Testing of a Green Monopropellant Integrated Propulsion System

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ABSTRACT

VACCO has application-engineered a green monopropellant Integrated Propulsion System (IPS) specifically designed for ESPA-class small satellites. The Integrated Propulsion System is a smart propulsion system with propellant storage, pressurant storage, feed system, controller, software and four flight-proven 1N non-toxic thrusters in a compact bolt-on package. This paper documents Protoflight testing of the first flight system against specified requirements.

Protoflight testing of the Integrated Propulsion Systems combines both acceptance testing that screens for workmanship and Protoflight and qualification testing that verifies the design. As with conventional propulsion systems, Integrated Propulsion Systems are not hot fire tested at the system level. The Bradford ECAPS LMP-103S 1N thrusters were already space qualified with 56 thrusters on-orbit. For this application, each thruster was acceptance tested, including hot fire testing, at the thruster component level. Separately, the system will be Protoflight tested with mass simulators in place of thrusters then electrically checked after thruster integration. A structurally identical Burst Pressure Unit was also built and will be tested. Twelve thrusters have successfully passed acceptance testing and the first flight system and Burst Pressure Unit are expected to pass protoflight qualification test requirements. Integrated Propulsion System Protoflight test data was not at the time of publication. This information will be included in the presentation.

INTRODUCTION

VACCO invented the Micro Propulsion System in 2002 and first presented it at Small Sat in 2003. In the years since, VACCO has produced flight systems of twenty-one unique designs for use in 1U, 3U, 6U and 12U CubeSats as well as small satellites. All three systems flown to date have successfully completed their missions including two MarCO systems that flew to Mars. Over the past 60 years, VACCO has produced thousands of components flying in LEO, MEO, GEO cislunar space, interplanetary space and interstellar space in addition to components on virtually all US rovers and landers. Three flight Integrated Propulsion Systems are currently being produced.

Integrated Propulsion System (IPS)

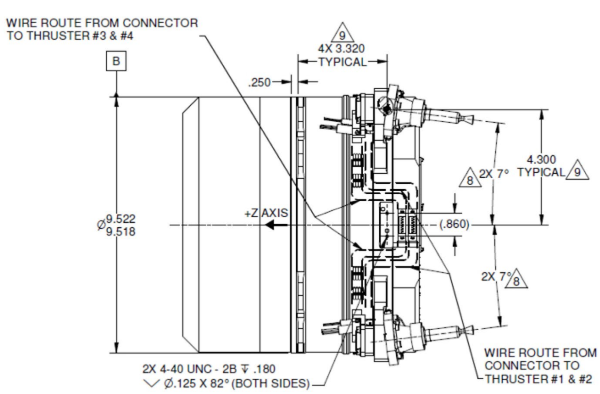
VACCO's Integrated Propulsion System provides a high-performance, propulsion option for ESPA-class small satellites. IPS is a highly reliable, intelligent, attitude control and delta-V solution capable of delivering 12,000 N-sec total impulse at up to 4N total thrust. It is a complete, bolt-on propulsion system including non-toxic LMP-103S propellant storage, helium pressurant storage, feed system, four 1N thrusters and a controller. Design, manufacturing and test methods used are the product of our extensive experience base, including forty complete cold gas, warm gas and "green" monopropellant systems.

The Integrated Propulsion System, as shown in Figures 1 & 2, is roughly the size of a basketball with thrusters mounted on four manifold extensions. It features an all-welded, high strength titanium alloy structure.

Figure 1: VACCO Integrated Propulsion System

The subject design is "range safety friendly" with three interrupts against propellant leakage, a leak before burst pressure boundary and separate power inputs for "Safe" and "Arm".

The integral controller features a Microcontroller with radiation resistant components and built-in radiation shielding. The controller requires less than 1W to operate in the stand-by mode where it can communicate over the RS422 digital interface. Robust, sophisticated, flight-proven software operates the system with substantial safeguards and the ability accept commands and output health monitoring information at a rate of 10Hz. Worst-case power consumption under all operating conditions is less than 50W at 28V.



