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ION PROPULSION: AN ENABLING TECHNOLOGY FOR THE DAWN MISSION

Charles E. Garner,* Mark M. Rayman,† Greg J. Whiffen‡, John R. Brophy** and Steven C. Mikes++

The Dawn mission, part of NASA's Discovery Program, has as its goal the scientific exploration of the two most massive main-belt asteroids, 4 Vesta, and the dwarf planet 1 Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H-9.5 rocket that placed the 1218-kg spacecraft into an Earth-escape (heliocentic) trajectory with an escape velocity of 11 km/s. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory which will provide an additional delta-V of approximately 11 km/s for the heliocentric transfers to each body and for all orbit transfers including orbit capture/escape and transition to the various science orbits. Deterministic thrusting to Vesta began in December 2007 and concluded with orbit capture at Vesta in July 2011. The transfer to Vesta included a Mars gravity assist flyby in February 2009 that provided an additional delta-V of 2.6 km/s and was the only post-launch mission delta-V not provided by IPS. The IPS was used during the 14 months at Vesta for all science orbit transfers and then for Vesta escape. Deterministic thrusting for Ceres began in late August 2012 with a planned arrival date at Ceres in early 2015, whereupon IPS will be used for all science orbit transfers. As of January 2013 the IPS has been operated for approximately 28,000 hours, consumed approximately 280 kg of xenon, and provided a delta-V of approximately 7.5 km/s, the most post-launch delta-V of any spacecraft yet flown. IPS performance characteristics are very close to the expected performance based on analysis and testing performed pre-launch. Use of the IPS together with a medium-priced launch vehicle enabled this high delta-V mission to be performed within the Discovery Program cost cap. This paper provides an overview of the Dawn IPS and its mission operations through departure for Ceres.

INTRODUCTION

NASA has performed a wide array of robotic missions to explore the solar system, starting with the Explorer mission series in 1958. These missions have been launched atop powerful rockets and then have coasted to their targets, typically using chemical propulsion systems to

* Engineer, Propulsion, Thermal, and Materials Engineering Section, Jet Propulsion Laboratory, California Institute of Technology
† Dawn Project System Engineer and Mission Manager, Jet Propulsion Laboratory, California Institute of Technology
‡ Mission Design Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology
** JPL Fellow, Propulsion, Thermal, and Materials Engineering Section, Jet Propulsion Laboratory, California Institute of Technology
++Senior Engineer, Flight System Avionics Section, Jet Propulsion Laboratory, California Institute of Technology

provide a small delta-V for small course corrections. In some cases the missions have been fly-bys, and in other cases rocket motors have been used to insert the robotic spacecraft into orbit around a single target body. Chemical propulsion relies upon high-energy propellants to convert the energy stored in the chemical propellant into kinetic energy of the exhaust gases used to change the spacecraft's trajectory. Typical exhaust velocities are in the range of 2,500 m/s for simple mono-propellant fuels such as hydrazine, and 2,800 to 3,500 m/s for space-storable bi-propellant fuels such as mono-methyl hydrazine with nitrogen tetroxide oxidizer. The gold standard for chemical propulsion is the Space Shuttle main engine using hydrogen and oxygen with exhaust velocities approaching 4,500 m/s. Chemical propellants make up a substantial fraction of the total spacecraft "wet" mass at launch, frequently exceeding the spacecraft body mass. Because of the large amount of propellant needed for space missions and limitations and cost of the launch vehicles, missions using chemical propulsion have been limited to flybys or to orbiting single targets.

Enhancement of mission trajectories has been made possible through the use of gravity assists [1] to impart substantial delta-V to spacecraft. Missions which have used gravity assists include Mariner 10, the Voyager spacecraft, Galileo, Ulysses, Messenger, Casini, and Solar Probe. But missions using gravity assists rely upon specific planetary alignments which limit their applicability for many missions. Once at target the spacecraft still must expend large amounts of propellant to enter orbit around the target, leaving little propellant left over to depart and go to another body, thus limiting missions to flybys or visits to a single body.

An alternative to chemical propulsion is electric propulsion. Chemical propulsion uses the energy stored in the propellant to heat the combustion products resulting in exhaust velocities in the range 1,000-4,500 m/s. Electric propulsion decouples the propellant from the energy used to accelerate it and imparts energy to the propellant from an on-board power source , typically a solar array. Thrust levels are power-limited and consequently are typically far lower than those obtained with chemical propulsion, requiring much longer operating times. Several flight-qualified electric propulsion thruster types are available now that can produce propellant velocities of 10,000 to 50,000 m/s depending upon the thruster type, greatly reducing the propellant mass needed to perform a mission. The first practical electric thruster was operated in a NASA laboratory in 1959. This technology, however, wasn’t used on a NASA science mission until the flight of the Deep Space 1 (DS1) spacecraft [2] in 1998 that validated ion propulsion technology for future NASA missions.

Electric propulsion systems for primary propulsion that have been demonstrated in flight can be categorized by the method in which the electric thruster types accelerate the propellant. Electrothermal thrusters (resistojets and arcjets) electrically heat the propellant using plasmas to higher temperatures than can be obtained using chemical propulsion, resulting in exhaust velocities ranging from 1,500 to 20,000 m/s. Electromagnetic thrusters (pulsed-plasma thrusters) accelerate the propellant using electromagnetic forces with exhaust velocities approaching 10,000 to 20,000 m/s. Electrostatic ion thrusters accelerate the propellant using electric fields. Gridded (ion thrusters) and non-gridded (Hall thrusters) versions have flown. The Dawn mission uses the gridded ion thruster validated on the DS1 flight.

Missions using electric propulsion have attained a high level of success and reliability of operation. As of June 2012 there are over 236 spacecraft successfully using electric propulsion for attitude control, orbit raising, station keeping and for primary propulsion [3]. DS1 operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its primary and extended missions. A PPS-1350 Hall thruster was used for primary propulsion on board the European Space Agency’s SMART-1 probe, with more flights planned [4]. European and U.S. communications satellites have been launched with SPT-100 based propulsion modules for attitude control and orbit boosting. The Hayabusa spacecraft returned to Earth after exploring asteroid 25143 Itokawa [5] and employed ion thrusters for primary propulsion. The Japanese ETS-VIII uses ion thrusters for north-south station keeping. ESA's GOCE mission, launched in March 2009, employs ion propulsion for precision orbital control in low Earth orbit [6], and ESA's Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [7]. Approximately 72 ion thrusters (13-cm-dia and 25-cm-dia) are aboard 32 communication satellites for orbit-raising and station-keeping functions, accumulating ~450,000 operating hours in flight [8]. In 2011 the U.S. Air Force satellite AEHF (Advanced Extremely High Frequency) was successfully placed into a geosynchronous orbit from a highly elliptical orbit around Earth using the spacecraft's Hall thruster station-keeping propulsion system [9] after the propulsion system originally intended for the orbit maneuver failed.

