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Neptune Orbiters Utilizing Solar and Radioisotope Electric Propulsion

Douglas I. Fiehler
QSS Group, Inc., Cleveland, Ohio

Steven R. Oleson
Glenn Research Center, Cleveland, Ohio

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Douglas I. Fiehler
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Douglas I. Fiehler
QSS Group, Inc.
Cleveland, Ohio 44135

Steven R. Oleson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

In certain cases, Radioisotope Electric Propulsion (REP), used in conjunction with other propulsion systems, could be used to reduce the trip times for outer planetary orbiter spacecraft. It also has the potential to improve the maneuverability and power capabilities of the spacecraft when the target body is reached as compared with non-electric propulsion spacecraft. Current missions under study baseline aerocapture systems to capture into a science orbit after a Solar Electric Propulsion (SEP) stage is jettisoned. Other options under study would use all REP transfers with small payloads. Compared to the SEP stage/Aerocapture scenario, adding REP to the science spacecraft as well as a chemical capture system can replace the aerocapture system but with a trip time penalty. Eliminating both the SEP stage and the aerocapture system and utilizing a slightly larger launch vehicle, Star 48 upper stage, and a combined REP/Chemical capture system, the trip time can nearly be matched while providing over a kilowatt of science power reused from the REP maneuver. A Neptune Orbiter mission is examined utilizing single propulsion systems and combinations of SEP, REP, and chemical systems to compare concepts.

I. Introduction

Various authors have studied the use of electric propulsion powered by radioisotope power sources for science missions beyond earth orbit.[1-5] 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% 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.

A Neptune Orbiter mission has been identified as a mission of much interest,[7] and the performance of many spacecraft configurations have been analyzed in reference to this mission. The NASA's Evolutionary Xenon Thruster (NEXT) Program used a Neptune Orbiter mission as one of its deep space design reference missions to help in the development of requirements for the system.[8] Many propulsion systems were traded against each other using this Neptune mission during the Integrated In-Space Transportation Planning studies.[9] These systems included chemical, SEP, NEP, solar and nuclear-thermal propulsion, solar sails, and tethers. An all-solar powered mission, utilizing power antenna technology, was also studied.[10]

The Vision for Space Exploration[11] 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 solar and radioisotope power, electric propulsion, and chemical propulsion as well as aerocapture are technologies that can enable many of these goals set forth in "The Vision."

The combination of these technologies has the potential to offer many benefits to the robotic explorers of the next decades. These technologies can also be applied, once demonstrated, to the human exploration missions to the Moon, Mars, and beyond that will follow these robotic explorers.

II. Systems Analyses

A. Spacecraft Analysis

A combination of propulsion systems make up the different spacecraft configurations examined in this study. These spacecraft configurations are detailed in Table 1, and include REP, SEP, and chemical propulsion systems individually and combined, as well as aerocapture. Depending upon the combination of propulsion options the science spacecraft will require a different design. Stage and Spacecraft designs originate from spacecraft concept studies conducted both at Glenn Research Center and at the Jet Propulsion Laboratory.

Table 1: Spacecraft Configurations

SEP-Aerocapture	Baseline case from the NEXT design reference missions.[1]
REP	Based on the NASA GRC REP concept study.
SEP-REP	Combination of SEP stage and REP spacecraft, using REP to capture at Neptune.
SEP-Chem	Combination of SEP stage and a chemical stage to capture at Neptune.
SEP-REP-Chem	Combination of SEP stage, REP spacecraft, and chemical stage for Neptune capture.
Chemical	Spacecraft utilizing only chemical propulsion to deliver the spacecraft.

1. Radioisotope Electric Propulsion Spacecraft

The baseline REP spacecraft was developed as part of an REP concept study led by the Advanced Concepts Branch at NASA GRC. 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 3.

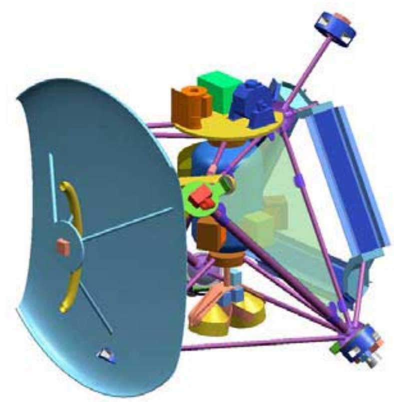

Figure 1: NASA GRC REP Concept Study Spacecraft

The ARPS in its baseline configuration provides 750 We of power for propulsion and approximately 60 We for housekeeping functions. However, the full 810 We 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 We/kg[12] in order to scale the spacecraft to higher power levels for this study, and the structure is scaled as 14% of the total spacecraft dry mass. Table 2 illustrates the scaling of the REP spacecraft from 0.81 kWe to 3.06 kWe.

