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Delivery of Colloid Micro-Newton Thrusters for the Space Technology 7 Mission

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Two flight-qualified clusters of four Colloid Micro-Newton Thruster (CMNT) systems have been delivered to the Jet Propulsion Laboratory (JPL). The clusters will provide precise spacecraft control for the drag-free technology demonstration mission, Space Technology 7 (ST7). The ST7 mission is sponsored by the NASA New Millennium Program and will demonstrate precision formation flying technologies for future missions such as the Laser Interferometer Space Antenna (LISA) mission. The ST7 disturbance reduction system (DRS) will be on the ESA LISA Pathfinder spacecraft using the European gravitational reference sensor (GRS) as part of the ESA LISA Technology Package (LTP). To achieve the nanometer-level precision spacecraft control requirements, each of eight thruster systems is required to provide thrust between 5 and 30 μN with resolution ≤0.1 μN and thrust noise ≤0.1 μN/√Hz. Developed by Busek Co. Inc., with support from JPL in design and testing, the CMNT has been developed over the last six years into a flight-ready and flight-qualified microthruster system, the first of its kind. Recent flight-unit qualification tests have included vibration and thermal vacuum environmental testing, as well as performance verification and acceptance tests. All tests have been completed successfully prior to delivery to JPL. Delivery of the first flight unit occurred in February of 2008 with the second unit following in May of 2008. Since arrival at JPL, the units have successfully passed through mass distribution, magnetic, and EMI/EMC measurements and tests as part of the integration and test (I&T) activities including the integrated avionics unit (IAU). Flight software sequences have been tested and validated with the full flight DRS instrument successfully to the extent possible in ground testing, including full functional and 72 hour autonomous operations tests. Delivery of the cluster assemblies along with the IAU to ESA for integration into the LISA Pathfinder spacecraft is planned for the summer of 2008 with a planned launch and flight demonstration in late 2010.

I. Introduction

Recent interest in high resolution space interferometry missions, such as the Laser Interferometer Space Antenna (LISA), that require precision formation flying has created an interest for developing precise, low-thrust propulsion technology. The primary objective of LISA is to detect and measure as yet unobserved gravitational waves produced by compact binary systems and mergers of super massive black holes. However, even interplanetary space is subject to minute disturbances, such as solar wind, radiation, and photon pressure that could mask the influence of gravitational waves on free-floating proof masses. To shield the gravitational wave instrument, LISA consists of a precisely controlled set of spacecraft that follow the array proof masses within approximately 10 nm and provide a disturbance free environment. Calculations have shown that to reach the

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sensitivity level of interest, the disturbances to the proof masses can be no more than 3×10^{-15} m s^{-2} $Hz^{-1/2}$ in the $3x10^{-5}$ to 1 Hz bandwidth[1].

The Disturbance Reduction System (DRS) for each spacecraft consists of capacitive position sensors in the Gravitational Reference Sensor (GRS), microthrusters as precision position control actuators, and drag-free control laws that maintain the spacecraft position and cancel out the environmental disturbances, mainly due to solar photon pressure. To measure gravitational waves, LISA must operate in a drag-free environment with stringent requirements on both the pointing and the translation of the spacecraft[2,3].

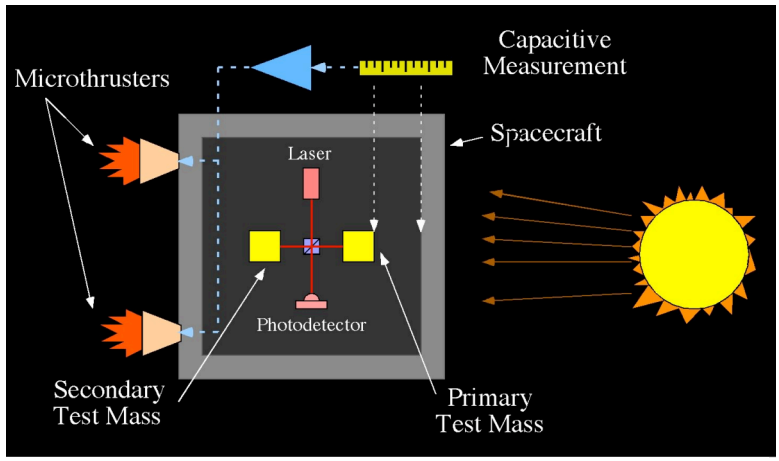

Figure 1. ST7 Disturbance reduction system (DRS) concept.

The European Space Agency (ESA) and NASA are sponsoring an international cooperative mission to develop and demonstrate the technology that will make space-based gravitational wave measurements possible. Each agency is developing a technology demonstration payload: NASA's Space Technology 7 (ST7), supported through the NASA New Millennium Program and managed by the Jet Propulsion Laboratory (JPL)[4], developed the DRS instrument, and the LISA Test Package (LTP) is being developed by ESA as part of the ESA LISA Program[5]. Both technology demonstration payloads will be placed on the same spacecraft (previously known as SMART-2) as part of the LISA Pathfinder Mission, scheduled to launch in late 2010. Once launched, the LISA pathfinder spacecraft will be maneuvered to a halo orbit about the Earth-Sun L1 Lagrange point for a six-month mission where all the new technologies will be demonstrated.

The technology goals of the ST7 mission are to demonstrate spacecraft position control to 10 nm/√Hz and thrust noise less than 0.1 μN/√Hz over a frequency range from 1 mHz to 4 Hz. These goals are accomplished by measuring the position of two test masses in the GRS (Figure 1)[6], which is part of the LTP, and providing the necessary actuation on the spacecraft through drag-free control laws and microthrusters. When the ST7 DRS is active, colloid microthrusters will be fired to provide fine spacecraft attitude control. At other times, three clusters of FEEP microthrusters developed by ESA will maintain the spacecraft attitude and provide drag-free operation. This paper describes the NASA ST7 technology development effort, focusing on the flight hardware testing and delivery of the Busek Colloid Micro-Newton Thruster (CMNT).

This paper is structured as follows: first, the microthruster requirements are described including the dynamic and thermal environmental proto-flight test levels. Second, the CMNT system is described briefly (more descriptions of the CMNT system and each of its subsystems can be found in other papers at this conference and within the references section of this paper). Third, the results from the qualification tests are presented showing successful completion of the qualification program for both CMNT clusters. Fourth, the as-delivered mass, power, and propellant load are presented along with a brief discussion of the activities that have occurred since delivery to JPL including CG, magnetic, and EMI/EMC measurements as well as flight software testing and sequence validation with the flight thruster assemblies.

II. Microthruster Requirements

ST7 mission requirements were derived to demonstrate the technology capability that meets LISA and other precision formation-flying mission needs (see Table 1 and Refs 1-4). To meet these requirements, the DRS must use the GRS that is part of the ESA LTP as its drag-free sensor. Note that the LTP sensing requirement is not a level 1 requirement on the DRS, but is necessary for the DRS to meet its full or minimum mission success criteria. For all the level 1 requirements, the position control and thrust noise requirements must be met over the measurement bandwidth, 1 mHz to 4 Hz (the high-end of the bandwidth was reduced from 5 to 4 Hz, see Table 2). For the operational lifetime, an assessment of the operability of the thrusters must be made including delivered thrust, thrust noise, specific impulse, latencies, controllability, throttleability, and accuracy. The maximum design life for ST7 is 90 days, including a commissioning phase at the beginning of the mission.

Lower level propulsion performance requirements are derived from the level 1 requirements[1-4], as shown in Table 2. The thrust range requirement is determined by the need to counter the solar radiation pressure on the spacecraft and provide full control authority in all axes. The thrust noise and resolution requirement are specified to

meet the spacecraft position control requirement, with the upper frequency range extended from 30 mHz to 4 Hz for control loop precision. Thruster operational lifetime includes the 90-day mission design for consumables including propellant, but the thruster lifetime demonstration goal is set at 3,240 hours to accommodate a standard 50% thruster lifetime margin. The biggest difference between the LISA and ST7 requirements is obviously operational life; thus this is the most important area of technology work remaining for the LISA project after the ST7 mission with a lifetime demonstration goal of approximately 60,000 hours (~5 years plus 50% margin).

