First IAA Symposium on Realistic Neat Term Advanced Scientific Space Missions
Turin, Italy ---- June 23-25, 1996

SOLAR ELECTRIC PROPULSION

E. Kane Casani
Manager, New Millennium Program

John L. Stocky
Manager, Advanced Propulsion Technology Section

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, California U.S.A 91109-8099

Acknowledgment - The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

The National Aeronautics and Space Administration's New Millennium Program (NMP) is a spare flight technology demonstration program that will validate the technologies needed to carry out the Earth and spare science missions NASA envisions for the 21st century. The program is employing an innovative decision-making process to select the specific technologies that will be flight validated. First, NM]' has articulated NASA's vision of science exploration for the next century, then it has defined the capabilities needed to execute that vision, and finally it will select and demonstrate the revolutionary technologies that provide those capabilities, thus enabling the science vision.

The selection criteria for the technologies include a four level process before the technologies arc evaluated for flight acceptance. '1 hese four steps are assessment of the technology value, assessment of the probability of its readiness, determination of its expected value, and a final stage of selection whereby the optimum mix of technologies is chosen for flight by the program manager before being recommended to NASA 1 Headquarters. After NASA HQ approval of a technology for flight, further classification takes place relegating technologies into an essential, fundamental, or enhancing category. The technologies must also pass through three readiness checkpoints to ensure they will be ready for flight.

The first NMP deep space mission selected is a comet/asteroid flyby, and a suite of 12 to 15 breakthrough technologies has been selected for flight validat ion on this mission. The mission plan for this first of the New Millennium Program's technology demonstration missions, 1) S- 1, will be presented. It will show the planned validation of 1 broad spectrum of technologies critical to future planetary exploration as well as the details of this mission's use of solar electric propulsion (SE])).

This type of propulsion has been selected for validation on the first mission because, once validated, SEP technology will allow future planetary missions to be conducted in shorter trip times while using smaller launch vehicles, thereby reducing the cost of solar system exploration. In this paper, the plan to validate ion propulsion technology will be summarized and the status of the activities implementing that plan will be described.

The evolution of SEP technology will improve the performance and reduce the cost of future planetary missions, whether directed toward the inner solar system or toward such outer planets as Uranus and Pluto. The path of such evolution will be described. In addition, the propulsion technologies being investigated for such demanding missions as examining the Kuiper Belt and the

Oort Cloud will be described, providing one insight into the future evolution of solar system exploration.

INTRODUCTION

The NASA vision of space and Earth science in the 21st century encompasses frequent, affordable missions with highly focused objectives. The New Millennium Program will enable this vision of scientific exploration by identifying shortcomings in current technology that prevent its realization. NMP has formed a science working group (SWG) representing the range of NASA'S scientific endeavors to articulate these high-priority capability needs, and breakthrough technologies providing affordable solutions will be sought from the technology community through the formation of integrated product development teams (IPDTs) comprising representatives from industry, universities, non-profits, and other government agencies. Technologies that are found to most significantly contribute to achieving the goal of frequent launches of exciting, affordable space and Earth science missions will be selected as high priority candidates for development and flight validation.

NMP will emphasize those technologies that significantly contribute to reducing the costs, increasing the frequency, and enhancing the scientific value of future science missions. It will sponsor revolutionary technology advances that offer significant new opportunities for future missions, but that have traditionally been difficult to incorporate into science missions because of the inherently high risk associated with their first use in space. "To validate these technologies, NMP will fly a series of validation flights serving as testbeds to demonstrate their performance in operational mode. Thus, the vision determines the technologies that are selected for flight, the technologies define the nature of the validation flights, the flights validate the technologies, and the technologies in turn enable the vision, as illustrated in Figure 1.

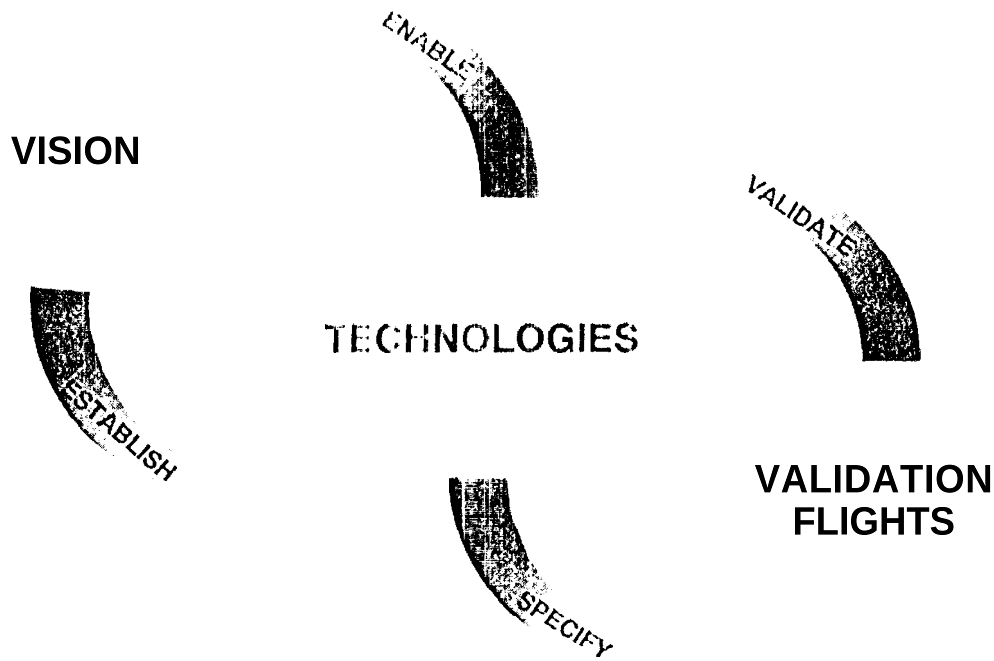


Figure 1. NMP Program Process

PI:OGRAM PROCESS

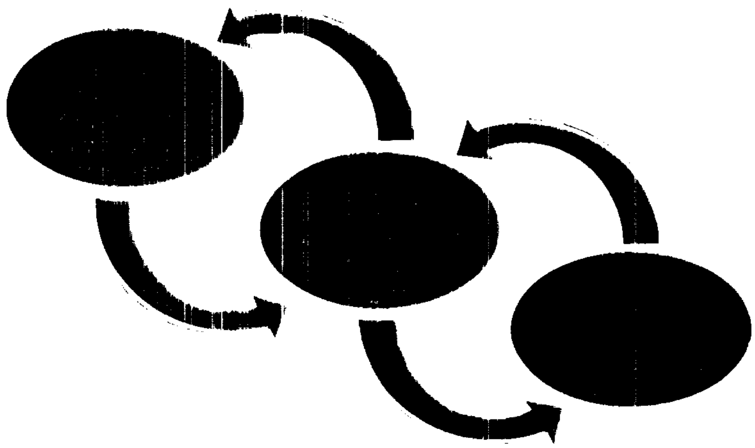


FIGURE 1

TECHNOLOGY SELECTION 1'1<(1(:ESS

Technologies validated on New Millennium flights will be determined in a three-pl)asc proms:

Phase I. Identification of candidate technologies

Phase II. Selection of technologies for flight development

Phase III. Delivery of technologies for flight

In the initial phase of technology selection, a bro.3 suite Of breakthrough technologies will be identified and incorporated within the tec 1 nolog plans, or road maps, of the Integrated Product Development Teams (IPDTs). These technologies will be chosen for their potential in enabling the low-cost, frequent science missions that NASA envisions for the 21st century. Concurrently, the Architecture Development Team (Al) I') will generate potential validation flights to serve as testbeds for these key areas of technology.

In the second phase, specific technologies recommended by the 11'1)'I's for flight validation will be subjected to a more rigorous selection process (riteria used to assess the inherent technical value of the proposed technologies will include long te m impact on science return and cost, the revolutionary nature of the technologies, and the degree of risk reduction offered by flight validation. The Program Office and Al)'I', with input from the Flight Team(s) and SWG, will consider the combined technical value of suites of I Pl)'I'-proposed technologies appropriate for validation on AIY1'-proposed flights along with the overall science value to be returned, and other programmatic and fiscal issues, in order to identify and recommend to NASA J IQ a set of validation flights and assoc. iated technology complements.

After NASA } IQ approval to proceed with the selected flights and technologies, a Flight Lead will be chosen, a Flight Team assembled, and a set of readiness checkpoints will be set up to ensure timely delivery of technologies to meet the flight schedules. This risk management approaches designed to produce the best balance between a technology-rich mission and launches cm schedule within cost. In this third phase, those technologies which successfull y pass these checkpoints will be integrated into and validated on the NMP flights.

PHASE 11: Selection of Technologies for Flight Development

Four individual evaluations take place in the process of identifying technologies for development for validation flights, as described in the following:

1. Assessment of Technology Value

Once the 11'11'1's have identified a set of revolutionary technologies, the question as to which of them should be space-fligl)t validated must be addressed. The following criteria have been established and will be applied relative to each technology to assess its value for incorporation into NMP validation flights:

A. impact on 21st century science missions

B. Revolutionary nature of breakthrough

C. Risk reduction by flight validation i) the combined Expected Value of the technologies and their compatibility for integration into candidate validation platforms.

In the not too distant future, space journeys using electric propulsion will be commonplace. These electric propulsion systems will be powered by large nuclear power generators to enable journeys for beyond the bounds of our system Just how fat in the future this will happen is hard to predict today, hut it will happen. The solar electric propulsion system to be flown on the NMP spacecraft is the first step in opening up the door to electric propulsion, be it solar or nuclear. This will be a small step in this direction similar to the first flight of the Kitty Hawk. Who would have predicted that through such a small step of powered flight today's aviation would grow. The Kitty Hawk's light was shorter than the wing span of today's 747 jumbo jet. Similarly, his modest solar electric propulsion system flight wil pave the way toward unimaginable electric propelled flights throughout our universe

The Appeal **of Electric Propulsion**

Electric propulsion is a relatively simple concept. In one of a variety of ways electrical energy is used to accelerate a propellant to an exhaust velocity greater than that possible using only the chemical energy available in the molecular bonds of the propellant. It is this higher exhaust velocity that provides the benefits of electric propulsion by increasing the impulse imparted to the spacecraft by each gram of propellant expended (measured by specific impulse, Isp). nut this increased exhaust velocity comes at a price. As can be seen from Figure E- 1, electric propulsion requires, in addition to the propellant supply system and the thrust producing device needed by chemical propulsion systems, a source of electric power and a power processor to produce the controlled voltages and currents needed by the thruster. These additional functions increase the dry mass of an electric propulsion system above that of a chemical propulsion system. "1'bus, the impulse required by a space mission must be above a threshold value before electric propulsion offers an advantage; and the greater the propulsion requirement, the greater the advantage electric propulsion provides.

For many such missions electric propulsion offers the opportunity to reduce the launch mass of the spacecraft to a degree that a smaller launch vehicle is required than that needed were chemical propulsion employed. Alternatively, this same advantage could be usc(I to increase the functional capability of the spacecraft. Thus, electric propulsion offers spacecraft and mission designers a spectrum of choices from reduced launch vehicle costs to more capable spacecraft than would be available were chemical propulsion used for the mission. This attribute is illustrated in Figure E-2, which shows that for a spectrum of comet rendezvous missions electrostatic ion propulsion carr increase the payload of a given launch vehicle by as much as a factor oft wo, or it can reduce the size of the launch vehicle required.

NASA's Program To Validate Ion Propulsion Technology

Electric propulsion can take several forms. At one end of the spectrum are resistojets and arcjets, which use electrical energy to heat a working fluid to a high temperature thereby obtaining specific impulses as high as 1,000 s, though more commonly in the range of 400 s to 600 s. At the high Isp end of the electric propulsion spectrum are electrostatic ion thrusters, which ionize a propellant and accelerate the ions through a large voltage difference to high exhaust velocities. Gridded ion thrusters, frequently called Kaufman thrusters and Hall effect thrusters are examples of this class of electric propulsion. Hall effect devices require simpler power processing than gridded ion thrusters but have not demonstrated adequate lifetime at specific impulses of interest to planetary missions. Gridded ion thrusters have shown an Isp well in excess of that optimal for planetary missions (3,000 see) and lifetimes approaching that needed for planetary missions.

