ELV Payload Safety Program Workshop
Green Propulsion Update
Outline

• Introduction to green propellant

• PRISMA spacecraft

• TDM solicitation and GPIM

• MSFC green propulsion roadmap

• Green auxiliary power units

• Future green thruster testing at MSFC

• Green thruster scale up

• Future mission opportunities

• Summary
Potential replacement to Hydrazine

Performance/Environmental/Safety Challenge

Hydrazines are SOTA spacecraft fuel:

- Increased Operations Costs:
  - Carcinogenic Vapor (Respiratory Route)
  - Dermal Toxicity
  - Strong Reducing Agent
  - Flammable (LEL = 4.7%, UEL = 100%)
- On-Orbit Propulsion Systems Affected
  
<table>
<thead>
<tr>
<th>System</th>
<th>Mission</th>
</tr>
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<tbody>
<tr>
<td>FltSatCom</td>
<td>Communications</td>
</tr>
<tr>
<td>STARDUST</td>
<td>Deep Space Probe</td>
</tr>
<tr>
<td>INTELSAT</td>
<td>Communications</td>
</tr>
<tr>
<td>HEAO-B</td>
<td>X-Ray Astronomy</td>
</tr>
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</table>
- Hundreds of Satellites Use Hydrazine for RCS & ACS

2011 Tommy Hawkins/AFRL Briefing to Partners in Environmental Technology Conference
Distribution Statement A: Approved for Public Release; Distribution Unlimited
Hawkins Cont’d

Energetic Ionic Liquids
Avenues to Lower Toxicity & Higher Performance

• History
  – An ionic compound that has a melting point at or below 100°C
  – Seminal work at USAFA (Wilkes et al.)
  – Industrial solvents, green chemistry
    – Low vapor pressure, low vapor toxicity
    – Wide solubility ranges

• ILs as Energetic Materials
  – First energetic ILs: chemical oddities
  – AFRL realizes chemical structure manipulation leads to new classes of highly, energy dense materials (HEDM) for advanced propulsion

Distribution Statement A: Approved for Public Release; Distribution Unlimited
‘Greener’ Chemical Propulsion—ILs in Advanced Monopropellants

ADN (M.P. 92°C) is also an Energetic Ionic Liquid

- ADN-based monopropellant (LMP-103S) from ECAPS, Swedish Space Corporation
- High performance ‘green’ propellant (30% improved Isp*Density vs. hydrazine)
- 1 N Thruster using thermal and catalytic ignition flight qualified and flown (PRISMA)

AF-M315E is US Air Force IL-Based Monopropellant

- Significant physical property and performance advantages (50% improved Isp*Density)
- Ongoing hardware developments

<table>
<thead>
<tr>
<th>Properties</th>
<th>LMP-103S</th>
<th>AF-M315E</th>
<th>Hydrazine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isp vac, lbf sec/lbm</strong> (e = 50:1 P_c = 300 psi)</td>
<td>252 (theor.) 235 (del)</td>
<td>266 (theor.) ~ 250 (del)</td>
<td>242 (theor.)</td>
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<tr>
<td><strong>Density, g/cc</strong></td>
<td>1.24</td>
<td>1.465</td>
<td>1.01</td>
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<tr>
<td><strong>Vapor Pressure (torr)</strong></td>
<td>Ammonia Methanol H2O</td>
<td>&lt;0.1 (w/o H2O)</td>
<td>14.3</td>
</tr>
</tbody>
</table>

* Sjoberg et al., Innsitive Munitions & Energetic Materials Technology Symp. Proc., Tucson, USA, May 11-14, 2009

Why “Green”

- What is “Green” Propellant:
  - Are there environmental issues with production?
  - How well does it transport/off-load?
  - What are the bi-products of combustion?
- Performance and Characteristics:
  - Storable Liquid monopropellant
  - High Specific and Density Impulse
  - Good pulse performance
- Safety:
  - Low Sensitivity & Toxicity
  - Non Carcinogenic
  - Environmentally Benign
- Lower overall mission cost:
  - Easy to handle and transport
  - Compatible with available COTS
Prisma Satellite – Launched June 2010

