GREEN PROPULSION ADVANCEMENT AND INFUSION

Henry W. Mulkey [(1)], Andrew P. Maynard [(2)], and Kjell Anflo [(3)]

[(1)] [(2)] NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, Md, 20771, U.S.A
Email: henry.w.mulkey@nasa.gov, andrew.p.maynard@nasa.gov

[(3)] ECAPS, P.O. Box 4207 SE-171 04 Solna, Sweden
Email: kjell.anflo@bradford-ecaps.com

KEYWORDS: green propulsion, propulsion components, new propellants

ABSTRACT:

All space missions benefit from increased propulsion system performance, allowing lower spacecraft launch mass, larger scientific payloads, or extended on-orbit lifetimes. Likewise, long-term storable liquid propellant candidates that offer significant reduction in personnel hazards and shorter payload processing schedules present a more attractive propulsion subsystem solution to spacecraft builders. Aiming to reduce risk to potential infusion missions and fully comprehend the alternative propellant performance, the work presented herein represents many years of development and collaborative efforts to successfully align higher performance, low toxicity green propellants into NASA Goddard Space Flight Center (GSFC) missions. High Performance Green Propulsion (HPGP), and the associated propellant technology, has advanced significantly in maturity through increased familiarity with LMP-103S propellant handling, the proven reduction in loading hazards, successful launches conducted at multiple international Ranges, and HPGP on-orbit flight heritage. As science missions move forward to the potential infusion of HPGP technology, the National Aeronautics and Space Administration (NASA) and its partners are working to address gaps in system performance and operational considerations.

NOMENCLATURE

ACS = Attitude Control Systems
CPSM = Chemical Propulsion Subcapability Management
DM = Demonstrator
ECAPS = ECological Advanced Propulsion Systems
EQM = Engineering Qualification Model
FCV = Flow Control Valve
FD = Flight Dynamics
FOI = Swedish Defence Research Agency
GPM = Global Precipitation Measurement
GPWG = Green Propulsion Working Group
GRC = Glenn Research Center
GSFC = Goddard Space Flight Center
HPGP® = High Performance Green Propulsion
IA = Implementing Arrangement
ICD = Interface Control Document
LMP-103S = Liquid Monopropellant 103S
MMS = Magnetospehric Multi-Scale
MSFC = Marshall Space Flight Center
NASA = The National Aeronautics and Space Administration
PACE = Plankton, Aerosols, Cloud, ocean Ecosystems
SNSB = Swedish National Space Board
SOW = Statement of Work
SPEC = Specification
TRL = Technology Readiness Level
WFIRST = Wide Field Infrared Survey Telescope

1. INTRODUCTION

Incorporating green propulsion technology trades early in mission studies and aligning potential performance, cost, schedule, and hazard benefits to mission opportunities has aided in identifying and guiding further green propulsion technology maturation efforts requisite to substantiate mission technology readiness. HPGP system trade studies have been evaluated against historical on-orbit GSFC missions: Global Precipitation Measurement (GPM), Solar Dynamics Observatory, Magnetospehric Multi-Scale (MMS), Lunar Reconnaissance Orbiter, and Mars Atmosphere and Volatile EvolutioN [1], as well as two current GSFC missions: Plankton, Aerosols, Cloud, ocean Ecosystems (PACE) and Wide Field Infrared Survey Telescope (WFIRST) [2]. Each of these mission trade studies represent a diverse set of requirements, as each have dissimilar scientific objectives. Mission requirements drive propulsion subsystem design, performance parameters, and life expectations. In each case evaluated, the missions benefited from HPGP propulsion subsystem design from the increased performance and propellant density offered. The flight heritage of Prototype Research Instruments and Space Mission technology Advancement (PRISMA) [3], the Planet SkySat HPGP propulsion constellation [4], as well as the Green Propellant Loading Demonstration [5] have demonstrated tangible benefits to both HPGP propulsion subsystem on-orbit performance and the ease of LMP-103S handling efforts as compared to the Self Contained Atmospheric Protective Ensemble operations required for highly toxic hydrazine propellant. Four major Range Safety organizations (U.S., European, Indian, and Russian) have gained familiarity with LMP-103S propellant loading operations and the associated handling benefits [6]. The most recent addition to this list is Vandenberg Air Force Base in California (U.S.) with six SkySat LMP-103S propellant loading operations conducted in 2017. In all, the traded missions gain in spacecraft processing as well as propulsive performance.

In 2013, NASA and the Swedish National Space Board (SNSB) outlined a collaborative Implementing Arrangement (IA) for the respective agencies to pursue increased HPGP technology maturation [7]. Each agency has been actively working the three principle objectives of this IA since its inception: 1) design, analyse, and manufacture a fully flight-like HPGP thruster in order to gather environmental and hot-fire life test data, 2) promote and advance LMP-103S Range Safety awareness and propellant handling capabilities, and 3) investigate and test LMP-103S propellant material effects and various other handling associated chemical properties. The IA is structured to reduce risk to performance, cost, and schedule in future HPGP thruster implementation and further advance the technical maturity critical for long-term investment in future NASA missions. Throughout the course of the IA, GSFC, SNSB, and EColgical Advanced Propulsion Systems (ECAPS), the HPGP technology owners, have collectively advanced HPGP thruster maturity in several meaningful ways. The HPGP thruster performance testing enables thorough evaluation of the readiness of the HPGP thrusters to meet upcoming NASA mission requirements. The investigations into LMP-103S chemical properties, including flashpoint testing, vapor profile, propellant tank fracture mechanics testing, and point-of-use propellant sampling at Range in order to confirm that the propellant meets specification, provide increased programmatic and system level confidence.

This paper focuses exclusively on the HPGP Engineering Qualification Model (EQM) 22 N thruster testing. Other objectives of the IA discussed above will be published at a later date, but are discussed here briefly for context and completeness in the IA discussion. The IA technology advancement goals enable HPGP technology mission proposals and utilization, positioning NASA to not only gain substantial knowledge and experience with HPGP technology, but additional insight into future implementation possibilities. The IA provides the ability to concentrate the technology maturation in a collaborative fashion and to gain first hand insight into the overall HPGP technology and LMP-103S propellant. It is implicitly acknowledged that flight technology development is challenging, both technically and programmatically, and NASA, SNSB, and ECAPS are working towards a common goal to systematically confront those challenges.

