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Implementation of the Dawn Ion Propulsion System

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Dawn will be the first use of ion propulsion on a full-up NASA science mission. The ion propulsion system for Dawn is based on that demonstrated on Deep Space 1 with modifications necessary to accommodate multiple thrusters, to make the system single fault tolerant, to reduce the mass of the mechanical gimbals, and to accommodate a much larger propellant load. Dawn will rendezvous with the two heaviest main-belt asteroids, Vesta and Ceres, with a launch scheduled for June 2006. To do this, the spacecraft will carry 450 kg of xenon and must operate over a 10-year time period. For comparison, DS1 carried only 81.5 kg of xenon, of which 73.5 kg were actually used, and had a mission duration of just over 3 years. The ion propulsion system for Dawn will provide a total ΔV of approximately 11 km/s, comparable to that provided by the launch vehicle.

I. Introduction

The objective of the Dawn mission is to rendezvous with and map the two heaviest main-belt asteroids, Vesta and Ceres. After being launched to Earth escape, the Ion Propulsion System (IPS) for Dawn will be used for the heliocentric transfer to Vesta, orbit capture at Vesta, transfer to a low Vesta orbit, departure and escape from Vesta, the heliocentric transfer from Vesta to Ceres, orbit capture at Ceres, and transfer to a low Ceres orbit. This will be the first mission ever in which a spacecraft will go into orbit about one body and then subsequently leave that body to go into orbit about a second body. The interplanetary trajectory is shown in Fig. 1 and the spacecraft configuration is given in Fig. 2 [1].

II. Ion Propulsion System

The Dawn IPS must provide a total ΔV of about 11 km/s. To accomplish this the IPS includes three 30-cm diameter xenon ion thrusters of the type flown on DS1 [2] and subjected to extensive long-duration testing [3,4]. The IPS also includes two Power Processor Units (PPUs), two Digital Control and Interface Units (DCIUs), three 2-axis Thruster Gimbal Assemblies (TGAs), a xenon tank capable of storing 450 kg of xenon, a Xenon Control Assembly (XCA), a High Pressure Subassembly (HPS), and an assortment of interconnecting tubing, service valves and cabling. The cabling diagram for the IPS is given in Fig. 3. Each DCIU is connected to a single PPU, that is, DCIU A is connected only to PPU1 and DCIU B is connected only to PPU2. Both DCIUs are connected to the XCA in such a way that each DCIU can operate all of the valves in the XCA. The xenon feed system diagram is shown in Fig. 4. Each of the DCIUs can also operate all three of the TGAs.

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The Current Best Estimate (CBE) for the mass of the ion propulsion system is given in Table 1. The current mass is based largely on measured masses of the major IPS components. The IPS mass is compared to the mass estimate made in the spring of 2001 during the Phase A study in Fig. 5. The total actual mass of the ion thrusters and PPUs is seen to be about 4 kg greater than estimated in 2001 even though these components are essentially build-to-print. The mass difference observed results from variations within the allowable fabrication tolerances. The mass increase in the DCIUs resulted from two changes, the first was a more than doubling of the number of latch valves that had to be operated (from 9 to 19), and the second was the addition of an isolated 28-V power supply to provide power to the PPU. This was necessary since the PPU as flown on DS1 does not meet JPL's design principles for grounding. The PPU requires two input power busses, a high-voltage input of 80 V to 140 V and a low voltage input of 22 V to 35 V. The PPU design ties the returns of these power busses together inside the unit. The isolated 28-V power supply added to the DCIU eliminates this grounding issue.

The tank mass indicated in Fig. 5 includes the main xenon tank and two plenum tanks. The plenum tanks are identical to those used on DS1. The mass increase indicated for the tanks in Fig. 5 is entirely in the main xenon tank. This increase resulted from two factors. First, the tank in the spring of 2001 was sized to hold only 360 kg of xenon, whereas the current tank is sized for 450 kg. Better definition of the actual tank design accounts for the rest of the increase. About half of the increase in the XCA mass is due to the inclusion of the XCA support plate, which previously was assumed to have been book-kept elsewhere (i.e., not with the IPS). The other half of the increase is due to things that were added to or left out of the original estimate including 10 new latch valves, solenoid valve pairs, and component support brackets.

The current TGA mass represents a 64% increase in mass relative to the 5/4/2001 estimate. This increase is entirely due to the design maturing with time.

The variation in the total IPS mass estimates with time is given in Fig. 6 dating back to the phase A study in the spring of 2001. Note, the only harnessing mass included in the IPS mass is for the high-voltage harnesses between the PPUs and the thrusters. The rest of the IPS harness mass is book-kept with the spacecraft.

III. IPS Throttle Table

The IPS for Dawn must be capable of operating over the full input power throttling range of the NASA 30-cm ion thruster. The PPU input power as a function of mission time is given in Fig. 7 for a representative Dawn trajectory. At the beginning of the mission there is much more power available from the solar array than can be used by the IPS so the PPU input power is capped at its maximum value of approximately 2.54 kW. At approximately 3.8 years into the mission, the spacecraft is far enough from the sun that the solar array can no longer provide sufficient power to operate the IPS at full power. From this point forward the IPS will be throttled to operate at the maximum available power.

To throttle the ion thruster there are 16 different combinations of flow rate settings which determine 16 unique throttle levels (TH). These 16 throttle levels are subdivided into 112 mission levels (ML) designated ML0 through ML111 by varying the beam voltage at constant beam current (and constant flow rate). The power difference between mission levels varies between 10 W and 28 W with the average being approximately 18 W.

Throttle Table History

Over the course of the NSTAR Project [5] that developed the ion propulsion system for Deep Space 1 (DS1), the ion thruster throttle table evolved through 17 versions starting with "Engine-A" and ending with "Engine-Q." The DS1 mission began with the Engine-Q throttle table. This throttle table was modified during the flight to account for the slightly lower thrust (about 1.4%) measured early in the mission at a few throttle levels. This modified throttle table became known as "Engine-Qmod." Qmod differs from Engine-Q in that all of the thrust levels in Engine-Q are multiplied by 0.986 to get the Qmod thrust levels. All other parameters are identical between Engine-Q and Qmod. Later in the DS1 mission,

the throttle table was modified again, this time to increase the neutralizer flow rate to prevent the neutralizer from going into plume mode during low power operation [6]. Plume mode is an undesirable operating condition that can potentially shorten the life of the neutralizer cathode. This throttle table is designated "Engine-R." During the Dawn Phase B activity a study was conducted to evaluate the benefits of IPS operation at power levels below the minimum identified in the Qmod throttle table. A new throttle table was generated that projected thruster/PPU operation at lower power levels to support this study. This throttle table is designated "Engine-S." Until recently Dawn has used the EOL Qmod throttle table in the trajectory calculations.

Engine-T Throttle Table

A new throttle table, designated "Engine-T" has been developed that incorporates the following changes to correct problems with the Qmod throttle table.

1. The ad hoc thrust reduction factor of 0.986 has been removed based on measurements of the thrust reduction factors made after the flight of DS1. The main features of this are improved corrections for the thrust loss due to multiply charged ions in the exhaust beam and beam divergence.
2. Increase in the neutralizer keeper current at low throttle levels to prevent plume mode operation. This approach is more effective and has less impact on the thruster performance than the flow rate increase used in Engine-R.
3. Increase in the main flow rate at some low power throttle levels. This change was made to reduce the discharge power losses at these throttle levels. The discharge losses observed on DS1 exceeded the EOL throttle table values at some low-power throttle levels.