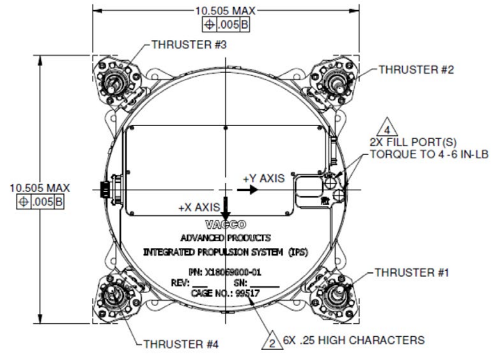


Figure 2: IPS Envelope

Detailed IPS specifications are delineated in Table 1.

SPECIFICATIONS		
SYSTEM PERFORMANCE	PROPELLANT:	PRESSURANT:
	LMP-103S	GHe
MEOP:	22.06 bar (320 psia)	53.09 bar (770 psia)
MDP:	44.12 bar (640 psia)	53.09 bar (770 psia)
PROOF PRESSURE:	55.15 bar (800 psid)	66.36 bar (962.5 psid)
BURST PRESSURE:	66.18 bar (960 psid)	79.64 bar (1155 psid)
DRY TANK VOLUME:	4532.5cc (to NCV1)	3851cc (to filter)
PROPELLANT VOLUME (97.5% FILL):	4420.3cc @ 20°C	
LMP-103S RATED FLOW PER THRUSTER, REF:	0.396 g/s WITH 19.32 bar (280 psia) @ Thruster	
MAX INTERNAL LEAKAGE (EACH THRUSTER):	1.0 X 10-4 sccs GHe	
MAX EXTERNAL LEAKAGE:	1.0 X 10-6 sccs GHe	
OPERATING TEMP:	+10°C TO 40°C (-10°C min, to turn on)	
NON-OPERATING TEMP:	-30°C TO 60°C Unfueled (transport) -15°C TO 40°C Fueled/Mission; requires adequate duration heating to avoid LMP crystals and achieve Operating Temp range	
LONGEST CONTINUOUS THRUST FIRING DURATION:	5 MINUTES	
MINIMUM TOTAL IMPULSE (@ 20°C):	12,000 N-s Based on 226 sec Isp @ 0.878N Thrust	
MAX DRY MASS @ 20°C, REF:	9.0 kg (19.8 lbs)	
MAX WET MASS @ 20°C:	14.7 kg (32.4 lb)	
ELECTRICAL		
OPERATING VOLTAGE FOR PWA & VALVES:	12 ± 0.3 Vdc	
OPERATING VOLTAGE FOR THRUSTER HEATERS:	28 ± 4 Vdc	
TO OPERATE ANY VALVES:	28 VDC supply must be applied	
12 VDC SUPPLY POWER:	25 W Max @ 12 VDC	
28 VDC SUPPLY POWER:	50 W Max @ 28 VDC; 1 Heater operating per thruster	
DATA INTERFACE:	RS-422	

Table 1: IPS Specifications

All functional components shown in Figure 3 are mounted to a titanium Manifold. No tubing or orbital welding is used. Key functional components include a 10micron filter, frictionless, high reliability micro valves and redundant pressure transducers. Normally closed valves, that close and seal upon loss of power, are used for redundant electronic pressure regulation, redundant propellant isolation and thruster control.

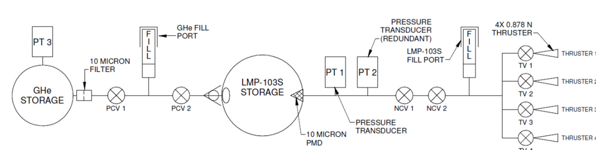


Figure 3: IPS Fluid Schematic

The chart in Figure 4 summarizes IPS parameter change from beginning of life (BOL) through end of life (EOL) as propellant is consumed.

