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The Ion Propulsion System For Dawn

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Introduction

The Dawn Project's mission is to rendezvous and map the two heaviest main belt asteroids Vesta and Ceres. The Ion Propulsion System (IPS) for Dawn will be used for the heliocentric transfer from the Earth to Vesta, orbit capture at Vesta, transfer to a low Vesta orbit, departure and escape from Vesta, the heliocentric transfer from Vesta to Ceres, orbit capture at Ceres, and transfer to a low Ceres orbit. In addition, the IPS will provide pitch and yaw control of the spacecraft during IPS thrusting. The total ΔV provided by the IPS is greater than 11 km/s. This is by far the largest ΔV ever provided by an on-board propulsion system for a planetary spacecraft.

Architecture

The driving requirements for the Dawn IPS are that it must be single fault tolerant while being able to process up to 450 kg of xenon over an input power range of 524 to 2567 W with input voltages from 80 to 160 V and a mission duration of ten years. The Dawn IPS is made up of building blocks designed to allow configurations ranging from a single thruster system like Deep Space 1 [1-6] to multiple thruster systems like Dawn. This section summarizes the architecture and functions of the flight IPS.

IPS Functional Description

The flight IPS is partitioned into the following six subsystems:

1. Flight Thruster (FT).
2. Power Processor Unit (PPU).
3. Digital Control Interface Unit (DCIU).
4. Xenon Feed System (XFS).
4. Gimbals and Gimbal Drive Electronics (GDE).
5. Mechanical Integration Hardware (MIH) including cabling.

The high-level block diagram given in Fig.1 indicates that the Dawn IPS consists of three ion thrusters, a 2-axis mechanical gimbal for each thruster, two PPUs, two DCIUs, a xenon feed system and the interconnecting cabling. This figure also indicates which IPS components are identical or similar to those demonstrated on Deep Space 1 [3], and which are new. The ion thrusters for Dawn are identical to the DS1 flight thrusters. The PPUs, DCIUs and Xenon Control Assembly (XCA) are modified versions of their DS1 counterparts, and the gimbals and xenon tank are new designs.

The PPUs are partially cross-strapped to the thrusters. PPU 1 is connected to Thurster 1 and Thruster 2. PPU 2 is connected to Thruster 2 and Thruster 3. Therefore, Thruster 2 is connected to both PPUs and is referred to as the "shared thruster." There are two DCIUs, each one is capable of controlling the entire IPS. Only one DCIU is used at a time, the other is maintained as a cold spare. The DCIUs are cross-strapped to the PPUs and to the xenon control assembly.

The block diagram of the Dawn IPS given in Fig. 2 shows the interfaces between IPS subsystems and the spacecraft. These interfaces reflect a conventional division of responsibility between the spacecraft, to be provided by Orbital Sciences Corporation, and an on-board propulsion unit. The spacecraft provides the electrical power, structural supports/mechanical devices, thermal control elements, command and data handling, and telecommunications for operation of the IPS. This figure also identifies the source for each of the major IPS components and the overall spacecraft.