Engine-U Throttle Table

The Engine-T throttle table was modified again to change the how the PPU efficiency variation over the throttle range is accounted for. In the Engine-T throttle table the worst-case PPU efficiency is used at each power level. In the Engine-U throttle table this conservatism has been removed and the PPU efficiency is described by the current best estimate (CBE) plus uncertainty at each throttle level. A short version of the Engine-U throttle table is given in Tables 2 through 4.

IV. Ion Thruster Acceptance Testing

Fabrication of all three ion thrusters for Dawn (designated FT1, FT2 and FT3) has been completed. Each thruster has completed initial functional testing, vibration testing, and post-vibe functional testing. In addition, two of the thrusters (FT1 and FT3) have completed all of the formal acceptance testing. Testing of the remaining thruster is ongoing as of this writing.

Thruster Magnetic Field Contours

A key requirement for the Dawn thrusters is that they must reproduce the operating characteristics of the NSTAR flight thrusters one of which was flown on DS1 and the other subjected to the 30-khr Extended Life Test (ELT) [3]. A necessary criteria to meet this requirement is that the interior magnetic fields of the Dawn thrusters must match those of the NSTAR thrusters. This proved more difficult than expected. Errors in the NSTAR drawings and insufficiently tight specifications resulted in the need to rework each of the Dawn thrusters in order to match the NSTAR magnetic field characteristics. The end result of this rework, however, was excellent. The magnetic field contours for FT1 are compared to the NSTAR thruster used in the ELT in Fig. 8. The magnetic field contours for all three Dawn thrusters are compared in Fig. 9. Taken together these figures indicate that the Dawn thrusters reproduce the NSTAR thruster magnetic field characteristics and that the thruster-to-thruster repeatability is good.

Acceptance Test Results

Each thruster is subjected to a formal acceptance test procedure that includes the following series of tests. The acceptance test procedure begins with an initial performance test. During this test the thruster is operated six different throttle levels (TH0, TH3, TH6, TH9, TH12 and TH15). At each throttle level all the thruster electrical parameters are measured, perveance and electron-backstreaming limits are determined, ion beam current density profiles are measured using a near-field Faraday probe, the double ion content of the beam on the thruster centerline is measured using an ExB probe, the thrust vector location is measured, and the neutralizer flow rate margin against plume mode operation is determined. After this initial functional test the thruster is removed from the vacuum system and subjected to a protoflight level vibration test. Vibration testing was preformed using the engineering model (EM) TGA in order to provide the most realistic loads into the thruster as possible. Following vibration testing the thruster is subjected to a post-vibe functional test at all six throttle levels followed by "thermal-vacuum" testing. A final functional test at all six throttle levels concludes the acceptance test procedure. The thermal vacuum test consists of two thermal cycles to the protoflight cold and hot extremes with thruster ignition tests at each temperature extreme for each cycle.

Some of the key results from the thruster acceptance tests are given in Figs. 10 through 13. The perveance characteristics of the thruster ion optics from the initial functional tests are given in Fig. 10 expressed in terms of the perveance margin. The perveance margin is the difference between the planned operating voltage for the beam power supply and the beam voltage at which the perveance limit is reached. The perveance limit is defined at the point where the slope of the accelerator grid current vs beam voltage equals -0.02 mA/V. As indicated in Fig. 10 the perveance margin significantly exceeds the Dawn specification and all three thrusters have very similar perveance characteristics. In addition, little change was observed in the perveance characteristics after vibration testing and after thermal-vacuum testing as indicated in Fig. 11.

Similarly there was little variation in electron-backstreaming characteristics observed over the course of each thruster acceptance test. The post-vibe electron-backstreaming characteristics for all three thrusters are given in Fig. 12. It is clear from these data that the thrusters do not meet the Dawn specification for electron-backstreaming over most of the throttle range, with the largest deviation occurring at full power (TH15). This is significant because the first life-limiting mechanism for the NSTAR ion thruster at full power is the onset of electron-backstreaming as observed in the Extended Life Test (ELT) of the DS1 flight spare ion thruster [3]. It should be noted, however, that the DS1 flight spare ion thruster used in the ELT also did not meet the Dawn specification during its acceptance testing. During the first functional test of this thruster the electron-backstreaming limit at TH15 was -161 V. After approximately 500 hours of operation the electron-backstreaming limit for the ELT thruster improved to -151 V. For the Dawn thrusters the electron-backstreaming limits at TH15 range from -164 V to -173 V. The implications of this will be discussed in a subsequent section on the thruster life.

The post-vibe discharge losses for each thruster are given in Fig. 13. Again there was little variation in discharge loss over the course of each acceptance test. The discharge chamber performance for FT2 and FT3 agree well with each other and are better than the Dawn specification over the entire throttle range. This was the expected result. The performance of the FT1 discharge chamber is consistently poorer (by roughly 10%) relative to FT2 and FT3 over the entire throttle range. This is due to a fabrication error in the magnetic circuit of FT1. This thruster has two magnets in sideways in the middle magnet ring. The sideways orientation of these two magnets was not detected during the measurements of the magnetic field contours of Fig. 9 because these measurements were only made in a single plane and this plane evidently was not close to the incorrectly oriented magnets. There are XXX magnets in each thruster so having two incorrectly oriented does not have a significant impact on the thruster's overall magnetic field. However, having a magnet in sideways makes it easier for energetic electrons in the discharge chamber plasma to reach the anode at this location which degrades the discharge chamber performance. To correct the orientation of these magnets would require extensive disassembly and rework of the thruster. Consequently, it was decided that the observed performance degradation was not

sufficient to warrant the cost, schedule impact, and risk associated with such a significant rework and so FT1 will be flown with the two magnets in sideways.

Thruster Life

The amount of propellant that each ion thruster must process, for a trajectory that is representative of the Dawn mission, is given in Fig. 14 as a function of throttle level. This figure assumes that the entire mission is performed using only two of the three ion thrusters in the IPS. That is, it makes the worst-case assumption that one of the ion thrusters fails right at the beginning of the mission. This figure also includes the amount of xenon processes at each throttle level during the ELT. Under the assumption that the entire Dawn mission is performed using only two ion thrusters, each thruster must process a total of 200 kg xenon with approximately 100 kg of this at full power (TH15) and about 35 kg at TH5. In contrast the ELT processed 235 kg of which 145 kg was at full power and 25 kg at TH5.

The ELT demonstrated that electron-backstreaming resulting from erosion of the accelerator is the first life-limiting mechanism for NASA's 30-cm ion thruster at full power. The thruster, however, was still fully functional at throttle levels of TH12 and below when the test was suspended.

Xenon Feed System

The xenon feed system consists of the XCA, Xe tank, two plenum tanks, a high-pressure subassembly (HPS), nine service valves, and the interconnecting tubing. The XCA was fabricated by Moog, Inc. and was delivered on schedule to JPL in October 2004. The entire xenon feed system was integrated onto the core spacecraft structure in November 2004 through January 2005 at JPL. A picture of the XCA on the core spacecraft structure is given in Fig. 15. One of the two plenum tanks is also visible in this picture, as is the HPS located near the bottom of the spacecraft. The flow control devices (FCDs) were procured from the Lee Company and calibrated at JPL before being provided to Moog for inclusion in the XCA.

