NEPSTP - AN INTERNATIONAL TESTBED FOR XENON ELECTRIC PROPULSION

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Abstract

The Nuclear Electric Propulsion Space Test Program (NEPSTP) is a BMDO sponsored technology demonstration of a Russian space nuclear reactor (TOPAZ 2) and an international complement of xenon electric thrusters. The mission is described along with some of the design accomplishments to date. The spacecraft description includes discussions on the TOPAZ 2 reactor, spacecraft bus and the propulsion module which supports the experimental electric thrusters. The baseline thruster set is presented highlighting the Russian, U.S. and UK participation. Part of the mission design includes issues related to the safety of the processing, launch and operation of reactor. Ground and flight test plans for the electric thrusters are described and several, though not all, of the key thruster/spacecraft integration and operational issues are addressed. Commercial and civil applications of xenon electric thrusters are mentioned for the specific electric thrusters manifested for this flight. The NEPSTP reached a preliminary design level in all significant areas in 1993. The unique scientific and engineering opportunity for NEP technologies and international collaboration on a major space program are obvious benefits of continuing through the launch and flight operation of this spacecraft.

Introduction

In December of 1991, The Johns Hopkins University Applied Physics Laboratory (JHU/APL), under the sponsorship of the Ballistic Missile Defense Organization (BMDO), began to design a cost effective mission to demonstrate and evaluate Nuclear Electric Propulsion. The USAF Phillips Laboratory (PL), in collaboration with Sandia National Laboratories, Los Alamos National Laboratory, and the University of New Mexico, was given the responsibility of procuring, testing, and modifying the Russian TOPAZ 2 space nuclear reactors, including the flight unit. APL is responsible for mission development, system engineering, spacecraft design and fabrication, integration and test, launch operations, mission

operations, and mission science.

Originally referred to as TOPAZ, this program is now called the Nuclear Electric Propulsion Space Test Program, or NEPSTP. Since the program inception at APL, the mission and spacecraft, which includes the developmental propulsion module, have achieved the preliminary design level. Some subcontract work has been initiated in the area of electric thrusters and the propulsion module (PM).

This paper highlights the international participation in the propulsion module and thrusters and describes the mission, spacecraft and PM designs. In addition, it points out the potential future applications of the electric thrusters that are to be flight tested with the TOPAZ 2 in this unique space test program. Reference 1 provides more detail on the mission system engineering issues.

Mission Design and Spacecraft Overview

The NEPSTP mission is a flight demonstration of Nuclear Electric Propulsion (NEP) technologies with international participation.

The NEPSTP goals are:

1. Demonstrate and evaluate the TOPAZ 2 Space Nuclear Power System (SNPS) in space;
2. Demonstrate and evaluate NEP technologies and techniques in space;
3. Characterize the self-induced environment resulting from NEP;
4. Conduct additional scientific research consistent with cost and schedule constraints.

The NEPSTP spacecraft is divided into three primary systems: the Space Nuclear Power System, the spacecraft bus, and the Propulsion Module (PM). The spacecraft bus is attached directly to the Propulsion Module; the spacecraft bus and Propulsion Module are separated from the reactor by a 10m long deployable boom to reduce the radiation dose at the spacecraft and PM.

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Space Nuclear Power System

TOPAZ 2 is a 135 kWth nuclear power source that generates 6 kWt at 27V using in-core thermionic conversion. The reactor is 3.9m high, 1.4m diameter, and weighs 1061 kg. TOPAZ 2 is designed for a three year lifetime (the NEPSTP spacecraft, however, is designed for a one year mission).

The reactor is fueled by ~27 kg of 96% enriched U-235 in the form of uranium dioxide (UO2) pellets. The system uses zirconium hydride to moderate the fast neutrons resulting from the fission of U-235.

The reactor core is surrounded by twelve rotating beryllium cylinders which have one third of the surface covered with boron carbide, which absorbs neutrons. When the B4C faces inwards, neutrons are absorbed. The remaining surface area of each drum can reflect neutrons back into the core to sustain criticality. Power is regulated by controlling neutron flux levels with the angular positions of the control drums. Several output power levels will be selectable by command.

The core of the reactor contains 37 single-cell Thermionic Fuel Elements (TFE's). Each TFE is a cylindrical structure containing a stack of toroidal UO2 fuel pellets. One major benefit of the single cell TFE is that fuel can be inserted or removed easily, a great advantage in launch site processing. A related benefit is that the fuel can be replaced by electrical heaters so that the reactor can be tested in a nonnuclear environment.

Thirty-four TFE's are connected in series to provide ~27V output power. The three remaining TFE's are connected in parallel to supply the electromagnetic pump used to circulate the coolant through the reactor system. The reactor includes a radiation shield of stainless steel filled with lithium hydride, creating an 8° half-angle shadow cone of reduced radiation. Behind this shield is the thermal radiator which radiates the waste heat to space.

Spacecraft Bus

Figure 1 shows the orbital configuration of the spacecraft. The NEPSTP spacecraft bus is separated from the reactor by a 10m structural boom. The spacecraft bus is a hexagonal right prism using a cylindrical center column to support the reactor loads during launch. Subsystem packages are mounted on the inside of six honeycomb panels that make up the hexagonal structure.