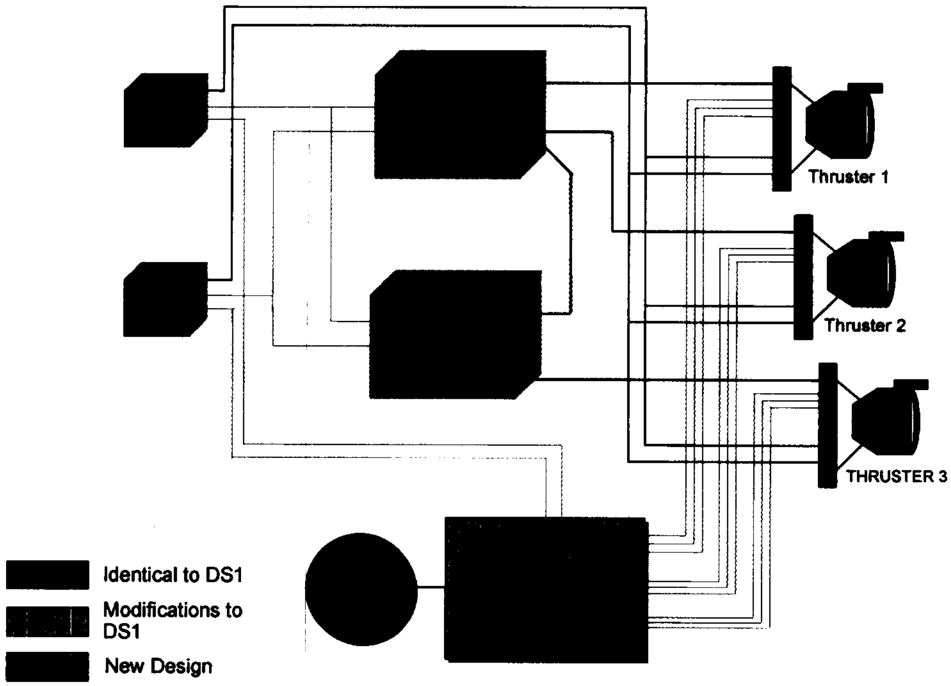

Fig. 1 High-level block diagram of the Dawn IPS.

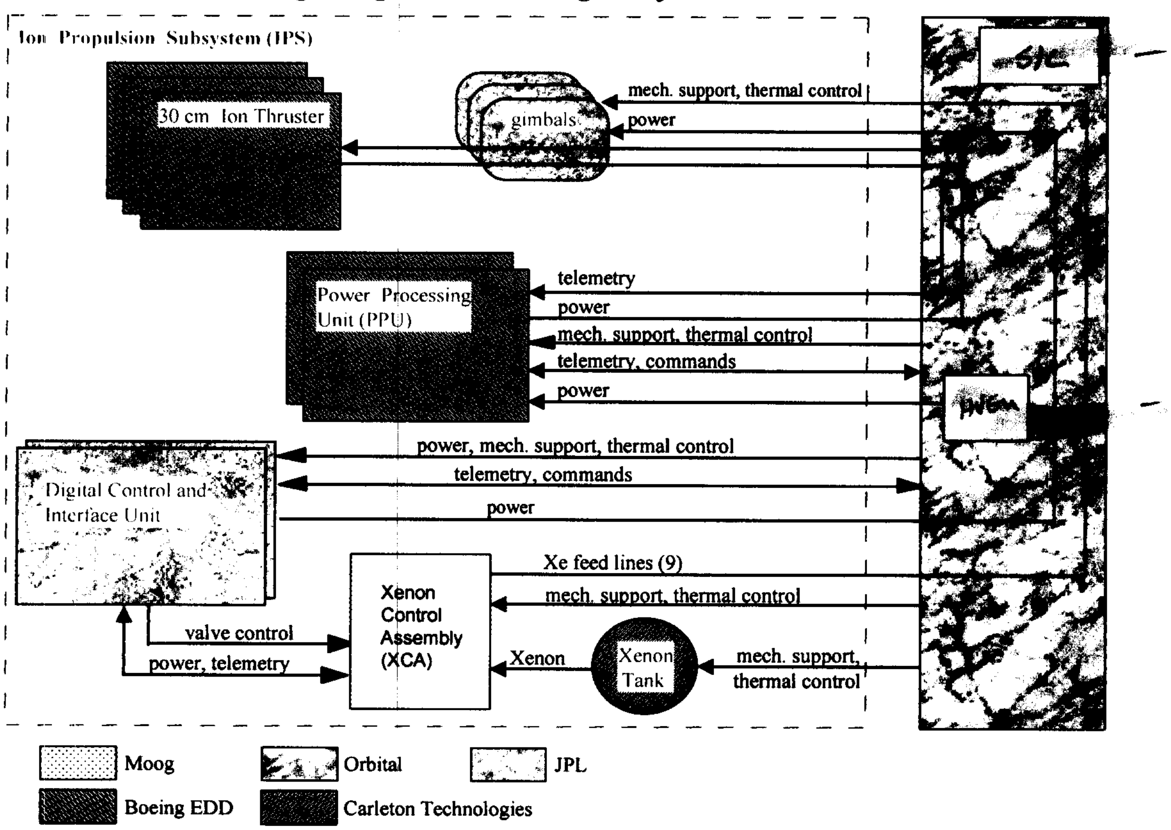

Fig. 2. Dawn IPS interface block diagram.

