NUCLEAR ELECTRIC PROPULSION MISSION SCENARIOS USING VASIMR TECHNOLOGY.
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Introduction: The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is the most powerful (among currently being tested) and highest specific impulse electric propulsion device operated to date. It is capable of operating at powers well over 200 kW per thruster with high efficiency and specific impulse varying from 3,000 to 5000s. Specific impulse as high as 30,000 s is possible. Recent experimental investigations on the VASIMR thruster have demonstrated over 70 % thruster efficiency at a power input level of 210 kW power level and 5,000 sec specific impulse [1]. Future Nuclear Electric Propulsion (NEP) missions will greatly benefit from using VASIMR technology by leveraging its high power and high specific impulse capabilities. Mission duration can be shortened and launch mass reduced relative to chemical based propulsion using solar electric power, but solar power sources are greatly restrictive as missions move deeper into space. This paper will present resent results using VASIMR-NEP for various missions. Net Power Efficiency is 60% and Specific Mass is 8 kg/kW for Power and Propulsion.

Robotic Mission to Mars: A parametric study of cargo delivery to Mars with 2 MW of power was performed for an *IMLEO = 20 mT*. The parameter varied was the minimum allowed specific impulse. The first segment of the mission is the spiraling from LEO with an initial altitude of 1,000 km to the Earth's SOI. The arrival speed was constrained to be 6 km/sec, assuming that aerocapture will be used for payload delivery to the Mars surface. For the optimized profile of the specific impulse, the total duration of the mission is about 3.5 months.

The results of the parametric study are shown in the Figure 1 for the same IMLEO in all cases and varying minimum I_{sp}. If the minimum I_{sp} is increased from 4,200 sec to 6,200 sec, the total trip time goes up by 14 days but the amount propellant required goes down by 1.7 mT, so more payload can be delivered.

Human Mission to Mars: The studies demonstrated the possibility of 12-18 MW missions arriving at Mars within 3-4 months, about half the time estimated in the Design Reference Architecture (DRA, [2]). The mission analysis assumed the exact same payload mass delivered to the atmosphere of Mars (60.8 mT) at the same velocity for aerocapture (6.8 km/s) as in the DRA for the crewed portion mission with VASIMR® engines. The crew time in space could be reduced by about one month by rendezvousing the crew with the VASIMR®-powered spacecraft in high earth orbit after the main vehicle had passed through the Van Allen belts.

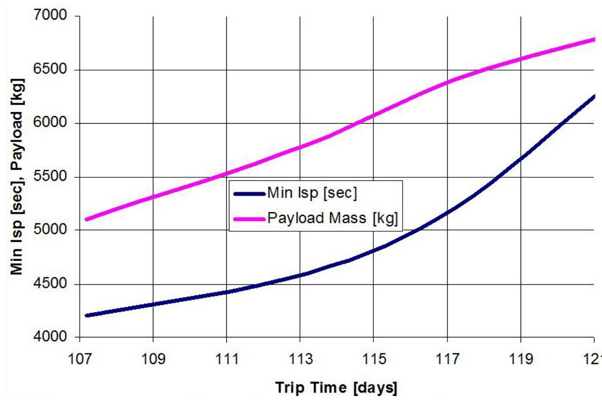

Figure1: 2 MW NEP Cargo Mission to Mars with variable Isp, optimized for minimal propellant

For this mission cargo must be pre-deployed both in Martian orbit and on the surface. In the DRA, one rocket transfers the cargo lander and another transfers an earth return vehicle with a living habitat for the crew to Mars. The total mass of those payloads is 91.4 mT as outlined in the DRA (including an aeroshell for the cargo lander sized appropriately for entry velocity). The VASIMR® mission proposes combining both payloads plus the return propellant on one vehicle to save propellant on the outbound journey. A VASIMR® system with one third the power, 4 MW, compared to the 12 MW of the crewed vehicle, transfers the payload more slowly.

The crewed spacecraft departs LEO with 12 MW of electric power for the duration of the trip. The Crew Transfer Vehicle (CTV) mass is 48 mT plus the propellant and propellant tank mass. The mass breakdown for the 60.8 mT Mars Lander (ML) is assumed to be 31.0 mT for the habitat, 13.5 mT for an aero-shell, and 16.3 mT for a descent system. The CTV, mated to the ML (Mars Lander), will transport the crew to Mars. The speed relative to the Earth is 2.5 km/s at the Earth's gravitational sphere of influence.