Since ion thrusters offer the opportunity for a large class of planetary missions to be accomplished in less time while using smaller launch vehicles, NASA decided to undertake the validation of ion propulsion technology. The NSTAR (NASA SEP Technology Application Readiness) Program was started in Fiscal Year 1993 (FY93) with the following objectives:

- To obtain the data necessary to allow a project manager to baseline ion propulsion on a spacecraft
- "1'0 stimulate commercial sources for and commercial uses of ion propulsion technology

Beginning in FY93 the NSTAR program has undertaken to validate ion propulsion technology using an approach with three principal elements:

- Identification of pertinent validation requirements by involving users in the process by which requirements are generated;
- Validation of lifetime, performance, and integration with a ground test program
- Measurement of the interactions between the ion propulsion system and the spacecraft, including the space plasma, by performing experiments in space.

The ion thruster selected for validation by the NSTAR program is a 30-cm gridded ion thruster that operates wit Xenon propellant and was designed at the Lewis Research Center (LeRC) to operate for 10,000 hours at 5 kW with a specific impulse of 3,200 s and an efficiency of 60%. Since the ion engine had never been tested for 10,000 hours, it was decided to "derate" the ion engine and under-lake to validate it to have a service life of 8,000 hours at a maximum input power of 2.3 kW (corresponding to 83 kg throughput of Xenon) and a specific impulse of 3,200 s and an efficiency of 60%. With this derating, the NSTAR system offers the potential of providing in the future a specific mass (kg/kW) twice that of the system being validated simply by validating it for its designed operation. A schematic of the ion thruster is shown in Figure E-3. It can be seen to consist of a cylindrical/conical discharge chamber in which Xenon is ionized by electrons emitted by a main cathode located on the centerline of the thruster, at its narrowest end. The discharge chamber is closed by two grids: an upstream screen grid and an accelerator grid. An external hollow cathode, called the neutralizer, provides the electrons that maintain the electrical neutrality of the plasma exiting the thruster.

The NSTAR program is jointly sponsored by NASA's Office of Space Science and Office of Space Access and Technology and is managed by the later. The NSTAR project is managed by NASA's jet Propulsion Laboratory (JPL), and is executed jointly by JPL, which is responsible for the Xenon propellant storage and control system and system diagnostics, and by NASA's Lewis Research Center (LeRC), which is responsible for the ion thruster and power processing unit.

The NSTAR program began by convening workshops to determine the performance and attributes identified by users as being important for an ion propulsion system. This information was assessed using a **QFD** process to prioritize these attributes and the functional parameters associated with their realization. Once potential users had identified the attributes they considered most important, and the QFD process had operated to identify the technical parameters associated with these attributes, the NSTAR program developed a set of specific validation requirements intended to demonstrate the ability of ion propulsion to provide the identified attributes. These highest priority validation requirements are shown in '1 able Ii-1. The data needed to satisfy these validation requirements arc obtained from the two principal activities of the NSTAR program: 1) ground-based testing to validate lifetime and performance and 2) in-space measurements to characterize the interactions between the spacecraft, including its nearby space plasma, and the ion propulsion system. Equipment for the in space portion of the NSTAR validation program, the ion thrusters, power processors, and the Xenon storage and control system is being provided by industry contractors.

The ground-based testing portion of the NSTAR program began with a 2,000-hour test of an engineering model thruster (EMT), designated EMT-1, with the purpose of identifying life-limiting mechanisms present during operation and of quantifying the rates associated with these processes. Following this test, several life-limiting mechanisms were identified which resulted in engineering modifications being made to the design of the main cathode, the screen grid electrical circuit, and the surface of the discharge chamber

Then the reworked version of the first EMT, designated EMT-1b, was subjected to a 1,000-hour, full-power test to determine the efficacy of the engineering changes. At the conclusion of this test it was determined that the life-lill~itillp rates observed in the earlier, 2,000 hour test had been reduced to negligible levels.

A new EMT (Figure E-4), designated EMT-2, was fabricated for use in an 8,000 hour, fLlll-power life demonstration test, which also used a breadboard power processing unit (BB PPU), shown in Figure E-5. Both the EMTs and the BB PPU were fabricated by LeRC. This test was intended to demonstrate the life capability of the ion thruster, as well as to demonstrate the ability ofa self-contained PPU to control the thruster at all power levels and to automatically place the system in a safe state in the event ofa malfunction

Two additional tests are planned for the NSTAR ground-test program. One is intended to demonstrate empirically the ability of the system to provide the required performance over the entire service lifetime, with a margin of 50% on life while operating for extended periods at throttled conditions, as would a spacecraft on a planetary mission. The required lifetime is 8,000 hours at full power, which translates to a Xenon throughput of 83 kg. A 50% margin requirement increases this throughput to 125 kg. Lifetime is then interpreted to mean a service life equivalent to a throughput of 83 kg, regardless of throttle level, with a similar interpretation for margin. Thus, the earliest test will demonstrate life at full power conditions, which are thought to be the most stressful for the ion thruster. The next test to be performed, the Throttled Thruster Test, will validate lifetime with extended operation at throttled conditions. Just as the earlier 8,000-hour test is using an ion thruster fabricated by the U.S. government, a thruster functionally identical to the flight units, and a government-supplied power processor, the subsequent Throttled Thruster Test will employ a flight ion thruster and a flight PPU. This test will be followed by another, the Thruster Cycling Test, which will also use a flight ion thruster and PPU and will demonstrate the on-off-cycling life of the NSTAR system.

The in-space element of the NSTAR program will consist of an ion thruster, a power processing unit, a digital control interface unit, a Xenon propellant storage and control unit, and a diagnostics system. The NSTAR-provided equipment will provide the propulsion for the first technology demonstration mission of the New Millennium Program, DS1, enabling the spacecraft to perform flybys of both an asteroid and a comet following its launch in the summer of 1998. A simplified block diagram of the NSTAR flight system for DS 1 is shown in Figure 3.-6. The power from the spacecraft, **provided** by **the** BMDO's **S**CARLET linear concentrator solar array, is used to supply high voltage (80 V to 160 V) and regulated 28 V to the Digital Control Interface Unit (DCIU) and the Power Processing Unit (PPU). The DCIU maintains the command and telemetry interface with the spacecraft (using a 1553 protocol), receiving and decoding commands from the spacecraft and providing telemetry data to be downlinked to the ground by the spacecraft. The power processing unit receives commands from the DCIU that turn the ion thruster on and off and set the operating power level established by the spacecraft. The PPU converts the input power from the spacecraft into the voltages and currents commanded by the DCIU for the ion thruster based on the operating power level commanded by the spacecraft. The DCIU also controls the flow control system in the Xenon Propellant Storage and Control System (PSCS) to ensure that the flow rates for each of the ion engine's two cathodes and that of the main flow are appropriate for the power level commanded by the spacecraft. The Xenon PSCS stores Xenon in a super-critical state and distributes it to the ion thruster.

