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NEP Early Flight Program: System Performance and Development Considerations

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NEP EARLY FLIGHT PROGRAM:

SYSTEM PERFORMANCE AND DEVELOPMENT CONSIDERATIONS

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Abstract

A mission/system study of Nuclear Electric Propulsion (NEP) for early robotic planetary science mission applications has been conducted. Subject missions considered included a Mars orbiter with a Phobos and Deimos Rendezvous; a Comet Kopff Rendezvous; a Multiple Mainbelt Asteroid Rendezvous (MMBAR); an Asteroid (Vesta) Sample Return; a Trojan Asteroid (Odysseus) Rendezvous; and a Jupiter mini Grand Tour. The purpose of the study was to determine if "near-term" NEP technology could be used on an early NEP flight to demonstrate the technologies while conducting a useful science mission. The analysis shows that, depending upon technology readiness date, the missions could be performed with low power NEP. The technology and system development costs associated with vehicle/stage development for a candidate mission are presented. The study assumed relatively mature space electric power and space electric propulsion technologies (more advanced technologies have been already shown by others to be enabling for many outer planetary missions). Thus, a very important first step in using NEP would be taken, which would contribute valuable solar system science, as well as reduce the risks associated with using NEP for more demanding outer planetary science mission applications.

Introduction

The National Aeronautics and Space Administration's (NASA's) Solar System Exploration Division foresees a need for Nuclear Electric Propulsion (NEP) for science missions to a number of planetary, asteroidal, and cometary destinations early in the 21st century. NEP provides greatly reduced trip times, launch date flexibility, and a large reduction in on-board propellant mass compared to state-of-the-art chemical systems. Mission and system studies assuming SP-100 [100 kilowatts-electric (kWe)] reactor and power conversion technologies and ion electric propulsion have been performed which show that an approximately 100 kWe NEP system enables a number of the proposed missions, and allows for orbiter missions to the major satellites of Jupiter, Uranus, Neptune, and Pluto, and yields more frequent launch opportunities[1]. The analysis of Yen and Sauer implies that successful performance of the desired planetary missions will require a space nuclear electric power source rated nominally at 7 to 10 years full power life, 100 kWe power, and 25 watts per kilogram (W/kg) and ion electric engines having a specific impulse (I_{sp}) of 5000 to 10,000 seconds, at least 15 kWe per thruster power rating, and 10,000 hours individual thruster life.

As an initial step in developing NEP for robotic planetary missions, a lower power, earlier flight initiative was proposed by the Solar System Exploration Division, and a mission/system study initiated at their request. Missions initially considered in this study were those requiring just 15-50 kWe and only a 3-year reactor full power life, relying on technologies projected to be in hand by the year 1994. Missions considered were: a Mars orbiter mission including a Phobos and Deimos rendezvous, a 3-body mainbelt asteroid multiple rendezvous, and a Vesta asteroid sample return.

The study task team was comprised of people from the Lewis Research Center (LeRC) and the Jet Propulsion Laboratory (JPL). The study was completed in March 1993.

Study Ground Rules

Based upon program planning guidance from an interagency Department of Energy (DOE)/ NASA) planning committee[2], the low power study focused initially on technologies that could by included in an NEP system for launch by 1998. As the study progressed, the prospects for an NEP mission beginning in 1998 dimmed, and the planning guidelines were significantly changed. The reference propulsion technology, against which the benefits of NEP were to be evaluated, changed from chemical to solar electric propulsion (SEP). Consequently, the playing field of technologies was widened to include NEP technologies that could be developed sometime during the 1990s, and the mission set was expanded to include missions very clearly enabled by NEP (and not by SEP).

As a result, the final mission set came to include a Mars orbiter with a Phobos and Deimos Rendezvous; a Comet Kopff Rendezvous; a Comet Kopff Sample Return; a Multiple Mainbelt Asteroid (Ceres, Irene) Rendezvous with Mars Gravity Assist; a Multiple Mainbelt Asteroid (Massalia, Nysa, Astraea) Rendezvous; an Asteroid (Vesta) Sample Return; a Trojan Asteroid (Odysseus) Rendezvous; a Multiple Mainbelt Asteroid (Massalia, Nysa) plus Trojan Asteroid (Anchises) Rendezvous; and a Jupiter mini Grand Tour (a tour of Callisto and Ganymede, the two outer moons of Jupiter). Yen et al[3] have documented this final mission set and its contribution to planetary science.

