SPACECRAFT AND MISSION DESIGN FOR THE
SP-100 FLIGHT EXPERIMENT

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Abstract

The design and performance of a spacecraft employing arcjet nuclear electric propulsion, suitable
for use in the SP-100 Space Reactor Power System (SRPS) Flight Experiment, are outlined. The vehicle
design is based on a 93 kW e ammonia arcjet system operating at an experimentally-measured specific
impulse of 1031 s and an efficiency of 42.3 percent. The arcjet/glance assemblies, power conditioning
subsystem, propellant feed system, propulsion system thermal control, spacecraft diagnostic instrumentation,
and the telemetry requirements are described. A 100 kW e SRPS is assumed. The spacecraft mass is
baselined at 5675 kg excluding the propellant and propellant feed system. Four mission scenarios are
described which are capable of demonstrating the full capability of the SRPS. The missions considered
include spacecraft deployment to possible surveillance platform orbits, a spacecraft storage mission and an
orbit raising round trip corresponding to possible OTV missions.

NOMENCLATURE

ELV Expendable Launch Vehicle
EMI Electromagnetic Interference
ESD Electrostatic Discharge
HEO High Earth Orbit
IERP Specific Impulse, s
JPL Jet Propulsion Laboratory
KSC Kennedy Space Center
MP/s Mass of Propellant Feed System
MPE Propellant Mass
NEP Nuclear Electric Propulsion
NH3 Ammonia
NSO Nuclear Safe Orbit; 28.5° inclination, 925 km altitude
OTV Orbit Transfer Vehicle
PGM Power Generation Module
PLF Payload Faring
PPU Power Processing Unit
QCM Quartz Crystal Microbalance
SDI Strategic Defense Initiative
SOA State of the Art
SP-100 Space Power at 100 kW e
SRM Solid Rocket Motor
SRPS Space Reactor Power Source
STS Shuttle Transportation System
UIM User Interface Module
\( \Delta V \) Velocity Increment

Units

A Amperes
cm Centimeters
g Grams
kg Kilograms
km Kilometers
kW e Kilowatts of Electrical Power
m Meters
ms Milliseconds

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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 will be needed to transfer high mass payloads from low earth orbit to their operational orbits.9-10 Nuclear Electric Propulsion (NEP) systems utilizing 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 was identified as either mission enabling or as the optimal propulsion choice.1-11 Several studies also considered the integration of power and electric propulsion subsystems into an NEP spacecraft.1,10,11-17

The future availability of viable NEP systems requires the simultaneous development of an SRPS and electric propulsion systems. The projected needs of the Strategic Defense Initiative (SDI) indicate unprecedented power level requirements (hundreds of kilowatts to hundreds of megawatts) and an order of magnitude increase in power density to 1.0 kW/kg. A program in space power and power conversion has been initiated for the development of the critical technologies required to meet these power needs.18 The four program elements are: requirements and assessment, multi-megawatt prime power, pulsed power conditioning and baseload power. The last element, baseload power, consists of SP-100 and alternative non-nuclear technologies. The nuclear technology assessment phase of the SP-100 program has been completed with selection of an SRPS concept which includes a fast-spectrum, liquid-metal cooled reactor coupled with an out-of-core thermoelectric conversion system.19 The primary objective of Phase II, which has been initiated, is the 1991 ground test of a 100 kW e SRPS based on the selected system concept.

The SP-100 Flight Experiment, a flight demonstration of a 100-kWe class SRPS, has been proposed as an adjunct to the SP-100 program using an electric propulsion module as an active load.20 The primary purpose of this proposed flight test is the demonstration of space-based nuclear power system operation. The SP-100 Flight Experiment will also demonstrate nuclear electric propulsion for orbit raising and maneuvering.

The Flight Experiment test goal is to operate the SP-100 SRPS for its seven year, full power life. An active power system load is required for up to six months to verify power system compatibility with a payload and satisfy potential users of this compatibility.20-22 No alternative to electric propulsion has been identified for the active load which meets the Flight Experiment constraints as
This paper outlines a baseline arcjet NEP spacecraft design for use in the SP-100 Flight Experiment. Detailed descriptions of the arcjet/gimbal assemblies, Power Conditioning Unit (PCU) subsystem, propellant flow subsystem, thermal control subsystem, diagnostics package and telemetry requirements are included. Expected propulsion system performance is described for two experimentally determined arcjet technology levels and two SRPS power levels (30 kWe and 100 kWe) with launches from the Kennedy Space Center (KSC) using the Shuttle Transportation System (STS) and the Titan IV expendable launch vehicle (ELV). The missions considered include spacecraft deployment to possible SDI platform orbits, a spacecraft storage mission and an orbit raising round trip. This paper builds on four previous papers10,15-17 and is aimed at better defining the SP-100 Flight Experiment NEP opportunity by using recently measured values of arcjet performance and providing a more detailed analysis of the spacecraft mission design, options and performance.

