In-Flight Operation of the Dawn Ion Propulsion System Through the Low Altitude Mapping Orbit at Ceres

Charles E. Garner,¹ and Marc D. Rayman²

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

The Dawn mission, part of NASA’s Discovery Program, has as its goal the scientific exploration of the two most massive main-belt objects, Vesta and Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H-9.5 (Delta-II Heavy) rocket that placed the 1218-kg spacecraft onto an Earth-escape trajectory. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory for the heliocentric transfer to Vesta, orbit capture at Vesta, transfer between Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, transfer between Ceres science orbits, and orbit maintenance maneuvers. Full-power thrusting from December 2007 through October 2008 was used to successfully target a Mars gravity assist flyby in February 2009 that provided an additional $\Delta V$ of 2.6 km/s. Deterministic thrusting for the heliocentric transfer to Vesta resumed in June 2009 and concluded with orbit capture at Vesta on July 16, 2011. From July 2011 through September 2012 the IPS was used to transfer to all the different science orbits at Vesta and to escape from Vesta orbit. Cruise for a rendezvous with Ceres began in August 2012 and completed in late December 2014. From December 2014 through June 2016 the IPS was used for transiting the spacecraft to the Approach phase, survey orbit, the high altitude mapping orbit (HAMO), and the low altitude mapping orbit (LAMO) with arrival to LAMO on December 13, 2015, almost eight years after the start of deterministic thrusting to Vesta. The LAMO orbit, at a mean altitude above Ceres of approximately 385 km, is the spacecraft’s final destination and there are no plans to move the spacecraft from LAMO once science operations there are completed. Since arrival at LAMO Dawn’s IPS has been used for occasional orbit maintenance maneuvers while the spacecraft performs scientific investigations. Dawn has successfully completed its science goals and Dawn’s primary mission is scheduled to end June 30, 2016. To date the IPS has been operated for approximately 48,458 hours, consumed approximately 401 kg of xenon, and provided a delta-V of over 11.0 km/s, a record for an on-board propulsion system. The IPS performance characteristics are close to the expected performance based on analysis and testing performed pre-launch. Dawn’s IPS continues to be fully operational as of June 2016. This paper provides an overview of Dawn’s mission objectives and the results of Dawn IPS mission operations from Survey orbit through the completion of Dawn’s primary mission.

1. Introduction

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 [1]. Deep Space 1 (DS1), the first interplanetary mission to use ion propulsion, operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its primary and extended missions [2]. A PPS-1350 Hall

¹ Engineer, Propulsion, Thermal, and Materials Engineering Section
² Dawn Chief Engineer and Mission Manager
thruster was used for primary propulsion on board the European Space Agency’s SMART-1 probe, with more flights planned [3]. 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 [4] 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, employed ion propulsion for precision orbital control in low Earth orbit [5], and ESA’s Artemis mission used the RIT-10 ion propulsion system for transfer to a geostationary orbit [6]. Approximately 148 ion thrusters (13-cm-dia and 25-cm-dia) built at L3 Communications, Torrance, CA are aboard 37 communication satellites built by Boeing Defense, Space and Security for orbit-raising and station-keeping functions, accumulating ~450,000 operating hours in flight [7]. 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 [8] after the propulsion system originally intended for the orbit maneuver failed. Since then two additional satellites with Hall thrusters on-board were successfully launched and operated.

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 [9]. 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 by 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 objects, Vesta and the dwarf planet Ceres for clues about the formation and evolution of the early solar system. Vesta is the second most massive main belt object with a mean diameter of 530 km. Ceres, with a diameter of 950 km, is the largest and most massive body in the asteroid belt. Ceres is classified as one of five dwarf planets in our solar system, and studies suggest it may have a large inventory of subsurface water. The science underlying the Dawn mission is described in [10,11]. To realize these science goals the Dawn spacecraft rendezvoused with and orbited each body. Dawn is the first mission to orbit a main belt object and the first to orbit two extraterrestrial targets. The Dawn mission is enabled by a three-engine ion propulsion system (IPS) that provided most of the velocity change needed for heliocentric transfer to Vesta and Ceres, orbit capture at Vesta and Ceres, transfer to Vesta science orbits and orbit maintenance, orbit escape and departure from Vesta, and transfer to science orbits and orbit maintenance at Ceres. 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 with a single launch.

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 [12]. Cruise operations for deterministic thrusting began December 18, 2007 leading to a Mars flyby in February 2009, and rendezvous and orbit capture at Vesta on July 16, 2011, with a science phase lasting approximately 13 months [13]. At the conclusion of the Vesta science phase in July 2012 the Dawn spacecraft departed Vesta for deterministic thrusting to Ceres, leading to a Ceres approach phase lasting approximately seven weeks, orbit capture at Ceres on March 6, 2015, arrival to the first science orbit on April 23, 2015, arrival to the second science orbit on June 3, 2015. Transfer using the IPS to all the remaining science orbits were completed in December 2015. This paper presents a summary of the Dawn mission operations from start of thrusting for survey orbit through the completion of Dawn’s primary mission on June 30, 2016.

