Electric Propulsion for Constellation Deployment and Spacecraft Maneuvering

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This paper outlines the near-term (1990's) advantages of electric propulsion for two Strategic Defense Initiative type missions: 1) deployment (orbit raising) of a constellation of spacecraft, and 2) continual spacecraft defensive maneuvering. Ammonia arcjet and xenon-ion electric propulsion systems are compared to advanced chemical propulsion for each of these missions. Analysis has shown that the number of launch vehicles required for constellation deployment can be reduced by up to a factor of two when electric propulsion upper stages are used in place of advanced chemical upper stages. This led to a substantial reduction in the total constellation deployment time. It was also shown that electric propulsion can provide significant benefits when used for continuous defensive maneuvering by enabling a large reduction in the initial spacecraft mass. The point at which electric systems became mass competitive with chemical maneuvering systems depended on whether power was included with the payload or carried by the propulsion system and on the electric propulsion system's thrust-to-power ratio.

Nomenclature

LEO	= low-Earth orbit, 185-km altitude at a 70 deg inclination
NH_3	= ammonia
MMH	= monomethyl hydrazine
SP-100	= U.S.A. SRPS development program for 100 kW_e
Xe	= xenon
ΔV	= velocity increment required to perform an orbital maneuver

Subscripts

e	= electric
t	= thermal

Introduction

ELECTRIC propulsion, powered by nuclear or solar power, can contribute to several important Strategic Defense Initiative (SDI) missions. Electric propulsion can be used for platform orbit raising from low-Earth orbit using a space reactor power system (SRPS). This option provides increased payload margins compared to advanced chemical propulsion.[1-3] Electric propulsion and SRPS power can also be used for continuous defensive maneuvering to make platform and satellite tracking a full-time job for an adversary. Housekeeping SRPS power coupled with electric propulsion can be used for platform stationkeeping, thus prolonging spacecraft orbital lifetime. Scheduled platform maintenance and resupply functions can best be accomplished using a high specific impulse, reusable, solar electric vehicle. Solar-powered electric propulsion would allow a ferry vehicle to come to very low orbits (250–300 km) without the adverse political or safety consequences associated with nuclear power, enabling a single vehicle to perform the complete resupply function. Finally, when a platform or satellite has reached the end of its useful life, the electric propulsion system can be used to boost the platform to a disposal orbit for decommissioning using the SRPS decay power. The development of suitable space power sources is key to enabling these capabilities.

The SP-100 SRPS is currently being developed by the Power Office of the Survivability, Lethality, and Key Technologies (SLKT) Directorate of the SDI Organization. The SP-100 power system is the nuclear option in the SDI baseload power development program and is based on a 2.6 MW_t, fast-spectrum, liquid-metal, cooled reactor coupled with an out-of-core thermoelectric conversion system.[4] An SP-100 flight experiment has been conceived as a first demonstration of space-based operation of the SP-100 SRPS with a primary goal being the demonstration of the 7-yr, full-power life of the SP-100 power system. Arcjet electric propulsion is baselined as the active load for the SP-100 flight experiment and will be used to demonstrate nuclear electric propulsion (NEP) orbit transfer and maneuvering capabilities. Demonstration of NEP is the second objective of the mission.

This paper outlines the near-term (1990's) advantages of electric propulsion for two SDI missions: 1) deployment (orbit raising) of a constellation of spacecraft covering a range of payload masses, into high-inclination orbits, and 2) continual spacecraft defensive maneuvering to complicate hostile tracking during times of threat. Ammonia arcjet and xenon-ion electric propulsion systems are compared to advanced chemical propulsion for each of these missions. A constellation of spacecraft is defined as a group of spacecraft or space platforms that work together to accomplish a particular mission. For constellation deployment, it is assumed that 100 kW_e of a power is onboard the platform and that launches are from Vandenberg Air Force Base, using either Titan IV or Advanced Launch System (ALS) launch vehicles. The defensive maneuvering analysis assumes that the power needed for the electric propulsion system is included in the payload or must be added to the propulsion system mass.

