The Express/T-160E Space Flight Test Program

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Abstract

This paper describes a program for demonstrating the use of a 4.5 kWe Hall Effect Thruster for stationkeeping of a Russian Express communications satellite. Project organization is described and the program objectives are defined. The key elements of integrating a Russian T-160 class thruster with a US built power processing unit onto an Express spacecraft are described. A baseline configuration is presented and the rationale for using this experimental propulsion subsystem for stationkeeping is discussed. The elements of the power processing unit design are presented from its functional perspective.

Background

In the early 1990's the Ballistic Missile Defense Organization (BMDO) took the lead in identifying and evaluating advanced propulsion technologies developed in the Former Soviet Union (FSU). Hall Effect Thrusters (HET's), utilizing xenon as the propellant, were quickly targeted as an area of interest. The early applications for these thrusters are likely to be for stationkeeping, but the technology, which is 5 times more fuel efficient than current chemical systems, can be used for any of the spacecraft propulsion functions.

The BMDO is now demonstrating the maturity of the technology through flight demonstrations of systems under the Russian Hall effect Thruster Technology (RHETT) program, and the follow-on Express project. In the first phase of the program, RHETT-1, five years of BMDO investment in electric propulsion component technology was brought together and demonstrated as a system in ground testing.[1,2] This system (shown in figure 1) included a T-100 built by Keldysh Research Center (KeRC) and a Power Processing Unit (PPU) built by Space Power Incorporated (SPI).

The RHETT-2 program is the technology provider for the Electric Propulsion Demonstration Module (EPDM) space flight program conducted by the Naval Center for Space Technology at the Naval Research Laboratory (NRL). RHETT-2 has sponsored the development of a Hall thruster (a Thruster with Anode Layer, the TAL D-55 manufactured by TsNIIMASh, which features a metallic discharge chamber as opposed to the ceramic versions of the Stationary Plasma Thrusters (SPT's), built by Fakel and the T-100/160), the associated PPU (developed by Olin Aerospace Company) and flow system components for EPDM. NRL has integrated the components, assisted in qualification testing of the hardware at the NASA Lewis Research Center (LeRC) and performed system integration and qualification for the EPDM.

The host spacecraft is expected to be launched in late 1997.

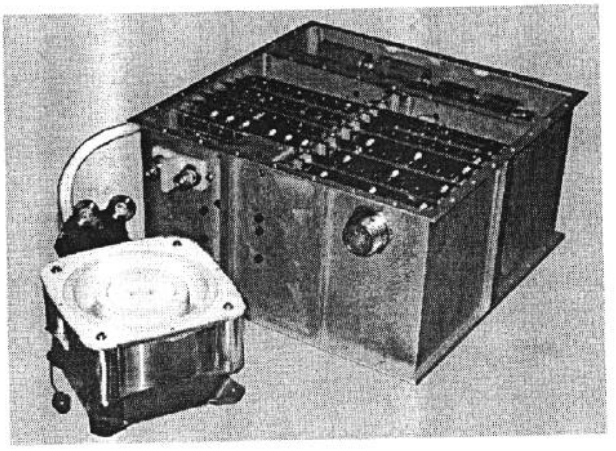

Figure 1. RHETT-1 PPU Manufactured by SPI and KeRC T-100 Thruster.

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Express Project Overview

In the fall of 1996, SPI was informed by KeRC of an opportunity to integrate, launch and operate, in space, an electric thruster system based on a Russian Hall Effect Thruster (RHET) and a US power PPU. Because of the strong technical payoff and the serious interest (based on considerable synergy with other efforts) from TRW - a potential user - the Science & Technology Directorate (BMDO/TOI) initiated the planning of this flight test. The offer comes from NPO-PM, a spacecraft production facility in Krasnoyarsk, Russia. SPI will provide a KeRC developed T-160E thruster and a PPU to be integrated and operated on the Express communications satellite.

The planned PPU design utilizes several of the module designs from the RHETT-1 PPU. The power available from the Express satellite is a minimum of 3000 watts and up to 5000 watts from a 35 volt bus. Xenon is carried on board, for use by the baseline system of eight 1.5 kW SPT's, and will be provided at the proper conditions for the thruster operation. Satellite launch is scheduled in mid 1999 and the flight model system delivery is required 6 months prior to launch, or late 1998. The project will include the participation of Space Power Inc. (SPI), TRW, KeRC, NPO-PM, and NASA Lewis Research Center (LeRC) and Schafer Corporation.