**TABLE 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Level</td>
<td>100 kWe</td>
</tr>
<tr>
<td>Primary Voltage</td>
<td>200 Vdc</td>
</tr>
<tr>
<td>Specific Mass</td>
<td>30 kWe</td>
</tr>
<tr>
<td>Secondary Power</td>
<td>300 W</td>
</tr>
<tr>
<td>Secondary Voltage</td>
<td>28 Vdc</td>
</tr>
<tr>
<td>Continuous Load Following</td>
<td>0.1 kWe/mg</td>
</tr>
<tr>
<td>Thermal Flux at User Interface</td>
<td>0.14 W/cm²</td>
</tr>
<tr>
<td>10 Year Radiation Fluence</td>
<td>&lt; 1013 neutrons/cm²</td>
</tr>
<tr>
<td>at User Interface</td>
<td>&lt; 5 x 10⁻² Rads</td>
</tr>
</tbody>
</table>

The arcjet propulsion module is comprised of: three (3) sets of four (4) engines with each set of engines on a single gimbaled platform, a PCU system, the propellant feed system, thermal control, a radiation/thrust efflux diagnostics package and associated.
During arcjet system operation, one engine from each platform operates to provide thrust. After 1500 hours of operation, these three engines are turned off and another three (one engine per platform) are turned on. This process repeats after the next 1500 hours of operation to accumulate a total operating time of 4500 hours. At that time the arcjet mission has been completed. A fourth set of three engines is provided as backup. There are two dedicated PCUs per gimbaled platform with one serving as a spare. Separate propellant feed lines provide ammonia to each platform. Three thrusters can be operated at maximum power using 93 kW of input power when accounting for the 98% efficiency of the PCU system.

The thruster module is enclosed within a 4.4-m outside-diameter, 6-m long cylinder with the propellant tank located on the end nearest the SRPS. The three sets of arcjet engines and gimbals are located on the end of the cylinder opposite the SRPS. The PCU subsystem is located within the cylindrical enclosure between the propellant tank and engine modules. The six PCU low-temperature radiators face space on the outer surface of the cylindrical enclosure. The combined thrust of this system is 7.5 N when three engines are operating at full power. The command, data handling and telecommunications functions are part of the spacecraft bus.

A mass summary of the spacecraft components is provided in Table 2. As discussed above, the mass goal for the 100-kWp SP-100 SRPS is given as 3000 kg,21,22. The propulsion system is assumed to have a mass of 575 kg excluding propellant, tankage and the feed system. The spacecraft bus, which includes the primary command, control and communications equipment, is assumed to have a mass of 1250 kg. The mass assumed for the diagnostics equipment is 300 kg. An additional 550 kg has been set aside as a contingency.

The SP-100 Flight Experiment spacecraft is shown in its stowed configuration within a Titan IV ELV payload faring (PLF) in Fig. 2. The SP-100 SRPS is located at the top of the ELV. The spacecraft bus attaches to the SP-100 UIM and the arcjet propulsion system. The expendable upper stage and contamination shield are located at the bottom of the Titan IV payload faring. This vehicle configuration also fits in the STS payload bay.

The SP-100 Flight Experiment launch and deployment sequences are shown in Figs. 3a and 3b using a Titan IV ELV. In Fig. 3a, the Titan IV lifts off using the SRMs. The stage I chemical engine ignites and is followed by SRM burnout and separation. The PLF is then jettisoned. After stage 1 burnout, stage 1 and stage 2 separate; then, stage 2 ignites to continue the vehicle into orbit. Once stage 2 burns out, it separates from the SP-100 Flight Experiment spacecraft and upper stage. The upper stage ignites to inject the SP-100 Flight Experiment vehicle into a 300 km by 925 km, 28.5° elliptical orbit.

As shown in Fig. 3b, the upper stage reignites to circularize the elliptical orbit into a 925 km, 28.5° parking orbit. A 925 km, 28.5° circular orbit will be defined as nuclear safe orbit (NSO) in this paper. The upper stage and contamination shield are then jettisoned. This is followed by the deployment of the separation boom, SP-100 radiator, and instrumentation. The SP-100 power system is activated and the spacecraft systems checkout tests are completed. Finally the arcjet NEP system is turned on and the mission spiral is begun.

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**Figure 2.** SP-100 Flight Experiment in stowed configuration in a Titan IV payload faring.
A block diagram of the arcjet SP-100 Flight Experiment vehicle is shown in Fig. 4. It includes all of the primary system components for converting SRPS power into thrust. The power system consists of the SP-100 PDM and UIM and provides both 28V and 200V (primary) outputs. The spacecraft bus contains the navigation and the command, data handling and telecommunications subsystems which receive and process ground commands and control overall system operation. The arcjet PCU subsystem starts and runs the arcjets. The propellant system runs parallel to the power train and includes the tankage, valves, lines, etc. required to provide a constant propellant flow rate to each operating engine. The diagnostic package provides the ability to monitor the reactor radiation-induced environment, to measure the particu-
late and field emissions from the arcjet thrusters in the vicinity of the electric propulsion module and to examine the spacecraft/space environment interactions. Thermal control allows for the rejection of waste heat from the arcjet and PCUs while the structural members tie all of the subsystems together.

PROPULSION SYSTEM COMPONENTS

Descriptions of the engine/gimbal assemblies, PCU subsystem, propellant handling subsystem, thermal control methodology, diagnostics package and telemetry needs are presented below.