The flight Xe tank is shown in Fig. 16 prior to blanketing and integration. The xenon tank is a composite overwrapped pressure vessel (COPV) with a titanium liner and a graphite-epoxy overwrap.

Table 1 IPS Current Best Estimate (CBE) Mass List

	QTY	CBE Unit Mass (kg)	CBE Mass (kg)
Thrusters & PPUs			**55.6**
Ion thruster	3	8.90	26.70
PPU	2	14.44	28.88
DCIU			**11.58**
DCIU	2	5.79	11.58
Tanks			**24.31**
Xenon Tank	1	21.6	21.6
Plenum Tank	2	1.37	2.74
XCA			**14.73**
Misc. XFS Components			**3.46**
Gimbals			**13.6**
Cabling			**4.6**
TOTAL DRY:			**127.9**

Table 2 Engine-U Throttle Table Input Parameters.

Throttle Levels		Input Parameters						
TH	ML	Beam Power Supply Voltage, V_B	Beam Power Supply Current, J_B	Accelerator Voltage, V_A	Neutralizer Keeper Current, J_{NK}	Nominal Main Flow	Nominal Cathode Flow	Neutralizer Flow
		(V)	(A)	(V)	(A)	(sccm)	(sccm)	(sccm)
15	111	1100	1.760	-180.0	1.500	23.43	3.70	3.70
14	104	1100	1.670	-180.0	1.500	22.19	3.35	3.35
13	97	1100	1.580	-180.0	1.600	20.95	3.06	3.06
12	90	1100	1.490	-180.0	1.700	19.86	2.89	2.89
11	83	1100	1.400	-180.0	1.800	18.51	2.72	2.72
10	76	1100	1.300	-180.0	1.900	17.22	2.56	2.56
9	69	1100	1.200	-180.0	2.000	15.98	2.47	2.47
8	62	1100	1.100	-180.0	2.100	14.41	2.47	2.47
7	55	1100	1.000	-180.0	2.200	12.90	2.47	2.47
6	48	1100	0.910	-180.0	2.300	11.33	2.47	2.47
5	41	1100	0.810	-180.0	2.400	9.82	2.47	2.47
4	34	1100	0.710	-180.0	2.400	8.30	2.47	2.47
3	27	1100	0.610	-180.0	2.400	6.85	2.47	2.47
2	20	1000	0.530	-180.0	2.400	6.11	2.47	2.47
1	13	825	0.530	-180.0	2.400	6.11	2.47	2.47
0	6	670	0.510	-180.0	2.400	6.28	2.47	2.47

Table 3 Engine-U Throttle Table Efficiency Parameters.

Throttle Levels		Efficiency Parameters						
TH	ML	Discharge propellant utilization efficiency, η_{ud}	Total propellant utilization efficiency, η_u	Engine-T Double ion fraction	Double ion thrust loss factor, α	Beam Divergence Thrust Loss, F_T	Thrust loss factor γ	PPU Efficiency (EOL)
15	111	0.894	0.786	0.082	0.978	0.981	0.959	0.929
14	104	0.901	0.796	0.082	0.978	0.981	0.959	0.928
13	97	0.906	0.804	0.082	0.978	0.981	0.959	0.928
12	90	0.902	0.800	0.103	0.973	0.981	0.954	0.927
11	83	0.908	0.805	0.103	0.973	0.981	0.954	0.927
10	76	0.905	0.801	0.103	0.973	0.981	0.954	0.926
9	69	0.896	0.790	0.077	0.979	0.980	0.959	0.925
8	62	0.897	0.783	0.077	0.979	0.980	0.959	0.924
7	55	0.896	0.772	0.077	0.979	0.980	0.959	0.922
6	48	0.908	0.770	0.068	0.981	0.979	0.961	0.920
5	41	0.908	0.756	0.068	0.981	0.979	0.961	0.918
4	34	0.908	0.739	0.068	0.981	0.979	0.961	0.914
3	27	0.902	0.713	0.058	0.984	0.976	0.960	0.909
2	20	0.851	0.661	0.058	0.984	0.976	0.960	0.900
1	13	0.851	0.661	0.058	0.984	0.976	0.960	0.894
0	6	0.803	0.626	0.022	0.994	0.980	0.974	0.886

Table 4 Engine-U Throttle Table Performance Parameters.

Throttle Levels		EOL Performance											
TH	ML	PPU Input Power (EOL)		Thruster Input Power (EOL)	Engine-U Thrust (EOL)		Isp (EOL)	Thruster Efficiency (EOL)	Discharge Loss (EOL)	Accelerator Current (EOL)	Discharge Current (EOL)	Discharge Voltage (EOL)	Neutralizer Keeper Voltage (EOL)
		(W)	Uncertainty	(W)	(mN)	Uncertainty	(s)		(eV/ion)	(mA)	(A)	(V)	(V)
15	**111**	2496	1.04%	2318	91.5	1.13%	3074	0.595	204	6.1	15.0	24.0	14.5
14	**104**	2376	1.07%	2206	86.8	1.17%	3113	0.601	207	5.6	14.0	24.7	14.5
13	**97**	2254	1.10%	2090	82.1	1.22%	3143	0.606	208	5.1	13.0	25.3	14.5
12	**90**	2129	1.14%	1973	77.1	1.28%	3114	0.596	207	4.7	12.0	25.7	14.6
11	**83**	2004	1.18%	1857	72.4	1.34%	3132	0.599	207	4.3	11.1	26.1	14.7
10	**76**	1866	1.23%	1728	67.2	1.43%	3119	0.595	207	3.8	10.2	26.3	14.8
9	**69**	1732	1.30%	1602	62.4	1.52%	3093	0.591	209	3.4	9.5	26.5	15.0
8	**62**	1601	1.37%	1479	57.2	1.64%	3065	0.582	215	3.0	8.9	26.5	15.3
7	**55**	1473	1.45%	1359	52.0	1.78%	3023	0.568	224	2.6	8.4	26.6	15.6
6	**48**	1362	1.54%	1253	47.4	1.94%	3021	0.560	237	2.3	8.1	26.5	15.9
5	**41**	1239	1.66%	1137	42.2	2.16%	2964	0.540	255	2.0	7.8	26.5	16.3
4	**34**	1116	1.81%	1020	37.0	2.44%	2897	0.515	280	1.7	7.5	26.5	16.7
3	**27**	992	2.00%	902	31.8	2.82%	2794	0.483	310	1.5	7.2	26.5	17.2
2	**20**	812	2.21%	732	26.3	3.23%	2468	0.435	300	1.3	6.0	26.5	17.6
1	**13**	714	2.11%	639	23.9	3.24%	2238	0.410	300	1.3	6.0	26.5	17.6
0	**6**	606	2.06%	537	20.9	3.37%	1934	0.370	300	1.3	5.8	26.5	17.7

