Arcjet Propulsion System for an SP-100 Flight Experiment

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The design and performance of an arcjet nuclear electric propulsion spacecraft, suitable for use in a space reactor power system (SRPS) flight experiment, are outlined. The vehicle design is based on a 92-kW ammonia arcjet system operating at a specific impulse of 1050 s and an efficiency of 45%. The arcjet/gimbal system, power processing unit, and propellant feed system are described. A 100-kW SRPS is assumed and the spacecraft mass is baselined at 5250 kg, excluding the propellant and propellant feed system. A radiation/arcjet efflux diagnostics package is included in the performance analysis. This spacecraft, assuming a Shuttle launch from Kennedy Space Center, can perform a 35-deg inclination change and reach a final orbit of 35,860 km with a 120-day trip time, thus providing a four-month active load for the SRPS. Alternatively, a Titan IV launch could provide a mass margin of 120 kg to a 1000 km, 58-deg final orbit in 74 days.

Nomenclature

I_{sp} = specific impulse, s
$M_{f/s}$ = mass of propellant feed system
M_p = propellant mass

Introduction

EXPLORATION and intensive study of the planets of our solar system will require high-power, electrically propelled spacecraft.[1-5] In addition, high-power, lightweight propulsion systems provide significant mass savings for the transfer of some high mass payloads from low Earth orbit (LEO) to their operational orbits.[6-10] Nuclear electric propulsion (NEP) systems using space reactor power systems (SRPS) and electric propulsion modules are being studied as options to satisfy these mission needs. Numerous mission studies have been conducted in which NEP is identified as either mission enabling or as the optimum propulsion choice.[1-11] Several studies also have been conducted on the integration of power and electric propulsion subsystems into an NEP spacecraft.[1,7,10,12-14]

The future availability of viable NEP systems requires the simultaneous development of electric propulsion subsystems and an SRPS to satisfy the mission requirements of various NEP users. To this end, a flight experiment of a 100-kW-class SRPS has been proposed as an adjunct to the SP-100 program using an electric propulsion module as an active load.[15] This flight test will demonstrate space-based nuclear power system operation, use of NEP for orbit transfer, and will test the ability to maneuver an orbiting spacecraft to enhance operations and survivability. An arcjet propulsion system has been baselined for this flight test since it meets the mission constraints of low developmental risk and cost, in addition to being scalable to power levels well beyond the 100-kW range being considered for the flight demonstration.[16]

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This paper outlines a baseline arcjet NEP spacecraft design for use in the SP-100 flight experiment. The expected system performance is provided for two different arcjet technology levels and considers launches using both the Space Transportation System (STS) and a Titan IV expendable launch vehicle.

Arcjet Technology

Arcjet Operation

A schematic of an arcjet engine is shown in Fig. 1. It consists of a one-piece plenum chamber-constrictor throat-expansion nozzle that also functions as the anode. The cathode is a conically tipped rod centrally located in the plenum chamber near the constrictor entrance. The constrictor is the narrow, cylindrical portion of the anode block upstream of the nozzle. An insulator holds the cathode in place and isolates the two electrodes.

The propellant gas is fed into the plenum chamber tangentially, through the chamber wall, and is heated by passing through and around an arc discharge. After the engine is started, a constricted arc in the form of a laminar column extends from the conical tip of the cathode through the constrictor throat and attaches to the small end of the nozzle as shown in Fig. 1. The arc is blown downstream through the constrictor channel by the propellant gas pressure in the plenum chamber. The bulk of the thermal energy is added to the propellant along a thin cylinder down the centerline of the device. As a result, the radial enthalpy and velocity distributions are highly peaked at the nozzle exit. References 17 and 18 review past arcjet testing and development.

