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PERFORMANCE ENHANCEMENT USING POWER BEAMING FOR ELECTRIC PROPULSION EARTH ORBITAL TRANSPORTERS

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ABSTRACT

An electric propulsion Earth orbital transport vehicle (EOTV) can effectively deliver large payloads using much less propellant than chemical transfer methods. By using an EOTV instead of a chemical upper stage, either a smaller launch vehicle can be used for the same satellite mass or a larger satellite can be deployed using the same launch vehicle. However, the propellant mass savings from using the higher specific impulse of electric propulsion may not be enough to overcome the disadvantage of the added mass and cost of the electric propulsion power source. Power system limitations have been a major factor delaying the acceptance and use of electric propulsion. This paper outlines the power requirements of electric propulsion technology being developed today, including arcjets, magnetoplasmadynamic (MPD) thrusters, and ion engines. Power supply characteristics are discussed for nuclear, solar, and power-beaming systems. Operational characteristics are given for each, as are the impacts of the power supply alternative on the overall craft performance. Because of its modular nature, the power-beaming approach is able to meet the power requirements of all three electric propulsion types. Also, commonality of approach allows different electric propulsion approaches to be powered by a single power supply approach. Power beaming exhibits better flexibility and performance than on-board nuclear or solar power systems.

INTRODUCTION

An electric propulsion Earth orbital transfer vehicle (EOTV) can be used for a variety of functions, which include but are not limited to satellite deployment, remote servicing of satellites, payload retrieval, and debris mitigation. For the purposes of comparison with chemical propulsion, only satellite deployment functions will be considered. However, the increased fuel efficiency of the electric propulsion EOTV might enable other missions that are not considered viable with chemical boosters.

Electric propulsion, which uses electrical energy to accelerate propellant to achieve thrust, has a much higher specific impulse than chemical rockets. Specific impulse (I_{sp}) measured in seconds (s) is the thrust produced divided by the propellant flow rate, divided by the gravitational constant (g). Advanced chemical rockets have specific impulses of around 400 to 450 s. Electric propulsion can have specific impulses of 1,000 to 10,000 s.

The thrust produced by electric propulsion is proportional to the power input and the thruster efficiency; it is inversely proportional to the specific impulse. Therefore, the thrust produced is dependent on the power available to the thruster. The power system mass is the limiting factor in using electric propulsion for primary transportation.

POWER BEAMING CONCEPT

Power beaming is an approach that allows separation of the energy source from the end-use system and links them with an energy beam. This is akin to a terrestrial system where the energy source is linked to the end-use system by transmission lines. In space, the energy source is linked to the end-use system by electromagnetic radiation.

The operating frequency selection depends on many factors: the level of technology and hardware readiness, the distance power is to be transmitted, the relative position of the energy source and end-use system (fixed or moving), the amount of end-use power needed, and even the type of energy required. The size of the transmit and receive antennas is a function of the frequency and the distance over which power is to be transmitted. To keep these components as small as possible and to utilize existing photovoltaic technology, a laser transmission system is selected.

ELECTRIC PROPULSION CHARACTERISTICS

Three different electric propulsion techniques are considered: arcjets, ion engines, and magnetoplasmadynamic (MPD) thrusters. Recent interest in electric propulsion has created many advances in available technology. Some performance characteristics cited in this paper may not be representative of hardware currently available, but literature and research trends indicate reasonable expectation of achieving the performance goals in a timely manner.

Arcjet Propulsion

Arcjet propulsion is a relatively mature technology. Arcjets are currently used for station keeping applications, with prime propulsion application planned for near-term missions, such as the SP-100 flight demonstration [1].

The principles behind arcjet operation are very similar to chemical propulsion. Both approaches create thermal energy that accelerates propellant through a nozzle, thereby creating thrust. The arcjet uses electrical energy, rather than a chemical reaction, to create thrust. Consequently, arcjet performance is similar to chemical propulsion with some improvement. Arcjet performance characteristics indicate a specific impulse of 1050 s, thruster efficiency of 45%, and specific mass of 0.13 kg/kWe. The performance criteria given are based on a 30-kW ammonia arcjet [1]. The arcjet requires about 120 V direct current (DC) during operation.