Mango
- 3-axis stabilized
- Attitude Independent Orbit Control
- 100 m/s Delta-V
- 145 kg launch mass
- 2.6 m “wing-span”
- 3 propulsion systems
- 4 RF systems

Tango
- 3-axis stabilized
- Solar Magnetic control
- No orbit control
- 40 kg launch mass

(Artists Impression – Courtesy of DLR)
Blended ADN Propellant

**LMP-103S**

**ADN-Based Liquid Storable ”Green” Monopropellant**

Higher performance:
- Isp >6%
- Density Impulse >30%

Reduced personal and environmental hazards:
- Low sensitivity
- Low toxicity
- Non carcinogenic

Simpler to transport and handle:
- SCAPE not required
- Approved for air transportation

**Exhaust species**

- ADN + Solvent + Fuel + Stabilizer
- Exhaust species:
  - H₂O
  - CH₃OH
  - NH₃
  - H₂
  - CO
  - CO₂
Basic Characterization Testing

- Material compatibility
- Storage temperature range
- Long-term storability
- Radiation tolerance
- UN transport classification
- Safety tests
- Chemical and physical properties
PRISMA Loading Advantages

PRISMA Launch Campaign

- LMP-103S is UN class 1.4S transport certified
  - Propellant was transported as air cargo together with the satellites and associated GSE
- HPGP operations required:
  - 3 partial working days (leak checks, fueling & pressurization, decontamination)
- All handling of LMP-103S (i.e. loading/de-loading, decontamination) declared by Yasny Range Safety as “Non-hazardous operations”
- Propellant Loading/De-loading did not require SCAPE operations
  - LMP-103S is not sensitive to exposure to air or humidity
- Only limited decontamination of the loading cart was required at the launch site:

<table>
<thead>
<tr>
<th></th>
<th>Hydrazine</th>
<th>HPGP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxic Waste</td>
<td>470 kg</td>
<td>3 kg</td>
</tr>
<tr>
<td>Propellant Waste</td>
<td>29 kg</td>
<td>1 kg</td>
</tr>
</tbody>
</table>

- A 2/3 cost reduction was realized for HPGP propellant, transportation and fueling (as compared to the hydrazine system flown)

www.sscspace.com/ecaps
LMP-103S Safety & Handling

Fueling:
• Using SCAPE’s are not required.
• LMP-103S is not sensitive to exposure to air or humidity.

Leak and Spills:
• Ammonia detectors can be used.
• LMP-103S spills should be taken up using adequate quantities of vermiculite absorbent.
• The saturated granules should be collected and stored in a suitable polyethylene container.
• The container and any other contaminated materials should be disposed.

Decontamination:
• Wash contaminated areas with plenty of water.
• Provide ventilation until all ammonia and methanol vapors are removed.
Status of MSDS

Apr 2008

ECAPS

SPACECRAFT PROPULSION SYSTEM

Contractual Document

Title of Document: Propellant LMP-1035 MSDS

Registration Number: DOX-RBS-46304 Issue Date: 2008-04-21

Contract: ESA Phase 3

Work Package Number: WP2000

Prepared By: 

Date: 2008-04-17

Approved By: 

Date: 2008-04-18

Released By: 

Date: 2008-04-21

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COMPANY CONFIDENTIAL

Dec 2011

Apr 2013

MATERIAL SAFETY DATA SHEET

MSDS No. 419C

Date issued: 07/25/2011

Date Revised: 12/19/2011

Approved By: A. Ignaz

I. PRODUCT IDENTIFICATION

A. Trade Name and Synonyms: LMP-1035, Liquid monopropellant

B. DOT Description and Shipping Classification: An as yet unclassified. Shipped in quantities of not more than 25 grams under DOT-SIP 13481 special permit as UN1178, Articles, explosive, n.o.s. (Ammunition detonite), 1.4E. Special permit shipping authorization expired May 31, 2013.

C. DOT Description and Shipping Classification: For the purpose of shipping the samples of LMP-1035 in Special Packaging for examination only, the following tentative shipping description and classification is assigned: Propellant, liquid, UN1895, 1.3C, CA-1996090005.

D. DOT Description and Shipping Classification: For the purpose of shipping the samples of LMP-1035 in Special Packaging for examination only, the following tentative shipping description and classification is assigned: Substance, explosive, n.o.s. (Ammunition detonite, methanol), UN1970, 1.1D, CA-1996090005.

