provided by the launch vehicle, via high C_3, with the EP system to provide the remainder of the energy and then, for the missions that require it, accomplish the rendezvous.[8] More details of these missions can be found in the following sections.

Each of the missions is designed to deliver a spacecraft similar to the REP spacecraft previously described, each with 750 W_e of power provided to the EP system.

REP spacecraft performance is shown in Table 3 for the five analyzed missions and the previously described spacecraft. Trip times for the first three missions are reasonable, and with some configuration changes, it is expected that trip time performance of the last two missions can be improved. These configuration changes are detailed in the following sections.

Table 3.—Spacecraft Performance for Analyzed Missions.

Mission	Trojan Asteroid	Centaur	Comet Sample-Return	Kuiper Belt	Interstellar Explorer
Launch C_3 (km^2/s^2)	146	142	150	137	129
Launch Mass (kg)	683	725	641	777	883
Propellant Mass (kg)	182	219	187	264	409
Trip Time (yr)	5.3	6.3	5.5	19.5	17.6
Optimal I_{SP} (s)	2714	2686	2547	4396	3606
REP ^{2}v (km/s)	8.3	9.5	11.5	17.9	22.0

While, some of these missions can be completed using other technologies, REP can be an enhancing or even enabling technology. The size and characteristics of the bodies selected for this study immediately limit the choices of technologies. For instance, none of the bodies selected have known atmospheres, and therefore aerobraking and aerocapture are not available. Because of the small sizes of these bodies, and thus low gravity, a direct mission on the same launch vehicle capturing with a chemical propulsion system, if not impossible, may not deliver sufficient mass for meaningful science return. An all chemically propelled mission may be possible, but may require gravity assists, which can add trip time, or a heavy-lift launch vehicle to deliver sufficient mass, or both. Solar electric propulsion (SEP) could be used for the comet missions and possibly the Trojan and Centaur missions potentially with a chemical system for capture, and nuclear electric propulsion (NEP) can be used for all of the missions, however the class of a NEP spacecraft may be beyond that feasible or desirable for most of these missions. No comparative analyses were performed using these other technologies for this study, however other studies have been completed for similar missions using SEP and NEP from which relative performance can be inferred.[7, 21, 22]

Multi-Trojan Asteroid Orbiter Mission

The Trojan Asteroid Mission was the baseline mission used for the design of the REP spacecraft used for this study. This mission was selected based on the known capabilities of this class of spacecraft and the selection of a Trojan flyby mission as a deferred mission in the Decadal Survey.[23] The Trojan Asteroids are located in a similar orbit to Jupiter, but are phased 60° in front of and behind Jupiter. The difference between the chosen Trojan Asteroid mission and the deferred Decadal Survey mission is that the chosen mission is actually a rendezvous mission with the possibility for science return at multiple Trojan Asteroids over long periods of time, as opposed to a flyby mission with a very brief period of science return.

The REP spacecraft performance numbers are provided in Table 3. Total trip time for this mission to rendezvous with the first Trojan Asteroid, chosen to be Hektor, the largest of the Trojan Asteroids, is approximately five years. A plot of this trajectory is shown in Figure 3. This trajectory is characterized by a high-C_3 launch (146 km^2/s^2) and a continuous thrusting period until rendezvous with Hektor. This continuous thrust arc serves to raise the trajectory's perihelion and shape the orbit to match Hektor's. During the transit to Hektor, the spacecraft actually passes in front of the Trojan Asteroid field and then slows enough, by passing outside the Trojan orbit, to allow the Trojan Asteroids to approach from behind. For almost two-thirds of this mission, the spacecraft is within 1 AU of the Trojan Asteroid field, allowing science collection to begin on "targets of opportunity" very early in the mission.

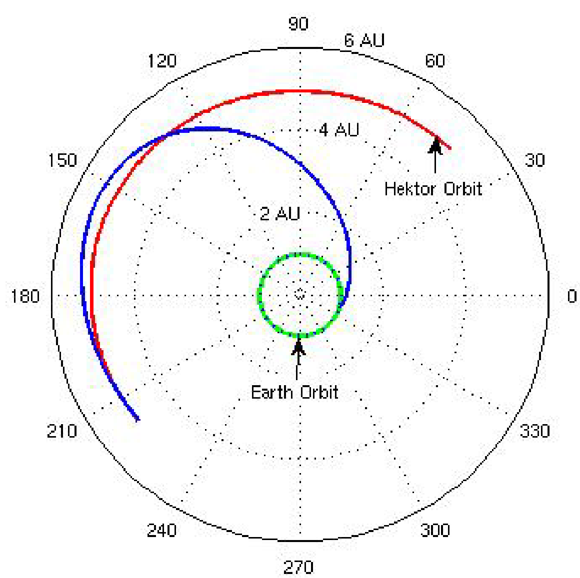

Figure 3.—Trojan Asteroid Mission Plot.