Subsystem Descriptions

Descriptions of the six flight IPS subsystems as configured for Dawn are described below.

Flight Thruster (FT)

Dawn will use the NASA 30-cm diameter ring-cusp xenon ion thruster developed under the NSTAR project [3] and validated on DS1 [3-6]. A photograph of the thruster is given in Fig. 3. The NSTAR/DS1 thruster has been subjected to over 58,000 hours of testing and in-flight operation including 16,265 hours on DS1 and 30,352 hours in the Extended Life Test at JPL [7]. The thruster can operate over an input power range of 0.5 to 2.3 kW with the end-of-life (EOL) performance indicated in Table 1. The capability to throttle thruster operation to match available input power is essential for the Dawn mission which must operate over a heliocentric distance from 1 AU to 2.8 AU. The Dawn spacecraft will operate only one thruster at a time and each thruster is expected to be subjected to no more than a few hundred on/off cycles. The total mass of a flight thruster is 8.2 kg.

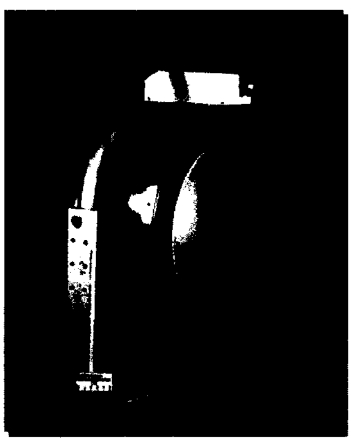

Fig. 3. The NSTAR/DS1 ion thruster is identical to the one to be used on Dawn.

Power Processor Unit (PPU)

The PPU converts the 80-160 V input power from spacecraft solar arrays into the currents and voltages needed to start and operate the thruster. The PPU is identical to the NSTAR/DS1 PPU [3] shown in Fig.4 with the following exceptions:

1. The interface between the PPU and the DCIU has been modified to enable multiple DCIUs to be cross-strapped to each PPU in the Dawn IPS.
2. An additional telemetry circuit has been added to enable the measurement of the peak-to-peak voltage on the neutralizer keeper electrode. This measurement is used to identify neutralizer operation in plume mode.
3. The neutralizer keeper current at low power has been increased from 2.0 A to 2.4 A to to increase the neutralizer flow rate margin based on the results from the plume mode survey performed during the DS1 Hyper-Extended Mission [6].
4. The maximum current capability of the grid-clear circuit has been approximately doubled from the original NSTAR design.

Each PPU can be switched between two thrusters, but can only supply power to only one thruster at a time. The PPU conversion efficiency is ≥ 90% at all combinations of input voltage, output power and baseplate temperatures. The PPU mass is ≈ 13.3 kg. Each PPU is required to be capable of operating two thrusters consecutively for their entire service life times.

Fig. 4. The NSTAR/DS1 PPU shown here is nearly identical to the PPUs to be used on Dawn.

Xenon Feed System (XFS)

The XFS includes the xenon propellant tank, a xenon control assembly (XCA), two plenum tanks, and several service valves used to enable cathode purging. A schematic of the DAWN XFS is shown in Fig. 5. The Dawn XFS is identical to the NSTAR/DS1 system [8] with the following exceptions:

1. The system has been expanded to provide xenon feeds to three thrusters
2. Redundant latch valves have been added to those used to select each thruster in order to make the system single fault tolerant.
3. Two latch valves have been added on the low pressure side of the XCA to enable evacuation of and vacuum bakeout after launch.
4. A new xenon tank is being developed by Carleton Technologies. This lightweight composite overwrapped tank is sized to hold up to 450 kg of xenon and has an estimated mass of approximately 19 kg.