Note that the DRS design has met all ST7 and LISA performance requirements except for the LISA lifetime requirement. Demonstrations have included direct thrust stand measurements of a single flight-like thruster system and analysis of test data from the flight units. For example, thrust stand measurements have demonstrated a thrust range of 4.35 to 35.8 μN and verified models of the thrust produced based on beam current, beam voltage, and temperature. The full operational extent of the thruster system was demonstrated during thermal environmental testing, and calculations based on the verified thrust model indicate an operational range of approximately 3-50 μN. However, operation at the extremes outside of the 5-30 μN range may result in higher thrust noise or reduced lifetime. All the qualification tests and verification of the requirements are discussed more in Section IV.

Table 1. ST7-DRS level 1 requirements including full and minimum success criteria (see Refs. 1-4).

Technology Requirement	Full Success Criteria	Minimum Success Criteria
LTP Sensing Noise	≤ 5 nm/√Hz	≤ 50 nm/√Hz
Spacecraft Position Control	≤ 10 nm/√Hz	≤ 100 nm/√Hz
Thrust Noise	≤ 0.1 μN/√Hz	≤ 0.5 μN/√Hz
Control Life	≥ 60 days	≥ 10 days

Table 2. Derived and demonstrated ST7 and LISA microthruster propulsion requirements (see Refs. 1-4).

Requirement	ST7	LISA	Demonstrated
Thrust Range	5 to 30 μN	5 to 30 μN*	4.35 to 35.8 μN§
Thrust Precision	≤ 0.1 μN	≤ 0.1 μN	0.08 μN (0.01 μN calculated)
Thrust Noise	≤ 0.1 μN/√Hz (5 Hz control loop)	≤ 0.1 μN/√Hz (5 Hz control loop)	≤ 0.01 μN/√Hz (3e-5 – 3 Hz) ≤ 0.1 μN/√Hz (3 – 4 Hz)
DRS Drag-Free Bandwidth	$1x10^{-3}$ to $3x10^{-2}$ Hz	$3x10^{-5}$ to 1 Hz	$3x10^{-5}$ to 4 Hz
Control Loop Bandwidth	$1x10^{-3}$ to 4 Hz	$3x10^{-5}$ to 4 Hz	$3x10^{-5}$ to 4 Hz
Thrust Command Rate	10 Hz (≤ 0.1 s latency)	TBD	10 Hz (0.1 s latency, 0.4 s settle time)
Thrust Range Response Time	≤ 100 s	TBD	< 10 s
Specific Impulse	≥ 150 s	TBD	≥ 150 s (≥ 200 s typical)
Operational Lifetime	≥ 2,160 hours (90 days)	≥ 40,000 hours (~5 years)†	3478 hours during FLT 2B (245 Ns of total impulse and 113 g of propellant)
Plume Half Angle	≤ 35º (includes 95% of beam current)	TBD	< 23º (includes 95% of beam current)

* The LISA thrust range requirement may be lower for the science phase and higher for tip-off recovery

† The LISA mission has an operational goal of 8.5 years that will require an additional 3.5 years worth of consumables

§ By calculation a range of approximately 3-50 μN is possible within the nominal operational constraints of the thruster

Table 3. Environmental requirements at CMNT cluster mounting flange[3].

Mode	Min (ºC)	Max (ºC)
Operating		
Design	10	30
Protoflight	-5	50
Non-Operating		
Design	0	40
Protoflight	-15	60

Environmental temperature requirements for the ST7 CMNT are shown in Table 3[3]. Operational temperature requirements are driven by the viscosity of the propellant at the minimum temperature and the conductivity of the fluid at the maximum temperature to produce the required thrust range. Below the minimum temperature, the fluid viscosity increases to the point where the bellows pressure is not large enough to compensate and provide adequate flow to the thruster head and reach maximum thrust. Fortunately, the ion to droplet ratio of the electrospray decreases with temperature, increasing the thrust for the same current level to provide adequate margin. Conversely, at the highest operating and temperatures, the maximum possible propellant flow rate increases with decreasing viscosity, while the thrust decreases for the same current level. The minimum non-operating temperature limit is driven by the risk of freezing the propellant. The maximum non-operating temperature limit has been reduced to 60°C due to propellant thermal expansion considerations. Dynamic environmental requirements are shown in Table 4[3].

Table 4. ST7 CMNT dynamic environmental requirements. See Reference 3.

Test	Axis	Frequency (Hz)	Flight Levels	Protoflight Levels
Quasi-Static	In Plane	N/A	16.0 g	20 g
Quasi-Static	Out of Plane	N/A	20.8 g	26 g
Sine Vibe	All Axes	5 to 21 21 to 100	8.8 mm 0-pk 16 g	11 mm 0-pk 20 g
Random Vibe	In Plane	20 20 – 80 80 – 400 400 – 2000 2000 Overall	0.024 g^2/Hz + 3 dB/octave 0.096 g^2/Hz - 5 dB/octave 0.007 g^2/Hz 8.48 g_{rms}	0.038 g^2/Hz + 3 dB/octave 0.15 g^2/Hz - 5 dB/octave 0.010 g^2/Hz 10.6 g_{rms}
Random Vibe	Out of Plane	20 20 – 80 80 – 400 400 – 2000 2000 Overall	0.048 g^2/Hz + 3 dB/octave 0.19 g^2/Hz - 10 dB/octave 0.0009 g^2/Hz 9.9 g_{rms}	0.073 g^2/Hz + 3 dB/octave 0.29 g^2/Hz - 10 dB/octave 0.0014 g^2/Hz 12.3 g_{rms}
Shock	All Axes	100 1500 10,000	N/A	20 g 1000 g 1000 g

III. CMNT System Overview

The two Colloid Micro-Newton Thruster (CMNT) clusters delivered by Busek Co., Inc.[2,3,7,8,9,10-15] each include four complete and independent thruster subsystems: 4 thruster heads, 4 propellant storage and feed systems (including microvalves), and 4 PPUs, as well as 1 cathode neutralizer and 1 DCIU for each cluster. Thrust is adjustable from 5-30 μN by changing the beam voltage (2-10 kV) and/or the propellant flow rate that determines the beam current (2.25-5.4 μA). Independent, fine control of both the beam voltage and beam current allow for precise control of thrust to better than 0.1 μN resolution with <0.1 μN/√Hz thrust noise. Figure 2 shows one flight thruster cluster with four thruster subsystems. A more detailed description of the sub-systems can be found in Ref. 10 and others presented at this conference (Refs. 11-15). We will now discuss the subsystems of the ST7 Busek CMNT.

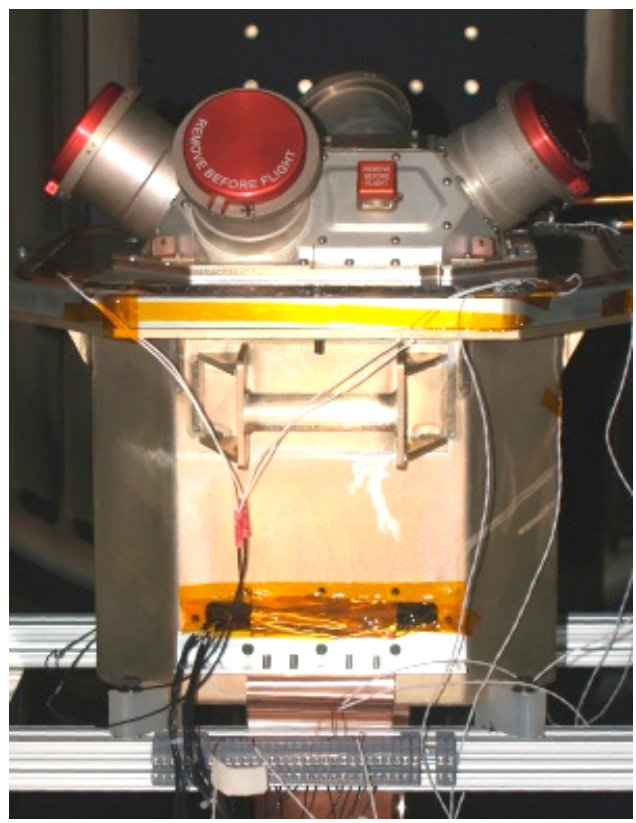

Figure 2. Busek Colloid Micro-Newton Thruster (CMNT) Flight Cluster 1 including four thruster heads, electronics, and cathode neutralizer (visible) in thermal-vacuum environmental test setup.