Arcjet Propulsion System Parameters

The arcjet system technology levels assumed for this study are presented in Table 1. Two system technology levels are examined to bound the SP-100 flight experiment performance. The baseline system parameters are derived from an arcjet duration test conducted in 1986.[19-21] During the course of arcjet performance evaluation preceding the duration test, engine performance was examined at flow rates between 0.25 and 0.30 g/s and input power levels ranging from 10.0 to 29.0 kW. Values of specific impulse as high as 940 s and thruster efficiencies up to 44% were noted.[20] The engine thrust ranged up to 2.4 N at an ammonia flow rate of 0.3 g/s. The values in Table 1 represent an extrapolation of the performance evaluation data up to a 30-kW power level.[20]

The advanced arcjet technology performance projections in Table 1 represent expected arcjet performance in fiscal year 1989 as a result of continued research and development activities. During the 1960's, ammonia arcjet testing demonstrated 30-kW power-level operation at specific impulses and efficiencies of 978 s at 38.0%[22] and 1012 s at 38.6%.[23] Based on these data, a major technology upgrade is the increase in thruster efficiency. Such a performance improvement can be facilitated by using a bell-shaped nozzle, which has shown potential nozzle efficiency improvements of up to 20%.[24,25]

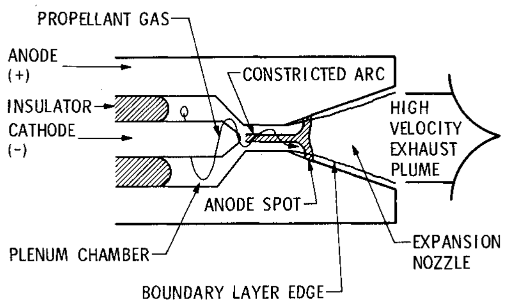

Fig. 1 Cross-sectional view of a thermal arcjet thruster.

Table 1 Arcjet performance characteristics assumed for this study

Parameter	Value	
Technology level	Baseline	Advanced
Propellant	NH_3	NH_3
Input power per thruster, kW	30	30
Thruster efficiency	0.37	0.45
PPU efficiency	0.98	0.99
Specific impulse, s	967	1050
System specific mass per engine,[a] kg/kW	1.81	1.26
Thrust per engine, N	2.35	2.6

[a]Excludes SRPS, propellant, tankage, and feed system.

SRPS Flight Experiment

Spacecraft Configuration

The proposed spacecraft configuration for the SRPS flight experiment is shown in Fig. 2. This system comprises a 100-kW SP-100 SRPS, a spacecraft bus, and an arcjet propulsion module, which includes a radiation/arcjet plume diagnostics package. This spacecraft concept uses an end thrust design, through the spacecraft centerline, so that the deployment boom is in compression during thrusting. A 100-kW power level is recommended for the SRPS flight demonstration.[15,16] The SRPS design chosen for this study is an out-of-core thermoelectric power conversion system coupled to a fast-spectrum, liquid-metal-cooled reactor, as outlined during the SP-100 development program.[26] The SRPS is considered herein only in terms of general performance specifications and the major SRPS/payload interface. The major SRPS parameters germane to this study are listed in Table 2.

The arcjet propulsion module is comprised of three sets of four engines with each set of engines on a single gimbaled pod, a power processing unit (PPU) system, the propellant feed system, a reactor radiation and thruster efflux diagnostics package, and associated structure. The four engines in each set provide an ample lifetime margin to conduct a six-month test at full power. Each engine is assumed to be capable of operating for 1500 h; one engine per set of four operates at a time. One of the four is a spare. Three thrusters can be operated simultaneously, one on each pod at maximum power using 92 kW after accounting for the PPU's 98% efficiency. The thruster module is enclosed for a 4.5-m-o.d., 6-m-long cylinder with the propellant tank located on the end nearest the SRPS. The three

Table 2 Space nuclear power system performance specifications[27]

Parameter	Specification
Power level, kW	100
Specific mass, kg/kW	30
Power type	dc
Voltage, V_{dc}	200