Systems

The following discussion of the low power NEP systems will provide further detail as to the technical assumptions, and an overview of the resulting system performance.

Technical Assumptions:

The technologies considered in this study for reactor, power conversion, heat rejection, and electric propulsion were only those believed mature enough to be ready at the component level [technology readiness level 4 - (TRL-4)] before the year 2000. Table I shows the readiness of the selected technology options as a function of three different TRL-4 dates.

SP-100 liquid-lithium-cooled reactor technology was the selected reactor technology no matter which technology readiness date, "1994" (near term), "1996" (mid term), or "1998" (far term), was chosen. The lifetime of the reactor subsystem was assumed to be longer for each TRL-4 date.

Power conversion options considered were Brayton (with up to a 1300 K turbine inlet temperature) or thermoelectrics (with up to a .85 K^{-1} figure of merit).

Heat rejection options considered were pumped loop (Brayton) and heat pipe (Thermoelectric), with the earliest option being a Space Station Freedom (SSF) type

Readiness Date	1994	1996	1998
Reactor	SP-100	SP-100	SP-100
Temp (K)	1375	1375	1375
Lifetime (years)	3/5	5/7	7/10
Power	Scaled	Scaled	Scaled
Power Conversion			
Type	Brayton (BRU) -	Brayton, TE	Brayton, TE
Turbine Temp. (K)	1144	1144	1300
or Figure of Merit (K^{-1})	-	0.67	0.85
Radiator			
Type	SSF Pumped Loop -	Pumped Loop, Ti Heat Pipe	Pumped Loop, C-C Heat Pipe
Temperature (K)	450	600 800	650 800
Thrusters			
Size (CM)	30	50	50
Propellant	Xe	Xe	Xe,Kr,A

BRU: Brayton Rotating Unit
TE: Thermoelectric
SSF: Space Station Freedom
Ti: Titanium
C-C : Carbon-carbon
Xe: Xenon
Kr: Krypton
Ar: Argon

Table I. - Low Power NEP Technology Options Considered

pumped loop radiator.

Thruster options were limited to ion engines in the 30 to 50 centimeter diameter range with Xenon (near term), and Krypton and Argon (far term) propellants considered.

Other general system assumptions follow. The reactor designs assumed a 1375 K reactor outlet temperature, with the reactor thermal power scaled to requirement. The Brayton power conversion unit provided electrical power at 208 V_{rms} at 1200 Hz. For the 1994 readiness date, the Brayton system was assumed to be of superalloy construction, with an 1144 K turbine inlet temperature (TIT), 20 kWe per unit, and a cooled alternator. For 1996, the Brayton rotating unit was redesigned, using the same materials, but scaled to the required power level. For 1998, a refractory metal turbine was assumed, allowing a 1300 K TIT.

Thermoelectric power conversion options assumed conductively coupled, Silicon-Germanium at 10 watts/cell (1996) and conductively coupled, Silicon-Germanium/ Galium Phosphide at 13 watts/cell (1998). For the ring cusp type ion engines a 10,000 hour lifetime was assumed. Propellant storage of Xenon was assumed supercritical, while only cryogenic storage of Krypton and Argon was considered.

In addition, some general NEP design considerations were: the dose plane distance for the payload being 22.5 meters; an assumed increase in electronics hardening as development time went on; at least one spare turboalternator on all Brayton power conversion systems; one spare PPU set; and multiple thruster sets to meet the lifetime requirements of each mission considered.