Ion Engine Propulsion

Ion engine technology exhibits excellent potential for future spacecraft propulsion. The ion engine accelerates ionized propellant through an electrostatic field. Current hardware development trends indicate ion engine performance for EOTV applications to have a specific impulse of 7800 s, thruster efficiency of 75%, and specific mass of 0.49 kg/kWe [2].

The ion engine requires three separate power sources. First, the propellant must be ionized, which requires a potential difference of about 30 V between the anode and the cathode. Ion acceleration is produced by voltage applied to the accelerator grid, which requires the second power source. This accelerating voltage is on the order of about 2000 V DC. Finally, the ionized propellant leaving the engine must be neutralized, which requires a third power supply. Most of the power is used in the accelerator, which governs the power supply design.

Magnetoplasmadynamic Thruster Propulsion

The MPD thruster magnetically accelerates a plasma through a nozzle to create thrust. The thruster is relatively small and lightweight, with the ability to handle very high power. The MPD thruster has a very high thrust density with excellent specific impulse.

MPD thruster characteristics for EOTV application are a specific impulse of 5000 s, thruster efficiency of 50%, and specific mass of 0.17 kg/kWe [2]. The MPD is a low-voltage, high-current device, requiring about 200 to 300 V DC.

POWER SUPPLY METHODOLOGY

Three types of power supply technology are nuclear electric, solar photovoltaic, and power beaming. This analysis is concerned chiefly with the overall specific mass and general operating constraints.

Nuclear Electric

The nuclear electric power system uses a nuclear reactor with either static or dynamic power conversion. The specific configuration and design details have been omitted here. The power supply provides electrical power to meet the propulsion system power requirements.

The nuclear electric system specific mass for this analysis is 25 kg/kW, which is essentially an SP-100 type system in the range of 0.1 to 1 MWe [3]. This includes the thermal source and conversion and conditioning equipment, as well as supervisory and control systems.

The nuclear electric system can be designed to match the power requirements of all three electric propulsion options. The arcjet and MPD propulsion systems both require low voltage and high current, while the ion engine requires high voltage. Interestingly, the increased costs associated with higher voltage are offset by the benefits of operating at lower current, yielding approximately the same specific mass for the power processing system in either case [3].

Solar Electric

The energy source for the solar electric power system is a photovoltaic array directed toward the sun. Batteries are included to provide power when the craft passes through the Earth's shadow. This mode of operation is not necessary because the EOTV could coast during non-illumination periods. However, to compare alternative power supply methodologies, the mode of operation shall remain consistent. Therefore, the solar electric power system includes battery mass to operate the propulsion system continuously for each orbit.

The size of the solar array is sufficient to operate the propulsion system and charge the batteries concurrently at the end of life (EOL). The battery charging power is determined by the fraction of time the craft is in the Earth's shadow each orbit and by the cycling efficiency of the battery system.

The complete solar electric power system has a specific mass of 35.7 kg/kW. This assumes that the array produces 100 W/kg at the EOL [4]. When including battery charging requirements, the array size increases by a factor of 1.83. The energy storage system uses NiH_2 batteries with a cycling efficiency of 80%. Neglecting depth of discharge, the battery specific energy storage density is 66 Wh/kg [5].

Power Beaming

The power-beaming approach is similar to the solar electric power system in that the power is collected by a photovoltaic array. With power beaming, the array tracks the laser transmitter rather than the sun. Also, there is no battery storage requirement because the power-beaming system provides global coverage using either multiple transmitters or strategically placed relay mirrors. Also, because the array has a higher conversion efficiency, it is much smaller than a comparable solar photovoltaic array.

The specific mass of a power-beaming system is 1 kg/kW [6, 7]. Because the receiver is a photovoltaic array, the mass per unit area is the same as conventional solar technology, around 3 kg/m^2. The receiver is tuned to convert energy at the laser wavelength, leading to much higher conversion efficiency than solar collectors. Current projections indicate that array efficiencies of 60% are possible for monochromatic reception. In addition, the laser transmitter can illuminate the receiver with higher power intensity than can incident solar radiation. The power intensity is constrained by receiver thermal heating.