II. MISSION AND SYSTEM FLIGHT OVERVIEW

The mission and flight system are described in detail in [14, 15], and are summarized here. A schematic diagram of the Dawn flight system is shown in Figure 1, with a mass summary for the Dawn flight system in Table 1. The Jet Propulsion Laboratory (JPL) was responsible for the high voltage electronics assembly (HVEA) and science payload development, IPS development and development of other spacecraft components, safety and mission assurance, project systems engineering, mission design, and navigation development, and is responsible for mission operations system development and mission operations which are conducted from JPL.
Figure 1. Schematic diagram of the Dawn flight system, from [10].
Orbital ATK (Orbital), Sterling, VA, was responsible for developing the spacecraft bus, flight system integration and testing, and launch operations. The spacecraft is based on Orbital’s Geostar [16] satellite platform series. The solar array (SA) consists of two large panel assemblies approximately 18 m² each and measuring almost 20 m tip to tip with triple junction cells providing more than 10 kW of electrical power at one astronomical unit (AU) and 1.3 kW for operations at Ceres. Articulation of the solar arrays is about the Y-axis. The spacecraft attitude control subsystem (ACS) employs four reaction wheel assemblies (RWA) for three-axis control of the spacecraft and makes use of the IPS for pitch and yaw control during normal IPS thrusting. The reaction control subsystem (RCS) uses hydrazine thrusters for direct three axis control of the spacecraft and was intended primarily for desaturating the reaction wheels. The spacecraft launched with 45 kg of hydrazine on-board for RCS use on this eight-year-long mission. Two of the four RWAs failed [17], so conservation of hydrazine was very important, but Dawn met its science goals for Vesta and Ceres through a hybrid RWA/ACS spacecraft control architecture.

### Table 1. Dawn Flight System Mass at Launch

<table>
<thead>
<tr>
<th>Description</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry spacecraft and avionics (except IPS)</td>
<td>573</td>
</tr>
<tr>
<td>Science instruments</td>
<td>46</td>
</tr>
<tr>
<td>Hydrazine</td>
<td>45</td>
</tr>
<tr>
<td>Ion Propulsion System (IPS)</td>
<td>129</td>
</tr>
<tr>
<td>Xenon</td>
<td>425</td>
</tr>
<tr>
<td>Flight system mass at launch</td>
<td>1218</td>
</tr>
</tbody>
</table>

The Dawn ion propulsion subsystem (IPS) developed at JPL is described in detail in [15] and is shown in the block diagram in Figure 2. The IPS is single-fault tolerant as configured for Dawn and is based on the single-engine ion propulsion system flown successfully on the DS1 mission [12], but modified for multiple thrusters and supporting hardware. The Dawn IPS includes three 30-cm-diameter xenon ion thrusters operated at a time, two power processor units (PPU), two digital control interface units (DCIU), three Thruster-Gimbal Assemblies (TGA) for two-axis thrust-vector control, a Xenon Control Assembly (XCA) for controlling xenon flow to the engines, and a single xenon storage tank. The ion thrusters and the PPUs are based on technology developed by NASA Glenn Research Center (GRC), and engineered and fabricated for flight by L-3 Communications Electron Technologies (L-3), Inc., Torrance, CA, with minimal modifications to their designs from DS1.

The two DCIUs, which accept commands from the spacecraft, command the PPU supplies, operate the valves on the XCA and actuators on the TGAs, return IPS telemetry and serve as a pass-through for spacecraft commands to the TGAs, were designed and fabricated at JPL. The design was modified from the DS1 design to meet the multi-engine system functionality and cross-strapping required for Dawn. Each DCIU interfaces to a single PPU, to the XCA components and xenon high pressure subassembly, and to each of the three TGAs. Each DCIU provides low voltage power to its corresponding PPU. Only one DCIU is powered up and operated at a time and the unused DCIU is left in an unpowered state. The DCIUs include software needed for automatic and autonomous control of IPS including thruster power levels, flow system valve actuation, and XCA flow control settings. Both DCIUs are mounted next to the PPUs to the same thermally-controlled plate within the core structure of the spacecraft.

The Dawn ion propulsion system is designed to be single-fault-tolerant. Ion thrusters using the 30-cm-diameter NASA design were operated for 16,265 hours on the DS1 mission [2] and 30,352 hours in an extended life test [18], however the Dawn mission required 400 kg (Table 2, xenon allocation summary) or 200 kg per ion thruster if one thruster fails at the beginning of the mission. To accomplish the mission at least two ion thrusters, two TGAs, one PPU, and one DCIU had to be fully functional throughout the mission [10]. Analyses [19] and test data [18] 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 2 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 HVEA which provides unregulated solar array power to the PPUs. FT3 can be powered by either of the two PPUs, while FT1 is connected only to PPU-1 and FT2 is connected only to PPU-2. The high voltage harnesses connecting the
PPUs to the ion thrusters appear as the red lines in Figure 2. Only one of the PPUs is powered on at any time, and the unused PPU is left in an unpowered state. The mission trajectory planned for Dawn is shown in Figure 3, and a list of important mission phases is summarized in Table 3 below.

The center-mounted thruster is designated FT3 (flight thruster 3), and can be powered by either PPU. The outboard thrusters are designated FT1 on the −X panel and FT2 on the +X panel. Each thruster is mounted to a TGA with two struts to each thruster gimbal pad in a hexapod-type configuration (six struts total per ion thruster). Actuators driven by electronics cards in the DCIU that are commanded by the spacecraft ACS are used to articulate two pairs of the TGA struts for 2-axis control of the thrust pointing vector through the spacecraft center of mass and to provide pitch and yaw control during ion thrusting.

