



Green Propulsion Advancement and Infusion

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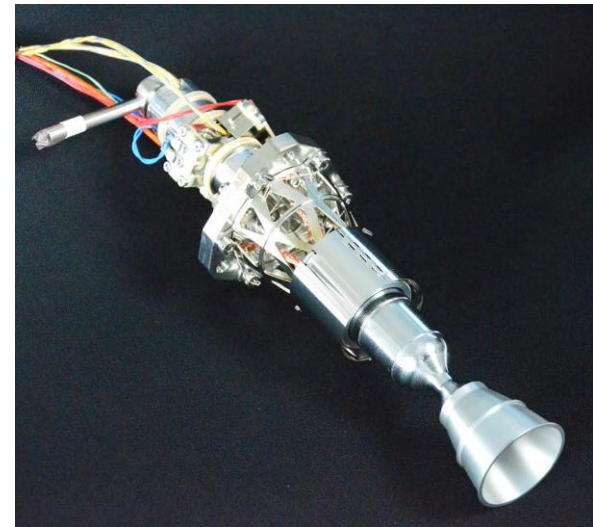
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Green Propulsion

- Meaning
 - Low toxicity, non hazardous hydrazine alternative propulsion
 - Increased performance and density versus monopropellant hydrazine
 - Easier and safer handling compared to hydrazine
- Potential Benefits
 - **Reduce propellant mass and wet mass**
 - **Increase ΔV**
 - **Increase payload mass capability**
 - **Reduce tank volume requirements**
 - **Range processing simplification**
 - **Reduce cost and schedule**
- Challenge:
 - To profit from the improved performance, the thrusters must demonstrate higher throughputs than currently shown
 - Infusion - perceived programmatic risk



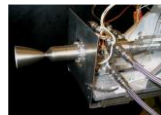
HPGP 22N Thruster – TRL 6



Background- Path to GSFC SMD Trades



PRISMA In-Space Demonstration
HPGP 1N Thruster TRL 7 – 9



2010

PRISMA Launched
Yasney, Russia
HPGP System
2 x 1N Thrusters

HPGP Thruster and
Technology Development
1997 – Present

2011

HPGP 22N
Thruster TRL 5

PRISMA HPGP-5
on-orbit testing

ECAPS Visit to
GSFC and WFF

LMP-103S US DOT
Certification 1.4S

2012

NASA Green
TIM at KSC

HPGP 5N
Thruster TRL 5

ECAPS awarded SkySat-3
Propulsion Module

NASA – SNSB
IA Development



IA Kickoff
Meeting

NASA Green
Propulsion
STMD TDM AO

HPGP 5N
Thruster TRL 5
16 Proposals

NASA STMD TDM awarded
GPIM AF-M315E System
5 x 1N Thrusters

2013

SMD Mission
Survey

HPGP 5N Thruster Testing
LMP-103S Blending
ATK Elkton

NASA – SNSB
IA Finalized

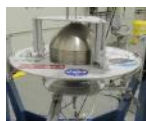
PACE HPGP
Mission
Trade #1

2014



ECAPS awarded
SkySat 12x
HPGP systems

Discussions
with Moog
regarding Tank
Loan – JPC 2014



HPGP 22N
Thruster
TRL 5+



GSFC – WFF
GPLD GOWG - 1

GSFC – WFF
GPLD GOWG - 5

GSFC – WFF
GPLD TRR



2015

NASA – SNSB
IA Implementation
Finalized

NASA – ECAPS
WFF Range TIM

GPLD - IRAD
Selected

SkySat-3 HPGP
propulsion module
delivered

NASA – SNSB
ECAPS
TIM

LMP-103S CE
certification
issued

ESA LMP-103S
Space Qualification
Initiated



2016



SkySat-3 Launched
SHAR India
HPGP System
4 x 1N Thrusters

PACE HPGP
Mission
Trade #2



NASA
ECAPS
Thruster
TIM

SkySat- 4-7 Launched
CSG, French Guiana
HPGP System
4 x 1N Thrusters



Orbital ATK and
ECAPS sign
agreement on
HPGP Technology

NASA
SNSB
ECAPS
Thruster
DCR

2017



Tank Fracture
Mechanics



HPGP 22N Thruster
Long Life Testing
TRL 6



SkySat- 8-13 Launching
VAFB USA
HPGP Propulsion System
4 x 1N Thrusters



Implementing Arrangement

Motivation: NASA is seeking green propulsion alternatives to hydrazine to **decrease environmental hazards and pollutants, to reduce operational hazards, to shorten spacecraft processing times and to increase propellant performance**. NASA is interested in conducting initial testing of the ECAPS HPGP technologies with a particular emphasis on thruster performance between LMP-103S and monopropellant hydrazine; life cycle cost assessment, as well as compliance of LMP-103S with Range safety and transportation requirements in the United States.