Multi-Centaur Orbiter Mission

Moving out through the solar system, and into more difficult missions, a Centaur mission is the next logical step for evaluating performance of the REP spacecraft. This mission, as part of the same deferred Decadal Survey mission as the Trojan Asteroid flyby mission, can actually rendezvous with a Centaur object, as opposed to being limited to a flyby, for extended science observations. Centaur bodies are typically defined as bodies with 20-100 km radii with semi-major axes beyond the orbit of Jupiter, most of which appear to be inactive.[24a]

The REP spacecraft also performed well for the Centaur mission. For this mission, Chiron, the first Centaur body discovered, was chosen for design of the trajectory. The REP spacecraft can rendezvous with Chiron in approximately 6 years (see second column in Table 3 and Fig. 4). Even though this rendezvous occurs past 10 AU, the trip time is only a year longer than the Trojan Asteroid mission (at 5 AU), because the eccentricity of Chiron's orbit makes the rendezvous maneuver less difficult than if it was in a circular orbit. The mission profile for this Centaur mission is similar to that of the Trojan Asteroid mission, that is, it includes one continuous burn from launch through rendezvous, except in this case the EP system adds energy at the beginning of the trajectory and then removes the necessary energy for rendezvous over the remainder of the trajectory.

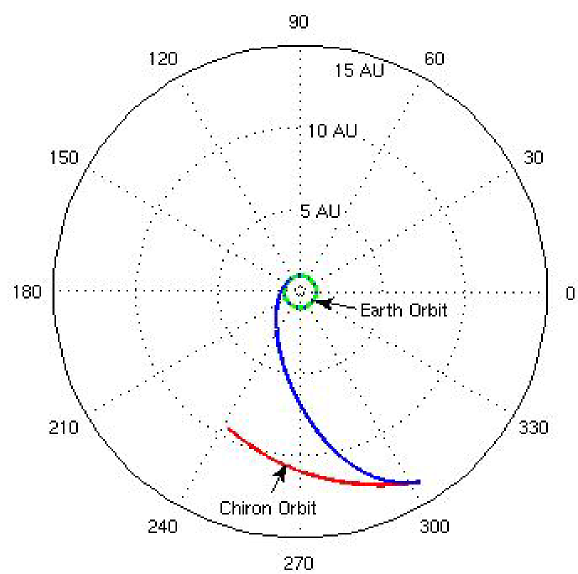

Figure 4.—Centaur Mission Plot.

Comet Encke Sample-Return

A Comet Surface Sample Return mission was identified as one of the priority missions in the Decadal Survey, and is the next mission chosen for application of the REP spacecraft. For this mission, it would be expected that some payload and spacecraft reconfiguration would be required due to the different nature of the science performed. A sample gathering mechanism would be required, as well as a return capsule to safely return the comet sample to Earth. Because a detailed study of the REP spacecraft configuration change was not completed, simple assumptions were made to complete the analysis. These assumptions include that all science payload mass allocation will be diverted to sample collection and return, the collection mechanism, assumed to have a mass of 50 kg, will be left at the asteroid, and the sample will be separated from the spacecraft on a free-return trajectory to Earth so the spacecraft can perform one final maneuver so that it does not return along with the sample.

Again, the spacecraft achieved the mission goals in reasonable trip times. The comet Encke was chosen as the target for this Comet Surface Sample Return mission, but similar performance could be expected for comets in similar orbits. This mission is completed in 5.5 years from launch to sample return (see third column in Table 3 and Fig. 5). The spacecraft is in close proximity for approximately half of one orbit of the comet around the Sun, starting at approximately 4 AU and separating at approximately 2 AU, but remaining fairly close throughout the close transit past the Sun. Because of the drastic differences in science payload and mission design, more effort into the spacecraft design is needed before higher fidelity trajectory work can be completed.

