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July 2003

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Abstract. The performance of Nuclear Electric Propulsion (NEP) in transporting cargo and propellant from Low Earth Orbit (LEO) to the first Earth-Moon Lagrange point (EML1) is examined. The baseline NEP vehicle utilizes a fission reactor system with Brayton power conversion for electric power generation to power multiple liquid hydrogen magnetoplasmadynamic (MPD) thrusters. Vehicle characteristics and performance levels are based on technology availability in a fifteen to twenty year timeframe. Results of numerical trajectory analyses are also provided.

MISSION DESCRIPTION

The interior collinear Earth-Moon Lagrange point (EML1) provides a potentially attractive waypoint for missions to the Moon, planets, and Earth-Moon and Earth-Sun Lagrange points. The objective of this analysis is to determine the applicability of high power NEP for cargo and tanker vehicles within the Earth-Moon system. The configurations of the cargo and tanker spacecraft are very similar except for the payloads carried and power level required by each.

The NEP cargo spacecraft is designed to carry three 40 t elements of surface lander hardware for the HOPE missions to Callisto (Troutman, 2003). Upon the vehicles arrival at EML1 the cargo will be transferred to another spacecraft and the NEP cargo ship will then return to LEO to pick up more cargo.

The NEP tanker will carry 128 t of liquid hydrogen (LH_2) propellant to the Lagrange point. Upon arrival the tanker will mate with a bimodal NTR vehicle and transfer its payload of LH_2 to the NTR spacecraft. It will then return to LEO to be replenished.

SPACECRAFT SPECIFICATIONS

This study is being conducted to determine the applicability of a high power NEP vehicle for missions within the Earth-Moon system. The Revolutionary Aerospace Systems Concept (RASC) 2002 study focused on the design of an architecture to support human missions to Callisto (Borowski, 2003). One of the assumptions made for the Callisto study was that a support infrastructure was in place at Earth-Moon L1. This study is being conducted to determine the feasibility of that supporting infrastructure. The propulsion and power generation systems used in this analysis are similar to those used by the Callisto cargo and tanker vehicles (McGuire, 2003), but with technologies that will be available on a more near-term basis.

Power Subsystem

Spacecraft power is provided via a gas-cooled fission reactor powered by uranium-235 in the form of uranium dioxide (UO_2) within a tungsten metal matrix "cermet" fuel with tungsten cladding. Cooling is provided by Brayton cycle power conversion using a helium-xenon gas mixture as the working fluid. The specific mass of the system is based on "Mid-Term" technology scaling projections expected in the next 15 to 20 years (Mason, 2001) and include an added contingency of 15%. Radiator mass is included for 1100 m^2 of radiator assuming an areal density of 3 kg/m^2, and also includes a 15% contingency factor. The mass of the hardware necessary to attach the radiator to the spacecraft is 1,840 kg. Cabling for power transmission has a specific mass of 0.214 kg per kilowatt of power output. The total mass of the power subsystem is:

$$M_{PS} = 0.214 kg / kW_e \cdot P_e + \left[\alpha_{PS} \cdot P_e + 1100 m^2 \cdot 3 kg / m^2 \right] \cdot 1.15 \qquad (1)$$

Propulsion Subsystem

The electric propulsion system consists of multiple 2.5 MW_e magnetoplasmadynamic (MPD) thrusters with an efficiency of 64.5% and a mass of 263 kg. The thrusters operate at a specific impulse of 8000 seconds. Each of the spacecraft's two thruster clusters carries three MPD thrusters and a power-processing unit (PPU). The round trip flight time of the mission extends the lifetime of one cluster, requiring four thrusters to complete the mission. Two thrusters are carried as backups, should one fail. Each thruster set contains a single power-processing unit, with an assumed specific mass of 1.25 kg/kW_e. Thus the mass of the EP system with 15% contingency is:

$$M_{EP} = \left[2 \cdot 1.25 kg / kW_e \cdot P_e + 6 \cdot 263 kg \right] \cdot 1.15 \qquad (2)$$