The project organization is straightforward: SPI acts as the prime contractor and manages subcontracts with TRW, KeRC and NPO-PM. SPI has the responsibility for the key US component - the PPU. In addition, they direct the subcontracts for the T-160E thruster to KeRC, the integration and mission operations costs (subcontract to NPO-PM). NASA LeRC provides management, technical expertise and facility use and Schafer Corporation provides coordination and system engineering assistance. TRW will provide system engineering support by defining the top level objectives and the specifics required to satisfy those objectives from the user perspective. They will also assist in the packaging design, fabrication, and qualification testing of the PPU.

The Program Objectives

The primary objective of this program is technology "push". To make RHETs useful on near-term DoD and commercial missions, the customers must be satisfied that the hardware is space flight qualified, that the systems offer overall cost advantages and are compatible with the satellite's other subsystems. The Russians have accepted and proven this notion for the smaller Fakel thrusters (SPT-70 and SPT-100). This program will provide both the Russians and the US with a second source of RHETs, qualified at a higher power level. In order to achieve this goal the objectives can be listed as follows:

- Validate the domestic and international programmatic process for developing, producing and integrating T-160E/spacecraft systems.
- Assure the compatibility between a high-power RHET system and the Satellite's communications systems.
- Evaluate the quality of the communication links for all of the operating modes of the thruster.
- Determine the impacts on the other spacecraft subsystems, primarily momentum and thermal exchange and degradation of surfaces (solar arrays, thermal radiator and sensors).
- Obtain engineering data during space flight operation on the RHET system.

The presumption is that the data required to meet these objectives will be available by monitoring the routine satellite telemetry over the course of the mission and the quality of the data transmission to and from several ground stations. No unique instrumentation will be required or provided for use on the satellite to assist in evaluations.

T-160E Thruster

An improved version of the KeRC T-160 Hall effect thruster (HET) will be used for the Express flight test.[3,4] These 4.5 kW_e class thrusters provide a thrust of 230 mN at a specific impulse of better than 1900 seconds. The latest version, the T-160E, incorporates a new magnetic system as well as mechanical enhancements. The improved magnetic system is expected to enhance performance while increasing erosion resistance. Patents for this new design have been filed in Russia, Europe, and the United States.[5]

The prototype T-160E (shown in Figure 2) includes a new magnetic system (with coaxial coils), improved cathode design, and a more robust mechanical structure. The new cathode design includes a heater for soft start and operates with a lower mass flow rate of xenon; it is also more vibration tolerant. Two prototypes T-160Es have been fabricated and preliminary testing of the first unit was completed by

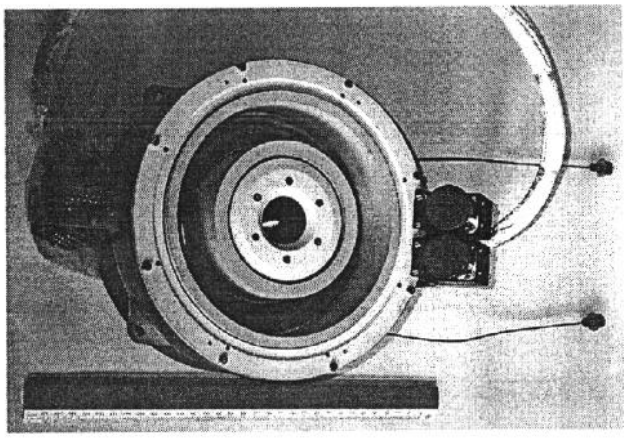

Figure 2. Prototype T-160E Thruster Manufactured by KeRC

mid-August, 1997. Smooth operation at full power was achieved at expected performance parameters of >50% efficiency and Isp >1800 sec. This prototype will be shipped to SPI for integration testing at NASA LeRC. Development work on the #2 prototype T-160E will continue at KeRC to optimize the magnetic configuration for both performance as well as thruster mass. Performance optimization goals are for an efficiency in the 55–60 percent range with an Isp > 1900 seconds. The #2 unit will also undergo vibration testing before the flight model design is finalized.