The Dawn mission is the ninth project in NASA's Discovery Program. The goal of the Discovery Program is to achieve important space science by launching regular smaller missions using fewer resources and shorter development times than past projects with comparable objectives [10]. The combination of low-cost and short development times presents substantial challenges to an ambitious mission such as Dawn. The Dawn mission is led by the principal investigator, Dr. Christopher Russell, from the University of California, Los Angeles, and the mission is managed for NASA at the California Institute of Technology-Jet Propulsion Laboratory .

The Dawn mission has as its goal the scientific exploration of the two most massive main-belt asteroids, Vesta and the dwarf planet Ceres for clues about the formation and evolution of the early solar system. To realize these science goals the Dawn spacecraft must rendezvous with and orbit each body. Dawn is the first mission to orbit a main belt asteroid and will be the first to orbit two extraterrestrial targets. The Dawn mission is enabled by a three-engine ion propulsion system (IPS) that will provide most of the velocity change needed for heliocentric transfer to Vesta and Ceres, orbit capture at Vesta and Ceres, transfer to science orbits, orbit maintenance, orbit escape and departure. Without ion propulsion, a mission to orbit Vesta alone would have been unaffordable within NASA's Discovery Program, and a mission to orbit both Vesta and Ceres would have been impossible without use of an extremely large and costly launch vehicle.

The Dawn spacecraft was launched from Cape Canaveral Air Force Station on September 27, 2007. The first 80 days of the mission were dedicated to a comprehensive spacecraft and IPS checkout [11]. Cruise operations for deterministic thrusting began December 18, 2007 leading to a Mars flyby in February 2009 [12], and rendezvous and orbit capture at Vesta on July 16, 2011, with a science phase lasting approximately 14 months. Near the conclusion of the science phase at Vesta in September 2012 the Dawn spacecraft began thrusting to depart Vesta, then resumed deterministic thrusting leading to a rendezvous with Ceres in February 2015. The end of the primary mission is scheduled for July 2015. This paper presents a summary of the Dawn IPS system design and operations from launch through the start of cruise to Ceres.

SIMPLE COMPARISON OF DAWN IPS TO CHECMICAL PROPULSION

Missions using electric or chemical propulsion must carry enough propellant and supporting propulsion system infrastructure (propellant tanks, electrical cables, propellant lines, thermal control, etc.) on-board to achieve the needed spacecraft velocity changes after ejection from the launch vehicle. The Dawn mission provides a useful comparison between the two propulsion options. The Dawn spacecraft was launched with an Earth escape velocity of 11 km/s so this will be used in the example comparison, where it is also assumed that the propulsion infrastructure (propellant lines, tank mass fractions, thermal, etc.) are comparable. The major difference in the dry mass (defined as the spacecraft mass excluding propellant and tanks) between the two options is that the spacecraft solar array mass for the IPS must be approximately twice the value for the chemically-propelled spacecraft to accommodate power needs of the IPS. In this example comparison, the solar array size and therefore its mass is driven by the assumption that the spacecraft exclusive of IPS requires approximately 600 W at Ceres.

The electric propulsion option is the 3-engine IPS presently flying on the Dawn mission and is described in [13] and in the following section of this paper. This option includes a solar array with approximately 11 kW power at 1 astronomical unit (AU) from the sun. A state of the art bipropellant system is assumed to have performance characteristics typical for mono-methyl hydrazine with nitrogen tetroxide oxidizer. It is further assumed that the solar array and Dawn spacecraft structure can handle the structural stresses of using a high-thrust bipropellant motor, although the reality is that the Dawn spacecraft in its present configuration would have to be modified substantially to accommodate the high-thrust bi-propellant system, resulting in increased cost. The delta-V for the ion propulsion option is assumed to be 11 km/s and 5.5 km/s for the chemical propulsion option. The rocket equation is used to calculate the propellant required for completing the mission. For the chemical propulsion option thrust times are based on the propellant flow rate and total propellant used. For IPS the thrust over time is based on detailed mission analysis including estimates for solar array output changes with increasing spacecraft/sun distances.

Table 1. Comparison between an ion-propelled spacecraft vs. a spacecraft using a state of the art bipropellant chemical propulsion system for a mission to Vesta and then Ceres.

	Exhaust Velocity (m/s)	Dry Mass (kg)	Thrust (N)	Thrust Time (hrs)	Propellant + Tanks (kg)	Total Spacecraft Mass (kg)
Biprop System	3,139	722	400	9.8	4731	5453
Dawn IPS	29,430	772	0.091 to 0.023	48,000	446	1218

Two significant differences are clear from Table 1: for chemical propulsion thrust time is much lower compared to IPS, and the propellant and propellant tank mass is more than a factor of ten greater than IPS, resulting in a total spacecraft mass at launch for the Dawn mission example which is approximately 4.5 times greater using state of the art chemical propulsion. This fact translates into an option to use a far less costly launch vehicle with IPS to accomplish the mission, which is the option the Dawn mission selected.

ION PROPULSION SYSTEM DESCRIPTION

The Dawn IPS, shown in the block diagram in Figure 1, is based on the single-engine ion propulsion system flown successfully on the DS1 mission, but modified for multiple thrusters, power processors, digital control and interface units, and supporting hardware. The Dawn IPS includes three each gridded ion thrusters, a two-axis thruster gimbal system (for each thruster), two power processing units, two digital control and interface units, a xenon propellant storage and flow control system, and supporting hardware. The three Dawn thrusters are designated FT1,

