SSC21-XI-08

Proto-Flight Testing of a Green Monopropellant Integrated Propulsion System

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ABSTRACT

The Integrated Propulsion System (IPS) is a bolt-on green monopropellant propulsion system specifically designed for ESPA-class Small Satellites. The purpose of this paper is to document Proto-flight testing of three Integrated Propulsion Systems.

The objective of Proto-flight testing is to certify systems for flight while preserving their ability to be subsequently flown and fulfill their mission requirements. This approach is widely used in the Small Sat community where program lead times are short and budgets tight.

Proto-flight testing of the Integrated Propulsion Systems combined both acceptance testing that screens for workmanship 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 LMP-103S 1N thrusters were already space qualified with 82 units successfully flown on 21 different spacecraft. For this application each of the twelve thrusters used were acceptance tested, including hot fire testing, at the thruster level. In parallel, the IPS systems were Protoflight tested with mass simulators in place of thrusters. After the thrusters were mounted, final electrical and functional checks were performed.

The subject paper is a follow-up to SSC20-IX-02 presented at the 2020 Small Sat Conference where Engineering Model testing, thruster hot fire acceptance testing and system Burst Testing results were presented. Now that Proto-flight testing is complete and the units have been delivered, the proposed paper will summarize the balance of test data and compare results with failure criteria. Specific data to be presented includes inspection for dimensional / mass compliance, proof pressure testing, electrical functional testing, surrogate liquid functional testing (including vibration to proto-flight levels) and proto-flight thermal vacuum testing.

The Integrated Propulsion System is a smart system with an integral microprocessor and flight software. Proto-flight testing includes a full suite of tests and calibration checks performed to verify compliant controller operation. Controller testing included output voltage, valve driver power step-down and data acquisition accuracy. Software was tested by virtue of operating the system during Proto-flight testing.

The capabilities of the Integrated Propulsion System are a key asset to the Small Satellite community. This paper will be a valuable tool for potential users to evaluate it against their mission requirements.

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 forty 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 even interstellar space (Voyager) in addition to components on virtually all US rovers and landers.

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 over 12,000 N-sec total impulse at up to 4N axial 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 IPS features an integral controller 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.

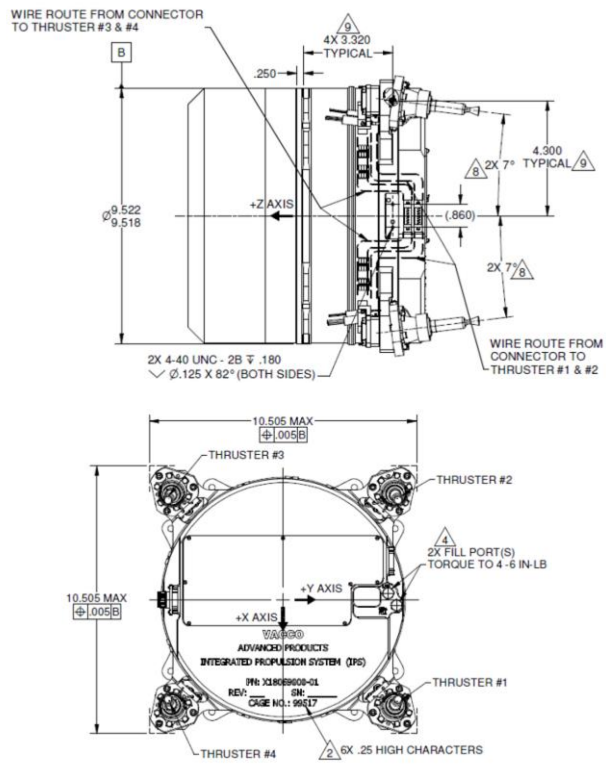

Figure 2: IPS Envelope

Detailed IPS specifications are delineated in Table 1.

SPECIFICATIONS		
SYSTEM PERFORMANCE	PROPELLANT: LMP-103S	PRESSURANT: 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.

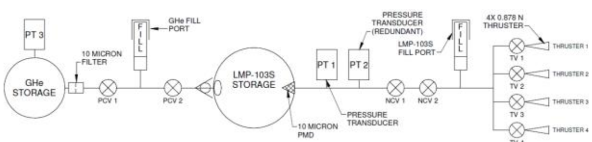

Figure 3: IPS Fluid Schematic

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

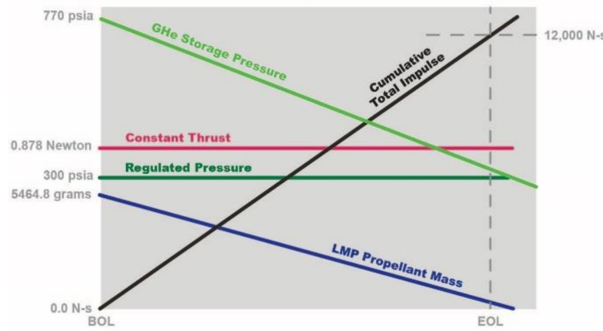

Figure 4: Graphic Summary of IPS Performance

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, eighty-two 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 were Protoflight tested along with the system.