Acknowledgments

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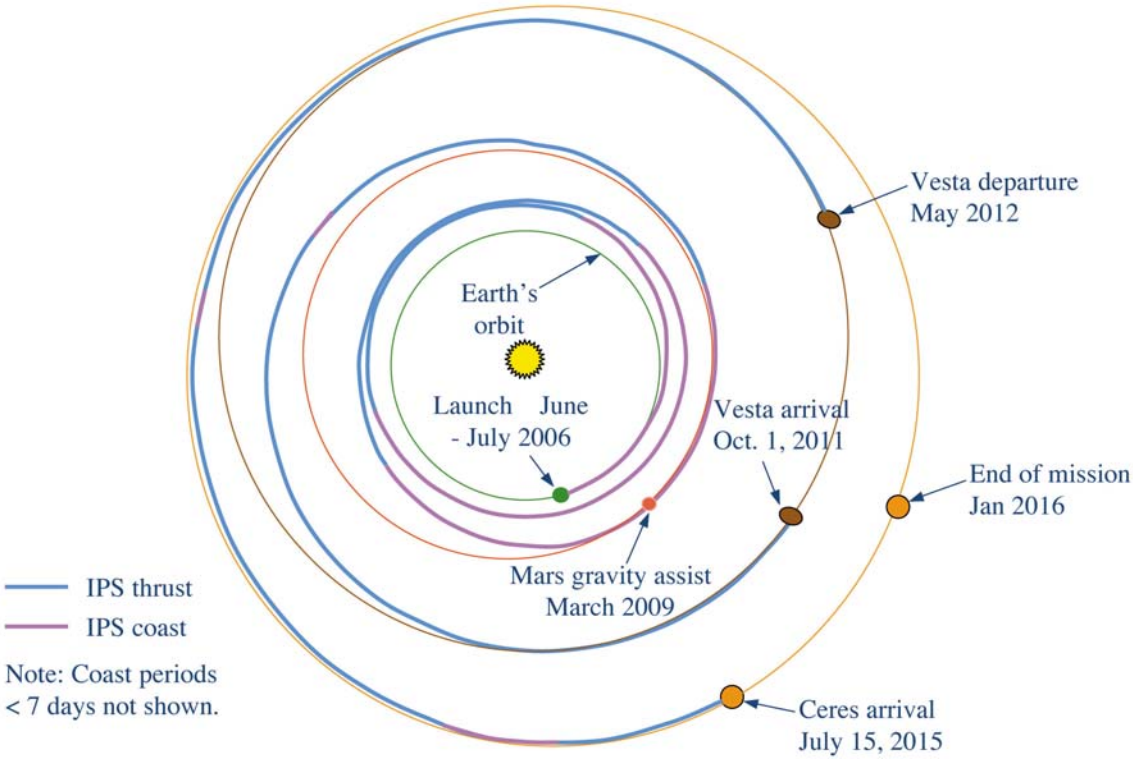

Fig. 1 Dawn interplanetary trajectory.

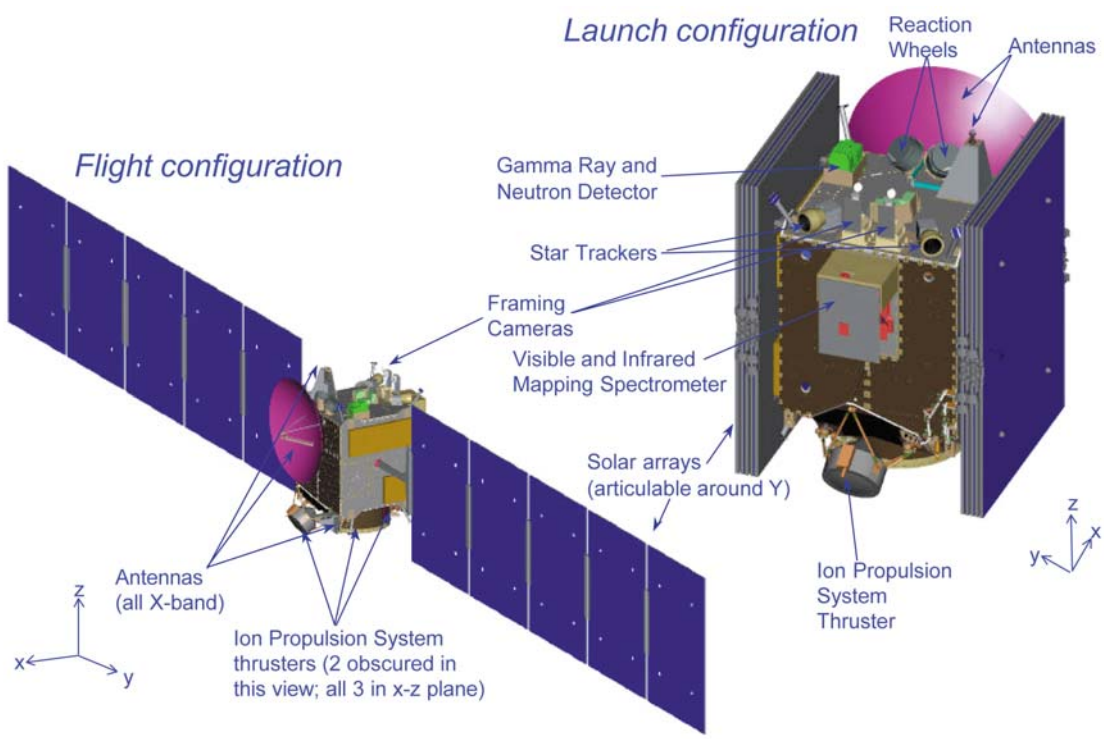

Fig. 2 Dawn spacecraft configuration.