Overview of CMNT Subsystems

Thruster Head

The thruster head comprises a manifold that feeds nine emitters in parallel, a heater to control propellant temperature and physical properties (i.e. viscosity, conductivity, etc.), and electrodes that extract and accelerate the propellant as charged droplets[11]. A flight design thruster head has been used in single-thruster system boxes for long-duration lifetime testing and performance validation measurements described later in this paper. All materials used in the thruster head have demonstrated compatibility with the propellant through long duration testing at high temperature. All thruster heads in each cluster are identical in design and function.

Propellant Feed System

Propellant is stored in four electrically isolated stainless steel bellows compressed by four constant force springs set to supply four microvalves with propellant at approximately 1 atm of pressure[12]. The microvalve is piezo-actuated using ~1 mW of power to control the propellant flow rate and current to better than 1 nA without significant physical motion[13]. This level of precision corresponds to ≤0.01 μN of thrust, with a response time over its full range of less than 0.5 s. The flight microvalve design has been part of multiple single- and multiple-emitter long-duration tests, accumulating over 15,000 hours of total test time without incident in the normal operating temperature range (10 to 30C). Before integration into the flight feed systems, each microvalve goes through an extensive screening process including flow, leak, proof, and temperature testing from -15 to 70C and particulate screening to a measured distribution of less than one 10-micron diameter particle over the lifetime of the mission.

Cathode Neutralizer

The cathode neutralizer developed by Busek is made from a carbon nano-tube (CNT) base with an extractor electrode[14]. The cathode is capable of producing 10 μA to 1 mA using extraction voltages of 250-800 V. One CNT cathode has been tested alone in an ultra-high vacuum chamber for over 13,000 hours at 100 μA without incident. CNT cathodes have also been tested successfully with operating thruster heads during the pre- and post-dynamic tests and in each full functional test during the thermal environmental qualification tests for each unit.

Thruster Electronics

The flight thruster electronics including 4 power processing units (PPUs) and one digital control and interface unit (DCIU) for each cluster have completed qualification testing at the component level and in flight assembly qualification testing[15]. EM and flight electronics have over 10,000 hours of operation under vacuum controlling complete thruster sub-systems. The PPU includes the high-voltage DC-DC converters that have been specifically designed and tested for this application by Busek Co. The DCIU controls all four thrusters and provides the command and telemetry interface to the spacecraft and DRS flight computer.

IV. Microthruster Qualification and Validation Tests

Test validation and qualification of the Busek CMNT design and flight hardware for ST7 presents several challenges for a traditional qualification program. The primary challenge is making direct performance measurements with the flight clusters due to the weight restrictions and difficulties of sub-micronewton resolution thrust stand measurements. Also, since thruster lifetime is expected to be independent of the number of operating thrusters (each thruster head has enough emitters to provide the full thrust range and operates independently of other thrusters in the cluster), assembling and testing an entire cluster to assess lifetime would be expensive, time intensive, and not necessary. To avoid this problem, the validation plan included certain qualification tests at the "box" level. One thruster box contains a single, flight-production thruster head and microvalve combination along with using flight-like electronics, bellows, and other feed-system components. Qualification tests at protoflight levels are performed at the flight cluster level (see Table 5) using verified models from box-level tests as the basis for analysis that demonstrates the requirement.

Table 5. ST7 CMNT simplified validation matrix including the status of each test.

Requirement	Box Level	Cluster Level	Status
Thrust Range	✓	By Analysis	Calculations show the flight thrusters meeting requirements, preliminary thrust stand data show that the calculations are within 2% of measurements, and final measurements as a function of temperature are ongoing
Thrust Precision	✓	By Analysis	
Thrust Noise	✓	By Analysis	
Thrust Response Time	✓	By Analysis	
Specific Impulse	✓	By Analysis	
Operational Lifetime	✓		Formal Life Test 2B complete with 3478 hours[9]
Plume Half-Angle	✓		Measurements complete; plume half-angle and stability meet or exceed requirements
Environmental Dynamics	(component-level testing)	✓	Both flight clusters passed full protoflight-level vibration and shock testing; reassembled clusters were retested at workmanship levels
Environmental Temperature	✓*	✓	Thermal-vacuum testing was performed on both reassembled clusters to proto-flight levels (see Table 3).

* Box-level thermal testing was run to qualification levels (larger temperature extremes, more cycles, etc.) to test thruster system components. Thermal environmental validation testing to protoflight levels was conducted at the cluster level.

Thrust stand measurements necessary for verifying thrust range, precision, noise, response time, and specific impulse requirements are made at the box level, where the smaller box mass enables reasonably accurate thrust measurements[16]. Using these box level thrust measurements, correlations between beam current, beam voltage, and thrust have been made to validate the thrust model. Current and voltage measurements are then made at the cluster level, and the model validated by thrust stand measurements allows calculation of thrust at the cluster level. Since lifetime, plume divergence, and specific impulse measurements are almost entirely independent of the cluster structural design and don't depend on how many thrusters are running at once, these requirements are also verified at the box level for test simplicity (See Ref. 11). The shock requirement and thermal model verification through a thermal balance test have been conducted on an EM cluster mock-up. The mock-up consisted of only one complete thruster system, four bellows filled with ethanol, and mass-equivalent replacements for the other three thruster systems. Since the structural and to some extent thermal design of the box is dissimilar to the cluster design, these requirements are validated at the cluster level by protoflight testing. See Tables 6 and 7 for a complete summary of the test results and requirement verification performed on single thruster "boxes", the EM cluster mock-up, and the flight cluster assemblies. The following subsections will go over some of the critical test results in more detail.

Table 6. Qualification testing and requirements verification performed at the "box" and EM levels

Test	Unit	Levels/Requirements	Results
Bellows Force Margin	EM Bellows	> 400 Torr at EOL	500 Torr, worse case
Plume	Thruster Box	> 95% beam in 35º half angle	> 95% beam in 23º half angle
Life	Thruster Box	> 3240 hours	ILBE failure repaired during test, total test duration = 3478 hours
Thrust Noise	Thruster Box	< 0.1 μN/√Hz from 1 mHz to 4 Hz	Thrust noise direct measurements: equal to background of 0.1 μN/√Hz from 10 to 100 mHz measurable range; calculations <0.1 μN/√Hz
Specific Impulse	Thruster Box	> 150 s at all conditions	240 s nominal, 155 s at worse case condition
Shock	EM Cluster Mock Up	1000 g	Passed functional and alignment test
Thermal Balance	EM Cluster Mock Up	Measure correlation with model	Test correlation with model acceptable

Table 7. Qualification testing and requirements verification performed on flight hardware.