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Table 1 Propulsion system parameters

Parameter, Propulsion System	Value: Chemical	Arcjet	Ion
Propellant	LH_2/LO_2	NH_3	Xe
Thruster input power, kW_e	—	30	4.5
Specific impulse, s	450	967	3890
Electrical efficiency	—	0.37	0.76
Thruster lifetime, h	—	1500	4500
Propulsion system specific mass, kg/kW_e	—	2.0	10.0
Dry mass/wet mass	0.15	—	—
Tankage fraction	—	0.20	0.15

Table 2 Space nuclear power system performance specifications[4]

Parameter	Specification
Power level	100 kW_e
Primary voltage	200 V dc
Specific mass	30 kg/kW_e

Analysis Methodology

The following analysis is based on well-known orbital mechanics for low-thrust, electric propulsion transfers.[3] Constellation deployment is characterized in terms of the number of launch vehicles required and the total deployment time. These depend on spacecraft mass, launch vehicle, upper-stage propulsion system, and the time between launches. The total constellation deployment time is also described as a function of the number of launches and the time between launches. Defensive maneuvering is described in terms of the initial platform mass, the number of evasive maneuvers, and the ΔV per unit time required for the maneuver.

Constraints and Assumptions

The upper-stage propulsion system parameters assumed for this study are summarized in Table 1. A chemical propulsion system with Centaur G′-type performance is assumed for the chemical upper-stage propulsion system. This system is based on liquid hydrogen/liquid oxygen (LH_2/LO_2) engine technology providing a specific impulse of 450 s. Two chemical maneuvering propulsion systems are assumed: 1) a baseline system with a specific impulse of 300 s, and 2) an advanced system with a specific impulse of 400 s. These systems effectively bound the present (N_2O_4/MMH with a specific impulse of 325 s) and near-term (use of a fluorinated or chlorinated oxidizer for a specific impulse of 370 s) maneuvering technologies. The analysis assumes a dry mass-to-fueled mass ratio of 0.15 for the chemical systems.

The performance values used for the electric propulsion systems are based on experimental measurements. The ammonia arcjet system performance is derived from a recent long-duration test.[5,6] This engine exhibited a specific impulse of 967 s and an efficiency of 37% at 30 kW_e. The analysis is conducted assuming an arcjet propulsion system specific mass of 2.0 kg/kW_e, an ammonia tankage fraction of 0.20, and an arcjet lifetime of 1500 h. A minimum system of three 30-kW_e arcjets is required to process the power and perform the orbit-raising function. If the orbit transfer requires more than 1500 h of burn time, then another set of arcjets must be included on the upper stage. The xenon-ion propulsion system performance is derived from recent tests of a 25-cm diam engine operated at 4.5 kW_e.[7,8] This engine exhibited a specific impulse of 3890 s and an efficiency of 76%. A propulsion system specific mass of 10.0 kg/kW_e, a xenon tankage fraction of 0.15, and an ion engine lifetime of 4500 h are assumed. A minimum system of 22, 4.5-kW_e ion engines is required to process the power and perform the orbit-raising function. It should be noted that although the thruster performance data described previously is experimentally measured, it has not necessarily been optimized for the following missions.

The pertinent SP-100 SRPS parameters for the electric propulsion systems considered in this paper are summarized in Table 2. The power system has a nominal electrical output of 100 kW_e at 200 V dc. The target specific mass is 30 kg/kW_e. The SP-100 SRPS is currently in the ground engineering system phase of development.[4]

Table 3 Assumed launch vehicle and orbital parameters

Parameter	Value	
Launch vehicle	Titan IV	ALS
Payload, kg	15,500	40,900
Inclination, deg	70	70
Orbital altitude, km	185	185

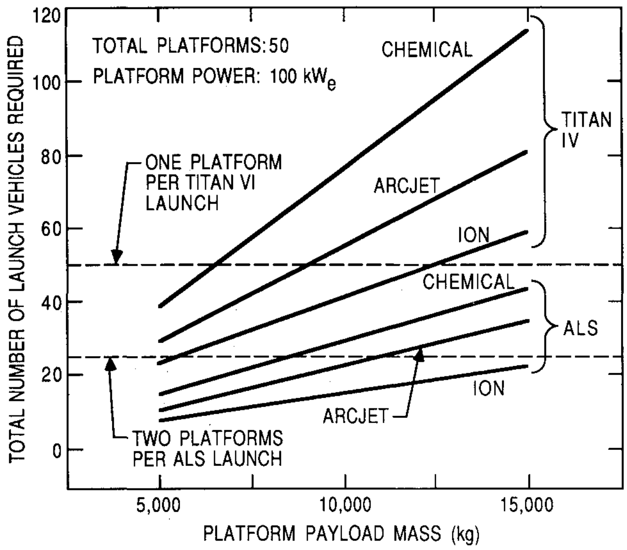

Fig. 1 Effect of platform payload mass on the number of launch vehicles needed for constellation deployment.