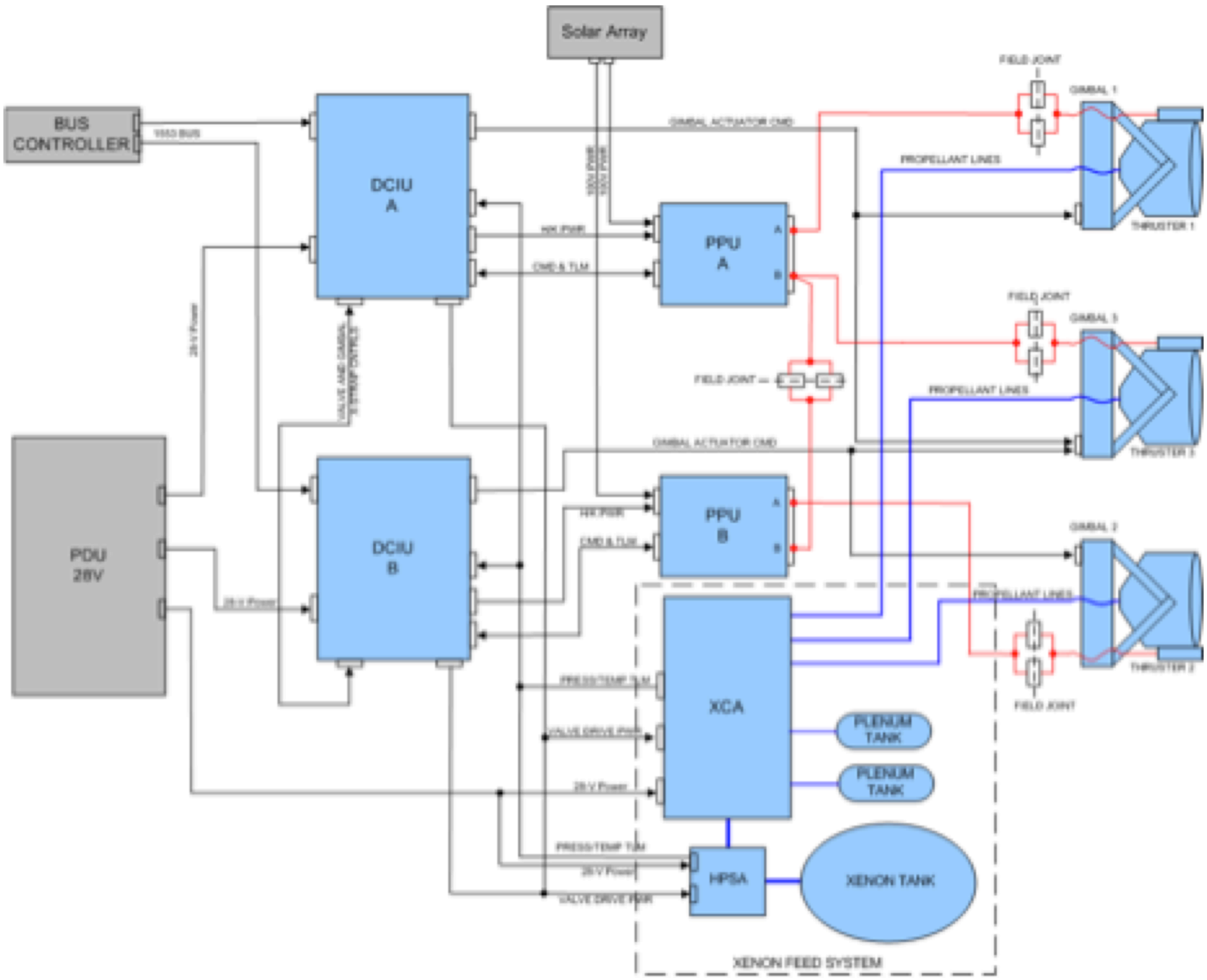

Figure 1. Simplified schematic diagram of the Dawn IPS.

located on the -X side of the spacecraft, FT2, located on the +X side, and FT3 which is the center-mounted ion engine. Each element of IPS is described separately below.

The Dawn ion propulsion system is designed to be single-fault-tolerant. An ion thruster using the 30-cm-diameter NASA design was operated for 30,352 hours in an extended life test [14] and demonstrated a total propellant throughput of 235 kg. The Dawn mission requires 381 kg (Table 2) or 190.5 kg per ion thruster if one thruster fails at the beginning of the mission. To accomplish the mission at least two ion thrusters, two thrust gimbal assemblies (TGA), one power processor unit (PPU), and one digital control and interface unit (DCIU) must be fully functional throughout the mission [13]. Analyses [15] and test data [14] indicate that a two-engine IPS can perform the Dawn mission with a low risk of failure due to ion thruster wear if the thrusters and PPUs are cross-strapped as shown in Figure 1 such that the loss of one thruster or PPU does not impact successful operation of the remaining two ion thrusters or PPU. Each PPU is connected to one DCIU and directly to the High Voltage Electronics Assembly (HVEA) which provides unregulated solar array power to the PPUs. Thruster FT3 can be powered by either of the two PPUs, while

FT1 is connected only to PPU-A and FT2 is connected only to PPU-B. The high voltage harnesses connecting the PPUs to the ion thrusters appear as the red lines in Figure 1. Only one of the PPUs is powered on at any time, and the unused PPU is left in an unpowered state.

Table 2. Xenon Allocation Summary

Description	Xenon Allocation (kg)
Initial Checkout	3.1
Leakage Allocation	10.0
Deterministic Thrusting To Vesta	246.8
Allocation for Vesta Operations	9.8
Deterministic Thrusting To Ceres	112
Allocation for Ceres Operations	10.5
Xenon Allocated For Thruster Restarts	3.0
Main Tank Residuals	5.0
Margin	25.0
Total	**425.2**
Total Xenon Used Through Operations at Vesta	259.6
Xenon Required for Cruise to Ceres	112

Thruster Description

The gridded ion thruster, depicted schematically below in Figure 2, consists of a discharge chamber about 30 cm in diameter and approximately 30 cm in length into which is fed neutral xenon gas at very low flow rates. The thruster mass is approximately 8 kg. Screen and accelerator grids with approximately 15,000 small holes are located at the downstream end of discharge chamber and are approximately 0.6 mm apart. Most of the elements making up the ion engine--the hollow cathode at the rear center, the screen grid, the anode, the discharge chamber magnet rings and the thruster body--are operated at a potential of approximately 1,100 V with respect to the spacecraft ground potential. The hollow cathode provides free electrons at a low energy cost. The electrons from the hollow cathode are attracted to the positive anode which is at a potential of +25 to +30 V with respect to the hollow cathode. This potential difference is sufficient to singly or doubly ionize a neutral xenon atom from an electron-xenon atom collision, creating an ion and one or more plasma electrons.

The permanent magnet rings depicted in the schematic create magnetic field lines in a so-called "ring-cusp" configuration that limits the migration of electrons to the anode and thus reduces the power consumed by the anode/hollow cathode discharge that creates the ions. Ions which migrate to the screen grid are accelerated out of the discharge chamber when they pass through one of the approximately 15,000 holes in the screen grid. The ions are accelerated by the electric field established between the screen and accelerator grids. Thus the Dawn ion thruster beam consists of approximately 15,000 individual beamlets. The neutralizer located downstream of the accelerator grid provides electrons at a low energy cost per electron to space-charge and current neutralizer the ion beam.

