NSTAR
OVERVIEW AND STATUS OF NASA'S PROGRAM TO VALIDATE ION PROPULSION TECHNOLOGY

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INTRODUCTION

In 1993 the National Aeronautics and Space Administration (NASA) began a program to validate ion propulsion technology for application to planetary missions. For almost the better part of three decades, NASA has worked to advance the technology of ion propulsion by concentrating on improving the operation of the ion thruster itself. Ion propulsion has always had a special allure for NASA. Its promise of high specific impulse (a factor of 10 more than that offered by chemical propulsion) and efficient conversion of electrical energy into directed kinetic energy offered the opportunity for the kind of deep space exploration that would otherwise have been impossible. By 1993 the cost of launch vehicles had been made part of the cost of each planetary spacecraft project, and the impetus to reduce the size of the launch vehicle required for a given mission was established. Ion propulsion at relatively low power levels offered the opportunity to reduce the size of the needed launch vehicle by at least one launch-vehicle class while reducing the trip time for many missions, thereby saving more than the incremental cost of the ion propulsion system. It was with the goal of realizing these benefits that NASA began the NASA SEP Technology Application Readiness (NSTAR) validation program.

NSTAR is the culmination of a relatively long history of work. Early in ion propulsion's development, the NASA advanced technology program had focused on Cesium as the propellant of choice for its low ionization potential minimized ionization losses. Other performance problems led, in the early 1970s, to the advanced technology program adopting mercury as the propellant for the ion engine, because mercury's high molecular weight increased the thrust developed with a given amount of input power. It was with mercury-fueled ion engines that NASA began its eventually canceled mission to Haley's Comet.

Mercury, however, proved (by the early 1980s) to be unacceptable as well. In addition to the environmental and health hazards presented by mercury, difficulties associated with vaporizing liquid mercury over the range of flow rates required, as the distance between the sun and planetary spacecraft changed, accented the impracticality of mercury. The culmination of the mercury ion thruster's advanced technology program was the so called J-Series 30-cm Thruster that operated at power levels as high as 10 kW and was tested for 10,000 hours at power levels between 0.5 kW and 2.5 kW in the vacuum facility at the NASA Lewis Research Center in 1975. The SERT II test in 1970 of two 15-cm ion thrusters in space, though failing to achieve its objective of 4,400 hours of operation at full power for each of the two ion thrusters, did demonstrate 5,800 hours (combined for both engines) of ion engine operation in space. In addition, more than 14,500 hours of in-space discharge operation were logged.

In 1981, work on an ion engine that used noble gases as propellant began where the work on mercury ion thrusters had stopped. A 30-cm, J-series ion thruster intended to operate at 10 kW was designed and testing was begun with xenon in the late 1980s. As a noble gas xenon did not present the panoply of problems associated with the use of mercury, yet its high atomic weight (131.3) and its moderate ionization potential (12.1 eV) promised a high performance ion engine coupled with an easily implemented propellant storage and control system. Design modifications to reduce the number of power supplies required to operate the thruster were later incorporated. The design and operation of the hollow cathodes were improved. The thruster's discharge chamber was changed from a right circular cylinder to a truncated cone and made of aluminum instead of steel to save weight. A long-duration test of almost 900 hours at 5.5 kW was accomplished with this 30-cm thruster using xenon. This ion engine was baselined for NSTAR.[1]

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[1] The brief history above was taken from
Brophy, J. R., Polk, J. E., Rawlin, V. K.; *Ion Engine Service Life Validation by Analysis and Testing* ; AIAA 96-2715; 32nd Joint Propulsion Conference; 7/1-3/96

BJECTIVES

The NSTAR ion propulsion validation program was begun with two objectives:

- Provide the data needed by a Project Manager to baseline the use of solar-powered ion propulsion on a spacecraft.

variations in performance as a function of
that has in effect been prequalified.
eviously unforeseen and insurmountable

Second, by providing data describing the operation of an ion propulsion system in space, NSTAR will provide the using project with the information needed to allow integration with its spacecraft to proceed and the confidence that will derive from the successful previous use in space of the ion propulsion system. As a result the risk that significant, unforeseen integration and operations difficulties may occur is greatly reduced and with it the risk of unplanned cost increases is reduced.