Results and Discussion

Constellation Deployment

Additional Assumptions

Constellation deployment is considered using two launch vehicles: the Titan IV and the ALS. The payload capabilities assumed for these launch vehicles are given in Table 3.[9] Only launches from Vandenberg Air Force Base are considered. The Titan IV can deliver a 15,500-kg payload to a 185-km, 70-deg inclination orbit, which will be defined as low-Earth orbit (LEO) in this paper. It is assumed that the ALS can deliver a 40,900-kg payload to LEO. Furthermore, it is assumed that the upper-stage propulsion system deploys the SDI constellation from LEO to a polar orbit (90-deg inclination) at an altitude of 2000 km. The SDI platforms are assumed to have 100 kW_e of electrical power onboard, which can be used by the electric propulsion upper stages during transfer. The platform mass, number of days between launches, and the number of platforms in the constellation are taken as variables in the analysis.

Platform Mass Considerations

Deployment of a constellation of spacecraft using electric propulsion upper stages results in a large reduction in the number of required launch vehicles, as seen in Fig. 1. Figure 1 shows how the total number of launch vehicles required to deploy a constellation of 50 space platforms varies as the platform payload mass is increased from 5000–15,000 kg. The reduction in the number of launch vehicles results primarily from a reduction in the propellant mass required in LEO when using electric propulsion to deploy the constellation. For example, deployment of a constellation of fifty 10,000-kg platforms using the Titan IV requires 76 launches with a chemical upper stage, whereas the number of launches is reduced to 54

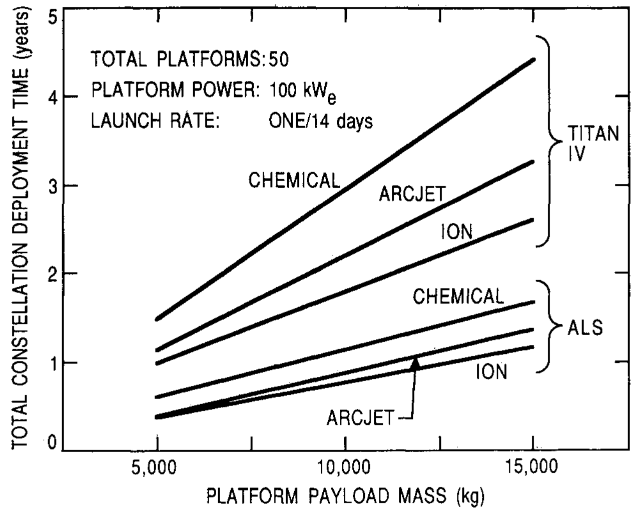

Fig. 2 Effect of platform payload mass on the total constellation deployment time.

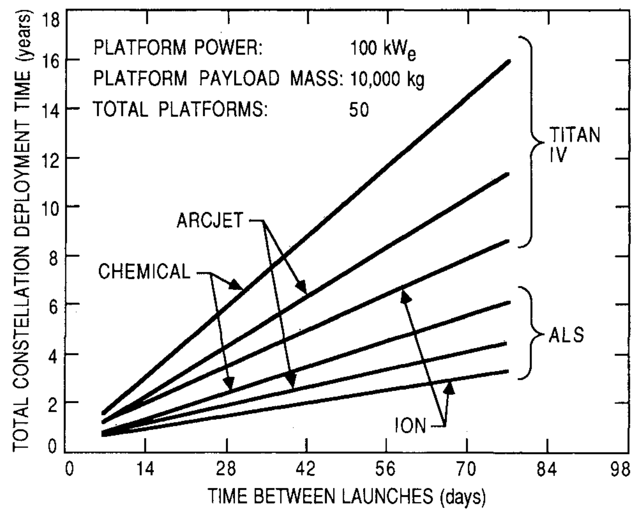

Fig. 3 Total constellation deployment time as a function of the time between launches.

with an ammonia arcjet upper stage and 40 with a xenon-ion upper stage because of their higher specific impulses. The same general trends occur when the larger ALS launch vehicle is considered.