The panels are broken down by subsystem function: two panels house the power subsystem, including the Reactor Control Unit, shunt electronics, and power switching; one half-panel is devoted to the storage battery; one whole and one half-panel are used for redundant command and data handling subsystems, including SGLS RF transponders, decryption equipment, critical command decoders, and command processors; one panel houses the attitude determination and control subsystem, including two star cameras, attitude reference gyros, and attitude processors; and the sixth pallet is the instrument panel, which houses all of the scientific instruments.

The instruments evaluate the self-induced environments of particles (neutrons, ions), fields, and waves (gamma rays, electromagnetic plasma waves). Also included are devices for measuring and characterizing contaminants and for measuring the acceleration imparted by the electric thrusters. The data is recorded continuously and downloaded to the ground for analysis. The spacecraft will also measure and record a variety of engineering parameters such as temperatures, voltages, and currents to assess reactor and thruster performance.

![Image of TOPAZ 2 spacecraft](image-url)

**Fig. 1. Spacecraft flight configuration.**

Mission Design

Mission Profile

The spacecraft is launched into a sufficiently high orbit consistent with the capabilities of the launch vehicle. The nominal initial orbit is circular with a 5250 km altitude at an inclination of 28.5°. Following boom deployment and reactor start-up the electric thrusters will be used to increase the orbital altitude. Initially, each thruster will be turned on and operated for a short time period (< 1 day) to verify and calibrate its performance in space. Following this checkout period each thruster will be operated for 1000 hours. This allows significant data to be gathered on each thruster within the first year of operation. Spacecraft instrumentation will measure the self-induced environment from TOPAZ 2 and the electric thrusters. At intervals of time and altitude, the thrusters will be shut down to allow measurement of the
reactor environment independent of the thruster effects. References 2 and 3 discuss the science plan and operational experiments in some detail. The planned thruster duty cycle is 97%. Once each thruster has been tested for 1000 hours, life testing of thrusters will begin.

It is advantageous to use the high thrust (low \( I_\text{sp} \)) engines first, as they provide the greatest acceleration and eject propellant mass most quickly. The lower thrust engines can be used more effectively at high altitude when the propellant mass has decreased. In order to accumulate hours of operation on the thrusters they will be used in pairs after the initial 1000 hour operating periods. Also, after reaching an altitude of 40000 km the spacecraft will begin inclination changes with no further altitude increase. The power of individual thrusters, and pairs of thrusters is limited to about 4500 Watts since that is the available power after accounting for the power system losses, the spacecraft bus power and thermal requirements. Also, it is advantageous to operate the reactor at power levels below 6 kW since that prolongs the life of the reactor. Figures 2 and 3 shows the altitude and propellant usage, respectively, as a function of time based on the preliminary mission design described above.

**Orbital Operations Considerations**

Operationally, the NEP spacecraft differs from all other spacecraft. For conventional spacecraft, orbital changes are impulsive maneuvers. Before and after such maneuvers, the orbit is regular. NEP orbital changes are performed in long, continuous thrust maneuvers; each consecutive orbit is different, which complicates tracking. Methods must be developed for tracking the spacecraft to allow command and data transmission.

If the reactor or thrusters perform other than predicted, the spacecraft will not arrive at the planned time. This requires a strategy to reacquire the spacecraft. If the reactor shuts down prematurely, the data must be recovered before battery depletion (~10 hours).

To insure acceptable orbital operations, efforts are underway to modify existing orbital propagators to include the effects of continuous thrust. APL is working with the U.S. Space Command (USSPACECOM) to address tracking issues for the NEPSTP spacecraft. USSPACECOM has agreed to provide daily (or more frequent) orbital element sets to assist in updates of the orbital propagation model. In return, APL will assist USSPACECOM in modifying its algorithms to accommodate continuous thrust trajectories.

The spacecraft storage battery contains energy to operate the spacecraft for 10 hours. If a reactor anomaly causes a premature shutdown, the power system will shut down all subsystems except the command and telemetry system, the attitude control system, and the science instruments; the spacecraft will continue to record science data for some period (20 minutes nominally), and will then shut down the science instrumentation. It takes 24 minutes to play back 10 hours of recorded data. Therefore, spacecraft health and status will be checked every 9.5 hours, if not more frequently. If a failure has occurred, this will allow the spacecraft sufficient time and energy to transmit the last 10 hours of recorded data.

In the event of a communications problem due to interference from the electric thrusters, the thrusters will only operate for 24 hours. After 24 hours, the thrusters are autonomously shut down unless a continuation command is received from the ground. This period of thruster operation cannot cause a significant orbital change with the extremely low thrust provided by the electric thrusters. If communications are normal, the continuation command will be sent to operate the thrusters, without interruption, for an additional 24 hours.

Close coordination is planned with USSPACECOM to anticipate potential interference with other space assets. Any interference concerns will be mitigated by changing the NEPSTP mission profile to avoid such events.

**Safety**

Due to public anxiety regarding nuclear power, the perception of safety is almost as important as the actuality. Safety is pervasive in all aspects of processing a nuclear payload.

