Hydrocarbon-Seeded Ignition System for Small Spacecraft Thrusters Using Ionic Liquid Propellants

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Hazards Associated with Hydrazine as Propellant for Small Spacecraft

- Hydrazine also presents significant toxicity and physical hazards
  - Highly energetic, anhydrous hydrazine can detonate from impact
  - *Low explosive flashpoint* at 38 C.
  - Highly toxic, both a reducing agent and oxidizer, corrosive to living tissue
  - *Extreme vapor hazard*, service and inspection operations require S.C.A.P.E suits
  - *Known carcinogen* for both short and long-term exposure.
  - Operational complexities of dealing with hazardous propellants especially expensive for emerging private-space entities.
  - Hydrazine not “ride share” friendly
  - Less toxic, moderate performance hydrazine mono-propellant replacements highly desirable.

- Conclusions of European Space Agency/European Space Research and Technology Center (ESA/ESTEC) study

Ionic Liquids as Hydrazine Replacement Alternatives

• Leading Candidates as Alternatives to Hydrazine
  - **Ionic Liquids** (Ammonium salts in aqueous solution) as “Reduced Hazard,” Improved Performance, “Green” mono-propellant formulations
    - Ammonium DiNitramide (ADN), HPGP, LMP103s
    - Hydroxylamine Nitrate (HAN), XM1846, HANGLY26, HAN269MEO, AF-M315E

1. Demonstrated High specific impulse > 230 sec vacuum
2. High Specific Gravity, Density $I_{sp}$ 1.5 > Hydrazine
3. Servicing operations performed without SCAPE suits
4. Significantly lower freezing points compared to Hydrazine
5. Low vapor pressure at room temperature
6. Minimum vapor hazard at room temperature
7. Servicing performed using minimum PPE, no SCAPE suits required.
Ionic Liquids as Hydrazine Replacement Alternatives

-Ammonium DiNitramide (ADN, $NH_4(NO_2)_2N$) – Based Propellants

- LMP-103s High Performance Green Propellant (HPGP)
  - Formulation 60-65% ADN, 15-20% methanol ($C_2H_5OH$), 3-6% Ammonia ($NH_3$), and 9-22% water
  - ESA/ECAPS developed propellant
  - Moog/ATK USA Distributors
  - ESA Prisma flight demo, 1 N LMP-103S thruster flown as demonstration experiment
- Catalytically decomposed
  - Proprietary high temperature catalyst, requires 30 minute preheat at 8.5 W.
  - Combustion products $H_2O$ vapor, $N_2$, $O_2$, and 2000 kJ/kg heat
- LMP-103S Classified as a DOT 1.3 explosive for field operations

Prisma “Mango”
Spacecraft

ECAPS 1-H HPGP
Thruster
Ionic Liquids as Hydrazine Replacement Alternative (2)

-Hydroxylammonium Nitrate (HAN, NH$_3$OHNO$_3$) – Based Propellants
  - US Army LP 1846 (XM 46)
    - Formulation 60.8% HAN, 19.2% tri-ethanol-ammonium nitrate (TEAN fuel), 20% Water.
    - Originally developed as monopropellant for artillery
  - Aerojet HANGLY26
    - Formulation 60% HAN, 14% Glycine (fuel), 26% Water.
  - Aerojet HAN269MEO,
    - Formulation 69.7% HAN, 14.8% Methanol (fuel), 14.9% Water, 0.6% Ammonium Nitrate (stabilizer)
  - AF-M315E Proprietary USAF Blend
    - Selected for NASA/Ball Aerospace Technology Demonstration Mission (2012)

NFPA/DOT Hazards Classification

HAN-Thruster Development Testbed (NASA GRC)
Development Issues Associated with IL Propellants

• Ionic Liquid (IL)-Based monopropellants
  - In dry form IL-salts are highly energetic, and can be subject to rapid, uncontrolled decomposition
  - Explosion potential buffered by working with aqueous solutions
  - Hanford and Savannah River nuclear site explosions caused by low water content HAN solution being used for equipment decontamination

• Ignition of IL-based monopropellants
  - High water content IL-solutions are safer to handle, but notoriously hard to ignite
  - Catalytic decomposition is current “method of choice”
  - Once ignited IL-based propellants burn significantly hotter than hydrazine ~ 1350-1700 C
    - Catalyst bed survivability is a significant issue
    - Cold-start capability does not current exist for IL propellants.
    - CATBED must be pre-heated to greater than 350 C before firing
    - Complex, heavy, and expensive to manufacture
    - Add considerably to dry mass of spacecraft
    - Present considerable disadvantage to small spacecraft where power and mass budgets are quite limited

  • ECAPS I-N Prisma thruster >25 kJ preheat energy consumed
Other Ignition Options for IL-propellants

- Pyrotechnic charge
  - Very high enthalpy output per unit mass
  - Single-use devices
  - Hazardous, can be triggered by static spark, ground loop or EM-radiation
  - Non-compliant with USAF and NASA requirements for hazards of electromagnetic radiation to ordnance (HERO) for “Rideshare” payloads

- Plasma torch
  - Requires large power source
  - Very high temperature but low mass flow, total enthalpy output

- Electric spark plugs with bi-propellant oxidizer and fuel injectors
  - Complex flow path, additional propellant source required
  - Potential combustion stability, hard start issues

- Pyrophoric ignition fluids
  - Significant vapor hazard, hazardous servicing procedures
  - Not “ride-share” friendly

- Issues associated with catalytically dissociation have been previously discussed
Hydrocarbon Seeded Micro-Hybrid Ignitor for IL-Propellants