A larger payload mass can be placed in orbit using electric upper stages, when compared to chemical upper stages, if a dedicated (single) launch vehicle is used to deploy each platform, as is done now. Use of dedicated launch vehicle alleviates the need for the on-orbit assembly required if multiple launches were to be used instead. Figure 1 shows the maximum platform payload mass per Titan IV launch is 6570 kg using a chemical upper stage; if an arcjet upper stage is used then the maximum payload is 9200 kg; and if an ion upper stage is used then the maximum payload is 12,750 kg. In the case of an ALS launch, two platforms with payloads of 8670 kg each can be placed in orbit using chemical upper stages, whereas two platforms with masses of 12,000 kg using arcjet upper stages and two platforms with masses of 17,000 kg using ion upper stages can be deployed. Properly optimized electric propulsion upper stages could perform even better relative to chemical upper stages. It should be noted that if the launch vehicle delivers its cargo to a polar (90%) low-Earth orbit, the mass savings using electric propulsion is less. The preceding analysis is meant to serve as a representative example. In addition, electric propulsion upper stages should provide the spacecraft designer more leeway. The initial mass of the platform should be less sensitive to payload mass changes since the use of electric propulsion provides a larger mass margin than chemical upper stage. Hence, the same launch vehicle can be used for a wider range of payload designs.

The total deployment time for a constellation of spacecraft can be much lower using electric propulsion upper stages, even though a single electric propulsion transfer takes longer than a chemical transfer. This is illustrated in Fig. 2 where the deployment time for a 50-platform constellation is plotted as a function of the platform payload mass assuming one launch every two weeks. The platform payload mass was varied from 5000–15,000 kg. The results are also presented as a function of launch vehicle and upper-stage technology. For a constellation of fifty 10,000-kg platforms launched by a Titan IV, a chemical upper-stage deployment requires 2.9 y, whereas an arcjet system requires 2.3 y, and an ion system requires 1.8 y. For the cases considered, the maximum individual transfer time occurs for the 15,000 kg payload and is 116 days for the arcjet and 187 days for the ion upper stage. The electric systems can deploy the constellation faster than the chemical system since they require fewer launches.

The time required for on-orbit assembly activities is not included in the deployment time reported in Fig. 2. Such assembly would be required when multiple launches are used to deploy a single space platform. This would, most likely, be a larger penalty when chemical upper stages are to be used due to the reduced platform payloads available. It is also important to consider that when multiple launches are used, some portion of the on-orbit assembly activities will likely deal with fueling the platforms. The fuels used by electric systems do not generally pose the contamination and explosion hazards associated with chemical propellants.

Effect of Launch Rate

Total constellation deployment time is also driven by the launch rate. This is shown in Fig. 3, where the deployment time for a constellation of fifty 10,000-kg platforms is presented as a function of the time between launches. The time between Titan IV and ALS launches is varied from 1 week up to 10 weeks. The total constellation deployment time is lower for the electric propulsion upper stages. The time savings increases as the time between launches increases when using electric propulsion upper stages. This same general trend is also exhibited when an ALS launch vehicle is used. Again, this is a reflection of the fact that fewer launches are required when using electric propulsion upper stages.

Effect of Constellation Size

Deployment of large constellations is driven primarily by the number of platforms and, hence, the number of launches; not by the upper-stage transfer time. This can be seen in Fig. 4, where the total constellation deployment time is presented as a function of the total number of platforms in the constellation. A launch rate of once every 2 weeks and a payload mass of 10,000 kg are assumed. The electric propulsion upper stages provide a reduced deployment time, compared to the chemical system, when more than 10 platforms are deployed by Titan IV launch. Ten platforms, a small constellation size, can be deployed by each upper stage in 7.2 months (the cross-over point) if the launch rate is once every 2 weeks. The cross-over point at which electric propulsion enables faster constellation deployment depends on individual upper-stage transfer times and the launch rate. As the time between launches becomes longer, the cross-over point at which electric propulsion becomes deployment-time competitive occurs for a smaller constellation size. As the individual upper-stage transfer time increases, the point at which electric propulsion becomes deployment-time competitive occurs for a larger constellation size.

