3-D Printing of HIGH PERFORMANCE GREEN HYBRID PROPULSION (HPGHP) Solutions

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Research Motivation: Why Develop “Green” Propellants?

• Small Spacecraft technology development mostly centered on spacecraft bus design and miniaturization of avionics, leaving propulsion component development obsolete by comparison.
• Only two operational alternatives for small spacecraft propulsion are currently available:
  o Higher-performing systems based on hydrazine,
  o Low-performing systems based on cold-gas.
• Monopropellant Hydrazine ($\text{N}_2\text{H}_4$) is most ubiquitous of present-day monopropellants.
  • Hydrazine is highly toxic and dangerously unstable.
  • Acute exposure can be lethal, and it is a suspected carcinogen.
  • Use of hydrazine requires expensive precautions.
• Emerging commercial spaceflight market will clearly support development of green alternatives to hydrazine.
Emergence of Additive Manufacturing for “Green” Small Spacecraft Propulsion

• Until recently, hybrid rocket systems never been seriously considered for in-space propulsion applications.
  • Hybrid rocket ignition historically involved pyrotechnics which cannot support multiple restart cycles.
  • During research investigating ABS as a fuel for hybrid rockets, it was discovered that 3-D printed plastic possesses unique electrical breakdown characteristics.
  • Application of a strong electric field induces a high-temperature arc along the surface of the ABS, concurrent with rapid production of hydrocarbon vapor.
  • This behavior forms the basis of a novel “on-demand” ABS arc ignition system.
3-D Printed Fuel Grain Technology

- 3D printing technology used to manufacture ABS fuel grains
- Flexibility to produce wide variety of shapes and sizes for tailored requirements
- Very low-cost production (relative to aerospace norms)
- Current grains produced with solid, embedded electrodes
- New capability for fully-printed electrodes using electro-conductive ink
- Scalable system to meet diverse performance and packaging needs
Low-Power Arc-Ignition System Technology

- 3D Printed ABS
  - Impingement shelves
  - Arc track doping
  - ESC embedding

Based on patented fabrication & ignition technology (Dr. Whitmore, PI):


UltraVolt D-Series 1D15-P6
- Power Output – 0 to 1000V at 6mA (6W max)
- Input Supply – 15Vdc

30 W, 6W HVPS Available

“ULTRAVOLT C Series High Voltage CAP-Charging Supplies,” Advanced Energy, Inc.,
Updated HPGHP Development Timeline

AY 2019-2020 Development Progress:

- October 2019, NASA Phase IIb STTR Award $200k
- May 2019 – December 2020, Nytrox Oxidizer Development Testing
- June 2019 – April 2020, 1-N Thruster Development Tests
- January 2020 April 2020, Low-Erosion, Long-Duration Nozzle Tests
- March 2020, NASA Spacecraft Technology Partnerships Award, $400k
- USU Campus goes “Virtual” due to Covid-19
- NASA NSTRF / SSTP Partnership Award

HPGHP Technology has been in development for 12+ years at USU/SDL
Utah State University, Marshall Among Partnerships Selected by NASA to Develop Small Spacecraft Technologies

NASA has chosen nine university partnerships — among them a joint effort by Utah State University in Logan and NASA's Marshall Space Flight Center — to develop small spacecraft technologies that will help pave the way for human and robotic lunar exploration, and aid NASA’s Artemis Program in returning humans to the Moon by 2024.

Currently, small spacecraft — ranging in size from a shoebox to a refrigerator — largely operate in low-Earth orbit. Technology advancements made via these collaborative partnerships will more fully realize the potential of SmallSats to extend the capabilities of complex lunar exploration missions as well.
Current SmallSat Market will Support HPGHP Propulsion Solution

Sub 3U Propulsion Systems with Flight Heritage

Critical technology gap area addressed by Micro Joe to enable RPO, Clusters, RCS, and operational missions
## Potential Mission Matrix for HPGHP Propulsion Module

<table>
<thead>
<tr>
<th>Mission Function</th>
<th>Spacecraft Size</th>
<th>1-N</th>
<th>25-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag Offset</td>
<td>Any</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>In-Space Maneuvering</td>
<td>Nano</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>In-Space Maneuvering</td>
<td>Small/Medium</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Reaction Wheel De-Saturation</td>
<td>Small/Medium</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Medium/Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station Keeping</td>
<td>Any</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>High ΔV Escape Trajectory</td>
<td>Any</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Formation Flying</td>
<td>Any</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>De-Orbit/Disposal</td>
<td>Nano</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>De-Orbit/Disposal</td>
<td>Small/Medium</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
## Current Technology Comparison (12U to ESPA Class)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Hydrazine</th>
<th>LMP-103S/AF-M315E</th>
<th>1-N HPGHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>High TRL</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold Start</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Schedule</td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>System Simplicity</td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Scalability</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Impulse Density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potential for some variants</td>
</tr>
</tbody>
</table>