<u>System Performance Analysis Results</u>

The system performance as analyzed was broken down into space electric power system (reactor, power conversion, heat rejection, and power management and distribution (PMAD)) performance and space electric propulsion system (thrusters and power processors) performance. For the Brayton space power systems considered, specific mass, in kilograms per kilowatt, ranged from 46 kg/kWe to 165 kg/kWe, depending upon the required power level and the technology readiness date chosen. For the Thermoelectric space power systems considered, specific mass ranged from 38 kg/kWe to 130 kg/kWe, depending upon the required power level and the technology readiness date chosen. For the ion electric propulsion systems considered, specific mass ranged from 15 to 70 kg/kWe depending upon the required specific impulse and the technology readiness date chosen.

Mission and System Performance Summary and Conclusions

The missions considered in the study can be performed to varying degrees by the low power NEP systems analyzed. Required bus electrical power varies between 11 and 60 kWe, while required specific impulse varies between 3600 and 9400 seconds I_{sp}, and required full power lifetime varies between 2.8 and 7.0 years. The Mars Orbiter with a Phobos/Deimos Rendezvous mission and the Comet Kopff Rendezvous mission only need 11-20 kWe, 3600-4000 seconds I_{sp}, and 2.8-3.1 years full power lifetime; while the MMBAR + Trojan Asteroid Rendezvous mission and the Jupiter mini Grand Tour mission require from 40-60 kWe, 5300-9400 seconds I_{sp}, and 4.2-7.0 years full power lifetime.

Delivered payload masses vary depending upon the mission and the technology level considered. Many of the missions considered can be performed by one or more of the assumed systems, with payloads being equal or greater than 1000 kg even when a large (30 percent) margin was assumed for NEP dry propulsion system mass.

The earliest available system, based upon the the Brayton rotating unit, has limited performance capability. The only mission it can perform (with a 30 percent margin on dry propulsion system mass) is the Mars Orbiter with a Phobos/Deimos Rendezvous. This system was limited by the radiator technology, but was the earliest system that could be deployed.

Either the 1996 or 1998 Thermoelectric or Brayton power conversion technology options yield performance suitable for a wide suite of missions, with assumed mass margins affecting the choice of mission.

System Development Schedule and Costs

The technology and system development costs associated with the vehicle/stage development for a candidate mission were also estimated for a 40 kWe system. A very detailed description of this baseline system has been previously reported[4].

This specific system was chosen because it was the nearest term system appearing to meet the transportation requirements of a three-body Multiple Mainbelt Asteroid Rendezvous (20-Massalia, 44-Nysa, 5-Astraea) mission having a near term launch date, which was in keeping with the original program planning guidance. Such a selection of a reference mission enabled a more refined science/ spacecraft definition, and provided programmatic focus for technology and system development schedule and cost.

The cost estimates included technology, phase B studies, and flight hardware development (phase C/D) costs to design, develop, test, evaluate, and deliver a flight qualified NEP planetary spacecraft including spacecraft bus with science payload. With the technology assumed being that which could be completed by 1994, very little technology work remained to be performed. The cost estimates did not include: 1) launch and launch integration, 2) airborne support equipment/ launch vehicle accomodations, and 3) mission operations support.

The summary schedule for the development of the flight system is shown in Figure 1. Launch is assumed at the end of the year 2000. Major activities assumed to take place in the development of the flight system were:

-technology development (complete by 1995 for the costed flight system, while continuing on for mid-term and far-term technology)

-safety and environmental impact assessments leading to a launch decision

-conceptual design

-development, including preliminary/ detailed design procurement, fabrication, and flight qual and acceptance of the flight hardware

- and integration.

System design/development cost estimates assume that the technology is "frozen" by the end of FY 1994. The technologies applied toward the system are:

1)reactor - liquid lithium cooled, pin type at 1375 K reactor outlet temperature,