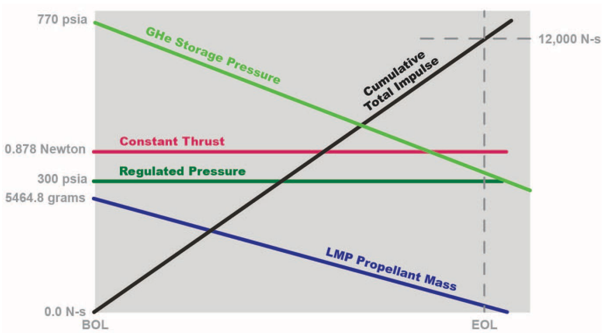


Figure 4: Graphic Summary of IPS Performance

LMP-103S 1N Thrusters

The IPS features four, flight-proven, double-canted, Bradford ECAPS 1N LMP-103S green monopropellant thrusters that generate a combined nominal axial thrust of 3.97N. First launched in 2010, fifty-six of these 1N thrusters have been successfully flown. During delta-V operations individual thrusters can be off-pulsed to achieve thrust vector control, roll control or reaction wheel desaturation. Given the high throughput capability of the thruster, system propellant and pressurant capacity can be expanded to increase total impulse with minimal impact to the overall design.

Figure 5: Bradford ECAPS 1N Thruster

Detailed thruster specifications are delineated in Table 2.

SINGLE THRUSTER SPECIFICATION (EXCLUDING VALVE)	
IPS RATED THRUSTER INLET PRESSURE:	19.32 bar (280 psia)
IPS RATED THRUST:	0.878 N (VACUUM EXIT)
IPS RATED Isp:	226 sec (VACUUM EXIT)
RATED THRUST (HIGH):	1N @ 22 bar (VACUUM EXIT)
RATED THRUST (LOW):	0.25N @ 5.5 bar (VACUUM EXIT)
LMP THROUGHPUT PER THRUSTER:	1.5 KG REFERENCE AT IPS RATED INLET PRESSURE (REGULATED)
LEVERAGED HERITAGE QUALIFICATION IN BLOWDOWN MODE FOR REFERENCE:	
QUALIFIED PULSES:	60,000
QUALIFIED PROPELLANT THROUGHPUT:	24 KG LMP-103S
QUALIFIED LONGEST CONTINUOUS FIRING:	1.5 HOURS
QUALIFIED ACCUMULATED FIRING TIME:	25 HOURS

Table 2: 1N Thruster Specifications

The heritage thruster flow control valve was incompatible with the IPS design. In the Integrated Propulsion System flight configuration, each 1N Thrust Chamber Assembly is mounted directly to the IPS Manifold extension containing its thruster valve. Minor adjustments to the high-temperature electrical cable routing for thruster heaters and temperature sensors were made to accommodate IPS wire routing needs. These changes preserve thruster heritage. The replacement VACCO thruster valves will be Protoflight tested at the system level.

TEST PLAN

The IPS test plan involves four phases of testing to verify the flight hardware. These four phases are outlined as follows:

1) 1N thruster acceptance testing performed by Bradford ECAPS at their facility.

2) IPS protoflight testing will be performed at VACCO's California facility using thruster mass simulators equipped with heaters and temperature sensors.

3) IPS testing in the final flight configuration will be performed after integrating the thrusters into the IPS Manifold. Testing consists of electrical checks and thrust vector alignment verification.

4) IPS testing by the customer after delivery. This testing is proprietary to our customer and is consequently beyond the scope of this paper.

As with any complex assembly, in-process testing is performed at various points in the assembly sequence. These tests incrementally verify components and sub-assemblies to ensure the resulting system will pass subsequent Protoflight testing.