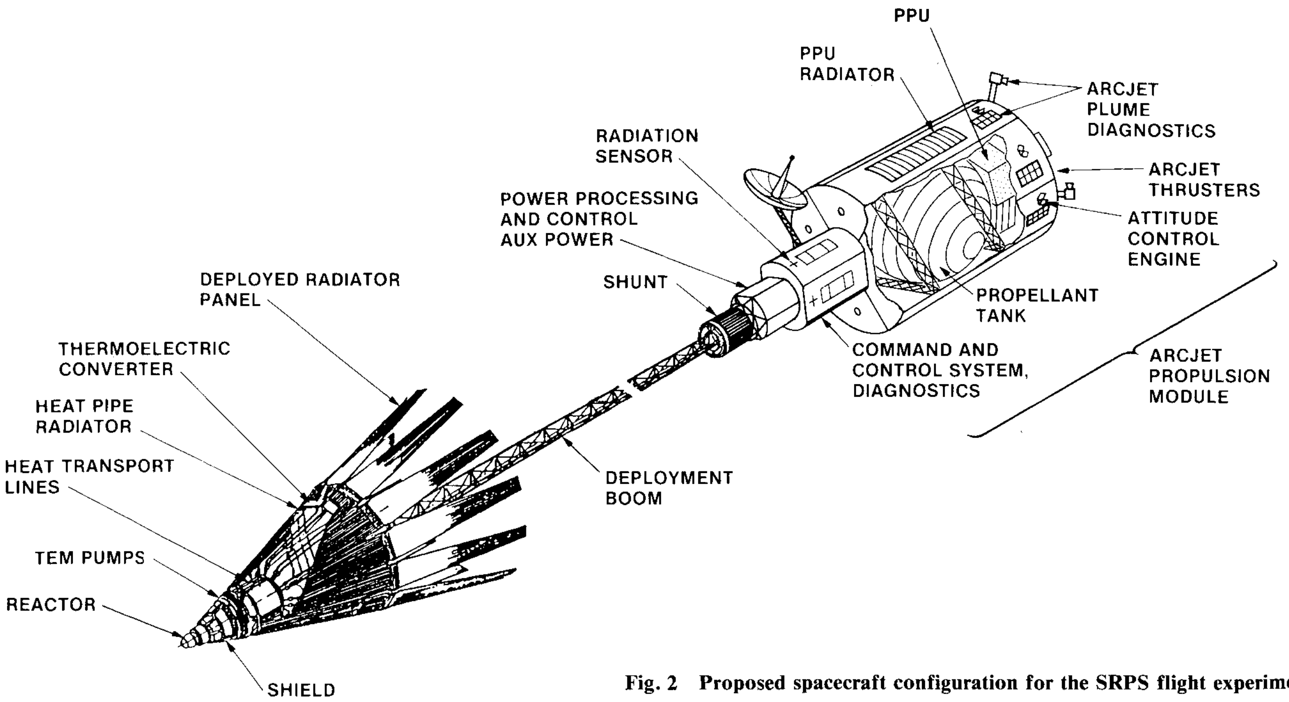

Fig. 2 Proposed spacecraft configuration for the SRPS flight experiment.

sets of arcjet engines and gimbals are located on the end of the cylinder opposite the SRPS. The PPU system is located within the cylindrical enclosure between the propellant tank and engine modules with its radiators facing space on the outer surface of the cylindrical enclosure. The combined thrust of this system is 7.8 N with three engines operating at full power. The command, data handling, and telecommunications functions are part of the spacecraft bus.

A block diagram of the SRPS flight experiment vehicle is shown in Fig. 3. It includes all of the primary system components for converting SRPS power into directed kinetic energy via interaction with arcjet engines. The arcjet PPU is used to start and run the arcjet. The propellant system runs parallel to the power train and consists of the tankage, valves, lines, and so forth, required to provide a constant propellant flow rate to each engine. The command, data handling, and telecommunications subsystems receive and process ground commands and control overall system operation. The diagnostic package monitors both the reactor radiation-induced environment and the particulate and field emissions from the arcjet thrusters. Thermal control allows for the rejection of waste heat from the arcjet engines and PPU's, whereas the structural members tie all of the subsystems together.

System Components

Detailed subscriptions of the thruster, PPU, propellant system, and diagnostics package are presented next.