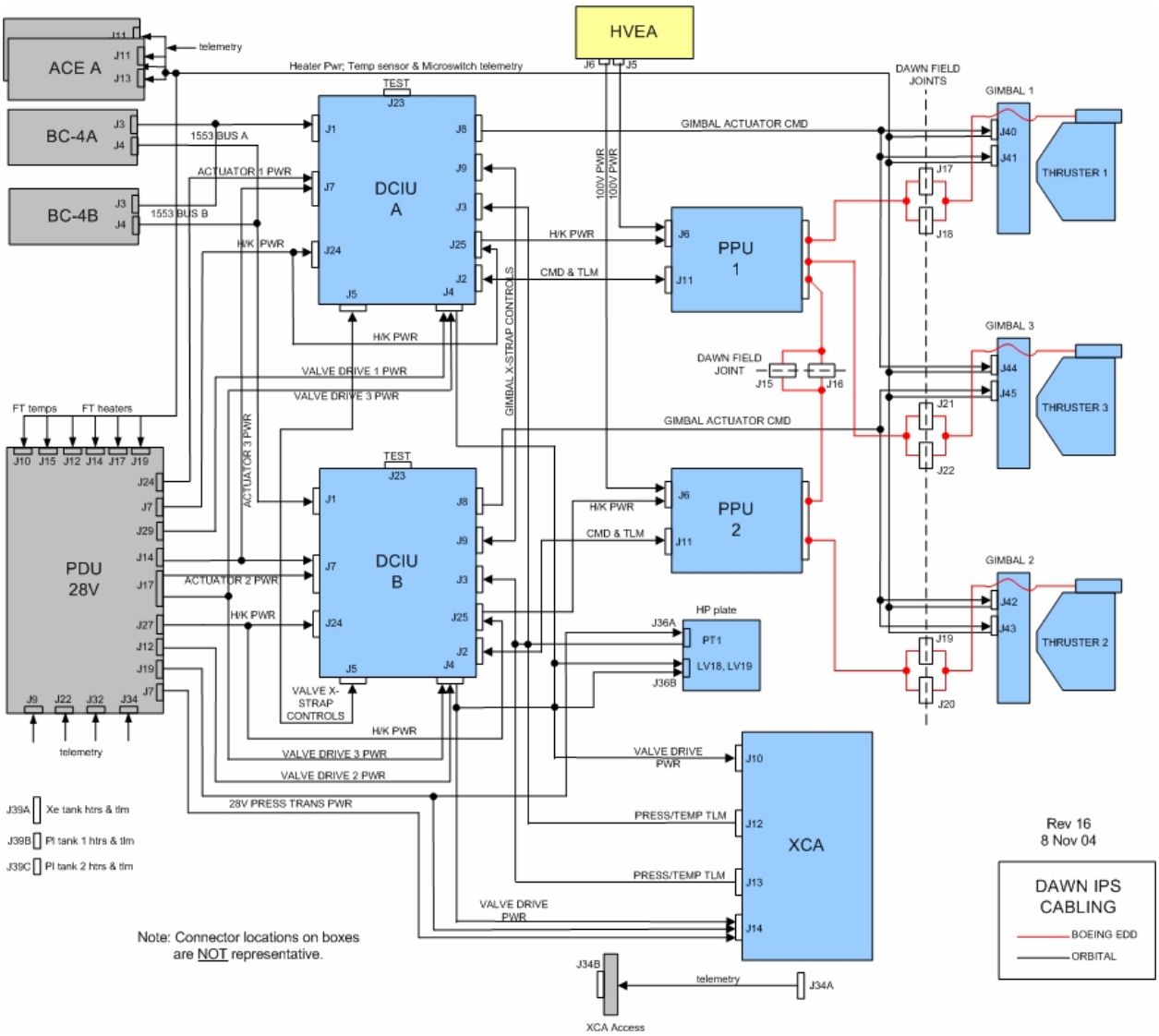

Fig. 3 Dawn IPS cabling diagram.

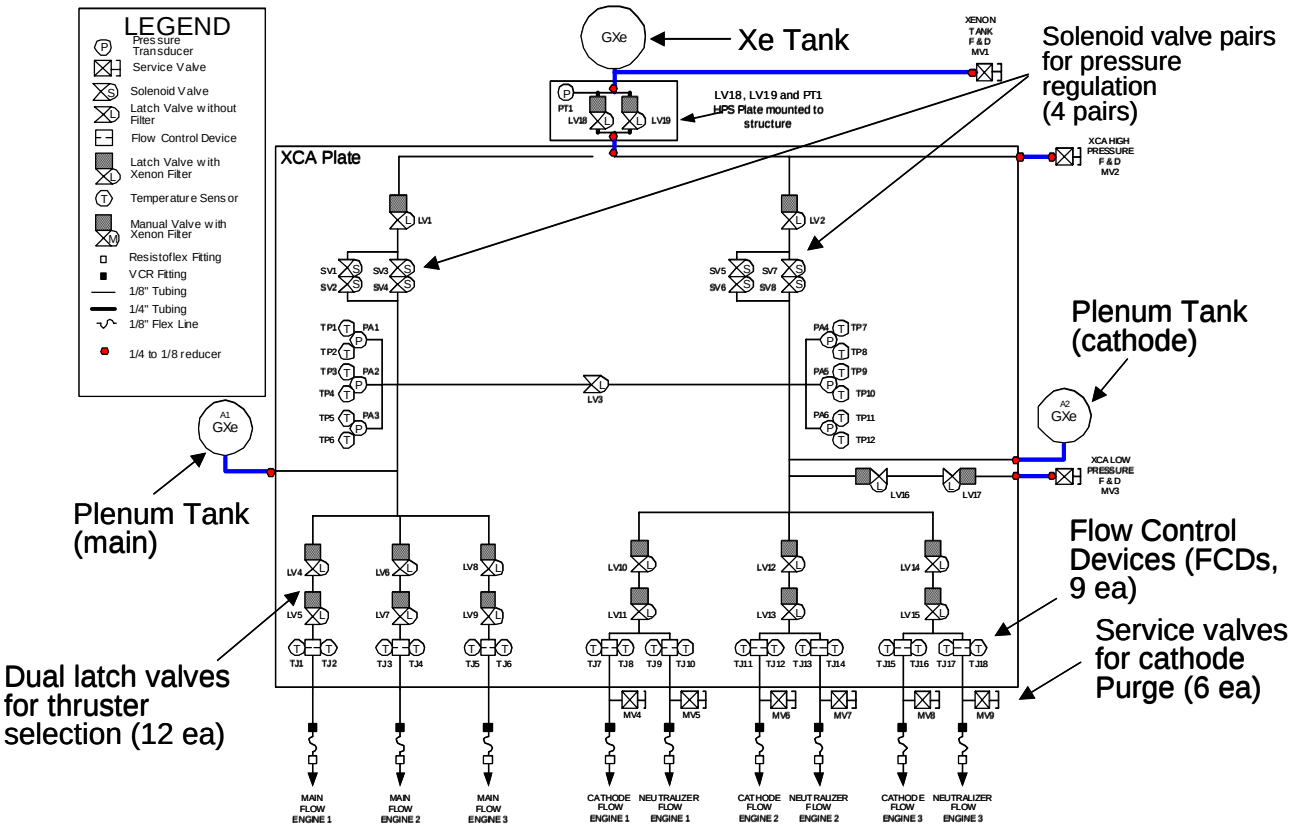

Fig. 4 Xenon feed system diagram.

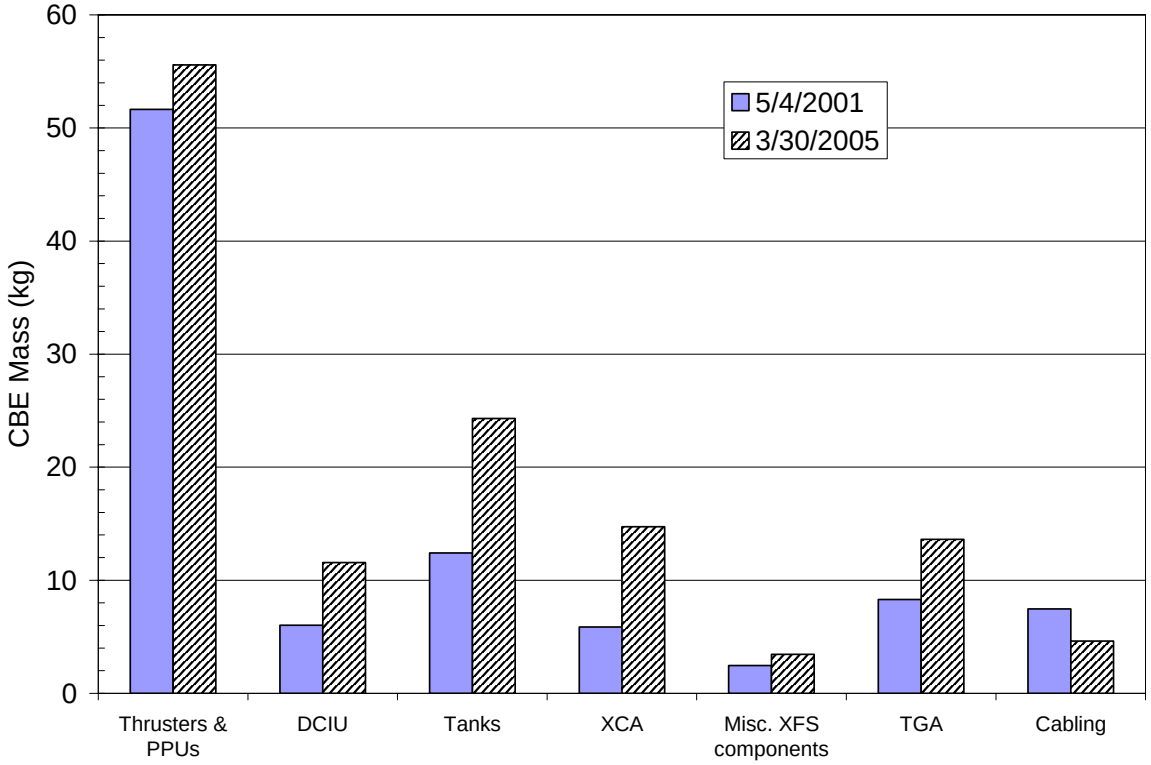

Fig. 5 Comparison of current component masses with mass estimates from the Phase A study.