The final element of the NSTAR flight system is the diagnostics system (1 igure *ii-7),* which consists of two multi-sensor units and a Digital Sensor Electronics Unit (DSEU). The DSEU distribute 28 V power from the spacecraft to each of the multi-sensor units and provides data to the spacecraft for transmission to the ground using a 1553 protocol Each of the multi-sensor units consists ofa Langmuir probe, a retarding potential analyzer, and a contamination monitor that uses a quartz crystal microbalance and an optical sensor. NSTAR's diagnostics system is based on JPL's successful SAM MIES distributed sensing system and is provided, through a contract with JPL, by

Scientific, inc. (PS1).

The experience gained during fabrication of the EMTs and a BB PPU by LeRC, and the results of the long-duration and development tests in which these units were used provided essential data for Hughes Electron Dynamics Division (HEDD), the contractor selected to provide the flight ion thrusters, PPUs, and DCIUs. HEDD, in turn, selected Spectrum-Astro to provide the DCIU under a subcontract. This contract is managed by LeRC.

Moog, Inc., Space Products Division and JPL entered into an agreement to develop and provide a qualified Xenon propellant storage and control system This system (Figure E-8) controls the flow rates of Xenon to the ion thruster's discharge chamber as well as to the two hollow cathodes with high flow resistance flow restrictors. The input pressure to these restrictors is sensed by pressure transducers monitored by the DCIU, which operates solenoid valves to maintain these pressures at a level consistent with the thruster's operating power level as determined by a preprogrammed table and algorithms. The Xenon is stored in a high-pressure, filament-wound tank capable of holding 83 kg of Xenon at super-critical conditions.

At this writing, the NSTAR system i.well under way. The ground test program has completed full-power tests with the EMTs that lasted 2,000 hours and 1,000 hours, and is now conducting an 8,000-hour, full power test with an EMT and a BB PPU. Prior to the start of the 8,000-hour test, a comprehensive review of all available data taken from tests of the thruster indicated wear-out rates consistent with a thruster life well in excess of the planned *8,000-* hour duration.

HEDD and Moog, inc. arc nearing completion of the designs for the flight equipment. The schedule for Critical Design Reviews and for the delivery of flight hardware to the NMP 1X-1 spacecraft arc shown in Table 1:..11, Indicated in Table III arc the planned test programs for each of the contractor-provided units. Acceptance tests consist of functional tests and a series of environmental tests designed to verify performance and workmanship. Protoflight tests consist of environmental tests to demonstrate the margin relative to the predicted flight experience. The Thruster Throttling Test and the Cycling Test constitute the remainder of the gt-outl~-test program. The Thruster Throttling Test is a long duration test using the hardware elements shown in Table E-11 I and is designed to validate the full service lifetime and Xenon throughput at reduced power levels. The Cycling test is designed to validate system operation at full power while providing a service cycle life of 5,000 on/off cycles

The il)-space portion of the NSTAR program is directed at measuring the interaction between the ion propulsion system and the spacecraft, including effects on the surrounding space plasma. The NSTAR diagnostics package will directly measure the contamination and plasma effects at critical points on the spacecraft and EMI. In addition, specialized experiments will measure the effects of ion propulsion on communications (Ground testing has indicated that the effects of ion propulsion on communications are negligible; these in space measurements are expected to verify these data.

Electrical parameters from the ion thruster and PPU measured on the spacecraft during ion thruster operation will be transmitted to the ground. In conjunction with data taken from navigation and tracking measurements, these data will be used to compare performance data taken during ground testing with in-flight experience. '1 he objective of this comparison is the validation of ground testing as either a "good" simulation of in-space operation of an ion thruster or as a conservative one. If ground testing is shown to be conservative, then an attempt to assess the degree of conservatism will be made.

Further, the experience of integrating an ion propulsion system onto the DS- 1 spacecraft and operating it during the mission flyby to an asteroid and a comet will be used to estimate the effect of incorporating an ion propulsion system on the DDT (design, development and test) and operations costs of a planetary mission

When completed, the NSTAR program will have validated the performance of a 2.5 kW ion propulsion system capable of operation over an input power range of 0.5 kW to 2.5 kW, having a service life equivalent to a throughput of 83 kg of Xenon (regardless of power level) and having a fu]l-power Isp of 3,100 s and overall efficiency of 55%. This validation will also have shown the relationship between ground testing results and those obtained in space. Further, the effect of operating an ion propulsion system on a planetary spacecraft will have been assessed. Importantly, industrial sources for ion propulsion, flight equipment will have been put in place (1 IEDD for ion thrusters, PPUs, and DCIUs and Moog, Inc for Xenon propellant storage and control systems).

Future Electric Propulsion Systems

The ion propulsion system validated by the NSTAR program represents the lowest level of the performance of which high-performance electric propulsion is capable. '1 he performance of electric propulsion systems is often characterized by its specific mass termed "a", that is the ratio of the mass of the electric propulsion system to the maximum power that system processes. The a of the NSTAR flight system for 1> S-1 is approximately 50 kg/kW, which includes propellant but not the mass of the solar array. For systems that use more than one thruster and power processing unit, the a for NSTAR could be expected to drop to a value of 30 kg/kW to 40 kg/kW. Relatively straightforward improvements to the NSTAR design, such as carbon-carbon grids to increase the power handling capability of the ion thruster and to extend its lifetime by a factor of two, could be expected to reduce *the* NSTAR a by a factor of 2 to 4. Further improvements would be effected by reducing the mass of the components used for Xenon propellant storage and control, and by designing the solar array so that the voltages needed by the electric thruster are provided by the solar array directly, thereby replacing the PPU with a device to configure the cells of the solar array electrically. Such a solar array configuration is frequently referred to as "direct drive". Such technology advances are expected to lead ultimately to an a of 2 to 5 for an electric propulsion system. A summary of the effect of these technology advancements on mission performance is shown in Figure E-9.

These improvements apply directly, like the NSTAR system, to planetary spacecraft having a mass greater than 25 to 50 kg, not including that of the electric propulsion system. For smaller spacecraft, a major technology challenge would be to keep the fraction of the spacecraft's launch mass associated with the electric propulsion system (or a chemical propulsion system) constant. To do so would require the mass of the propellant storage and control system's components, of the PPUs, and of the thrusters themselves to drop proportionally with the reduction in the mass of the spacecraft. Such a reduction implies the application of technology advancements not being pursued today.