If the more capable ALS launch vehicle is used, the deployment time tradeoff between the upper-stage systems changes, as shown in Fig. 4. The cross-over point is 23 platforms for the

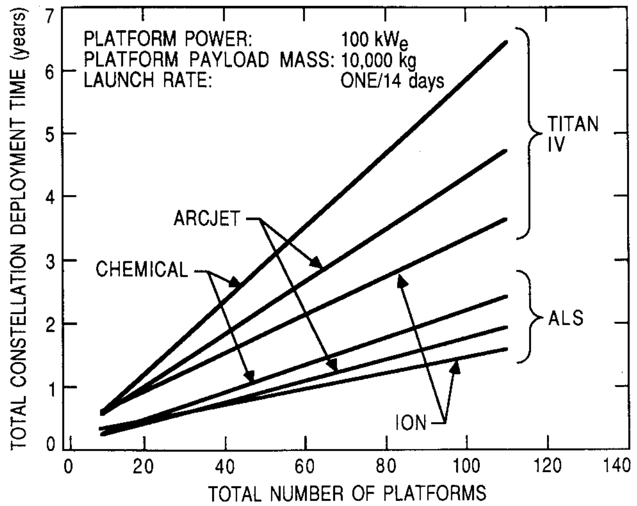

Fig. 4 Effect of platform number on constellation deployment time.

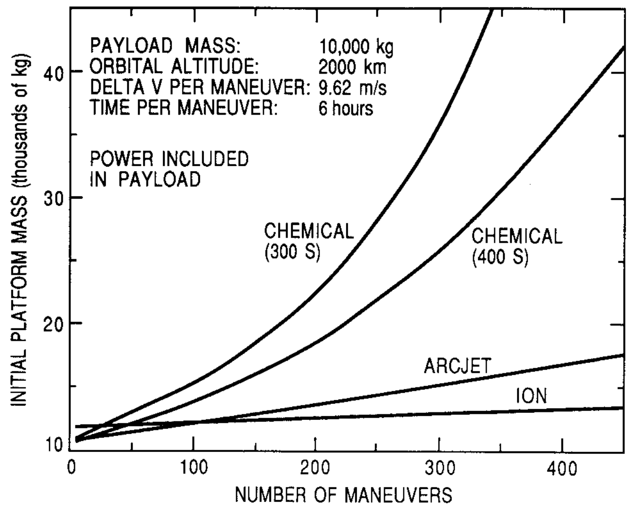

Fig. 5 Initial platform mass as a function of the number of maneuvers (power included in payload).

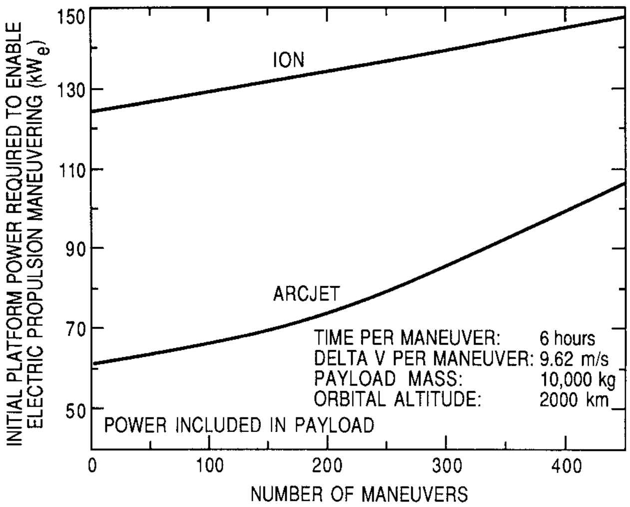

Fig. 6 Initial payload power required to enable electric propulsion maneuvering as a function of the number of maneuvers.

arcjet system and 28 platforms for the ion system when compared to chemical propulsion. If more than 33 platforms are involved, the ion system enables faster deployment times than the arcjet system. This cross-over point is driven by the higher dry mass of the ion system and its longer transfer times. It should be noted that even though the chemical system can deploy small constellations slightly faster than electric systems, more launches are required to get the chemical upper stages into LEO adding to the costs of deployment.

Spacecraft Maneuvering

There are two types of defensive maneuvers: 1) the fast maneuver to dodge an incoming threat,[10] and 2) the continuous, low-thrust maneuver that produces non-Keplerian orbits.[11] The purpose of the latter type of maneuvering, which is addressed in this paper, is to complicate hostile tracking in order to prevent an attack. This is accomplished by disrupting correlation of the tracking measurements, which then forces a need to do a reinitialization of the target, a process that can take hours or days to accomplish.