The uranium dioxide fuel is not the significant hazard one might expect. The activity of the entire fuel load is approximately 2 curies on the launch pad, which is more than five orders of magnitude below the 400,000 curie activity of a typical Radioisotope Thermoelectric Generator. A reactor with fresh fuel is not a radiological health hazard. The primary concern is the prevention of inadvertent criticality. Criticality must be prevented by careful planning of all phases of reactor testing and launch preparation, fuel management, and control system safety interlocks. Only when a "safe orbit" has been achieved can criticality be allowed.

In ground processing, the reactor is unfueled for virtually all test and integration activities. The unfueled reactor is integrated and tested with the spacecraft. Once the reactor is fueled, safety "arming plugs" are used to prevent control drum rotations for all ground test operations. For transport and launch, four of the thirty-seven TFE's are unfueled to prevent inadvertent criticality. The fuel is inserted into these TFE's by ground command after sufficiently high orbit is achieved.

Although radiologically cold at launch, an operating reactor quickly accumulates a radioactive inventory.
Fig. 2. Spacecraft altitude throughout mission.

Fig. 3. PM xenon consumption throughout mission.
After a year of operation, it may take 300 years or more for the fission product inventory to decay to a safe level. A “sufficiently high orbit” (SHO) is an orbit of such longevity as to allow any fission product inventory to decay to the level of the actinides. Until the reactor achieves SHO, it must be prevented from achieving criticality.

After orbital insertion, an independent ground radar is used to ascertain the orbit achieved. Following this and assuming the arming plugs were placed prior to launch, three events must take place before the reactor can achieve criticality: 1) Launch Vehicle separation switches must indicate that separation has occurred; 2) power must be applied to the Reactor Control Unit (once powered, it cannot be unpowered by ground or remote command), and; 3) two encrypted commands must be sent and executed, namely the start-up arming command followed by the reactor start-up command.

Another important issue is nuclear “safeguards”. The fuel for TOPAZ 2 is 96% enriched U-235 in the form of UO2 fuel pellets, which is considered “Special Nuclear Material” (SNM). Due to its potential application for weapons, this material must be protected against theft, loss, or diversion. All transportation, storage, and handling of fuel must afford proper security. Once the reactor is integrated with the spacecraft and fueled, the spacecraft must be secured. Launch operations must minimize the possibility of loss or diversion of the SNM.

To prevent theft, loss, or diversion of SNM, all transportation and storage of the fuel will use DOE approved containers and vehicles; appropriate physical security will be enforced at all times the fuel is present. A sonar location device will be attached to the reactor to ensure that the reactor can be located underwater in the event of a launch abort. During launch, a special team will be in place to conduct recovery operations in the event of a launch accident.

**Propulsion Module Description**

Figure 4 illustrates the basic concept of the propulsion module (PM) and shows the major power and signal interfaces between the PM and the NEPSTP spacecraft. APL has selected Space Systems/Loral (SS/L) to design and build the PM and subcontracts have been placed for thruster subsystems (TS’s) from 3 sources. The terms PM and TS are defined as follows:

**Propulsion Module (PM)** - The total, integrated module as it will be configured for flight on the spacecraft. This includes tanks & propellant, tubing, pressure regulators, valves, heaters, cold gas (or electrothermal) thrusters, harnessing, interface connectors, gimbals and drives, structure and engineering performance monitoring sensors.

**Electric Thruster Subsystems**

- **PPU’s and FCU’s may be located on stationary portion of PM**

**Fig. 4. Propulsion Module functional and interfaces.**
Thruster Subsystem (TS) - A single electric thruster, with its associated power processing unit (PPU) and propellant flow control unit (FCU). The TS components are integrated into the PM.

PM Overview

The PM is envisioned as a "test bed" for electric thruster technologies, with participation from the U.S., Russia, United Kingdom and possibly other European countries. The set of thrusters presented here does not necessarily constitute the final design. The PM will consist of 6 TS’s, 8 cold gas (or electrothermal) thrusters and 700 kg of xenon. The TS’s are of 4 different types as shown in table 1 and the cold gas thrusters may actually be electrothermal (ET) thrusters utilizing heated xenon to conserve fuel. All of the thrusters will use xenon as the fuel. For determination of the number of electric thrusters that can be operated simultaneously the available power level of -4.5 kW is used. Table 1 presents the basic parameters of 5 representative TS's.

At the base of the PM is a 2-axis gimbaled platform which is to have motion capabilities of +/- 10°. This platform contains all of the electric thrusters, and can be as large as 50 inches in diameter and still fit within most launch vehicle adapters. Figure 5 illustrates this thruster arrangement concept. The thrusters will be mounted on this platform such that the exit planes of all 6 thrusters are coplanar. The cold gas thrusters will be mounted orthogonal to the long spacecraft axis in pairs, not on the gimbal platform. By this mounting scheme any of the TS’s can control the vehicle in 2 axes. The third axis control is provided by the cold gas thrusters. As a backup (improperly operating electric thrusters), and during times of thruster shutdown, the cold gas thrusters will be used for 3 axis vehicle control.

There will be one Power Processing Unit (PPU) per thruster for a total of 6 units. No modulation capabilities other than that required to maintain nominal thrust levels will be required. The input power to all units will be approximately 27 +/- 0.8 volts.