Implementation: The National Aeronautics and Space Administration (NASA) of the United States of America and the Swedish National Space Board (SNSB) of the Kingdom of Sweden; recognizing a mutual interest in the exploration and use of outer space for peaceful purposes and over three decades of successful space cooperation between the Implementing agencies; have outlined a collaboration contained in the Implementing Arrangement (IA) in which the agencies will perform initial testing for spacecraft applications of High Performance Green Propulsion (HPGP) technologies.

IA Signed: Sept 2013 (3-year duration)
IA Extended: Sept 2016 (3-year extension)
NASA dedicated Point of Contact – GSFC

IA Guiding Implementation

IA NASA/SNSB-HPGP Overarching SOW
IA NASA/SNSB-HPGP Thruster SOW
IA NASA/SNSB-HPGP Thruster SPEC



GSFC – IA Risk Reduction

- HPGP risk reduction activities investigated the following:
 - Loading Demonstration → Handling and Range Acceptance
 - Successfully Completed Dec 2015
 - First LMP-103S handling / loading at U.S. Launch Range, WFF
 - NASA GSFC Propulsion personnel managed all aspects of the operation
 - Gained first-hand knowledge of LMP-103S handling through loading operations
 - Direct comparison to N_2H_4 loading from recent hydrazine-based missions
 - Global Precipitation Measurement (GPM)
 - Magnetospheric Multiscale (MMS)
 - Tank Fracture Mechanics → Tank Qualification
 - First round complete – Test performed in GSFC Area 400
 - Handling benefit further validated through loading and decontamination
 - KSC/GSFC collaboration
 - LMP-103S Chemical Property Data
 - WSTF has LMP-103S propellant and testing is on-going
 - 22N Thruster Long Life Testing → Performance Data
 - **22N test campaign**



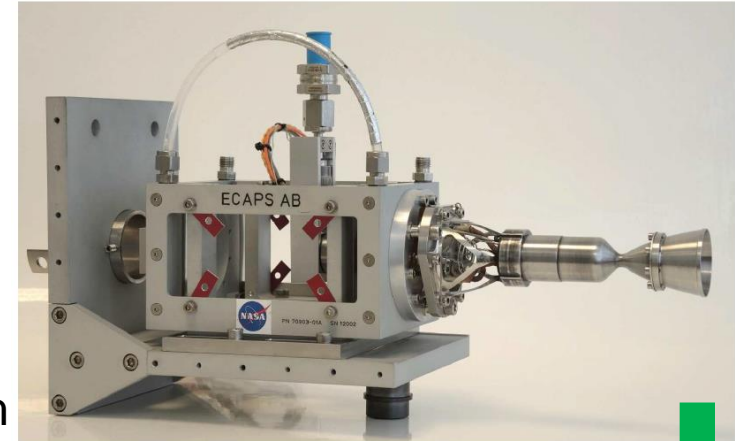
IA HPGP 22N Thruster Design Iteration

- **IA Thruster Design**

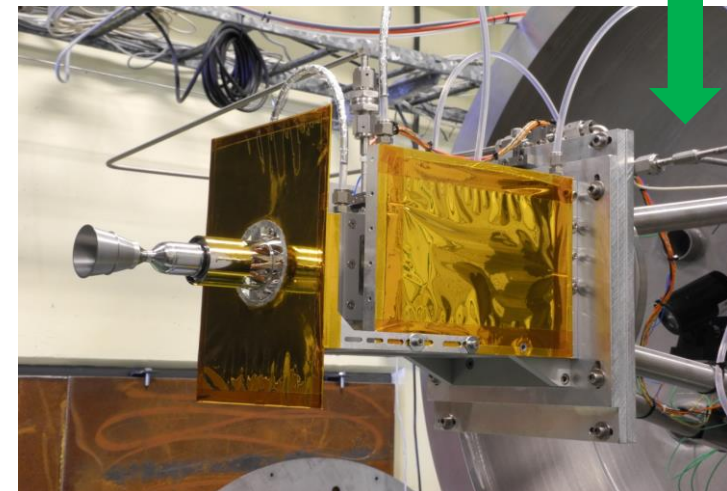
- In order to meet GSFC mission requirements for a typical SMD mission, ECAPS has been iterating on the IA HPGP 22 N thruster design
 - Guided by GSFC IA Thruster Specification and Statement of Work
- ECAPS actively hot-fire testing the 22 N thruster during the timeframe of the IA Design review Technical Interchange Meeting in March 2015
- ECAPS finalized IA thruster design – Frozen
- Formal Design Conformance Review – 2016