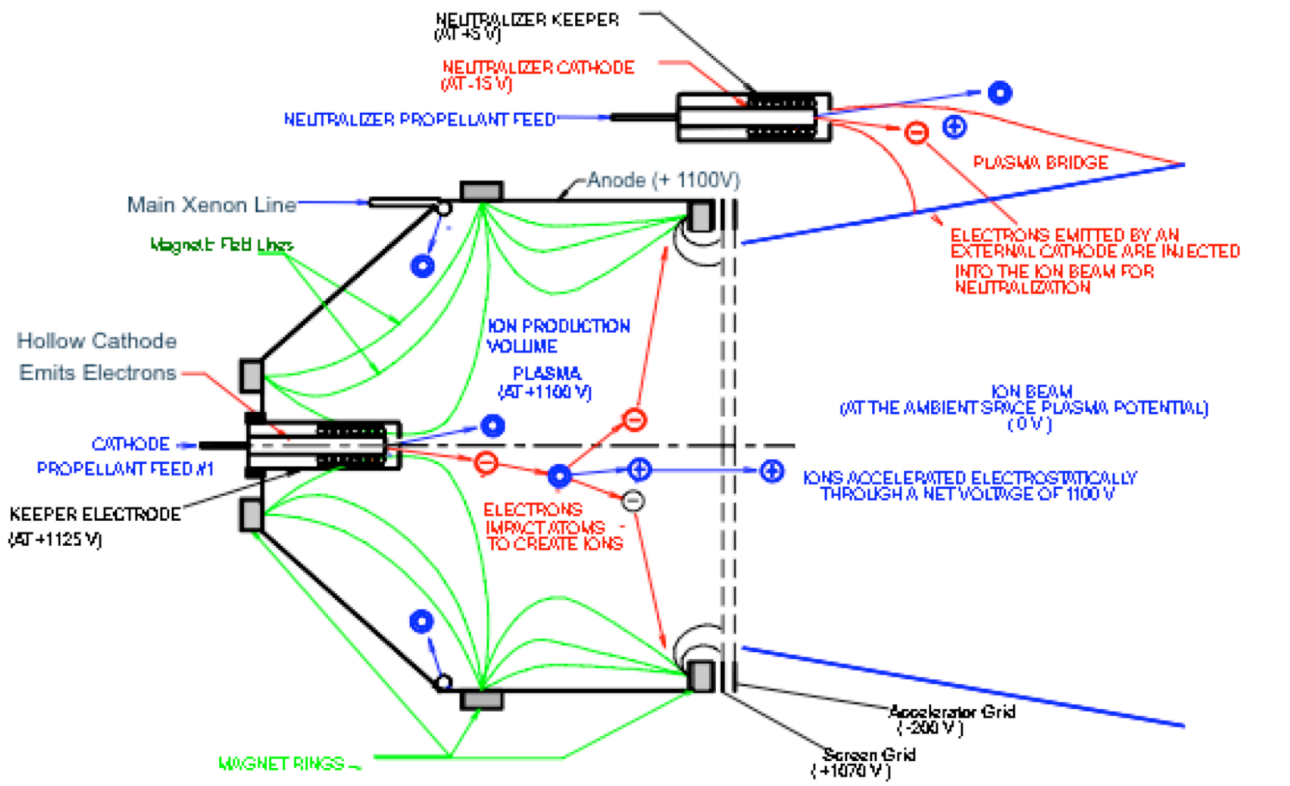

Figure 2. Schematic diagram of a gridded ion thruster.

An ion thruster is operated by flowing neutral xenon into the discharge cathode, neutralizer cathode, and engine discharge chamber, and then turning on the power supplies. First the engine and neutralizer cathodes are started, creating a low voltage, high current plasma discharge between the thruster anode to thruster cathode and between the neutralizer start electrode and the neutralizer cathode. Once stability in the plasma is reached, which takes about 20 seconds, the screen and accelerator grid power supplies are ramped up to their proper voltages and currents, and the thruster is then at full operation providing thrust. A photograph of a ring-cusp ion thruster in operation is shown in Figure 3, and the placement of the three Dawn thrusters on the spacecraft is shown in Figure 4.

At full power a Dawn ion engine consumes about 2,300 W new (approximately 2,330 W after several hundred hours of operation), uses about 11 g of xenon per hour, and delivers approximately 91 mN of thrust. This low thrust can be used for attitude control or for primary propulsion over months and years. Dawn ion thrusters are designed with a demonstrated lifetime of approximately 19,000 hours of operation at full power, and can be operated for longer time periods at reduced power [14]. By way of comparison, a Dawn ion thruster operating at full power for 16,363 hours imparts a total momentum transfer of 5.36 million N-s, an impulse equal to firing a large orbit-insertion thruster for approximately 3.7 hours. An ion thruster uses about 1/10 the fuel mass for each N of thrust generated compared to a state of the art bi-propellant thruster.

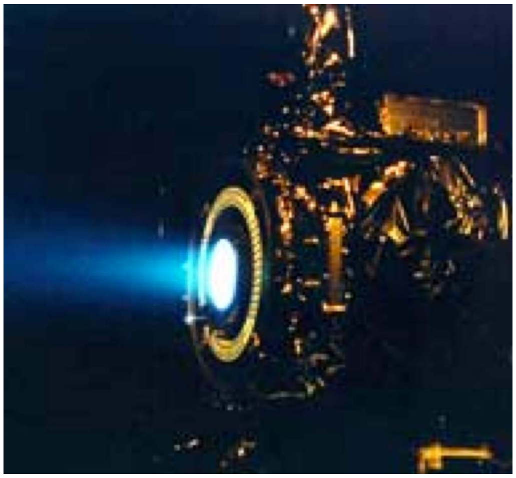

Figure 3. Photograph of an ion thruster operating in a vacuum chamber.

Figure 4. Photograph of the three ion thrusters (with dust covers) on the Dawn spacecraft.

Thrust Gimbal Assembly (TGA) Description

Each thruster is mounted to a TGA with two struts attached to each of three gimbal pads in a hexapod-type configuration (six struts total per ion thruster). Actuators driven by electronics cards in the digital control and interface unit that are commanded by the spacecraft attitude control system are used to articulate two of the TGA struts for 2-axis control of the thrust pointing vector ±12 degrees in one axis and ±8 degrees in the other. Under normal IPS thrusting the ion thrust is used to control the spacecraft attitude in the pitch and yaw axes, which reduces demand for hydrazine for the reaction control jets and revolutions on the reaction wheels. Each ion thruster generates a small amount of roll torque of approximately 20-50 μN-m when operating during normal thrusting. Roll about the thrust axis, which is a combination of thruster-generated roll and from other small forces such as solar torque, is taken out using the spacecraft attitude control system. Each thruster TGA actuator has been qualified for 30 million equivalent revolutions, and it is expected that the TGA set on FT3, the most used of the three thrusters, will undergo as much as 2.7 million equivalent revolutions by the end of the mission. Xenon from the flow system is carried to the thruster across the TGA via three each flexible propellant lines that allow the TGA to move as required.