Table 2: Scaling of the REP Spacecraft with Increasing Power (Masses include approximately 30% Contingency).

Spacecraft Power	0.81 kWe	1.06 kWe	1.56 kWe	2.06 kWe	2.56 kWe	3.06 kWe
Science	48 kg	48 kg	48 kg	48 kg	48 kg	48 kg
ACS	46 kg	46 kg	46 kg	46 kg	46 kg	46 kg
Comm. & C&DH	71 kg	71 kg	71 kg	71 kg	71 kg	71 kg
Structures	66 kg	71 kg	81 kg	91 kg	101 kg	112 kg
Thermal	25 kg	25 kg	25 kg	25 kg	25 kg	25 kg
Power & Propulsion	216 kg	247 kg	309 kg	371 kg	433 kg	495 kg
	472 kg	508 kg	580 kg	652 kg	724 kg	797 kg

Table 3: REP Concept Study Mass Equipment List

REP OPTO 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 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 s 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, a low-gain antenna, Ka-band traveling wave tube, and X-band solid-state amplifier among other pertinent communications equipment.

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.

For this study the REP propulsion system is assumed integrated with the Neptune science spacecraft. Two options are explored; REP only for capture via a spiral-in and REP combined with a chemical system to capture at Neptune.

2. Solar Electric Propulsion Stage

The SEP stage design is the design conceived for the NEXT Team-X study completed in October 2003[14] (see Fig. 2). It consists of a large solar array system that powers a NEXT ion propulsion system. It also includes the required structure and thermal control. The SEP stage does not include avionics or attitude control hardware, as these functions are to be controlled by the attached orbiter. The total dry mass of the baseline SEP module is approximately 1200 kg. The SEP module is jettisoned at a distance of approximately 3 AU where the solar flux is insufficient to provide power for the NEXT thrusters.

A maximum of 30 kWe is provided to the SEP stage in its baseline configuration. Two solar array wings carrying three circular Ultraflex solar arrays each provide the power. Each array is approximately 5 m in diameter.

The NEXT ion propulsion system consists of the hardware developed under the NEXT project. The thruster is a 40 cm beam diameter ion thruster that operates at up to 7 kWe of input power.[15] The NEXT program is also developing the PPU[16] and xenon propellant management system[17] designs. The tank is assumed to be a single ultralight composite tank kept cold by layers of thermal multi-layer insulation. The baseline SEP stage configuration includes up to four operating thrusters and PPUs and one spare of each for a total of five thrusters and PPUs. The thrusters are switched on and off as solar array power changes with distance to the Sun.

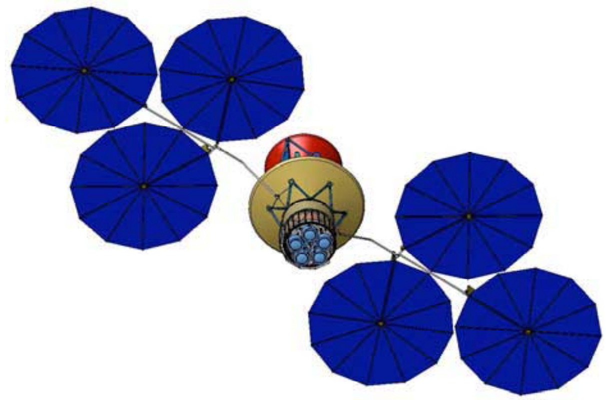

Figure 2: SEP Module Conceptual Design

The science orbiter propelled by the SEP stage consists of several options for this study. The non-REP science orbiters include a 500 kg bus and science mass including 200 W of power.[18] This was the mass assumed in the previous SEP-aerocapture studies and is assumed to include all science, power, propulsion, communications, avionics, etc. needed for an extended science mission in orbit of Neptune with flybys of Triton. In addition this 500 kg orbiter must provide attitude control for the combined SEP/orbiter (approximate total of 3000 kg), a separation system, and thermal system for the extremes of Venus to Neptune. In addition to the 500 kg orbiter an additional aerocapture system (approximately 250 kg) as well as a chemical system (approximately 100 kg) to raise the periapsis of the aerocapture orbit out of the Neptune upper atmosphere is required. No breakdowns for this 500 kg orbiter mass were available (except an approximate 50 kg science mass) from the SEP-aerocapture studies. It is assumed that the design uses similar technologies and margins to the REP design to make the two orbiters comparable in required function. (Further studies are warranted to break out all of the various different function depending upon scenario and assess the mass impacts.) For the All Chemical, REP, and REP/Chemical options the science orbiter will have the appropriate propulsion system(s) integrated with the spacecraft.