Arcjet Engine/Gimbal Platform

A schematic of a proposed engine/gimbal platform configuration is shown in Fig. 5. Each engine/gimbal platform consists of four 30-kW arcjet engines, a heat shield/platform, a high-power, high-current switch, a propellant distribution manifold, and a gimbal mechanism including a set of flexible high-current power leads and propellant lines. Three platforms are used and are located on the aft end of the spacecraft. (see Fig. 1) with one engine per platform operating at a time. The arcjet technology level assumed for the SP-100 Flight Experiment spacecraft, as defined in this study, is given in Table 3 and is based on experimentally derived performance data. These performance values were measured while running a new engine design over a 9-hour period, 7 1/2 hours of which was at a power level between 30.1 kW and 30.9 kW. This performance level will be defined as State-of-the-Art (SOA) in this paper. The high-power, high-current switch selects the arcjet engine to be operated on that platform. As engines reach the end of their useful life a new engine can be switched into operation.

There will be two (2) PCUs associated with each engine gimbal platform. One PCU will serve as

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>NH₃</td>
</tr>
<tr>
<td>Engine Input Power, kWₑ</td>
<td>30.3 ± 0.2</td>
</tr>
<tr>
<td>Specific Impulse, s</td>
<td>1031 ± 35</td>
</tr>
<tr>
<td>Engine Efficiency</td>
<td>0.423 ± 0.025</td>
</tr>
<tr>
<td>Arc Voltage, V</td>
<td>106 ± 3</td>
</tr>
<tr>
<td>Arc Current, A</td>
<td>284 ± 5</td>
</tr>
<tr>
<td>Mass Flow Rate, g/s</td>
<td>0.25 ± 0.002</td>
</tr>
<tr>
<td>Thrust, N</td>
<td>2.53 ± 0.12</td>
</tr>
<tr>
<td>Engine Mass, kg</td>
<td>7</td>
</tr>
<tr>
<td>Lifetime,** hours</td>
<td>1500</td>
</tr>
</tbody>
</table>

Engine run for 9 hours at JPL on July 6, 1988.

**1500 hour lifetime assumed.

Figure 4. Arcjet NEP system block diagram for the SP-100 Flight Experiment.
a spare. Each PCU consists of a pulsed, low-power, high-voltage "starter" circuit in parallel with a high-power, low-voltage "run" power supply. The "run" power supply is based on a three phase "buck" regulator design which is efficient, reliable and compact.24,25 The PCU is shown schematically in Fig. 6. The constricted arc in the arcjet has a negative dynamic resistance. A modified current mode feedback, which compares the actual arc current with the desired current, and an improved control algorithm reduce ripple amplitude and provide more positive control of the arc. The PCU specific mass is taken as 0.4 kg/kW e at an efficiency of 98%. The PCUs are self-radiating, rejecting 0.65 kW e of power while maintaining the component base plate at a temperature of less than 300 K. The high power and elevated temperature electronic components could be mounted directly to the PCU baseplate which might be a honeycomb panel heat pipe/radiator. This type of light-weight radiator has been investigated and shows promise for use as a low temperature radiator.26,27

Propellant Flow Subsystem

The propellant flow system includes the propellant storage tank and a feed system to supply a constant propellant flow to each operating thruster. Ammonia propellant storage and feed systems are a mature technology which have been flown several times.28-31 A schematic of the proposed ammonia propellant flow system is shown in Fig. 7. The propellant system specifications are summarized in Table 4. Ammonia is stored in a spherical titanium tank at about 150 psia. Titanium was chosen for the tank material due to 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 maintain the 150-psia tank pressure. Multilayer insulation minimizes the number of heating cycles required to maintain ammonia vapor in the propellant tank. The tank is loaded with the proper mission-dependent propellant mass prior to launch. A space-based propellant refill capability is assumed should future testing or other needs require restart of the arcjet NEP system.

**TABLE 4**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>NH3</td>
</tr>
<tr>
<td>Tank Capacity</td>
<td>13,150 kg</td>
</tr>
<tr>
<td>Storage Pressure</td>
<td>150 psi</td>
</tr>
<tr>
<td>Internal Tank Diameter</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Tank Material</td>
<td>Ti</td>
</tr>
<tr>
<td>Flow to Each Platform</td>
<td>0.25 g/s</td>
</tr>
</tbody>
</table>

The feed system consists of the propellant lines, valves, transducers, filters, regulators, heater/vaporizers, flow controllers, structure, etc., required to provide the proper propellant flow rate to the arcjet thrusters. Electronic flow controllers
This equation includes a 10 percent contingency on all components. This system provides a constant mass flow of 0.25 g/s of ammonia to each operating arcjet thruster for the full mission duration. The maximum tank storage capacity is 13,150 kg of ammonia using a 3.5 m internal diameter tank.