PERFORMANCE RESULTS

The EOTV mission performance is presented for the three power supply approaches and the three electric propulsion types. For the nine cases, the reusable EOTV delivers a 5000-kg payload to equatorial geosynchronous orbit, starting from a 28.5° inclination 330-km orbit. Because the craft is reusable, it returns to low Earth orbit after delivering the payload. The EOTV has continuous thrust while performing orbital change maneuvers.

Figure 1 shows performance comparisons between the nine configurations studied. The figure shows the total mass required initially in low Earth orbit to perform the mission, which includes the payload, power system, and propellant and tankage for the round-trip transfer. This mass is given as a function of deployment time, which is the outward leg of the overall mission. The analysis assumes no power limitation. The EOTV has sufficient power available to perform the mission with the deployment time given. However, because the propulsion system operates with continuous thrust, the only method available for adjusting the deployment time is changing the propulsion power input, thus affecting the power system mass.

A chemical propulsion upper stage delivering a 5000-kg payload to geosynchronous orbit has a low Earth orbit gross mass of approximately 18,000 kg for a nonreusable system. Reference to Figure 1 shows that the nuclear electric and solar electric EOTV have deployment times greater than 200 days to compete with chemical deployment. The power-beaming system has less initial mass in low Earth orbit than either the nuclear electric or solar electric EOTV for any given deployment time. The mass of the power-beaming EOTV is relatively independent of the deployment time because of the low specific mass of the power system. This feature is important considering that experience with Van Allen radiation exposure indicates that transfer times greater than 100 days should be avoided.