![Diagram](image_url)

**Figure 2. Simplified block diagram of the Dawn IPS.**

A titanium-lined composite-overwrap xenon tank developed for Dawn with a volume of 267 liters was mounted inside the core structure of the spacecraft and loaded with 425 kg of xenon prior to launch, with a xenon storage density at launch of approximately 1.6 g/cm³. The ratio of tank mass to xenon mass is 0.05 and represents a true breakthrough in total IPS mass reduction.

The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters and to be single-fault tolerant. It includes the XCA placed outside the spacecraft core cylinder with two 3.7-liter
plenum tanks identical to those flown on DS1, and uses the same xenon flow rate control design to control pressure to flow rate control devices (flow orifices), latch valves and solenoid valves (similar to those used on DS1), service valves, interconnecting tubing, and nine flexible propellant lines (three for each thruster across the TGA interface). The flow orifices were carefully calibrated pre-flight for flow rate determination based on pressure and temperature at the flow orifices. Total xenon consumption is calculated by integrating the pressure and temperature at the flow orifices. A different method for calculating total xenon consumption makes use of the xenon storage tank pressure and estimates of the bulk xenon temperature. The two methods agree to within approximately 5 kg, or approximately one percent of the total xenon used. Xenon use appears well within the allocation for all remaining mission phases (Table 2). In Table 2 the xenon consumption is based on the FCD calibrations.

The mission trajectory for Dawn is shown in Figure 3, and a list of important mission phases is summarized in Table 3 below. The complete mission \( \Delta V \), from the initial checkout through conclusion of Ceres science operations and including the Mars gravity assist, is approximately 13.6 km/s (Table 3). The IPS provided 11 km/s of this \( \Delta V \) and used approximately 401 kg of xenon for the complete mission.

![Dawn mission trajectory](image)

**Table 2. Xenon Allocation Summary**

<table>
<thead>
<tr>
<th>Description</th>
<th>Xenon Allocation (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Checkout-</td>
<td>Actuals 3.1</td>
</tr>
<tr>
<td>Deterministic Thrusting To Vesta</td>
<td>Actuals 246.0</td>
</tr>
<tr>
<td>Vesta Operations</td>
<td>Actuals 10.3</td>
</tr>
<tr>
<td>Deterministic Thrusting To Ceres</td>
<td>Actuals 117.9</td>
</tr>
<tr>
<td>Ceres Operations</td>
<td>Actuals 23.6</td>
</tr>
<tr>
<td>Additional IPS Operations Allocation for Final Operations</td>
<td>1.0</td>
</tr>
<tr>
<td>Main Tank Residuals</td>
<td>6.3</td>
</tr>
<tr>
<td>Margin</td>
<td>17.0</td>
</tr>
<tr>
<td>Total</td>
<td>425.2</td>
</tr>
</tbody>
</table>

![Figure 3. Dawn mission trajectory.](image)
Table 3. Dawn Mission Summary. Bold font indicates the mission phase has been completed.

<table>
<thead>
<tr>
<th>Description</th>
<th>Time Period</th>
<th>Distance S/C to Sun (AU)</th>
<th>Power Level To IPS (kW)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>09/27/2007</td>
<td>1.0</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Initial Check-out</td>
<td>09/2007 - 12/2007</td>
<td>1.0 - 1.16</td>
<td>2.6</td>
<td>$\Delta V = 0.07$ km/s</td>
</tr>
<tr>
<td>Cruise prior to MGA</td>
<td>12/2007 - 11/2008</td>
<td>1.16 - 1.40</td>
<td>2.6</td>
<td>$\Delta V = 1.80$ km/s</td>
</tr>
<tr>
<td>Optimal Coast and Mars Gravity Assist (MGA)</td>
<td>11/2008 - 06/2009</td>
<td>1.40 - 1.60</td>
<td>NA</td>
<td>$\Delta V = 2.60$ km/s (From MGA)</td>
</tr>
<tr>
<td>Cruise to Vesta</td>
<td>06/2009 - 07/2011</td>
<td>1.40 - 2.26</td>
<td>2.6 -1.7</td>
<td>$\Delta V = 4.84$ km/s *</td>
</tr>
<tr>
<td>IPS Operations at Vesta</td>
<td>07/2011 - 09/2012</td>
<td>2.26 - 2.53</td>
<td>1.7 -1.3</td>
<td>$\Delta V = 0.25$ km/s</td>
</tr>
<tr>
<td>Cruise to Ceres and Approach</td>
<td>09/2012 - 04/2015</td>
<td>2.51 - 2.84</td>
<td>1.3 -0.9</td>
<td>$\Delta V = 3.85$ km/s **</td>
</tr>
<tr>
<td>Ceres Science Operations</td>
<td>04/2015 - 07/2016</td>
<td>2.84 - 2.98</td>
<td>0.4-0.6</td>
<td>$\Delta V = 0.33$ km/s</td>
</tr>
<tr>
<td>Total From IPS</td>
<td></td>
<td></td>
<td></td>
<td>$\Delta V = 11.14$ km/s</td>
</tr>
<tr>
<td>Mission Total</td>
<td></td>
<td></td>
<td></td>
<td>$\Delta V = 13.74$ km/s</td>
</tr>
</tbody>
</table>

