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Abstract

Mission studies reveal that Earth orbit transfer missions, station keeping, and elusive maneuvering missions benefit from the application of efficient electric propulsion (EP) systems. The *Dual Mode* of utilizing significant on-board power (i.e., >10 kW) for the main mission coupled to electric propulsion for orbit transfer and maneuvering is creating new EP opportunities. Space experiments involving EP are being planned around two state-of-the-art thruster types: arcjet and ion. Long term research on high thrust-density ion propulsion is aimed at 5 to 25 kW operation in the 5000 s specific impulse (I_{sp}) range. Shorter term research is focused on the NH_3 arcjet for the SP-100 flight mission. Demonstrated 30 kW arcjet sustained life (versus <3 kW demonstrated sustained life for the ion engine) and the arcjets's inherent simplicity offer low risk and minimum cost for the SP 100 flight demonstration objectives. In addition, solar power flight experiments offer near term opportunities to acquire flight experience on these nearly-developed high power arcjet systems.

Introduction

The Strategic Defense Initiative Organization (SDIO) requires both high levels of electrical power to meet its mission objectives and advanced propulsion to reduce deployment costs. High power electric propulsion reduces deployment costs and simplifies deployment of large SDI constellations. SDIO's Innovative Science and Technology Directorate (SDIO/IST) is funding research addressing performance and reliability of high power arcjets and feasibility issues of high power ion engines. Figure 1 shows arcjet and ion engine operating regimes. The NH_3 arcjet has high thrust, moderate efficiency and specific impulses in the 1000 s range, while ion engines have low thrust, high efficiency and considerably higher specific impulses. As shown in Fig. 2 the optimum specific impulse (which minimizes power and propulsion mass) for orbit raising transfer times of interest to the SDI, overlaps the arcjet performance regime. The solid curves represent demonstrated performance; the dotted curves represent performance extrapolations. Arcjet technology is being accelerated by the Key Technologies Directorate of SDIO (SDIO/KT) for flight system development.

Electric Propulsion Applications

Three categories of electric propulsion applications offer payoffs for SDI missions: 1) orbit raising, 2) on-orbit station-keeping, and 3) elusive defensive maneuvering. Two types of orbit velocity changes (delta V) are considered. The most common is the increasing orbital velocity needed to achieve a higher orbit; however, many DoD missions require large plane changes, e.g., to high inclination orbits. These also require large delta Vs. The larger the delta V (a measure of expended energy), the greater the mass savings and hence, the greater the payoffs using electric propulsion.

Orbit Raising

Orbit raising is the transfer of a payload from a low Earth orbit (LEO, typically 300 km where it is deployed by the launch vehicle) to a higher orbit up to and beyond geosynchronous (35,400 km). The higher the final orbit, and the greater the orbit plane change, the greater the delta V required for the maneuver. Mass savings are illustrated in Fig. 3 where electric propulsion upper stages, over a range of specific impulses, are compared to an advanced chemical (Centaur G') upper stage in terms of the mass needed in low Earth orbit. In this case, the payload mass was 6000 kg, typical of a BSTS satellite. The vertical dotted line on the horizontal-axis indicates that for delivery to geosynchronous altitude, electric propulsion upper stages reduce initial mass by 40 to 60% over mass required with an advanced chemical upper stage.

6000 kg is the maximum payload that Centaur G' can lift to geosynchronous orbit because Centaur's performance is fuel mass limited by launch vehicle constraints. Electric propulsion, on the other hand, can carry much heavier payloads (9000 to 15,000 kg) because the same propellant mass generates more total impulse. This capability enables missions, which are too heavy for chemical deployment.

The mass saving enabled by electric propulsion pays off in a number of ways. Direct savings in launch costs occur because less mass is required in orbit. In some cases, the propulsion mass savings enable two satellites to be launched on a single vehicle. Such dual payload launches cut in half the number of launch vehicles and, depending on the constellation size, can decrease total deployment time.[1]

On-Orbit Station Keeping

Mass savings using electric propulsion for orbit maintenance is about 15%. This is calculated assuming requirements similar to north/south station keeping maneuvers. Mass savings are shown in Fig. 4 where initial spacecraft mass is plotted as function of auxiliary propulsion mass for SSTS, BSTS, and SBI spacecraft. These savings can be interpreted a number of ways: 1) the spacecraft mass is 15% less for a given payload, 2) a 15% greater payload mass can be carried on a given spacecraft, 3) on-orbit life (without refueling) can be extended by a factor of 3 to 10 times that of chemical auxiliary propulsion. The latter payoff may be the most important because it reduces and may even eliminate the need for on-orbit refueling.

Elusive Defensive Maneuvering

Two types of defensive maneuvers are the: 1) fast maneuver to dodge an incoming threat,[2] and 2) continuous, low-thrust maneuver which produces non-Keplerian orbits.[3] The purpose of the latter type is to complicate hostile tracking in order to prevent an attack. This is accomplished by disrupting correlation of the tracking measurements which forces a need to reinitialize the target, a process which can consume critical time.