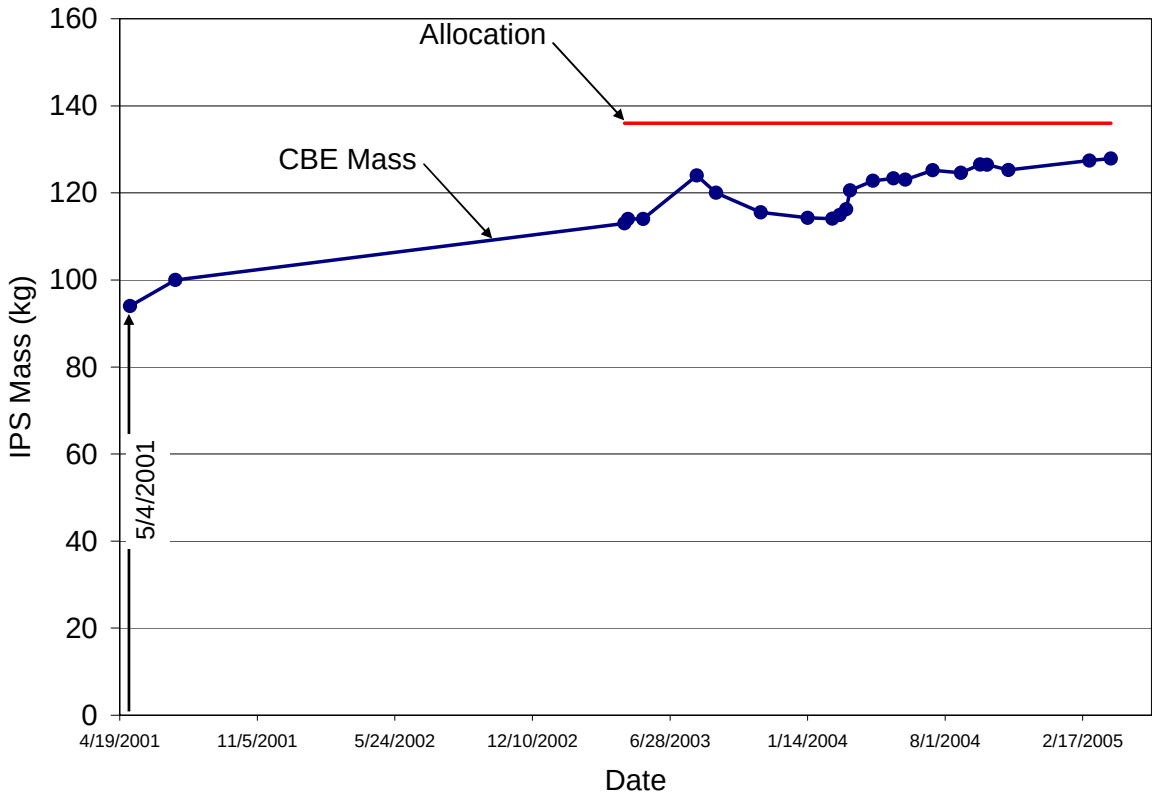

Fig. 6 Change in the Current Best Estimate (CBE) of the total IPS mass with time.

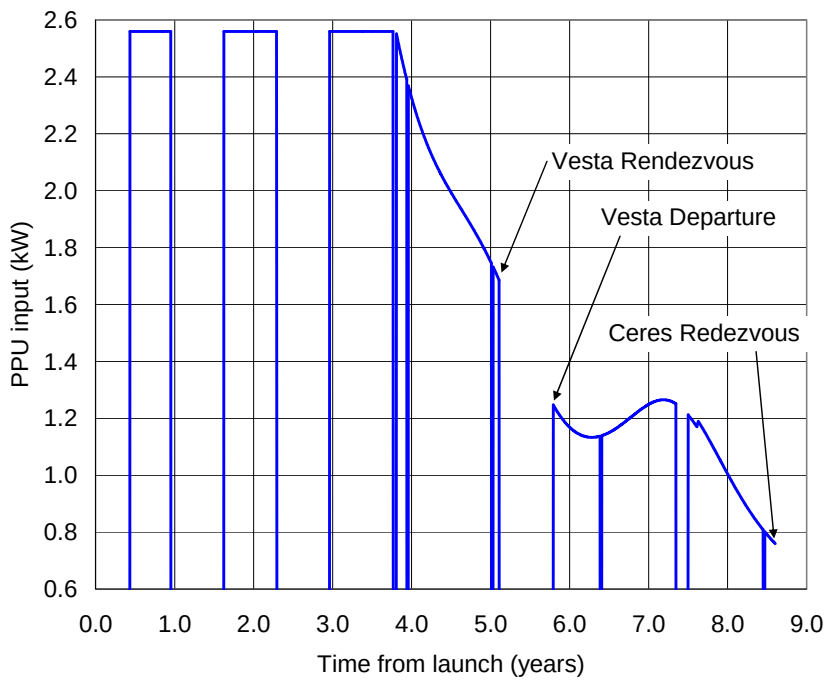

Fig. 7 PPU input power variation for a representative Dawn trajectory.

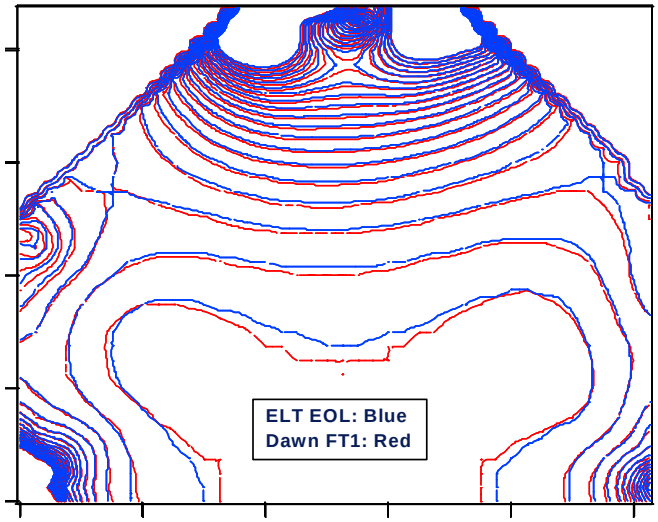

Fig. 8 The Dawn FT1 magnetic field contours in red agree well with those from the NSTAR thruster used in the Extended Life Test (ELT) in blue. Note, the grids are located at the bottom of this figure and the contours are in 10-gauss intervals. The aspect ratio of this figure is not correct. These data were taken without the cathodes in place.