* From start of cruise to orbit capture at Vesta
** From start of cruise to Ceres to the first science orbit at Ceres (RC3)

III. Overview of IPS Operations and Performance at Ceres

Operations Overview

Thrusting for cruise to Ceres began on July 25, 2012 with the spacecraft in a high altitude mapping orbit around Vesta at an altitude of approximately 673 km, leading to escape from Vesta on September 4, 2012, arrival to the Ceres approach trajectory on December 26, 2014, and orbit capture on March 6, 2015 [20]. A top-level summary of the IPS for maneuvering and orbit maintenance at Ceres is shown in Table 4. Ceres IPS operations were implemented for supporting the science goals, with four major activities, all requiring delta-V from Dawn’s IPS. These major activities are:

1. Mapping orbit #1 (RC3, science goals described in [20])
2. Mapping orbit #2 (survey):
   a. Obtain higher resolution global color imaging
   b. Measure and map the mineral composition with visible + IR spectroscopy
3. Mapping orbit #3 (HAMO):
   a. Obtain highest resolution global color imaging
   b. Obtain stereo images for topography
   c. Measure and map the mineral composition with visible + IR spectroscopy in selected regions
   d. Measure the gravity field
4. Mapping orbit #4 (LAMO):
   a. Obtain neutron and gamma ray spectroscopy
   b. Measure the gravity field (bonus)
   c. Obtain global imaging (bonus)
   d. Obtain color images, visible and IR spectra in selected regions

Table 4. Summary of IPS thrusting for Ceres science orbits. Colored rows indicate activities using IPS.

<table>
<thead>
<tr>
<th>Event</th>
<th>Time Period</th>
<th>Altitude Above Ceres (km)</th>
<th>Xenon Consumption (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC3</td>
<td>04-23-15 to 05-09-2015</td>
<td>13,600</td>
<td></td>
</tr>
<tr>
<td>Transfer: RC3 To Survey Orbit</td>
<td>05-09-2015 to 06-03-2015</td>
<td>13,600 to 4,400</td>
<td>2.7</td>
</tr>
<tr>
<td>Survey Orbit</td>
<td>06-04-2015 to 07-01-2015</td>
<td>4,400</td>
<td>0</td>
</tr>
<tr>
<td>Transfer: Survey To HAMO</td>
<td>07-01-2015 to 08-13-2015</td>
<td>4,400 to 1,470</td>
<td>3.3</td>
</tr>
<tr>
<td>HAMO Orbit</td>
<td>08-13-2015 to 10-16-2015</td>
<td>1,470</td>
<td>0</td>
</tr>
<tr>
<td>Transfer: HAMO To LAMO</td>
<td>10/16/2015 to 12-13-2015</td>
<td>1,470 to 375</td>
<td>5.1</td>
</tr>
<tr>
<td>LAMO Orbit</td>
<td>12-13-2015 to End of Mission</td>
<td>375</td>
<td>0</td>
</tr>
<tr>
<td>LAMO Orbit Maintenance</td>
<td>01-01-16 to 06-30-2016</td>
<td>375</td>
<td>0.1</td>
</tr>
</tbody>
</table>

RC3 science was completed successfully on May 9, and Dawn used the IPS to transfer to the second science orbit, known as survey orbit. To reach this circular orbit at an altitude of 4,400 km, Dawn used four thrust sequences, 534.4 hours of beam-on time, and 2.70 kg of xenon. All thrusting was performed using FT3 at an input power to the thruster of approximately 600 W.

Following operations in the survey orbit, Dawn IPS was used to transfer to the third science orbit, HAMO, at a mean altitude of 1,470 km altitude. Reaching this circular orbital altitude required seven thrust sequences, 645.3 hours of beam-on time, and 3.3 kg of xenon. The plan was to use FT3 for transfer to the HAMO orbit, but very early in the first thrusting sequence to HAMO an anomaly relating to changes made to FT3 TGA control did not work as planned, so the flight team quickly switched to one of outboard thrusters (FT2) to complete the transfer to HAMO. IPS performance during the transfer was flawless after the switch to FT2. The spacecraft was placed into HAMO slightly ahead of schedule as the spiral maneuver went very smoothly and no trajectory correction maneuvers were required.

Following operations in the HAMO orbit, Dawn IPS was used to transfer to the fourth and final science orbit at Ceres, LAMO, at a mean altitude of 375 km altitude. In the lowest altitude orbit (LAMO), the spatial resolution of images has been approximately 850 times better than the best views provided by the Hubble Space Telescope. In addition, the spacecraft has acquired neutron, gamma ray, visible, and infrared spectra as well as high accuracy measurements of the gravity field. Reaching this circular orbital altitude required nine thrust sequences including two small trajectory correction maneuvers, 1011.5 hours of beam-on time, and 5.1 kg of xenon. FT2 was used for all thrust sequences for the transfer at an input power of approximately 580 W to the thruster, with thrust averaging approximately 24.8 mN.