The ML will separate from the CTV at Mars arrival. The ML is designed to approach Mars with a relative velocity of 6.8 km/s and execute a direct descent to the surface. The ML descent maneuver is identical to that outlined in the DRM. The CTV will initially execute a flyby of Mars, close enough to drop off the ML. The CTV will continue past Mars in an arcing trajectory to be captured by the planet approximately four months later.

Ascent from Mars to the Return Habitat is accomplished with a chemical ascent capsule, as in the DRA. This capsule stays attached to the CTV during interplanetary flight and is used for direct descent to the Earth surface. Since the capsule is designed for a reentry at a relative velocity to Earth of 6.8 km/sec, the vehicle is targeted to approach Earth with that velocity. The return mission follows a similar strategy.

Robotic Missions to Jupiter: NEP missions to Jupiter were analyzed for VASIMR® thruster of few (2 – 15) megawatt of total power. Assume that the missions depart Earth Sphere of Influence so only heliocentric transfer is optimized. We will be looking for missions with Earth SOI – Jupiter SOI Transfer time not more than 2 years. Arrival velocity to the Jupiter SOI is assumed to be zero. The initial mass will be optimized in order to deliver required payload with mass of 50 mT.

The power scan was conducted for NEP missions to Jupiter optimized for a minimal propellant, assuming mission duration of 24 months. The VASIMR® thruster will be working with Variable Isp in the range of [5,000 – 30,000] sec or with constant Isp of 5,000 sec with optional coasting period. The power scan gives us the optimal power value of 3MW for both Variable and constant Isp missions, which correspond to minimal initial mass. Low power missions use more propellant due to the fact that the thruster needs to be working at lower Isp in order to achieve 24 months mission trip time. High power missions use more propellant because the total mass of the spacecraft goes up. The Variable Isp can save significant amount of propellant vs the constant Isp mission. The advantage of Variable Isp becomes more evident for high power missions.

Figure 2 demonstrate optimal 3 MW mission with variable Isp, optimized for a minimal propellant. It has ESOI Departure initial mass of 97 mT and uses 23 mT of the propellant. The mission includes long intermediate period corresponding to maximal specific impulse with negligible propellant use.

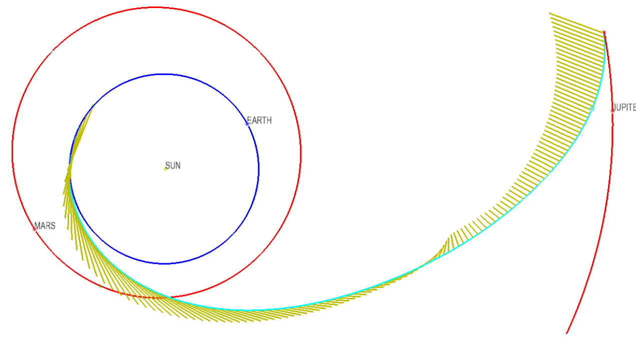

Figure 2: 3 MW NEP Cargo Mission to Jupiter with variable Isp, optimized for minimal propellant

Precursor Interstellar Mission: Robotic NEP missions from Earth LEO outside of the solar system to the distance of 1000 AU were analysed with VASIMR® thruster of few (1 – 8) megawatt of total power. Net Power Efficiency is 70% and Specific Mass is 8 kg/kW for Power and Propulsion. The initial mass will be scaned between 50 mT and 150 mT. The VASIMR® thruster is assumed running at constant specific impulse in the range between 5,000 sec and 30,000 sec. The power, initial mass and specific impulse will be optimized in order to deliver required payload with mass of 5 mT at minimal time.

The fastest mission to 1000 AU was found for specific impulse of 20,000 sec, power of 5 MW, initial mass of 150 mT (400 km). The mission involves LEO – ESOI transfer, lasted for 11 months and required 5.4 mT of propellant. The whole mission involves thruster operation for 18.2 years, until all propellant is used: 105 mT. After all propellant is used, the dry mass of the vehicle becomes 45 mT (40 mT of Power and thruster and 5 mT of payload). The maximal reached velocity is 224 km/s. The mission lasts 32.6 years in order to get to the distance of 1000 AU.

Table below demonstrates the list of the fastest missions for different initial masses:

IM [mT]	T [years]	P [MW]	Isp [s]
50	35.8	2	24,000
70	34.8	2.5	23,000
100	33.9	3.5	22,000
150	32.6	5	20,000

Reference: [1] Squire J. P., et al. (2011) IEPC-2011-154; [2] Hoffman, S. J., Kaplan, D. I. (1997) NASA/SP—6107–ADD.