Power Processor Unit Description

The power processing unit (PPU) converts the power generated by the spacecraft solar arrays (90-130 V, 10-25 A) into the voltages and currents needed to start and operate the ion thruster as determined by the digital control and interface unit. The individual supplies within the PPU provide for: pre-heat for the discharge chamber and neutralizer hollow cathodes (9 A, 9 V), cathode ignitor pulses (650-800 V), engine discharge supply (14 A, 24 V), beam (screen) supply (1.8 A, 1100 V), accelerator supply (-270 V, 5 mA), neutralizer discharge supply (2.5 A, 15 V), and engine current and voltage telemetry. PPU power conversion efficiency is approximately 93%. Each PPU has external dimensions of 37 x 50 x 8 cm and weighs about 13.3 kg.

Digital Control and Interface Unit (DCIU) Description

The DCIU, the "brain" of the Dawn IPS, accepts and executes commands from the spacecraft, controls the set-points for the PPU power supplies, operates the valves in the xenon feed system to control xenon flow rates, contains the motor drive electronics to articulate the TGAs as commanded by the spacecraft attitude control system, contains the software required to operate IPS autonomously, provides system status and telemetry from the thrusters, PPUs, TGAs, xenon feed system, xenon tank, and selected IPS temperature sensors, and provides limited fault protection. Normal thrusting can require as few as four simple commands from the spacecraft to select a thruster and an operating power level- IPS operations software stored within the DCIU's non-volatile memory is used to operate IPS components at the appropriate set points and operating sequences. Also imbedded within the DCIU is a throttle table which includes the power supply operating set points and xenon feed system configuration for 112 distinct operating power levels. During normal cruise operations it is frequently necessary to change the operating power level of IPS, which is accomplished with a single power level command from the spacecraft. Finally, fault protection within the DCIU turns off IPS and sets IPS in a safe configuration if certain operating dead bands are exceeded.

Xenon Storage and Xenon Control Assembly (XCA) Description

The xenon storage and feed system includes manual valves for filling the propellant system with xenon, stores the xenon propellant, and controls the flow rates of xenon to the thrusters. The xenon storage tank is an oval-shaped composite-overwrapped pressure vessel 270 liters in volume that weighs only 21.6 kg and stored 425 kg of xenon at launch, making the tank mass fraction approximately 5%. At launch the density of the xenon, stored as a super-critical fluid, was approximately 1.6 g/cm^3. Xenon stored in the xenon tank is connected to the XCA through stainless steel tubing and latch valves.

The XCA includes latch valves for flow isolation, a discharge chamber xenon flow storage tank (main plenum tank) with a volume of 3.7 L, a neutralizer and discharge cathode flow storage tank (cathode plenum tank) with a volume of 3.7 L, pressure transducers to measure plenum tank pressures, pressure transducer temperature sensors, solenoid valve pairs, flow control devices (FCD) that control flow rates to the thrusters based on FCD temperatures and pressures in the main and cathode plenum tanks, and FCD temperature sensors. There are three separate flow lines between the XCA and the thruster: the main flow line which is connected to the thruster discharge chamber, the discharge cathode flow line, and the neutralizer flow line.

Plenum tank pressures used for controlling flow rates to the thrusters are controlled using the solenoid valve (SV) pairs in a "bang-bang" pressure regulation scheme. The DCIU selects the thruster to receive xenon flow based on spacecraft commands and maintains the correct flow rates to the thruster. The xenon flow system can be controlled by either DCIU, but with only one operating one at a time.

Supporting Hardware Description

Supporting hardware includes electrical harnesses, propellant tubing, temperature sensors on the propellant lines and IPS subsystem components, thermal control of the PPUs, DCIUs, TGAs, XCA, tanks, thrusters, propellant lines, and structural elements such as the beam shield and the plate connecting the thrusters to the spacecraft.

IPS MISSION OPERATIONS

IPS mission operations to date can be divided into four major activities: the initial check-out, cruise to Vesta, Vesta orbit operations, and cruise to Ceres. Each activity is described below.

Initial Check Out (ICO)

The Dawn spacecraft was launched on September 27, 2007. The first 80 days after launch were dedicated to a checkout of the spacecraft systems including the IPS to assess system health and performance [13]. IPS was prepared for operation by establishing proper operation of the DCIU. This was followed by a propellant line bake-out to remove water vapor absorbed on the propellant lines walls, cathode conditioning to remove contamination of the hollow cathode inserts, pressurization of the main and cathode plenum tanks, and a bake-out of the discharge chamber for each thruster using a 300-W thruster plasma discharge to heat the discharge chamber. In addition the XCA valves and the TGAs were initialized. Each ion thruster, PPU, DCIU and the xenon feed system were checked to verify the components were operating properly. IPS thermal control was checked, and thrust control and stability with the spacecraft hydrazine thrusters and the reaction wheels was verified. Thruster electrical operating parameters and PPU efficiencies agreed well with preflight expected values based on acceptance test data. Thrust measurements determined from electrical operating parameters agreed well with thrust measured using radiometric means. The IPS checkout activity included a long duration system test where IPS and the spacecraft were operated autonomously for one week to verify all systems performed as planned for cruise to Vesta, and a final test to validate the spacecraft software.

Mission Operations for Cruise to Vesta

The goal for the cruise to Vesta phase of the mission was to modify the spacecraft's heliocentric trajectory leading to a Mars gravity assist in February 2009 and orbit capture at Vesta in 2011. This phase of the mission included using IPS for cruise, a trajectory correction maneuver, and spacecraft engineering tests. Cruise commenced on December 17, 2007 with the spacecraft at about 1.1 astronomical units (AU) from the sun and was completed successfully 3.6 years later on July 16, 2011 with orbit capture at Vesta.

The mission plan included several time periods of no thrusting for engineering activities that are incompatible with the IPS thrust attitude and for coasting times that optimized the mission trajectory. An important part of this phase was an optimal coasting period from late October 2008 to early June 2009 leading to a Mars gravity assist (MGA) which provided for a plane change and approximately 1 km/s of heliocentric energy increase and is the only part of the mission following launch in which a needed velocity change is not accomplished by the IPS. Prior to the closest approach to Mars IPS was operated for engineering tests and a single trajectory correction maneuver (TCM) but was not operated for primary propulsion. On November 20, 2008, Dawn completed the only TCM required to target the MGA. Operations for the TCM were performed using FT1 and were no different from interplanetary cruise thrusting. The maneuver yielded 0.6 m/s of delta-V and approximately 655 N-s of impulse and was so accurate that another TCM scheduled for January 2009 was canceled. Closest approach to Mars occurred as planned on February 17, 2009 and was followed by another coasting period of just under 4 months in duration. During this last coasting phase IPS was operated only for routine maintenance activities and for system engineering tests. Deterministic thrusting for heliocentric transfer to Vesta resumed on June 8, 2009.