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. This phase is complete and documented in SSC20-IX-02.

2) IPS Protoflight testing of three flight systems performed at VACCO's California facility using thruster mass simulators equipped with heaters and temperature sensors. This phase is complete and documented herein.

3) IPS testing in the final flight configuration (performed after integrating the thrusters). Testing consists of electrical checks and thrust vector alignment verification. This phase is complete and documented.

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). Commands are applied to ensure the control electronics and software properly responds under various conditions such as temperature extremes and over-current.

Separate from the flight items, other tests were conducted to verify both the electronic and structural design. An electronic simulator or Flat Sat was successfully tested at VACCO and by the customer. Flat Sat test results were documented in the SSC20-IX-02 slide presentation.

In addition, a structurally representative unit was successfully Burst Pressure tested. Burst test results were documented in the SSC20-IX-02 slide presentation.

IPS Protoflight Test Plan

Protoflight testing of the IPS was planned in stages beginning with the system utilizing simulators installed in place of the 1N thrusters. Controller hardware and flight software were verified at the system level by virtue of using them to operate the system throughout Protoflight testing. At the completion of IPS assembly level Protoflight testing, the thruster simulators were replaced by flight thrusters.

A list of IPS Protoflight tests carried out is listed below:

- Examination of product including dry weight with thruster mass simulators (9 kg or 19.8 lbm)
- Proof pressure testing of both pressurant (68.40 bar or 992.0 psid) and propellant tank (56.88 bar or 825 psid).
- Functional testing with gas includes:
  - External leakage (1x10^-6 sccs GHe; at 53.09 bar or 770 psid pressurant & 22.06 bar or 320 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 22.06 bar or 320 psid propellant)
  - All 8x valves operation/response testing
  - 2x Pressurant valve regulation setpoint verification (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)
- Flow verification (5 second), with no visual indication of liquid leakage

- Random Vibration (gas and water filled), including post-vibe wet functional test
- Throughput verification (4400 cc; a one-time design test)
- Thermal Vacuum (8.5 cycles), including pre- and post-ambient temperature functional testing
- Pressurant isolation valve internal leakage
- Thruster integration and thrust vector verification
- Thruster electrical verification
- Final examination and packaging for shipment

TEST RESULTS

IPS Protoflight Test Data

VACCO had produced and Protoflight tested a total of three (3) IPS systems. All of three systems successfully completed Protoflight testing and were delivered to the customer in Q1 of 2021. Reported herein are results from selected Protoflight Tests carried out on production IPS as outlined in the test plan.

Examination of product

All three IPS passed dimensional inspected against their Interface Control Drawing. Typical final dry mass was 8.57 kg or 18.9 lbm, well under the 9 kg or 19.8 lbm requirement.

Proof Pressure

Prior to dynamic and thermal testing, each IPS was verified for its structural integrity via Proof Pressure testing. This included both the pressurant (68.40 bar or 992.0 psid) and propellant (56.88 bar or 825 psid) sections of the system. Figure 6 shows the Proof Pressure test setup in a blast proof chamber. Pressure was applied at ambient temperature for five (5) minutes minimum, with the pressure adjusted higher to account for reduced material strength at maximum temperature. Post-test visual and dimensional inspection verified all three flight systems successfully passed Proof Pressure test without structural degradation or permanent deformation.