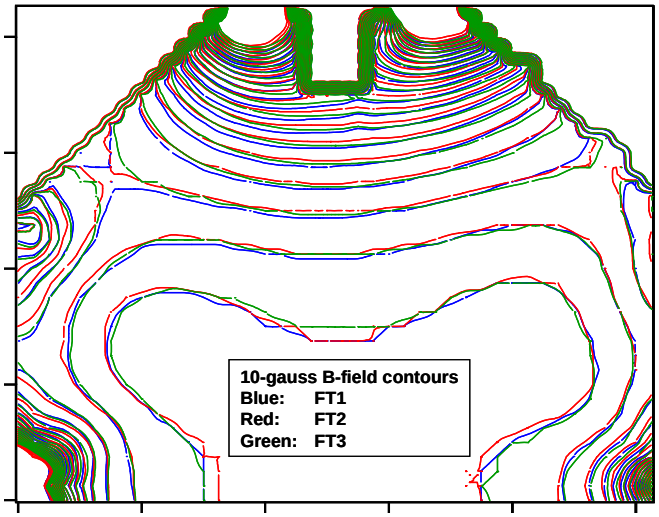

Fig. 9 Excellent repeatability of the magnetic field contours for each of the Dawn ion thrusters was obtained . These data were taken with the cathodes in place. The aspect ratio of this figure is not correct.

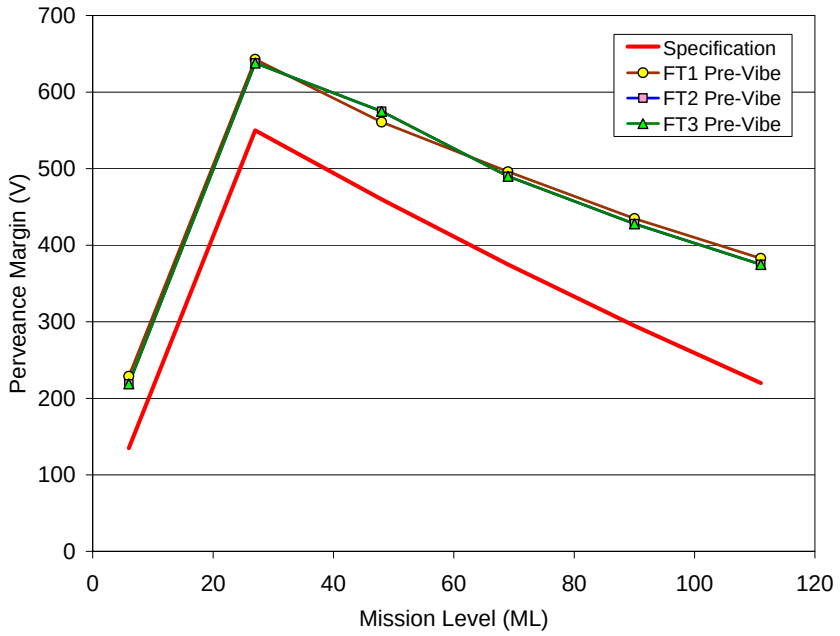

Fig. 10 The Dawn thruster ion optics have excellent perveance characteristics and little grid-to-grid variation.

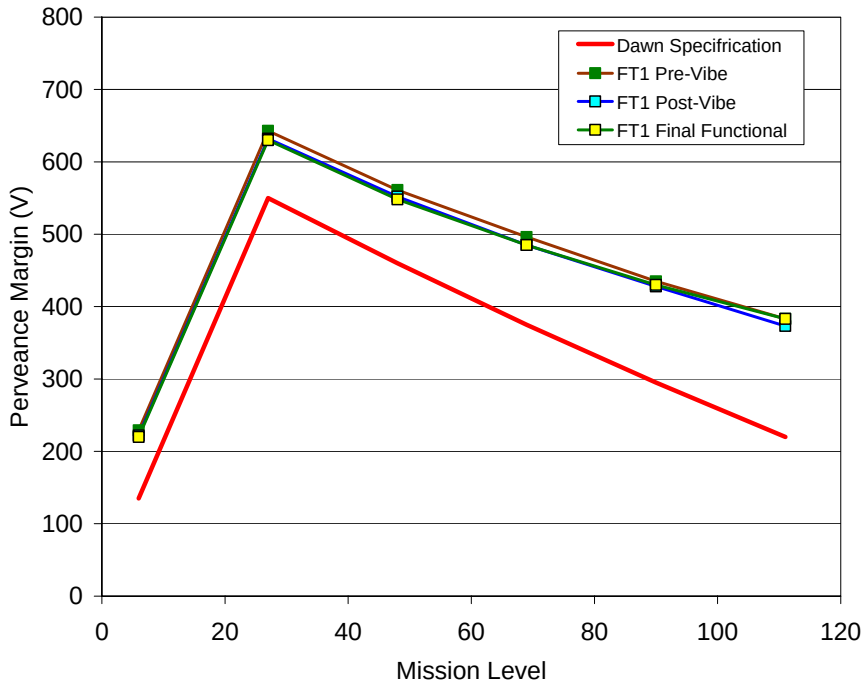

Fig. 11 Little variation in perveance characteristics was observed as a result of vibration and thermal-vacuum testing.

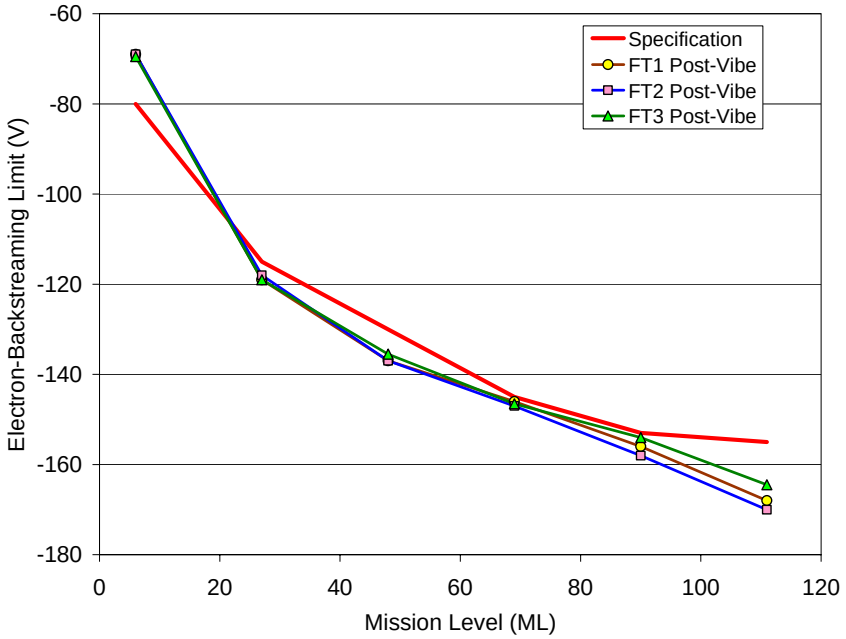

Fig. 12 All three thrusters have electron-backstreaming characteristics that don't meet the Dawn specification.