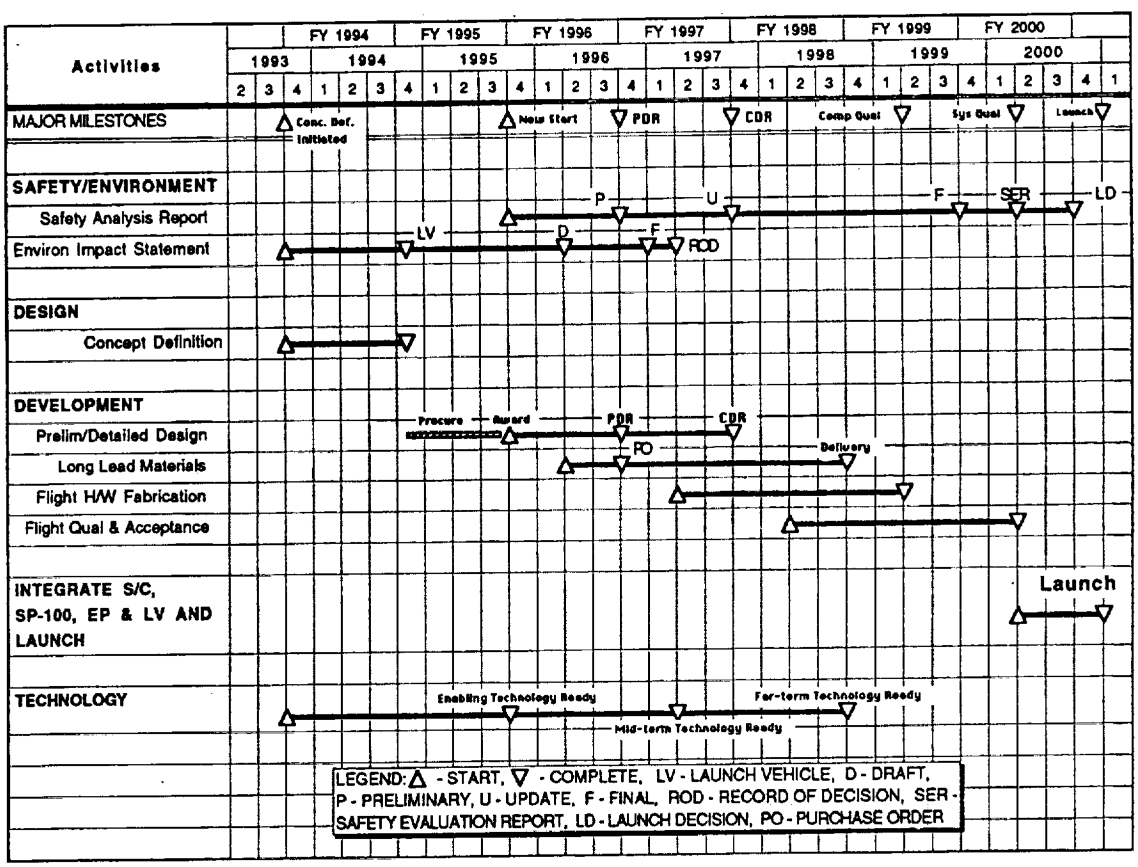

Figure 1. - 40 kWe NEP System Development Summary Schedule (1994 Technology)

2) shielding - tungsten/ lithium hydride,

3) power conversion - Brayton rotating unit (superalloy construction, 1144 K turbine inlet temperature, 38000 hours life) heritage at 20 kWe/unit,

4) heat rejection - Space Station Freedom aluminum/ toluene pumped loop radiators (450 K maximum temperature), and

5) thruster - 30 centimeter diameter Xenon ion engine at 5000 seconds I_{sp}.

Only the enabling (near term) technology was included in the cost estimate. This includes the following:

-thermoelectromagnetic (TEM) pump test, and control drive assembly validation to insure reactor readiness,

-validation of hot side heat exchanger material compatibility

- and validation of 30 cm diameter ion thruster (and power processing unit) performance and life.

No other technology activities were included in the cost estimate.