- **Plankton Aerosol Cloud ocean Ecosystem (PACE) 22N HPGP Thruster Design**

- IA Thruster SOW and SPEC assessed for PACE requirements
- Formal CM review by PACE Spacecraft subsystems
- Engineering Qualification Model (EQM) complete – June 2017



HPGP 22 N – TRL 5



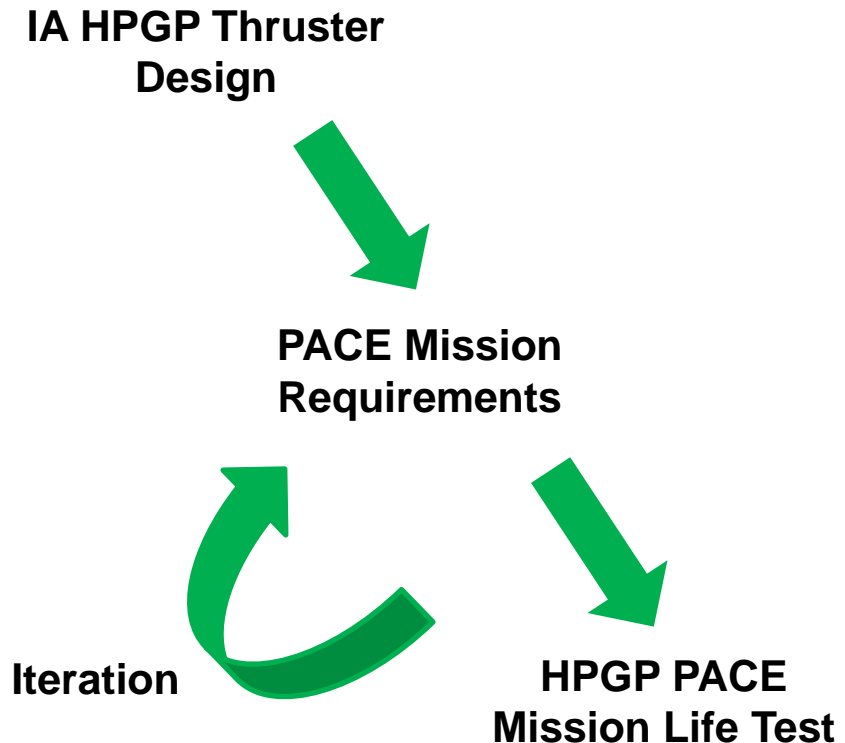
HPGP 22 N EQM – Flight



HPGP 22N PACE Specific Life-Test

GOAL: Plan and conduct a robust HPGP 22N life-test meeting PACE requirements, in order to comprehensively test HPGP 22N thruster

- Propellant Throughput
 - Tank volume
 - Thruster quantity
- ACS Simulations
 - Thruster Duty Cycle
- FD Simulations
 - DV required
 - SK and De-Orbit
- Other Requirements
 - Interfacing subsystems
 - Quality