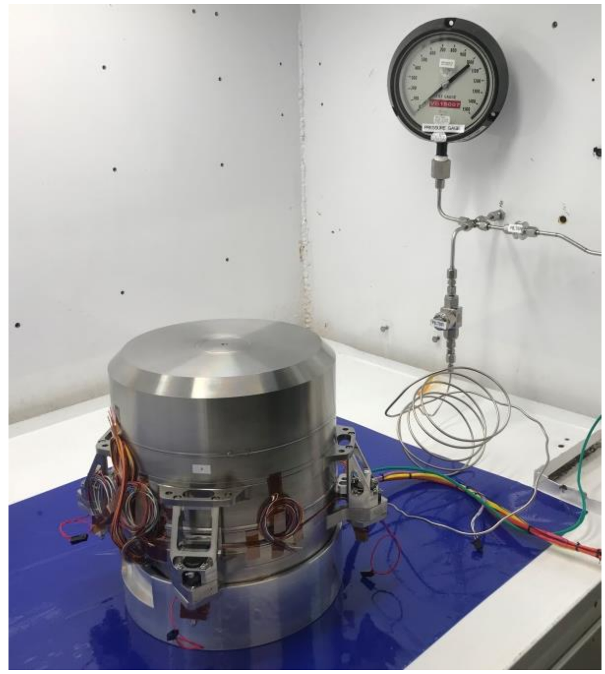

Figure 6: IPS Proof Pressure Test Setup

Random Vibration Test

Prior to Random Vibration each IPS underwent mechanical and electrical functional checks. It was crucial to accurately simulate a fully fueled system at launch. To accomplish this the thruster simulators remained attached to the system and an equivalent mass of deionized water was loaded into the propellant tank to simulate LMP-103S propellant. The pressurant section was pressurized to maximum operating pressure with gaseous Helium. The test setup pictured in Figure 7 shows the IPS mounted to the fixture in a manner representative of the spacecraft installation interface.

The IPS was subjected to Protoflight Random Vibration levels of 10.76 Grms on the lateral axes (2x), and 13.94 Grms in the axial direction (1x). Pre- and post-random vibration low-g sine sweeps were conducted for each orthogonal axis to ensure assembly integrity. Additional electrical functional checks verified proper IPS controller and software operation. All production IPS successfully passed Protoflight Random Vibration test requirements including post-test functional checks.

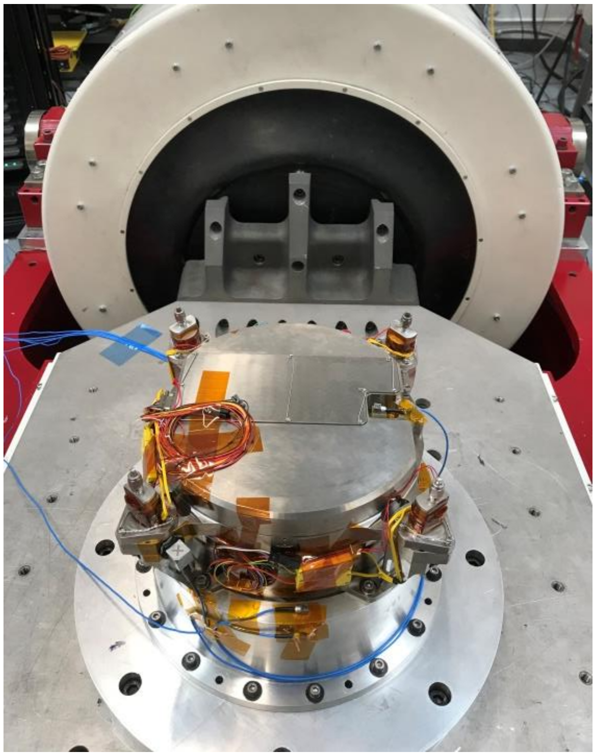

Figure 7: IPS Random Vibration Test Setup

Thermal Vacuum Test

Depicted in Figure 8 is the Thermal Vacuum test setup with instrumentation on the IPS. Heating and cooling of the unit was via thermal conduction plates that were installed on upper and lower surfaces of the IPS. The IPS unit was subjected to a total of 8.5 thermal cycles. A typical cycle included ramp up and ramp down legs between the operating temperature extremes (+65°C & -5°C) with the IPS powered. This was followed by a one hour hot or cold thermal soak after achieving thermal equilibrium. Functional testing occurred during both the first and last thermal cycle after soaking at the operational temperature plateaus. Functional testing included simulated thruster firing, internal leakage and telemetry verification. The non-operating temperature range was demonstrated during the first thermal cycle by additional temperature dwells at +75°C & -15°C with the IPS unpowered. While at temperature the controller was power-up to verify IPS is capable of hot and cold starts at non-operational temperature extremes. The IPS units successfully passed all post-thermal functional checks. This demonstrated their capability to function after being exposed to both operating and non-operating temperatures extremes in a vacuum environment.