The cost estimate is shown in bar chart form in figure 2. Costs are in constant 1993 dollars from 1994 to 2000. Cost categories included: technology, conceptual design (phase B), and preliminary/ final design and development (phase C/D). Included within the preliminary/final design and development category are prime phase C/D costs (for

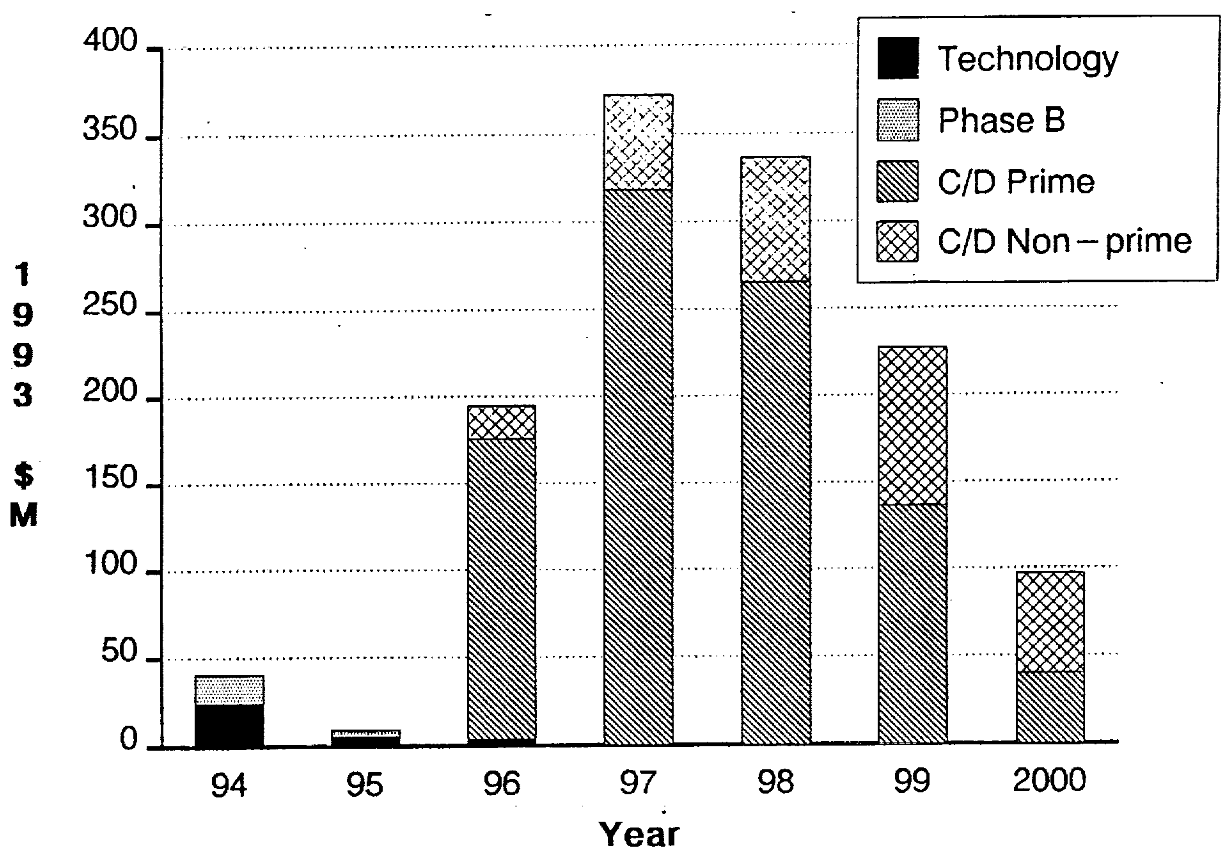

Figure 2. - 40 kWe NEP System Development Costs

spacecraft bus with science payload, nuclear power system, electric propulsion system, and overall integration and test) and non-prime phase C/D costs (reserves, government laboratory support, and government support/ management). The total costs ranged in the neighborhood of $1.3B in 1993 dollars.

Summary and Conclusions

An encapsulation of a mission/system study of low power NEP for planetary science jointly conducted by NASA LeRC and JPL has been given. The study showed that there is an interesting planetary science mission set with valuable science return which could be performed by low power NEP.

Since the study assumed relatively mature space electric power and space electric propulsion technologies, and these technologies have already been shown by others to enable other outer planetary missions, this lower power application would be valuable. Selecting a mission from this low power set could thus serve to gain valuable solar system science, as well as to reduce the risks of using an NEP system for the first time on demanding outer planetary science missions.

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