Electric propulsion can play a role in continuous low-thrust maneuvers.[1] Figure 5 compares chemical propulsion (I_{sp} = 350 s) for this application with electric propulsion (I_{sp} = 1000 s). As shown in the figure, electric propulsion enables this maneuver because chemical propellant mass becomes excessive with an increasing number of maneuvers. This example was calculated for a spacecraft similar to BSTS in terms of its mass and electrical power. Similar findings apply for more massive spacecraft (on the order of 10,000 kg) with more available electrical power (10's kW).[4]

Power and Electric Propulsion

SDIO is developing power sources for space use. Two of these developments provide opportunities for high power electric propulsion: 1) SUPER[5] (Survivable Solar Power), a hardened solar power source, survivable to SDI threats, in 5 to 10 kW modules, and 2) SP-100,[6,7] a nuclear reactor system capable of 10 kW to 1 MW electrical power, presently being designed for 100 kW. Flight tests are planned for both power sources.

SUPER is in Phase 2 of a conceptual design program. Critical design, fabrication, assembly and test are expected in the 1991-92 time frame, with delivery of a flight unit in 1992, and a flight test in 1993-94. The flight will carry a single power module of 5 to 10 kW power. Electric propulsion is being considered as one of the candidates for the payload(s). In addition, the Air Force's ELITE (Electric Insertion Transfer Experiment) is considering incorporation of the SUPER flight experiment in ELITE.[8] These flights provide opportunities for both high power arcjet and ion propulsion, especially an opportunity to obtain flight data on an arcjet system prior to the SP-100 flight demonstration.

The SP-100 ground reactor test is expected to start in the 1992-94 time frame, followed by a flight demonstration in the latter half of the 1990s. The primary purpose of the flight demonstration is to demonstrate space operation of 30 to 100 kW reactor system, and the secondary purpose is to demonstrate arcjet orbit maneuvering.

The power level for the SP 100 flight is presently under review. Strong arguments can be made for a 30 kW flight.[9,10,11] Since much of the planning was performed at the 100 kW level, results for both 30 and 100 kW systems are being offered.[12] Thus, there maybe some ambiguities as SP-100 policy evolves.

In addition to the above programs, SDIO is funding studies to look at multi-megawatt space power sources.[13] Hardware development for multi-megawatt sources is much further downstream than SUPER and SP-100, but will eventually offer incentive and opportunities for development of higher power electric propulsion concepts, such as the magnetoplasmadynamic (MPD) thruster, and others not yet on the drawing boards.

SP-100 Flight Arcjet Program

The primary emphasis of the SDIO electric propulsion program is development of a 30 kW ammonia arcjet system for the SP-100 flight demonstration. The flight demonstration, its power level, mission, etc. are still being defined by SDIO.[7] JPL, with SDIO funding, is managing the flight arcjet program.[14] Phase A of this program consists of the two contracts discussed in the next section. In Phase B the contractor will design, build, and test a single-string engineering model of a 30 kW ammonia arcjet propulsion system, consisting of an arcjet, power processor, and propellant system. The design from Phase A will be used as a basis for the design of Phase B. In Phases C/D the contractor will design, fabricate, and qualify subsystem and preliminary design test models, leading to the design, fabrication, acceptance test and delivery of a flight propulsion system.

SP-100 Arcjet System Definition

SDIO/KT initiated contracts, through JPL[14], with General Electric (with Rocket Research Corp. as a subcontractor) [15] and TRW [16]. These contracts are precursors to an SP-100 arcjet flight system development. The 11 month studies started in March 1989. Their purpose is to define the design of a single-string engineering model of a 30 kW ammonia arcjet propulsion system. This design will be used as the basis for a follow-on, competitive procurement, program to build and test an engineering model 30 kW arcjet system. In the process of defining the engineering model, the contractors conducted a survey of SDI missions, to identify potential arcjet applications. The survey results were used to determine an Interim Reference Mission (SP-100 Flight Demonstration). The SDIO, through the Air Force Weapons Laboratory, is conducting a more rigorous mission definition study. [9] The purpose of the interim mission is to provide a basis for the arcjet system design, however the final mission scenario should have little impact on the arcjet design. The driving factor in arcjet design, besides power, is the total delta V, not delta V of individual maneuvers. The same 30 kW arcjet unit is suitable for meeting any SP-100 power level eventuality up to 100 kW plus, and down to 30 kW.

SP-100 Flight Demonstration

The flight experiment test goal is to operate the SP-100 reactor system sufficiently long to demonstrate space operation and compatibility with a payload. The constraints on the payload include low developmental risk and cost, wide performance throttleablity, and scaleablity to future SDI power levels well beyond the 30 to 100 kW range being considered for the flight demonstration. The arcjet has been selected as the payload that best meets this criteria. Analysis has shown that several baseline arcjets, as tested at JPL in 1986[17] and discussed later in this paper, could meet the SP-100 requirements.[18] SDIO/IST is addressing issues pertaining to improved arcjet performance and issues pertaining to other of the arcjet subsystems, such as the power processing unit.