Test	Levels/Requirements	Results
Card Level Random Vibe	Lateral = 10.6 g, Longitudinal = 12.3 g	All Cluster 1&2 electronics units passed
Card Level TVAC	2 cycles, -15º C to 65º C	All Cluster 1&2 electronics units passed
Valve Level Thermal Cycle	-5º C to 50º C op, -15º C to 70º C non-op	8 out of 8 flight microvalves passed
Cluster Functional	Full-Scale Response Time < 100 s, Thrust Range 5 to 30 μN	Cluster 1&2 (all thrusters): Response Time <10 s, Thrust Range = 5 to 35.8 μN
Cluster Sine Vibe	20 g PF, 16 g FA	Cluster 1 completed FA level, no sine retest Cluster 2 completed PF level, no sine retest
Cluster Random Vibe	Lateral = 10.6 g PF, 8.48 FA Longitudinal = 12.3 g PF, 9.9 g FA	Cluster 1 completed PF level and FA retest Cluster 2 completed PF level and FA retest
Cluster TVAC	-5º C to 50º C op (4 cycles), -15º C to 60º C non-op (1 cycle),	Cluster 1 passed post TVAC full functional test after low temperature start up anomaly Cluster 2 passed post TVAC full functional test with no anomalies
Cluster EMC	B < 4 μT, E < 20 V/m	Cluster 1&2 Completed measurements at JPL

A. Formal Life Test 2B

The operational requirement for the ST7 mission is 60 days (1440 hours), including the colloid microthrusters. The thrusters have been designed for a 90-day (2160 hour) mission, including consumables and lifetime of all subsystems. To increase the chance for mission success, 50% margin has been applied to the 90-day lifetime design target, giving a goal for lifetime demonstration of 3240 hours. During the mission, we expect the sun-opposing thrusters to operate at higher thrust levels than the sun-facing thrusters, and these conditions are more strenuous on the thrusters. With an expected thrust level for the sun-opposing thrusters of 18.0 ± 4.5 μN, the thrusters are required to produce <140 μNs of total impulse, consuming <58 g of propellant over the entire mission.

Formal Life Test 2B (FLT 2B) began on May 23rd, 2006 at Busek Co. with a complete, flight-like colloid thruster system, including thruster head, microvalve, propellant feed system, bellows, and electronics[9]. The test was stopped voluntarily after 172 days on November 10th, 2006. As shown in Figure 3, the CMNT system accumulated 3478 hours of operation, and based on thrust calculations produced 245 Ns of impulse, consuming 113 g of propellant during the entire test (see Figure 4). In addition, many of the performance requirements were tested and validated through calculation during the test (the performance model is verified by direct thrust measurements). The completion of FLT 2B has validated the lifetime of the thruster head, microvalve, electronics, and bellows (not including all feed system components) for the flight design and in-space operation over the ST7 mission duration.

Reference 9 has a more detailed description of the test results. In summary, the first 500 hours of FLT 2B were focused on removing bubbles from the feed system by running near maximum flow rate. This period also simulates the maximum thrust level that could be expected during the early stages of the mission, commissioning and tip-off. The thruster began meeting the thrust noise requirement after 232 hours of operation and was completely bubble free after 600 hours of operation. Due to a new pre-test procedure, other "box-level" tests (including in this test near hour 2040 after the propellant refill) and the flight hardware have demonstrated complete bubble free operation in <100 hours. Near test hour 500 a small leak in the feed system was repaired with epoxy without disturbing any other thruster components. After the repair, a slight amount of residual propellant provided a temporary low-impedance (still >1 GOhm) path that was cleared near test hour 1000. Just after 1000 hours, the thruster was set into mission simulation mode with a series of repeating thrust commands provided by the DRS control algorithm team from NASA Goddard, with an example shown in the inset of Figure 3. After nearly 2400 hours, the bellows ran out of propellant and was refilled to complete the test. A full functional test at the end of the test along with post-test disassembly and inspection verified the unit had demonstrated the lifetime requirement.

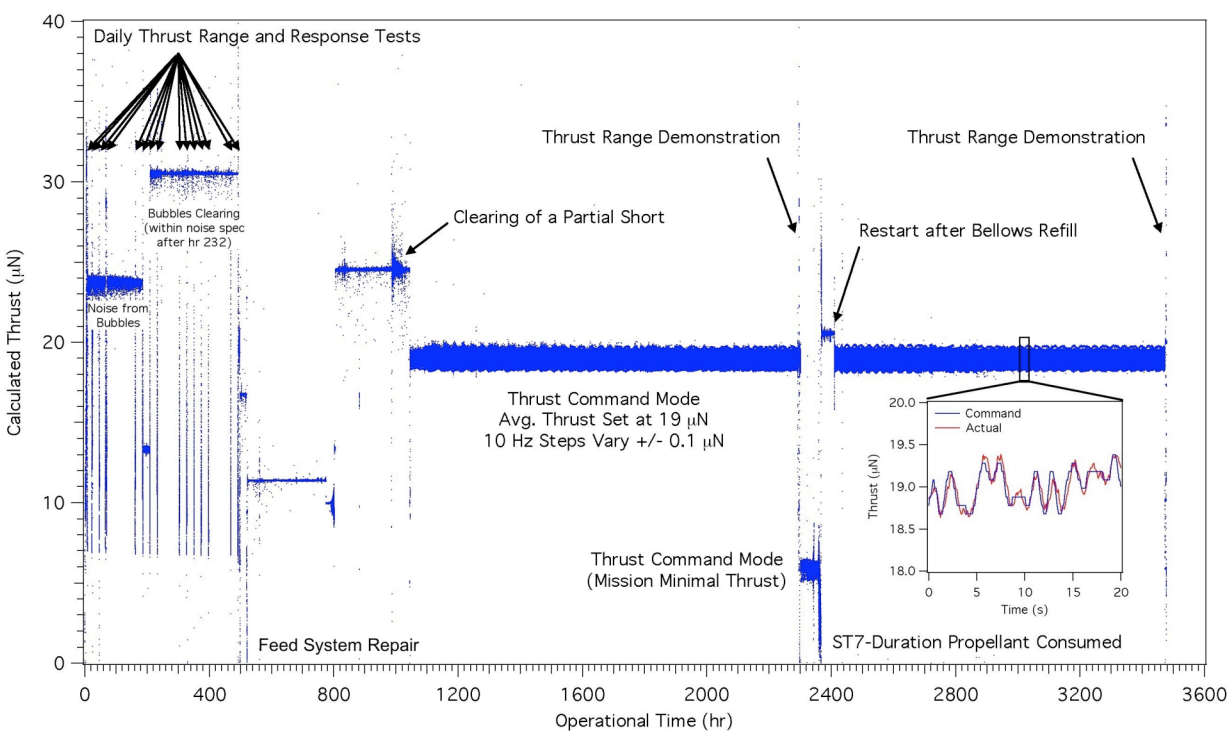

Figure 3. Graph of calculated thrust over the operational duration of FLT 2B. Daily thrust range and response tests, feed system repair, thrust commands mode, and bellows refill are all indicated.

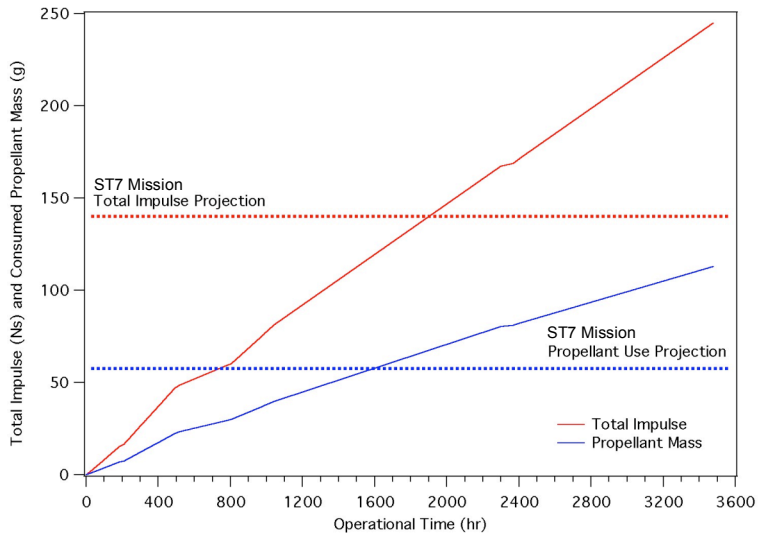

Figure 4. Graph of calculated total impulse produced and propellant consumed during FLT 2B. The total impulse production and propellant usage during FLT 2B are both greater than the projected requirements for the sun-opposing thrusters by more than 50%.