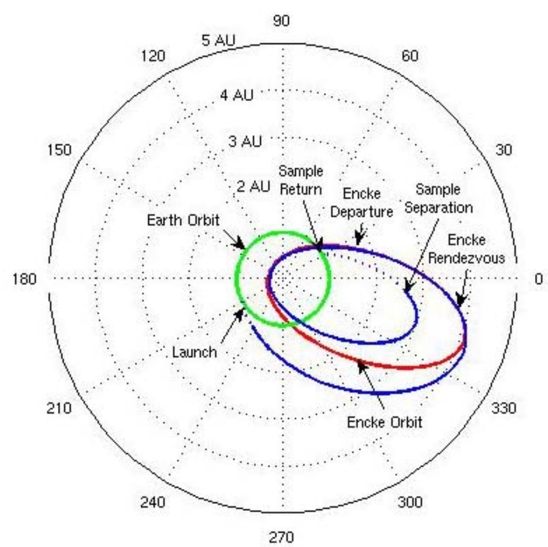

Figure 5.—Comet Encke Sample Return Mission Plot.

Kuiper Belt Mission

The Kuiper Belt, containing "objects populating space beyond the orbit of Neptune but inside 1000 AU"[24b], is the next target for the REP spacecraft study. This mission, in the form of the Kuiper Belt-Pluto Explorer mission, was also identified as a priority mission in the Decadal Survey. Quaoar, the chosen target body for this mission, is one of the largest and most recently discovered Kuiper Belt objects. The spacecraft configuration for this mission would be very similar to that of the Trojan Asteroid and Centaur missions for the baseline case presented here.

The limits of the REP spacecraft, in its baseline configuration, seem to be reached with this mission. With a trip time of 19.5 years (see fourth column in Table 3 and Fig. 6), some reconfiguration of the spacecraft to improve performance is warranted. One candidate to improve the trip time is to use a small chemical stage to capture into orbit about Quaoar. This technique performed well for a Neptune Orbiter mission[7], but because of the drastically reduced size of Quaoar as compared to Neptune (Quaoar's diameter is approximately 2.5 percent the size of Neptune's), this approach may not provide the desired trip time reduction. Another option to reduce the trip time for this mission is to increase the spacecraft power level. Increasing the spacecraft power to approximately 1100 W_e decreases the trip time to approximately 18.5 years. Further improvements can be obtained by increasing the launch vehicle capability. Changing launch vehicles to a Delta IV Heavy staged with a Star 48 followed by a Star 37 upper stage can decrease the trip time to approximately 17.5 years. To achieve a more reasonable trip time of 14 years, some advancement in the design of the spacecraft is needed. To reach the 14-year trip time goal, the dry mass of the 1100 W_e spacecraft must be reduced by approximately 125 kg (see Table 2 for starting mass). One other option, not explored, is the use of a gravity assist to reach Quaoar. This option may provide the required

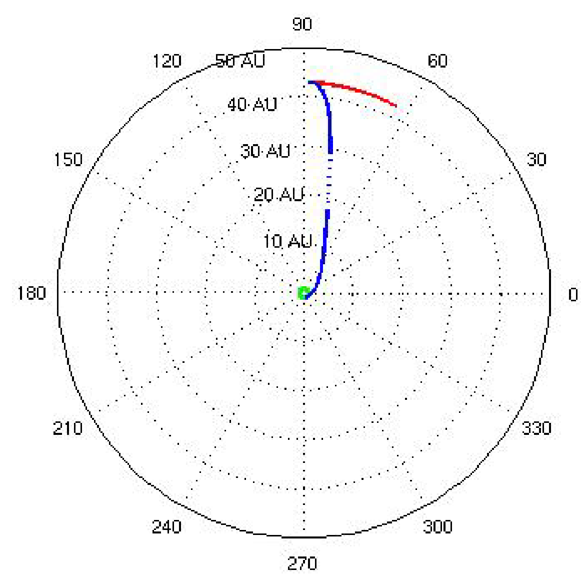

Figure 6.—Kuiper Belt Mission Plot.

additional energy to reach Quaoar in 14 years, but may necessitate an increase in power due to the higher velocity achieved and the need to rendezvous with Quaoar using the electric propulsion system.

Interstellar Explorer

The final mission examined with the REP spacecraft design is the Interstellar Explorer mission. The goal of this mission is to reach a distance of 200 A.U. from the Sun in 15 years or less. To reach the heliopause (the boundary of the solar system[24c]) quickest, the spacecraft is targeted in the direction of the origin of the interstellar wind because the heliosphere is thinnest at this point. The purpose of this probe is to obtain measurements of the interstellar medium that can only be addressed by instrumentation that actually penetrates outside of the heliosphere.