The SP-100 mission provides an unique opportunity to examine the control scenarios required for nuclear electric orbit transfer, to examine the maneuvering of an orbiting spacecraft for enhanced operations and survivability, and to examine a representative transfer similar to that required for the SDI.[19]

Arcjet System for SP-100 Flight Demonstration

The specific impulse gains to be achieved by using the current arcjet design are significant with respect to chemical propulsion. Thus, SDIO's guidelines for arcjet system development are straight forward: keep the *design simple* and conservative, and keep *costs low*. SDIO's intent is not to demonstrate an optimum performing electric thruster, but rather to demonstrate a thruster with acceptable performance and high reliability. Thrusters with enhanced performance will progress after the user community has accepted electric propulsion. Costs should be kept low so that SP-100 electric propulsion does not become an issue at budget time.

The basic building block for the SP-100 arcjet system is the 30 kW ammonia arcjet. Three of these operating concurrently process about 95 kW (accounting for power processing efficiency). As mentioned earlier, this modular approach allows the arcjet system to meet a range of SDI missions from 30 to 100 kW plus.

Figure 6 is a block diagram for a proposed SP-100 spacecraft showing the power system, spacecraft bus and arcjet propulsion system. The technology development status of the subsystems comprising the arcjet system are shown in Figs. 8 and 9.[20] Technology status is indicated by a circular symbol and ranges from an open circle for basic research to a closed circle denoting the component is ready for Critical Design Review (CDR).

The first three subsystems (arcjet, power processing unit, and propellant distribution and storage) are the most crucial in terms of validation of the flight system concept. All three will be addressed in an engineering system test and evaluation next year as part of Phase B of the SP-100 arcjet flight system development program. Arcjet lifetime is the primary issue, although as mentioned previously, lifetime demonstrated in 1986 is sufficient for the SP-100 mission. The primary issue for power processing is high conversion efficiency to reduce active cooling requirements and minimize overall system mass and complexity.

An important adjunct to the arcjet flight system is a diagnostics package for monitoring arcjet plume, plasma environment, material deposition, and electromagnetic radiation. These measurements would validate ground measurements, which are difficult to make, but which are critical to potential users.

Arcjet Technology

The IST, through its ISTC (Innovative Science and Technology Center) at JPL is funding research in critical technologies for high-power electric propulsion. Specifically, technical issues which affect performance and operational reliability of the 30 kW ammonia arcjet are being addressed (e.g., Ref. [21]). Figure 7 shows progress made by the SDIO/IST arcjet technology program, measured with respect to performance generated in the 1986 Astronautics Laboratory (AFAL) funded JPL arcjet endurance test. For the most part, except for demonstration of lifetime, SDIO's goals have been achieved.

Specific impulse values of over 1000 seconds and thruster efficiencies greater than 40% were demonstrated in the SDIO/IST program. These improvements were achieved by harnessing more of the engine's thermal energy through design and implementation of a bell shaped nozzle and improvements in the arcjet thermal design.

The biggest question concerning long term operation is not cathode erosion, but rather the formation of whiskers on the cathode tip. Research is underway to determine whether these whiskers could momentarily short the cathode to the anode as they appear to have done in the 1986 test. Cathode erosion rates at 30 kW have been measured over a range of cathode configurations and operating conditions and were shown to be sufficiently low for useful thruster life. Mass loss rates from 1 to 5 mg/hour were measured. These rates correspond to less than 0.5 cm^3 material loss, approximately the size of the cathode tip, in 1500 hours operation.[21,22]

The Pulsed Power Laboratory at Texas Tech University is being funded by SDIO/KT to investigate cathode materials in terms of erosion characteristics and whisker growth potential. The most promising materials, determined from a literature search and from the Laboratory's experience with electrode erosion, electrode materials development, arc physics, etc., will be tested in arcjet operation. Some of the materials being considered include: 1) thoriated tungsten (for comparison with benchmark arcjet results), 2) lanthanum hexaboride impregnated tungsten because of its low work function, and 3) propellant filled porous and capillary cathode materials.[23,24]

A workshop on electrode erosion in electric propulsion space engines was held in March 1989. It was funded by SDIO, administered by Texas Tech University, and addressed arcjet erosion issues. Conclusions from the workshop can be categorized in terms of near and long term research issues. Near term issues included propellant additives which burn off cathode whiskers, and improved radial propellant injection for improved propellant vorticity and improved arc formation and stability. Long term issues included engine modelling (strongly coupled to measurements) for understanding flow phenomena in electric and magnetic fields, energy transfer from the arc to the propellant, frozen flow losses and interactions at plasma materials interfaces. A particularly important issue was identified as the understanding of arcjet ignition and the shut down sequence.