2. THRUSTER DESIGN

As stated above, trade studies to implement HPGP have been conducted for two NASA GSFC in-house missions, PACE and WFIRST. Each of these missions have different propulsion subsystem requirements, but similar thrust class engines (22 N). PACE is a sun-synchronous polar, Low Earth Orbit, Earth Science mission with major propulsive maneuvers conducted at End-of-Life for safe spacecraft system disposal. WFIRST is an Astrophysics mission at Sun-Earth L2 orbit, in which its foremost propulsive maneuvers are at Beginning-of-Life. Both PACE and WFIRST are designed to utilize a blow-down propulsion subsystem; however, PACE will use solely 22 N thrust class engines, and WFIRST will use both 22 N and 5 N thrust class engines. Together with the 1 N engine already in commercial use, the 5 N and 22 N thrust class sizes fulfil the needs of characteristic NASA Science Mission Directorate missions [8]. ECAPS, through PRISMA and the SkySat Constellation have already matured the 1 N thruster with multiple HPGP 1 N units currently performing on-orbit. The IA HPGP maturation effort, therefore has been focused on the 5 N and 22 N thruster designs. NASA GSFC Propulsion, in collaboration with ECAPS, developed mission specific thruster life testing requirements in order to set forth GSFC's desired test conditions and firing sequences. These environmental and hot-fire performance requirements were tested through an extensive campaign conducted on a HPGP 22 N flight-like EQM thruster (shown in Fig. 1). Through this testing the HPGP 22 N EQM thruster has demonstrated the robustness of the HPGP propulsion thruster technology and increased the Technology Readiness Level (TRL) by undergoing environmental testing (vibration and shock to qualification levels) as well as hot-fire performance life testing.

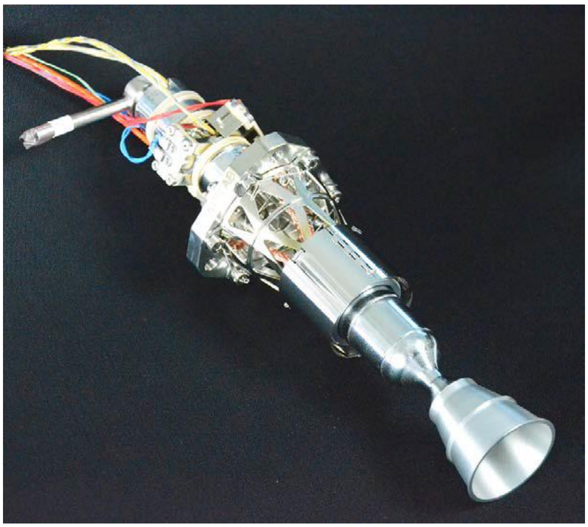

Figure 1. 22 N HPGP EQM

At the onset of the NASA/SNSB IA, ECAPS had TRL 4 Demonstrator (DM) versions of the HPGP 5 N and 22 N thrusters already built. NASA GSFC Propulsion developed HPGP thruster Statement of Work (SOW) and Specification (SPEC) documents for ECAPS to meet to advance the HPGP 5 N and 22 N thruster designs with the goal of ensuring that future evolutions would meet realistic NASA requirements for flight components. Furthermore, this arrangement allowed for NASA to identify and address the operational differences between HPGP and typical mono-propellant hydrazine propulsion components and systems. The SOW detailed the requirements for the HPGP thruster manufacturing effort, program management, quality, and workmanship standards. The SPEC documented the performance and environmental requirements to meet common NASA mission needs. The IA HPGP thruster SOW and SPEC attempted to represent a set of typical thruster requirements based on historical GSFC missions.

At the time these documents were written there was not a specific upcoming mission to use as a basis for outlining the HPGP thruster requirements, the MMS and GPM missions were chosen as models for thruster requirement development under the IA. Due to a perceived greater market interest, the initial priority was focused on the HPGP 22 N thruster. NASA GSFC has a standardized basic set of environmental (vibration and shock) mechanical requirements encompassing multiple launch configurations and vehicles (referred to as the Generalized Environmental Verification Specification). There are also governing programmatic guidelines for workmanship, quality, and contamination. These fundamental documents allowed for the definition of a representative basic requirement set germane to HPGP thruster design and construction. The more challenging requirements come from mission specific implementation for thruster operation, specifically pulse-mode vs steady state, duty cycles, and required propellant throughput.

In order to capture hot-fire thruster operation requirements for the IA development, past GSFC missions and ground testing operation were studied and a broad-spectrum “wish list” outlining a thruster that could perform across a large array of mission architectures was provided to ECAPS for consideration. While difficult to attain, it is ideal to have a robust thruster that can operate at both steady state and in pulse mode operation at any duty cycle, delivering repeatable high performance and long life. ECAPS worked to these operational goals and in 2015 advanced the HPGP 22 N thruster design to a TRL 5 configuration (Fig. 2). This version of the 22 N DM thruster included a qualified series redundant Flow Control Valve (FCV), flight-like thermal standoff and thrust chamber joint, and an improved injection scheme from the previous DM model.

Through this design and test iteration, the alignment to meet the NASA GSFC pulse mode performance capability was demonstrated. Table 1 displays the HPGP 22 N TRL 5 campaign totals and Figure 3 shows the pulse mode duty cycle mapping profile tested. In this testing, the thruster was fired at a range of duty cycles to a pulse count of 100. This operation allowed the thruster to reach thermal steady state from the pre-heat start temperature of 350 °C, which represents a thermal cycle. Post this demonstration testing, a formal Design Conformance Review was held at the ECAPS facility in Solna, Sweden in 2016 to evaluate the design, analysis and testing before outlining the EQM manufacturing plan. NASA GSFC programmatic and propulsion supported this technical interchange meeting.

