Green Propulsion Advancement and Infusion

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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 $\Delta V$
  – 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
Background - Path to GSFC SMD Trades

2010
- PRISMA Launched
  Yasney, Russia
  HPGP System
  2 x 1N Thrusters

2010
- HPGP Thruster and
  Technology Development
  1997 – Present

2011
- HPGP 22N
  Thruster TRL 5

2011
- PRISMA HPGP-5
  on-orbit testing

2011
- ECAPS Visit to
  GSFC and WFF

2011
- LMP-103S US DOT
  Certification 1.4S

2012
- NASA Green
  TIM at KSC

2012
- NASA Green
  Propulsion
  STMD TDM AO

2012
- 16 Proposals

2012
- NASA STMD TDM awarded
  GPIM AF-M315E System
  5 x 1N Thrusters

2012
- Discussions with Moog
  regarding Tank Loan – JPC 2014

2013
- HPGP 22N
  Thruster TRL 5+

2013
- NASA – SNSB
  IA Development

2013
- ECAPS awarded SkySat-3
  Propulsion Module

2013
- NASA – SNSB
  IA Development

2013
- NASA – ECAPS
  WFF Range TIM

2013
- GPLD - IRAD
  Selected

2013
- SkySat-3 HPGP
  propulsion module
  delivered

2015
- NASA SNSB
  ECAPS TIM

2015
- HPGP 22N Thruster Long Life Testing
  TRL 6

2015
- Tank Fracture
  Mechanics

2016
- SkySat-3 Launched
  SHAR India
  HPGP System
  4 x 1N Thrusters

2016
- NASA ECAPS
  Thruster TIM

2016
- SkySat- 4-7 Launched
  CSG, French Guiana
  HPGP System
  4 x 1N Thrusters

2016
- Orbital ATK and
  ECAPS sign
  agreement on
  HPGP Technology

2017
- NASA SNSB
  ECAPS
  Thruster DCR

2017
- ESA LMP-103S
  Space Qualification
  Initiated
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 N₂H₄ 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

• 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
**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 22N EQM Test Goals

<table>
<thead>
<tr>
<th></th>
<th>LMP-103S Propellant, per specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Propellant Throughput</strong></td>
<td>65 kg (Flight) / 130 kg (2x Life)</td>
</tr>
<tr>
<td><strong>Thrust</strong></td>
<td>22.9 N @ 24 bar / 6.1 N @ 5.5 bar</td>
</tr>
<tr>
<td><strong>Specific Impulse</strong></td>
<td>242 sec @ 24 bar / 232 sec @ 5.5 bar</td>
</tr>
<tr>
<td><strong>Total Impulse</strong></td>
<td>150,000 Ns (Flight) / 300,000 Ns (2x Life)</td>
</tr>
<tr>
<td><strong>Total Pulses</strong></td>
<td>50,000</td>
</tr>
<tr>
<td><strong>Impulse Bit</strong></td>
<td>0.020s minimum pulse width</td>
</tr>
<tr>
<td><strong>Blowdown Operation</strong></td>
<td>24 – 5.5 bar</td>
</tr>
<tr>
<td><strong>Duty Cycle</strong></td>
<td>&lt;1 - 100 %</td>
</tr>
<tr>
<td><strong>Longest Continuous burn</strong></td>
<td>3600 seconds / (45 minutes)</td>
</tr>
<tr>
<td><strong>Sine Vibration</strong></td>
<td>12.5 g’s – 3 axis / 2 octaves/min (5-100 Hz)</td>
</tr>
<tr>
<td><strong>Random Vibration</strong></td>
<td>14.1 grms - 3 axis / 2 minutes per axis</td>
</tr>
<tr>
<td><strong>Shock</strong></td>
<td>1500 g’s peak – 2 axis / 2 shocks per axis</td>
</tr>
</tbody>
</table>
HPGP 22N EQM Test Program
Environmental Testing – Vibration

**Sine Vibration Levels**

<table>
<thead>
<tr>
<th>Level (G)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.63 in (double amplitude)</td>
<td>5 - 20</td>
</tr>
<tr>
<td>12.5 G</td>
<td>20 - 100</td>
</tr>
</tbody>
</table>

**Power Spectral Density**

<table>
<thead>
<tr>
<th>Qualification</th>
<th>Hz</th>
<th>G²/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.1 Grms</td>
<td></td>
</tr>
</tbody>
</table>

**Shock Qual**

<table>
<thead>
<tr>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1 Grms</td>
<td>100</td>
</tr>
</tbody>
</table>

**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

Propellant Feed Pressure (Bar a)

Accumulated Propellant Throughput (kg)

EQM-1 Test – Status
Test Day # 25
PACE Flight Throughput

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

Single Pulse Performance Area

Dutie Factor (%) vs. TON (s)

Planned
Fired

HPGP 22 N EQM – Hot Firing
Performance

**HPGP 22 N EQM – Pulse Mode Specific Impulse**

- **Thrust vs Inlet Pressure**
- **Specific Impulse vs Inlet Pressure**

**HPGP 22 N EQM – Thrust vs Inlet Pressure**

Measurement Accuracy Band ± 1%

**HPGP 22 N EQM – Specific Impulse vs Inlet Pressure**

Minimum Required $i_s$
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>LMP-103S Propellant, per specification</td>
</tr>
<tr>
<td>Propellant Throughput</td>
<td>53 kg</td>
</tr>
<tr>
<td>Firing Sequences</td>
<td>292 kg</td>
</tr>
<tr>
<td>Burn Time</td>
<td>180 min</td>
</tr>
<tr>
<td>Longest Continuous Firing</td>
<td>2280 seconds / (38 minutes)</td>
</tr>
<tr>
<td>Total Pulses</td>
<td>26,481</td>
</tr>
<tr>
<td>Thermal Cycles</td>
<td>292 cycles from preheat to nominal firing temperature</td>
</tr>
<tr>
<td></td>
<td>25 cycles from room temperature to nominal firing temperature</td>
</tr>
<tr>
<td>Thrust</td>
<td>20.7 N @ 24 bar / 5.5 N @ 5.5 bar</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>255 sec @ 24 bar / 242 sec @ 5.5 bar</td>
</tr>
<tr>
<td>Total Impulse</td>
<td>116,434 Ns</td>
</tr>
<tr>
<td>Impulse Bit</td>
<td>0.35 Ns (24 bar, 0.020 pulse width)</td>
</tr>
<tr>
<td>Time to 90% Thrust</td>
<td>0.025 seconds</td>
</tr>
<tr>
<td>Drop to 10% Thrust</td>
<td>0.060 seconds</td>
</tr>
<tr>
<td>Inlet Pressure Range</td>
<td>24 – 5.5 bar</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>&lt;1 - 100 %</td>
</tr>
<tr>
<td>Valve Operating Voltage</td>
<td>Nominal 24 – 32 VDC, with 10 VDC holding</td>
</tr>
</tbody>
</table>
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.
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.
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

- NASA GSFC Propulsion and specifically:
  - Ms. Caitlin Bacha
  - Dr. Eric Cardiff
  - Dr. Rich Driscoll

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  - Dr. Dan McGuinness

- PACE and WFIRST Project Managers and System Engineers

- Swedish National Space Board (SNSB)

- ECAPS and Swedish Defence Research Center, FOI

- NASA MSFC and GRC