Summary

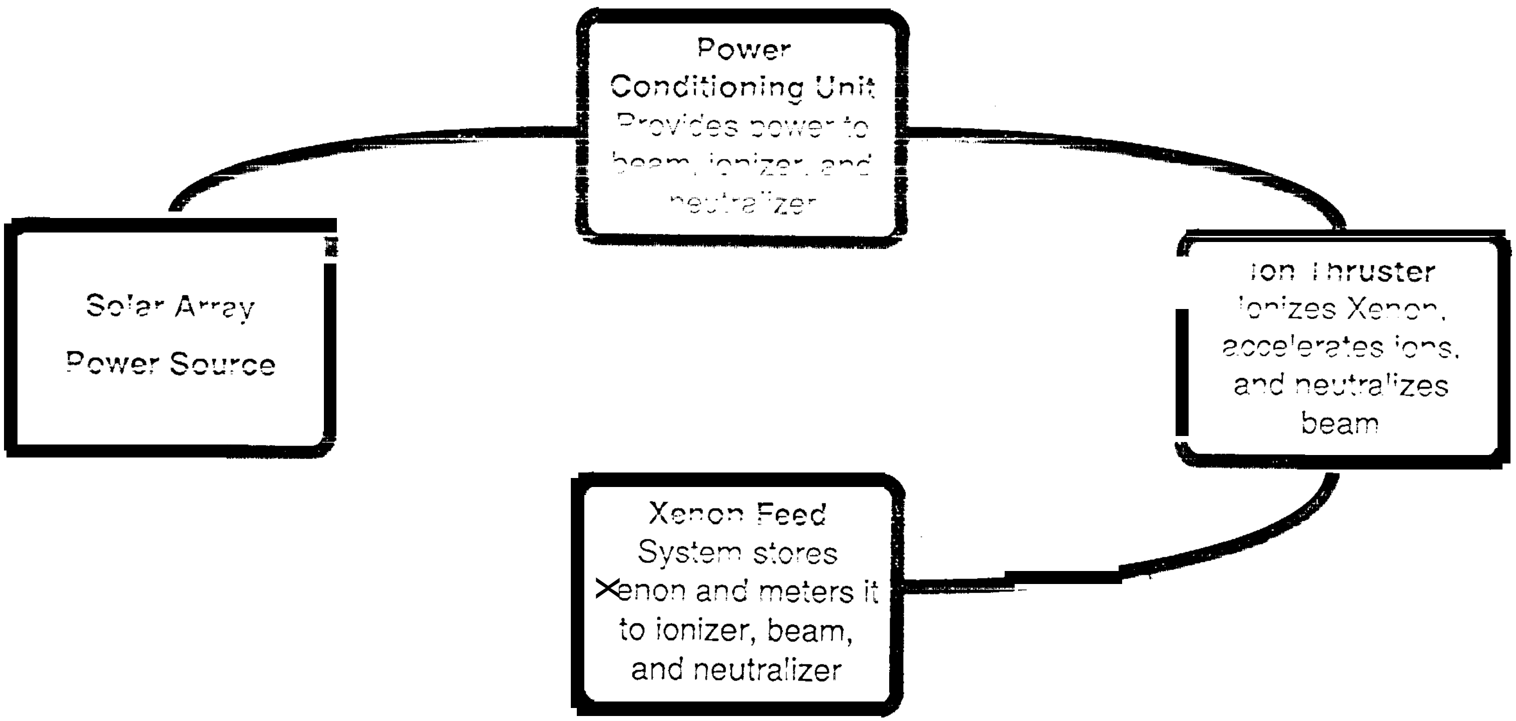
- The NSTAR program will validate performance and lifetime of low-power ion propulsion technology for planetary mission applications.
- The NSTAR program is on schedule to accomplish its objectives and provide a flight ion propulsion system for the DS 1 spacecraft of the NASA New Millennium Program.
- Future technology advancements for electric prolusion are to be directed at:
  - Reducing the specific mass of ion propulsion systems.

- Maintaining, or reducing, the fraction of spacecraft launch mass devoted to electric propulsion as the launch mass of planetary spacecraft is reduced below 25 kg.