B. Component Requalification

As first described in Reference 9, during the initial flight-cluster TVAC tests in 2007 both clusters experienced feed system issues that had not been observed in any previous testing of the flight or developmental hardware. From evidence uncovered during thruster disassembly, a failure investigation team (including members from both Busek and JPL) found that a seal material used in the feed system was not compatible with the propellant at high temperatures. The failure investigation team's main recommendation was that the material be replaced throughout both clusters with a compatible material. After extensive compatibility tests with various replacement materials and successful component-level testing to higher than protoflight level thermal requirements, both clusters were rebuilt.

The component requalification program included the thruster head, microvalve, and feed system between the microvalve and thruster head using the replacement materials. Both the bellows and the electronics were not affected; therefore, EM units (the same used in the FLT 2B life test) were used for testing the other components (an overall plan of the program is shown in Figure 5). Two microvalves were built using flight-batch materials specifically for dynamic and thermal environmental testing to flight qualification levels, demonstrating that the new hardware could survive where the previous hardware failed. Accelerated tests with a full flight-like thruster system including electrochemistry and valve cycling tests demonstrated the new materials did not impact the thruster lifetime, allowing the life test results to still be considered valid (more details of these tests can be found in Reference 11). While the flight-component rebuild and assembly activities were conducted in parallel, the new materials and designs for the thruster head and microvalve were not considered ready for integration into the flight cluster units until after the requalification tests were completed successfully.

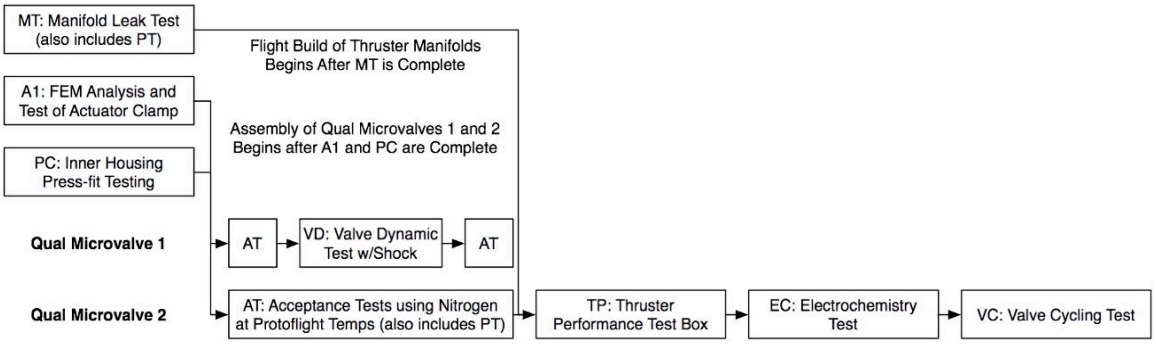

Figure 5. Component-level requalification plan after the failures experience during TVAC testing in 2007. All tests were completed successfully. After all the tests, the thruster head and microvalve components were considered qualified and ready for integration into the flight cluster units.

C. Thrust Stand Measurements

Direct measurements of thrust with better than 0.1 μN resolution have been made using a single thruster system on the Busek Maglev Thrust Stand (see Ref. 16). The purpose of the thrust stand measurements was to verify the thrust range, resolution, noise, and thruster response time. During these tests, the thrust model based on beam current and voltage (see Refs. 7 and 8),

$$T = C_1 * V^{0.5} * I^{1.5}, \qquad [1]$$

was also verified with the thrust coefficient, C_1, determined to within 2% at the nominal beam voltage (6 kV) and operational temperature (25C). A sample test run is shown in Figure 6. In this test both beam voltage and current were varied at different rates to verify the model's power relations and test the thrust stand response. While the initial estimate of C_1 was found to be slightly high (the initial, larger value was used for the "calculated" trace shown in Figure 6), it was later readjusted to provide <2% error between calculated and measured thrust at the nominal beam voltage. At non-nominal voltages Taylor cone losses and beam divergence effects can impact the thrust, but by <2% for beam voltages between 4-8 kV, <5% for the full range of typically allowable beam voltages (2-10 kV) and by <20% for beam voltages <2 kV. Temperature also influences the value of C_1, which increases at colder temperatures and decreases at warmer temperatures. The exact relation between C_1 and temperature has been predicted using models including the physical properties of the propellant and verified by measurement (see Ref. 11). Since there is no time dependence in Eq. 1, as long as temperature is held constant, this verified relation can be used to accurately predict thrust based on beam voltage and current measurements over the full bandwidth requirement for ST7, from 1 mHz to 4 Hz.

Direct measurement of the thrust noise produced by the ST7 colloid thruster was also conducted during the thrust stand measurements. As shown in Figure 6, the background noise of the thrust balance is near or below 0.1 μN/√Hz from approximately 0.007 to 0.07 Hz. At higher frequencies, the natural frequency of the stand itself (near ~0.3 Hz) and external vibrations add to the background noise, while at lower frequencies long-term drifts such as changes to test facility footing and lab-wide activity can increase noise. All useful trials were conducted at night with the stand operated remotely over network connections. When the thruster is active, the thrust stand response as a function of frequency does not change, indicating no thrust noise is produced by the thruster above the background levels. Outside of the available thrust stand bandwidth the thrust noise requirement is verified based on calculations using validated thrust model (Eq. 1). On orbit, the fine sensitivity of the GRS will actually be able to provide measurements of the true thrust noise, which is one of the motivations for flight demonstration of the DRS technologies including the colloid microthrusters.

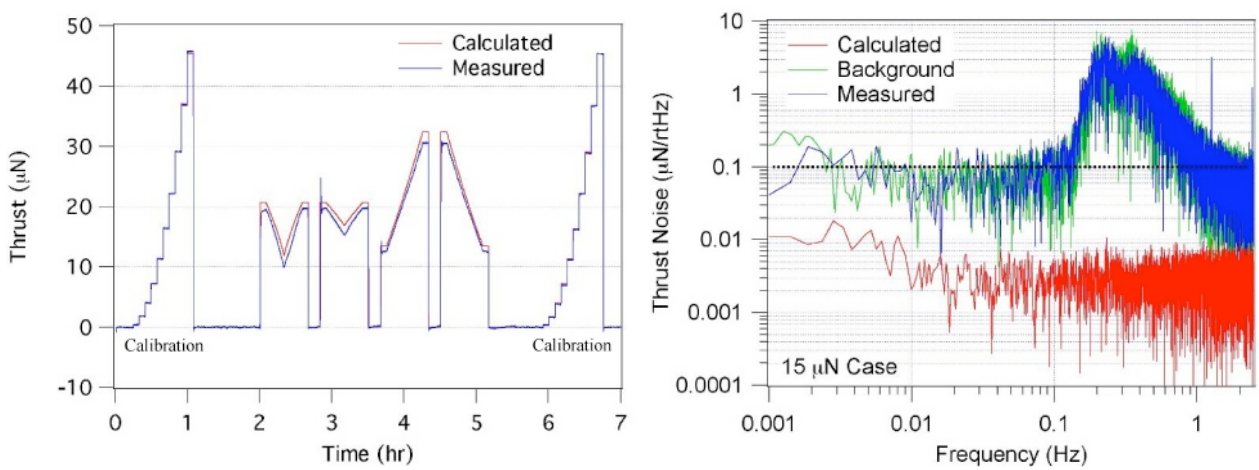

Figure 6. Graphs of direct thrust stand measurements including one 7 hour trial with varying thrust tests to verify the thrust model (the model was later adjusted slightly to improve measured and calculated correlation) and the results from thrust noise measurements at 15 μN. The thrust noise measurements show the calculated thrust noise is an order of magnitude below the requirement and the thrust stand noise does not change with the thruster on (measured) or off (background).