3. Configurations Utilizing a Chemical Capture System

Several configurations utilize a chemical propulsion stage to capture into Neptune orbit. This system is assumed to be an advanced pressure-fed, Earth storable bipropellant chemical propulsion stage with an I_{SP} of 328 s.[19] The dry mass of the chemical system is assumed to be 11% of the mass of propellant required.[19]

B. Launch Vehicle

Two launch vehicles are examined as part of this study. When comparing the performance of different spacecraft (i.e. REP vs. SEP-REP), a Delta IV M+ (4,2) is used. This Delta IV launch vehicle was chosen because of its use in the NEXT design reference mission studies. A secondary part of this study was performed to see the benefit of changing launch vehicles to an Atlas V 551. This launch vehicle was chosen because of its use as the baseline launch vehicle in the aforementioned REP concept study. Similar performance to the Atlas V 551 could be achieved using a Delta IV M+ (5,4). For

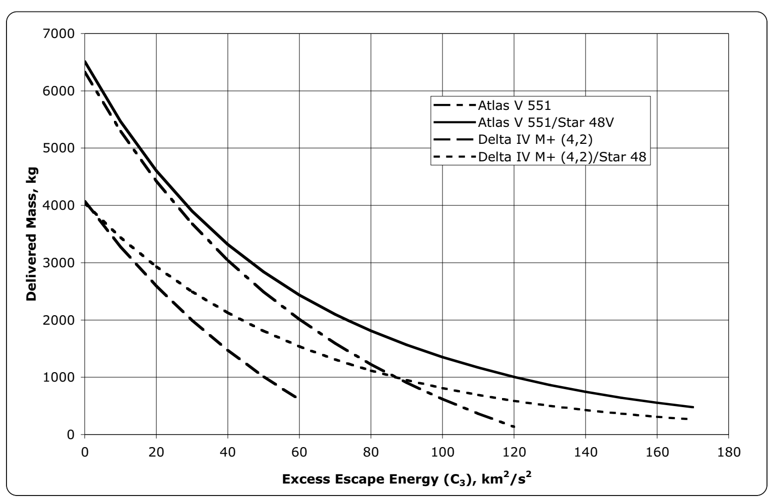

Figure 3: Atlas V 551 and Delta IV M+ (4,2) Launch Vehicle Performance with and without the Star 48 Motor[20-23]

configurations not using the SEP stage, a high excess escape energy (C_3) launch was performed with a Star 48 motor topping the Delta and Atlas launch vehicles. Such high-energy escapes are needed for REP related mission scenarios not using SEP. The performance of these vehicles with and without the Star 48 motor can be seen in Fig. 3.

III. Mission Analyses

A. Mission Descriptions

Two general mission profiles are used for this study, SEP stage injection and high-energy launch vehicle injection. The SEP stage injection launches approximately 3000 kg to a departure C_3 of approximately 10 km^2/s^2. It then performs a Venus flyby to increase the spacecraft's velocity and propel it to the Neptune encounter (see Fig 4). The high-energy launch scenario launches from 450 to 700 kg to departure C_3s of 140 to 75 km^2/s^2. The high-energy launch provides most of the energy needed to reach Neptune[24] (see Fig. 5).