Subassembly testing is performed on the pressure transducers, pressurant filter and propellant management device (PMD) before they are installed. In addition, the pressure control valves, isolation valves, thruster valves, check-valve, and installed PMD are tested before final IPS close-out welds are made.

Electronics and software are also tested at various levels of assembly. The controller Printed Wiring Board (PWA) is fit-checked using an additively manufactured mockup of the PWA enclosure. This verifies mounting, connector positioning and screens for potential interferences. Both software and electronics are then tested for proper command decoding, telemetry output, sensor reading, heater driver operation and valve driver operation by technicians using a custom Graphic User Interface (GUI). Stimulus is applied to ensure the control electronics and software properly respond to various conditions such as temperature extremes and over-current.

Separate from the flight item, there were other tests planned and conducted to verify both the electronic and structural design. An electronic simulator or FlatSat was tested at VACCO and by the customer. Also, a structurally representative unit will be Burst Test tested. Further detail can be found in the following sections.

Thruster Acceptance Test Plan

Acceptance testing of the fight-proven 1N Thrusters was conducted by the supplier, Bradford ECAPS, at their facilities in Sweden. VACCO reviewed and approved all acceptance test data before the thrusters were shipped to the US for integration into the IPS. Bradford ECAPS heritage acceptance test plan leveraged wherever possible. Minor modifications were made to the heritage hot fire test plan to account for off-pulsing required by the IPS application. To maximize "test as you fly", testing was conducted using VACCO valves. Test valves were representative of the IPS manifold and thruster valve in terms of wetted materials, flow path and valve seat geometry. The valve actuator used is identical to the flight design including the inclusion of back EMF suppression diodes. Engine testing otherwise used existing Bradford ECAPS tools and fixturing.

The test plan involved the following items:

- Examination of product including nozzle vector alignment to mounting plane
- Heater thermal rise within 30 second maximum time limit in a vacuum environment
- Proof pressure with nozzle plugged (33 bar or 478.6 psid)
- Functional testing including of external leakage and electrical checks
- Random vibration testing followed by radiographic inspection (2x 11.47 Grms lateral & 1x 16.23 Grms axial or thrust axis)
- Functional testing and alignment check
- Hot fire testing included 3x 30 second single pulse firing and 300x 300 millisecond on, 25% duty cycle pulse firings at 3 fixed inlet pressures that generally achieve 1 N (22 bar), 0.55 N (12 bar) and 0.25 N (5.5 bar) thrust. An additional 100x pulse firing at 22 bar inlet pressure occurs at 100 milliseconds on and 25% duty cycle.
- After decontamination, a post functional test occurs with alignment verification

IPS Protoflight Test Plan

Protoflight testing of the IPS was planned in stages beginning with the system utilizing simulators installed in place of the thrusters. Controller hardware and flight software will be verified at the system level by virtue of using them to operate the system during Protoflight testing. All test results will be documented in a Protoflight Test Report. The Protoflight test plan is as follows:

- Examination of product including dry weight with thruster mass simulators (9 kg or 19.8 lbm)
- Proof pressure testing of both pressurant (66.36 bar or 962.5 psid) and propellant sections (55.15 bar or 800 psid). Proof pressure applied at ambient temperature is adjusted to account for reduced material strength at maximum temperature.
- Initial functional testing with gas includes:
  - External leakage (1x10^-6 sccs GHe; at 53.09 bar or 770 psid pressurant & 44.12 bar or 640 psid propellant)
  - 2x Pressurant valve isolation internal leakage (1x10^-5 sccs GHe at 53.09 bar or 770 psid pressurant)
  - 2x Propellant and 4x thruster isolation valve internal leakage (1x10^-4 sccs GHe at 44.12 bar or 640 psid propellant)
  - All 8x valves operation/response testing
  - 2x Pressurant valve regulation testing (22 bar or 320 psia)
  - 3x pressure sensor verifications
  - Power & telemetry verifications
- Electrical functional test specifically checks thruster thermal control loop using surrogate heaters and temperature sensors, plus PWA heater powering and corresponding sensor output