HPGP 22 N EQM – Test Philosophy

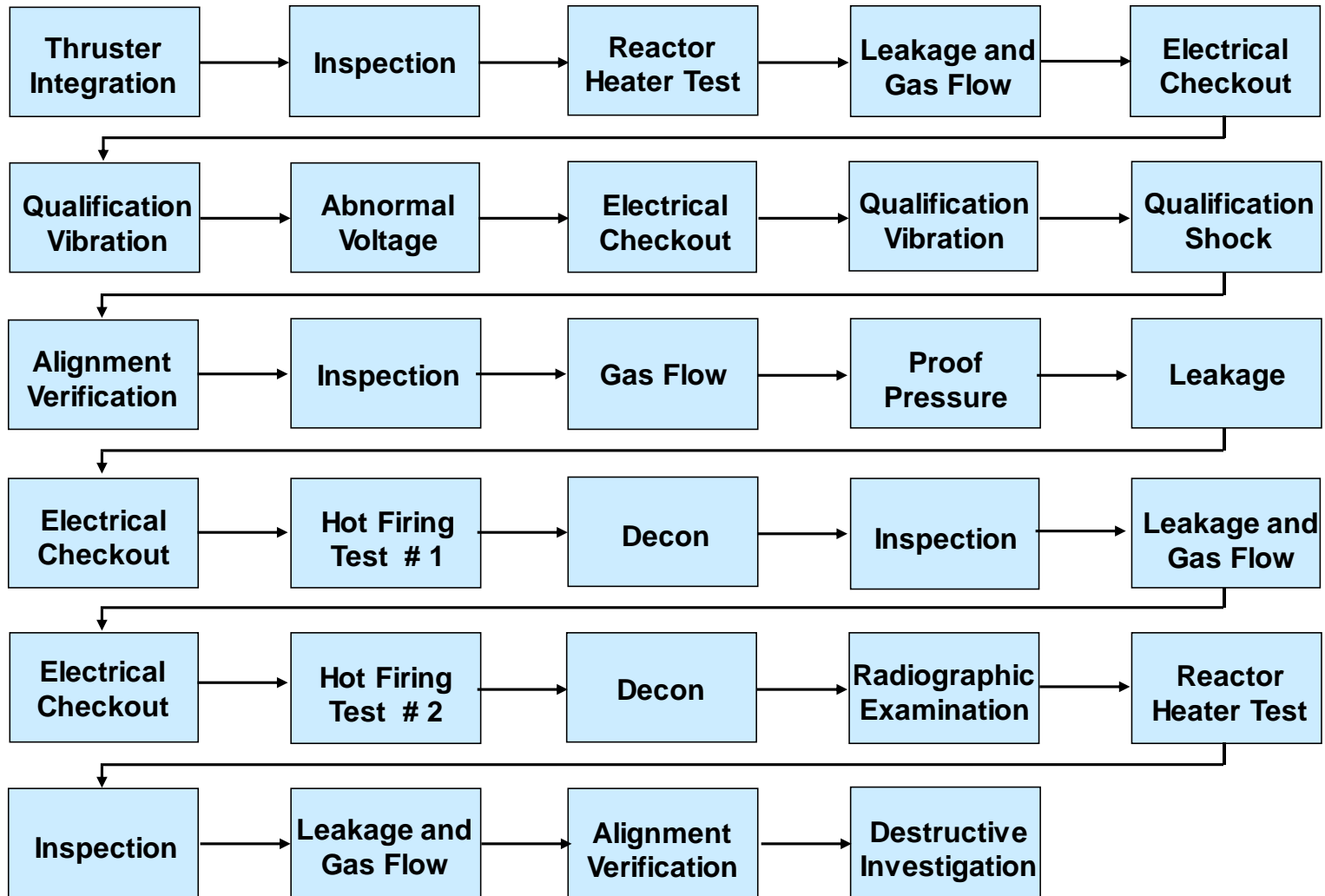


HPGP 22N EQM Test Goals

Propellant	LMP-103S Propellant, per 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	0.020s 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