<table>
<thead>
<tr>
<th>Thruster Name</th>
<th>SPT-100</th>
<th>NASA 30 cm</th>
<th>T5-ITS</th>
<th>XIPS-13</th>
<th>T-160</th>
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</thead>
<tbody>
<tr>
<td>Size</td>
<td>10 cm</td>
<td>30 cm</td>
<td>10 cm</td>
<td>13 cm</td>
<td>16 cm</td>
</tr>
<tr>
<td>Type of Engine</td>
<td>Xe TML</td>
<td>Xe Ion</td>
<td>Xe Ion</td>
<td>Xe Ion</td>
<td>Xe TML</td>
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<td>Power into thruster (kw)</td>
<td>1.35</td>
<td>4.1</td>
<td>0.65</td>
<td>0.43</td>
<td>4.13</td>
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<tr>
<td>Thrust (mN)</td>
<td>83</td>
<td>164</td>
<td>25</td>
<td>17.8</td>
<td>230</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>1630</td>
<td>3600</td>
<td>3200</td>
<td>2585</td>
<td>1970</td>
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<tr>
<td>Thruster Efficiency</td>
<td>0.491</td>
<td>0.706</td>
<td>0.603</td>
<td>0.525</td>
<td>0.538</td>
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<td>PPE Efficiency</td>
<td>0.93</td>
<td>0.91</td>
<td>0.87</td>
<td>0.88</td>
<td>0.92</td>
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<tr>
<td>Total PPU &amp; FCU Power (w)</td>
<td>103</td>
<td>407</td>
<td>70</td>
<td>60</td>
<td>370</td>
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<tr>
<td>Total Power (kw)</td>
<td>1.453</td>
<td>4.507</td>
<td>0.720</td>
<td>0.490</td>
<td>4.500</td>
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<tr>
<td>Overall Efficiency</td>
<td>0.457</td>
<td>0.642</td>
<td>0.545</td>
<td>0.460</td>
<td>0.494</td>
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<tr>
<td>Total Acceleration* (m/s²)</td>
<td>2.37E-05</td>
<td>4.69E-05</td>
<td>7.14E-06</td>
<td>5.09E-06</td>
<td>6.57E-05</td>
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<tr>
<td>Total Acceleration* (µg/s)</td>
<td>2.42</td>
<td>4.78</td>
<td>0.73</td>
<td>0.52</td>
<td>6.70</td>
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<tr>
<td>M-Dot (mg/s)</td>
<td>5.19</td>
<td>4.65</td>
<td>0.80</td>
<td>0.70</td>
<td>11.91</td>
</tr>
<tr>
<td>Annual fuel usage (kg)</td>
<td>164</td>
<td>146</td>
<td>25</td>
<td>22</td>
<td>375</td>
</tr>
<tr>
<td>Annual Delta-V* (m/s)</td>
<td>766</td>
<td>1510</td>
<td>226</td>
<td>161</td>
<td>2192</td>
</tr>
<tr>
<td>Expected Lifetime (hrs)</td>
<td>4000</td>
<td>&gt;10000</td>
<td>10000</td>
<td>12000</td>
<td>&gt;8000</td>
</tr>
</tbody>
</table>

* Based on a 3500 kg spacecraft mass.
thusters will be used to control the vehicle. For attitude control maneuvers using the cold gas thrusters it is assumed that they have a force of 0.5 N and two thrusters are fired simultaneously. Xenon has an $I_{sp}$ of only 28 seconds, but because of the expected low duty cycle of the cold gas thrusters, the fuel consumption is tolerable over the mission. A crude estimate of the events and quantities of fuel required for the cold gas thruster firings results in a 30 kg xenon requirement for the mission.

The xenon cold gas thruster system is the simplest, least expensive way to achieve attitude control independent of the electric thrusters with the only disadvantage being low $I_{sp}$ (higher fuel mass). Electrothermal thrusters using xenon could possibly increase the $I_{sp}$ of xenon to 50 - 60 seconds resulting in a factor of two savings in the attitude control fuel requirement.

**Power, Thermal and Electronics Design**

Power distribution within the PM is not a difficult task since the output of the PPU's is at high voltage (300 - 1000 V) and relatively low current. Power switching to the PPU's will require large relays and will be provided by the PM, not the thruster subassemblies themselves. Start up of the thrusters is typically done in stages, e.g. first heaters, then discharge supply, and then the start up circuit, so concern about transients will be lessened. The shut down, however, is typically done by cutting off power to the PPU so this may require some analysis and testing to insure power system stability and tolerable conducted emissions. The TOPAZ 2 differs from conventional space power systems in that the reactor can be damaged by voltage spikes on its output bus.

A power distribution unit will contain the power switching relays that control the distribution of power to the electric thrusters. Input to this unit will be the 27 V power and the command signals (relay pulse commands) from the Data Interface Unit. Output of this box will be the power lines (27 V & Return) to the individual thruster PPU's as well as status of all relays within the unit.

The PPU will have typical spacecraft electronics interfaces but the thrusters will be allowed a much wider temperature range. They will be nearly thermally isolated from the structure and will get quite hot when operating and quite cold when shut off. The thrusters are designed to survive this wide range.