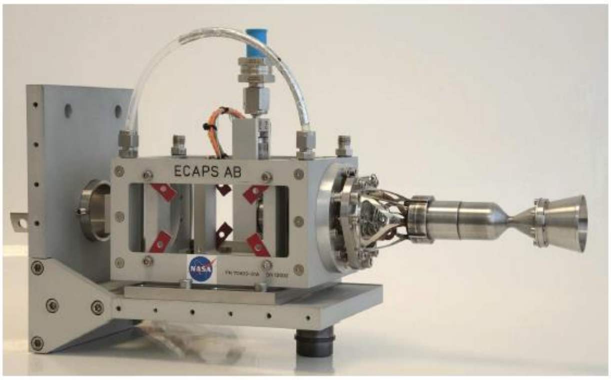

Figure 2. 22 N HPGP TRL 5 - #59B in Thrust Stand

Table 1. 22 N HPGP TRL 5 - #59 Test Totals

Demonstrated	
Propellant	LMP-103S Propellant
Propellant Throughput	10 kg
Burn Time	30 min
Longest Continuous Firing	180 sec (3 min)
Total Pulses	4000
Thermal Cycles	400

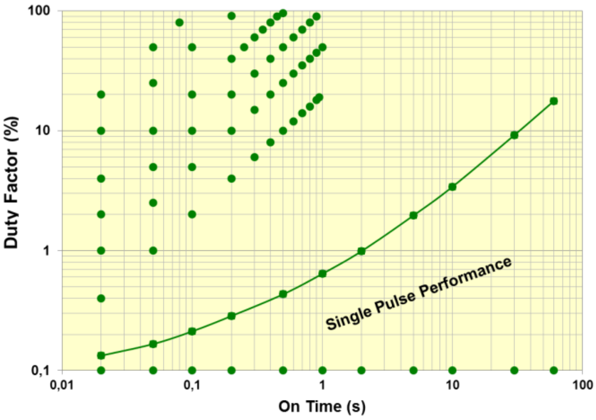

Figure 3. 22 N HPGP TRL 5 - #59B Pulse Mode Mapping

As testing on the TRL 5 unit progressed, NASA's PACE and WFIRST missions matured in their designs. NASA GSFC took this opportunity to revise the IA thruster SPEC and SOW to align with real upcoming mission needs. As the PACE propulsion subsystem requirements gained greater maturity faster, they were chosen to serve as the new baseline for the next HPGP 22 N EQM thruster design and qualification effort. The EQM test philosophy evolution is shown in Fig. 4. A PACE-specific version of the SOW and SPEC were drafted, using the IA HPGP thruster SOW and SPEC as a starting point. These new documents were then vetted by other PACE subsystems (e.g. electrical, thermal, avionics, and mechanical) in order to ensure that subsystem crossover requirements were properly codified in terms of the thruster design, development, manufacturing, and testing. Similarly, the WFIRST mission requirements will serve as the new baseline for the HPGP 5 N EQM thruster, which is nominally on track to be tested in 2018. A similar documentation vetting process will be conducted for the HPGP 5 N EQM thruster requirements. The overall intent is to define a realistic set of flight requirements for the development of the IA HPGP 5 N and 22 N engines to achieve. However, as the IA is a partnership in hydrazine alternative technology maturation and not contractual, the requirements identified within the SOW and SPEC documents are treated as design goals and not strict requirements.

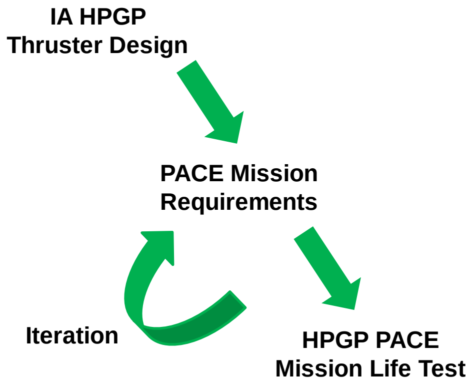

Figure 4. 22 N HPGP EQM – TEST PHILOSOPHY

3. TEST GOALS AND MANUFACTURING

Table 2 outlines the HPGP 22 N EQM principal performance and environmental test goals. These were derived using the PACE mission required propellant load and tank blowdown profile, flight thruster quantity, detailed Attitude Control Subsystem (ACS) maneuver simulations to characterize thruster operational duty cycle, and Flight Dynamics (FD) simulations to determine delta-V requirements. The PACE mission Propulsion, ACS, and FD engineering teams worked iteratively to frame the thruster hot-fire testing requirements, as each subsystem contribution was vital to the test matrix. The 2x Life requirement in Table 2 is indicative of the NASA GSFC Gold Rules for margin in phase A. The initial EQM test philosophy was to test two identical mission blowdowns in order to meet the 2x life requirement. Other general programmatic requirements, such as mechanical loads, thermal, electrical, workmanship, and quality were also included in the HPGP 22 N EQM manufacture and test goals. The environmental vibration and shock test requirements are presented in Table 2 as provided by the PACE mechanical. The random and sine vibration levels are standard and serve as generic mechanical guidelines; however, the shock load is enveloping of the Launch Vehicle requirements, with a PACE-specific propulsion configuration attenuation.

A manufacturing readiness review was held with NASA and ECAPS in May 2017, and the integration of the EQM thruster began in June 2017. The EQM thruster was fabricated according to newly developed flight-like ECAPS production line manufacturing and test procedures, developed for the EQM and 22 N thrust class engines. The HPGP 22 N EQM thruster completed assembly on June 17, 2017. This build timeframe included the requisite hardware workmanship inspections as the build process proceeded. All manufacturing was performed at ECAPS facilities in Solna, Sweden.

4. TEST HARDWARE

The HPGP 22 N EQM test article is shown in Fig. 5 on the Hot Fire test stand. The HPGP 22 N EQM inlet pressure range is a blowdown operation from 24 bar to 5.5 bar, with the nominal 22 N thrust provided at 24 bar. The EQM uses a series redundant FCV, propellant feed tube, injector, thrust chamber and nozzle assembly. The FCV has thermal hardware made up of two thermostats wired to a dual element heater that maintains valve temperatures during pre-heat and operation. In addition, there is a dedicated reactor heater for thruster pre-heat and a thermocouple for reactor heater temperature readout. The HPGP 22 N EQM thruster was built to be a flight-like test article, manufactured with flight production procedures and with flight qualified components.