Power Processing Unit (PPU) Development

A power processing unit was designed, built and operated at full power on a 30 kW arcjet at Space Power Inc. in 1986 in a program funded by the AL. IST expanded on the program and funded it as part of the Small Business Innovation Research (SBIR) program. In the SBIR Phase 1, Space Power Inc. upgraded the PPU with a starter circuit, and tested it with a resistor load. The starter circuit included a current control circuit designed to suppress start-up surge current.

Under the SBIR Phase 2, the upgraded PPU was tested at full power with input voltage over 200 V and output voltage over 120 V. Testing is planned with an ammonia arcjet at JPL, and further testing at Rocket Research Corp. The purpose of this testing will include the demonstration of arcjet starting at full-flow rate and further characterization of the arcjet PPU. The starter circuit has also been improved to achieve a starting voltage above 2000 V.[25]

This program is an example of how a properly planned SBIR program can directly feed a flight program. The PPU is also a candidate for use in the AFAL arcjet Advanced Technology Development program, which leads to a flight demonstration.

Other SDIO Electric Propulsion Programs

In addition, exploratory programs cover other high power concepts including ion engines, higher power (up to 100 kW) ammonia arcjets, kW level pulsed thrusters, and 10 to 60 kW hydrogen arcjets. The first four subtopics are being managed by NASA Lewis Research Center, and the remaining item is managed by the AL.

High Power Ion Engine

High power xenon, ion engine feasibility, is a concept which has been explored at NASA.[26] Larger diameter, higher thrust ion engine technology is under development at the Electric Propulsion Laboratory. This SDIO/IST supported SBIR Phase 2 program utilizes an unique annular discharge chamber and ion optics design to overcome the span-to-gap limitations of conventional ion engine accelerator systems. By using inner and outer grid electrode mounts, an annular accelerator system can potentially maintain the same grid gap spacing as present accelerator system designs, but can have an effective grid extraction area at least four times that of existing engines, resulting in much higher thrust levels.

The first phase of this SBIR program demonstrated proof of concept by building and operating a 50 cm diameter annular ion engine and testing the engine with a simulated annular grid ion extraction system.[27] This apparatus is being refined during the second phase of the program for grid electrode thermal displacement measurements of a three-grid annular accelerator system. Extensive theoretical models describing the annular grid thermal/mechanical behavior were developed for comparison to these experimental measurements and incorporated into an overall accelerator system design model.[28] Accelerator system fabrication techniques and beam extraction characteristics are being developed simultaneously with a scaled down annular ion engine.[29]

Spacedrive System and Mission Model

The Electric Propulsion Laboratory has a SBIR Phase 2 contract to develop an IBM PC/Compatible based system for calculating mission parameters, sizing arcjet and ion engines, and conducting literature reference searches. The Spacedrive computer program is highly interactive and includes a number of consistency checks for practical and phenomenological limits. One of its objectives is to assist mission planners and propulsion systems engineers in making more quantitative comparisons with chemical propulsion systems.

Pulsed Electrothermal Thrusters (PET)

GT Devices is pursuing a SBIR Phase 2 contract to demonstrate the time averaged specific impulse of the PET.[30] Emphasis is placed on achieving total impulse measurements.

30 to 100 kW Arcjet

Stuttgart University has initiated research to provide an analytical basis for scaling self-cooled arcjets to powers greater than 30 kW.

Hydrogen Arcjet

An Electric Propulsion Laboratory SBIR Phase 1 proposal on hydrogen arcjet investigations was selected by the SDIO/IST for negotiation. This activity is being managed by the AL. Hydrogen arcjet operation will be investigated over a large power and specific impulse range, e.g., from 10 kW, 1500 s to 60 kW, 700 s. Seals, regenerative cooling, nozzle design, and cathode physics are among the topics being studied. The overall objective is to demonstrate the capability of this engine to be throttled over a wide range of thrust and specific impulse commensurate with mission requirements.

Conclusions

The advent of missions requiring major power levels (e.g., >30 kW) is prompting mission planners to consider the advantage of the *Dual Mode* of operation, i.e. of using mission power to also power electric propulsion for orbit raising, station-keeping, and elusive maneuvering. Flight demonstrations of solar power and nuclear power are in advanced planning stages. Electric propulsion has been positioned as the load and secondary flight objective for both demonstrations. Cooperative programs among the SDIO, Air Force, NASA, and DOE are providing the research and development for flight hardware. These activities are centered around a conservative ammonia 30 kW arcjet design.

Mission studies are revealing a rich assortment of payoffs for using arcjet and ion engines. Life tests and hardware definition studies are providing for a steady progression towards flight validation missions. Longer term fundamental research is exploring approaches for enhancing thruster power density, efficiency and life time. Payoffs will carry over to many civilian sector applications, such as communication satellites, direct broadcast systems, space science missions, etc.