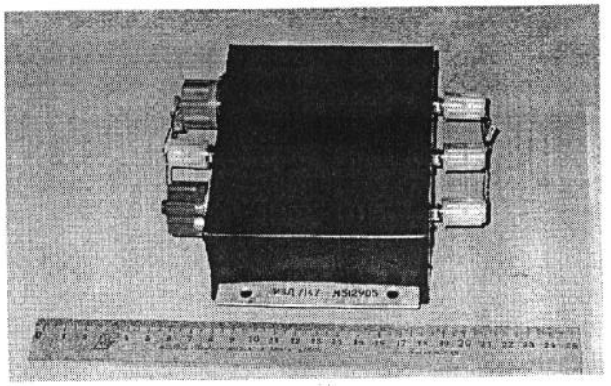

Figure 3. Photograph of the Flow Control Unit.

A five valve flow control unit (FCU) is also under development. This new FCU design is shown in Figure 3. This FCU design includes redundant flow paths with dual shut-off valves in series and redundant throttles, a temperature regulated cathode throttle heater, and a cathode flow filter/getter. Anode flow is controlled by a thermothrottle which is regulated to maintain the anode discharge current. This new design provides better reliability with a decrease in mass.

The Mission

Initial dialogues with NPO-PM have resulted in a basic definition of the mission. The Express satellite carries eight (four are reserves) SPT-100's to perform North-South and East-West stationkeeping (NSSK & EWSK).[6] Normally, a single engine is fired at a power level of ~1.5 kW for stationkeeping. The T-160E will be mounted in the best possible location to perform the function of the SPT-100's providing the Northward force for NSSK. Currently, the plan is to place the thruster on the South side of the satellite in order to minimize interference with the Polaris star tracker. Since the thrust vector must pass through the satellite center of mass, the T-160E must be mounted at an offset angle constrained by geometry; preliminary layout indicates this angle as about 20-28 degrees. Orbit perturbations induced by the off axis thrust component are effectively canceled out by choosing the radial direction. At an angle up to 28 degrees, 88 percent of the T-160E thrust will still be available for NSSK. A sketch of this concept is shown by figure 4.

Since the T-160E thrust is nearly three times that of the SPT-100, the T-160E can accomplish the N-S stationkeeping function with only a nominal thirty minute firing per day. After allowing for the offset angle, the effective Isp of the T-160E thruster is still

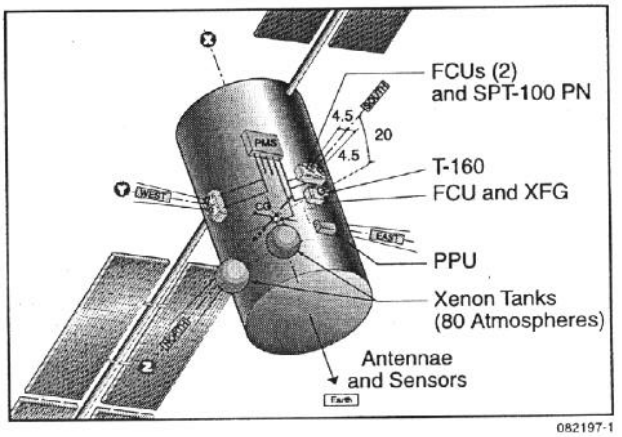

Figure 4. Baseline Configuration for the T-160E on an Express Satellite.

greater than that of the SPT-100. Therefore, the T-160E configuration will be more propellant efficient than the baseline and will save xenon over the course of a mission. The critical implication of this result is that the T-160E can act as a functional replacement for the conventional system with a positive impact on the main platform mission. Although the satellite contract calls for a minimum goal of one hundred hours of T-160E operating time, the demonstration system may operate as long as it is performing properly.

Mission operations are to be conducted from a control center located in Krasnoyarsk, Russia. The payload transmissions will be monitored at a location in Moscow where the majority of users are located. In the event of transmission trouble the satellite control center is notified by telephone immediately and they can then begin investigating and taking corrective actions from the Krasnoyarsk control center.