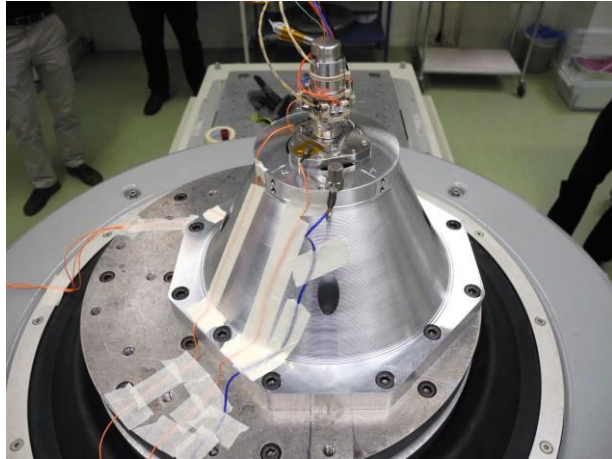


HPGP 22N EQM Test Program

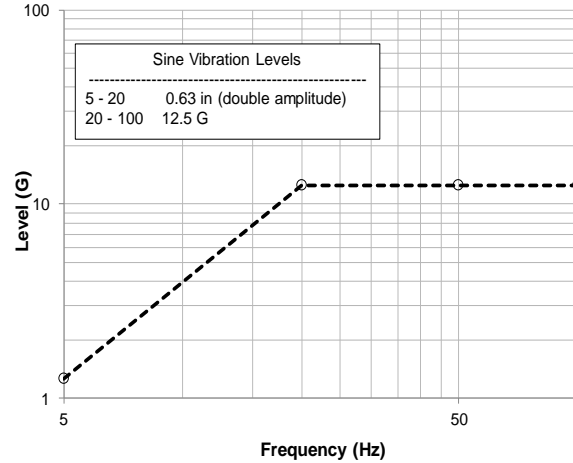




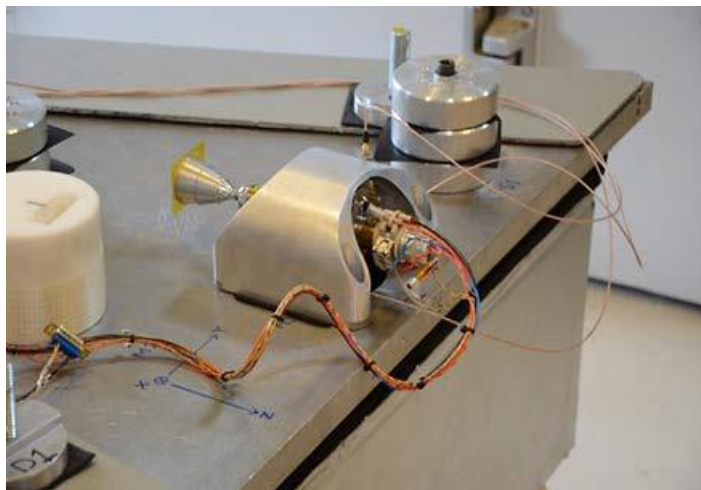
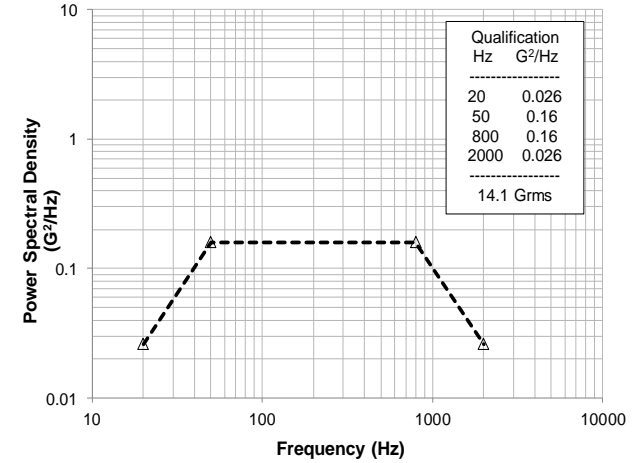
Environmental Testing – Vibration