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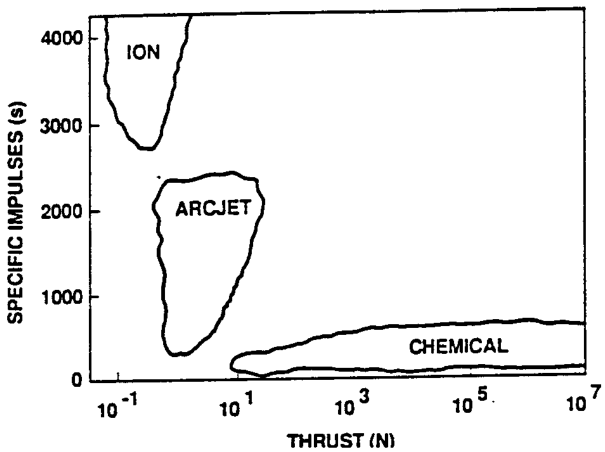


Fig. 1 Thruster operating regimes, showing that arcjet has high thrust relative to ion engine.

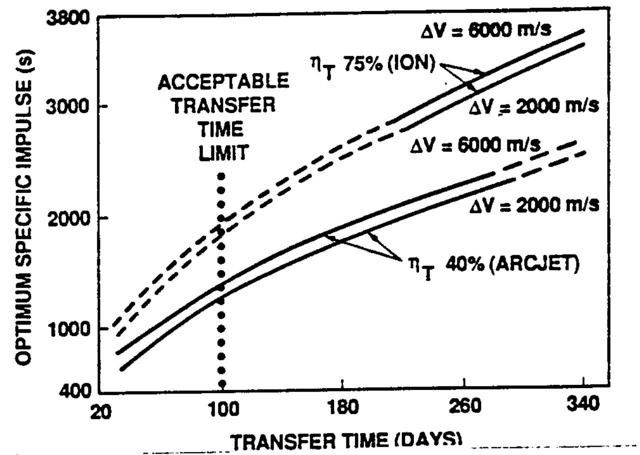


Fig. 2 Optimum specific impulses coresponding to LEO to geosynchronous orbit transfers. The lower Isp of the arcjet achieves transfer times of less than 100 days.