Thermal Control

Thermal control for the arcjet module is achieved by standard engineering techniques. For instance, it is estimated that 10% of the arcjet power input is distributed in the anode electrode, amounting to 3 kW per engine. This power is readily self-radiated by the anode at 2300 degrees Kelvin. If the surface is treated with a high emissivity coating (emissivity greater than 0.9) the temperature requirement can drop to 1900 degrees Kelvin. The arcjet platform acts as a radiation shield between the spacecraft and the hot arcjets. In addition, conducted heat from the platform to the spacecraft is minimized by using propellant cooling of the interconnecting structures. The thermal control design for the I0 engines consists of low temperature radiators located on the outside of the propulsion module. The thermal control of the propellant storage and feed system is accomplished by the straightforward application of multi-layer insulation around the tank in conjunction with an internal tank heater.

Diagnostics Package

A diagnostics package is carried on the SP-100 Flight Experiment to monitor the SRPS-induced radiation environment at and beyond the user interface, to examine the arcjet propulsion system particulate and field emissions and to examine the spacecraft/environment interactions. Such a diagnostics package will enable future users of both the SP-100 SRPS and arcjet engines to better assess the potential impacts of these systems on their payloads.

SRPS-INDUCED RADIATION ENVIRONMENT The SRPS will be emitting neutrons and gamma rays, the levels of which will have to be evaluated. As shown in Table 1, the design goal for the 10 year total doses of neutrons and gamma rays are less than 10¹³ neutrons/cm² and 5 x 10¹⁰ rads, respectively, at the user side of the UIM. Also, the SP-100 SRPS thermal environment is designed to be less than 0.14 W/cm² (less than one sun) at the UIM. Instrumentation is included on the SP-100 Flight Experiment spacecraft, as defined in this paper, to evaluate these levels.

PROPELLATION SYSTEM DIAGNOSTICS Three primary types of measurements needed to characterize the performance and effects of the arcjet propulsion system. These measurements are summarized in Table 5 and include the monitoring of thrust operation, arcjet dynamics, and arcjet/spacecraft interactions.

Thrust Operation The engine performance will be evaluated and compared to ground test measurements and theoretical models. Measurements of arc jet current and voltage, mass flow rate and component temperatures will be made. The thrust will be monitored using accelerometers mounted onboard the SP-100 Flight Experiment spacecraft. These measurements will allow verification of ground test experiments and models.

Arcjet Dynamics Measurements of the components of an arcjet plume could enable a deeper understanding of thrust operation, leading to improved arcjet design. Space-based measurements eliminate ground test facility effects and act to verify the ground test measurements. Measurements of plasma density, species concentrations, temperature distributions and plume spatial extent could provide the desired information on arcjet dynamics. This information would provide a better understanding of arcjet physics.

Arcjet/Spacecraft Interactions A small portion of the exhaust plume will extend back behind the thrust nozzle exit plane, due to gas dynamic expansion, and will impinge on the arcjet module
and SRPS. Particulate contamination is expected to be minimal since the gas is rarified and the volatile contaminant density is very low. 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 will condense on most surfaces they contact. 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 tests. Previous work has shown that only a very small fraction of the tungsten loss would reside in the plume backflow. 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 radiate electromagnetic energy since they produce a plasma. The effects of EMI on such spacecraft systems as communications, guidance, navigation and power control electronics must be examined. Since the SP-100 Flight Experiment onboard spacecraft power is almost two orders of magnitude greater than that of present-day spacecraft, EMI guidelines will require extensive revision. Thermal radiation from arcjet thrusters can also present a problem since up to 10% of the arcjet input power is radiated away by the nozzle alone. The global platforms serve as heat shields to reduce radiative heating of the upstream spacecraft components.

**SPACECRAFT/ENVIRONMENT INTERACTIONS**

No spacecraft of this size with so many different materials exposed to the space environment and with as high an onboard power level has ever been flown. As a result, the potential for spacecraft/space environment interactions is high. Possible effects such as spacecraft frame charging, differential charging of neighboring spacecraft surfaces, electrostatic dis-charge (ESD), parasitic power drain to the spacecraft plasma, and the long term effects of the SRPS radiation environment and propulsion system effluents on overall spacecraft integrity will need to be carefully monitored. Previous space experiments have shown that spacecraft charging and its related effects can be reduced by electric thruster operation.

**Telemetry Needs**

S-band and X-band communications capabilities will meet the telemetry needs of the SRPS and SRPS and up to three arcjets can operate simultaneously on a spacecraft with a 100 kW e SRPS for either arcjet technology.

**TABLE 5**

<table>
<thead>
<tr>
<th>NEED</th>
<th>MEASUREMENTS</th>
<th>INSTRUMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>THRUSTER OPERATION</td>
<td>ARC CURRENT, ARC VOLTAGE, MASS FLOW RATE, TEMPERATURES</td>
<td>VOLT METER, AMMETER, FLOW CONTROLLER, THERMOCOUPLES</td>
</tr>
<tr>
<td>ARCJET DYNAMICS</td>
<td>ELECTRON DENSITY, ION DENSITY, TEMPERATURE DISTRIBUTIONS, PARTICLE SPECIES</td>
<td>FARADAY PROBES, LANGMUIR PROBES, MASS SPECTROMETER, VIDEO CAMERA</td>
</tr>
<tr>
<td>ARCJET/SPACECRAFT INTERACTIONS</td>
<td>PARTICLE DEPOSITION, PARTICLE SPECIES, SPACECRAFT CHARGING, EMI TEMPERATURES</td>
<td>QCM, SOLAR CELL WITNESS PLATES, MASS SPECTROMETER, LANGMUIR PROBE, ANTENNAS, INFRARED MONITORS</td>
</tr>
</tbody>
</table>