The Dawn XCA uses the same "bang-bang" pressure regulation system used on DS1 [8]. The Maximum Expected Operating Pressures (MEOP) are 15 MPa absolute (2175 psia) for the high pressure side, and 683 kPa absolute (99 psia) for the low pressure side.

The current best estimate of the mass of the XFS for the Dawn including the xenon tank, XCA, plenum tanks, service valves and propellant tubing is approximately 24 kg.

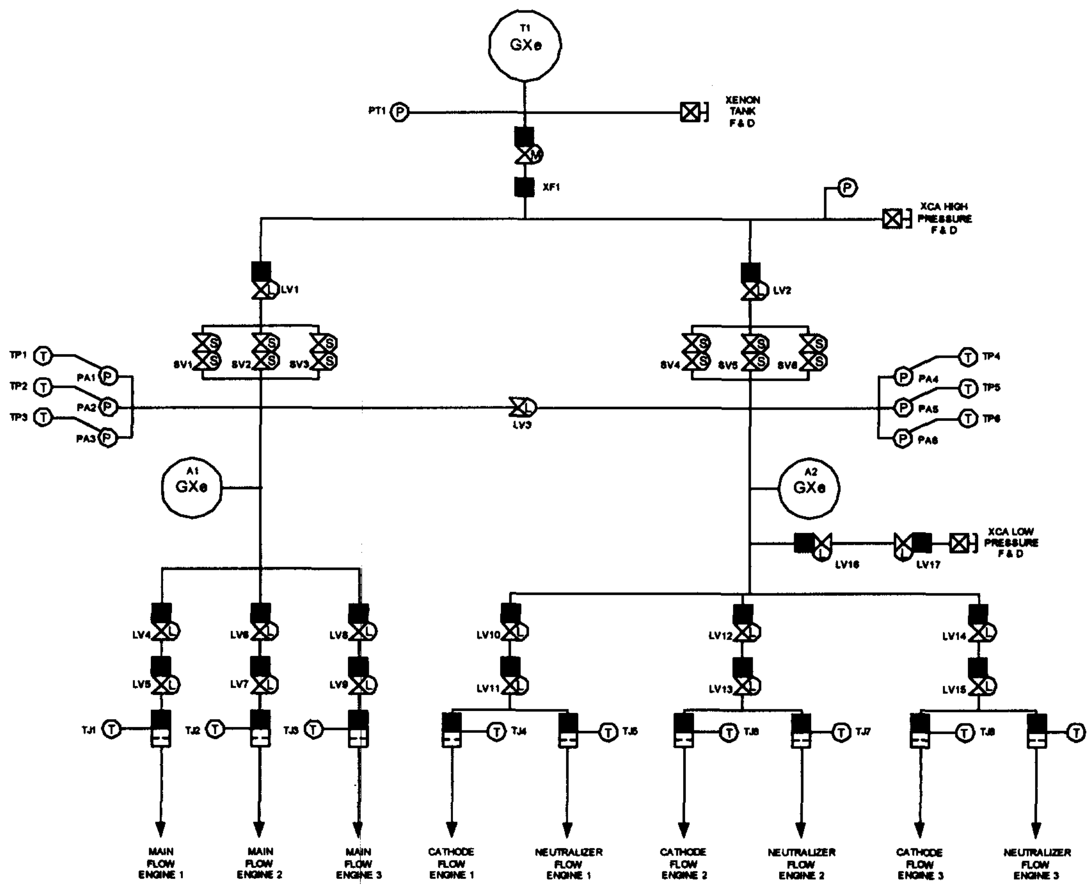

Fig. 5. IPS XFS block diagram (service valves used for cathode purges are not shown).