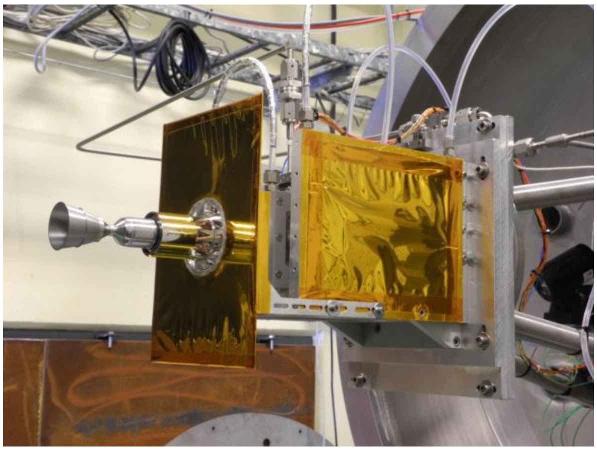

Figure 5. HPGP 22 N EQM – Hot Fire Test Stand

Table 2. 22 N HPGP 22 N EQM Test Goals – Performance and Environmental

Propellant	LMP-103S Propellant, Specification
Propellant Throughput	65 kg (Flight) / 130 kg (2x Life)
Thrust	22.9 N @ 24 bar 6.1 N @ 5.5 bar
Specific Impulse	242 sec @ 24 bar 232 sec @ 5.5 bar
Total Impulse	150,000 Ns (Flight) 300,000 Ns (2x Life)
Total Pulses	50,000
Impulse Bit	< 0.44 Ns (0.020 s minimum pulse width)
Blowdown Operation	24 – 5.5 bar
Duty Cycle	1 - 100 %
Longest Continuous burn	3600 seconds (45 minutes)
Sine Vibration	12.5 g's – 3 axis 2 octaves/min (5-100 Hz)
Random Vibration	14.1 grms - 3 axis 2 minutes per axis
Shock	1500 g's peak – 2 axis 2 shocks per axis

5. TEST PROGRAM

The objective of the EQM test program was to validate the thruster design and manufacturability with respect to a typical NASA GSFC mission. The PACE mission was selected as the benchmark to lay the foundational set of requirement goals, as listed in Tab. 2, for the HPGP 22 N EQM thruster. The test flow is shown in Fig. 6. The guiding principle was to plan and conduct a robust HPGP 22 N life-test highlighting that the design meets PACE mission requirements. This would comprehensively test the thruster, demonstrating the maturation of the thruster design and TRL to 6, and ultimately support the PACE HPGP propulsion subsystem trade study, pushing towards HPGP 22 N thruster mission qualification.

Performance and functional EQM cold testing was performed at the ECAPS facility in Solna, Sweden. EQM shock and vibration testing was performed at Innventia Transport Testing Center in Kista, Sweden. The shock tests were performed using the ECAPS in-house pyro-actuated shock table. The vibration tests were conducted using an electrodynamic shaker. The vibration test equipment used was an air cooled electrodynamic shaker of type IMV EM2605 Model J260-CE. The EQM thruster hot fire testing was performed in ECAPS Hot Firing Test Facility located at the Swedish Defence Research Agency (FOI) test range, Grindsjön, Sweden.

Through this program, the HPGP EQM 22 N thruster demonstrated steady state and pulse mode operational capability with increased propellant thruster throughput. This effort represents a significant accomplishment of comprehensive HPGP 22 N EQM life testing and furthers the HPGP technology advancement in order to meet typical NASA GSFC mission requirements.

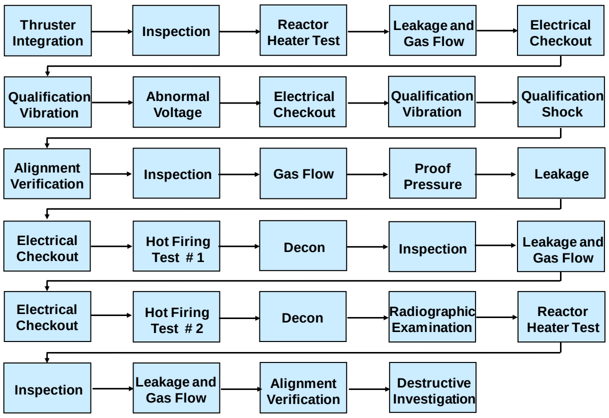

Figure 6. HPGP 22 N EQM – Test Flow

5.1. Cold Testing

Hardware inspections were conducted throughout the test program. For these tests, the EQM was visually inspected to verify all visual subcomponents were free of scratches, cracks, severe oxidation, and noticeable damage. After thruster integration, during the first inspection testing, the EQM physical dimensions and mass measurement were also performed to ensure that the EQM was in accordance with the HPGP 22 N EQM Interface Control Document (ICD). Visual inspections were recurrent throughout as the EQM thruster progressed in the test program as shown in Fig. 6.

Functional testing was also conducted throughout the EQM test program. These checks demonstrate compliance with the guidelines set forth in the HPGP 22 N EQM SPEC and the test results were trended over the course of the campaign. The functional testing included external leakage with the FCV set to open and the thruster plugged, FCV seat internal leakage, gas flow testing in order to verify no flow impedance through the thruster, and electrical testing (insulation and circuit resistance, FCV pull-in and drop-out voltages, and thermostat open/close verification). An "abnormal voltage test" was executed as planned on the EQM in which all electrical components were exposed to 40 VDC for 0.5 seconds. Directly following, an electrical checkout was made to verify no damage to the EQM.

Reactor Heater testing was performed at the beginning and end of the test program as seen in Fig. 6. This test was conducted in vacuum as required to characterize the reactor heater performance at different power levels. This pre- and post-hot fire reactor heater checkout tested the thermal effect of oxidation in regards to EQM pre-heat time to temperature at different power levels. Proof pressure testing and alignment verification were also competed in the EQM cold testing.

The FCV opening and closing response times were not measured during each functional test but were characterized at the FCV Acceptance Verification Procedure level prior to integration, during the EQM hot-fire testing, and post hot-fire testing at final inspection.