To date ten orbit maintenance maneuver burns have been performed with the IPS to optimize ground coverage. Orbit maintenance maneuvers are required due to the spacecraft’s close proximity to Ceres’s irregular gravity, to use of the hydrazine thrusters, and to other small forces. The orbit maintenance
maneuvers were all performed with an input power to the thruster of approximately 580 W. Although periodic orbit maintenance maneuvers are required for science return, the spacecraft's orbit is very stable and the spacecraft can remain in the LAMO orbit for thousands of years or longer without impacting Ceres.

IPS System Power and PPU Performance

Spacecraft heliocentric range for the complete mission is plotted in Figure 4. The blue line color in the figure depicts periods during the mission when IPS was used for thrusting. As expected for a low thrust mission, the IPS is on and thrusting for the majority of mission time. After reaching a solar distance of 2.98 AU the Dawn spacecraft is now moving inbound to the sun, increasing the power available to the IPS. Data on power to the PPUs for operation of the thrusters are plotted in Figure 5. Data points in Figure 5 are the values averaged at a fixed power level. The data include telemetry for unregulated high voltage and current from the solar array to the PPUs and do not include PPU housekeeping power of approximately 20 W. Orbit transfers and orbit maintenance maneuvers were performed at a fixed power to FT2 of approximately 580 W. Operation at fixed power results in no flow rate transients from the bang-bang pressure regulator system and minimizes maneuver execution errors.

Both PPUs have operated perfectly throughout the mission to date, and PPU performance throughout the mission has been excellent. PPU efficiencies at 2.5-1.25 kW are similar to the efficiencies measured preflight and are consistently in excess of 93% at full power. PPU efficiencies at lower power are greater than measured pre-flight, likely due to telemetry calibration inaccuracies at low power. Beam currents controlled by the beam supplies in both PPUs were typically within 0.997 of the set point values, and neutralizer current and accelerator grid voltage were at the set point.

In Figure 6 data (averaged over individual thrust arcs) from temperature sensors inside the PPU indicate that PPU temperatures changed a few degrees C during cruise at full power, and decreased upon start of power throttling. 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 12.7 degrees C with PPU-1 operating at 0.52 kW. The fact that the PPU baseplate temperatures are near room temperatures even for full power operation is a reflection of the excellent thermal heat rejection system on the Dawn spacecraft. After the start of cruise to Ceres PPU control surface temperature was set to a low value to conserve heater power, but the PPUs have been kept well within their flight allowable temperature limits.

Temperatures of the harness connectors mating the thrusters to the PPUs are shown in Figure 7. The data indicate that at full power operation connector temperatures ranged between 10 to 45 degrees C, and at lower power the harness connector temperatures were as low as -6 degrees C, well within operational temperature limits of -55 to +90 degrees C. The temperature excursions experienced by the FT3 harness connector in 2011 and the FT2 harness connector for operations at Ceres are due primarily to changing solar exposure to the spacecraft, a consequence of orbit operations.

XFS Performance

The xenon flow system has operated perfectly throughout cruise, with the exception of the higher than expected solenoid valve cycling rates (as described in [12]) which do not pose a threat to mission reliability. Plenum tank pressures are controlled by actuation of the solenoid valve pairs between the main xenon tank and plenum tanks. To date the primary solenoid valve pair used to regulate main plenum pressure has been cycled approximately 1.25 million times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 0.67 times (Figure 8). Solenoid valve cycle rates at fixed flow rates increase as the density of the xenon in the main tank decreases and as the pressure differences between the inter-solenoid valve space and plenum tanks decrease. Solenoid valve cycle rates for the cathodes also increase when operated at full-power cathode flow rates for Ceres operations, where cathode flow will account for approximately 52% of the total xenon used. The solenoid valves on the Dawn XFS have a flight allocation of 1.25 million cycles, and there are redundant valves that have not yet been cycled in flight but could be used in the event of primary valve failure. The controlling temperature for the xenon control assembly plate was reduced early in cruise to reduce the solenoid valve cycle rate [13]. There are no indications of solenoid valve or latch valve leakage based on observations of steady-state pressure measurements of both plenum tanks. Figures 9a-9d indicate little change in the pressure transducer output telemetry from the six each plenum tank low pressure transducers.
Figure 4. Spacecraft heliocentric range from launch through June 2016. Blue line color denotes IPS thrusting.

Figure 5. Solar array input voltage and PPU operating power from start of cruise to Vesta through operations at Ceres LAMO.
Figure 6. PPU-1 and PPU-2 temperatures from start of cruise to Vesta through operations at Ceres LAMO.

Figure 7. Harness connector temperatures from start of cruise to Vesta through operations at Ceres LAMO.
Figure 8. Cumulative number of discharge and cathode SV cycles vs. xenon consumed from launch through operations at Ceres LAMO.

Figure 9a. Discharge plenum tank pressure transducer differences over time as measured by DCIU-1.
Figure 9b. Cathode plenum tank pressure transducer differences over time as measured by DCIU-1.

Figure 9c. Discharge plenum tank pressure transducer differences over time as measured by DCIU-2.
To date xenon consumption on Dawn integrated flow rates over time to estimate total xenon use. This FCD model, which uses plenum tank pressures and FCD temperatures for calculating flow rates, is considered to be the most accurate way of estimating xenon use for individual xenon-consuming events. Over Dawn’s almost nine year years of operations, however, errors/uncertainties from FCD calibrations and flight telemetry data have accumulated such that although the errors are a low percentage of the propellant used, they are a high percentage of the estimated xenon remaining.