II. PHYSICAL DATA

A. Appearance and Odor: Clear to light yellow liquid; odd, pungent odor

B. Volatilities: Methanol, Ammonia

III. PHYSICAL DATA

A. Physical Form: Liquid

B. Odor: None

C. Hazardous Contents: Hydrazine monomethyl nitrate (HAN)-based propellant

D. Specific Gravity: 1.48

E. Flash Point: Not Applicable

F. Autoignition Temperature: >400°C (flame temperature onset for slow cool-off)

G. Flammable Limits in Air (% by Volume): Lower: Not Applicable

H. Unstable: Not Applicable

I. Unstable: Not Applicable

J. Thermal Stability: Stable

K. Chemical Stability: Stable

L. Presence of Other Substances: None
TDM Solicitation

• After presenting to this forum in Dec 2011, I held a Green Propulsion TIM at KSC in January 2012.

• Coinciding with that meeting was the BAA announcement for the Technology Demonstration Mission focused on green propulsion.

• The BAA solicited demonstrations of monopropellant alternatives:
  – in-space RCS
  – in-space primary propulsion
  – launch vehicle RCS
  – launch vehicle power generation

• When the dust had settled, 16 proposals were received competing for a cost cap of $50M and a single award was granted in Aug 2012.
Objective:
In-space demonstration of a green monopropellant propulsion system with the purpose of infusing the technology into the marketplace.

Approach/Status:
- Three-year program to develop and fly AF-M315E monopropellant propulsion system
  - Base period: Ground testing of thrusters to TRL 7
  - Option 1: Qualification of propulsion system to TRL 7
  - Option 2: 60-day, on-orbit demonstration of propulsion system to TRL 9
- GPIM team led by Ball Aerospace with AFRL, NASA GRC, and Aerojet as co-investigators; mission support from USAF SMC and NASA KSC
- Launch scheduled for September 2015
MSFC approach to future

- History of taking mid-range TRL propulsion technologies to flight.

- Basic elements of green propulsion:
  - MSFC interested in the system solution, replacing hydrazine for both spacecraft propulsion as well as auxiliary power units for booster gimballing.
  - Agnostic about propellants, want to see more than one succeed to maximize usage by industry and government.
  - Scale up thruster technology to the 100-200 lbf class (440 to 880N).
  - Infuse the hardware, as thruster classes mature, into near term missions to expedite acceptance by community.
  - Safety protocol by various ranges can create precedence for the different propellant mixtures.
MSFC Green Propulsion Roadmap

Current activities:
- TDM investment in GPIM.
- MSFC is testing 0.2 lbf AF-M315E and 5 lbf LMP-103S thrusters.
- MSFC utilizing discretionary funds to test green prop in power units.

Pilot test projects leading to scale up:
- Use of green prop in F-16 EPU’s.
- Materials compatibility and stability testing.
- Flight results of GPIM.
- Use of advanced manufacturing to reduce costs and schedule.

Future implementation:
- Scale up thruster technology to 100 lbf class.
- Integrate thrusters into cubesat and LEO sat missions.
- Focus on duty cycles for HEOMD thrusters and sustained thrust for landers.
- Demonstrate in APU hardware.

Pre-2012
- The Swedes have worked over the past decade with propellant blends, material compatibility and resultant space mission with PRISMA.
- The USAF investigates their propellant blend.

International

WE ARE HERE!

MSFC leadership in green propulsion will enable replacement of hydrazine monopropellant over a large range of applications.
Continued interest from MSFC

• MSFC purchased a 22N green propellant thruster from ATK & ECAPS in August 2012.
  – Acceptance testing in Sweden was completed in March 2014 with continued testing at MSFC planned.

• Flight Programs and Partnerships Office funded excess hardware shipment to MSFC.
  – 2 F-16 emergency power units from the Davis-Monthan AFB.
  – Spare gas generator previously used on SRB APU for nozzle gimbal.
  – 30+ year old Orbiter-heritage APU from WSTF.
  – Myriad of power unit components from KSC.

• MSFC Engineering purchased 0.1N and 1N AF-M315E thrusters and have begun test campaigns.