- Proposed innovation uses unique ABS-plastic properties to ignite hybrid device electro-statically
  - ABS plastic has a very high dielectric strength, 53.1 kV/mm, high current impedance
  - Significant electrical energy can be dissipated before material breaks down.
  - When a high voltage is applied, charge buildup electrifies the grain
  - Spark jumps gap across the fuel port
  - Spark vaporizes small amount of material locally
  - Residual spark energy triggers local reaction between ablated fuel and oxidizer flow
  - Vaporized hydrocarbon “seeds” combustion reaction with oxidizer flow
**Proof-of-Concept Prototype**

- **Original concept developed as stand-alone micro-thruster**
  - Initially used a commercial “stun gun” to generate low-current, high-voltage spark
  - Later design replaced TASER with Precision, High Voltage, Current Limited Power Supply (13 mA)

- **Micro-hybrid thruster adapted as non pyrotechnic ignitor for 98 mm, 800-N thrust hybrid rocket motor**
  - Ignitor propellants GOX/ABS
  - Multiple-consecutive relights of main motor demonstrated
Proof-of-Concept Ignitor Test Results

- Electrical Input Power < 10 Watts, 5.6 Joule mean ignition energy
- Ignitor Output Power > 30 kW … Energy amplification factor of > 1000!
- Only limit to number of successive ignitions is amount of ABS in ignitor grain
Adapting the Micro-Hybrid Ignitor for IL Propellants

- Currently undergoing fabrication at Utah State University.
- Simulation model used to obtain propellant dwell time and reactor volume (225 cm.).
- Operating pressure is between 1,000 kPa (145 psia) and 2,000 kPa (290 psia), yielding thrusts of roughly 12.5-25 N (2.8-5.6 lbf)
- HAN enters reactor via a coaxial impinging plate injector to improve atomization
- 300-series stainless steel, quartz glass, and Teflon gaskets used for Material compatibility
- Developmental tests used to gather data for model development and verification

<table>
<thead>
<tr>
<th>Ignitor</th>
<th>( P_{\text{in}, \text{atm}} )</th>
<th>( D_{\text{in}, \text{in}} )</th>
<th>( C_{\text{in}, \text{in}} )</th>
<th># of Ignitors</th>
<th>( C' ) Efficiency</th>
<th>( \Delta T_{\text{ignition}} )</th>
<th>O/F Ratio</th>
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<tr>
<td>HAN/H( _2 )O</td>
<td>2100</td>
<td>3175</td>
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<td>Combustion Chamber</td>
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<td>12</td>
<td>0.9</td>
<td>225</td>
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<td>4.0</td>
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<td></td>
<td>1000</td>
<td>12</td>
<td>0.9</td>
<td>225</td>
<td>0.35</td>
<td>4.0</td>
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Adapting the Micro-Hybrid Ignitor for IL Propellants (2)

- Below 25% solution (by mass) ignitor provides insufficient output to initiate HAN decomposition.

- From 25-60% igniter initiates decomposition, but energy released by HAN is cannot overcome latent heat of water.

- Initial tests make use of ~65% HAN solutions, and the concentration will be progressively increased.

- Chamber Length Designed to Ensure sufficient “Dwell time” to ensure high probability of efficient

Allowable HAN-Solution to Ignitor Mass Flow Ratio for Ensured Ignition (65% Solution)
Infusion Potential for Technology

3-U IL-Propulsion Bus Concept
# Potential Mission Matrix for Proposed IL Propulsion Module

<table>
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<tr>
<th>S/C Function</th>
<th>S/C Size</th>
<th>1-N</th>
<th>25-N</th>
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<tr>
<td>Drag Offset</td>
<td>Any</td>
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<tr>
<td>In-Space Maneuvering</td>
<td>Nano</td>
<td>x</td>
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<tr>
<td>In-Space Maneuvering</td>
<td>Small/Medium</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Reaction Wheel De-Saturation</td>
<td>Small/Medium</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Station Keeping</td>
<td>Any</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>High ΔV Escape Trajectory</td>
<td>Any</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Formation Flying</td>
<td>Any</td>
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</table>
Summary and Conclusion

1. “Microhybrid” gas generation cycle that employs ABS hydrocarbon-seeding with electrostatic charge adapted as ignition system for 98-mm hybrid rocket motor.
2. Multiple consecutive starts achieved using a single ignitor propellant load, no hardware changeover or propellant replenishment
3. No propellant or catalyst preheat required
4. Non-pyrotechnic ignition power/energy input < 10 Watts/8 Joules, (900 V at 1s mA)
5. Output power from ignitor > 25 kJ, with current design single ignitor capable of producing more than 100 kJ total enthalpy output.
6. This approach allows the simplicity of mono-propellant ignition system, while still providing the high-energy and performance of a bi-propellant ignition system.
7. The ignitor propellants, GOX and ABS are 100% non-toxic, inert, and environmentally benign.
8. Low ignition latency, multiple ignition capability, very high enthalpy > 25 kW output
9. Approach to motor ignition highly resistant to Hazards of Electromagnetic Radiation to Ordnance (HERO).
Conclusion

10. “Seeding” ABS segments easily and inexpensively fabricated using FDM fabrication.
11. Because the aqueous ADN or HAN solutions have significantly higher densities than hydrazine, this application would offer significantly longer run-times or reduced overall system volumes.
12. By varying the HAN concentration within the mixture, the exhaust gas temperature can be moderated to insure a trade-off between ignition reliability and downstream component survivability.
13. HAN/Hybrid design would be inherently safe, potential to significantly exceed Hydrazine performance
14. “Rideshare” friendly technology, significant power, mass , and cost savings compared to existing CATBED designs.
15. Technology applicable to wide range of gas-generation systems where aqueous HAN or AND-based solutions replace hydrazine as the working fluid.
16. When Binary HAN-solution testing is concluded .. We’d love to test donated LMP-103S and AF M315E propellant samples.