Arcjet Thruster

The arcjet technology labeled as "Advanced" in Table 1 is assumed as the technology level for the arcjet NEP flight experiment spacecraft in this study. An expanded set of projected operating characteristics is given in Table 3 for this thruster technology. A 30-kW ammonia arcjet is assumed with an efficiency of 45% and a specific impulse of 1050 s. The thermal radiation from the engine will be shielded from the spacecraft by a heat shield. Successive layers of tantalum or molybdenum foil will form the heat shield. The first layer will be highly reflective to prevent waste heat accumulation in the heat shield. A thermal dam forward of the heat shield will minimize conductive heat loss from the engine.

Arcjet Power Processing Unit

Each arcjet engine will have a separate power processing unit (PPU), which will start and operate the thruster. Each PPU consists of a pulsed, low-power, high-voltage "start" supply in parallel with a high-power, low-voltage "run" power supply. The "run" power supply is based on a "buck" regulator design, which is efficient, reliable, and compact.[27] The stated goal for the PPU specific mass is 0.2 kg/kW. The PPU's are self-radiating, rejecting 0.61 kW of power while maintaining the component baseplate at 300 K.

The "start" supply sends rapid high-voltage pulses to the thruster causing a voltage breakdown through the propellant gas and heating the cathode. Once the cathode tip reaches thermionic emission temperatures, the "run" power supply takes over and is ramped up to full power in several tens of seconds. This technique allows the arcjet to be started rapidly and in a nondestructive manner. In addition, the design of the PPU/ignition system must be hardened to the SP-100 radiation environment and compatible with its thermal environment. The "run" supply provides approximately 250 A at 120 V, steady state, at full power following arcjet startup.

Propellant Flow Subsystem

The propellant flow system includes a propellant storage tank and a feed system. Ammonia propellant storage and feed systems are a mature technology.[28-31] A schematic of the proposed ammonia propellant flow system is shown in Fig. 4. Ammonia is stored in a spherical titanium tank at about 150 psia. Titanium is chosen for the tank material because of its low mass and chemical compatibility with ammonia. At 150 psia, ammonia boils at 298 K, implying that a minimum of propellant thermal control is required. An electric heater system provides heat to vaporize the ammonia and to maintain the

Table 3 Projected arcjet thruster operating characteristics

Parameter	Value
Propellant	NH_3
Engine input power, kW	30
Specific impulse, s	1050
Engine efficiency	0.45
Arc voltage, V	120
Arc current, A	250
Mass flow rate, g/s	0.25
Thrust, N	2.8
Engine mass, kg	11
Lifetime, h	1500