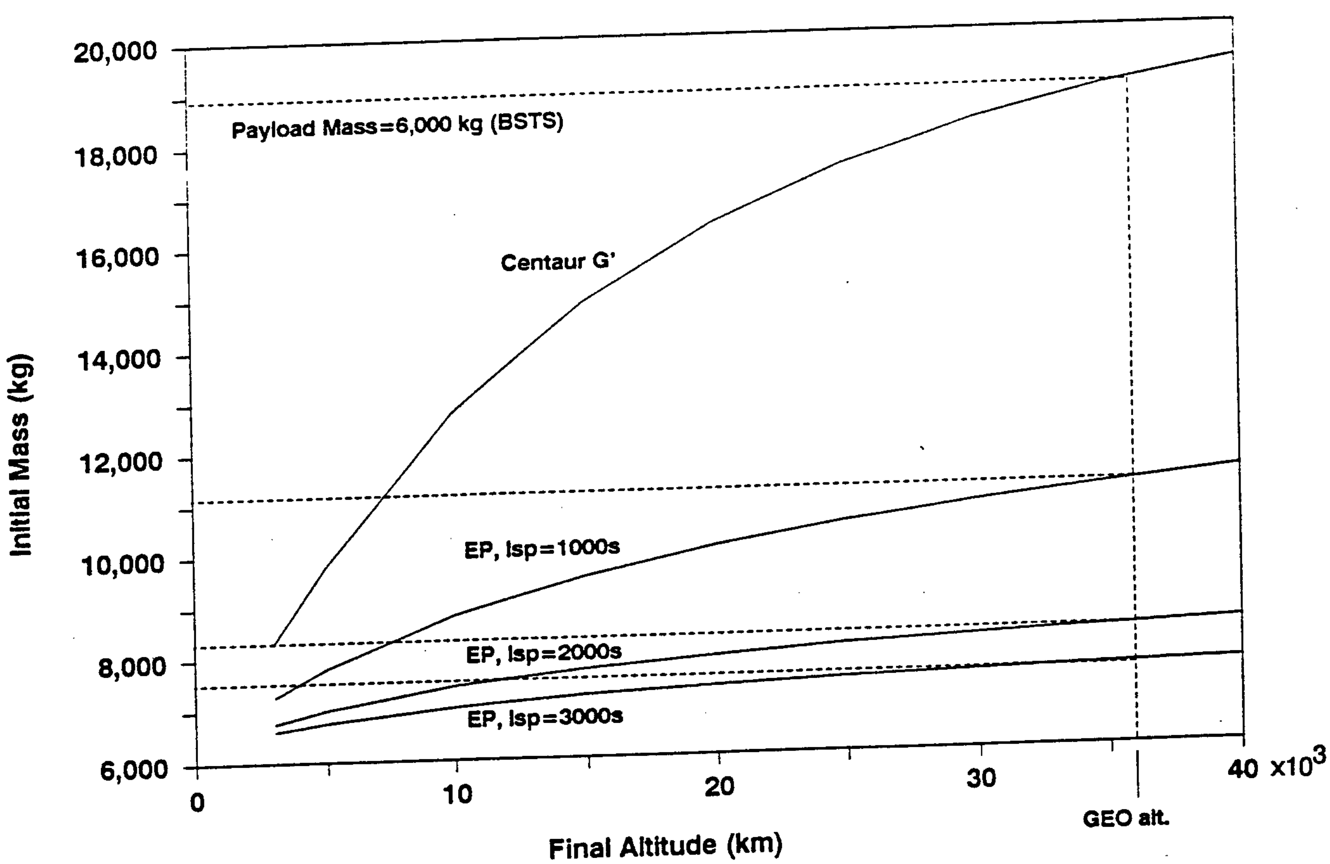


Fig. 3 Initial mass required in LEO as function of final orbit (NH_3 arcjet I_{sp} approx. 1000 s).

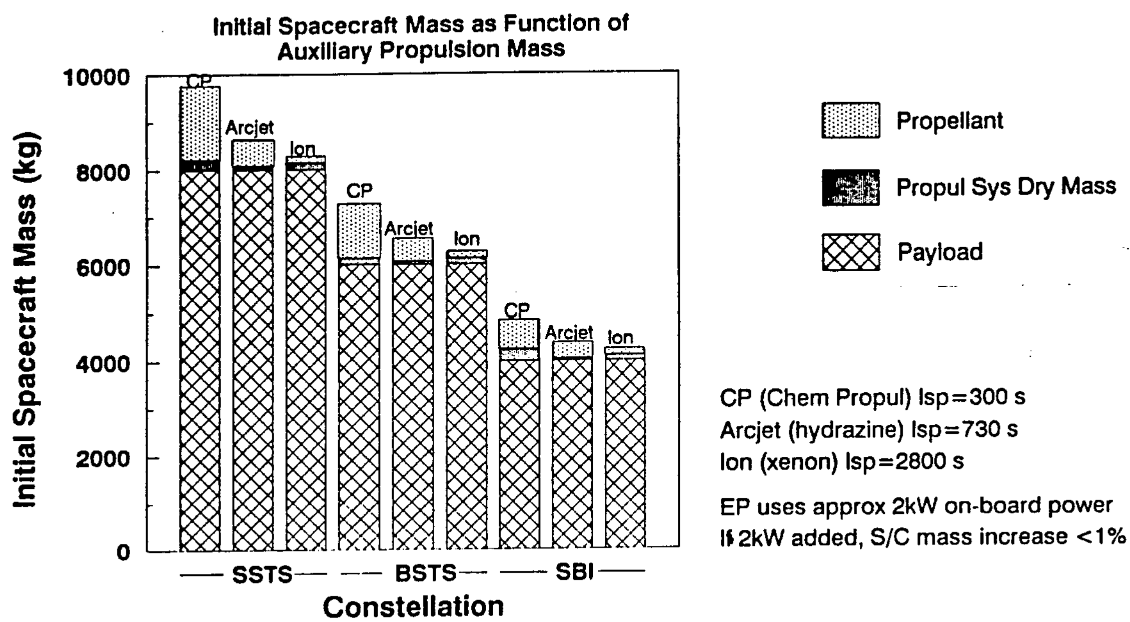


Fig. 4 **Payoffs using orbit maintenance electric propulsion compared to chemical propulsion.**