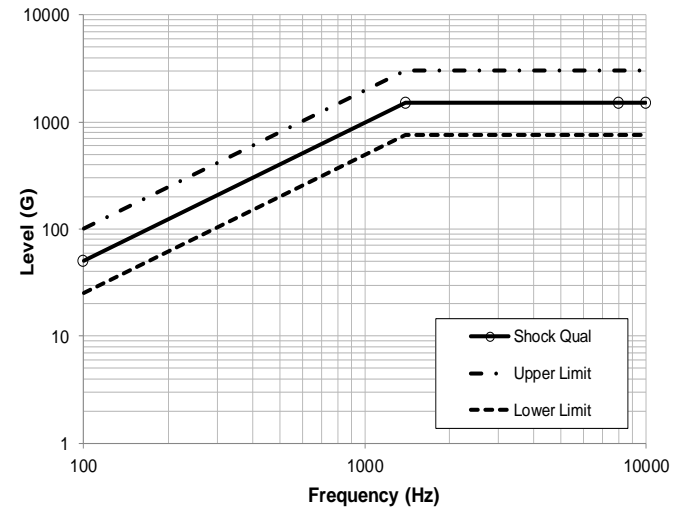
HPGP 22 N EQM – Vibration Fixture



HPGP 22 N EQM – Demonstrated Sine and Random Vibration



HPGP 22 N EQM – Shock Fixture

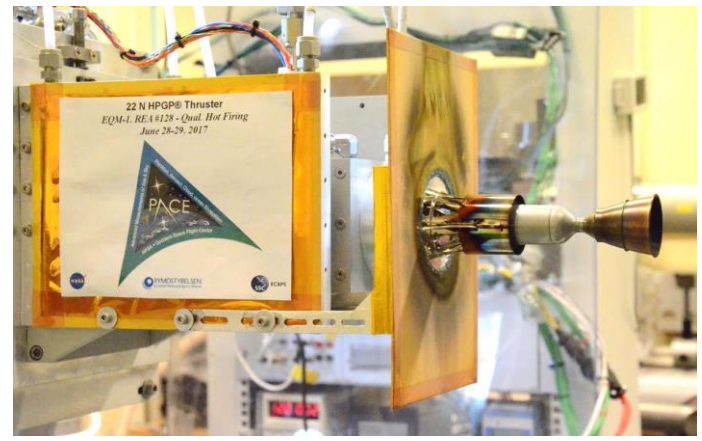
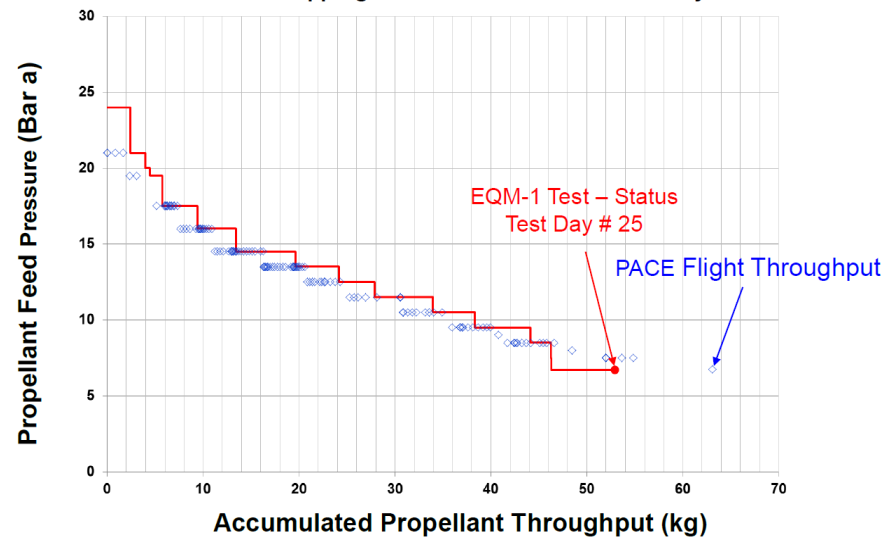


HPGP 22 N EQM – Shock Spectrum

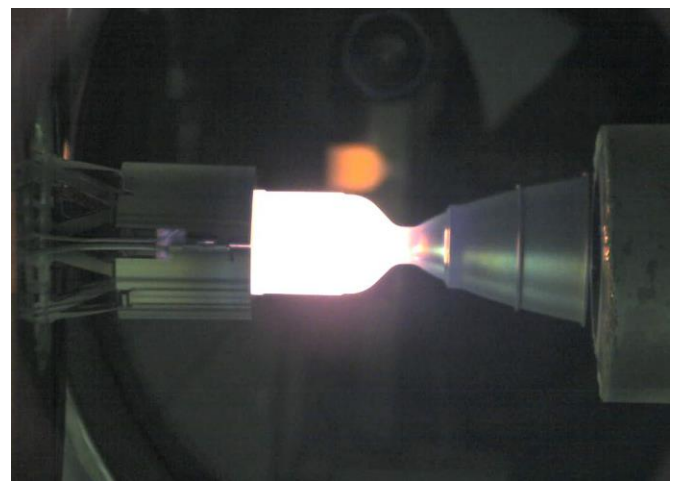


HPGP 22N EQM – Hot Fire

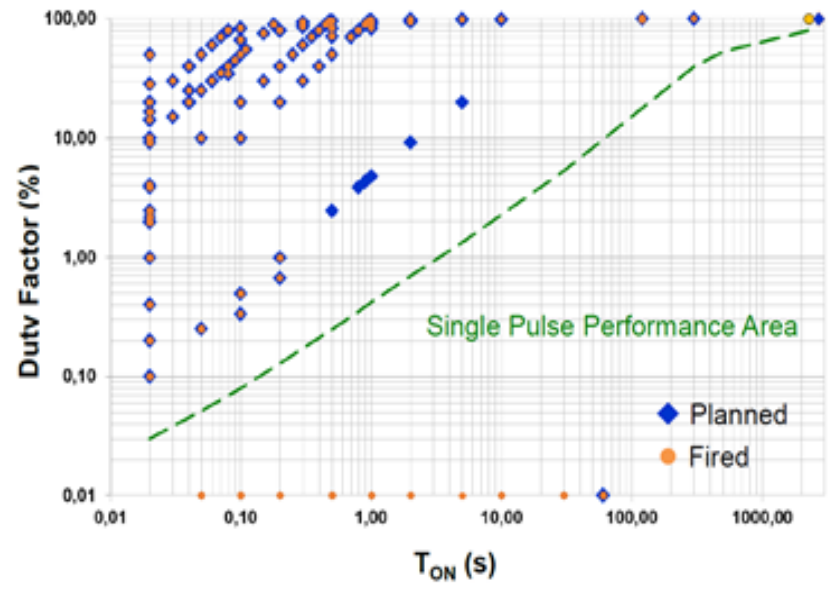
Performance Mapping and 1st Life Test Blow-down Cycle