Gimbals

The key requirements for the Dawn IPS gimbals the differ from DS1 are:

1. A range of motion of ±5 deg. in one axis and ±7 deg. in the other.
2. A service life of several million partial-stroke cycles.
3. A ten-year survival life in space.
4. A mass goal of 3 kg. (The DS1 gimbal had a mass of approximately 15 kg.)

The Dawn gimbal is pictured in Fig. 6. This hexapod gimbal approach was selected on the basis that it was the most likely to meet the key requirements listed above. The gimbal drive electronics for the actuator motors are located in the IPS DCIUs.

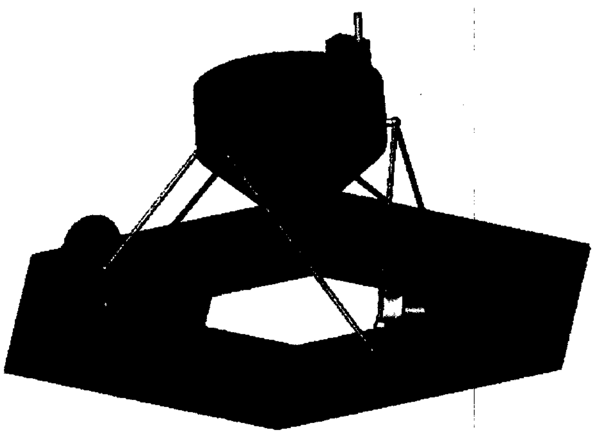

Fig. 6. Drawing of the Dawn hexapod gimbal.

Digital Control Interface Unit (DCIU).

The DCIUs control and monitor the PPUs and XFS. PPU functions are controlled through a dedicated bus to a PPU command/telemetry interface unit, and the XFS functions through drive and control circuitry located in each DCIU. A dedicated command/telemetry interface in the operating DCIU channels all IPS data to the spacecraft command and data subsystem; i.e., no spacecraft commands or IPS telemetry bypass the DCIU. The spacecraft, however, controls all primary power supply to the IPS (high and low power buses) and the overall thermal state of the IPS. Once the IPS has been initialized (through the judicious powering of the selected DCIU and PPU, and an initialization command), DCIU software includes all commands to automatically configure the PPU and XFS to take the thruster from dormancy, through startup, to steady state operation at one of 111 thruster input power setpoints, or to throttle the thruster from a current operating point to a new command setpoint. The pressure in the xenon plenum tanks are regulated to match neutralizer and discharge cathode and main xenon flows to the thruster input power setpoint.

The DCIUs differ from the NSTAR/DS1 flight units in three ways:

1. They include a larger number of valve driver circuits because of the XCA must accommodate three ion thrusters.
2. They are cross-strapped to the PPUs and XCA. The capability was not included in the original PPU design.
3. They include the motor drive electronics for the gimbal actuators.

Other DCIU functions include configuring of the XFS after launch, conditioning thruster cathodes, safing of the IPS, and collecting status data and engineering data for telemetry to the spacecraft; e.g. currents, voltages, IPS internal temperatures and XFS main and plenum tank pressures. The current best estimate of the Dawn DCIU mass is 3.5 kg. A block diagram of the DCIU is given in Fig. 7.

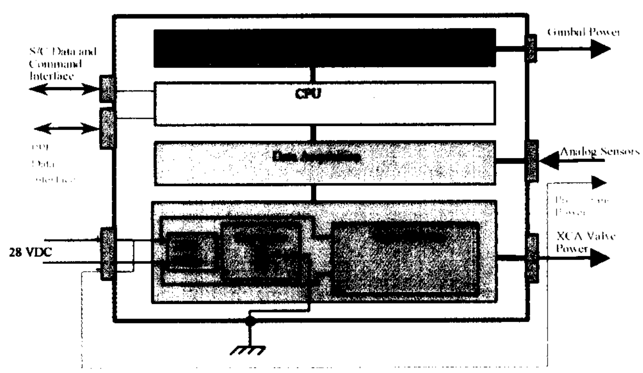

Fig. 7. DCIU block diagram.