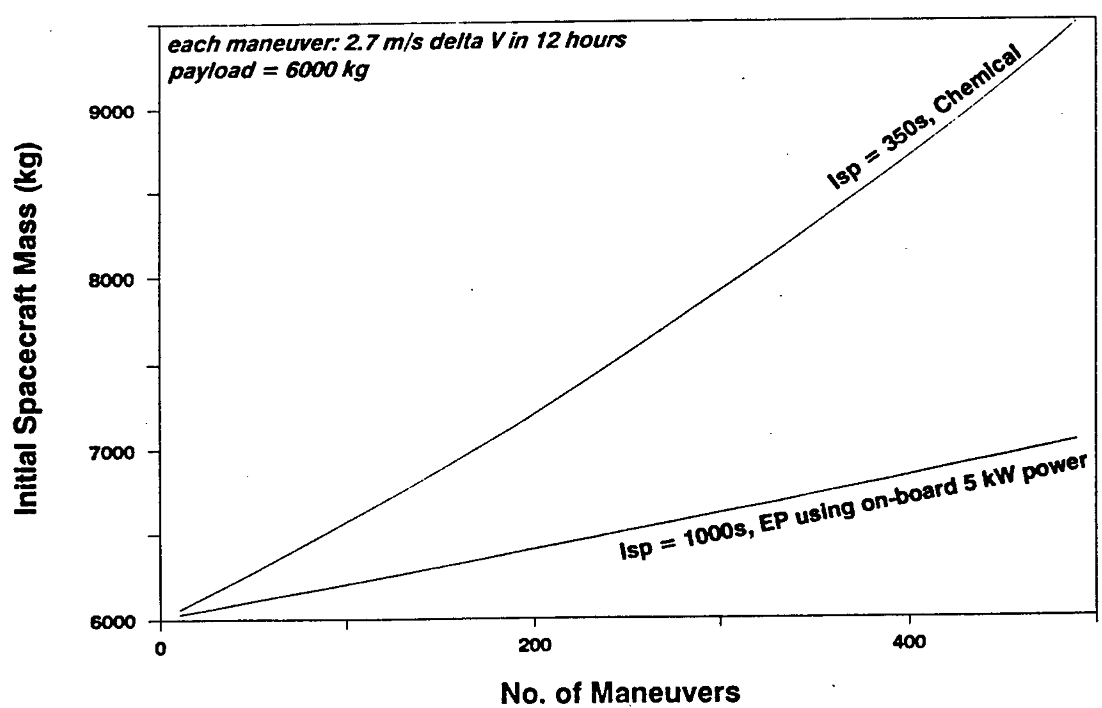


Fig. 5 **Mass saving from using EP for continuous defensive maneuvering becomes significant as the number of manuevers increases**

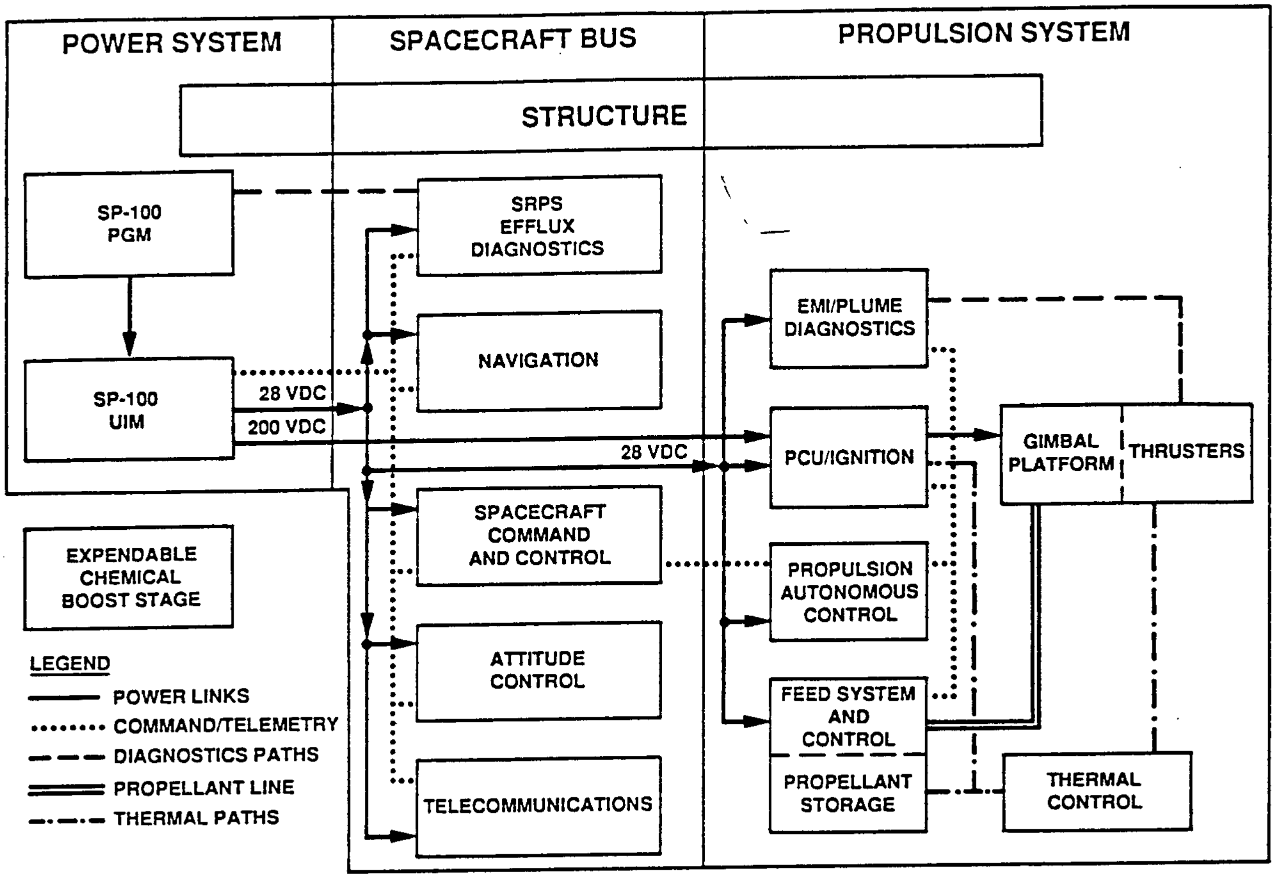
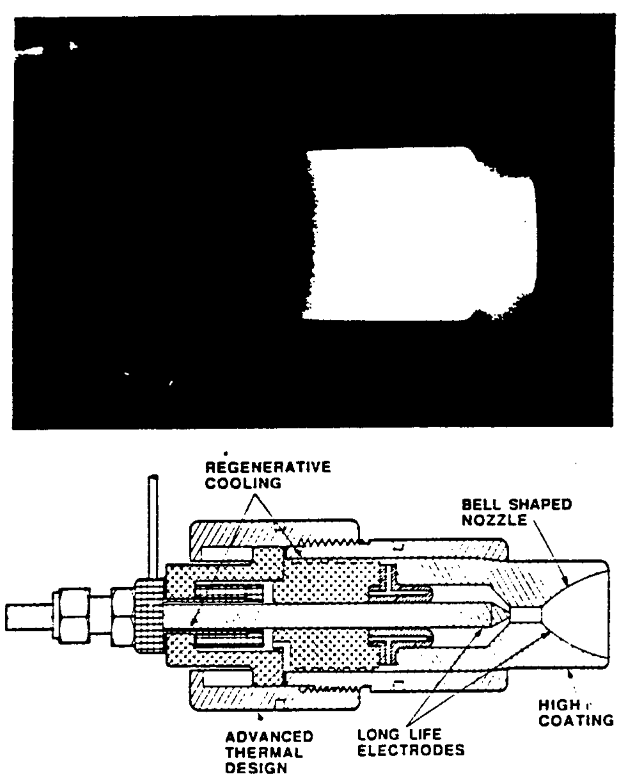