- Functional testing with water including pressure regulation (20.34 bar or 295 psia) and liquid (propellant side) valve pulse (100 millisecond) and flow verification (5 second), with no visual indication of leakage
- Random Vibration (gas and water filled; 2x 10.76 Grms lateral & 1x 13.94 Grms axial) including post-vibe wet functional test (water):
    - Note: this level is only permitted with mass simulator; system level exposure is 2x 7.09 Grms lateral & 1x 6.71 Grms axial
- Throughput verification (4400 cc; a one-time design test)
- Thermal vacuum testing (8.5 cycles) including pre and post ambient temperature functional testing. Additional functional testing occurs at both first and last cycle operational temperature plateaus, including IPS PWA cold and hot starts. Initial cycle also includes additional, non-operational, temperature exposure dwells (+75°C & -15°C unpowered). Thermal cycling is otherwise conducted with the IPS controller powered (+65°C & -5°C powered), including during thermal transitions.
- Pressurant isolation valve internal leakage
- Thruster integration and thrust vector verification
- Thruster electrical verification
- Final examination and packaging for shipment

Additional testing occurs at the customer after delivery. This testing is unique to the customer and consequently outside the scope of this paper.

IPS Burst Test Plan

Since the tank geometry and pressures are unique to the IPS, a flight-representative Burst Test Unit (BTU) was built to qualify the design against burst pressure requirements.

All major structural components of the BTU were identical to the flight item (identical part numbers) and were taken from the same lot of parts. BTU pressure vessel weldments involve the same welds as the flight item.

The valve design utilized is qualified for 3,000 psi service and was not included in the BTU. Valve locations were plugged to allow application of pressure. Exterior brackets were also omitted since they are not part of the structural pressure boundary.

BTU test plans involve an initial acceptance verification including proof pressure and external leakage testing before proceeding into qualification testing. Consequently, the test plan involves:

- Acceptance
    - Proof pressure testing of both pressurant (66.36 bar or 962.5 psid) and propellant sections (55.15 bar or 800 psid). Proof pressure applied at ambient is increased to account for weaker material properties at maximum temperature.
    - External leakage (1x10^-6 sccs GHe; at 53.09 bar or 770 psid both pressurant & propellant)
- Qualification
    - 50x Pressure Cycling (53.09 bar or 770 psid both pressurant & propellant)
    - Burst pressure testing of both pressurant (79.64 bar or 1155 psid) and propellant sections (66.18 bar or 960 psid). Burst pressure applied at ambient is increased to account for weaker material properties at maximum temperature.
    - Rupture testing (both pressurant & propellant). Leak before burst is expected.

IPS FlatSat Test Plan

A high-fidelity electrical representation of the IPS, called a FlatSat, was designed, built and tested in-house early in the program. This facilitated early verification of controller component selection, electrical schematic and software. The FlatSat was then delivered to our customer where it was used to verify proper spacecraft software, power consumption and telemetry interaction. As shown in Figure 6, the FlatSat includes pressure sensors with ports as shown in the upper left of figure. Pressure can be applied to simulate pressure telemetry and verify closed-loop pressure regulation. Internal electrical loads simulate the valves and heaters so that commanding valve actuation or setting a heater to a temperature setpoint will cause a corresponding and realistic increase in power consumption. Heaters are matched with temperature sensors so that thermal regulation of catalyst bed heaters are also simulated.

Figure 6: IPS FlatSat Electrical Simulator

The FlatSat test plan includes tests to verify operation of the controller and software. First, power is carefully applied and nominal power consumption is verified. Next, flight software is programmed into the FlatSat and status indication LEDs verify basic software and electrical functionality. After that, a long series of tests are performed to verify every input and output of the controller. Two variable voltage power supplies (for valve pull-in and hold voltages) are tested and adjustability verified. Each thruster is individually commanded to fire and the correct sequence of isolation valves and appropriate thruster valve are verified operational. Thermocouple temperature sensors are independently tested using a thermocouple calibrator. Each heater and associated temperature sensor are also operated. Closed loop thermal regulation are verified for each heater/sensor pair. All analog inputs are verified good and varied, whenever possible, to verify accuracy at multiple operating points (input voltage, valve hold voltage, etc.).