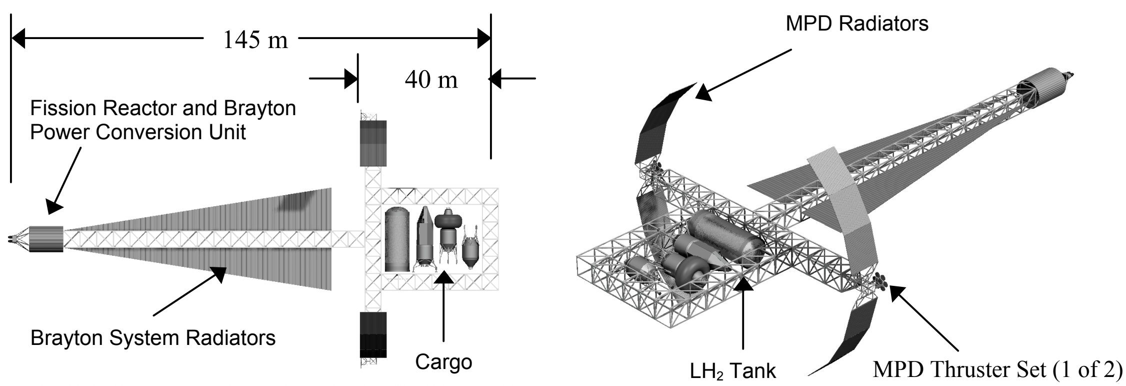

FIGURE 1. NEP Cargo Vehicle.

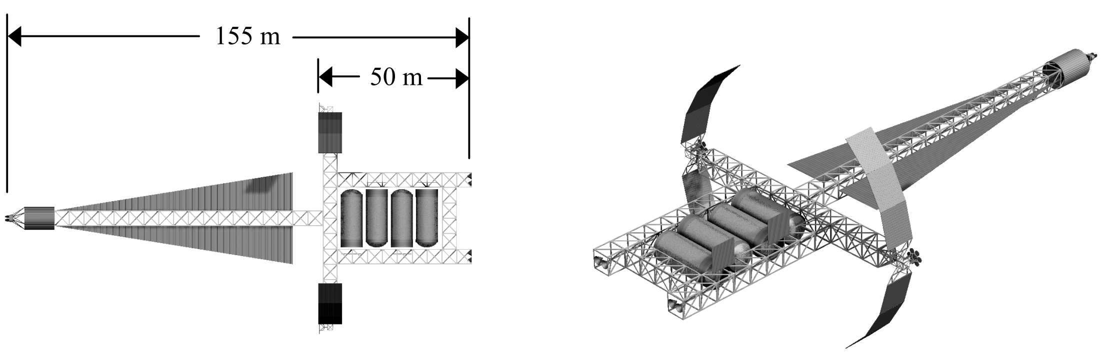

FIGURE 2. NEP Tanker Vehicle.

The cargo spacecraft, shown in Figure 1, carries one 19.0 m x 7.6 m cylindrical propellant tank for the LEO to EML1 mission. With hardware for attachments and refrigeration, and a 15% contingency, the tankage mass for the cargo spacecraft is 11.538 t. The maximum usable propellant load for the cargo vehicle is 47.657 t, which accounts for 2% trapped residual propellant in the tank.

The tanker spacecraft, shown in Figure 2, carries a total of four 19.0 m x 7.6 m cylindrical propellant tanks. Three are used to store its LH_2 payload of 128 t, and one is needed for the storage of the tanker's own propellant. Accounting for hardware for refrigeration and plumbing, the total tankage mass for the tanker vehicle is 46.152 t. The maximum propellant load is the same as that of the cargo vehicle.

MISSION ANALYSIS

Both the NEP cargo vehicle and the NEP tanker are examined for round-trip supply missions from LEO to Earth-Moon L1. Earth-Moon L1 could potentially serve as a hub for future exploration and development of space, and its utility could be significantly enhanced with a supporting architecture for large payload delivery. It offers an ideal staging platform for both interplanetary missions as well as missions to the lunar surface. In this study the effects of the particular size and shape of the halo orbit are not taken into account.

LEO to Earth-Moon L1 Cargo Transfer and Return

The first Earth-Moon Lagrange point (EML1) has been receiving increasing interest lately as a staging point for missions to the Moon as well as other planets and asteroids. In this architecture, an NEP spacecraft could serve as a high performance cargo ship, delivering large payloads from LEO to an orbital outpost at L1. For this analysis, the performance of an NEP vehicle is assessed for the transfer of 120 t of payload from LEO (407 km circular) to a halo orbit about EML1, followed by the return of the spacecraft to LEO with no cargo. Trajectory analysis was done using SNAP, a tool currently under development at NASA Glenn Research Center. The results presented show performance of the NEP vehicle at various power levels, and are not necessarily optimal trajectories.