The following analysis is based on the well-known orbital mechanics equations for electric propulsion transfers and on the propellant feed subsystem characterization given above. Launches from Kennedy Space Center (KSC) using the STS launch vehicle and Titan IV ELV are assessed for four proposed Flight Experiment scenarios. The analysis assumes two different SP-100 SRPS power levels: 100 kW e and 30 kW e, and two different arcjet/PCU technology levels: baseline and State-of-the-Art (SOA). It is assumed that only one arcjet operates on a spacecraft with a 30 kW e SRPS and up to three arcjets can operate simultaneously on a spacecraft with a 100 kW e SRPS for either arcjet technology.

**ARCJET PROPULSION SYSTEM PARAMETERS**

The two arcjet system technology levels used for this mission analysis are presented in Table 6. The baseline system parameters are derived from a recent 573-hour long duration test of an arcjet engine. The baseline values shown in Table 6 represent averaged arcjet engine performance over the 573 hour duration test at 25.1 kW e and provide an effective lower bound for arcjet performance. A baseline engine/PCU requires 27.9 kW e of input power when accounting for the 90 percent efficiency of the PCU. Therefore, a system of three engines requires 83.7 kW e.

As mentioned previously, the SOA arcjet technology level in Table 5 (see Table 3) also represents measured arcjet performance. These performance values were measured while running a new engine design over a 9 hour period, 7 1/2 hours of which was at a power levels between 30.1 kW e and 30.9 kW e. The engine incorporates a bell-shaped nozzle which has shown potential engine efficiency improvements of up to 20 percent. In addition, improved
Arcjet Performance Characteristics Used for this Study*34,48

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Technology Level</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>Baseline SOA</td>
<td>NH3, NH3</td>
</tr>
<tr>
<td>Input Power Per Thruster (kWe)</td>
<td>25.1</td>
<td>30.3 ± 0.2</td>
</tr>
<tr>
<td>Thruster Efficiency</td>
<td>Baseline</td>
<td>0.39 ± 0.025</td>
</tr>
<tr>
<td>Specific Impulse (s)</td>
<td>Baseline</td>
<td>887 ± 1011</td>
</tr>
<tr>
<td>Thrust Per Engine (N)</td>
<td>Baseline</td>
<td>2.3 ± 2.53</td>
</tr>
<tr>
<td>Thruster Lifetime (hours*)</td>
<td>Baseline</td>
<td>573 ± 1500</td>
</tr>
<tr>
<td>PPU Efficiency</td>
<td>Baseline</td>
<td>0.90 ± 0.98</td>
</tr>
</tbody>
</table>

Specific Mass Per Engine** (kg/kWe): 2.0 ± 1.6

*573 hour lifetime measured, 1500 hour lifetime assumed.
**Excludes SRPS, spacecraft bus propellant, tankage and feed system.

Propellant cooling helps recover some of the conducted power loss through the cathode. Such cooling also preheats the propellant gas and should enable a small increase in overall engine efficiency. This new engine design is described in detail in Reference 52. A 1500-hour lifetime is assumed for this engine. Finally, a high-temperature, high-emissivity coating could be applied to the outer nozzle surface to improve its radiative cooling properties. This reduces the nozzle temperature and should enhance the thruster durability.52 An SOA arcjet/PCU requires 30.9 kWe of input power with a three engine system needing 92.7 kWe.

CONTRAINTS AND ASSUMPTIONS

Due to safety concerns, the SRPS can not be operated until the spacecraft has reached a 925 km (500 mile) NSO. An expendable chemical upper stage will boost the NERF flight demonstration spacecraft to NSO from STS orbit or Titan IV separation orbit. It is further assumed that the upper launch mass limit for the STS is 23,182 kg,53 that 4,100 kg of Airborne Support Equipment (ASE) is needed, and that a single, dedicated shuttle launch from KSC is required for the Flight Experiment. It is also assumed that the upper limit is a mass limit for the Titan IV ELV is 17,700 kg,54,55 that 3300 kg of ASE type equipment is needed and that a dedicated Titan IV ELV is required. The orbit and launch vehicle assumptions are summarized in Table 7. An expendable chemical upper stage (ISP = 300 s) used to orbit raise to NSO corresponding to a ΔV of 338 m/s, weighs 2380 kg and has a dry to fueled mass ratio of 0.15. The chemical upper stage does not perform any part of required plane changes.