Third, by creating a commercial source for NSTAR-validated ion propulsion hardware, a using project will have the confidence that comes from being able to enter into a contractual arrangement with a supplier for proven equipment. The financial risk associated with using NSTAR-validated hardware is thus reduced as compared to equipment that has not been reduced to commercial practice.

APPROACH

NASA's plan for executing the NSTAR Program called for participation by the Jet Propulsion Laboratory (JPL) and by the Lewis Research Center (LeRC) while the overall program was to be managed by JPL. The approach taken by the NSTAR program to accomplish its objectives has three major elements.

- Assuring that ion propulsion technology is validated to realistic requirements by basing the technology requirements on the needs of potential users.
- Demonstrating performance and lifetime adequate for planetary missions in a ground test program.
- Measuring interactions between the ion propulsion subsystem and the host spacecraft while demonstrating operation of the ion propulsion subsystem on the New Millennium Program's DS-1 spacecraft.

Table 1. NSTAR Validation Requirements

PERFORMANCE	REQUIREMENT
Power Level	
Efficiency	
Specific Impulse	>3,100 lbf-sec/lbm
Input Voltage Range	80 V to 160 V
Thrust	100 mN, max
Lifetime	
Ion Engine	
PPU	16,000 hr
Mass	
Ion Engine	9.2 kg
PPU	12.1 kg
DCIU	2 kg
PSCS	17.5 kg
Propellant	83 kg/thruster, max

In this reference are also described the tests and progress made by Hughes developing the Xenon Ion Propulsion System.

The potential users of ion propulsion technology surveyed included project managers, spacecraft manufacturers, propulsion system vendors, purchasers of communications services, and designers of planetary missions. Their requirements were prioritized using a Quality Function Deployment (QFD) methodology. Subsequently, NSTAR program personnel, working with ion propulsion technologists, selected a subset of the user-identified requirements as the validation requirements to which the NSTAR program would be directed. These validation requirements met several criteria: first, if successfully satisfied they would yield an ion propulsion system that would offer the performance needed to provide a significant improvement when compared to the systems-level performance offered by chemical propulsion systems; second, the validation requirements were requirements that were within our technical ability to satisfy; and third, they were validation requirements that could be met within the funding constraints of the NSTAR program. The NSTAR validation requirements are shown in Table I.

The NSTAR Program's approach to achieving its objectives began with its thruster selection. The 30-cm ion thruster had been under development by NASA's LeRC for several years. It was derived from the J-Series thruster that had first been tested with mercury in the late 1970s. The 30-cm ion thruster to be used as the basis for the NSTAR flight thruster's design was originally designed to operate at 10 kW for 10,000 hours using xenon as propellant. Because lifetime is a critical technical requirement, this thruster was *derated* for its operation on NSTAR to a maximum power of 2.5 kW and a service lifetime of 8,000 hours. This derating was intended to minimize the risk of failure during the NSTAR validation process while validating an ion thruster design that had significant growth potential.

Validation requirements fell naturally into a group that could be validated in tests in vacuum chambers on Earth and a second group that could only be addressed with operation in space. Those that could be addressed with ground testing were those tests to validate lifetime and performance. Those tests that could only be performed in space consisted of tests that would measure the interactions of an ion propulsion system with the spacecraft on which it was integrated, and its interactions with the surrounding space plasma. In addition to the validation tests planned for ground tests, a series of development tests were anticipated. These development tests would address detailed design issues, obtaining data that would contribute to the design of the flight thruster and power processing unit.

To ensure an effective transfer of' the expertise developed by NASA to industry, the opportunity to design and fabricate the ion thruster, power processing unit (I'I'LI), and digital control interface unit (DCIU) was competitively awarded 10 the Hughes Electron Dynamics Division (HEDD), Torrance, CA. Similarly, a partnership with Moog, Inc. of East Aurora, NY was established for the design and fabrication of the propellant control portion of the Propellant Storage and ('01)1101 System (PSCS).

Requirements

Analyses of the missions for which ion propulsion would yield a significant cost advantage led to a set of validation requirements, shown in Table I, to which NSTAR would be directed. To address these requirements, the NSTAR Program selected the NASA 30-cm, ring-cusp, electron-bombardment ion thruster as the thrust producing device it would use to validate ion propulsion technology. To accommodate the reduction in available power concomitant to the increasing distance to the sun for many deep-space missions, the thruster is required to operate over an available power range of 0.5 kW to 2.5 kW with an input voltage between 80 V and 160 V and to be able to process 83 kg of xenon.