Figures

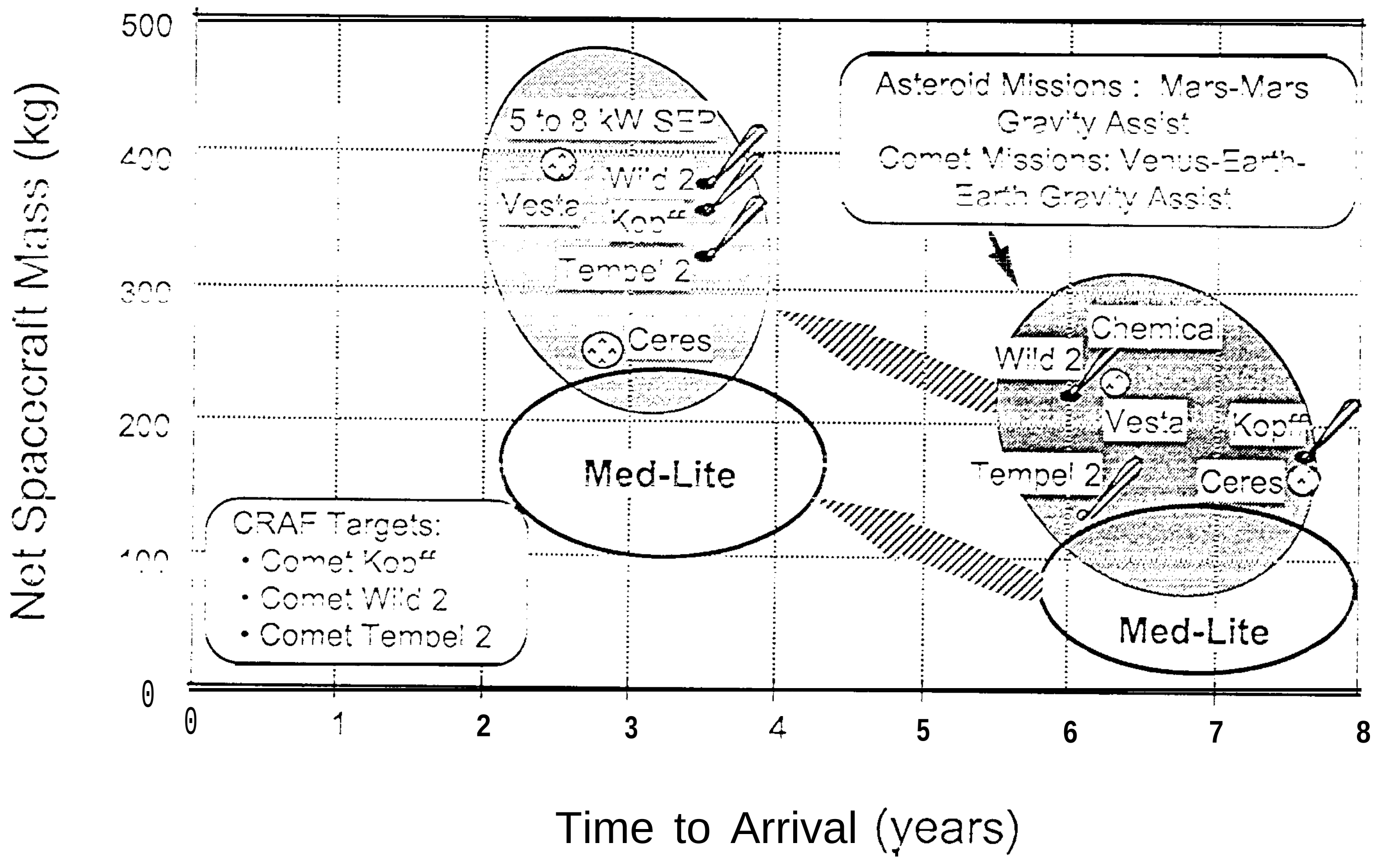
Tables

Ion Propulsion Requires Four Elements



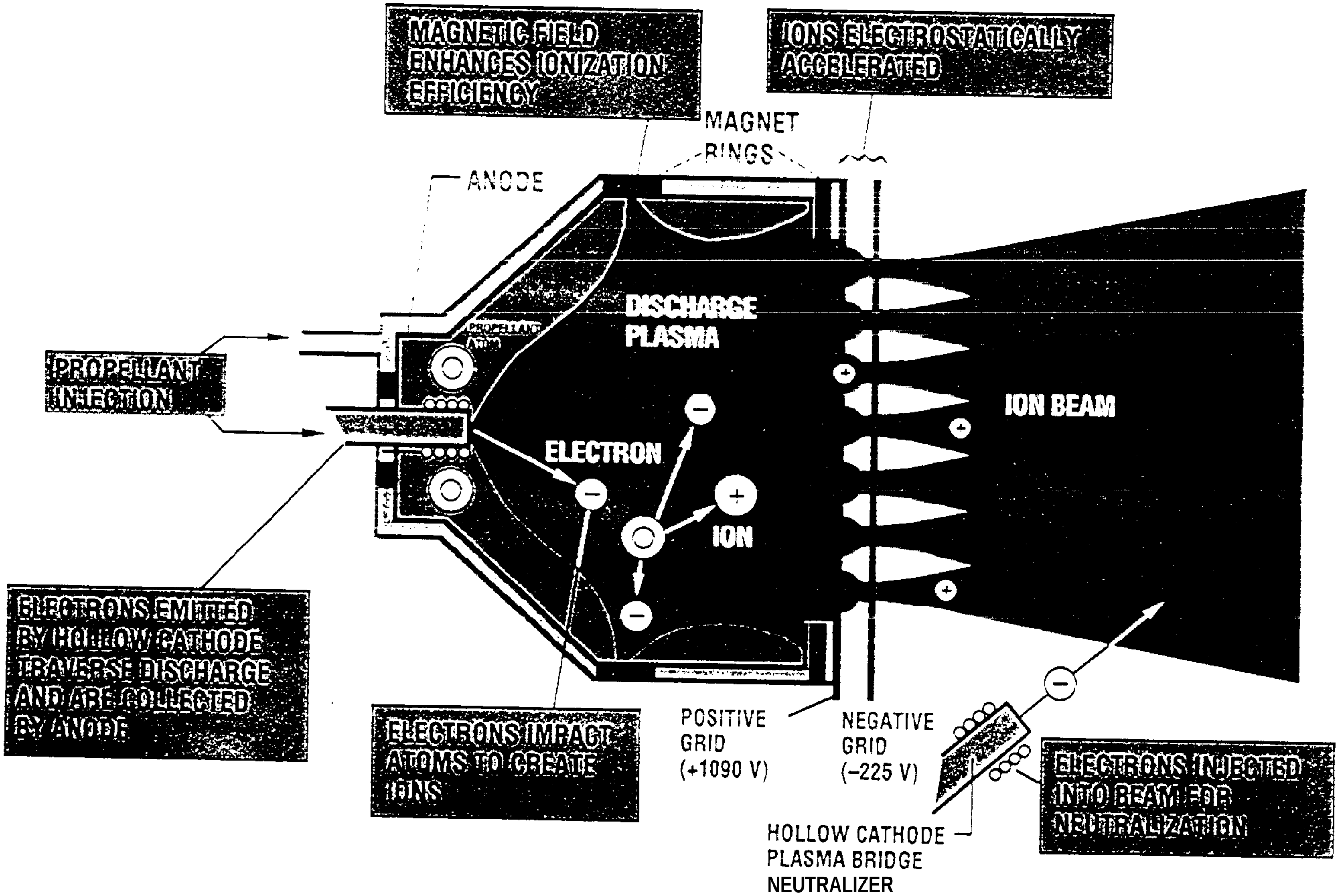
E-2

Comparison of SEP and Chemical Propulsion Asteroid and Comet Rendezvous Missions Launched by Delta II (7925)