Additional Assumptions

Effective continuous maneuvering has been found to be possible depending on the assumptions made about an adversary's detection capabilities. Rudolph[11] assumed a detection field of view of 2 deg. For a satellite in geosynchronous orbit, this translated into a requirement that the satellite move a minimum of 190 km in 6 h corresponding to a ΔV of 3.64 m/s. It was also determined that the propulsion system required a specific impulse between 1000–1500 s in order to keep the power requirements below 100 kW_e when maneuvering a 20,000-kg payload.

Continuous maneuvering of a platform with a 10,000-kg payload in a 2000-km polar orbit is considered in this paper. Rudolph's[11] assumptions are applied in this paper in that the platform must move out of a 2 deg field of view in 6 h. This maneuver requires three complete orbits and has a ΔV of 9.62 m/s. Two cases are considered: 1) the power required for electric propulsion maneuvering is included in the 10,000-kg payload mass, and 2) the electric propulsion system must carry its own power source. The performance of the electric maneuvering systems is presented in Table 1. Two chemical maneuvering systems are considered: a baseline technology with a 300-s specific impulse, and an advanced technology with 400-s specific impulse.

Power Included in Payload

Electric propulsion evasive-maneuvering systems can greatly reduce the initial mass of a platform when the payload includes the necessary power. Figure 5 presents the initial platform mass as a function of the number of maneuvers. An arcjet upper stage results in a lower initial platform mass, when compared to the chemical maneuvering systems, regardless of the number of evasive maneuvers. The higher dry mass of the ion upper stage results in a higher initial platform mass compared to both the chemical systems and the arcjet system for up to 50 maneuvers. For more than 50 maneuvers, the ion upper stage will result in a lower initial platform mass compared to the chemical systems, and for more than 110 maneuvers, the ion system results in a lower initial platform mass than the arcjet upper stage. For example, if 200 maneuvers are required during the platform lifetime, use of the baseline chemical maneuvering system will require an initial platform mass of 20,700 kg including a 10,000-kg payload. Use of an advanced chemical system results in an 18,200-kg initial mass, use of an arcjet system results in a 13,100-kg initial mass, and use of an ion system results in a 12,100-kg initial platform mass.

The electric power requirements for evasive maneuvering are fixed by the maneuver time and the electric engine thrust-to-power ratio. The initial platform power required to enable electric propulsion system maneuvering is given as a function of the number of maneuvers in Fig. 6 for a maneuver time of 6 h. The platform mass decreases as maneuvers are completed. Consequently, Fig. 6 gives the power required for the first maneuver of a series. Since the ion engine has a lower thrust-to-power ratio (about half that of the arcjet), it requires approxi-

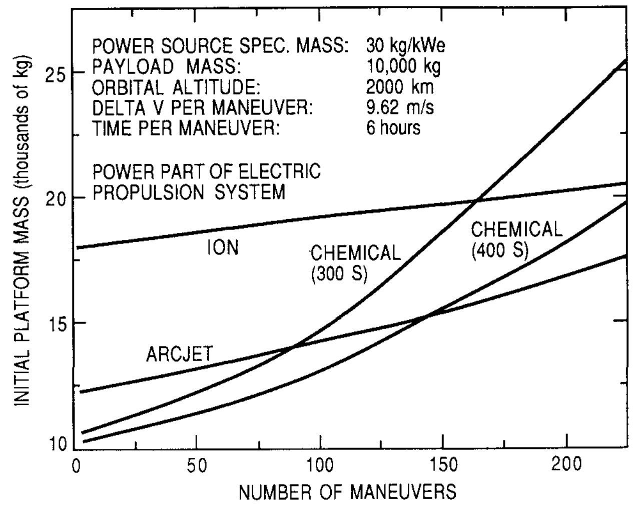

Fig. 7 Initial platform mass as a function of the number of maneuvers (power part of electric propulsion system).