TABLE 7

Launch Vehicle and Orbit Assumptions53,54

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STS</th>
<th>Titan IV</th>
<th>3000 km Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload (kg)</td>
<td>23,182</td>
<td>17,700</td>
<td>3000 kg</td>
</tr>
<tr>
<td>ASE mass (kg)</td>
<td>4,100</td>
<td>3,300</td>
<td></td>
</tr>
<tr>
<td>Altitude (km)</td>
<td>300</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>Inclination (degrees)</td>
<td>28.5</td>
<td>28.5</td>
<td>55°</td>
</tr>
<tr>
<td>NSO altitude (km)</td>
<td>925</td>
<td>925</td>
<td></td>
</tr>
<tr>
<td>NSO inclination</td>
<td>28.5</td>
<td>28.5</td>
<td>85°</td>
</tr>
</tbody>
</table>

A mass summary for the different SP-100 Flight Experiment spacecraft configurations is given in Table 8 as a function SRPS power level and arcjet system technology level. The specific mass for the 30 kWe SRPS is assumed to be 65 kg/kWe22 and for the 100 kWe SRPS, 30 kg/kWe22. The spacecraft bus is assumed to have a mass of 1100 kg on a spacecraft powered by a 30 kWe SRPS and 1250 kg on a spacecraft powered by a 100 kWe SRPS. A diagnostics package with a mass of 300 kg is included for all spacecraft configurations. Contingencies of 255 kg and 350 kg are included for the 30 kW and 100 kW spacecraft, respectively.

TABLE 8

SP-100 Flight Experiment Spacecraft Mass Summary

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Based on 30 kWe SRPS</th>
<th>Based on 100 kWe SRPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRPS</td>
<td>1950 kg</td>
<td>3000 kg</td>
</tr>
<tr>
<td>SRPS Specific Mass</td>
<td>65 kg/kWe</td>
<td>30 kg/kWe</td>
</tr>
<tr>
<td>Spacecraft Bus</td>
<td>1100 kg</td>
<td>1250 kg</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>300 kg</td>
<td>300 kg</td>
</tr>
<tr>
<td>Contingency</td>
<td>265 kg</td>
<td>550 kg</td>
</tr>
<tr>
<td>Propulsion System*</td>
<td>Baseline</td>
<td>720 kg</td>
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<td></td>
<td>SOA</td>
<td>288 kg</td>
</tr>
</tbody>
</table>

*Excludes propellant, tankage and feed system.
Includes engines and spares for 4500 hours of propulsion system operation.

The propulsion system mass is also given in Table 8 for the two different arcjet technology levels assuming that the propulsion system must operate for a total of 4500 hours. The values in Table 8 do not include the propellant, tankage and feed system masses which are given in Table 6 and also depend on the launch vehicle mass limits. The baseline system has a mass of 720 kg when the available spacecraft power is 30 kWe. Since the baseline engine has a lifetime of 573 hours, 8 baseline arcjet engines are required and an additional 4 are included as spares in the mass value. When the spacecraft power is 100 kWe, the baseline propulsion system mass increases to 1800 kg. This value includes 30 engines, 6 of which are spares. Using SOA arcjet technology, a propulsion system based on a total of 6 engines (3 of which are spares) has a mass of 288 kg on a spacecraft with 30 kWe on board. Finally, the propulsion system mass is 575 kg for a spacecraft with 100 kW of onboard SRPS power and SOA arcjet technology, as discussed in the *SP-100 Flight Experiment Spacecraft Configuration" section above.

MISSION SCENARIOS AND RESULTS

Four missions are examined which could be used to demonstrate SRPS operation. The first two missions involve powered system deployment to possible SDI platform orbits of 3,000 and 10,000 km. An advantage of these orbits is that they contain a minimum of man-made orbital debris, reducing the chances of a collision.53 The third mission involves a spacecraft storage demonstration to very high orbits. The final mission examines an orbit raising round trip to and from NSO.

3000 km Orbit

A 3,000 km circular orbit, with a final inclination between 55° and 85°, has been identified as a potential SDI platform orbit. As a result, this orbital altitude was chosen for this study so that the mission would address the control scenarios required for low-altitude, high-inclination change, low thrust mission.57 The orbital analysis is done such that the entire available propellant load is consumed to reach the highest inclination possible for each of the arcjet technologies described in Table 6, the launch vehicle characterizations summarized in Table 7 and the spacecraft power levels as shown in Table 8. The results of this analysis are summarized in Table 9. If the transfer time is greater than 100 days, the propulsion system has
Titan IV
STS baseline
AV on the SOA arcjet system and Titan IV launch for a non-throttled total AV. The SOA arcjet technology with an STS launch enables capability of this technology with an STS that the entire available propellant are summarized in Table 10. The baseline arcJet for each to reach the greatest that the entire available propellant

for each

10,000 km

be reached with respect to the values discussed in Table 8 to account for the larger number of engines required. For example, an SP-100 Flight Experiment vehicle using the baseline arcjet system enables a 100 kW e SRPS to be delivered to a SOA final inclination in 114 days at an orbital altitude of 3,000 km using the STS as a launch vehicle. If the vehicle used SOA arcjet technology, a 100 kW, SRPS, and was launched in the STS, it would be capable of achieving a 3,000 km, 72° final orbit in 142 days. A Titan IV launch of a vehicle based on the SOA arcjet technology and a 100 kW e SRPS would achieve a 60.5° inclination, 3000 km orbit in 88 days.