Ground Tests

NSTAR's formal ground test program consists of two tests:

- A test of an *engineering model thruster* with a bread board power processing unit (BBPPU) (both designed and fabricated by the government) for 8,000 hours at full power. The purpose of this test was the validation of the performance and lifetime of the functional design of the ion thruster. Operation of the ion thruster at full power is the most stressful operating condition for the ion thruster. Thus, operation for 8,000 hours at full power, consuming 83 kg of propellant, demonstrates the ability of the ion thruster to process 83 kg. of propellant at any power level within the thruster's operating range. As of October 1, 1996, 1,600 hours of the planned 8,000 hours had been completed with no significant problems encountered.

- A *Mission Profile* test intended to demonstrate the ability of the NSTAR ion propulsion system to process 83 kg of xenon (equivalent to the concept of a service lifetime) with a power profile intended to simulate a "typical" outward bound deep space mission. The test is also intended to demonstrate a 50% lifetime margin on the 83 kg service lifetime requirement, resulting in a test during which 125 kg of xenon will be consumed. The power profile to which the ion propulsion system will be operated will provide operation for significant periods of time at each of the system throttle points from minimum to maximum.

  The test hardware for the mission profile test will consist of:

  - One flight ion thruster fabricated by **11}11)I).**
  - One flight Power Processing Unit and controller from HEDD
  - One engineering model propellant storage and control system

In addition to these major ground tests, the ground test program includes an extensive series of tests termed *development tests.* The development tests are intended to provide specialized information to aid in the design of the ion thruster, power processor, or the propellant storage and control system.

Prior to the start of the 8,000-hour, full power test, two tests of the **ion** thruster were conducted; the first **of"** which was intended to identify life limiting mechanisms operating in the ion thruster and to quantify their rates. This first test was to last for **2,()()()** hours during which the government-designed engineering model **ion** thruster was to operate at full power. Prior **10** this test, **erosion"** of the ion thruster's accelerator grid by charge-exchange ions was expected to be the principal life-limiting mechanism. Following the test four observations **were** made:

- Accelerator grid erosion was less than anticipated.
- Discharge cathode erosion was severe.
- Screen grid erosion was significant.
- Loose flakes of sputtered material were found in the discharge chamber.

The engineering model ion thruster was reworked by incorporating a new discharge cathode having an enclosed keeper, by maintaining the screen grid at cathode common potential instead of allowing it to "float" electrically, and by surface texturing and adding fine wire mesh to the interior surface of the discharge chamber.

A subsequent 1,000-hour, full-power test of the ion thruster indicated that the problems observed following the conclusion of the 2,000-hour, full-power test had been successfully corrected. These changes to the original design were then incorporated in a new engineering model thruster built for the 8,000-hour test.

Thermal development tests have been and are being used to define the thermal environment in which the ion thruster will operate, to assess its thermal performance in that environment, to define the qualification requirements to which the ion thruster must be designed, and to normalize the thermal model of the ion thruster. Recent tests of the ion thruster determined that the lowest temperature to which the ion thruster could be conditioned, non-operating, in the vacuum chamber was -105°C. This test then set the lower, non-operating qualification temperature limit for the ion thruster. These data, when combined with the thermal margin requirements, then set the temperature at or above which the thermal design of the spacecraft would be required to maintain the non-operating ion thruster. This minimum allowable flight temperature is -90°C.

Vibration development tests were and are being used to provide the data needed for the structural design of the ion thruster. These tests have been used to assess the accuracy of the structural model of the ion thruster and to evaluate candidate designs.

IN-SPACE DEMONSTRATION

The NSTAR ion propulsion system is hosted as an advanced technology to be validated (in part), on the first technology demonstration mission (referred to as "DS1") of the New Millennium Program. On DS1 the NSTAR ion propulsion system consists of one ion thruster, a PPU, a DCIU, a xenon PSCS, and a diagnostics system to measure the effect of the operation of the ion propulsion system on the DS1 spacecraft and the surrounding space plasma. The ion thruster ionizes xenon, accelerates it electrostatically to 31 km/sec, and neutralizes the departing plasma. The PPU conditions the power provided by the SCARLET solar array to the voltages and currents required by the ion thruster. The PPU accepts DC input power in a voltage range of 80 V to 160V and requires a small amount of 28 V housekeeping power. The DCIU (Figure 1) interfaces the ion thruster system with the spacecraft, accepting high level commands from the spacecraft (e. g. thrust on, thrust off, power level NN, etc.) and in turn causing the PPU and the propellant storage and control system to execute the correct sequence of operations to effect those commands. The DCIU also provides NSTAR's telemetry to the spacecraft for transmission to Earth. For the DS1 spacecraft the NSTAR ion propulsion system serves as the spacecraft's primary propulsion system, providing the impulse needed to effect an asteroid flyby followed by a comet flyby from the escape trajectory on which the DS1 spacecraft is placed by the Delta launch vehicle.