HPGP 22 N TRL 6 Thruster – Post Hot Fire Test #1

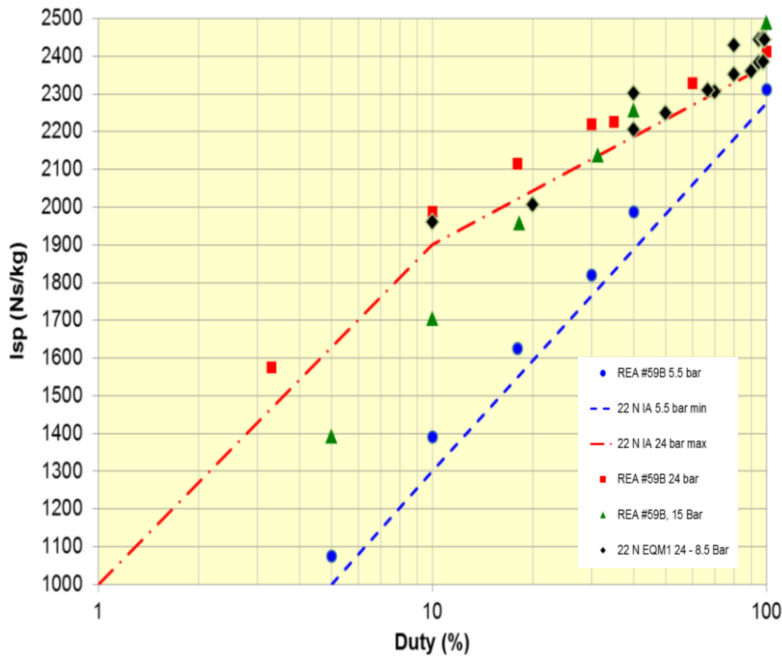


HPGP 22 N EQM – Hot Firing

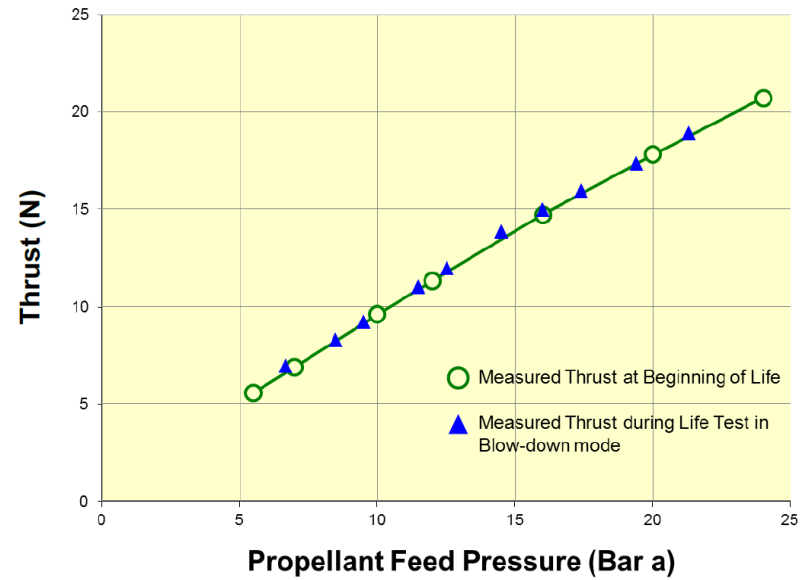




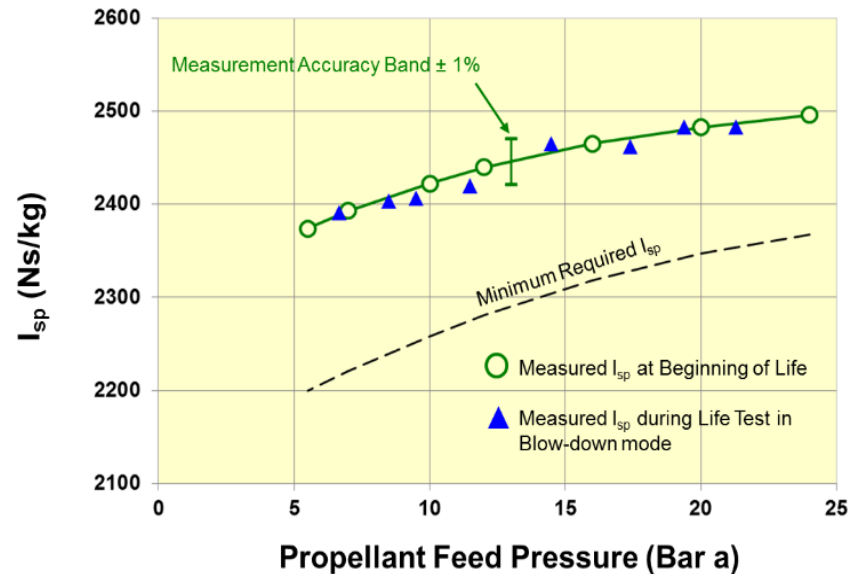
Performance



HPGP 22 N EQM – Pulse Mode Specific Impulse



HPGP 22 N EQM – Thrust vs Inlet Pressure



HPGP 22 N EQM – Specific Impulse vs Inlet Pressure



Test Conclusion

- End of Hot Fire
 - Anomaly observed at approximately 53 kg of LMP-103S throughput
 - Off nominal thrust and propellant flow rate fluctuations
- Further hot fire testing was halted in order to perform analysis of test data and perform a visual inspection
- After agreement with NASA GSFC, the HPGP 22N EQM thruster was removed from the test-stand in order to perform non-destructive investigation and determine the root cause for the off-nominal performance.
- Halting the test resulted in a fully intact thruster which allowed for full destructive testing to perform inspection post life.
- Radiographic inspection was performed, and it was determined that an internal retainer had become displaced at some point after initial assembly.
 - This retainer geometry is being corrected by a straightforward modification to the design



HPGP 22N EQM – Demonstrated Totals

Propellant	LMP-103S Propellant, per specification
Propellant Throughput	53 kg
Firing Sequences	292 kg
Burn Time	180 min
Longest Continuous Firing	2280 seconds / (38 minutes)
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
Total Impulse	116,434 Ns
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
Duty Cycle	<1 - 100 %
Valve Operating Voltage	Nominal 24 – 32 VDC, with 10 VDC holding



Conclusions

- The first flight-like HPGP 22 N thruster was designed and built to substantiate the thruster design, build process, and testing 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.
 - 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
- This work advances the test, analytical, and risk reduction activities for candidate green propellant LMP-103S and HPGP technology.



Conclusions

- 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.



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



NASA GSFC Propulsion Personnel visit ECAPS Hot Fire Facility – During Hot Fire Test #2



HPGP Thruster Path Forward

- The HPGP 5 N and 22 N thruster designs will be updated to incorporate the lessons learned during this test campaign