Operating Time Summary

For the first 2.75 years of cruise to Vesta IPS was operated at full power thrusting at seven-day thrusting periods (thrust arcs) with off-times for data playbacks and command uplinks limited to approximately six to nine hours. IPS telemetry from the DCIU was retrieved during weekly spacecraft data playbacks in approximately seven day intervals. A low data rate thrust verification pass was typically conducted approximately 3-4 days after thruster ignition to confirm to mission controllers that the spacecraft and IPS were operating as planned. Thruster operation at full power consumed 181 kg of xenon with 13,362 hours of beam extraction time. At approximately 2 AU distance from the sun the solar arrays could no longer provide all of the power needed by the spacecraft and simultaneously full power to IPS so that for the remainder of cruise to Vesta, from August 2010 until orbit capture at Vesta, IPS was operated power-throttled at power levels consistent with providing power necessary for the spacecraft to operate nominally. Beyond 2 AU power to IPS ranged from 2,470 W to 1,909 W. Upon arrival at Vesta, IPS had been operated for a total of 23,219 hours (Table 3), consumed 250 kg of xenon (Table 4), and delivered a total delta-V to the spacecraft of 6.9 km/s (Table 5), the most post-launch delta-V ever provided to any spacecraft by an on-board propulsion system.

Table 3. Thruster Operating Time Summary Through July 2011*

Thruster	Initial Checkout Beam On-Time (hr)	Vesta Cruise Beam On-Time (hr)	Total Beam On-Time (hr)
FT1	42	7583	7625
FT2	22	7647	7669
FT3	214	7711	7925
Total	**278**	**22,941**	**23,219**

Table 4. Thruster Xenon Usage Summary Through Orbit Capture at Vesta*

Thruster	Initial Checkout Xenon Use (kg)	Vesta Cruise Xenon Use (kg)	Total Xenon Use (kg)
FT1	0.4	84.2	84.6
FT2	0.3	82.3	82.6
FT3	2.4	80.4	82.8
Total	**3.1**	**246.8**	**250.0**

*Includes operating time for spacecraft engineering tests and maintenance activities, but does not include operating time from ground testing and discharge-only operation (diode mode).

Table 5. Dawn Mission Summary. Bold font indicates the mission phase has been completed.

Description	Time Period	Distance S/C to Sun (AU)	Power Level To IPS (kW)	Comments
Launch	**09/27/2007**	**1.0**	**NA**	
Initial Checkout	**09/2007 - 12/2007**	**1.0 - 1.16**	**2.6**	**ΔV = 0.06 km/s**
Cruise prior to MGA	**12/2007 - 11/2008**	**1.16 - 1.40**	**2.6**	**ΔV = 1.80 km/s**
Mars Gravity Assist (MGA)	**11/2008 - 06/2009**	**1.40 - 1.60**	**NA**	**ΔV = 2.60 km/s (From MGA)**
Cruise to Vesta*	**06/2009 - 08/2011**	**1.40 - 2.26**	**2.6 -1.7**	**ΔV = 4.90 km/s**
Vesta Science Operations	**08/2011 - 08/2012**	**2.26 - 2.51**	**1.7 -1.3**	**ΔV = 0.48 km/**
Cruise to Ceres	07/2012 - 02/2015	2.51 - 2.84	1.3 -0.9	ΔV = 3.55 km/s
Ceres Science Operations	02/2015 - 07/2015	2.84 - 2.93	0.9	ΔV = 0.48 km/s

* Includes approach and insertion into Survey orbit

PPU, TGA, XCA Summary

The PPUs have operated perfectly to date. PPU efficiencies are similar to the efficiencies measured preflight and were consistently in excess of 92% at full power. The PPU baseplate temperature sensors are mounted to the part of the PPU chassis in contact with the spacecraft thermal control surface, and have ranged between 27 degrees C with the thrusters operating at full power to 20 degrees C with the thrusters operating at 1.5 kW. The fact that the PPU baseplate temperatures are near room temperature even for full power operation is a reflection of the excellent thermal heat rejection system on the Dawn spacecraft. Temperatures of the harness connectors mating the thrusters to the PPUs ranged between 10 C and 25 C, and at lower power the harness connector temperatures were as low as -6 C, well within operational temperature limits -55C to +90 C.

The xenon flow system has operated perfectly throughout cruise, with the exception of the slightly higher-than-expected solenoid valve cycling rates. These higher cycling rates do not pose a threat to the valve cycle life. Total xenon stored in the xenon tank can not be determined accurately using the tank temperature and pressure telemetry because of the non-ideal gas properties of the pressurized xenon. The uncertainty in the bulk xenon temperature and pressure require that the xenon consumption be estimated by integrating total xenon flow over time. Xenon flow rates to the thrusters are calculated from plenum tank pressure/flow control device (FCD) temperature telemetry based on curve fits to FCD calibrations obtained in ground testing.

The TGAs have also operated flawlessly in cruise. Each TGA, consisting of two motor/tripod assemblies (side A and side B) per FT, is used to position the thrust vector to control the spacecraft pitch and yaw. This mode is known as thrust vector control (TVC). Reaction wheels or hydrazine thrusters are used to control the spacecraft roll axis. The TGA motors have accumulated the equivalent of between over 1,000,000 motor revolutions through Vesta science operations. The motors were tested to 30,000,000 revolutions.

Thruster Performance

Through orbit capture at Vesta there have been a total of 378 thruster starts in flight. All thruster start attempts have been successful. Data taken at one second intervals indicate that in every start attempt in flight after the ICO, the cathodes ignited within one second of the command for application of the igniter voltage pulses. Heater power has increased only a few percent since launch, indicating that the heaters and cathode start electrode are in good condition. Total thruster power use is near the power levels expected from testing performed prior to launch. Accelerator grid erosion is the first life-limiting mechanism for ion thrusters using the Dawn design; accelerator grid current levels are near the expected values as well, indicating that the accelerator grids are healthy. Another measure of thruster health is arcing between the screen and accelerator grids, called recycling. Most recycles on Dawn thrusters occurred during full-power operation and well after the start of beam extraction, indicating that debris accumulated as part of the spacecraft integration and test process was still being cleared. The recycle rate, already low, decreased as thruster power decreased. For example, FT3 has not had a recycle over the last 14 months and 3,870 hours of operation with beam extraction. A final measure of thruster health is neutralizer operation. Neutralizer voltage and electronic noise in the neutralizer voltage are at values expected from data taken pre-launch.