Trajectory

The spacecraft trajectory was modeled using SNAP, an N-Body trajectory code under development at Glenn Research Center. It employs three separate phases as it progresses from LEO to EML1. In order to reduce the complexity of the analysis the spacecraft's initial state is in a halo orbit about EML1. The trajectory is then propagated backwards in time until the spacecraft's perigee altitude about the Earth is 407 km. This method has proven to be more reliable than starting in LEO and attempting to target a halo orbit in forward time propagation.

The first phase of the trajectory propagates the spacecraft away from L1 using tangential thrusting. The first phase stops when the perigee of the spacecraft orbit decreases to approximately 125,000 km. This value was selected because it offered an orbit that was stable around the Earth but high enough to minimize the propellant consumption during the circularization and change in inclination that occur during the second phase.

The second phase uses a blended combination of steering vectors. One vector defines a continuous-thrust inclination change steering vector (Falck, 2002), while the other thrusting vector changes the eccentricity of the orbit at the maximum possible rate (Gefert, 1999). When the true anomaly of the spacecraft dictates relatively little efficient use of thrust in changing the inclination of the orbit, more thrust is devoted to the eccentricity changing steering vector. As a result, the orbit of the spacecraft is circularized during this phase, and its inclination is changed to 28.5^{o}.

Once the spacecraft orbit is relatively circular (e□0.003) the third and final phase of the trajectory begins. The thrust vector of the third phase is defined by a combination of the tangential thrust vector, used to spiral the spacecraft to LEO as fast as possible, and the maximum rate of eccentricity steering vector to ensure the orbit is properly circularized in LEO. When examined with forward time propagation starting in LEO, the result is a trajectory that smoothly changes the eccentricity and inclination of the spacecraft's orbit such that it will be pulled into a halo orbit about EML1 without the need for impulsive correcting maneuvers.

The L1 to LEO return trajectory is very similar to the outbound leg except for two issues. Since a return from EML1 to LEO and the starting point is again EML1, forward time propagation was used. In addition, the thrust vectors described above were all offset by 180^{o} to achieve an inbound trajectory. Figures 3 and 4 provide a visual comparison of the two trajectories. The trajectories are shown in a normalized Earth-Moon rotating frame of reference, to emphasize the halo orbit.

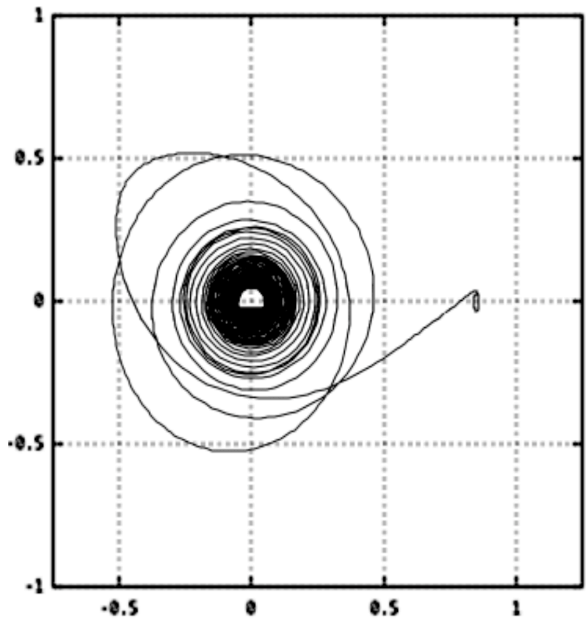

FIGURE 3. LEO to EML1 NEP Trajectory.