TEST RESULTS

Thruster Acceptance Test Data

Acceptance testing of twelve flight IPS thrusters has been successfully completed by Bradford ECAPS. Measured hot fire thrust was slightly higher compared to heritage 1N thrusters at the identical inlet pressure. This was expected as the IPS incorporates a single seat thruster valve immediately upstream of the thruster inlet as opposed to the heritage series redundant valve. A summary of the test results in indicated in Table 3. See earlier plan information for details of the test conducted. Example results are included in corresponding figures.

Table 3: Thruster Acceptance Test Results

Test	Summary	Notes/Reference
Examination	Pass	0.212 kg & ≤ 0.5° align (Figure 1)
Heater Rise Time	Pass	<30 minutes
Proof	Pass	33 bar; Figure 2
Functional	Pass	
Random Vibration & Radiographic Inspect	Pass	Figure 3 & Figure 4
Functional & Align	Pass	
Hot fire	Pass	Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, & Figure 10
Functional & Align	Pass	

Figure 7: Thruster Nozzle Alignment Check

Figure 8: Thruster Pressure Test

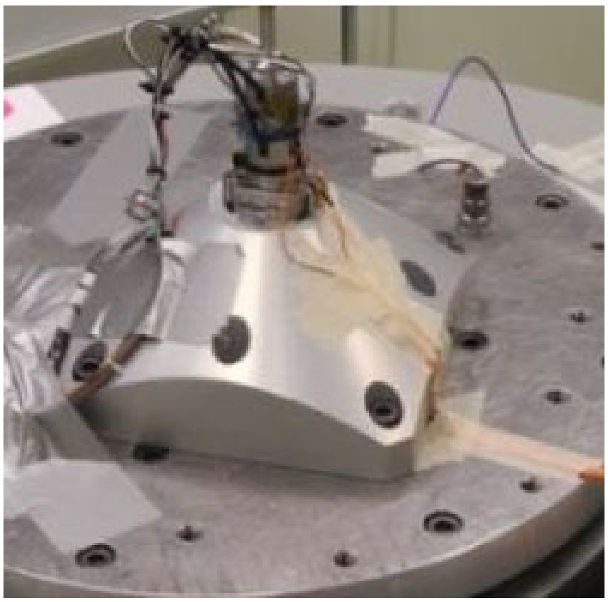
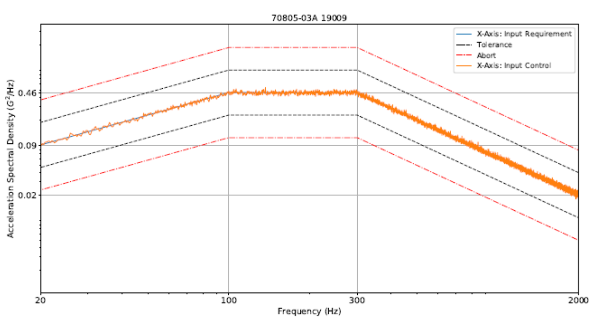