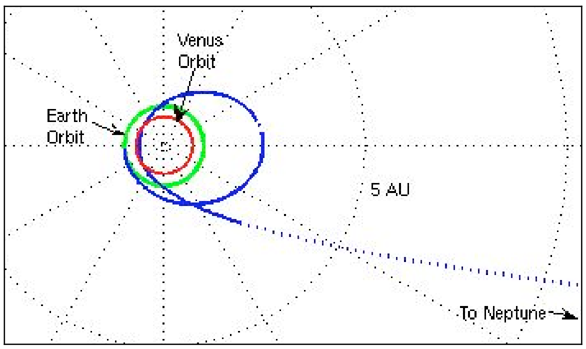

Figure 4: SEP Trajectory

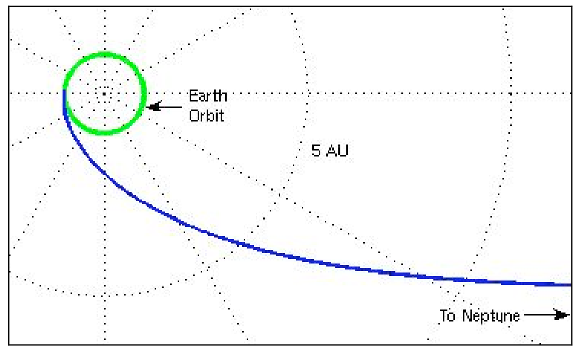

Figure 5: REP Trajectory

Two different final orbits are attained at Neptune, depending on the capture technique. Aerocapture, chemical, and combined REP/Chemical capture attain a highly elliptic orbit around Neptune with periodic flybys of Neptune's moon, Triton. This orbit is 6191 km by 330,000 km altitude. REP capture without chemical propulsion utilizes the electric propulsion system to spiral to the same orbit as Triton and then into a Triton orbit as the final science orbit.

B. 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.[25] The DTOM numerically integrates the three-dimensional equations of motion using modified equinoctial orbital elements to accommodate circular orbits (eccentricity of 0).[26] 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.[27]

The total trip times of the different configurations were used for comparison. In the cases where an REP spacecraft was part of the configuration, the power level into the PPUs was varied between 0.75 kWe and 3.0 kWe, and the appropriate dry mass was added, to complete the trade of trip time versus REP spacecraft power. REP spacecraft power, in this case, is defined as the power into the PPUs plus 60 We of housekeeping power available for spacecraft operation during ion thruster cruise. The baseline case used for comparison was the SEP-Aerocapture case with a trip time of approximately 10.5 years to a final Neptune orbit. This baseline case delivers a spacecraft with a mass of approximately 500 kg as described in the spacecraft analysis section.

C. Performance of the Various Spacecraft Configurations

Trip times of the previously described spacecraft configurations ranged from 10 to 20 years when launched on a Delta IV M+ (4,2) (see Fig. 6). The SEP-Aerocapture configuration achieved the minimum time to Neptune orbit of 10.4 years, and the REP took the longest time. However, the worst performing configuration was the direct all-chemical spacecraft with a trip time of 12 years, this all-chemical configuration could only deliver an insufficient 80 kg spacecraft to Neptune. The REP-Chem, SEP-Chem, and SEP-REP-Chem configurations delivered their respective spacecraft to Neptune orbit in between 12 and 15 years, whereas the SEP-REP configuration required between 14 and 18 years.

The REP configurations employing the chemical capture stage were relatively stable with changing spacecraft power levels as compared to those using REP as the capture means. The trip times decreased by approximately one year for the chemical capture cases and approximately 4 years for the REP capture cases with an increase of 1.5 kWe. However, the trip time curves flatten out dramatically above 1.5 kWe, diminishing the trip time savings associated with higher spacecraft power.

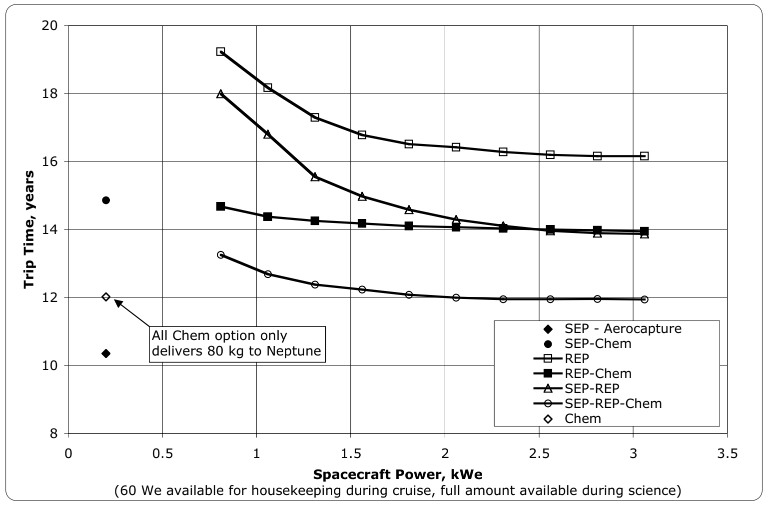

Figure 6: Trip Time Performance of the Various Spacecraft Configurations Launched on a Delta IV M+ (4,2) (Cases without SEP include a Star-48 Upper Stage.)