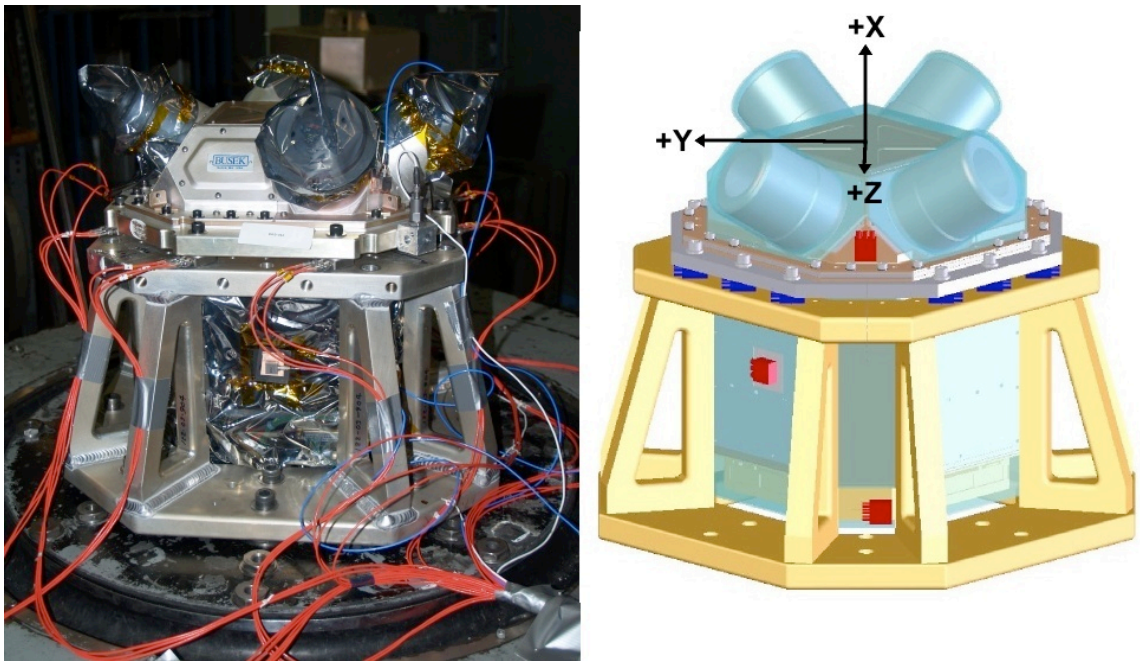

Figure 7. Picture of CMNT flight cluster 1 mounted on vibe table (left) and a CAD drawing showing the location of force transducers (blue) and response accelerometers (red).

D. Dynamics Environmental Validation

To meet the dynamic environmental requirements specified in Table 4, a combination of testing on the flight units and a structural mock up was performed. Shock testing was performed on a structural mock up of the flight cluster due to concerns about damaging the flight clusters with protoflight level loads. The structural mock up was nearly identical to the flight cluster. The only significant differences were mass mock-ups used for three of the four PPUs, microvalves, thruster heads, and the DCIU. This configuration was justified because all the flight components, except the DCIU, were tested to the protoflight shock levels at flight positions. Due to the structural isolation for the DCIU located on the -x axis of the cluster, it was not considered necessary to shock the DCIU because the resulting dynamic loads would be enveloped by flight cluster vibration testing. Shock testing was performed by impact hammer at the Dayton T. Brown, Inc. facility with the cluster mounted on the x-axis for all testing. Cluster component verification of shock environment survival included pre- and post-visual inspections of the bellows and cathode assemblies, alignment measurements of the thruster head emitters, flow and leak testing of the microvalve, and electrical testing of the PPU. No significant differences were observed between the pre- and post-test performance and inspection measurements; thus, the cluster shock requirement has been validated.

Sine, random, and quasi-static load testing was performed on both clusters with a vibe table at NTS, Inc. The clusters and mass dummy were all mounted on a vibe fixture to interface with the vibe table (Figure 7). Eight three-axis force transducers were placed between the cluster flange and the vibe fixture. These force transducers were used for force limiting according to the quasi-static limits defined in Table 4. Two three-axis control accelerometers were placed on the vibe fixture top flange, for control to the required spacecraft dynamic interface levels. Three three-axis response accelerometers were placed on the cluster to measure the resulting response (Figure 7). Loads were initially set using a mass dummy in each axis. Cluster 1 was tested to the flight acceptance levels defined in Table 4 while cluster 2 was tested to protoflight levels. Pre- and post-testing of both clusters included functional testing of the clusters and visual inspections. No significant differences were observed between the pre- and post-test functional and inspection measurements; thus, the cluster vibe requirement has been validated.

After dynamic environmental testing was complete and due to problems encountered during thermal vacuum testing in 2007, both clusters were disassembled for repairs. After the clusters were reassembled, both were put through full three-axis vibration testing at flight acceptance levels (see Table 4) at NTS to verify workmanship. These tests did not include the 16g or 20g sine sweep due to concerns about over-testing and damaging the flight clusters. Since the structural design did not change after reassembly, the cluster design is considered to be fully qualified by the proto-flight level tests (including the 20g sine test) performed in 2007 and the flight acceptance level tests in 2008. Both cluster showed no changes in performance in pre- and post-vibe functional tests.

E. Thermal Environmental Validation

After successfully passing dynamic environmental testing, both clusters entered into thermal vacuum (TVAC) environmental testing, one at a time. The expected environment on the spacecraft for the colloid thruster clusters is in the shade of the solar panels with heaters at the cluster flange and in the thruster heads running to maintain operating temperature. As shown in Table 3, the normal operating range of the colloid thruster is from 10°C to 30°C with the non-operating temperatures 10°C above and below the operating temperatures. Protoflight testing levels are set 15°C below the minimum temperatures and 20°C above the maximum temperature to demonstrate adequate margin. For TVAC testing, as shown in Figure 8, a flange temperature profile including thermal cycling and soaking was developed to qualify each cluster. A 3 m diameter, high-vacuum facility with a liquid nitrogen cooled shroud to simulate the radiative background of space was used for the thermal qualification testing. Both clusters passed through the entire thermal profile with full functional tests performed at ambient, -5°C, 50°C, and finally ambient conditions again (see Figure 9 for results from the final full function test at the end of the TVAC environmental qualification test) showing the required thruster performance by direct measurements of beam current and voltage; thus, the thermal requirements have been validated.

Thermal balance testing of the flight units will not be performed until spacecraft integration; however, a thermal balance test of a cluster mock-up was performed in the test facility to provide preliminary validation of the cluster thermal model. The purpose of these thermal environmental tests was to qualify the thrusters for the expected thermal environment as, up to that point, only component level testing had occurred at temperatures outside of the design range (including the life test that had operated for more than 3400 hours between 10-30°C). At the component level, the electronics had already been put through full environmental testing, and a flight-like thruster head manifold had already been put through thermal cycle and soak tests.

As mentioned previously, during the initial flight-cluster TVAC tests in 2007, both clusters experienced feed system issues that had not been observed in any previous testing of the flight or developmental hardware. After successful component-level testing to higher than protoflight thermal requirements, both cluster units were rebuilt. All thruster head and feed system components that were taken from the first build were cleaned and demonstrated particulate cleanliness to Busek and JPL flight-build standards. All microvalves were rebuilt and replaced. Again, post-assembly acceptance, dynamic, and thermal environmental tests showed that both clusters passed all performance tests and met all requirements