The PM must be able to control its own temperatures via radiative surfaces and heaters. The vehicle can assume any roll attitude during the mission life. Thus, the radiator sink temperatures can vary widely. The PPU's generate the major portion of the heat in the PM when operating. The PPU's will all be mounted on a common deck, with imbedded heat pipes, and a direct connection

**Cold Gas Usage**

When the electric thrusters are turned off or additional torque is needed for a maneuver the cold gas

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**Fig. 5. Conceptual arrangement of thrusters.**

Xenon Storage and Feed

The fuel storage system must have the capacity for 700 kg of xenon at a temperature and pressure above the critical point (16.6°C, 844 psia). The peak temperature should not exceed 50°C. As the pressure drops during the mission the temperature of the fuel shall be maintained to keep the fuel in a gaseous state. The xenon for all testing and flight will be of research grade purity (99.995%). It has been decided not to incur the unnecessary cost and risks of developing a new xenon storage system. A new design could be done either with a minimum mass pressure vessel with optimal space utilization or with a solid xenon dewar. Either is technically possible and would offer weight and volume advantages but the use of pressure vessels of existing design and flight heritage is the logical approach for this program. Several candidate flight qualified tanks have been identified as being suitable for this application.

As depicted in figure 4, the remainder of the propellant feed system looks very similar to other spaceflight propulsion systems. Two regulators are required. The pressure will be regulated down from the tanks to the cold gas thruster pressure (100 - 200 psi) and then to the Flow Controller Units (FCU) into the thrusters (-2 atm. - 36 psi - pressure). Flow meters will be provided by the PM to measure the system xenon flow enabling maintenance of a vehicle mass estimate. The accuracy will be as high as is achievable with readily available techniques. A flexible joint must carry the propellant across the gimbal to the thruster platform.
to the radiator to maintain appropriate temperatures.

A Data Interface Unit will be the signal interface to the spacecraft and will utilize a 1553 bus interface as the only signal interface. This unit will be fully redundant and include the required software for processing of commands and telemetry. Signal interfaces to each of the electric thruster PPU's will be through a signal connector and cable which can carry analog and digital signals. The PPU's will provide the necessary health and status information via this signal connector.

**Thruster Subsystem Overview**

Following is a brief discussion on the baseline set of TS's for the NEPSTP flight. Refer to table 1 and the references for specifics on each thruster. Table 2 provides information on the thrusters acquired (or to be acquired) by BMDO. The SPT-100 represents state-of-the-art proven technology. The NIITP T-series offer important lifetime, power density, and control growth options.

**Table 2: Hall type thrusters acquired by BMDO.**

<table>
<thead>
<tr>
<th>Russian Source</th>
<th>Thruster</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIITP through Space Power Inc.</td>
<td>T-100, 1.35 kW</td>
<td>Life 8000 hr. (goal) Control of EMI Heaterless cathode</td>
</tr>
<tr>
<td>T-160*, 4.5 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fakel through SS/L</td>
<td>SPT-100*, 1.35 kW</td>
<td>Proven Performance: 1600 s, 48 to 50% eff., 3000 to 4000 hr. life</td>
</tr>
</tbody>
</table>

* For NEPSTP through APL subcontract.

**SPT-100**

The SPT-100 is a Russian developed thruster that is flight qualified to their standards. The 100 in the name refers to the size (mm) of the exit aperture. Smaller versions of this thruster have flown on numerous Russian spacecraft. The Russian organization Fakel Enterprises builds and tests the thruster and has entered into a joint venture with Space Systems/Loral (SS/L) to market thruster subsystems. SS/L will design and build the PPU. Often termed the Hall or “closed-drift” thruster, the operational theory of this device is difficult to explain. For the purpose of illustrating the difference between this device and the ion engines the following summary is provided.

Xenon is injected into both the hollow cathode and the main discharge chamber. A discharge voltage of about 300 V is applied between the anode and the cathode. The xenon is ionized in a region of the chamber where the electric field is largely axial. An electromagnet creates a radial magnetic field which acts as an impedance to the flow of electrons from the cathode to the anode which then helps establish the potential difference between the anode and the cathode in the magnetic field region (as opposed to in-the-sheath regions adjacent to each electrode). The resultant electric field in the plasma is in the axial direction; the direction of the exhaust propagation. Electrons which diffuse to the anode do so in a region of crossed electric and magnetic fields. It is this electron drift which is analogous to the Hall effect and the drift paths are circular, closing back on themselves giving rise to the names “closed-drift” and “Hall effect” thruster.

As in ion thrusters, nearly all of the thrust is produced by the electrostatic acceleration of ions, only by the gridless scheme described above. The velocity of the exiting ions is ~16,000 m/s. Electrons are drawn from the cathode and the exhaust beam is largely neutralized.

**T-160**

There are other Russian Laboratories with relevant experience in electric thrusters. One such facility is the Scientific Research Institute of Thermal Processes, or NIITP. Space Power, Inc. (SPI), has a joint venture with NIITP to develop and market a thruster that is similar to the SPT-100. NIITP claims to have design changes that will improve the lifetime and provide a more focused beam compared to the older design of the SPT-100. NEPSTP desires to procure such a thruster, paired with an SPI designed PPU to operate at 4.5 kW. This effort would result in a thruster that utilizes all of the available power, with reasonable combination of \( I_p \) and thrust and would further improve the access of western companies to Russian electric thruster technologies.