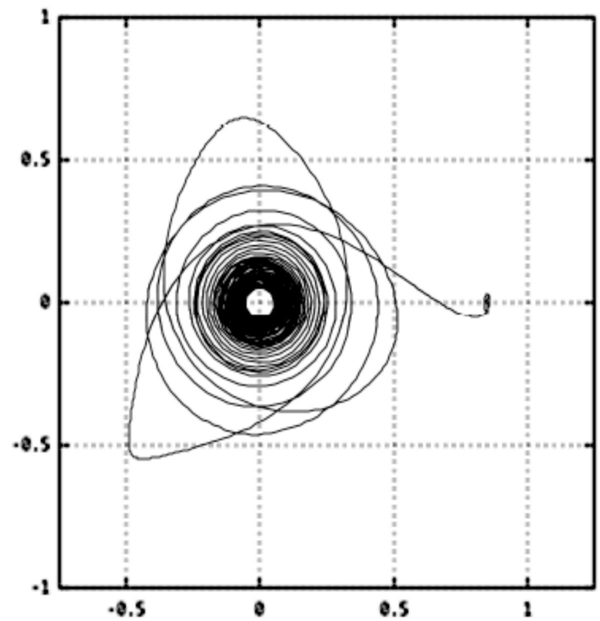

FIGURE 4. EML1 to LEO NEP Trajectory.

RESULTS

Trajectory results for an outbound transfer of no more than one year are shown in Table 1 below. Although the tanker spacecraft's payload of 128 t is only slightly larger than that of the cargo spacecraft, the addition of four tanks to hold the LH_2 propellant makes the power level and IMLEO of the tanker significantly more than those of the cargo spacecraft. The propulsive power and IMLEO of the tanker exceed those of the cargo spacecraft by approximately 28%.

TABLE 1. Trajectory Results for One Year LEO to Earth-Moon L1.

	Cargo Spacecraft	Tanker Spacecraft
Propulsive Power (kWe)	2685	3455
Outbound Trip Time (days)	365	365
Inbound Trip Time (days)	122	160
Total Round Trip Time (days)	**487**	**525**
Outbound Propellant (t)	17.75	22.84
Inbound Propellant (t)	5.92	10.01
Total Propellant Expenditure (t)	**23.67**	**32.85**
Spacecraft Dry Mass (t)	62.45	104.34
IMLEO (t)	206.12	265.19

Table 2 shows the results for the same missions with an outbound transfer time constrained to six months. The larger power demands of the tanker are amplified by constraining the maximum trip time to a smaller value. The larger power requirements also affect the configuration of the spacecraft. For the larger power levels required here eight thrusters are used, with four operating at any given time and four used as backups. It is interesting to note, however, that the cargo ship in this case is very similar to that designed for the HOPE 2002 Callisto mission (McGuire, 2003). The vehicle in that mission was sized using far-term power system assumptions, as opposed to the mid-term assumptions used here, but the power levels and vehicle sizing for both cases are very similar.

TABLE 2. Trajectory Results for Six Months LEO to Earth-Moon L1.

	Cargo Ship Spacecraft	Tanker Spacecraft
Propulsive Power (kWe)	7374	9400
Outbound Trip Time (days)	180	181
Inbound Trip Time (days)	85	100
Total Round Trip Time (days)	**265**	**281**
Outbound Propellant (t)	24.02	30.79
Inbound Propellant (t)	11.37	17.00
Total Propellant Expenditure (t)	**35.39**	**47.79**
Spacecraft Dry Mass (t)	117.97	174.87
IMLEO (t)	273.37	350.66

CONCLUSIONS AND FUTURE STUDY

The results of this analysis indicate that NEP propulsion is capable of transferring very large payloads to Earth-Moon L1 within one year at moderate power levels. More aggressive six-month transfer times show a good bit of commonality with NEP systems designed for interplanetary transport. This could potentially reduce the time and cost of developing systems for future space exploration, in contrast to the current practice of designing systems specifically for and capable of a single specific mission. Trajectories presented here are not necessarily globally optimal, and NEP trajectories from LEO to EML1 should be reexamined with different methods for trajectory optimization to determine if any significant improvements can be achieved.

NOMENCLATURE

α - specific mass (kg/kW$_e$)
e - eccentricity
EML1 - Earth-Moon L1
EP - electric propulsion
HOPE - Human Outer Planet Exploration
IMLEO - initial mass in low Earth orbit (kg)
kW$_e$ - kilowatts electrical power
LEO - low Earth orbit
LH_2 - liquid hydrogen
MPD - magnetoplasmadynamic
MW$_e$ - megawatts electrical power
NEP - nuclear electric propulsion
P_e - electric power output (kW$_e$)
PPU - power processing unit

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