- The HPGP 5 N EQM is next to be tested in summer 2018, and all requisite design and manufacturing updates will be implemented into the design and build process.
- 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.

NASA GSFC will continue to pursue risk reduction activities in order to capitalize on potential mission infusion opportunities and fully comprehend propellant and thruster performance, through the NASA-SNSB IA.



NASA's Green Propulsion Focus

- As an Agency, NASA has recognized the need for better internal coordination and collaboration on Green Propulsion.
- In response to this need, the Green Propulsion Working Group (GPWG) was formed
- The group is chaired by NASA Marshall Space Flight Center (MSFC) and co-chaired by NASA Glenn Research Center with additional representation from NASA Goddard Space Flight Center (GSFC).
 - MSFC and GRC focus on technology development, investment, and maturation
 - GSFC provides mission infusion and technology “pull” element
 - NASA Ames Research Center (ARC) and the Jet Propulsion Laboratory (JPL) have recently been invited to the group
- Working Group is interested in engaging on any viable ionic liquid “hydrazine replacement” propellant technologies, regardless of organization or national origin



Agency Roadmap

- The Working Group has written a Green Propulsion Roadmap for the Agency to:
 - Establish an Agency Vision for Green Propulsion
 - Provide guidance for focus energies and resources
 - Support knowledge archiving, distribution, and utilization
- The Roadmap identifies hurdles to making the technology broadly infusion-ready for NASA missions of all classes and attempts to provide focus for technical challenges common amongst the currently emerging technologies
- Primary focus is on relatively small scale thrust classes (100 mN to 22 N) in the near term as these are likely to have the shortest path to mission infusion
- The Working Group is also attempting to foster more partnerships in Green Propulsion
 - Intra-NASA (Center to Center)
 - Inter-Agency (NASA to other U.S. Government Agencies)
 - Public-Private (NASA to U.S. commercial interests)
 - International (NASA to foreign government or commercial entities)



Acknowledgements

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- NASA MSFC and GRC