The US participants will be given access to the satellite telemetry data, informed of overall mission performance, payload performance and the use of the T-160E throughout the lifetime of the satellite (assuming the T-160E is being used). Operation of the T-160E will be the standard mode, unless problems are found early in the mission, in which case NPO-PM will resort to using the SPT-100's exclusively.

Spacecraft Integration

The use of a commercial communications satellite for the demonstration of the T-160E and its associated PPU at the 4.5 kW_e power level result in special constraints on spacecraft integration. The main principles for this space flight test on an Express satellite are:

- Minimize the additional work and modifications to the spacecraft required to accommodate the T-160E thruster system.
- Timely and full delivery of engineering and flight models of the propulsion system for spacecraft integration.
- Absence of any harmful interference with spacecraft key operations.
- Use of the T-160E as a functional replacement for stationkeeping.
- Capability to shut down the T-160E system in case of extraordinary situations.

General specifications for the space flight test include a mass allowance of 50 kg, up to 5 kW_e of unregulated DC power for 30 minutes per day, external mounting of hardware with minimal thermal impact, and simplified command and control interface by autonomous thruster control with 5 command signals. The telemetry allotment includes 8 bi-level signals and 5 analog signals. The thruster/satellite interface is summarized by the block diagram in figure 5. Starting from the left-hand side of figure 5, ground commands are transmitted to the spacecraft computer, which gives commands to the PPU. Power input is provided by three battery banks, which are decoupled from the main satellite bus to minimize interference with the satellite. The satellite batteries are protected by an NPO-PM supplied "diode" block. This unit protects against reverse currents and independently (from our PPU) switch off power in response to undervoltage and/or current surges.

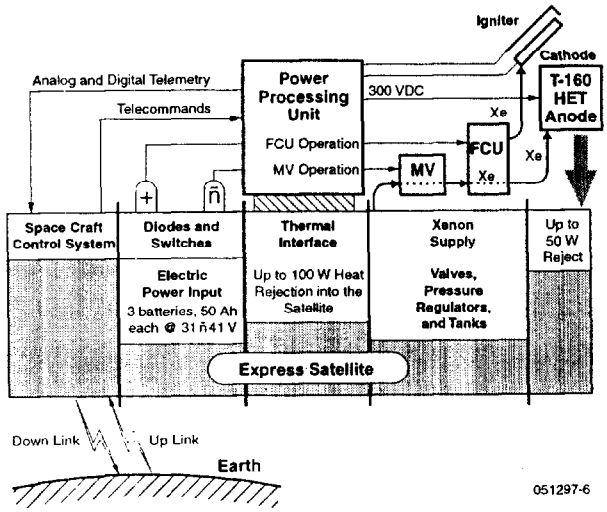

Figure 5. Express/T-160E Interface Block Diagram.

The thermal interface is limited to radiation coupling between the PPU base and T-160E base and satellite temperature controlled (nominal 20 C) platform; a maximum heat rejection of 100 W is permitted into the platform from the PPU and 50 W from the T-160E. Since our thruster system is a functional replacement, it can use the onboard xenon propellant

supply. Only an NPO-PM supplied shutoff valve and low pressure plumbing lines are required for our propulsion system. Indeed, it is the availability of an existing xenon feed system that allows the potential for hundreds of hours of accumulated operation with a 50 kg mass allowance.

Since about 500 W of heat is produced during PPU operation, thermal management requires a heat sink design to meet the interface requirement. Time dependant finite element modeling of a generic PPU weakly coupled to the spacecraft has been completed during the preliminary design phase. These results validate the feasibility of operating with a passive metal heat sink for 30 minutes and then rejecting the heat at a slow rate over a 24 hour cycle. In addition, phase change heat sink designs are under evaluation for mass savings and reduced temperature excursions for electronic equipment.

The 50 kg mass allotment can be met by the following mass goals: T-160E/FCU (9 kg), PPU (14 kg), heat sink (6 kg), and integration components (21 kg). The base area available for the PPU is 20 cm x 41 cm. NPO-PM will be responsible for the design and fabrication of all spacecraft mounting hardware (up to the mounting flanges of the T-160E and PPU) and electrical harnesses up to the PPU enclosure. SPI and KeRC will be responsible for all interfaces between the T-160E/FCU and the PPU.