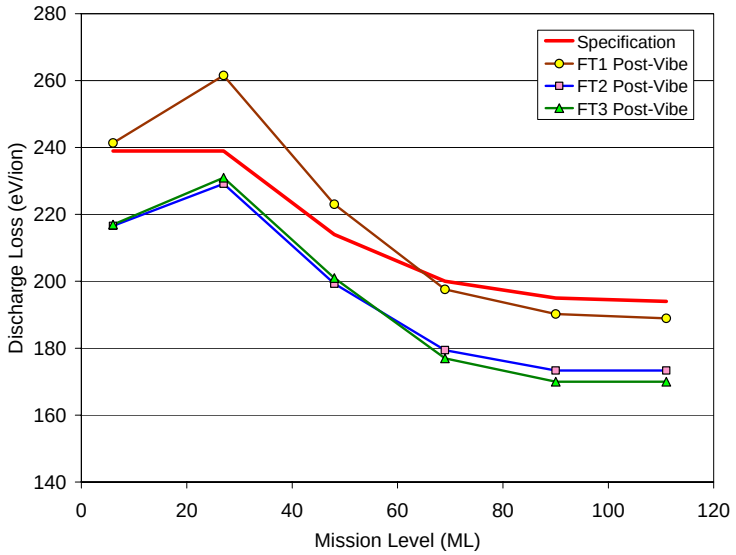

Fig. 13 The discharge loss characteristics for FT2 and FT3 agree well with each other and are better than the Dawn specification as expected. The discharge losses for FT1 are poorer because two magnets in the middle magnet ring were inadvertently installed sideways.

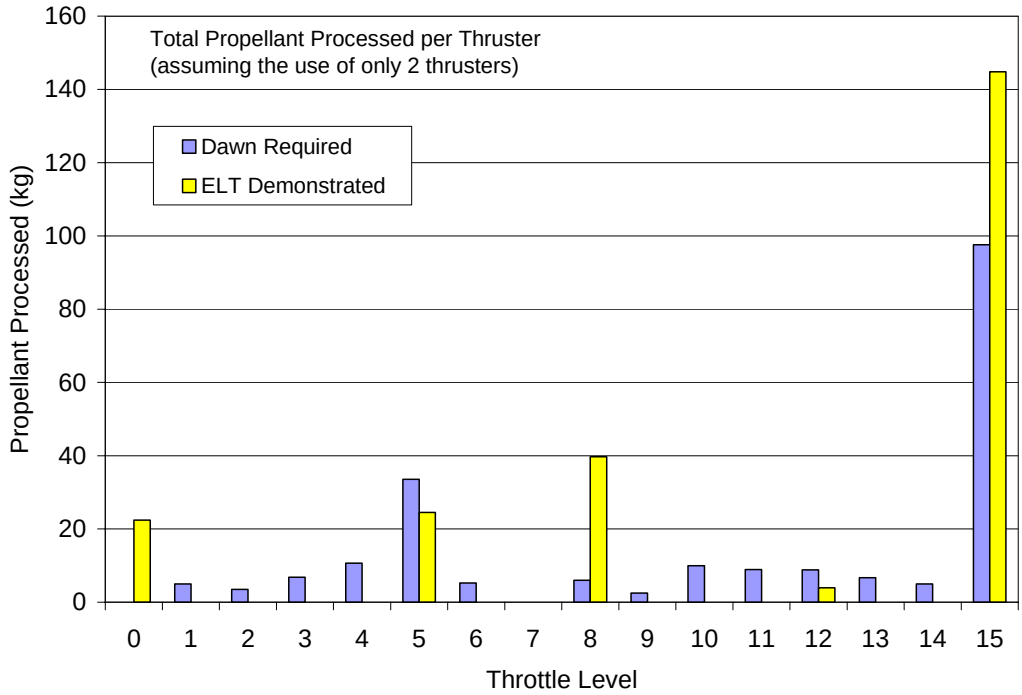

Fig. 14 Comparison of the propellant that must be processed at each throttle level per thruster for Dawn (assuming the entire mission is preformed by only two thrusters) with the propellant throughput demonstrated in the ELT with the DS1 flight spare ion thruster.

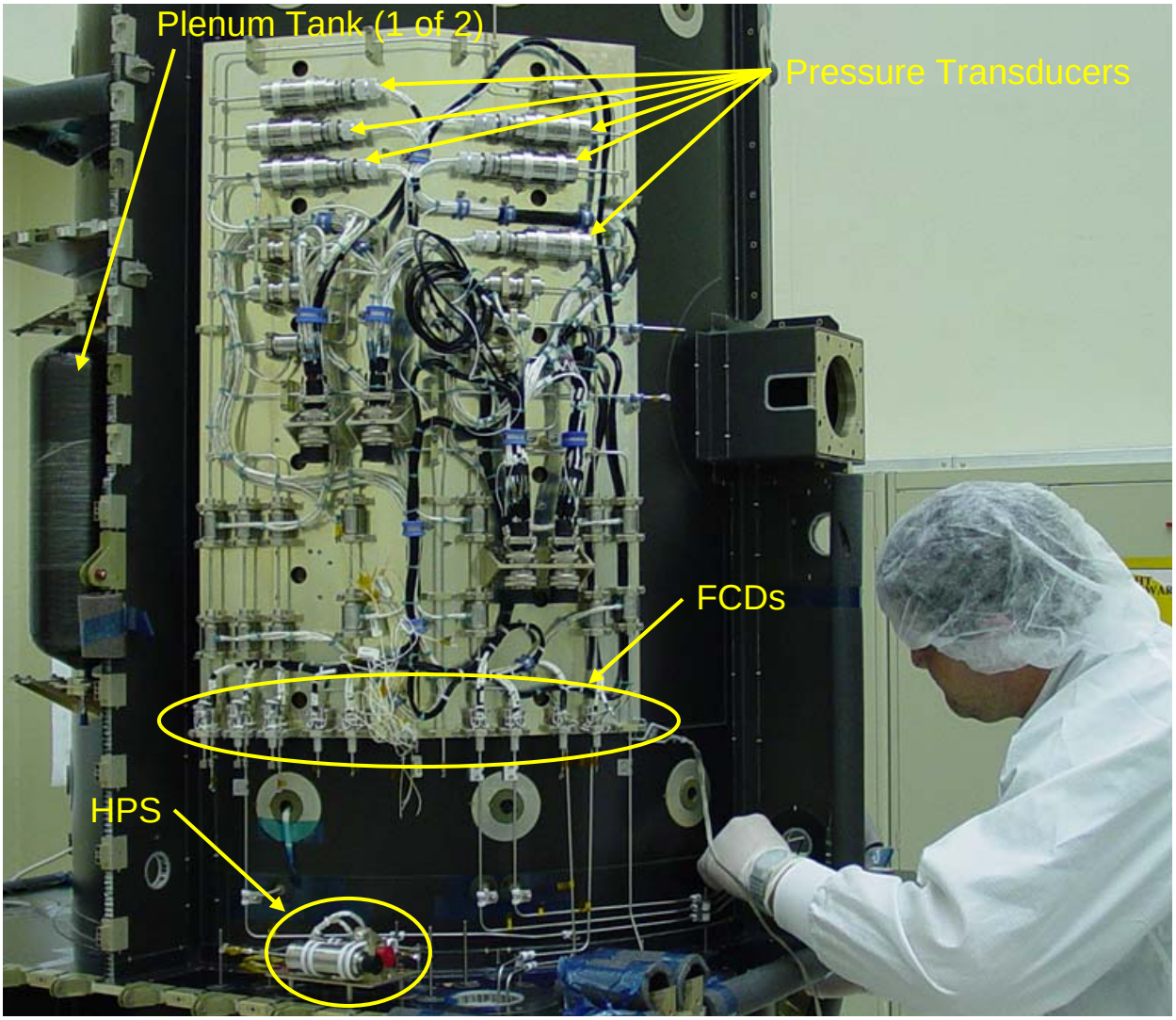

Fig. 15 Integration of the xenon feed system onto the core spacecraft structure.

Fig. 16 Xenon tank prior to integration.