Figure 9: Thruster Vibration Test



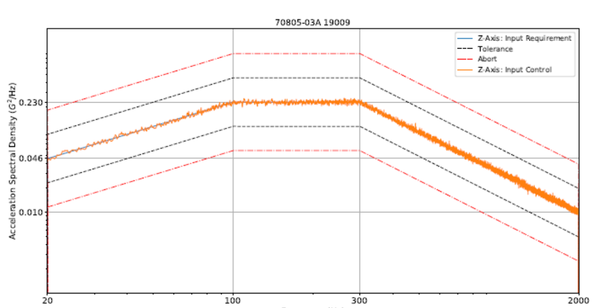


Figure 10: Thruster Vibration Lateral (upper) and Axial (lower) Input

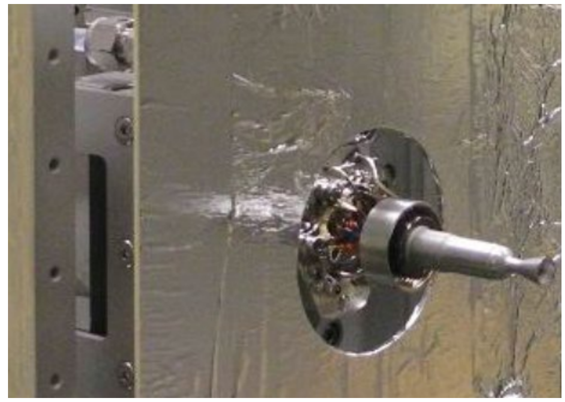


Figure 6: Thruster Hot Fire Test Set-Up

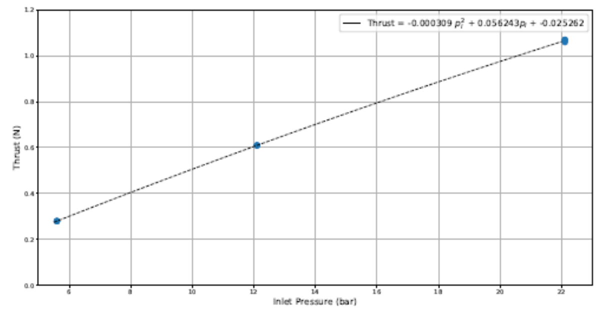


Figure 7: Hot Fire Thrust vs Inlet Pressure

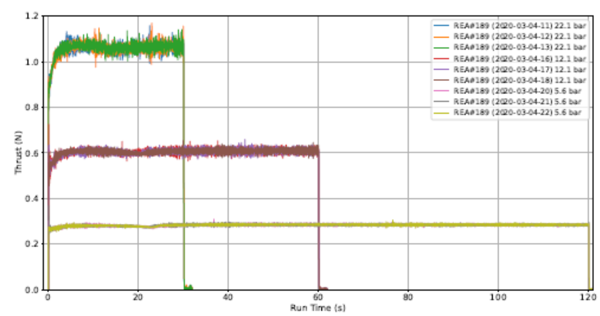


Figure 8: Hot Fire Thrust vs Time, Single Pulse

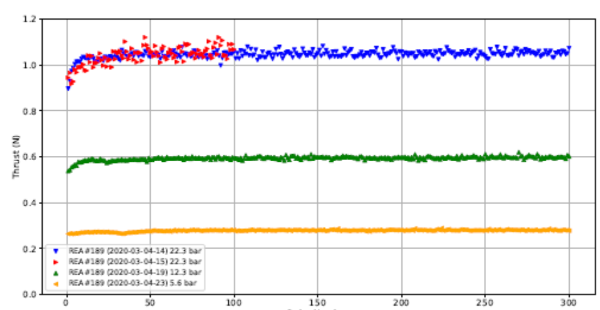


Figure 9: Hot Fire Thrust vs Pulse Mode Quantity

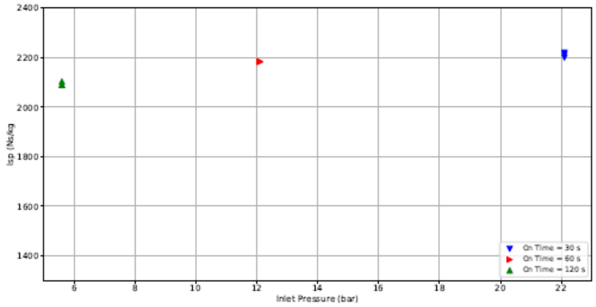


Figure 10: Hot Fire Isp vs Inlet Pressure

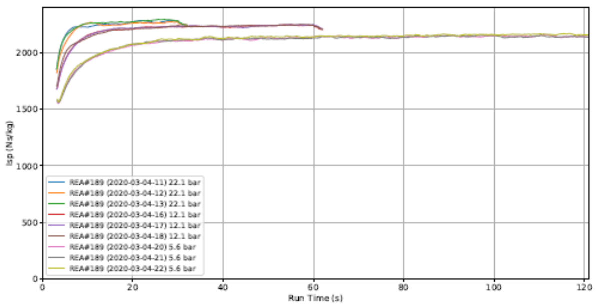


Figure 11: Hot Fire Isp vs Time, Single Pulse

IPS Protoflight Test Data

As of the submittal of this paper, the first IPS was entering Protoflight testing. Consequently, a complete set of test results will be included in the presentation sides. A view of the IPS assembly with thruster mass simulators is shown in 17.

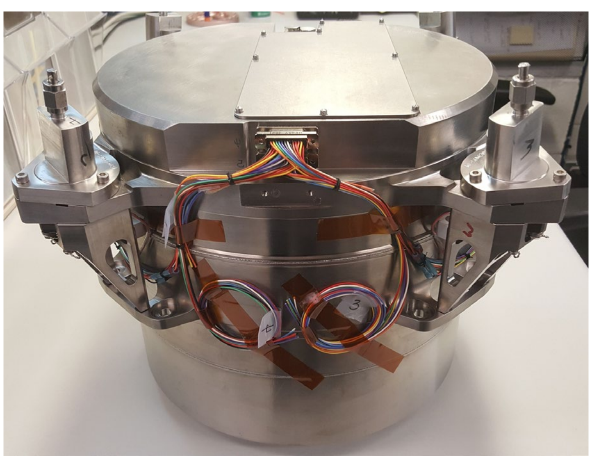


Figure 12: IPS with Thruster Mass Simulators

A view of the IPS assembly about to undergo proof pressure testing is shown in Figure 18.

Figure 13: IPS Proof Test

IPS Burst Test Plan

As of the submittal of this paper, the IPS Burst Test Unit (BTU) was entering acceptance testing. Consequently, a complete set of test results will be included in the presentation sides. A view of the IPS BTU is shown in Figure 19.

Figure 14: IPS Burst Test Unit

CONCLUSIONS