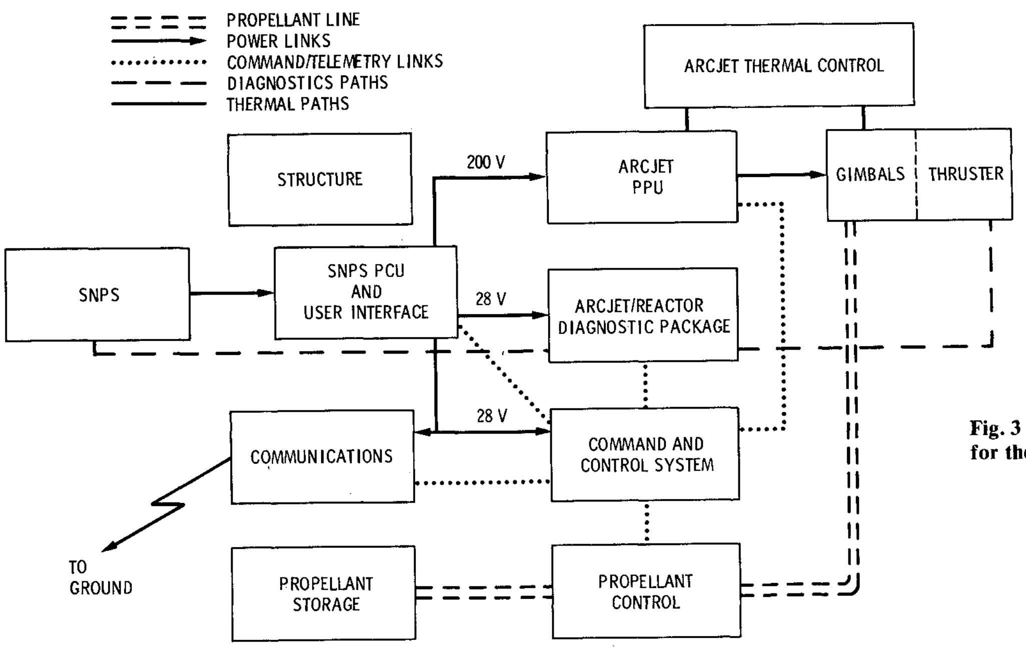

Fig. 3 Arcjet NEP system block diagram for the SRPS flight experiment.

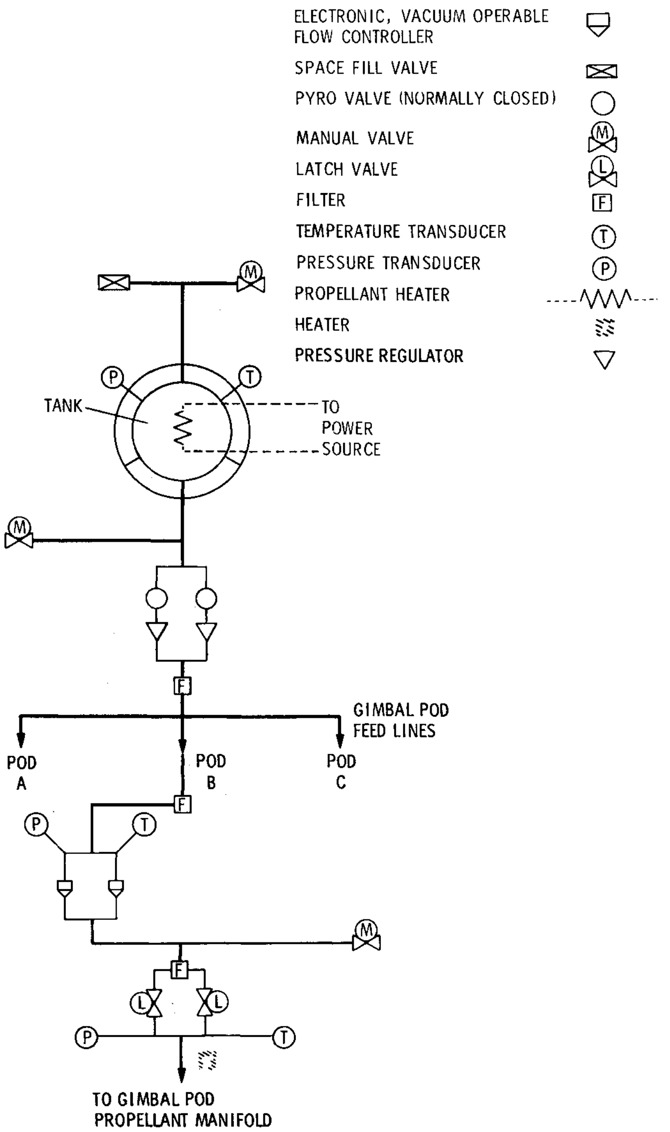

Fig. 4 Ammonia (NH_3) feed system schematic.

150-psia tank pressure. At these storage conditions, the maximum ammonia propellant load possible is 18,278 kg using a 4-m i.d. tank. A 10% ullage is assumed for the mission analysis discussed later in this paper.

The feed system consists of the propellant lines, values, transducers, filters, regulators, electronic vacuum-operable flow controllers, structure, etc., to provide the proper propellant flow rate to the arcjets. The total tankage and feed system mass, $M_{f/s}$, consists of a fixed component independent of propellant load and a variable component dependent on propellant load, M_p. The feed system mass is given by the following equation, which was used in the mission analysis discussed later in this paper.

$$M_{f/s} = 100.0 \text{ kg} + 0.20\, M_p \tag{1}$$

This equation includes a 10% contingency on all components. This propellant system provides a constant mass flow of 0.25 g/s of ammonia to each operating arcjet. The propellant requirement for six months of operation is 11,700 kg.