Xenon consumption and remaining xenon on-board was re-evaluated after the last orbit maintenance maneuver in April 2016 to support concept studies of options for extending Dawn’s mission beyond June 2016. Two different approaches were evaluated to develop estimates for xenon remaining on the Dawn spacecraft: the flow control device model (FCD) that has been used to account for xenon consumed since launch, and a pressure-volume-temperature (PVT) model. For the FCD and PVT methods, nominal xenon remaining and uncertainties were evaluated based on standard practices used by JPL’s Propulsion Section for determining quantity and uncertainties for hydrazine and helium tanks. Results are summarized in Table 5. Analysis from the FCD model indicates there are 24.3 ±7.2 kg of xenon remaining at 2-sigma uncertainty, and the PVT model indicates there are 29.4 ±4.0 kg of xenon remaining at 3-sigma uncertainty. Based on the analysis the PVT model is considered to be the most accurate model for determining xenon remaining on-board Dawn now. Solenoid valve cycling rates depend upon the density of the xenon in the xenon storage tank. Solenoid valve cycle rate data from the last time Dawn IPS was operated with xenon flow are consistent with a xenon storage tank pressure measurement and temperature measurements made from 2016-101-132, leading to additional confidence in the PVT model.

Table 5. Xenon Remaining on the Dawn Spacecraft June 2016

<table>
<thead>
<tr>
<th>Evaluation Method</th>
<th>Minimum Xenon Remaining (kg)</th>
<th>Nominal Xenon Remaining (kg)</th>
<th>Maximum Xenon Remaining (kg)</th>
<th>Uncertainty (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCD</td>
<td>17.2*</td>
<td>24.3</td>
<td>31.4*</td>
<td>7.2*</td>
</tr>
<tr>
<td>PVT</td>
<td>25.3</td>
<td>29.4</td>
<td>33.4</td>
<td>4.0</td>
</tr>
</tbody>
</table>

*FCD model minimum, maximum and uncertainty values include uncertainty in the estimate of xenon loaded into the xenon storage tank pre-launch (±0.35 kg)
TGA Performance

The TGAs have also operated very well in orbit at Ceres. Each TGA consisting of two each motor/tripod assemblies (side A and side B) per FT is used to move the ion thruster vector to control the two axes normal to the thrust direction. This mode is known as thrust vector control (TVC). RWAs or RCS hydrazine thrusters are used to control the axis around the thrust vector. Cumulative TGA actuator motor revolutions for the A-side motors for each FT are shown in Figure 10. The B-side motors have almost the same number of revolutions. The data indicate that through June 2016 the TGA motors for FT2 have accumulated the equivalent of over 2.863 million motor revolutions for TGA-2. The motors were qualified to 30 million revolutions. The spacecraft is operated in TVC mode during normal thrusting, including during desaturations of the RWAs, which are typically sequenced approximately every 12 hours. TGA duty cycle has varied between 0.05% in cruise to up to 9% for orbit operations. In normal operation the TGAs “dither”, or rotate, a small amount around a target center. The duty cycle and number of TGA actuations per kg of xenon used are greater with RWA control. In Figure 10, the actuation rate for FT2 and FT3 decreased when the spacecraft switched to hydrazine thrusters for attitude control starting in June 2010. In May 2011 and again in December 2014 the spacecraft switched to the wheels for attitude control as part of operations for Vesta approach and Ceres approach and the TGA duty cycle increased substantially. TGA duty cycle rates under RWA control may increase because under RWA control the spacecraft issues more correcting commands to slew the TGAs than is done under jet control. Approximately every two months for TGAs in use (and six months for unused TGAs) lubricant in the actuators is redistributed by vectoring the thrusters from their null locations to the hard stops and then back to their null locations.

Figure 10. Cumulative number of TGA side A cycles vs. xenon consumed, from launch through orbit operations at Ceres LAMO.
Thruster Performance Through Arrival to Survey Orbit at Ceres

Thruster performance data from the ICO were presented in [12] and detailed thruster performance from the start of cruise to Vesta to Ceres orbit operations are presented here. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness, which is estimated to be approximately 15 W for the discharge and 18 W for the thruster at full power. During operations at Vesta, and for some of cruise to Ceres and Ceres orbit operations the thrusters were operated at full power discharge cathode and neutralizer flow rates to minimize maneuver execution errors as described in [21].

IPS Operating Time and Xenon Consumption

Table 6 summarizes operating time for each thruster/PPU and xenon throughput from launch through June 2016. The xenon throughput in Table 6 uses values estimated from the FCD model as described previously. Dawn is on track to complete the mission with a cumulative total of approximately 48,800 hours of thruster beam-on time, close to the estimate at launch. FT2 has accumulated the most number of operating hours and xenon throughput, and Dawn has operated all three thrusters to more evenly distribute the total xenon consumed by each thruster. For transfers from one science orbit to another around Vesta and Ceres, in which the operational schedule requires a rapid design and implementation of the thrust profile, FT3 is preferred because FT3’s thruster axis is aligned with the principal axis of the spacecraft. Nevertheless, transfers with the other thrusters are feasible and any of the three Dawn thrusters can be used for any maneuver. FT3 was used for Vesta operations and both FT2 and FT3 were used for Ceres operations. In Table 6 PPU operating time is defined as when any of the individual supplies within the PPU, including cathode heater supplies, are on and outputting power.