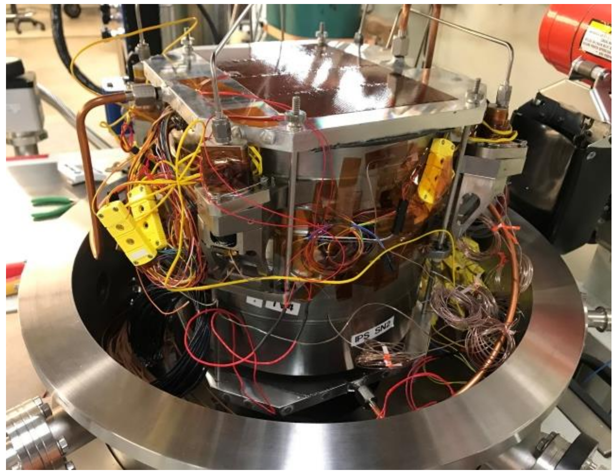

Figure 8: IPS Thermal Vacuum Test Setup

Functional Testing

Each IPS underwent a battery of functional tests before and after every potentially destructive test. A sample set of final leakage test data is summarized in Table 3.

Valve internal leakages	sccs GHe
PCV1	7.8e-6
PCV2	7.3e-6
NCV1	1.1e-5
NCV2	9.3e-6
TV1	1.6e-6
TV2	7.2e-8
TV3	7.2e-8
TV4	8.1e-5
Reverse thruster valve leakages at 10 psid	**sccs GHe**
TV1	8.9e-7
TV2	7.8e-7
TV3	7.9e-7
TV4	6.3e-5

Table 3: Final Functional Test Data

1N Thruster Integration and Verification

Upon successful completion of dynamic and thermal testing, the IPS entered the final stage of Prototype testing where the thruster simulators were replaced with flight thrusters. Figure 9 shows the four (4) 1N thrusters installed onto an IPS with electrical wiring completed. The IPS underwent thrust vector verification on a CMM followed by a series of thruster electrical functional checks. These thruster electrical tests were designed to verify both the primary and redundant catalyst heater control loop operation prior to IPS delivery to the customer. All production IPS completed and met the required electrical test and verification steps per the Protoflight test procedure.

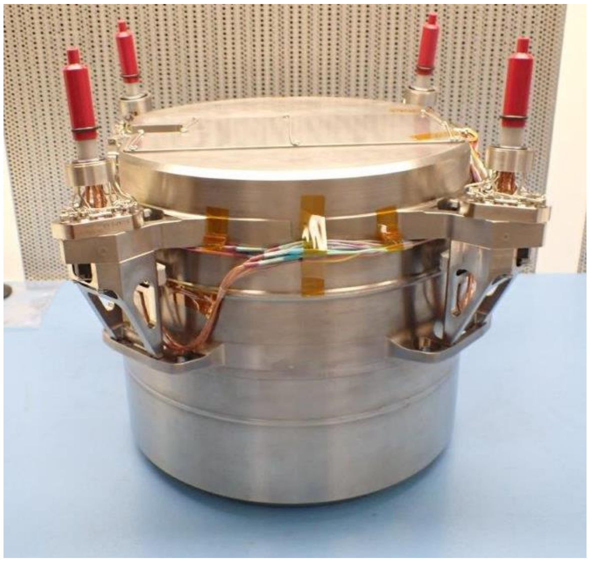

Figure 9: Integrated Flight 1N Thrusters on IPS

All three (3) delivered IPS have been integrated into their respective satellites and completed final check-outs. Satellite level IPS testing is proprietary to our customer and, as such, is outside the scope of this paper.

Conclusions

VACCO has application-engineered, built and qualified three green monopropellant Integrated Propulsion Systems (IPS) specifically designed for ESPA-class small satellites. Integrated Propulsion Systems are smart propulsion systems with propellant storage, pressurant storage, feed system, controller, software and four 1N thrusters in a compact bolt-on package. Each IPS is capable of imparting >12,000 Newton-seconds of total impulse to the host satellite.

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 before delivery to VACCO.

Burst Pressure Testing of a non-flight unit including Proof pressure, External leakage, Pressure Cycling, Burst Pressure and Rupture Pressure was successfully completed.

Protoflight testing of all three IPS flight systems was undertaken. Examination of Product, Proof Pressure, Electrical Functional Testing, Liquid Pressure Regulation and Flow, Random Vibration, Throughput Verification, Thermal Vacuum Testing and Valve Leakage were all successfully completed. After mounting the thrusters, electrical testing was conducted followed by final Examination of Product.

ACKNOWLEDGEMENTS

The authors and VACCO acknowledge and extend special thanks to Bradford ECAPS staff, past and present, for their contributions to the IPS effort and this paper. This includes alphabetically Kjell Anflo, Stuart Bucknell, Mathias Persson, Olivia Ryu, Patrick van Put, and many others. Their product and efforts enabled this work.

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

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