The theory of operation of this thruster is nearly identical to the SPT-100. The improved field configuration and beam control are expected to more than double the T-series lifetime compared to the SPT-series lifetime. In addition, the T-160 will utilize a heaterless cathode which simplifies the power processing unit (PPU). The T-160 PPU which is being developed jointly by NIITP and SPI incorporates recent experience in controlling the onset of destructive Electro Magnetic Interference (EMI).

**XIPS-13**

This ion engine utilizes 3 accelerator grids to successively accelerate ions in the thrust direction. The exit aperture is 13 cm. Much higher exit velocities are
achievable for a given power level than with the SPT-type thrusters (25,000 - 40,000 m/s). The difference is that mass flow rates are not comparable to the SPT's, hence the thrust level is much lower (at constant power). Representative numbers are given in Table 1. An ion engine will be more fuel efficient but will require much longer trip times in an orbit raising application.

Hughes Research Laboratories has been developing this thruster for a number of years and has built and tested 13 cm and 25 cm aperture versions. Current work is focusing on the 13 cm size for use on geostationary spacecraft as the primary means of North-South station keeping. The principle of operation is summarized here.

Xenon enters the discharge chamber and permanent magnets produce a magnetic field which confines the discharge electrons. The 3-grid ion extraction assembly is used to extract, focus and direct approximately 3000 individual beamlets which form the thrust beam. A separate neutralizer emits electrons to combine with the thrust beam positive ions and produce a neutral “far-field” beam.

This engine has a simple PPU and FCU in order to increase reliability and lifetime. A constant propellant flow rate is maintained and the power and thrust levels are allowed to vary over the lifetime of the thruster. It is designed for a 12,000 hour total operating life. This could be continuous (~16 months) or include several thousand on/off cycles to meet the GEO application for >12 years.

**TS-ITS**

This device is quite similar to the XIPS-13 but the exit aperture is only 10 cm. The thrust level is comparable. The control scheme of this thruster is more complex in that there are 4 control loops and propellant flow rate are varied to maintain a constant ion exit velocity (I<sub>ep</sub>).

There are two sources for this engine; Matra Marconi Space and Atomic Energy Authority (AEA) Culham Laboratories. The thruster for both sources would come from the Defence Research Agency, Farnborough (DRA). The Matra Marconi version has been developed for long life communication satellites and the quality and cost is beyond the NEPSTP requirements. Culham Laboratories has the capability to build a suitable version of the PPU, integrate and test the entire TS and will likely do so for NEPSTP.

**NASA Ion-30 cm**

The NASA Lewis Research Center (LeRC) has been involved in electric propulsion since the early research phase and now has a mature 30 cm ion thruster. This device has been tested over a range of power of ~200 watts to ~11 kW. NEPSTP is proposing to demonstrate this thruster with a 2.5 kW input power level. At present, LeRC is beginning to “industrialize” this thruster by teaming with an industrial partner to build flight thrusters and repackage and build the flight PPU. This will result in a flight qualified TS available for future applications “off-the-shelf”.

The Ion -30 is a two grid thruster, with a 30 cm exit aperture, that operates in a similar fashion to the other gridded Ion thrusters. Sometimes the thrusters is termed “derated” because it can operate at lower I<sub>ep</sub> values (higher thrust for given input power) than originally designed (3500-4000 s), yet maintain reasonable overall efficiencies. This is an ideal thruster to scale up for higher power applications such as interplanetary missions. LeRC has done some development work on a similar thruster with a 50 cm aperture that would operate at 10 - 15 kW.

**Other Potential Candidates**

Space and mass margin is available to carry a sixth thruster on the NEPSTP spacecraft. Thrusters that have been explored include the RIT-35 (large German Radio-frequency Ion thruster), the UK-25 (a 25 cm version of the TS-ITS) and the ESA-XX (an ESA effort to develop a hybrid of the RIT-35 and the UK-25 using UK-25 ion optics and RIT-35 Ionization techniques).

In addition to this there are other sources of Russian thrusters, exemplified by the recently announced Societe Europeenne de Propulsion (SEP) joining of the Fakel/SS/L joint venture. This international team (US, French and Russian) could potentially produce a TS that would suitably complement the NEPSTP thruster set.

**Thruster Evaluations: Ground and Flight Test Plans**

NEPSTP is attempting to leverage as much current and planned development and testing work on the electric thrusters as possible. This work includes efforts funded by industry, NASA and BMDO. Examples of ongoing efforts include:

1. Testing and industrialization of the NASA 30-cm by LeRC, funded by NASA and possibly the Air Force.
2. Testing of the SPT-100 by JPL and LeRC, funded by BMDO.
3. PPU development for communications satellite applications, by both Hughes and SS/L.
4. Industrialization of the UK small Ion thrusters, by the UK government and industry.
5. Development and testing of a 1.5 kW version of the T-160 (NIITP) thruster, funded by BMDO.
The current status of the BMDO testing is:

- **T-100**: Life test at NIITP
- **T-160**: Performance and control test at NIITP
- **SPT-100**: Life tests at JPL, >800 hours

Performance, PPU, & EMI experiments at NASA LeRC

**Laboratory Characterization of Vehicle Interactions**

In anticipation of the NEPSTP requirements, NASA LeRC is currently testing a Fakel SPT-100 thruster acquired from SS/L. The LeRC effort focuses on evaluation of thruster performance and integration impacts. Most of the testing is being performed in a large (5m diameter by 20m long) space simulation chamber. This test bed allows plume diagnostics to be placed up to 4 m from the thruster and includes large antennas for EMI measurements. Ambient pressures of approximately $3 \times 10^{-6}$ torr are maintained at the SPT 100 operating point; at flow rates associated with 4.5 kW T-160 operation, an ambient pressure in the $5 \times 10^{-5}$ torr range is anticipated.