Table 6. Operating time and xenon throughput for Dawn ion thrusters from launch through operations at Ceres LAMO.

<table>
<thead>
<tr>
<th>IPS Element</th>
<th>Neutralizer On-Time (Hours)</th>
<th>Beam On-Time (Hours)</th>
<th>Xenon Throughput (kg)</th>
<th>Thruster Starts</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT1</td>
<td>9524</td>
<td>9468</td>
<td>95.1</td>
<td>122</td>
</tr>
<tr>
<td>FT2</td>
<td>19916</td>
<td>19848</td>
<td>155.7</td>
<td>190</td>
</tr>
<tr>
<td>FT3</td>
<td>19299</td>
<td>19141</td>
<td>150.1</td>
<td>367</td>
</tr>
<tr>
<td>Thruster Totals</td>
<td>48742</td>
<td>48458</td>
<td>400.9</td>
<td>679</td>
</tr>
<tr>
<td>PPU-1</td>
<td>(Hours)</td>
<td>28872</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPU-2</td>
<td>(Hours)</td>
<td>19938</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPU Totals</td>
<td>(Hours)</td>
<td>48810</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IPS Operating Time and Xenon Consumption

Figures 11-12 include input power to the thrusters vs. xenon throughput and beam extraction operating time. Thruster power was throttled beginning in 2012 as the spacecraft’s distance from the sun increased, decreasing output from the solar array and reducing power available to the IPS. For Ceres operations thruster power was approximately 580 W.
Figure 11. Dawn thruster input power from start of cruise to Vesta through orbit operations at Ceres LAMO.

Figure 12. Dawn thruster input power from start of cruise to Vesta through orbit operations at Ceres LAMO.
Discharge Voltage

Discharge voltage and current telemetry for the three Dawn ion engines through operations at Ceres LAMO are shown in Figure 13. Telemetry with closed symbols indicate operation of an engine at off-nominal (high) cathode flow rates, and during the last part of cruise to Ceres and through operations at Ceres LAMO high cathode and discharge flow rates were used while thrusting with FT2 and FT3. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness. Full power cathode flow rates were used for Vesta operations to address the thrust stability issues that are described in [21]. This change resulted in extremely reliable and consistent maneuvers, and suppressed the discharge voltage (Figure 13). Operation with nominal cathode flow rates was resumed beginning October 1, 2012, until April 2014 when all three engines were switched to operations at rich cathode flow rates (the closed symbols in Figure 13).

For all three engines at full power, discharge voltage initially increased then stabilized. This is likely related to accelerator grid hole wear characteristics, which result in higher grid transparency to ions. Abrupt changes in discharge voltage exceeding approximately one volt are related to changes to the cathode flow rates from nominal values to full power values or to power level changes.

At approximately 101 kg of xenon throughput for FT2 and 111 kg of xenon throughput for FT3 the discharge voltage for both FT2 and FT3 began to increase at a rate of approximately 0.1 V per kg of xenon consumed. Both engines were operating at nominal cathode flow rates when the discharge voltage characteristics began changing. The most significant differences in operations on FT2 vs. FT3 are that FT2 has more operating time at lower power levels, fewer starts and substantially less operating time at high cathode flow rates. It is not known if the discharge voltage characteristics are indicative of wear in this thruster design. Presently at approximately 580 W of thruster input power the discharge voltage on FT2 is at 19.1 V at the maximum cathode flow rate. Dawn has had substantial margin to the discharge voltage for orbital operations at Ceres, and the discharge voltage is increasing over time at a very low rate.

Thruster Starts

From launch through operations at Ceres LAMO there have been a total of 679 thruster starts in flight, with 122 starts using FT1, 190 starts using FT2, and 367 starts using FT3. Almost half of these engine starts were on the discharge only for one hour (called "diode mode) to prepare the engine thermally for beam extraction. The cathode heater preheat duration for all starts was six minutes. Data taken at one second intervals indicate that in every start attempt in flight after the ICO, the discharge and neutralizer cathodes ignited within one second of the command for application of the igniter voltage pulses. Discharge cathode and neutralizer cathode heater power appear unchanged over time, possibly indicating low levels of keeper electrode erosion over time. Beginning in December 2014 all thrusters were started without using a thruster discharge pre-heat cycle. The highest power level for a thruster start without a thruster discharge pre-heat was at approximately 800 W on FT3.
Neutralizer Operation

Dawn thruster neutralizer keeper voltage data for operation from start of cruise to Vesta through operations at Ceres LAMO are shown in Figure 14. From the start of cruise to approximately 80 kg of xenon throughput neutralizer keeper voltages decreased in a similar way for all three Dawn thrusters. Dawn thruster neutralizer voltage changes may be related to improved cathode conditioning over time in the clean environment of space. Smaller changes to the neutralizer voltage appear to be due to thruster power changes, while larger changes are related to operating the engines at moderate to low power with rich cathode flow rates, which suppresses the neutralizer voltage (Figure 14).