Diagnostics Package

A diagnostics package is carried on the SRPS flight demonstration to monitor the SRPS induced radiation environment at and beyond the user interface and to examine the arcjet

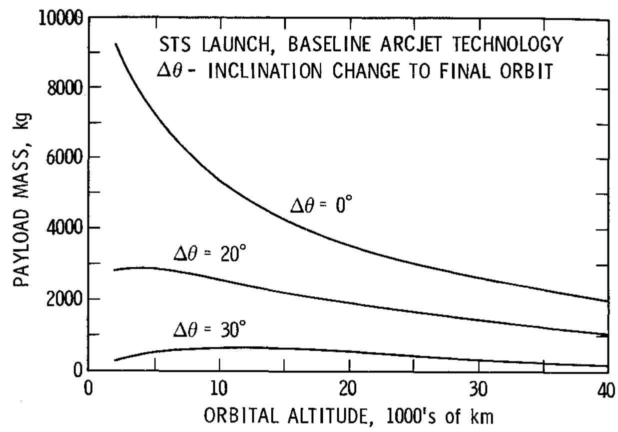

Fig. 5 Arcjet SRPS flight experiment payload capability as a function of orbital altitude and inclination. STS launch of baseline arcjet system to a 28.5-deg inclination.

Table 4 Projected mass summary for the 100-kW arcjet SRPS reference mission spacecraft

Subsystem	Mass, kg
SRPS	3000
Spacecraft bus	1000
SRPS/thruster system diagnostics	500
Arcjet module	250
Propellant feed system	—[a]
Miscellaneous	500

[a]Depends on propellant load; see Propellant Flow Subsystem section.

propulsion system particulate and field emissions. Such a diagnostics package will enable future users of both the SRPS and the arcjet engine to assess better the potential impacts of these systems on their payloads.

Arcjet efflux can be of some concern since a small portion of the exhaust plume extends behind the thruster nozzle-exit plane, due to gasdynamic expansion, and impinges on the arcjet module and the SRPS. Particulate contamination is expected to be minimal since the gas is rarefied and the volatile contaminant density is very low.[32] The primary particulate contaminants are expected to be hydrogen, nitrogen, tungsten, boron, and thorium. Of these, the metals and boron pose the greatest potential hazard since they adhere well to most any surface. For a six-month mission, the maximum expected tungsten loss from all engines totals less than 30 g based on erosion data from previous arcjet test.[21,33-35] All of this material would have to be focused to one area to cause a significant problem.

The electromagnetic interference (EMI) characteristics of arcjet thrusters are not well known but the engines are expected to be "noisy" since they produce a plasma. Considering that the onboard spacecraft power is almost two orders of magnitude greater than that of present-day spacecraft indicates that EMI guidelines will need extensive revision. Thermal radiation from arcjet thrusters also can be severe since up to 10% of the engine input power can be radiated away by the nozzle alone.[36,37] Therefore, heat shields are required to reduce radiative heating of the upstream spacecraft components.

Finally, the SRPS will be emitting neutrons and gamma rays, the levels of which will have to be evaluated. As a result of these spacecraft self-contamination issues, a diagnostics package is included as part of the add-on equipment.

Arcjet SRPS Spacecraft Performance

The following analysis is based on the well-known orbital mechanics equations for electric propulsion transfers[38] and the propellant feed, PPU, and arcjet subsystem characterizations

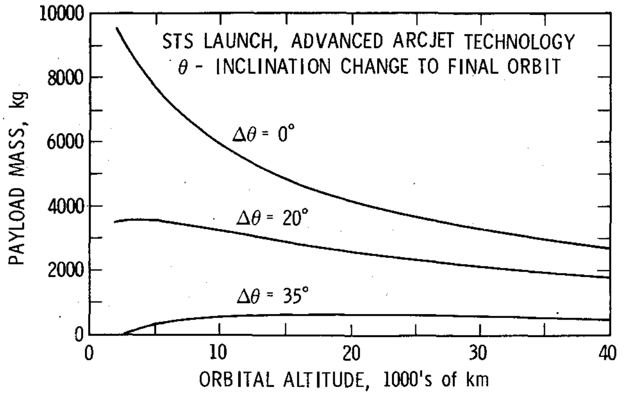

Fig. 6 Arcjet SRPS flight experiment payload capability as a function of orbital altitude and inclination. STS launch of advanced arcjet system to a 28.5-deg inclination.