Power Processing Unit For Express Flight

The Express PPU provides electrical power to the T-160E and its associated xenon Flow Control Unit (FCU). The PPU is powered from a 31V-41V unregulated battery bus (see figure 5) and delivers to the thruster 4.5 kW steady state power at 300 V and peak power up to 6 kW during engine start-up phase. For the Express application, the spacecraft controller exercises a very limited control of the PPU, HET and FCU operation. The spacecraft interface for our thruster system is minimized by incorporating autonomous control with a small set of five commands. Consequently, a custom (non MIL-STD-1553B interface) PPU logic control is being designed to ensure proper operation of the PPU, HET and FCU system and telemetry data flow to the Express spacecraft computer.

The Express PPU is comprised of the following blocks: (i) the HET Power Supplies System, (ii) the FCU Power Supplies System, (iii) the Thruster Selection Electronics (TSE), (iv) the Logic Control, and (v) the Input ElectroMagnetic Interference (EMI) Filter (see figure 6).

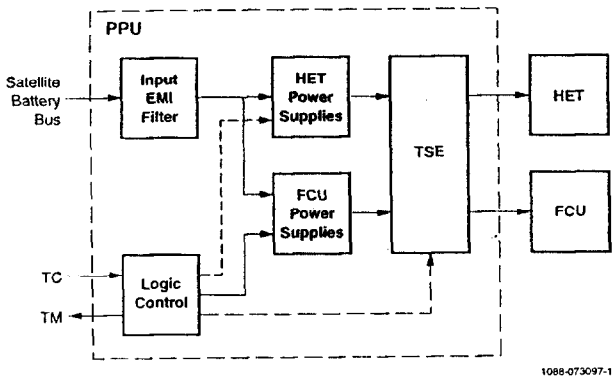

Figure 6. The HET Power Supply System Block Diagram.

The T-160E Hall Effect Thruster has two warm cathodes (prime and redundant), a heater for each cathode, an ignitor electrode for each cathode and a magnet coil system. The magnet windings (inner and outer) are configured in series and are placed in series with the anode circuit (no magnet power supply is required). The HET power supplies provide galvanic isolation from the input battery bus and are secondary referenced to the cathode electrode.

Discharge Power Supply

The Anode Power Supply, which is comprised of a step-up converter (Discharge Power Supply) and a decoupling filter (Output Filter), is able to provide 4.5 kW (15A @ 300V) steady-state power to the HET anode circuit. The Discharge Power Supply, implemented in a N+1 redundant modular configuration, employs a series-parallel array of 12 high power density (100 W/cin) DC-to-DC converters. The array has four paralleled strings of three modules each with their outputs connected in series. Each module is rated at 500 W (5A @ 100 V) steady-state power and weights only 220 grams. Accurate power sharing is ensured through a synchronized master-slave configuration, while N+1 redundancy is achieved by using a double master

approach. The Discharge Power Supply has built in protection for input overvoltage, output overvoltage, input undervoltage and output short circuit. A double pole Decoupling Filter protects the Discharge Power Supply against heavy anode current oscillations due to plasma instability during HET steady-state operation.

Auxiliary Power Supplies

Each cathode has a heater, but only one is active at one time. The Cathode Heater Power Supply is a current source, which provides power to the heater element prior to the cathode ignition or during the reconditioning process. The Thruster Selection Electronics allows power application to the selected cathode heater. The supply employs only one miniature DC-to-DC converter (60 grams) and has built in the same protection as the Discharge Power Supply.

Each cathode also has an ignitor, of which only one is active at one time. This Ignition Power Supply is comprised of a high-energy source of high voltage pulses (the Ignitor Power Supply), coupled to a follow-through low energy current source (the Keeper Power Supply). The Ignitor Power Supply initiates the ionization of the Xenon around the cathode, while the Keeper Power Supply maintains the ionization. The Thruster Selection Electronics connects the Ignition Power Supply to the selected cathode. The Ignitor supply employs an autoreseting transformer configuration, while the Keeper supply uses a miniature (60 grams) DC-to-DC converter, which allow for a very light construction.