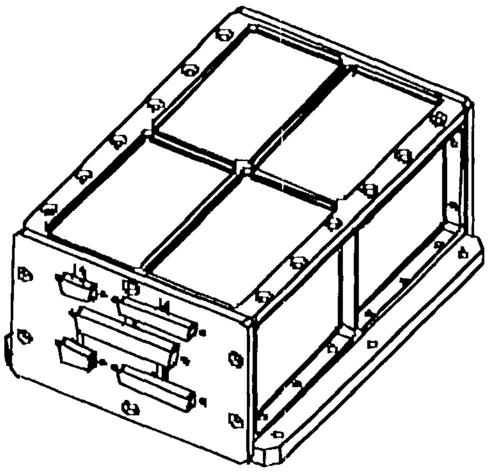

Figure 1. NSTAR DCIU

HEDD, of the Hughes Telecommunications and Space Company was competitively selected to provide the ion thruster, PPU and DCIU for the DS1 spacecraft. HEDD will also provide the ion thruster, PPU, and DCIU for the Mission Profile Test. LeRC is the contracting organization working with HEDD to transfer NASA's knowledge and experience to U. S. industry. The critical design reviews (CDR) for the ion thruster, PPU, and DCIU were completed on October 3, 1996.

The schematic for the xenon PSCS is shown in Figure 2. Flow rate control is effected by maintaining the pressure in the plenum tanks at an appropriate level as determined by the calibration of the flow control devices. Pressure control is done by the DCIU, which compares the measured pressure in the plenum tanks to a preprogrammed set point and actuates the solenoid valves, admitting xenon from the storage tank to maintain that set point. The PSCS is designed and fabricated jointly by JPL and their competitively selected industry partner, the Space Products Division of Moog, Inc., East Aurora, NY. JPL provides the propellant storage and plenum tanks and the calibrated flow resistance devices for flow rate control; Moog provides the remainder of the components. Testing of an engineering model of the PSCS was started in September, 1996. The CDR for the PSCS was completed on September 19, 1996.

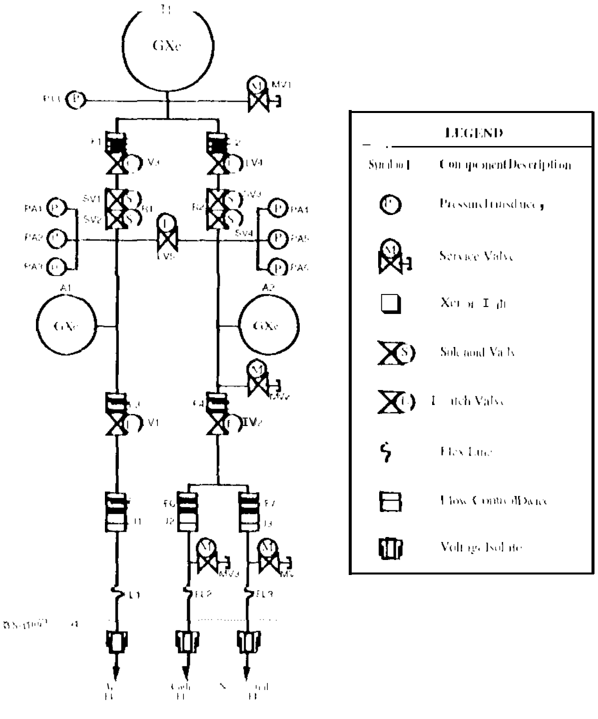

Figure 2. Schematic of the NSTAR Propellant Storage and Control System

Table II. Schematic of the NSTAR Propellant Storage and Control System

NSTAR Provided	DS1 Spacecraft Provided
Flux Gate and Search Coil	Spacecraft Communications Link
Plasma Wave Antenna	Ion Mass/Energies
Retarding Potential Analyzer	Electron Energy and S/C Potential
Langmuir Probe	Optical System Performance
Calorimeter	
Quartz Crystal Micro-balance	