10,000 km Orbit

A 10,000 km circular orbit was chosen as the target altitude for an arcjet NEP spacecraft throttling demonstration and is compared to a non-throttled case. Again, the analysis is done such that the entire available propellant load is consumed to reach the greatest orbital inclination possible for each of the characterizations and levels described in Tables 6 through 8. Only the 100 kW e SRPS is considered in this case. The non-throttled cases are summarized in Table 10. The baseline arcjet technology with an STS launch provides a total AV capability of 5559 m/s corresponding to a 10,000 km, 59.5° final orbit with an 115 day trip time. The SOA arcjet technology with an STS launch enables a non-throttled total AV of 7856 m/s corresponding to a final orbit of 10,000 km at 77.0° and a trip time of 142 days. A 10,000 km, 62.5° final orbit could be achieved in 88 days with a spacecraft based on the SOA arcjet system and Titan IV launch for a AV of 5965 m/s.

<table>
<thead>
<tr>
<th>SRPS*</th>
<th>Trip</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>Power</td>
<td>Arcjet Technology</td>
</tr>
<tr>
<td>Vehicle</td>
<td>(kWe)</td>
<td>(days) (degrees)</td>
</tr>
<tr>
<td>STS 100</td>
<td>baseline</td>
<td>114</td>
</tr>
<tr>
<td>STS 100</td>
<td>SOA</td>
<td>142</td>
</tr>
<tr>
<td>STS 30</td>
<td>baseline</td>
<td>412</td>
</tr>
<tr>
<td>STS 30</td>
<td>SOA</td>
<td>500</td>
</tr>
<tr>
<td>Titan IV 100</td>
<td>baseline</td>
<td>68</td>
</tr>
<tr>
<td>Titan IV 100</td>
<td>SOA</td>
<td>88</td>
</tr>
<tr>
<td>Titan IV 30</td>
<td>baseline</td>
<td>267</td>
</tr>
<tr>
<td>Titan IV 30</td>
<td>SOA</td>
<td>324</td>
</tr>
</tbody>
</table>

*Propulsion system designed for total trip time when greater than 180 days.

The cases for which the propulsion system is throttled are summarized in Table 11. Again, only the 100 kW e SRPS is considered. As above, the increased propulsion system mass was accounted for if the total trip time was greater than 180 days. The calculations were conducted as follows: with three arcjets operating at full power, the Flight Experiment spacecraft is raised from a 925 km, 28.5° orbit to a 10,000 km, 28.5° orbit corresponding to a AV of 1,827 m/s. From this orbit, a vehicle using SOA arcjets is moved to a 10,000 km, 38.5° orbit, a AV of 1,567 m/s, with one arcjet operating at full power. The next leg is accomplished using two SOA arcjets operating at full power and results in a final orbit of 10,000 km, at 48.5° for an additional AV of 1,325 m/s. The final leg is completed with three SOA arcjets operating at full power until all the available propellant is consumed. This results in final orbits of 10,000 km at 54.5° assuming a Titan IV launch and 10,000 km at 70.5° assuming an STS launch corresponding to AVs for the final legs of 1,187 and 3,120 m/s, respectively. A similar methodology was followed when considering the baseline arcjet technology. Throttling of the engines provides a demonstration of the SRPS load-following capability in splitting power between the user and power system shunt and demonstrates the flexibility of both the arcjet NEP system and the SP-100 SRPS.

**Spacecraft Storage Mission**

The third mission demonstrates low thrust control scenarios to very high orbits. A spacecraft storage mission from NSO to an altitude of 107,580 km with a return to 35,860 km was selected. The first leg of the trip has a AV of 6,211 m/s and the return leg a AV of 1,204 m/s. The results for this scenario are summarized in Table 12 for the different launch vehicles, SRPS power levels and arcjet technology levels. For example, the baseline arcjet system could not reach 107,580 km with a 100 kW e SRPS, but

<table>
<thead>
<tr>
<th>SRPS*</th>
<th>Trip</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>Power</td>
<td>Arcjet Technology</td>
</tr>
<tr>
<td>Vehicle</td>
<td>(kWe)</td>
<td>(days) (degrees) (m/s)</td>
</tr>
<tr>
<td>STS 100</td>
<td>baseline</td>
<td>115</td>
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<tr>
<td>STS 100</td>
<td>SOA</td>
<td>142</td>
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<tr>
<td>Titan IV 100</td>
<td>baseline</td>
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<td>SOA</td>
<td>88</td>
</tr>
</tbody>
</table>