The FCU Power Supply System is comprised of five power supplies implemented with miniature high power density DC-to-DC converters, which provide galvanic isolation from the input battery bus and the required built-in protections. The supplies are secondary referenced to the chassis ground to mitigate EMI effects. The FCU Power Supply System provides adequate power to a two channel (redundant) FCU and to the spacecraft main valve. Selection of the FCU channel is achieved through the Thruster Selection Electronics under Logic Control commands.

The Xenon Flow Valves Supply powers the three valves of the selected FCU channel, which have their coils connected in parallel. The supply applies a voltage impulse of less than one-second duration to open the valves, followed by a lower DC voltage to maintain the valves in open position.

In order to warm-up the Flow Control Unit (prior to the engine ignition) to a predetermined temperature (set by a FCU thermistor) the FCU Heater Power Supply in required. After activation by the Logic Control, this supply operates continuously until the set temperature is reached, followed by a "bang-bang" mode, which maintains the FCU condition within the required temperature band.

The Filter Getter Supply provides power to the Filter Getter Element when xenon flows through the FCU. Also, the supply is activated during the reconditioning process (filter and cathodes cleaning) which is required immediately after the launch or when commanded by the spacecraft controller during mission.

When an Operating Mode is initiated by the Logic Control, the FCU shall be connected to the spacecraft xenon tank. At that time, under Logic Control command, the Main Valve Power Supply energizes the Main Valve coil, which allows the tank xenon to flow to the FCU.

The anode current magnitude is proportional to the xenon flow rate and shall be maintained constant during thruster operation. The temperature of the thermothrottle determines the propellant flow rate by changing the xenon viscosity. The Thermothrottle Power Supply current is regulated by an error signal resulting from the comparison of the anode current with a predefined anode current set point (15A nominal). The Thermothrottle Power Supply has two modes of operation: the Warm-up mode and the Control mode. Prior to the ignition process, the thermothrottle is warmed-up for a predetermined period of time by the Thermothrottle supply, which operates at a 50% duty cycle. After a successful ignition, the Logic Control switches the Thermothrottle supply to the Control mode. During this mode, the average thermothrottle current is determined by the error signal of the comparator, which causes the supply to operate in a bang-bang mode.

The Thruster Selection Electronics is a switching unit subordinated to the PPU Logic Control which performs the selection of the HET prime cathode or

redundant cathode, and the selection of the FCU prime channel or redundant channel. The TSE unit is equipped with vacuum relays which connect the outputs of the PPU power supplies to the selected elements of the HET and FCU. Switching of the elements is performed at no current and no voltage prior to the HET and FCU operation.

The EMI Filter brings the PPU equipment in compliance with the satellite requirements for conducted emission and susceptibility. Upstream of the filter there is an input switching section which provides the means of in-rush current limitation when the PPU is connected to the satellite batteries. The EMI filter capacitors are charged with a current much lower than the steady-state current. A single point failure propagation into the battery bus is avoided by the proper fusing of the PPU DC-to-DC converters and by the satellites battery bus interrupters.

PPU Logic Control

The PPU Logic Control executes the necessary programs to ensure proper operation of the PPU, FCU and HET. The Logic Control provides in a proper sequence control signals to enable and disable the PPU power supplies, to process the spacecraft direct telecommands, to control the Thruster Selection Electronics, and to convey data to the satellite computer through the telemetry channels (see figure 7).

When the PPU is connected to the satellite batteries, the Logic Control places the equipment in an idle mode. At this point all power supplies (except the housekeeping and the logic power supplies) are disabled, but the PPU is ready to accept a PPU ON command from the spacecraft controller. The PPU ON command places the PPU in the stand-by mode which allows for selection and reconditioning operations. If RED K and RED FCU commands are received, the Logic Control selects the redundant cathode and the redundant FCU channel. If the selection commands are not received, the Logic Control assumes the default condition (prime elements are selected). The spacecraft computer can initiate the reconditioning operation of the Xenon Filter Getter and both cathodes by sending the REC ON command.