**Endurance Testing at JPL**

Operation of the SPT-100 on the NEPSTP mission could require several thousand hours of cyclic operation. Previous lifetests in the Russian chambers were not conclusive because of small amounts of oil contamination being deposited on the insulators. Thus, evaluation of the long term operating characteristics of the SPT-100 is a critical aspect of the preflight test program. A cyclic life test is being performed under a cooperative program between SS/L, BMDO, and JPL. One of the test goals is to demonstrate over 4000 hours of operation.

The vacuum facility at JPL is 3m in diameter and 5m long. Pumping is provided by three 1.2m diameter cryopumps. The cryopumps eliminate the source of oil contamination. Graphite panels arranged in a chevron pattern are used as a beam target to minimize sputter back deposition on the thruster. The thruster is being operated by a breadboard power processing unit developed by SS/L. Endurance testing was initiated on July 1, 1993 and over 850 hours of operation and 1000 cycles had been accumulated as of the beginning of September. Thruster performance and erosion appear to be nominal through the first 640 hours of operation. The SPT-100 experiences 2 to 4% efficiency drifts requiring field current adjustments.

**NEPSTP Flight Qualification Testing**

Each NEPSTP flight TS will undergo a vacuum chamber test where the thrust vector is measured and the conducted and radiated emissions are characterized.

At the PM level, the thrusters will be powered once more for thermal, EMC and self susceptibility tests on the PM. During spacecraft level integration and test, thruster simulators will be used to verify the proper operation of the PPU’s until launch.

Once on orbit, a very accurate accelerometer is required to determine the magnitude of thrust from the electric thrusters. Given a 3500 kg spacecraft using a single small ion thruster (20 mN), the acceleration is only 0.6 microg’s. Assuming that an accuracy of 1 - 5% is required, this implies an accelerometer with a resolution of 5 - 30 nanog’s. This accuracy is only attainable with an electrostatic accelerometer. It will be important to take “beginning-of-life” measurements on all thrusters and compare those with later measurements to assess the degradation of thrusters.

Each thruster subassembly should also measure the following parameters and the spacecraft will include these data in the health and status data stream: PPU input current, PPU input voltage, thruster input current, thruster input voltage, and fuel flow rate. Additionally, there will be several temperature monitoring points and at least 1 pressure transducer within each TS.

As these parameters change throughout the mission, the thruster degradation modes and lifetimes can be evaluated and data can be compared with ground test data and models of engine performance.

**Key Spacecraft Integration Issues**

**Contamination**

Both the reactor and thrusters emit many potential contaminants. After reactor start-up, the start-up battery is vented, releasing approximately 4.2 kg of potassium hydroxide electrolyte. The reactor also releases cesium (0.5g per day) along with other gases in small quantities (krypton, hydrogen, carbon monoxide, carbon dioxide, helium, and argon) during normal operation.

Due to the velocity of the ions expelled from the electric thrusters, thruster materials erode as the units operate. Ion thrusters lose molybdenum from their grids and SPT’s lose ceramic materials from the walls of the thrusters. There is also the possibility of xenon and propellant contaminants condensing on surfaces.

A complete modeling program is planned to predict the deposition rates on the NEPSTP spacecraft; thermal designs will use adequate margins to assure proper thermal management can be maintained. Optical instruments (star cameras) may use covers to protect sensitive surfaces during events of concern. A complete suite of instruments will characterize this environment for future NEP missions.
Electromagnetic Compatibility

Electromagnetic compatibility (EMC) is a concern for NEP spacecraft, due to both the reactor and thrusters. Communications interference may be attributable to EMI. The PPU's produce multiple voltages that have the potential to interfere. Large transients are expected when these units turn on or off. Potential communications interference concerns will be dealt with using operational mitigation which was described previously. Ground testing will be conducted with the thrusters and PPU's to measure radiated and conducted interference. Additionally, the PPU's will be operated (using simulated loads) during Thermal Vacuum testing of the entire spacecraft. It is anticipated that potential communications problems will be eliminated during ground testing.

The EM pump, on TOPAZ 2, which uses 1000A of current in orbit, may cause substantial magnetic fields, as may the current from the reactor to the spacecraft. These magnetic fields may interact with the earth's field, causing disturbance torques which affect the attitude determination and control system. A magnetic model is being developed for the entire spacecraft, including the effects of the EM pump and the power transmission lines. This will be used to predict interference and magnetic disturbance torques.

Another EMC concern is spacecraft charging. Due to the thrusters, the spacecraft is expected to be enveloped in charged or neutral plasmas. The dimensions and surface material characteristics of the spacecraft may cause interactions between the spacecraft and the ambient environment. To minimize spacecraft charging, typical mitigation techniques, such as the use of conductive surface materials and coatings, will be employed to prevent charge buildup. A model will be created using available tools to predict the levels of charging and evaluate proposed mitigation strategies.