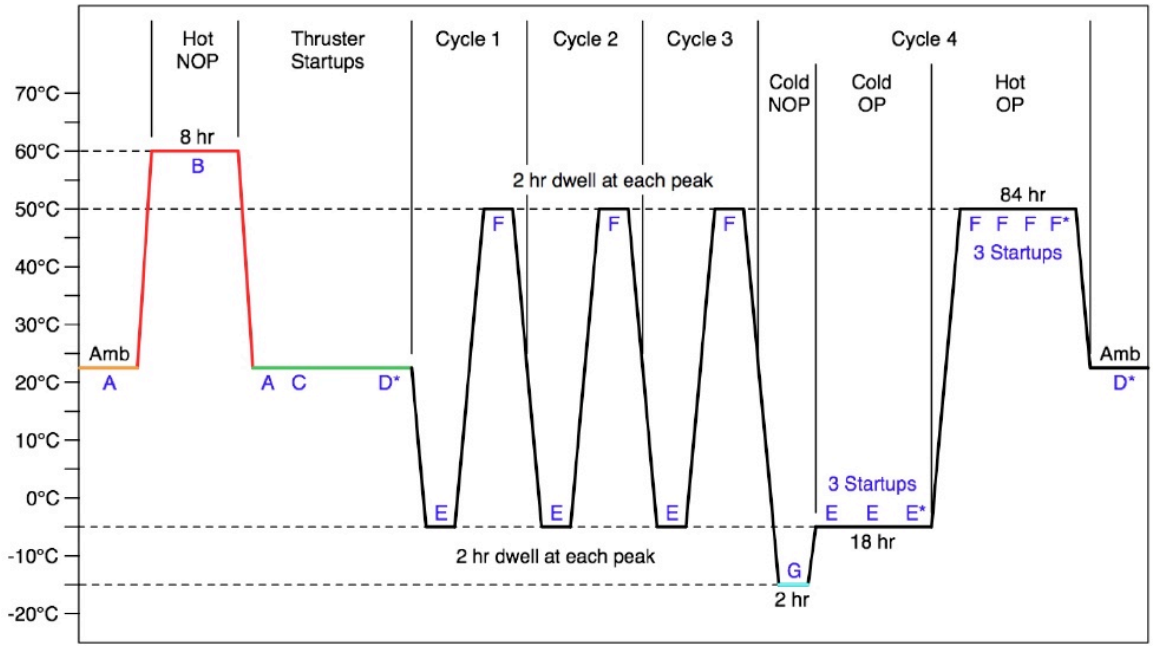

Figure 8. Temperature profile of the cluster mounting flange for thermal vacuum qualification testing of the CMNT clusters to proto-flight levels. Each thermal and test condition is designated by a letter (A through G) where thruster function was demonstrated. Both clusters passed through the full thermal profile without incident passing the full functional tests at conditions D* (two), E*, and F*.

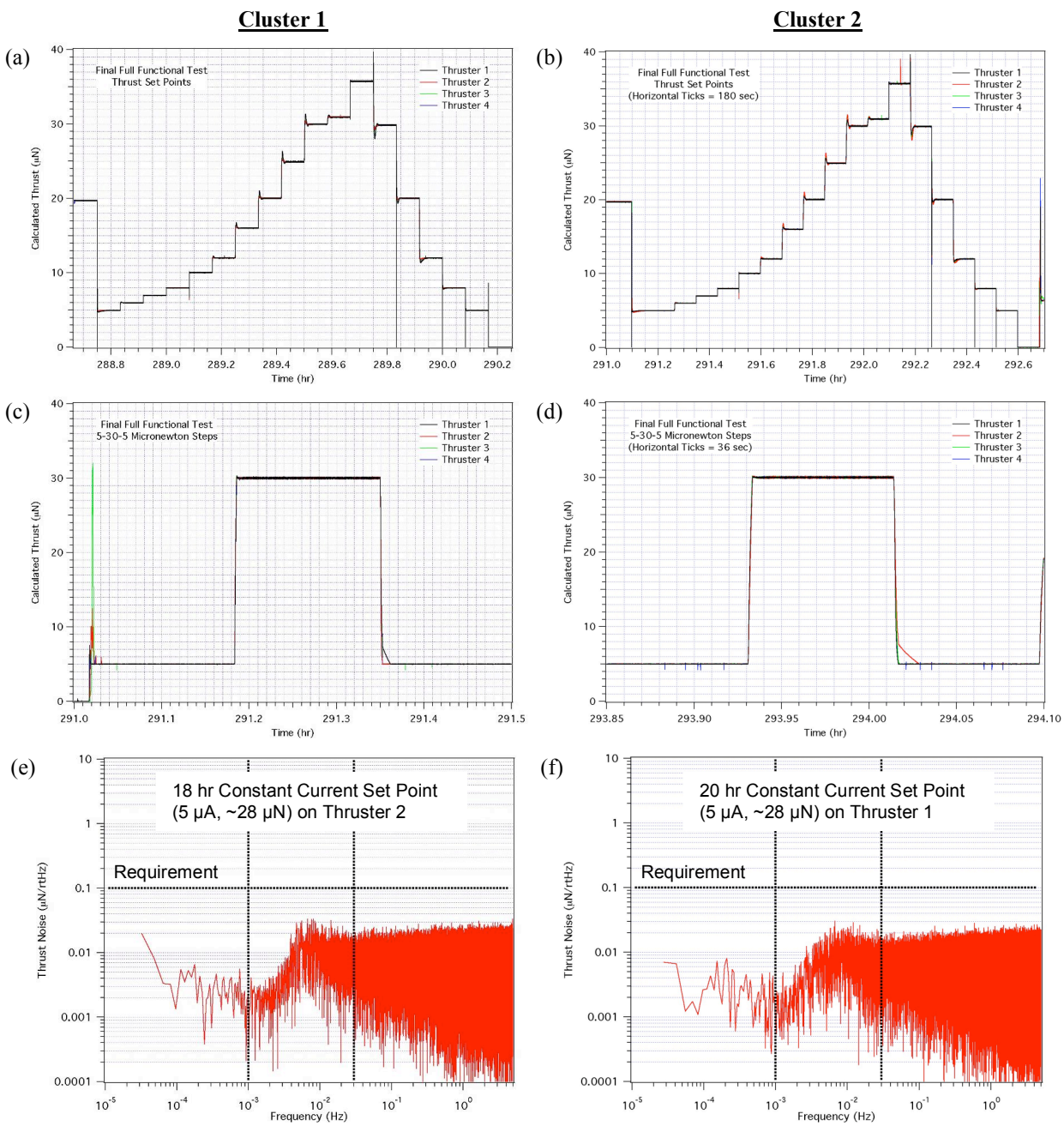

Figure 9. Cluster 1 (left column) & 2 (right column) performance during the final full-functional acceptance test at ambient temperatures (temperature of flange interface). Graphs (a) and (b) show thrust steps of various sizes for all four thrusters in each cluster produced in diagnostic mode with direct current and voltage commands. Graphs (c) and (d) show min-to-max-to-min thrust steps executed in thrust command mode (note that thrust command mode does not experience the same transients as found in diagnostic mode). Graphs (e) and (f) show calculated thrust noise at constant current operation for extended periods. Thrusters 2 (Cluster 1) and 1 (Cluster 2) were chosen based on which of the four thrusters in each cluster had the longest uninterrupted operating span.

V. Delivery and Integration and Test Activities at JPL

Integration and Test of the ST7 instrument at JPL was limited because much of the testing, such as the Dynamic and TVAC environmental tests, was completed at the subsystem level by the Busek and Broadreach Engineering sub-contractors prior to delivery to JPL. As delivered mass, power, and propellant loads are shown in Table 8.

Table 8. As-delivered mass, power, propellant load, and operational time accumulated prior to JPL delivery.

	Mass (kg)	Power (Watts)	Remaining Propellant Load (Operational Days)	Operational Time
Allocation/ Requirement	31 kg (Total)	53 Watts Maximum (Total)	90 days (T1/T2: 20 μN, T3/T4: 30 μN)	60 days (1440 hours)
Cluster 1 Measured	14.794	16.5 Nominal 24.6 max as tested; 23.8 max w/reduced heater power	T1: 137.6 T2: 129.3 T3: 97.1 T4: 93.1	Thrusters: ~100 hours Electronics: 700-800 hrs (3478 hours demonstrated in life test)
Cluster 2 Measured	14.784	17.1 Nominal 25.4 max as tested; 24.6 max w/reduced heater power	T1: 108.5 T2: 99.1 T3: 98.4 T4: 96.1	Thrusters: 150-200 hrs Electronics: 500-600 hrs (3478 hours demonstrated in life test)

Prior to shipment, in order to test the flight software and DRS flight computer without the clusters, hardware ground support equipment (GSE) was designed, built, and tested at JPL. A box was made to simulate the cluster electrical load (~18 watts), bellows temperature thermistor, and isolate the communication line between the GSE and the flight integrated avionics unit (IAU). A computer running a software-based cluster simulator (called V-Sat) was built and designed by Hammers Corporation under direction and with models from Goddard Space Flight Center. V-Sat was used for closed loop testing of the entire instrument since the ESA GRS and ST7 thrusters cannot be operated in ambient conditions. Three testbeds with either an EM IAU unit and/or V-Sat simulators were designed, built and used for ground-based testing. One testbed was for software development activities, one was for flight software and sequence verification, and one for the flight hardware testing.