Mechanical Integration Hardware (MIH)

The MIH includes structural and thermal hardware integral with IPS elements and cabling between IPS subsystems and components. Structural elements for installing the IPS, heat rejection elements integral with the spacecraft, and cabling between the spacecraft and the IPS will be furnished by Orbital. The current best estimate for the MIH is approximately 9 kg.

IPS Mission Requirements

The Dawn mission goals are to rendezvous with the two heaviest main-belt asteroids Vesta and Ceres. The detailed trajectory analyses are still being performed. However, an example of the input power to the PPU as a function of mission time from a representative trajectory is given in Fig. 8. Early in the mission the solar array provides more power than can be used by the IPS, and the input power is fixed at its maximum value of 2.56 kW. As the spacecraft gets farther from the sun the available solar array power decreases until it can no longer support full power IPS operation. At this point the thruster is throttled to follow the available power. The average PPU input power for the heliocentric transfer to Vesta is slightly less than 2 kW. For the heliocentric transfer from Vesta to Ceres the average PPU input power is approximately 1 kW.

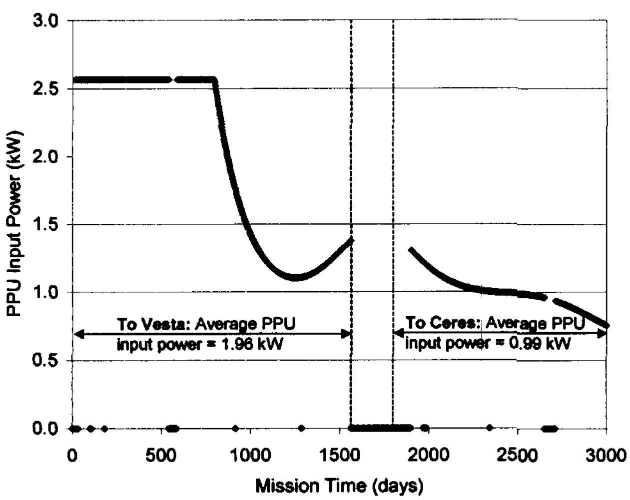

Fig. 8. Representative variation in PPU input power with mission time.

The propellant used as a function of IPS operating time is given in Fig. 9. This figure indicates that nearly 300 kg of xenon are needed to get to Vesta. The current operations plan for Dawn will use two of the three IPS thrusters for the transfer to Vesta, keeping the third thruster as a spare. This enables the IPS to be single fault tolerant through the mission to Vesta. Each of the first two thrusters must process approximately 150 kg of xenon at an average PPU input power of 2 kW. The third thruster is used for the transfer to Ceres and must process approximately 110 kg of xenon at an average PPU input power of 1 kW. The propellant processed in the Extended Life Test (ELT) of the DS1 flight spare ion engine [7] is also plotted in Fig. 9 for comparison. However, Dawn will plan to use two thrusters to process the propellant required to get to Vesta

The xenon used for each mission phase and loaded for contingencies is given in Fig. 10.

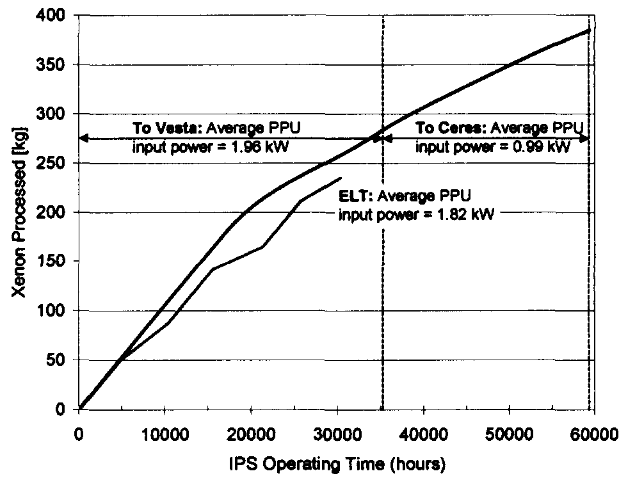

Fig. 9. Xenon usage as a function of IPS operating time.