Again the limits of the REP spacecraft design are reached for this mission (see fifth column in Table 3 and Fig. 7). The spacecraft only reaches 100 A.U. in approximately 18 years, far short of the goal of 200 A.U. in 15 years. At its current design speed, it would take approximately another 7 years to reach 200 A.U., about 10 years longer than the goal. However, with some configuration changes, it may be possible to come closer to meeting the goal of 200 A.U. in 15 years. Reducing the spacecraft's dry mass will shorten the trip time by allowing a higher C_3 launch, thus obtaining more of the needed energy to reach 200 A.U. from the launch vehicle. Different combinations of launch vehicles and upper stages could also benefit this mission. By using a heavy launch vehicle with several upper stage motors, as seen in the Quaoar analysis, an equivalent mass can be launched to higher C_3 than with the previously assumed AtlasV 551/Star 48 launch combination. Higher thrust, by means of more power available on the spacecraft, may also shorten the trip time.

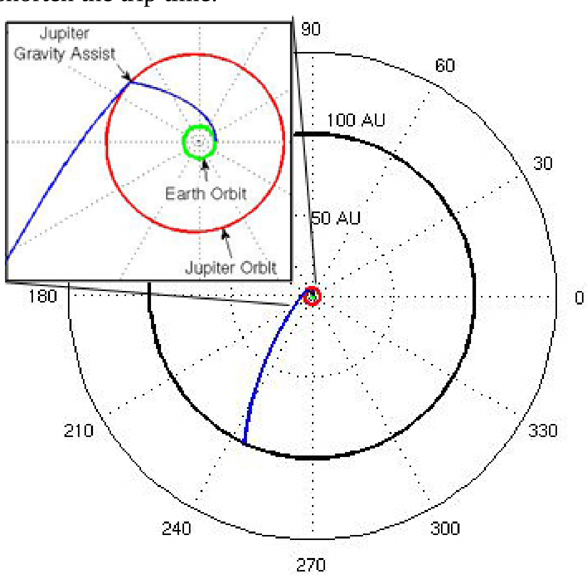

Figure 7.—Interstellar Explorer Mission Plot.

One other option that may improve the performance of this mission is trajectory variations. Multiple planetary flybys or a near-sun flyby followed by a planetary flyby may also improve the trip time to 200 A.U. These options will be examined as part of the Innovative Interstellar Explorer study.[25]

CONCLUSIONS

The REP spacecraft, as designed, is a very capable spacecraft for interplanetary missions to small bodies throughout the solar system. Analysis shows that it could complete missions to bodies such as the Trojan Asteroids or Centaurs in reasonable trip times and could also complete comet sample return missions with long science observation and sample gathering periods with some minor modifications for the sample-return. In order to provide reasonable trip times to the Kuiper Belt and interstellar space, next generation spacecraft are needed with mass reductions of 20-30 percent, as well as next generation power and propulsion technologies.

The purpose of this paper was to examine the performance of this Trojan Asteroid REP spacecraft point design. It is very likely that an identical spacecraft could be flown for a Centaur mission, but for each of the other missions examined, changes would be needed either to accommodate a different science package, or to improve the performance of the spacecraft for the given mission. For this study, modeling of these changes was done at a very basic level, and further study is needed to provide spacecraft designs of higher fidelity. However, the REP spacecraft design yields a very capable spacecraft that could perform a wide range of missions.

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13. ABSTRACT *(Maximum 200 words)*

A study was conducted that shows how a single Radioisotope Electric Propulsion (REP) spacecraft design could be used for various missions throughout the solar system. This spacecraft design is based on a REP feasibility design from a study performed by NASA Glenn Research Center and the Johns Hopkins University Applied Physics Laboratory. The study also identifies technologies that need development to enable these missions. The mission baseline for the REP feasibility design study is a Trojan asteroid orbiter. This mission sends an REP spacecraft to Jupiter's leading Lagrange point where it would orbit and examine several Trojan asteroids. The spacecraft design from the REP feasibility study would also be applicable to missions to the Centaurs, and through some change of payload configuration, could accommodate a comet sample-return mission. Missions to small bodies throughout the outer solar system are also within reach of this spacecraft design. This set of missions, utilizing the common REP spacecraft design, is examined and required design modifications for specific missions are outlined.

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