Guidance and Control

A continuously thrusting spacecraft is a navigational challenge. Adequate attitude control relies upon knowledge of orbital ephemeris, which depends upon knowledge of the spacecraft acceleration. The spacecraft must have a knowledge of thruster performance (e.g., force and mass flow rate). Errors can accumulate requiring daily updates.

The key task in orbit raising is to keep the thrust vector aligned with the velocity vector. The major disturbances are expected to be: 1) gravity gradient; 2) thrust misalignments and; 3) magnetic fields. The relatively large, 2-axis gimbal motion capability should be easily counteract the gravity gradient and thrust vector misalignment torques, but the magnetic field torque may require the cold gas attitude control thrusters to maintain vehicle control, depending on the orientation.

Due to uncertainties in the position of the spacecraft, ground and flight software will require algorithms which account for acceleration due to thruster operation in the navigator routines. The software must utilize knowledge of thrust vector, vehicle mass (continually decreasing) and thrust vector orientation relative to the velocity vector.

The baseline for controlling the NEPSTP spacecraft uses gimbaled electric thrusters. The vehicle will fly in an Earth-referenced, 3 axis stabilized mode, meaning it will pitch 1 revolution per orbit. The cold gas thrusters will control the vehicle a small percentage of the time.

Simple system analysis has been performed to quantify disturbance torques and control torque authority to verify control capability. The basic control law has been modeled with the gravity gradient disturbance torque using a selected control system bandwidth of 2 mHz (0.002 Hz). This low bandwidth ensures no interference with the boom lateral bending which should have a fundamental frequency of >1 Hz.

Other control options such as Hydrazine thrusters, momentum wheels, and reaction wheels were considered and rejected due to cost and complexity.

Applications and other Flight Tests of Thrusters

The NEPSTP propulsion module design and test plan will space qualify several Xe fueled thrusters. On a world wide basis, both the Hall type and gridded-ion thrusters appear increasingly promising for commercial applications. Numerous mission studies show that these thrusters more than double the on station life time of satellites at GEO by more efficient use of propellant. Also, the aggressive approach of using Hall thrusters for LEO-to-GEO orbit transfer permit satellites to be launched on smaller, less expensive launch vehicles by greatly reducing the fuel mass required for orbit transfer.

The BMDO program is currently focusing on the evaluation of the Hall thrusters for applications that include orbit transfer, orbit repositioning, stationkeeping, and evasive maneuvering. The high performance values (e.g., Isp ~ 1600 s at efficiencies near 0.50 for life times approaching 4000 hr) provided by thrusters make them attractive for a broad range of commercial and government missions if integration issues can be resolved and life requirements can be met. Typically, 1 to 5 kW are available for propulsion functions. A majority of the BMDO electric propulsion program is aimed at the demonstration of 1.3 to 1.5 kW-class devices. Growth versions of the Hall thrusters are also being considered for eventual application with space
nuclear power systems such as the 40 kW Topaz 3 being pursued by Rocketdyne and Space Power, Inc.

The NEPSTP propulsion module is largely independent of the power source, i.e. either a 6 kW Topaz or a 6 kW solar power system can be used.

The advent of solar power systems incorporating dual bandgap photovoltaics and concentrator arrays promise approximately 90 W/kg and the ability to slowly transit the Van Allen belts with only a few percent loss of efficiency.

Among the other flight opportunities being pursued by Rocketdyne and Space Power, Inc. complete science and diagnostic instrumentation will provide a wealth of data to be analyzed for the purpose of improving future uses of space nuclear reactors and electric propulsion.

Finally, the international working relationships established on NEPSTP will serve as an example and pathfinder for many future space programs.

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Conclusion

All aspects of NEPSTP have reached a level of maturity equivalent to preliminary design during 1993. This includes the mission design, spacecraft design, TOPAZ 2 modification, test and qualification procedures, launch and orbital operations, safety, science instruments and measurement plans, the propulsion module and its suite of electric thruster subsystems. No “show-stoppers” have been identified to date and NEPSTP is looking forward to a successful flight demonstration.

The electric thruster performance parameters (i.e., \( I_p \sim 1600 \text{ s at efficiencies near } 0.50 \) for lifetimes approaching 4000 hr) of the SPT-100 and T-100 thrusters are sufficient for several of the BMDO small satellite applications. Importantly, the available BMDO spacecraft power matches the power required for the thrusters. FY94 activities will focus on preparing this class of thrusters for flight demonstration using solar power. The NEPSTP propulsion module experience feeds directly into this process. For the U. S. competitive position, thruster performance is not the issue; the issue is the lack of U. S. flight experience. Thus, the immediate goal is to take advantage of the NEPSTP propulsion module design efforts to pursue components for a prototype 1.3 kW SPT-100 type propulsion system to seize flight opportunities on solar powered experimental satellites.

The PM and the TOPAZ 2 are truly international efforts and the realization of this spacecraft and mission provides a unique opportunity to demonstrate the valuable technologies associated with NEP. The diversity of the TS’s assures that success and wide applicability of space electric propulsion will result. The complete science and diagnostic instrumentation will provide a wealth of data to be analyzed for the purpose of improving future uses of space nuclear reactors and electric propulsion.

Finally, the international working relationships established on NEPSTP will serve as an example and pathfinder for many future space programs.
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