The neutralizer cathode must be operated at the proper flow rate and neutralizer keeper emission current to result in the nominal operating mode referred to as “spot” mode. A potentially damaging neutralizer operating condition called “plume mode” is characterized by greater than nominal neutralizer keeper voltage and greater alternating current (AC) noise in the direct-current (DC) neutralizer keeper plasma. This mode can lead to life-limiting erosion in the neutralizer. A plume mode detection circuit in each Dawn PPU converts variations in the AC component of the neutralizer keeper voltage to a DC voltage. The plume mode circuit voltage telemetry is monitored in flight to evaluate the health of the neutralizer. Dawn thruster plume mode circuit output data for each engine averaged over individual thrust segments are shown in Figure 15. In normal operation the plume mode circuit voltage increases after cathode ignition, when the neutralizer cathode is known to operate in plume mode. Plume mode circuit output then decreases to a lower, steady-state voltage during normal neutralizer operation, with the plume voltage decreasing at lower power levels and rich cathode flow rates. During all of Dawn IPS operations since launch there have been no indications of neutralizer cathode operation in plume mode after the initial start-up transients. Dawn’s thrusters now have accumulated substantial operating time at low power, but plume mode circuit output data do not indicate any issues regarding plume mode as observed on the DS1 mission [2].
Figure 14. Dawn thruster neutralizer voltage from start of cruise to Vesta through operations at Ceres LAMO.

Figure 15. Dawn plume mode circuit output voltage from start of cruise to Vesta through operations at Ceres LAMO.
Accelerator Grid Current and Thruster Recycles

Accelerator grid current data for Dawn ion thrusters from start of cruise to Vesta through operations at Ceres LAMO are plotted in Figure 16. The accelerator grid current increased during the first 1,700 hours of operation at full power and leveled off after that. This is unlike the behavior of the accelerator grid impingement current noted in the ELT [18], which started at a higher level and then decreased over a period of approximately 1,000 hours to approximately 6.5 mA after that. Step changes in accelerator grid current are related to changes in thruster operating power and accelerator grid voltage. At a fixed flow rate and beam current thruster power can be finely controlled with step changes of approximately 10 V in beam voltage, which explains the step changes in accelerator grid current. All Dawn FTs have reached end of life (EOL) xenon throughput, which is defined as reaching a total thruster throughput of 70 kg of xenon. After reaching approximately 65-75 kg of xenon throughput the accelerator grid voltage was changed for each FT, from -200 V to -272 V, to provide additional margin to electron backstreaming from thruster wear. The effect of changing the accelerator grid voltage was a slight increase in beam divergence and reduced discharge loss, caused by an increase in the grid transparency to ions. Arcing or other faults can occur from grid spacing changes or from debris that bridges the gaps between the grids. The PPU is designed to clear these faults by quickly reducing discharge power, power-cycling the beam supplies, then re-establishing the discharge and beam currents to their nominal values, a process called high voltage recycling. High voltage recycles from start of cruise through operations at Ceres LAMO are shown in Figure 17. FT1 accumulated 67 recycles, FT2 44 recycles, and FT3 64 recycles. The data indicate that after initially increasing over a period of thousands of hours of operation, recycle rates have decreased over time and with decreasing power levels. There have been very few recycles from cold starts with the thruster front masks at temperatures below -80 degrees C. Recycle rates seemed to increase on thrusters which were re-started after months or years of disuse.

![Figure 16. Dawn thruster accelerator grid current from start of cruise to Vesta through operations at Ceres LAMO.](image_url)
DCIU Operation

The DCIUs control the PPUs and the XFS, including valve control and flow rates to the engines. The DCIUs include fault protection software to turn off the power supplies and close the solenoid valves and certain latch valves if certain fault conditions are detected. Generally one of the DCIUs is kept powered on because main xenon storage tank and plena tank pressure and temperature telemetry are provided by the DCIUs. Only one DCIU is powered on at any time. Since being powered on during the initial check out phase in the fall of 2007 the DCIUs have been on for approximately 76,000 hours. In that time, a period spanning almost nine years, the DCIUs have operated almost flawlessly. All DCIU commands were accepted and executed. Two operational errors, occurring several years apart, were likely related to Dawn’s space environment.

The DCIU-1 fault in 2014 occurred near the peak in sensitivity to missed thrust during the 2.5-year interplanetary transfer from Vesta to Ceres. The operations team responded swiftly and productively to minimize the duration of the interruption in thrusting. That included devising an entirely new approach trajectory to Ceres, taking advantage of the flexibility provided by the IPS and the mission. The new approach, with geometry very different from what previously been planned, was accomplished successfully and there were no significant consequences for science data acquisition.

V. Conclusions

The Dawn mission has successfully used its ion propulsion system for the heliocentric transfer to the main-belt protoplanet Vesta, for science operations in orbit, for departure from Vesta, cruise to the dwarf planet Ceres, Ceres approach, orbit capture at Ceres, transit to all four science orbits, and orbit maintenance maneuvers at Ceres LAMO orbit. To date the IPS has operated for approximately 48,458 hours with beam extraction, used almost 401 kg of xenon, and imparted a delta-V of over 11.0 km/s to the spacecraft. June 30, 2016 marks the end of Dawn’s primary mission. The Dawn IPS has proven to be extremely reliable and
capable with very few operational problems during its almost nine-year journey. The Dawn ion propulsion system and Dawn spacecraft are presently fully operational, and ready for continued orbital operations at Ceres.

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