Examining the spacecraft configurations' mass breakdowns (see Fig. 7), conclusions can be drawn about the performance shown in Fig. 6. Usage of the launch vehicle is determined by the existence of the SEP stage. Configurations with the SEP stage launch to a low departure C_3, approximately 10 km^2/s^2, to accommodate the high mass of the configuration whereas those without launch to a high departure C_3, approximately 80-140 km^2/s^2, to accommodate their much lower mass. That is, the SEP stage provides much of the energy, in conjunction with a Venus flyby, needed to reach Neptune, whereas the configurations without the SEP stage utilize the launch vehicle to provide most of the energy needed to reach Neptune without a Venus flyby. A second conclusion that the mass breakdown makes apparent is the relative performance of capturing using a chemical propulsion system versus the electric propulsion system. The total masses of the REP and REP-Chem and the SEP-REP and SEP-REP-Chem are very close, however the trip times of the configurations using a chemical propulsion system to capture are more than 2 years shorter. Up until the capture, the performance of these systems is fairly equal, but because of the different means of capture, the capture time is dramatically different. A chemical propulsion system can complete the capture maneuver and deliver the spacecraft to its final orbit in a matter of hours, whereas the electric propulsion system takes months or years to deliver the spacecraft. The relative scientific value of the different orbits – flybys of Triton using a chemical capture versus orbiting Triton need to be assessed.

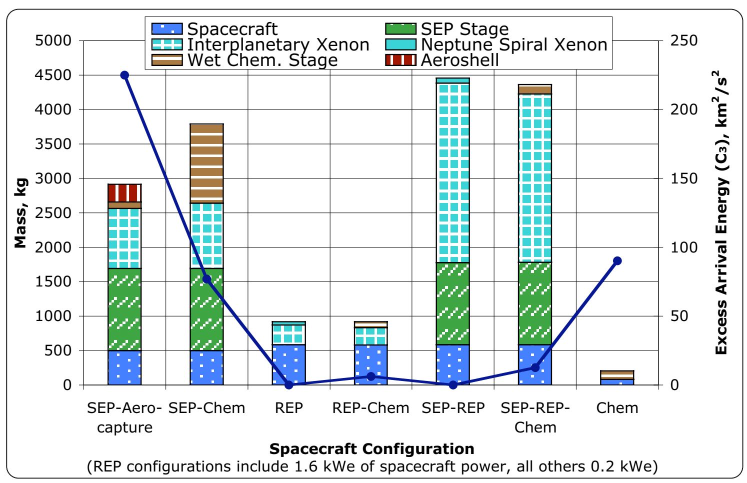

Figure 7: Mass Distribution of the Different Configurations Launched on a Delta IV M+ (4,2)

The arrival C_3 (see Fig. 7) also helps to explain the performance of these configurations. The high arrival C_3 of the SEP-Aerocapture configuration and its low mass compared to other SEP configurations is the reason for the short comparative trip time to Neptune. The Chem and SEP-Chem configurations cannot accommodate as high of an arrival C_3 because of the low I_{SP} of the chemical system and therefore the amount of propellant required for capture at Neptune. Comparing REP versus REP-Chem and SEP-REP versus SEP-REP-Chem, one can see that the shortened trip time of the chemical capture configurations results in non-zero arrival C_3s. Thus in these chemical capture configurations, the REP system is not required to remove as much energy from the spacecraft trajectory in favor of the chemical system performing a short capture burn near Neptune to remove the energy. The capture is performed more efficiently and quicker near Neptune as opposed to more than a year of spiraling with the ion thrusters to reach the final science orbit.

The I_{SP} of the REP ion system was optimized by DTOM in each of the analyses. Total propulsion system performance (efficiency) was varied based on required I_{sp} by the function: Efficiency = $(bb * I_{sp}^2) / (I_{sp}^2 + dd^2)$ where bb = 0.8358 and dd = 2152.99 seconds. This trend is representative of sub-kilowatt thruster test data at similar power levels.[28-31] Optimal REP ion thruster I_{SP}s for the REP and REP-Chem spacecraft are between 4000 and 5500 s whereas the REP ion thruster optimal I_{SP}s for the SEP-REP and SEP-REP-Chem configurations are between 2800 and 4500 s (see Fig. 8), and in each case increase with spacecraft power level. I_{SP}s are higher for the non-SEP configurations, because the REP ion thrusters are performing more of the total mission Δv than in the configurations with SEP, thus more efficient use of the propellant is required. The constrained launch mass of the high departure C_3 non-SEP configurations also demands more efficient use of the onboard propellant.