Power use by the ion thrusters is driven primarily by the beam power, but total thruster electrical efficiency is also a function of the amount of discharge power required to maintain the beam current at nominal engine flow rates. Discharge current, discharge power, and discharge loss for Dawn thrusters during cruise are at values expected from data taken during thruster acceptance testing.

Thrust Measurements and Roll Torque

Direct thrust measurements were obtained during the ICO using changes in the Doppler shift of the radio signal from the spacecraft [13]. During cruise, thrust levels developed by the IPS are reconstructed from measurements of the spacecraft's velocity and location made between the approximately seven day thrusting arcs. Uncertainty in these thrust reconstructions is a function of the location of the spacecraft and thrust direction with respect to Earth, the presence and absence of thrusting and thrust variability over time, the ability to correct for solar pressure, effects from the RCS, pointing errors, the tracking precision of the Deep Space Network, and the number of thrust arcs included in the orbit determination process [16]. Uncertainty (1-σ) for all thrust estimates is better than ±0.4 mN. Thrust values determined radiometrically during the ICO were at the expected values for all power levels checked. However, during cruise each of the three Dawn thrusters indicated a slight decline in thrust relative to values estimated from thruster operating parameters. The decrease was under 1.5% and was observed (using radiometric means) to occur over thousands of hours of operation. For mission modeling and future orbit determinations a worst-case thrust of 97% of nominal is assumed, so the in-flight performance for the thrusters provides margin to the mission in the form of missed thrust days and xenon.

The Dawn requirement for roll torque produced during thrusting is 60 mN-m at all thruster power levels. The screen and accelerator grid holes are not perfectly aligned, resulting in a net force on the thruster that creates a roll about the thruster axis. Roll torques measured about the thruster axis are determined based on analysis of hydrazine and reaction wheel use. The data indicate that the Dawn thrusters have consistently operated with roll torques under the flight requirement. Instead of being a static value roll torques for Dawn thrusters have decreased as power to the thrusters has decreased.

DCIU Operation

The Dawn DCIUs have operated almost flawlessly to date, with the one exception noted below. There have been no cases of missed commands, incorrectly applied power levels, etc. The DCIUs have completely fulfilled the requirement to successfully operate the PPUs and XCA, obtain IPS telemetry, and place the IPS in a safe configuration as a result of occasional spacecraft or IPS anomalies.

DCIU-A Anomaly

On June 27, 2011 the spacecraft was thrusting normally until 08:31:32 UTC when thrusting abruptly stopped and the spacecraft transitioned to safe mode. The fault, which was discovered one day later on a scheduled Deep Space Network track, resulted in a loss of thrusting of approximately 29 hours. A review of the IPS telemetry indicated that a 5-V valve control enable signal was lost causing the IPS to terminate thrusting. The 5-V signal is used in the DCIU valve driver circuits to enable control of all latch valves and solenoid valves in the xenon feed system. The solenoid valves are used in the bang-bang pressure regulator that maintains the plenum tanks at the correct pressures to control xenon flow to the ion thrusters. Telemetry indicated that main and cathode plenum tank pressures began to decrease as soon as the 5-V signal was lost. This was accompanied by a gradual increase in the ion thruster discharge voltage and discharge current, as well as changes in the neutralizer cathode keeper voltage, which are consistent with a decreasing of flow rate due to decreasing plenum tank pressures. The DCIU internal fault protection detected the low plenum tank pressure condition, terminated thrusting and transitioned the IPS to safe mode. In safe mode the PPU power supplies are turned off and all latch valves are commanded closed, however due to the 5-V valve driver power failure the latch valves did not close as indicated by the continued decrease in pressure in both plenum tanks. The rate of pressure decrease in the main and cathode tanks was consistent with that expected by the release of xenon through the flow control devices.

An evaluation of the rest of the IPS and the spacecraft indicated that other than the 5-V valve power failure the IPS was healthy and fully functional and that the failure of the 5-V valve control power in DCIU-A had not affected other parts of IPS. This evaluation concluded that it was safe to restart thrusting by switching to DCIU-B, PPU-B and FT2. DCIU-A was powered off and

DCIU-B was powered up on June 30, 2011 at 02:30 UTC. Valve closure commands are issued by the DCIUs as part of the power-up process, and telemetry indicated the valves closed as commanded. All telemetry indicated IPS was nominal and commands were issued to re-pressurize the plenum tanks. Subsequent telemetry data indicated that the solenoid valves were cycling and were successfully pressurizing the plenum tanks. The following day telemetry indicated that the plenum tanks were at their proper pressures, the solenoid valves had cycled the correct number of times for the pressurizations, and the plenum tank pressures were stable indicating the latch valves were closed. Thrusting using FT2 resumed on June 30, 2011 at approximately 19:45 UTC. The Dawn IPS is single-fault tolerant and the full mission to Ceres could be completed with DCIU-B, PPU-B, thrusters FT2 and FT3.

Analysis of the failure indicated a single event upset (SEU) transient as the likely cause of the 5-V valve control signal failure and that power-cycling the DCIU would likely restore its functionality. On July 20, 2011 DCIU-A was restarted and telemetry showed that 5-V valve control power was nominal. Additional tests were then performed and established that DCIU-A was once again fully functional. DCIU-A has been used since August 2011 without incident.

Operations at Vesta

Deterministic thrusting to Vesta began on December 18, 2007 and concluded with orbit capture on July 16, 2011 at approximately 04:48 UTC. At capture the spacecraft was approximately 16,000 km altitude above Vesta with a velocity relative to Vesta of approximately 27 m/s, approaching Vesta from its south pole. The low velocity relative to Vesta was a consequence of Dawn's interplanetary ion thrusting approach which reshaped the spacecraft's heliocentric orbit to closely match that of Vesta. In contrast to missions that use high-thrust chemical propulsion, Dawn did not have a typical planetary orbit insertion with a critical short maneuver to achieve a rapid change in the trajectory. Rather, capture by Vesta's gravity occurred during routine IPS thrusting.

The Dawn science plan includes four different near-polar mapping orbits around Vesta to achieve its science goals: Survey orbit, a high altitude mapping orbit (HAMO-1), a low altitude mapping orbit (LAMO), and a second high altitude mapping orbit (HAMO-2). The IPS was used to transition the spacecraft to all the Vesta science orbits as well as to perform orbit maintenance maneuvers (OMMs). FT2 was used for the transition from orbit capture to Survey orbit, and FT3 was used for all remaining orbit maneuvers at Vesta. Orbit transfers were completed using a series of low thrust maneuvers that spiraled the spacecraft to the required orbits. Uncertainties in ACS pointing of the IPS thrust, IPS thrust magnitude (typically less than 0.25%), thrust from the use of the RCS to desaturate reaction wheels, Vesta's gravity field, and other perturbations resulted in only small errors in performing the orbit maneuvers. Transfers were performed in relatively short segments to minimize the accumulated effect of these error sources. For example, the transfer from HAMO-1 to LAMO required thrusting over approximately 180 orbits around Vesta in ten sequential designs with a total of 31 separate thrust maneuvers. A summary of IPS thrusting activities for Vesta science orbits is shown in Table 6. Thrusting for Vesta orbit maneuvers occurred from July 16, 2011 through June 6, 2012.