Fig. 6 Arcjet nuclear electric power system block diagram for flight demonstration.



PARAMETER PER ENGINE	VALUE ACTUAL 1986	IST GOALS	ACTUAL 1988
PROPELLANT	NH_3	NH_3	NH_3
ENGINE INPUT POWER (kWe)	25	30	30.2
THRUST (N)	2.4	2.6	2.53
SPECIFIC IMPULSE (s)	870	1050	1031
ENGINE EFFICIENCY (%)	37	45	42.3
ARC VOLTAGE (V)	109	120	106
ARC CURRENT (A)	230	250	286
MASS FLOW RATE (g/s)	0.27	0.25	0.26
ENGINE MASS (kg)	4	4	3.1
TEST DURATION (hrs)	573	1500	108
TOTAL IMPULSE (N-s)	5×10^6	1.4×10^7	9.8×10^5

Fig. 7 Arcjet characteristics achievements and goals.

SUBSYSTEM	STATUS	ISSUES	COMMENTS
THRUSTER	◑	REDUCE ANODE TEMPERATURE MINIMIZE CATHODE EROSION IMPROVE INJECTOR LIFE	INCREASE ANODE EMISSIVITY REQUIRE 1500 HOUR CATHODE LIFETIME WITH 570 HOURS DEMONSTRATED
POWER PROCESSING	◑	INCREASE EFFICIENCY OF PPU PPU ISOLATION FROM SPACECRAFT GROUND NON-DESTRUCTIVE ENGINE IGNITION FLEXIBLE, HIGH CURRENT POWER LINKS	LOWER SP MASS, HIGHER EFFICIENCY ENABLED BY BUCK REGULATOR PPU DESIGN BI-FLUID ENGINE IGNITION READY, WORKING FLUID IGNITION REQUIRES DEVELOPMENT (MAY NEED 800–1000 V)
PROPELLANT DISTRIBUTION AND STORAGE	◕	REDUCE DRY MASS	OPTIMIZED THROTTLABILITY ENABLED BY DEVELOPMENT OF ELECTRONIC FLOW CONTROLLER LOWER MASS ENABLED BY TANK INTERNAL HEATER
GIMBAL PLATFORM	◕	NONE	MUST BE QUALIFIED FOR THIS APPLICATION
DIAGNOSTICS	●	NONE	FLIGHT QUALIFIED VERSIONS OF INSTRUMENTS TO MONITOR PLUME CHARACTERISTICS AND EMI EXIST, NEED TO BE INTEGRATED FOR THIS APPLICATION
AUTONOMOUS CONTROLLER	◑	DEVELOP CONTROL ALGORITHMS	DYNAMICS OF LARGE SPACECRAFT UNDER LOW CONTINUOUS THRUST ARE UNKNOWN
THERMAL CONTROL	◕	PPU EFFICIENCY	LOWER EFFICIENCY REQUIRES MORE ACTIVE CONTROL STANDARD ENGINEERING DESIGN SATISFIES ALL NEEDS
STRUCTURE	◕	NONE	MISSION SPECIFIC

○ BASIC RESEARCH
◔ TECHNOLOGY DEVELOPMENT STARTED
◑ CONCEPT VALIDATED
◕ FUNCTIONAL REQUIREMENTS MET
● PASSES COMPONENT LEVEL CDR

Fig. 8 Technology issues: Arcjet propulsion system for flight demonstration.