5.2. Environmental Testing

Environmental testing was conducted in the HPGP 22 N EQM test program in order to ensure the thruster's capability of meeting performance requirements after exposure to launch vehicle induced mechanical loading. The specific tests performed on the HPGP 22 N EQM thruster were low-level sine sweeps, sine and random vibration, and shock. Each of the dynamic tests was completed in each orthogonal axis. Sine sweep was performed before and after vibration and shock with the initial sine sweep establishing the reference to show compliance with fundamental frequency requirements. A post-test sine sweep verified that there was no discernible shift in fundamental frequencies. The sine sweeps were executed in each axis at 0.5 G acceleration over a 5 to 2000 Hz range, sweeping at two octaves per minute. Sine vibration testing was conducted to verify workmanship quality and to simulate launch vehicle loading conditions. The sine vibration testing was swept through the frequency range at two octaves per min as shown in Fig. 7. Random vibration test was conducted to demonstrate workmanship quality and to simulate launch vehicle aerodynamic environmental levels. Random vibration testing was performed at 120 seconds per axis as shown in Fig. 8. The EQM thruster is shown in the vibration test fixture in Fig. 9.

The EQM thruster was subjected to mechanical shock twice in the x-axis and twice in the z-axis. Due to the symmetric nature of the y and z-axis, the shock response was similar, and it was determined that the two hits in the z-axis was sufficient to verify the EQM design. The EQM thruster was slightly under-tested in the 500 – 900 Hz frequency range due to the characteristics of the shock table and HPGP 22 N EQM test fixture. Shock table test setup and calibration were performed using a thruster mass simulator in order to validate the shock response; however, the actual HPGP 22 N EQM shock response was slightly different than anticipated. This was the first time the 22 N thrust class size was shock tested using the fixture and table combination and performance is anticipated to be improved in future tests. The HPGP 22 N EQM shock profile is shown in Fig. 10 and the HPGP 22 N EQM is shown in the shock test fixture in Fig. 11.

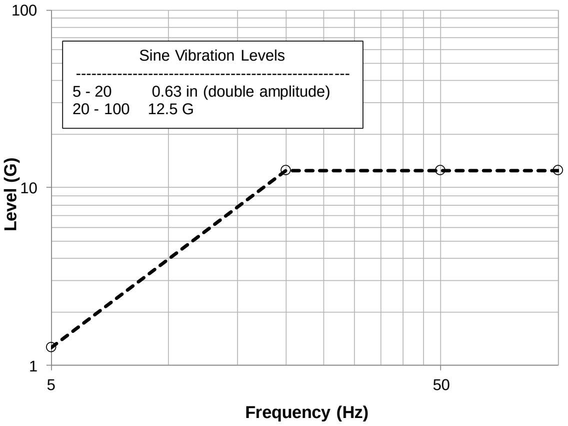

Figure 7. HPGP 22 N EQM – Demonstrated Sine Vibration

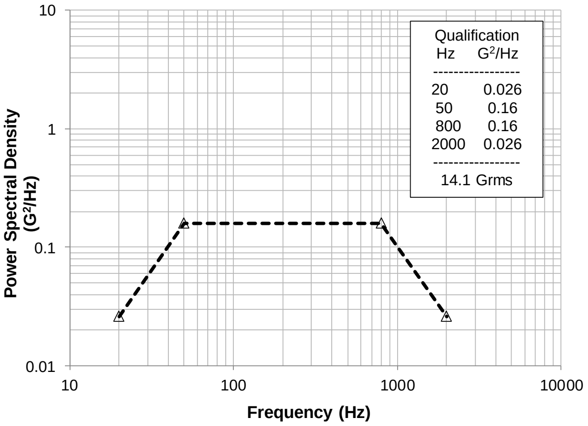

Figure 8. HPGP 22 N EQM – Demonstrated Random Vibration

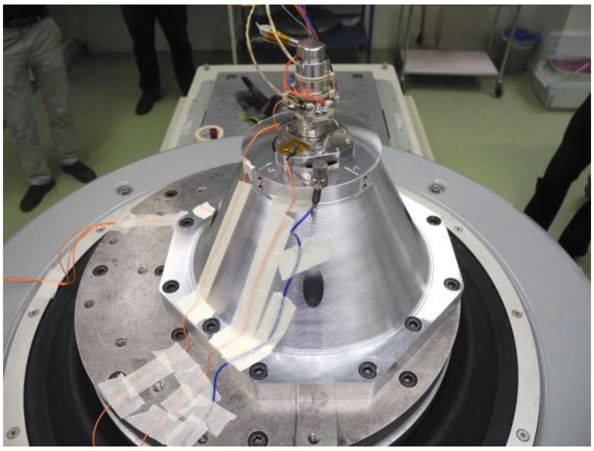

Figure 9. HPGP 22 N EQM – Vibration Fixture

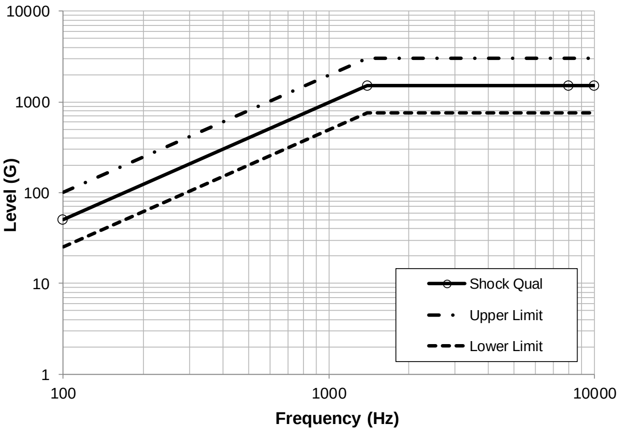

Figure 10. HPGP 22 N EQM – Shock Spectrum

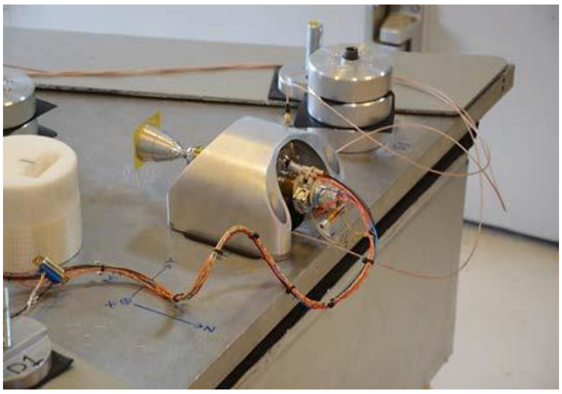

Figure 11. HPGP 22 N EQM – Shock Fixture

5.3. Hot Fire Testing

The HPGP 22 N EQM Thruster was hot fire tested to achieve the performance goals detailed in Tab. 2 and as derived by the SPEC. Figure 12 shows the HPGP EQM 22 N thruster in hot fire testing. The hot fire test matrix involved a mix of performance mapping and characterization firings, and a life test developed to represent PACE mission maneuvers and operational duty cycles. The PACE life test was comprised of initial on-orbit thruster checkouts, launch vehicle dispersions, orbit maintenance, and controlled re-entry. During the controlled re-entry testing phase, small momentum management firings were also tested. As seen in Fig. 6, two hot fire test campaigns were performed. The first was conducted just before the FOI summer facility shutdown, and covered performance mapping, characterization, and steady state firings. The second test battery started just after the facility was operational again and continued until the end of hot fire testing as described below.