**Table 11**

Summary of Arcjet Throttling Orbital Analysis, NSO to a 10,000 km Final Orbit

<table>
<thead>
<tr>
<th>Launch System</th>
<th>Arcjet Technology</th>
<th>Operating Arcjets</th>
<th>Power (kWe)</th>
<th>Initial Orbit Alt., Incl. (km, degrees)</th>
<th>Final Orbit Alt., Incl. (km, degrees)</th>
<th>Trip Time (days)</th>
<th>Total AV (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS baseline</td>
<td>3</td>
<td>83.7</td>
<td>925, 28.5</td>
<td>10,000, 28.5</td>
<td>60</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>27.9</td>
<td>10,000, 28.5</td>
<td>10,000, 33.5</td>
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<td></td>
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</tr>
<tr>
<td>2</td>
<td>55.8</td>
<td>10,000, 33.5</td>
<td>10,000, 38.5</td>
<td>19</td>
<td></td>
<td></td>
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<tr>
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<td>83.7</td>
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<td>10,000, 51.5</td>
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<td>5559</td>
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<td></td>
</tr>
<tr>
<td>SOA 3</td>
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<td>92.7</td>
<td>925, 28.5</td>
<td>10,000, 28.5</td>
<td>57</td>
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<td></td>
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<td></td>
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<tr>
<td>2</td>
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<td>10,000, 45.5</td>
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<td></td>
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<tr>
<td>3</td>
<td>92.7</td>
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<td>7839</td>
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<td>Titan IV baseline</td>
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<td>925, 28.5</td>
<td>10,000, 28.5</td>
<td>45</td>
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<td>27.9</td>
<td>10,000, 28.5</td>
<td>10,000, 31.5</td>
<td>19</td>
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<tr>
<td>2</td>
<td>55.8</td>
<td>10,000, 31.5</td>
<td>10,000, 35.5</td>
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<tr>
<td>3</td>
<td>83.7</td>
<td>10,000, 35.5</td>
<td>10,000, 38.5</td>
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<td>3809</td>
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<tr>
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<td>925, 28.5</td>
<td>10,000, 28.5</td>
<td>43</td>
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<td>1</td>
<td>30.9</td>
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<td>10,000, 38.5</td>
<td>58</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>61.8</td>
<td>10,000, 38.5</td>
<td>10,000, 48.5</td>
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<tr>
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<td>92.7</td>
<td>10,000, 48.5</td>
<td>10,000, 54.5</td>
<td>9</td>
<td>5906</td>
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</tr>
</tbody>
</table>

**Table 9**

SP-100 Flight Experiment Performance from NSO to a 3000 km Final Altitude

**Table 10**

SP-100 Flight Experiment Performance from NSO to a 10,000 km Final Orbit, Unthrottled

**Table 11**

Summary of Arcjet Throttling Orbital Analysis, NSO to a 10,000 km Final Orbit
Transfer not possible.

Titan  
STS 30 SOA 387 52 2941

Vehicle Launch onboard, 28.50 in 97 days and return to NSO in SOA arcjet greater than 180 days. For example, a round trip-type OTV mission.

The SOA arcjet propulsion system is resized if trip times greater than 180 days.

Titan IV launch vehicle is launched using the STS with a 100 kW e SRPS. The SOA could achieve an HEO of 27,000 km at 28.50 in 171 days and return to NSO in 96 days.

Table 12

<table>
<thead>
<tr>
<th>Launch</th>
<th>SRPS</th>
<th>Arcjet</th>
<th>Trip-time</th>
<th>Residual Vehicle Power Tech.</th>
<th>NSO-SSG0*</th>
<th>SSQ-SS0*</th>
<th>Mass (kW)</th>
<th>(days)</th>
<th>(kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS</td>
<td>100</td>
<td>baseline</td>
<td>130</td>
<td>12,400</td>
<td>40</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STS</td>
<td>100</td>
<td>SOA</td>
<td>126</td>
<td>27,000</td>
<td>53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STS</td>
<td>30</td>
<td>baseline</td>
<td>391</td>
<td>22,000</td>
<td>151</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>STS</td>
<td>30</td>
<td>SOA</td>
<td>387</td>
<td>58,000</td>
<td>190</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titan IV 100</td>
<td>baseline</td>
<td>*</td>
<td>55</td>
<td>12,800</td>
<td>32</td>
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<td></td>
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</tr>
<tr>
<td>Titan IV 100</td>
<td>SOA</td>
<td>55</td>
<td>12,800</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titan IV 30</td>
<td>SOA</td>
<td>171</td>
<td>12,300</td>
<td>96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Propulsion system designed for total trip time when greater than 180 days.

Orbital analysis was conducted to evaluate the SP-100 Flight Experiment vehicle performance. A single dedicated STS or Titan IV launch was assumed from KSC. A number of candidate missions were proposed with no attempt to recommend one over another. The intent was to present options, any one of which might be representative of future mission deployment requirements. The analysis showed that this vehicle is capable of mission AVs of 6,000 to 7,900 m/s. A propulsion system throttling demonstration would verify the SRPS load-following capabilities.

Four specific missions were examined which included power system deployment to possible surveillance platform orbits, a spacecraft storage mission and a round-trip OTV mission. Analysis has shown that the vehicle could reach 3,000 km, 72° inclination final orbit in 142 days with an STS launch. A 10,000 km, 62.5° final orbit could be achieved in 88 days with a Titan IV launch. A spacecraft storage mission with power system deployment to a high altitude was also examined. The upper leg required 126 days while the return required 16 days following an STS launch. The final mission, a round-trip OTV-type demonstration, achieves a HEO of 27,000 km at 28.50 in 97 days with return to NSO in 53 days assuming an STS launch.

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REFERENCES