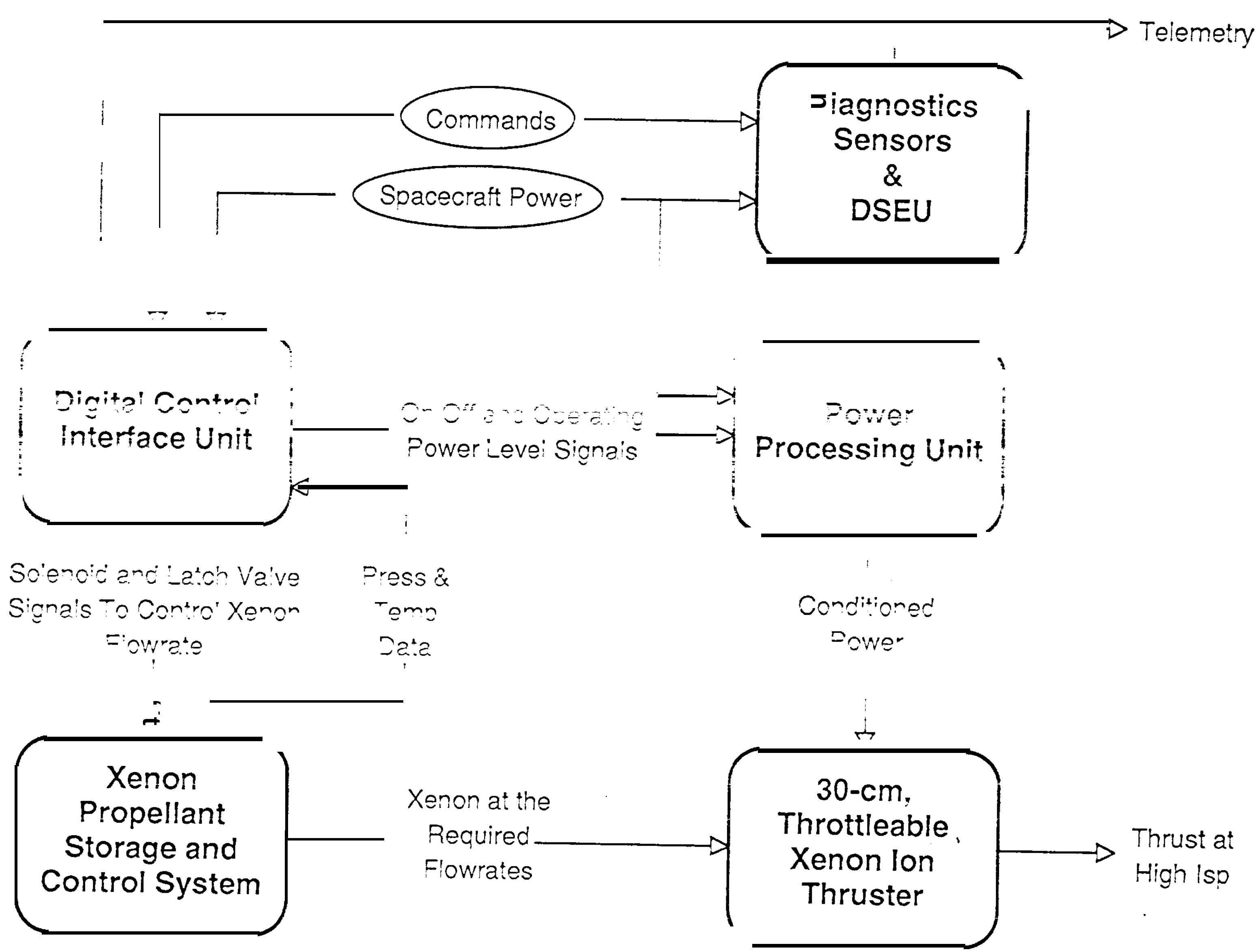


E3

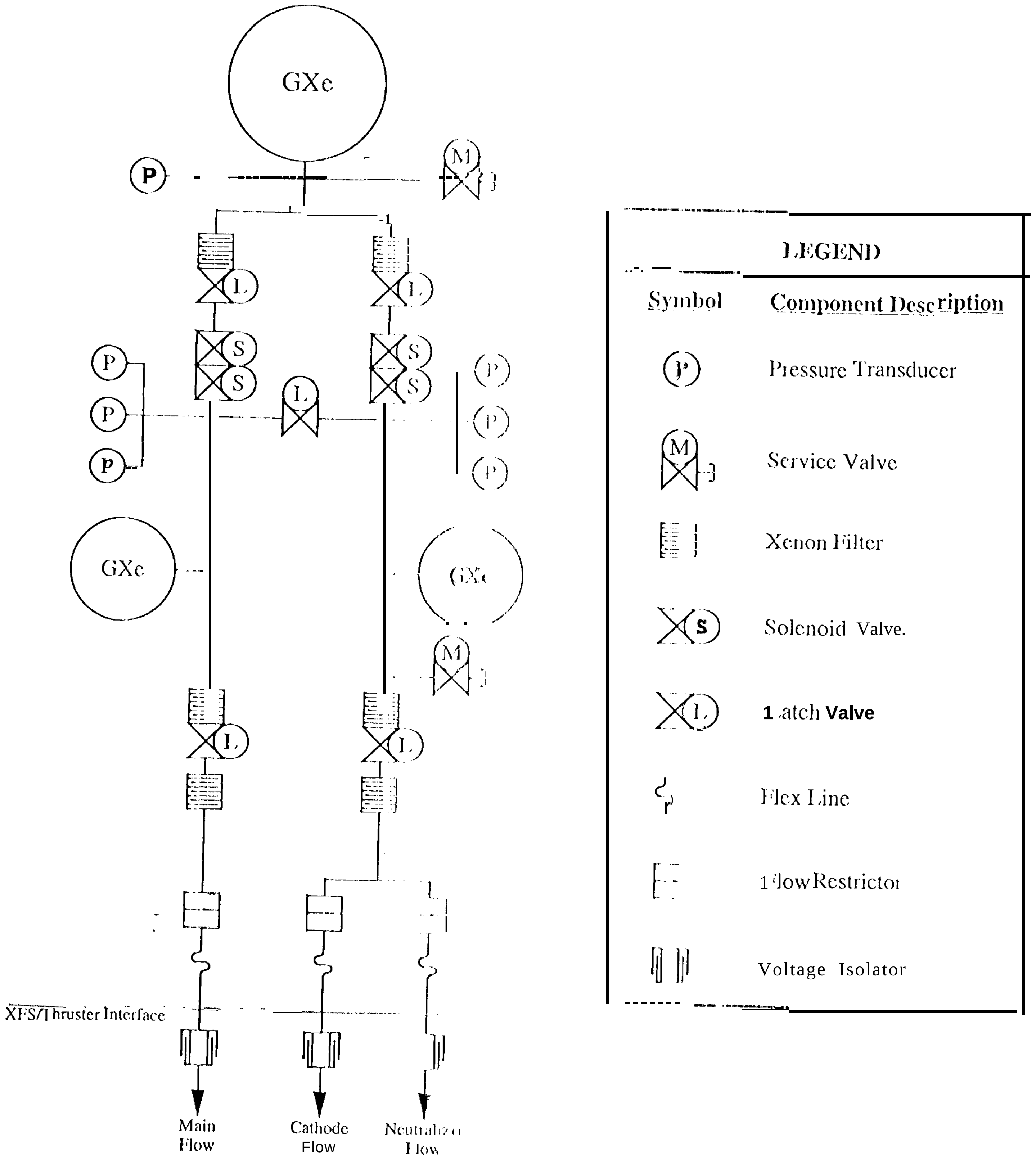
ION THRUSTER ELEMENTS AND FUNCTIONS



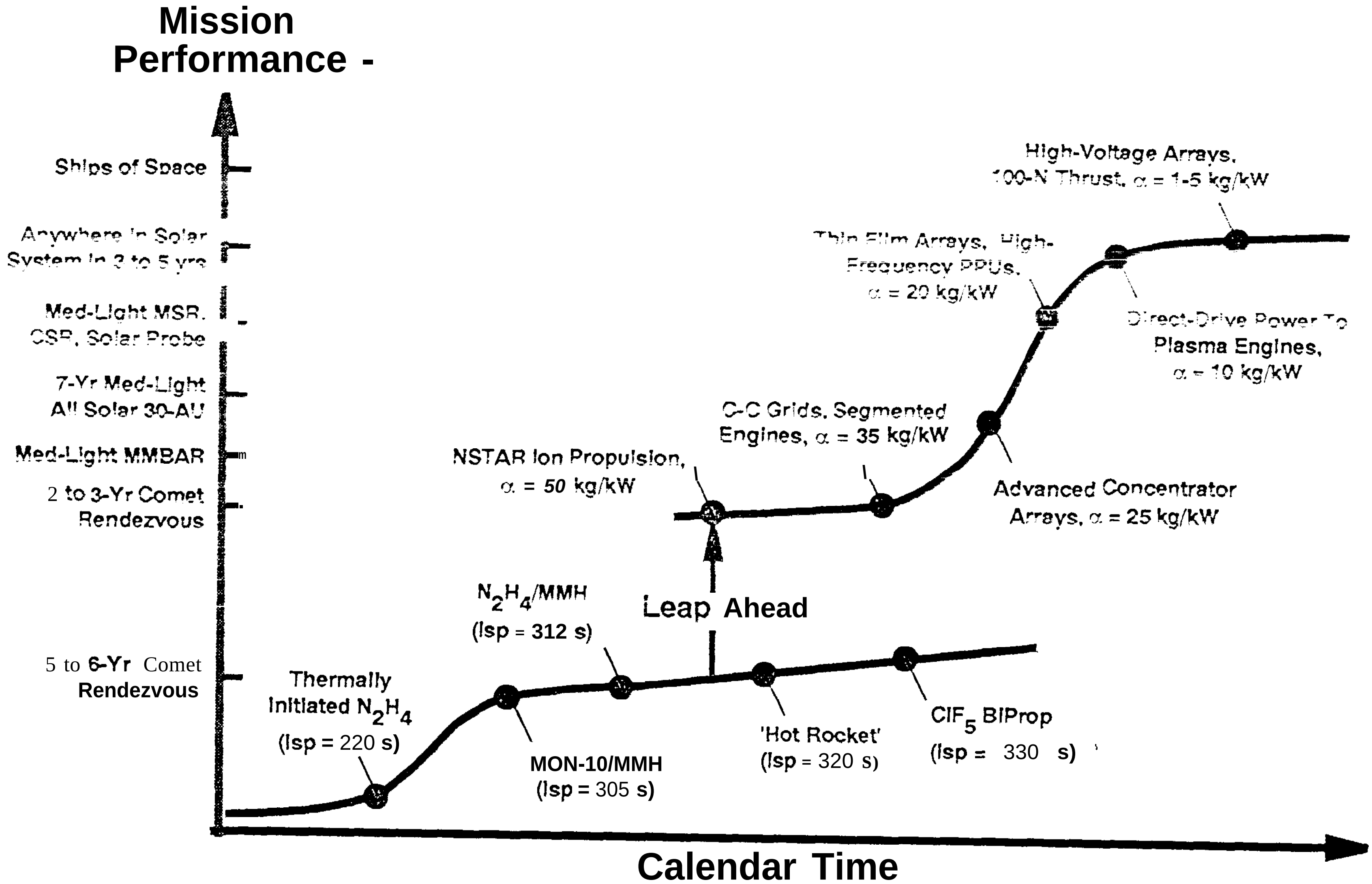
NSTAR DS-1 Block Diagram



NSTAR Xenon Propellant Storage and Control System



NSTAR Begins a New Era In Solar System Transportation



Overview of Validation Requirements

Validate

Life

- Demonstrate a throughput of 83 X 1.5 kg of Xenon

Performance

- Isp = 3,160 sec
- Eff. overall > 55% (max. pwr.)

Mass

- Total dry mass < 55 kg

Power

- Throttleable from 0.5 kW to 2.5 kW

Measure in-Space Interactions

Direct

- Contamination, communications, EMI, plasma

Indirect

- GN&C and Mission Operations

Major NSTAR Program Events

Critical Design Reviews

Date	Review	Location
6/18/96	Ion Thruster	HEDD
6/18/96	Power Processing Unit	HEDD
6/18/96	Digital Control Interface Unit	HEDD
7/23/96	Propellant Storage and Control System	JPL
8/14/96	Diagnostics System	JPL
10/15/96	NSTAR	JPL

Flight Deliverables

Delivery Date	Deliverable Item
8/1/97	Propellant Storage and Control System
8/1/97	Diagnostics System
8/5/97	Ion Thruster
8/5/97	Power Processing Unit
8/5/97	Digital Control Interface Unit

Principal Ground Tests

Date	Test	Hardware
11/94	2,000 Hours at full power	Engineering Model Thruster (EMT)
10/95	1,000 hours at full power	Modified EMT
4/96	8,000 hours at full power	EMT & Bread Board PPU
12/97	Life Margin Test with Throttling	Flight Ion Thruster and PPU Engineering Model PSCS
8/97	Cycle Life Test	Flight Ion Thruster and PPU Engineering Model PSCS