5.4. End of Hot Fire

At approximately 53 kilograms of propellant throughput the HPGP EQM 22 N thruster performance began to slowly fluctuate off the nominal thrust and propellant flow rate. The 50 pulse count sequence was competed and toward the end of the train, the thruster regained near nominal thrust, propellant flow, and specific impulse. Further hot firing was halted in order to analyse the test data and perform visual inspections. After discussion and agreement between NASA GSFC and ECAPS, the HPGP 22 N EQM thruster was removed from the test stand in order to perform non-destructive testing and identify the root cause for the off-nominal performance. Radiographic inspection was performed, and it was determined that an internal retainer had become displaced at some point after initial assembly. Further analysis of the low-level sine sweep test data identified that the displacement occurred during the random vibration testing as evidenced by a small frequency shift that was not readily apparent until the team knew what they were looking for. This retainer geometry is being corrected by a straightforward modification to the design and will be verified with respect to structural integrity and qualification environments in the future.

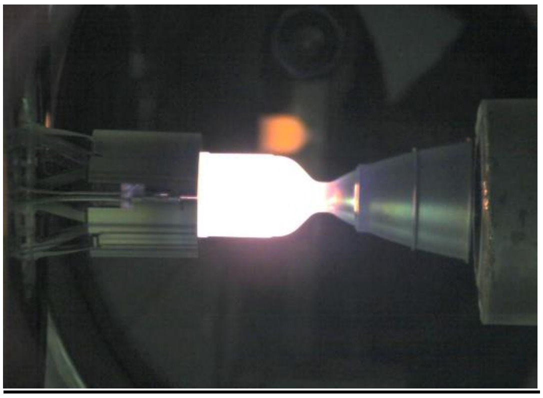

Figure 12. HPGP 22 N EQM – Hot Firing

6. Test Results

The measured thrust versus inlet propellant pressure for the HPGP 22 N EQM thruster is shown in Fig. 13 and the delivered steady state specific impulse is shown in Fig. 14. The pulse mode thruster operation is detailed Fig. 15 and is compared to the earlier HPGP 22 N DM TRL 5 thruster. The HPGP EQM 22 N thruster demonstrated ~ 203 seconds at 20% duty, and ~ 250 seconds at 90%. The demonstrated firing sequences are detailed in Fig. 16 and the tested blowdown profile in Fig. 17.

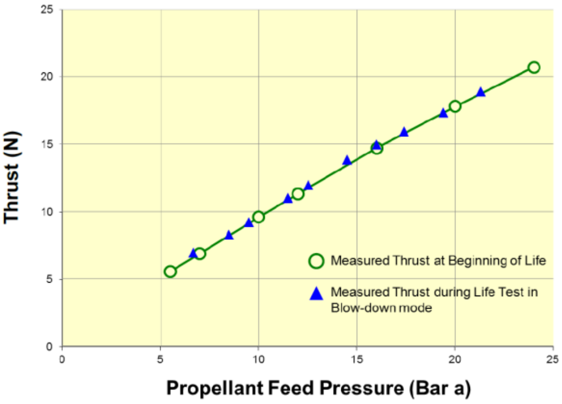

Figure 13. HPGP 22 N EQM – Thrust vs Propellant Inlet Pressure

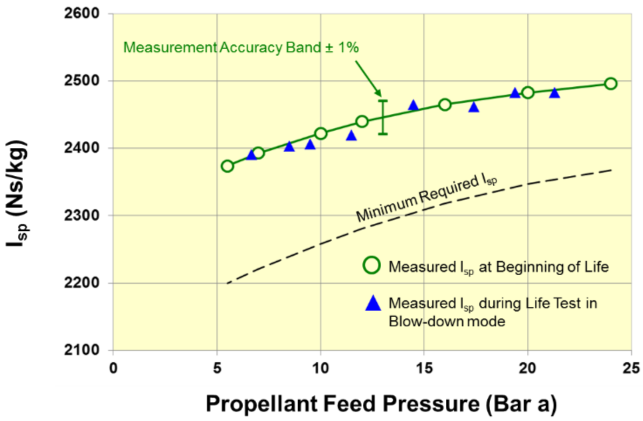

Figure 14. HPGP 22 N EQM – Specific Impulse vs Propellant Inlet Pressure

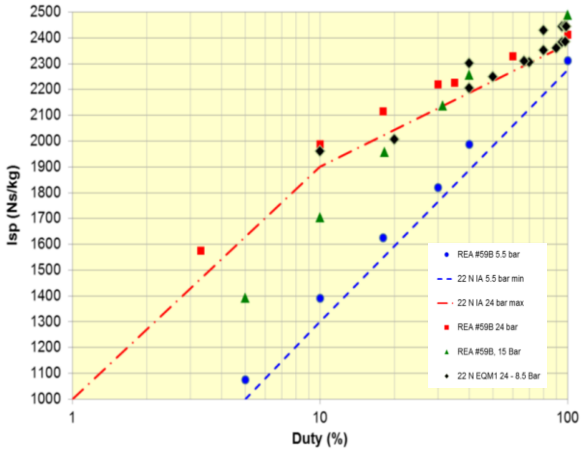

Figure 15. HPGP 22 N EQM – Pulse Mode Specific Impulse

Table 3 details the HPGP 22 N EQM testing totals in terms of the demonstrated performance and environmental test goals. The HPGP 22 N EQM experienced over 26,000 pulses, 292 thermal cycles from pre-heat temperature to the nominal firing temperature of 1550 °C, for a cumulative propellant throughput of 53 kg. Compared to the previous HPGP 22 N TRL 5 unit (identified as # 59B), the HPGP 22 N EQM accomplished significantly higher throughput and burn time with commendable performance.