Integration of the flight clusters to the IAU was straightforward. Early prototype testing with the EM IAU and a prototype cluster helped ensure the software was compatible. A safe-to-mate was performed prior to initial integration of the clusters to the IAU (see Figure 10a), which uncovered an unexpected secondary inrush causing minor design modifications to the power switches in the IAU. After the correction, the IAU was able to power and enable both clusters repeatedly without incident.

Testing at JPL included center of gravity, mass and magnetics characterizations as well as electromagnetic measurements. A polarity test to ensure that the commanded head was correct and a test to ensure that the instrument can run for three days of autonomous operation without any problems were also performed successfully.

The center of gravity test was performed on a Space Electronics KGR 500 (see Figure 10c). The unit measures the CG in 2 axis and it was rotated during the test to produce data in all three axis. This, along with the overall cluster mass measurement, was feed into a mass model to produce a detailed mass-mesh table for both clusters and the IAU. It was augmented by previous piece part mass and CG measurements of internal components.

The magnetic measurements were performed in a Helmholtz coil at JPL that was configured to zero out the earth's magnetic field. The DC magnetic filed was measured as delivered, then the unit was de-permeated to ≤50 Gauss, re-measured, then permeated up to 3 Gauss and measured again. This test ensured that the magnetic effect on the gravity sensor proof masses would not affect the main DRS instrument measurement, even in the event that the unit was later subjected to a 3 Gauss magnetic field, as it might be during the spacecraft dynamics testing. Each unit was measured individually and they will all be combined into a three dimensional field gradient model to show that there will be no effects on the LTP gravity sensor.

The EMC testing included the flight IAU and one flight cluster, cluster 1 that will be mounted closely to the IAU (see Figure 10d). The test included a set of radiated emissions, conducted emissions, radiated susceptibility and conducted susceptibility measurements as well as inrush and AC magnetic field measurements. There were some minor non-conformances of the entire assembly (not the thrusters specifically) that will require a waiver from the spacecraft. These non-conformances should not impact meeting the level 1 mission requirements.

During susceptibility tests, the cluster electrodes were set to 1KV, a safe voltage for operation at ambient temperature (25C) and pressure (1 atm) conditions. The telemetry to the s/c simulator was viewed in real time and post processed to ensure that external conditions did not cause an interruption in the telemetry or damage to the hardware through arcing or opening the microvalve. During emissions and other tests that required the cluster to be "noisy", a sequence was used to simulate thruster operations under normal flight conditions, with a limit of 2KV set on the beam voltages. Again this was done to avoid high voltage arcing because the testing was done in air.

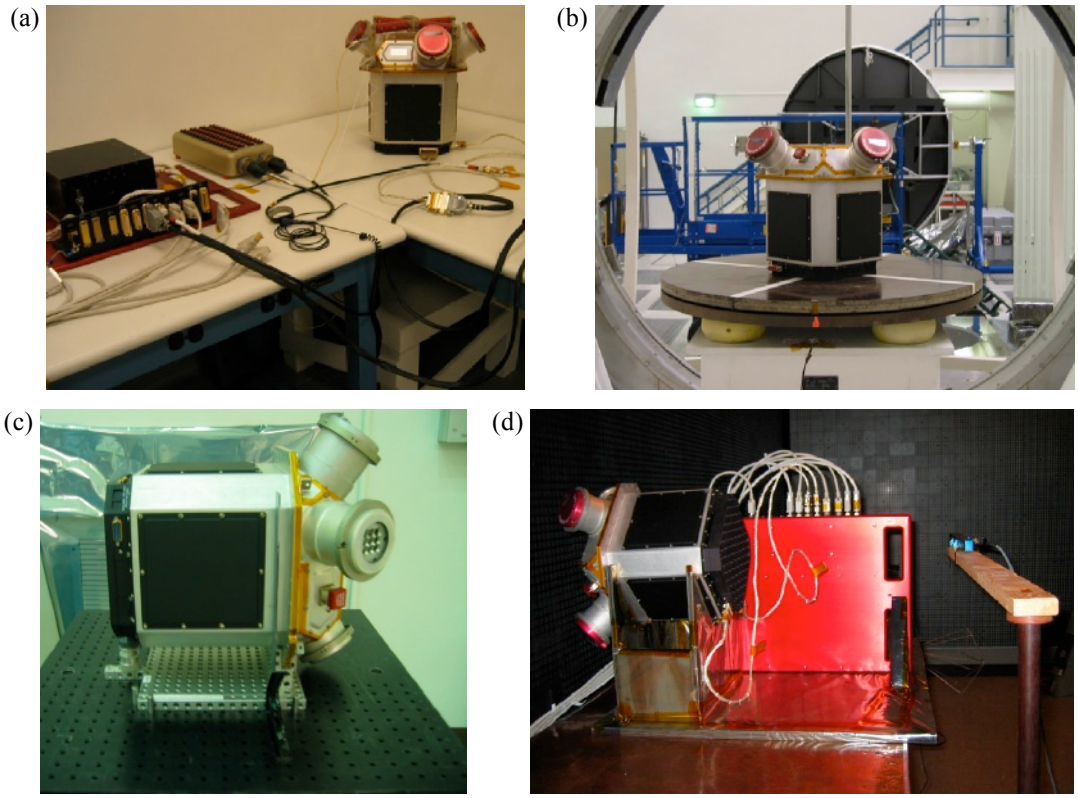

Figure 10. Photos of cluster 1 during various I&T activities at JPL including (a) safe-to-mate with the IAU, (b) magnetics testing, (c) center-of-mass measurements, and (d) EMI/EMC testing with the IAU.

Note that for all ground testing at JPL (and eventually at ESA facilities), a series of safety flags are built into the software to ensure against commanding 1) operation at voltages that would cause arcing in air and 2) opening the microvalve. Prior to use with the flight hardware, all test sequences were validated in the GSE EM testbed with an EM cluster electronics unit equipped with alarms set to measure the electrode and microvalve output voltages.

Much of the post-delivery closed loop testing with the cluster dynamics models will be accomplished without using the flight clusters. The ATLO tests with the flight clusters at ESA will include running the thruster susceptibility sequences with all heads at 1KV, thrust noise sequences, and a self-test. Most of the level 1 requirements will truly be verified and validated post-launch, since they cannot be tested on the ground.

VI. Conclusion

With developmental and all of the qualification testing complete, the ST7 Colloid Micro-Newton Thruster validation testing and flight hardware production is complete. Both flight clusters have been delivered to JPL. Formal Life Test 2B was completed demonstrating more than 3400 hours of operation of a complete single-thruster system before being stopped voluntarily. Performance measurements based on validated thrust models using measured beam voltage and current show the CMNT technology meets or exceeds the precision formation flying and drag-free propulsion range, resolution, and noise requirements of ST7 and LISA. In 2007, during thermal vacuum testing and at high temperature, a material and propellant incompatibility issue caused qualification testing to stop while the cause was determined and corrected. All material compatibility and component-level requalification testing was completed successfully prior to reassembly of both clusters. Both clusters have now passed through full functional testing before and after environmental dynamics and thermal vacuum testing to protoflight levels without any issues, meeting all requirements. Post-delivery integration and test activities at JPL have included center of gravity, mass and magnetics characterizations as well as electromagnetic measurements. All testing with the flight computer and integrated avionics unit has been completed successfully. In the near future, the flight hardware including both colloid thruster clusters will be packaged and shipped to Europe for ATLO activities with the ESA LISA Pathfinder spacecraft. The launch of LISA Pathfinder and the completion of the ST7 mission will be the first space-flight demonstration of colloid thrusters and a US micropropulsion system capable of providing drag-free propulsion for future gravity wave and interferometry precision formation flying missions.

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