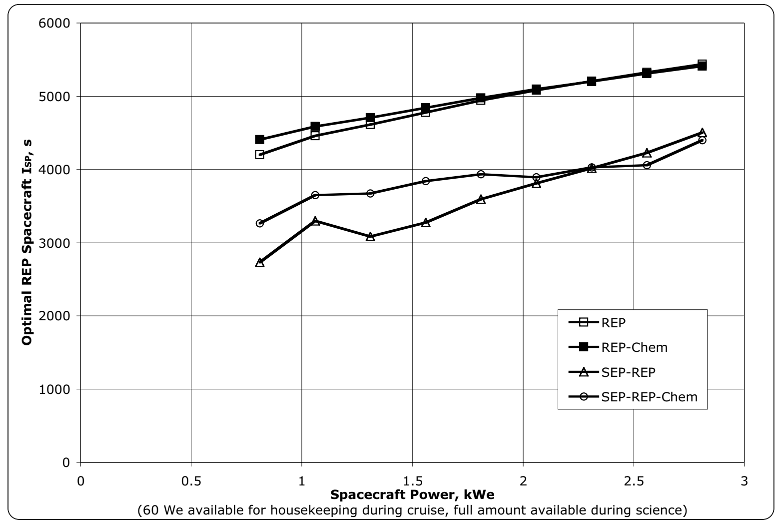

Figure 8: Optimal REP Spacecraft I_{SP}s when Launched on a Delta IV M+ (4,2)

D. Launch Vehicle Performance

Increasing the launch vehicle size from a Delta IV M+ (4,2) to an Atlas V 551 has trip time benefits for each of the configurations examined (see Fig. 9). Trip times decreased for non-SEP configurations by approximately three years, irrespective of the spacecraft power level. The SEP-Aerocapture trip time only decreased by 1.5 months due to the number of constraints on that trajectory (i.e. Venus flyby and maximum aerocapture velocity), which is the case for the other SEP configurations, also. Changing launch vehicles from the Delta IV M+ (4,2) to the Atlas V 551 increases the launch vehicle cost by approximately \$20 million (2001 dollars),[32] but with REP power levels around 1.5 kWe, the performance of the REP-Chem configuration is comparable to SEP-Aerocapture and even attains shorter total trip times than the SEP-REP-Chem configuration launched on a Delta IV M+ (4,2).

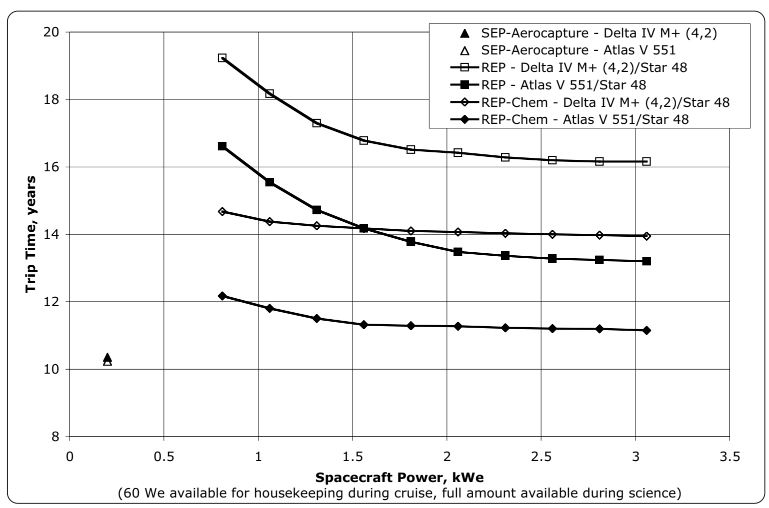

Figure 9: Spacecraft Performance on Different Launch Vehicles

IV. Conclusion

Combinations of SEP, REP, and chemical propulsion systems, as well as aerocapture, were applied to a Neptune Orbiter mission. REP spacecraft power levels were varied to allow examination of the effect of REP power level on total mission trip time. When launched on a Delta IV M+ (4,2), the SEP-Aerocapture configuration delivered the spacecraft to its final Neptune orbit in the least amount of time. The best-performing configurations with REP delivered the spacecraft to its final orbit with trip times 2-4 years longer than the SEP-Aerocapture configuration. Increasing the power level of the REP configurations did decrease total trip time with moderate power increases, but the benefit diminished with power levels over 1.5 kWe. The benefit of an increase in launch vehicle size, from a Delta IV M+ (4,2) to an Atlas V 551, was also analyzed. The larger launch vehicle decreases the non-SEP configurations' trip times by approximately 3 years, independent of REP power level. The larger launch vehicle shortens the trip time of the REP-Chem configuration to within approximately 1 year of the SEP-Aerocapture configuration.