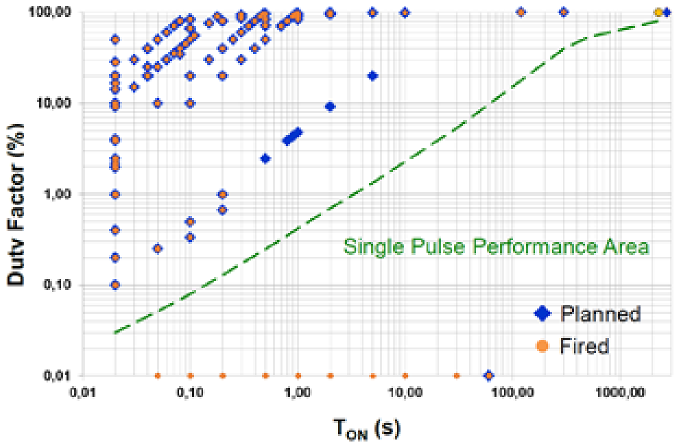

Figure 16. HPGP 22 N EQM – Demonstrated Firings

Table 3. 22 N HPGP EQM – Testing Totals

Demonstrated	
Propellant	LMP-103S Propellant, per LMP-103S Specification
Propellant Throughput	53 kg
Firing Sequences	292
Burn Time	180 min
Longest Continuous Firing	38 min
Total Pulses	26,481
Thermal Cycles	292 cycles from preheat to nominal firing temperature 25 cycles from room temperature to nominal firing temperature
Thrust	20.7 N @ 24 bar 5.5 N @ 5.5 bar
Specific Impulse	255 sec @ 24 bar 242 sec @ 5.5 bar
Minimum Pulse Width	0.020 seconds
Impulse Bit	0.35 Ns (24 bar, 0.020 pulse width)
Time to 90% Thrust	0.025 seconds
Drop to 10% Thrust	0.060 seconds
Inlet Pressure Range	24 – 5.5 bar
Valve Operating Voltage	Nominal 24 – 32 VDC, with 10 VDC holding

Figure 16. HPGP 22 N EQM – Demonstrated Firings

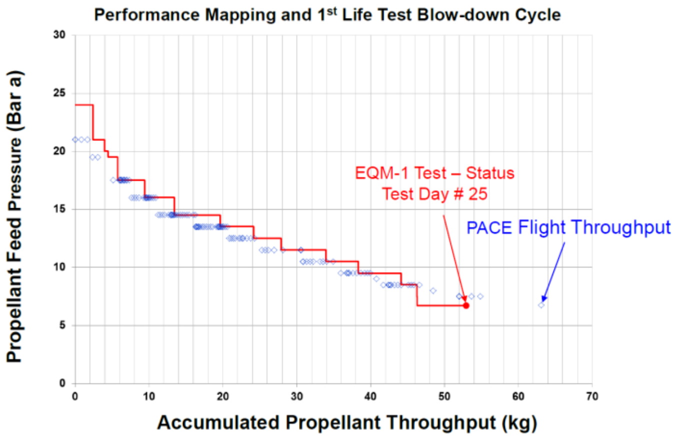

Figure 17. HPGP 22 N EQM – Blowdown profile

7. CONCLUSIONS

The first flight-like 22 N HPGP thruster was designed and built to substantiate the thruster design, build process, and testing with respect to the NASA GSFC PACE mission requirements under the auspices of the international IA. This test program was developed to comprehensively test the thruster, the technology, and foremost to increase the HPGP 22 N TRL level. The HPGP 22 N EQM was tested to environmental qualification levels prior to hot fire performance testing to represent the relevant end-to-end environment (launch to on-orbit operation). Prior to the discontinuation of the hot firing tests, the HPGP 22 N EQM had successfully met all hot fire performance requirements over a wide range of single, continuous, and pulse mode firings over a feed pressure range of 24 – 5.5 bar. The HPGP 22 N EQM post hot fire test #1 is pictured in Fig. 18. At this point in the test program, the EQM thruster had achieved TRL 6, as confirmed by NASA GSFC chief engineers.

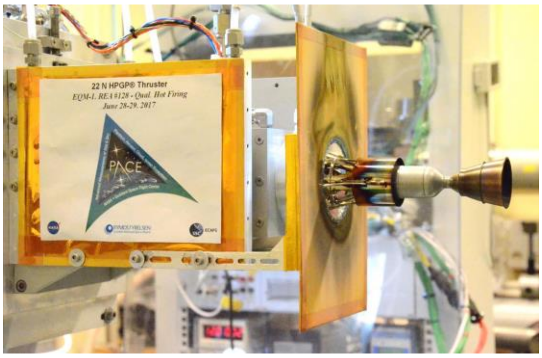

Figure 18. HPGP 22 N EQM – Post Hot Fire Test #1

The HPGP 22 N EQM test campaign has strengthened the HPGP 22 N thruster technology and design. Since this was the first flight-like design and manufacture, lessons were learned throughout the development, manufacturing and testing process. The most immediately significant being the retainer design that ultimately resulted in the end of hot fire. However, halting the test resulted in a fully intact thruster which allowed for full destructive testing to perform inspection post life. It has been concluded that the retainer displacement occurred during random vibration and can be corrected by a simple redesign. This updated design is in progress and will be integrated in the next HPGP 22 N EQM thruster build.

Of perhaps more significant benefit from this test program, however, was the opportunity to make both NASA GSFC projects and engineering, and other NASA Centers aware of the NASA SNSB IA work and the maturing HPGP technology. NASA GFSC personnel continuously supported the test program, gaining a significant benefit from the exposure. During the active test portion in 2017, the PACE observatory manager, PACE spacecraft systems engineer, and Safety and Mission Assurance Chief travelled to the ECAPS facility to meet with ECAPS and receive first hand test briefings, greater familiarity with the LMP-103S propellant manufacturing and toured the hot fire facility as shown in Fig. 19. In addition, the WFIRST observatory manager and propulsion lead have had the opportunity to visit the ECAPS facility. The NASA GSFC Propulsion Branch Head has been involved in the IA testing since 2015, and has been fortunate to follow the HPGP technology maturation. Pushing forward to HPGP infusion on a mission, this type of involvement of the NASA GSFC project, systems, and mission assurance communities is essential to realizing a future HPGP flight opportunity.