Current Effort Will increase TRL of HPGHP, which is leading in other major metrics.
<table>
<thead>
<tr>
<th>Propellant</th>
<th>Hydrazine</th>
<th>LMP-103S</th>
<th>AF-M315E</th>
<th>HPGHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame Temperature</td>
<td>600-750 °C</td>
<td>1600 °C</td>
<td>1900 °C</td>
<td>3000 °C****</td>
</tr>
<tr>
<td>Isp, s</td>
<td>220-225</td>
<td>252 (theory), 235 (delivered)</td>
<td>266 (theory), 245 (delivered)</td>
<td>300 (theory), 294 (delivered)††††</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.01</td>
<td>1.24</td>
<td>1.465</td>
<td>0.650 (87% N₂O)</td>
</tr>
<tr>
<td>Density Impulse, N.s/liter</td>
<td>2270</td>
<td>3125 (theory), 2915 (delivered)</td>
<td>3900 (theory), 3650 (delivered)</td>
<td>2800 (theory), 2600 (delivered)</td>
</tr>
<tr>
<td>Preheat Temperature</td>
<td>315 °C, cold-start capable</td>
<td>300 °C</td>
<td>370 °C</td>
<td>N/A none-required</td>
</tr>
<tr>
<td>Required Ignition Input Energy, Joules</td>
<td>N/A</td>
<td>12,000 J (10 Watts @ 1200 seconds)</td>
<td>27,000 J (15 Watts @ 1800 seconds)</td>
<td>2-5 J (4-10 Watts for 500 msec)</td>
</tr>
<tr>
<td>Propellant Freezing Temperature</td>
<td>1-2 °C</td>
<td>-7 °C</td>
<td>&lt; 0 °C (forms glass, no freezing point)</td>
<td>-70 °C</td>
</tr>
<tr>
<td>Cost</td>
<td>$</td>
<td>$$$</td>
<td>$$$</td>
<td>$</td>
</tr>
<tr>
<td>Availability</td>
<td>Readily Available</td>
<td>Restricted Access</td>
<td>Limited Access</td>
<td>Very Widely Available††††</td>
</tr>
<tr>
<td>NFPA 704 Hazard Class</td>
<td>4-3</td>
<td>6-0</td>
<td>1-0</td>
<td>4-0</td>
</tr>
</tbody>
</table>

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§§§ Data for hydrazine, LMP-103S and AFM315-E were taken from Ref. 7.

**** Due to the high pyrolysis energy of the ABS fuel, 3.1 MJ/kg, ABS Hybrid motors are self-ablative and do not get hot externally.

†††† Extrapolated to vacuum conditions based on ground test data.

80-90% N₂O solutions easily manufactured, as per procedure in this paper.

Based up the constituent components, Hydroxyl Ammonium Nitrate (HAN) and 2-Hydroxyethylhydrazine (HEHN)
HPGHP Space Flight Test

- Multiple Systems Ranging from 5-900 developed/built on USU campus
- Successful flight demonstration in March 2018 (sub-orbital, NASA Terrier Improved Malamute)
  - 5 successful restarts in space, 5-N Nominal Thrust
  - Total of 15 seconds burn time limited by oxidizer supply, packaging constraint
Baseline 1-N Flight System Overview

• Hybrid Propulsion System
  • Oxidizer: Nytrox
    • Gaseous Oxygen (GOX)/Nitrous Oxide (N₂O) Blend
  • Fuel: ABS/PMMA/Polyamide

Test Burn of the Core Burning 5N Thruster

Lab Weight End Burning 1N Thruster on Test Stand
HPGHP Flight System Components

- Ignitor and fuel combined (ABS)
- Ignitor (PMMA)
- Graphite spacer
- Combustion chamber
- PMMA
- PVC
- Top of combustion chamber (w/ ignitor)
- Fuel Grains
- PMMA partially spent
- ABS
- ABS (short)
- Back of nozzle
Potential Flight-Configuration Thruster Options Enabled by AM

- Single Stick
- Conformal Tank
- End Burner

3-U 4-Poster
6-U 4-Poster