VACCO has application-engineered a green monopropellant Integrated Propulsion System (IPS) specifically designed for ESPA-class small satellites. The Integrated Propulsion System is a smart propulsion system with propellant storage, pressurant storage, feed system, controller, software and four flight-proven 1N non-toxic thrusters in a compact bolt-on package. It is capable of imparting 12,000 Newton-seconds of total impulse to the host satellite.

The IPS features four, flight-proven, Bradford ECAPS 1N LMP-103S non-toxic monopropellant thrusters. They are mounted double-canted to provide both attitude control and delta-V. Acceptance testing of twelve flight thrusters was successfully completed by Bradford ECAPS at their facility.

Burst Pressure Testing of a non-flight unit including Proof pressure, External leakage, Pressure Cycling, Burst Pressure and Rupture Pressure is ongoing. Test data will be included in the presentation sides.

IPS system-level Protoflight testing of each flight system will include Examination of Product, Proof Pressure, Electrical Functional Testing, Liquid Pressure Regulation and Flow, Random Vibration, Throughput Verification, Thermal Vacuum Testing and Valve Leakage. After mounting the thrusters, electrical testing will occur followed by final Examination of Product.

As of the writing of this paper, the first IPS was at the entry point of Protoflight testing. All test results will be documented in the presentation slides.

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The authors further acknowledge the customer and VACCO program and support staff team that made the Integrated Propulsion System a reality.

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