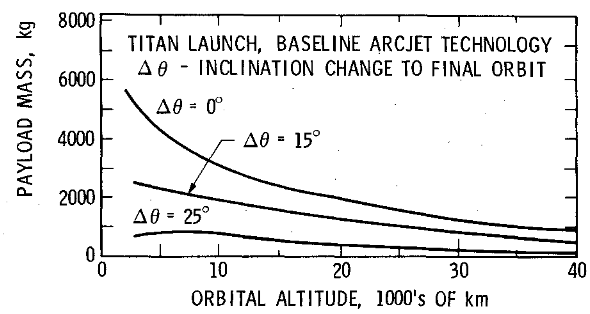

Fig. 7 Arcjet SRPS flight experiment payload capability as a function of orbital altitude and inclination. Titan IV launch of baseline arcjet system to a 28.5-deg inclination.

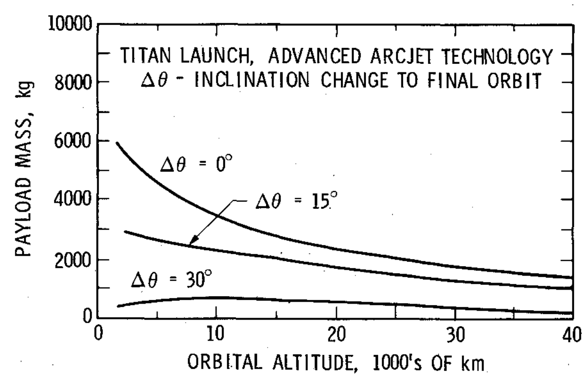

Fig. 8 Arcjet SRPS flight experiment payload capability as a function of orbital altitude and inclination. Titan IV launch of advanced arcjet system to a 28.5-deg inclination.

previously given. Flight experiment spacecraft performance is outlined for both arcjet technology levels presented in Table 1. Launches from Kennedy Space Center (KSC) using both the STS and Titan IV launch vehicles are assessed for this flight demonstration. It is assumed that the launch vehicle places the SRPS spacecraft in a low-altitude, 28.5-deg inclination orbit.

A vehicle mass summary is given in Table 4. The projected mass of a 100-kW SRPS is 3000 kg.[27] The propulsion system is assumed to have a mass of 250 kg, excluding propellant, tankage, and the propellant feed system. The spacecraft bus, which includes the primary command, and control and communications equipment, is assumed to have a mass of 1000 kg. The mass assumed for the diagnostics equipment is 500 kg. An additional 500 kg is added for miscellaneous spacecraft systems.

Constraints and Assumptions

As a result of safety concerns, the SRPS will not be operated until the spacecraft reaches a 925 km (500 n.mi.) orbit. Different mission scenarios are required for STS and Titan launches. An integrated chemical stage must be employed to boost the NEP flight demonstration spacecraft to 925 km from STS orbit, which is assumed to be 280 km (150 n.mi.), 28.5-deg inclination, for this study. This chemical system (specific impulse of 280 s) provides a ΔV of 349 m/s and weighs 2555 kg. It is also assumed that the upper launch mass limit for STS is 22,700 kg, 4100 kg of airborne support equipment (ASE) is needed, and a single, dedicated Shuttle launch from KSC is required. The initial spacecraft mass delivered to the 280-km circular orbit is 18,600 kg.

If a Titan IV is the launch vehicle, the maximum payload carried to LEO is assumed to be 12,100 kg. This delivered payload mass is adjusted to account for 3300 kg of ASE-type mission equipment. The Centaur upper stage of the Titan IV injects the spacecraft into the desired 925-km circular orbit. This eliminates the need for the integrated chemical stage required for the STS launch, saving 2555 kg of initial mass for payload.