In response to the ongoing IA work and other green propulsion efforts currently being pursued at other NASA Centers, a green propulsion stakeholders organizing structure is in work as described below.

Figure 19. NASA GSFC PACE Personnel visit ECAPS Hot Fire Facility – Post Hot Fire Test #1

8. NASA GREEN PROPULSION EFFORTS AND INTEREST

As an Agency, NASA has demonstrated an interest in hydrazine alternative technologies, and specifically HPGP, since 2011. Agency efforts, however, have not been particularly well coordinated amongst the various NASA Centers. In the past year, however, there has been a concerted effort to change that. In the Spring of 2017 the NASA Chief Engineer organized the Chemical Propulsion Subcapability Management (CPSM) effort with the goal of efficiently and effectively utilizing existing and emerging Agency chemical propulsion capabilities across the multiple Centers. This CPSM effort was also specifically tasked with addressing the need for greater coordination and unified direction for Agency work in the field of hydrazine alternative technology (colloquially referred to as Green Propulsion). To this end, the Green Propulsion Working Group (GPWG) was established, focusing on the coordination and advancement of Green Propulsion efforts for the Agency.

The Green Propulsion Working Group is chaired by a representative from Marshall Space Flight Center (MSFC) and Co-chaired by a representative from Glenn Research Center (GRC). GSFC also has representation on the working group as a key stakeholder and implementer for Green Propulsion flight systems. One of the first products the GPWG will be producing in Spring 2018, is the NASA Green Propulsion Technology Development Roadmap. This Roadmap is an initial attempt to outline the context for Green Propulsion at the Agency and seeks to achieve three goals:

1) Establish Agency Vision for Green Propulsion
2) Provide Guidance to Focus Energies and Resources
3) Knowledge Archiving, Distribution and Utilization

The NASA Roadmap focuses Agency investment in Green Propulsion in a way that is agnostic to any specific propellant formulation. It lays out hurdles to making the technology flight infusion-ready (accurate plume modelling, ignition power and techniques, throughput capability) and attempts to address some of the technical challenges common amongst the emerging technologies (material properties, response time, performance modelling). Additionally, the Roadmap addresses infrastructure needs such as propellant supply challenges and manufacturing techniques.

The focus of the Roadmap is on relatively small thrust classes (100 mN, 1 N, 5 N, 22 N) in the near term (3 - 5 years) with expansion to the 50 N, 110 N, and 440 N thrust classes over time (5 – 10 years). It is anticipated that the small satellite market is the most likely user set that would be interested in embracing a new propellant technology as demonstrated by the commercial SkySat constellation of satellites using HPGP. As budgets become constrained, small satellites are being considered for more and more demanding roles, often requiring innovative solutions. This is a prime area where low toxicity, high energy propulsion systems could find welcome opportunities in both the public and private sectors.

The GPWG is also working to foster more partnerships in the Green Propulsion arena. These include intra-NASA partnerships between operating Centers, inter-agency partnerships between NASA and other U.S. Government agencies, public-private partnerships between NASA and private commercial entities, and international partnerships with space agencies and companies across the planet. There is an understanding that it will be through these partnerships that Green Propulsion technology can be brought to bear rapidly and widely across the global aerospace industry.

9. WAY FORWARD

This work advances the test, analytical, and risk reduction activities for candidate green propellant LMP-103S and HPGP technology. NASA GSFC will continue to pursue risk reduction activities in order to capitalize on potential infusion mission opportunities and fully comprehend propellant and thruster performance, through the NASA-SNSB IA.

The HPGP 5 N and 22 N thrusters will be updated to incorporate the lessons learned during this test campaign. The 5 N is next to be tested in summer 2018, and all requisite design and manufacturing updated will be implemented. The HPGP 22 N thruster design and manufacturing will follow in parallel, and the next HPGP 22 N EQM will also include anything identified in the 5 N EQM test campaign. Additionally, anything learned from the continued on-orbit commercial use of the 1 N thrusters will be incorporated going forward.

ACKNOLEDGEMENTS

The authors wish to acknowledge the support from the NASA GSFC propulsion, specifically Ms. Caitlin Bacha, Dr. Eric Cardiff and Dr. Rich Driscoll, the PACE and WFIRST Missions, SNSB, and all co-workers from ECAPS, Swedish Defence Research Agency, and NASA MSFC and GRC.

REFERENCES

[1] Cardiff, E., Mulkey, H. W., and Bacha, C., An Analysis of Green Propulsion Applied to NASA Missions, Space Propulsion 2014, Cologne, Germany (19-22 May 2014).

[2] Mulkey, H. W., and Rao, A., HPGP Mission Trades, Pathways Beyond Low Earth Orbit In-Space Chemical Propulsion, Technical Interchange Meeting, Huntsville, AL, (4-6 April 2017).

[3] Anflo, K., “Concluding a 5 year In-Space Demonstration of an ADN-Based Propulsion System on PRISMA,” *Space Propulsion 2016 3124919,* Rome, Italy, 2-6 May 2016.

[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., and Anflo, K. "On-Orbit Operation and Performance of Ammonium Dinitramide (ADN) Based High Performance Green Propulsion (HPGP) Systems", 53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2017-4673)

[5] Mulkey, H. W., Miller, J., and Bacha, C., "Green Propellant Loading Demonstration at U.S. Range", 52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2016-4576)

[6] Anflo, K., Thormählen, P, Ferring, S., Friedhoff, P., Mulkey, H. W**.,** Bacha, C. E., and Conomos, H., “High Performance Green Propulsion On the Way for Three Launches from Three Continents,” *Space Propulsion 2016 3124920,* Rome, Italy, 2-6 May 2016.

[7] Mulkey, H. W., Bacha, C., Anflo, K., Persson, M., Dinardi, A., NASA and SNSB Implementing Arrangement Status, Green Monopropellant Alternatives to Hydrazine, Technical Interchange Meeting, Huntsville, AL, (3-4 August 2015).

[8] Bacha, C., Johnson, C., Johnson, M. A., Robinson, J. W. and Deans, M.C., “A Systems Approach for the Transition of NASA Missions to Green Propulsion,” *Space Propulsion 2016 3125325,* Rome, Italy, 2-6 May 2016.