The measurements to be made on the DS1 spacecraft by the NSTAR diagnostics system are listed in Table II. The diagnostics system consists of a diagnostics sensor electronics unit which monitors the diagnostics sensors and prepares their data for transmission to Earth by the spacecraft. The sensors measure the contamination produced by the ion thruster and the effects of the NSTAR's transient and steady-state electric and magnetic fields on the DS1 spacecraft and the surrounding space plasma. These data will in turn be used by future spacecraft designers and the designers of future space fields and particles experiments to design systems compatible with ion propulsion systems.

The DS1 mission consists of a flyby of the asteroid McAuliffe and of the comet West-Kahontek-Ikemura in the course of which the spacecraft receives a gravity assist from a flyby (~1000 km) of the planet Mars. The electric propulsion portion of this mission begins after the spacecraft is separated from the Delta launch vehicle at a velocity slightly greater than escape velocity. The ion thruster thrusts in two lengthy periods following the power profile of the SCARLET (Solar Concentrator Array using Linear Element Technology) solar array as shown in Figure 3. The total thrust period for the ion propulsion system is 7,080 hours during which 47 kg of propellant is consumed, corresponding to 57% of the 83 kg service life of the ion thruster.

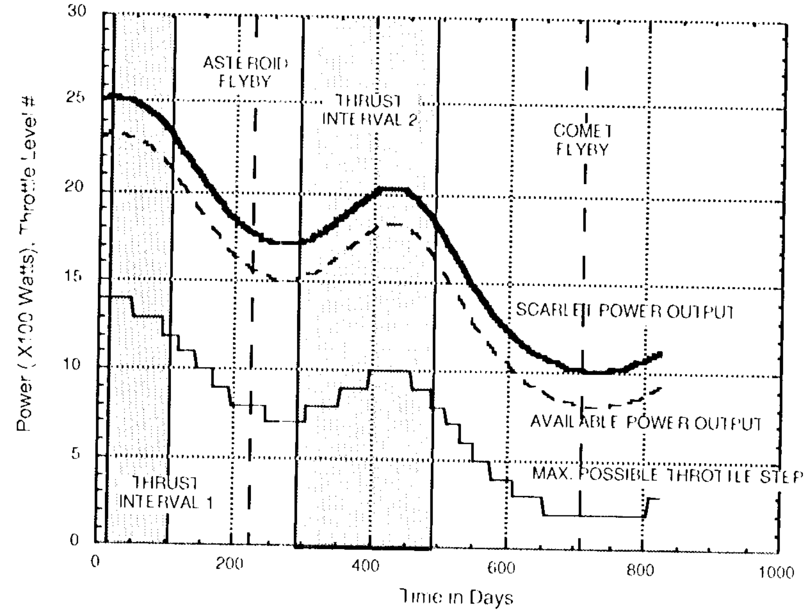

Figure 3. Predicted available power and NSTAR operating points during the DS1 mission

SUMMARY

The NSTAR team is excited at the prospect of validating the initial ion propulsion system that will be used both to reduce the cost of planetary exploration and to begin an era characterized by deep space missions that could not have otherwise been accomplished. The NSTAR ion propulsion validation program will result in commercially available ion propulsion hardware that will have been demonstrated empirically to meet the requirements shown in Table I. This demonstration will have been done in a series of ground tests, which demonstrated a lifetime corresponding to a xenon throughput of 83 kg with an Isp in excess of 3100 lbf-s/lbm and an efficiency greater than 60%. In addition ,the hardware will have been integrated on the New Millennium Program's DS1 spacecraft and used as the primary propulsion for a asteroid flyby/comet flyby mission

But we also know that NSTAR is just the beginning. Future evolution of the NSTAR hardware, yielding higher performance, lower mass, and longer life, will be accomplished by industry in response to competitive pressures. A path to these improvements has been identified as a result of NASA's advanced technology program. The reduced sputter yield of carbon-carbon grids, for example, is expected to allow dramatically longer lived, higher powered versions of the NSTAR 30-cm thruster. The anticipated success of the NSTAR validation of ion propulsion will spur the use and development of electric propulsion for a wide spectrum of Earth-orbiting and deep-space spacecraft.