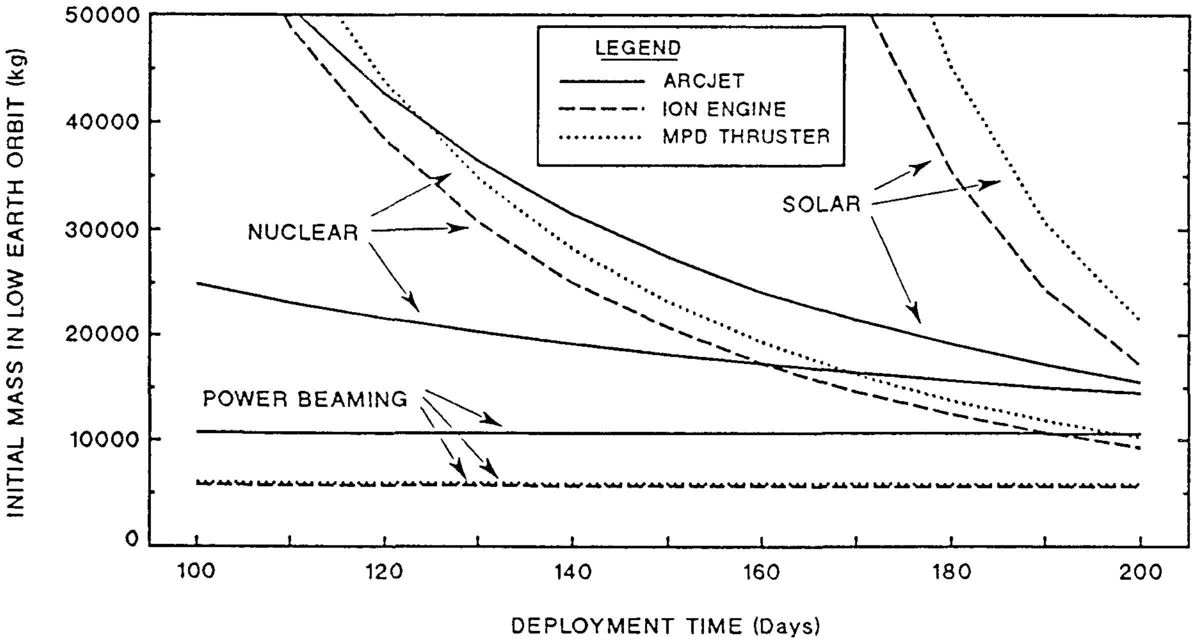

Figure 1: EOTV Performance Comparisons for 5000-kg Payload Deployment

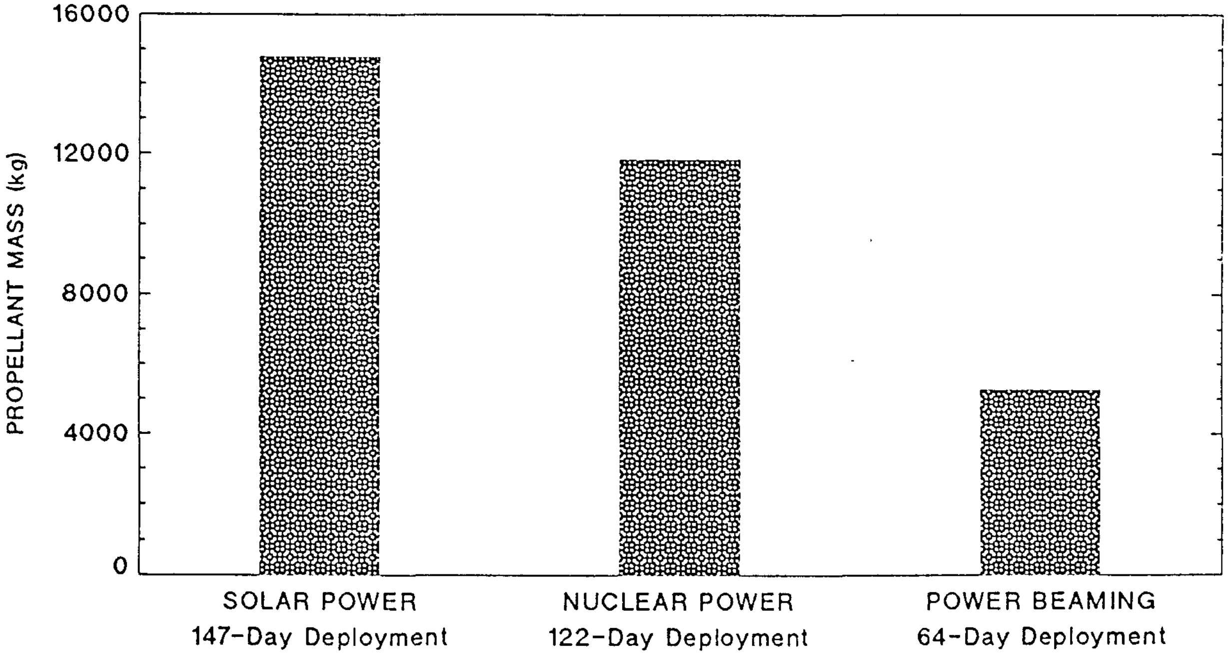

Figure 2: Propellant Consumption for 100-kWe Arcjet EOTV for 5000-kg Payload

Figure 2 shows propellant consumption for a 100-kW arcjet EOTV deploying a 5000-kg satellite from low Earth orbit to geosynchronous orbit, as before. The power-beaming approach, in addition to providing the quickest transit time and least mass on orbit, also consumes 64% less propellant than the solar-powered EOTV and 56% less propellant than the nuclear-powered EOTV.

CONCLUSIONS

The electric propulsion Earth orbital transporter can transfer large payloads between various orbits much more effectively than chemical propulsion. However, the power system mass can have a significant impact on the mission, particularly if it is constrained by deployment time. The nuclear electric and solar electric power systems tend to drive the EOTV mass extremely high for such missions. Because Van Allen radiation exposure is an important concern for low-thrust orbital transfer, the power-beaming approach significantly enhances the electric propulsion EOTV. Power beaming, coupled with electric propulsion technology, offers significant launch mass reduction, which could revolutionize future satellite deployment techniques.

ACKNOWLEDGMENTS

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