By no means was this study of the fidelity that is required for a flight program, but it does show the effects of the implementation of these technologies individually and in cooperation with each other. Only one mission was examined, but similar performance changes can be expected for similar outer solar system missions. Future work, if requested, can focus on adding more detail to the spacecraft designs. Currently, only the all-REP spacecraft and the SEP stage have been studied in sufficient depth to provide reliable mass estimates. As part of this study, assumptions were made to estimate the mass change in response to the configuration changes.

There appears to be promise in further investigation into the REP-Chem spacecraft. Not only does it deliver the spacecraft to Neptune with comparable trip times to the SEP-Aerocapture configuration, but it also provides a spacecraft with more power and a fully functional electric propulsion system. This REP system could also provide the capability to change orbits and complete the science investigations at Neptune and its moon Triton.

References

[1]Oleson, S.R., Gefert, L., Schreiber, J., McAdams, J., "Sub-Kilowatt Radioisotope Electric Propulsion for Outer Solar System Exploration", Forum on Innovative Approaches to Outer Planetary Exploration 2001-2020, Lunar and Planetary Institute, Houston, Texas, Feb, 2001.

[2]Oleson, S.R., Gefert, L., Patterson, M., Schreiber, J., Benson, S., McAdams, J., Ostdiek, P., "Outer Planet Exploration with Advanced Radioisotope Electric Propulsion", IEPC-2001-0179, 27th International Electric Propulsion Conference, Pasadena, California, October, 2001.

[3] Noble, R.J., "Radioisotope Electric Propulsion of Small Payloads for Regular Access to Deep Space", AIAA 93-1897, 29th Joint Propulsion Conference, Monterey, California, 1993.

[4]Noble, R.J., "Radioisotope Electric Propulsion for Small Robotic Space Probes", British Interplanetary Society 49, 455-468, (1996).

[5]Noble, R. J., "Radioisotope Electric Propulsion of Sciencecraft to the Outer Solar System and Near-Interstellar Space", Nuclear News, Nov. 1999, pp 34-40.

[6]Oleson, S.R., Benson, S., Gefert, L., Patterson, M., Schreiber, J., "Radioisotope Electric Propulsion for Fast Outer Planetary Orbiters", AIAA-2002-3967, *38th Joint Propulsion Conference*, Indianapolis, Indiana, July, 2002.

[7]National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, National Academies Press, Washington, D.C., 2002, Chapter 7.

[8]Oleson, S., Gefert, L., Benson, S., Patterson, M., Noca, M., Sims, J., "Mission Advantages of NEXT: NASA's Evolutionary Xenon Thruster," AIAA Paper AIAA-2002-3969, 38th Joint Propulsion Conference, Indianapolis, IN, July 2002.

[9]Neptune Orbiter Mission Package, In-Space Integrated Space Transportation Activity by the IISTP Systems Analysis Team, April, 2001.

[10]Alagheband, A., Corazzini, T., Duchemin, O., Henny, D., Mason, R., Noca, M., "Neptune Explorer – An All Solar Powered Neptune Orbiter Mission," AIAA Paper AIAA-1996-2980, 32nd Joint Propulsion Conference, Buena Vista, FL, July 1996.

[11]"The Vision for Space Exploration," National Aeronautics and Space Administration, February 2004.

[12]Schreiber, J. G., Thieme, L. G., "Overview of NASA GRC Stirling Technology Development," AIAA Paper AIAA-2003-6093, First International Energy Conversion Engineering Conference, Portsmouth, VA, August 2003.

[13]Pencil, E. J., Kamhawi, H., Arrington, L., "Overview of NASA's Pulsed Plasma Thruster Development Program," AIAA Paper AIAA-2004-3455, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

[14]Oberto, R., Sweetser, T., et al., "Advanced Projects Design Team, Titan Orbiter 2003-10," JPL Report ID #658, 2003.

[15]Patterson, M., Domonkos, M., Foster, J., Haag, T., "NEXT: NASA's Evolutionary Xenon Thruster Development Status," AIAA Paper AIAA-2003-4862, 39th Joint Propulsion Conference, Huntsville, AL, July 2003.