Table 6. Summary of IPS thrusting for Vesta science orbits. Colored rows indicate activities using IPS.

Event	Time Period	Altitude Above Vesta (km)	Number of IPS Maneuvers	Thrust Time (hrs)	Xenon Used (kg)
Transition: Orbit Capture To Survey	07/16/11 to 08/02/11	16000-2735	6	231	2.0
Survey Orbit	08/02/11 to 08/31/11	2735	0	0	0
Transition: Survey To HAMO-1	08/31/11 to 09/28/11	2735-670	16	276	2.5
HAMO-1 Orbit	09/28/11 to 11/02/11	670	0	0	0
Transition: HAMO-1 To LAMO	11/02/11 to 12/12/11	670 - 210	31	288	2.6
LAMO Orbit	12/12/11 to 04/27/12	210			
LAMO OMM	12/12/11 to 04/27/12	210	11	9	0.2
Transition: LAMO To HAMO-2	05/01/12 to 06/06/12	210-670	22	305	2.4
HAMO-2 Orbit	06/06/12 to 07/23/12	670	0	0	0
IPS Vesta Operations Totals (Orbit capture to HAMO-2)	07/16/11 to 07/23/12		86	1109	9.8

The spacecraft's standard near-polar orbit over Vesta at all altitudes took the spacecraft over the north pole (which was in darkness, because it was in northern hemisphere winter at that time), then over the terminator (the boundary between the illuminated and un-illuminated sides), down over the equator, over the south pole, and then across the terminator again to pass over Vesta's night side. The spacecraft was never occulted by Vesta at any time during all operations at Vesta, which prevented shadow on the spacecraft's solar panels. At injection into each science orbit the orbital eccentricity was near-circular. Small forces acting on the spacecraft contributed to maneuver execution errors [16] which overall were remarkably small. There were 2 TCMs during HAMO-1, and 11 orbit maintenance maneuvers during LAMO. For all operations at Vesta there were 89 thrust arcs using 9.8 kg of xenon over 1109 hours of thrusting time. Summaries of the total thruster operating times and propellant processed through the end of Vesta operations is given in Tables 7 and 8.

Table 7. Thruster Operating Time Summary Through End Of Operations at Vesta*

Thruster	Initial Checkout	Vesta Cruise	Vesta Operations	Total
	Beam On-Time (hr)	Beam On-Time (hr)	Beam On-Time (hr)	Beam On-Time (hr)
FT1	42	7583	0.0	7625
FT2	22	7647	231	7900
FT3	214	7711	876	8802
Total	**278**	**22,941**	**1,109**	**24,327**

*Includes time for spacecraft engineering tests and maintenance activities, but does not include operating time from ground testing and discharge-only operation (diode mode).

Table 8. Thruster Xenon Usage Summary Through End Of Operations at Vesta *

Thruster	Initial Checkout	Vesta Cruise	Vesta Operations	Total
	Xenon Use (kg)	Xenon Use (kg)	Xenon Use (kg)	Xenon Use (kg)
FT1	0.4	84.2	0.0	84.6
FT2	0.3	82.3	2.2	84.7
FT3	2.4	80.4	7.6	90.4
Total	**3.1**	**246.8**	**9.8**	**259.6**

* Includes xenon used for spacecraft engineering tests, maintenance activities and diode mode burns, but does not include xenon throughput from ground testing.

Operations for Cruise to Ceres

IPS operations for HAMO-2, the last science orbit at Vesta, ended on June 6, 2012. Thrusting for escape from Vesta began on July 25, 2012 at an IPS input power level of 1,262 W, just over 50% of the full power level and it is expected that by arrival to Ceres, planned for 2015, IPS power will be as low as 700 W.

The trajectory used for escape from Vesta resulted in a spiral of slowly increasing radius, reaching escape on September 4, 2012 at an altitude above Vesta of 16,000 km. During the departure phase, Dawn stopped thrusting for some final observations of the northern hemisphere of Vesta. To date IPS has operated for a total of 27,811 hours of operation with beam extraction and has processed 280.9 kg of the 425.2 kg of xenon loaded into the xenon tank at launch. Xenon use to date is well within the allocation for deterministic thrusting to Ceres (Table 2). Times for thrust arcs have increased, from seven days to 14-28 days, to reduce hydrazine consumption. Thus far only FT3 has been used since departing Vesta. Data indicate nominal power use by IPS and thrust levels about 99.5% of the thrust determined from thruster electrical parameters.

CONCLUSION

The Dawn mission has successfully used its ion propulsion system for the heliocentric transfer to the main-belt asteroid Vesta, for science operations in orbit, for escape from Vesta and the start of deterministic cruise to the dwarf planet Ceres. Deterministic thrusting for Vesta began on December 17, 2007 and concluded with orbit capture by Vesta on July 16, 2011. The cruise phase to Vesta included a Mars gravity assist which provided delta-V for a plane change and the heliocentric transfer to Vesta and was the only part of the mission following launch in which a needed velocity change was not accomplished by the IPS. Dawn Science orbits reached using IPS included Survey at 2735 km altitude, HAMO-1 at 670 km altitude, LAMO at 210 km altitude, and HAMO-2 at 670 km altitude but with different viewing conditions compared to HAMO-1. Other orbital characteristics such as orbital plane varied depending upon the science requirements. Following science operations at Vesta IPS was used to escape Vesta on September 5, 2012 and begin deterministic thrusting to the dwarf planet Ceres. IPS has operated virtually flawlessly throughout the mission to date, accumulating over 27,800 hours of beam-on time and consuming almost 281 kg of xenon that resulted in almost just over 7.5 km/s of ΔV to the spacecraft. Maneuver execution errors in reaching the science orbits were low. All the IPS components--the thrusters, DCIUs, PPUs, XCA, and TGAs—have operated nominally, with the exception of a single DCIU-A anomaly that resulted in a temporary loss of thrust for less than 30 hours. IPS, with its robust system architecture design, was re-started within days of the anomaly. The anomaly, likely due to a single event upset in a valve driver board, was rectified by power cycling and DCIU-A has been used since August 2011 without incident. Rendezvous with the dwarf planet Ceres is scheduled for February 2015. The Dawn ion propulsion system has shown itself to be extremely reliable and capable and is presently fully operational to continue cruise operations to Ceres.

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