Results

NEP transfers are assumed to start at a 925-km (500-n.mi.) altitude, 28.5-deg inclination, and extend through a range of altitudes to 40,000 km (21,598 n.mi.). Orbital inclination changes are also exercised to define a complete travel envelope. In some cases, NEP can drive the spacecraft beyond 40,000 km, the maximum altitude considered in this analysis. "Payload" is taken as the mass margin at a specific orbital altitude and inclination. This extra mass can accommodate additional propellant and scientific instruments to enable the SRPS to operate longer and to characterize spacecraft operations better.

Baseline Arcjet System, STS Launch

Figure 5 shows payload mass delivery capability to various altitudes and inclinations assuming an STS launch using a baseline arcjet system. The STS places the SRPS spacecraft into a 28.5-deg inclination; hence, the inclination changes shown in this figure and the following figures are taken from 28.5 deg. Analysis shows, as indicated in Fig. 5, that a 100-kW NEP system based on the baseline arcjet propulsion module can deliver the spacecraft to geosynchronous Earth orbit (GEO) with a payload mass margin of 240 kg. The transfer time, not shown in Fig. 5, is 120 days. The spacecraft travel envelope extends through inclination changes of greater than 30 deg and includes the complete study altitude range of 925–40,000 km.

Advanced Arcjet System, STS Launch

Use of the advanced arcjet technology results in a lighter-weight propulsion system with enhanced efficiency and specific impulse, which, in turn, can deliver the SRPS spacecraft to higher energy orbits. As shown in Fig. 6, 500 kg can be delivered to GEO. The transfer time is 114 days (transfer time not shown). Here, the spacecraft travel envelope extends through inclination changes of greater than 35 deg and, again, includes the complete altitude range considered in this study.

Baseline Arcjet System, Titan IV Launch

The Titan IV lift capacity is 65% of the STS capability. Nonetheless, arcjet electric propulsion can still execute significant orbit transfer maneuvers. As shown in Fig. 7, a 25,000-km, 28-deg orbit can be achieved in 57 days (transfer time not shown) with a spacecraft mass margin of 1620 kg. However, because of the reduced Titan IV lift capability, not enough fuel can be carried for this vehicle to reach GEO, which required an inclination change of 28.5 deg. In this case, the spacecraft travel envelope extends through inclination changes of greater than 25 deg for the altitude range considered in this study.

Advanced Arcjet System, Titan IV Launch

A spacecraft based on the advanced ammonia arcjet system will reach GEO in 74 days (transfer time not shown) with a mass margin of under 500 kg (see Fig. 8). In this final case, the spacecraft travel envelope extends through inclination changes of greater than 30 deg and, again, extends through the complete altitude range considered in the study.

Conclusions

The design and performance of an arcjet nuclear electric propulsion (NEP) spacecraft suitable for conducting the SP-100 space reactor power source (SRPS) flight experiment have been presented. A proposed vehicle consists of a 100-kW SRPS, a radiation/arcjet efflux diagnostics package, and an arcjet propulsion module, in an end-thrust configuration. The propulsion system module consists of three 30-kW ammonia arcjets operating at a specific impulse of 1050 s and an efficiency of 45%. A total system thrust of 7.8 N is generated with three engines operating at full power. The baseline vehicle mass is 5250 kg, excluding the propellant and feed system.

Orbital analysis has been conducted to evaluate the proposed SRPS vehicle performance. A single, dedicated Space Transportation System (STS) or Titan IV launch is assumed from Kennedy Space Center. The vehicle is capable of raising itself to geosynchronous Earth orbit (GEO) in 114 days with a payload margin of 500 kg assuming an STS launch. Alternatively, the vehicle could reach 10,000 km and include a plane change of 35 deg with a payload margin of 500 kg. As a result of the 30% reduction in Titan payload delivery capability with respect to the Shuttle, the reference mission vehicle mass margin to GEO is reduced significantly to 69 kg. A 1000-km, 58-deg final inclination can be achieved in 74 days with a mass margin of 120 kg.

Acknowledgments

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