[16]Phelps, T. K., Wiseman, S., Komm, D. S., Bond, T., Pinero, L., "Development of the NEXT Power Processing Unit," AIAA Paper AIAA-2003-4867, 39th Joint Propulsion Conference, Huntsville, AL, July 2003.

[17]Aadland, R. S., Engelbrecht, C. S., Ganapathi, G. B., Browning, D. A., Wilson, F., Hoskins, W. A., "Xenon Propellant Management System for 40 cm NEXT Ion Thruster," AIAA Paper AIAA-2003-4880, 39th Joint Propulsion Conference, Huntsville, AL, July 2003.

[18]Gershman, R., "Propulsion and Power Technology Needs of Future Solar System Exploration Missions," Solar System Exploration Theme Overview Presentation, March 1999.

[19]TRW Space & Technology Division, "Storable Thruster Upgrade Technology Program, Informal Report: Mission Analysis Task," Prepared for NASA GRC under contract NAS3-00176, September 2001.

[20]The Boeing Company, "Delta IV Payload Planner's Guide," MDC 00H0043, October 2000.

[21]The Boeing Company, "Delta IV Payload Planner's Guide Update – April 2002," MDC 00H0043, April 2002.

[22]International Launch Systems (ILS), "Atlas Launch System Planner's Guide," Rev. 9, September 2001.

[23]Morton Thiokol, Inc., "Space Rocket Motors," June 1987.

[24]Fiehler, D. I., Oleson, S. R., "Mission Steering Profiles of Outer Planetary Orbiters Using Radioisotope Electric Propulsion," NASA TM-2004-212877, January 2004.

[25]Kluever, C. A., "Optimal Low-Thrust Interplanetary Trajectories by Direct Method Techniques," Journal of the Astronautical Sciences 45, 247-262 (1997).

[26]Betts, J. T., "Optimal Interplanetary Orbit Transfers by Direct Transcription," Journal of the Astronautical Sciences 42, 247-268 (1994).

[27]Sauer, C., "A Users Guide to VARITOP: A General Purpose Low-Thrust Trajectory Optimization Program," Advanced Projects Group, Jet Propulsion Laboratory, November 1991.

[28]Patterson, M.J. and Grisnik, S.P., "Scaling of Ion Thrusters to Low Power," IEPC-97-098, 25th International Electric Propulsion Conference, Cleveland, Ohio, August 1997 Also NASA TM-1998-206530.

[29]Patterson, M.J., "Low-Power Ion Thruster Development Status," AIAA Paper No. 98-3347, 34th Joint Propulsion Conference, Cleveland, Ohio, July 1998.

[30]Foster, J.E. and Patterson, M.J, "Enhanced Discharge Performance in a Ring Cusp Plasma Source," IEPC 99-159, 26th International Electric Propulsion Conference, Kitakyushu, Japan, October 1999, Also NASA TM-2000-209765.

[31]Menart, J.A. and Patterson, M.J., "Magnetic Circuit for Enhanced Discharge Chamber Performance of a Small Ion Thruster," AIAA Paper No. 98-3343, 34th Joint Propulsion Conference, Cleveland, Ohio, July 1998.

[32]Isakowitz, S. J., Hopkins, J., Hopkins Jr., J. P., *International Reference Guide to Space Launch Systems*, 3rd ed., AIAA General Publication Series, AIAA, New York, 1999, pp. 55, 97.

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In certain cases, Radioisotope Electric Propulsion (REP), used in conjunction with other propulsion systems, could be used to reduce the trip times for outer planetary orbiter spacecraft. It also has the potential to improve the maneuverability and power capabilities of the spacecraft when the target body is reached as compared with non-electric propulsion spacecraft. Current missions under study baseline aerocapture systems to capture into a science orbit after a Solar Electric Propulsion (SEP) stage is jettisoned. Other options under study would use all REP transfers with small payloads. Compared to the SEP stage/Aerocapture scenario, adding REP to the science spacecraft as well as a chemical capture system can replace the aerocapture system but with a trip time penalty. Eliminating both the SEP stage and the aerocapture system and utilizing a slightly larger launch vehicle, Star 48 upper stage, and a combined REP/Chemical capture system, the trip time can nearly be matched while providing over a kilowatt of science power reused from the REP maneuver. A Neptune Orbiter mission is examined utilizing single propulsion systems and combinations of SEP, REP, and chemical systems to compare concepts.

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