After reconditioning and selection operations, the Logic Control automatically initiates the operating modes of the PPU: initialization, ignition and steady-state. During the initialization mode the system is prepared for the thruster ignition: the FCU Heater and Cathode Heater Power Supplies are turned-on to warm-up the FCU and the selected cathode for a predetermined period of time, the spacecraft Main Valve is opened and the Xenon Filter Getter is activated. At the beginning of the ignition mode, the valves of the FCU selected channel are opened, the Discharge Power Supply is enabled and the Thermothrottle Power Supply is turned-on in the warm-up mode.

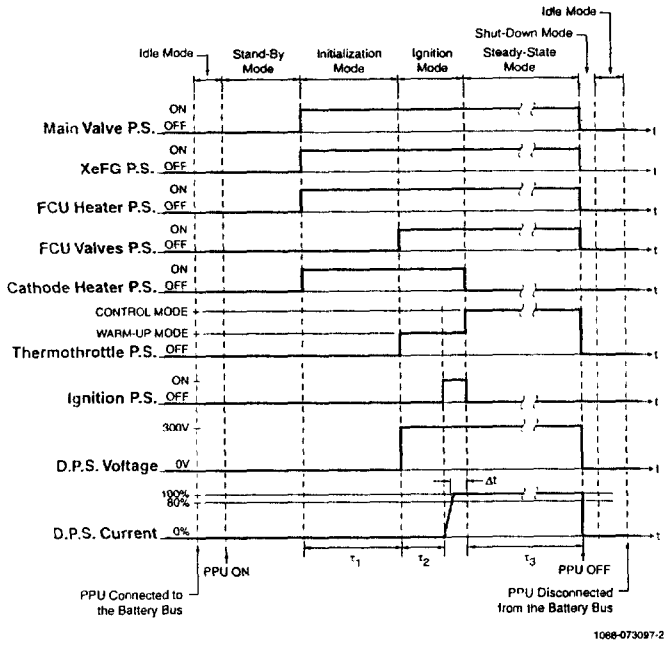

Figure 7. PPU Logic Control Timing Diagram

After a certain time period the Logic Control triggers the cathode ignition process by enabling the Ignition Power Supply. The ignition is considered successful if the discharge current exceeds 80% of its nominal value for at least Δt seconds. At that time the PPU is placed in the steady-state mode, which allows for normal operation of the FCU and HET: the Ignition and Cathode Heather Power Supplies are turned-off, and the Thermothrottle Power Supply is switched to the control mode. A PPU OFF command received from the spacecraft computer adjourns the system operation: most of the power supplies are turned-off and the PPU is switched back to the idle mode. In the event of an unsuccessful ignition, the Logic Control program allows for multiple ignition attempts using all possible combinations of HET cathodes and FCU channels. Based on an architecture trade study, the

elected Logic Control implementation is a hardware state machine employing discrete integrated logic devices.

Only five direct telecommand lines are allocated for the PPU: PPU-on, PPU-off, Reconditioning-on, select redundant cathode, and select redundant FCU channel. System status is reported to the spacecraft controller through five analog and eight bi-level telemetry lines. Analog telemetry signals are: anode current, anode voltage, PPU temperature, FCU temperature and HET temperature. Digital telemetry signals are: PPU status (On/Off), cathode selection status (prime/redundant), FCU channel selection status (prime/redundant), Main Valve status (On/Off), anode current, reconditioning status (in progress/completed), ignition status (successful/failure), selection operation status (in progress/completed).

Summary

The viability of using electric propulsion at the 4.5 kWe level on a commercial communications satellite will be demonstrated by this test flight. The qualification of a Russian built T-160E thruster with a US built PPU will be carried out on a Russian Express satellite. This thruster system will act as a functional replacement for NS stationkeeping and utilize the existing battery banks and onboard xenon propellant supply. Since the T-160E is more propellant efficient than the existing system, its successful operation will increase the satellite lifetime margins. For this reason, we have the opportunity to acquire hundreds of hours of operational experience with a low cost program.

Acknowledgments

The authors wish to express their gratitude for the encouragement and funding provided by the Innovative Science and Technology Office of BMDO (BMDO/TOI) and the executing agency NASA LeRC respectively. In particular, Dr. Leonard Caveny, former director of BMDO/TOI, deserves credit for recognizing the value of this project and providing enthusiastic direction and support it from it's inception.

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