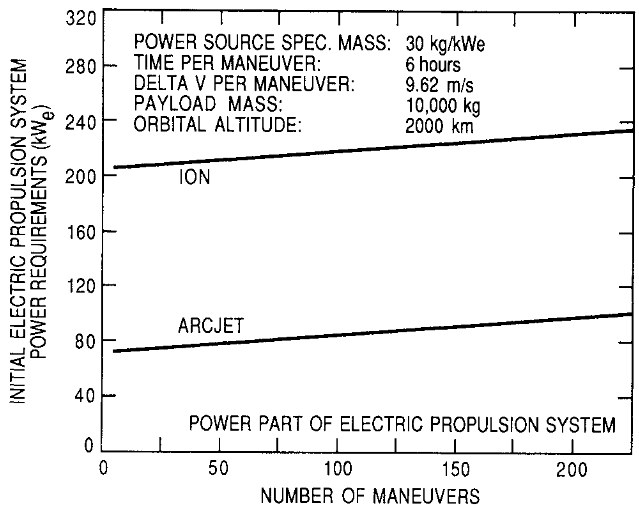

Fig. 8 Initial electric propulsion system power required for maneuvering as a function of the number of maneuvers.

mately twice the power to complete a maneuver. For example, if 200 maneuvers are needed, then the arcjet system will need 75 kW_e, whereas the ion system will need 134 kW_e to complete the first maneuver. This means that the arcjet system allows a larger nonpower platform payload. Finally, it should be noted that if 100 kW_e is the maximum power available, then only the arcjet system is capable of making the required defensive maneuver, providing a capability for up to 425 maneuvers as shown in Fig. 6.

Power Part of Electric Propulsion System

Figure 7 presents the initial platform mass as a function of the number of maneuvers for the case where the electric propulsion system carries its own power source. The curves assume that the power source specific mass is 30 kg/kW_e—the goal of the SP-100 SRPS development program. In this case, the electric propulsion systems will be more massive and, as a result, more maneuvers will be required before the electric systems become mass competitive with the chemical systems. For example, more than 90 maneuvers are required before the arcjet system provides a mass benefit compared to the baseline chemical system and more than 144 maneuvers before a payoff is demonstrated with respect to the advanced chemical system. Over 170 maneuvers are required before the ion system shows a benefit with respect to the baseline chemical system, and more than 240 maneuvers to show a mass benefit with respect to the advanced chemical system. If the SP-100 power source has a specific mass of 40 kg/kW_e, the number of maneuvers required to make the electric propulsion systems mass competitive increases another 20–30%.

The 50% increase in initial platform mass required by the ion system compared to the arcjet system is primarily a result of the increased power requirements of the ion system. The electric propulsion system initial power requirements are presented in Fig. 8 as a function of the number of maneuvers. Again, this is the electric power required to complete the first maneuver of a series. The arcjet system requires an initial power of 71 kW_e to complete 10 maneuvers, whereas the ion system requires 203 kW_e for 10 maneuvers. A 100-kW_e SRPS will enable the arcjet system to complete 228 maneuvers, whereas an ion system will not be capable of conducting any 9.62-m/s maneuvers in 6 h.

Conclusions

Analysis has shown that, for typically sized SDI constellations and reasonable launch rates of advanced ground launch systems, the use of electric propulsion upper stages can significantly reduce the number of launches and deployment time compared to those achievable with advanced chemical upper stages. As was shown in this paper, the number of launch vehicles required to deploy a constellation of fifty 10,000-kg platforms could be reduced by up to a factor of two when electric propulsion upper stages were used in place of advanced chemical upper stages. This resulted primarily from a reduction in upper-stage propellant requirements. In addition, it was found that the total deployment time for a constellation was driven primarily by the number of platforms in the constellation and the launch rate, and not by the individual upper-stage transfer time. Therefore, the reduction in the number of launch vehicles resulted in up to a 40% reduction in the constellation deployment time.

Continuous defensive maneuvering using electric propulsion systems can enable lower initial platform masses than with chemical maneuvering systems. The number of maneuvers (as discussed in this paper) at which electric propulsion becomes mass competitive depends primarily on whether the power supply to drive the electric propulsion system is accounted for in the payload or in the electric propulsion system. In the example cases presented, it was shown that when power was considered part of the payload, an arcjet maneuvering system was lighter than a chemical system regardless of the number of maneuvers, and the ion system was lighter if more than 50 maneuvers were needed. When the mass of the power supply was included with the electric propulsion system, arcjet and chemical systems became mass competitive around 100 maneuvers and an ion system around 200 maneuvers. The ion system required approximately three times the power of an arcjet system to perform a given number of maneuvers since it has a lower thrust-to-power ratio and a higher dry mass. The ion system required more than 100 kW_e of power to meet the maneuvering requirements, whereas the arcjet system was able to demonstrate a substantial maneuvering capability with less than 100 kW_e for all of the cases considered.

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