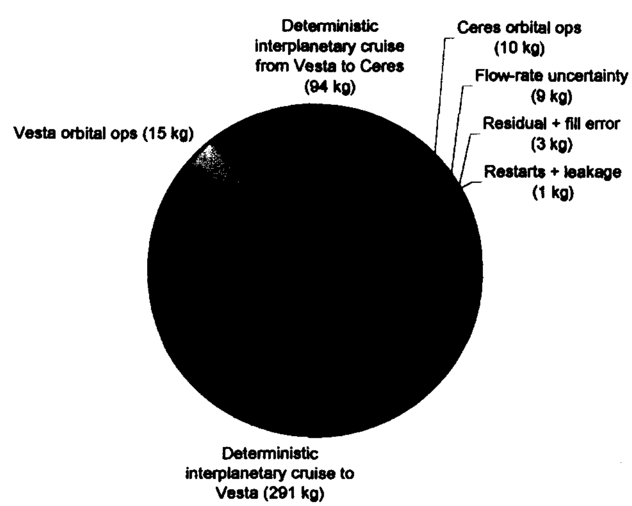

Fig. 10. Required xenon for Dawn mission phases.

Summary

The Dawn mission will be the first use of ion propulsion on a full up science mission for NASA. The ion propulsion system for Dawn is based on that demonstrated on Deep Space 1 with modifications necessary to accommodate multiple thrusters, to make the system single fault tolerant, to reduce the mass of the mechanical gimbals, and to accommodate a much larger propellant load. To rendezvous with the two heaviest main-belt asteroids, Vesta and Ceres, Dawn will carry 450 kg of xenon, whereas DS1 carried only 81.5 kg of xenon.

Acknowledgements

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References

1. M. D. Rayman, P. Varghese, D. H. Lehman, and L. L. Livesay, "Results From The Deep Space 1 Technology Validation Mission," IAA-99-IAA.11.2.01, Presented at the 50th International Astronautical Congress, Amsterdam, The Netherlands, 4-8 October, 1999, Acta Astronautica 47, p. 475 (2000).
2. M. D. Rayman and P. Varghese, "The Deep Space 1 Extended Mission," Acta Astronautica 48, No. 5-12, pp. 693-705 (2001).
3. Brophy, J. R., et al., "Ion Propulsion System (NSTAR) DS1 Technology Validation Report," JPL Publication 00-10, October 2000.
4. J. E. Polk, et al., "Validation of the NSTAR Ion Propulsion System on the Deep Space One Mission: Overview and Initial Results," AIAA 99-2274, presented at the 35th Joint Propulsion Conference and Exhibit, 20-24 June 1999, Los Angeles, California.
5. J. E. Polk, et al., "Demonstration of the NSTAR Ion Propulsion System on the Deep Space One Mission, IEPC-01-075, Presented at the 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October, 2001.
6. Brophy, J. R., Brinza, D. E., Polk, J. E., Henry, M. D., and Sengupta, A., "The DS1 Hyper-Extended Mission, AIAA-2002-3673, presented at the 2002 Joint Propulsion Conference, Indianapolis, IN, July 7-10, 2002.
7. Sengupta, A., Brophy, J. R., Goodfellow, K. D., "Status of the Extended Life Test of the Deep Space 1 Flight Spare Ion Engine after 25,700 Hours of Operation," AIAA-2003-4558, to be presented at the 2003 Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.
8. Ganapathi, G. B. and Engelbrecht, C. S., "Performance of the Xenon Feed System on Deep Space One," *J. Spacecraft and Rockets*, vol. 37, No. 3, pp 392-398, May-June 2000.