• Center Innovation and SLS Advanced Development have funded testing of EPU’s and thrusters at MSFC.
APU Test Plan

(2) F-16A EPUs

Phase 1 Feasibility Testing

Phase 2 Gas Generator Testing

Phase 3 System Testing

SRB GG5116

Orbiter APU Engineering Test Unit S/N-008

Additional hardware being excessed from SLS Core Stage:
- 9 gas generators
- 2 gas generator valve modules
Status of APU Feasibility testing

- MSFC received key drawings, operations manuals and acceptance test procedures for the F-16 EPU.

- In collaboration with AFRL, we are working on reactivity of Hydroxyl Ammonium Nitrate (HAN) based propellants for use in power generation.

- MSFC has removed a gas generator (GG) from one assembly and are preparing to test.

- Based on the EPU GG testing, we will reinstall into assembly for additional testing.

- MSFC has had discussions with Edwards Air Force Base about a ground demo with F-16.
22N Acceptance Testing, Grindsjon, Sweden

- 0.5 kg throughput
- 22 test sequences
- 3 test pressures
- 200 pulses
- 10 sec max firing time
- 1.2 minutes total duration

Propellant Area

FLIR Camera to detect any leaks

Thruster inside vacuum chamber
Aerojet has also built a 220N thruster and is beginning test campaigns.
Upcoming Missions

• GPIM is currently scheduled to fly in late 2015.
  – 1st flight from domestic source at KSC.

• Skybox Imaging has purchased 13 shipsets of LMP-103S hardware (52 thrusters plus spares).
  – Skysat-3 launch scheduled for 3rd quarter 2015 from India.
  – 6 more Skysats will launch on Minotaur C from VAFB late 2015/early 2016.

• Sierra Nevada selected by USAF Space Test Program to fly STPSat-5 in late 2016.
  – Will utilize (4) 1N LMP-103S thrusters.

• MSFC would like to see industry adopt use of green thrusters in ascending thrust classes as they become available.
Summary of Center Involvement

• MSFC is engaged on the system solution: thrusters and power units.

• GRC is working plume diagnostics/modeling and independent thruster testing on GPIM.

• GSFC is working slosh characteristics on GPIM tank.

• JPL and ARC continually interested to infuse green propellant as potential replacement to hydrazine.

• Mike Gazarik, AA of STMD, has requested MSFC lead the development of an Agency-level green propellant roadmap involving multiple Centers.  
  – Tentatively planned for August 2015 in Huntsville.
Backup
How MSFC got involved

- Starting in FY2010, OCE/OCT funded the Nano Energetics Propulsion Project (NEPP) led out of MSFC.
- During the execution of this project, annually-held technology assessment group meetings occurred to evaluated propellant candidates.
- In the Spring of 2011, one of the top oxidizers under consideration was ammonium dinitramide (ADN).
- MSFC was visited by ATK, ECAPS and the Swedish National Space Board to brief their development of an ADN-based monopropellant for use on the PRISMA satellite.
- By Sept 2011, personnel from MSFC, ARC and GSFC traveled to Sweden to participate in PRISMA flight operations, visit the propulsion test facilities and tour the propellant vendor.
- MSFC has become more active in the evaluation of the top two leading green propellants: LMP-103S and AF-M315E.
## MSFC In-Space Propulsion Experience

<table>
<thead>
<tr>
<th>Spacecraft or System Name</th>
<th>Most Recent Activity*</th>
<th>Human Rated</th>
<th>Biprop (MMH/NTO)</th>
<th>Mono-prop (N2H4)</th>
<th>Oxygen/Methane</th>
<th>Hydrogen Peroxide, JP-8</th>
<th>Dual Mode</th>
<th>Cold Gas</th>
<th>Non-Toxic</th>
<th>Cryogenic</th>
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<tbody>
<tr>
<td>Robotic Lunar Lander</td>
<td>Ongoing</td>
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<td>(MMH/MON-25)</td>
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<td>Orion Service Module Propellant Tanks</td>
<td>Ongoing</td>
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<td>●</td>
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<tr>
<td>Chandra</td>
<td>Flying</td>
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<tr>
<td>Ares I Upper Stage ReCS</td>
<td>Ongoing</td>
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<td>●</td>
<td>●</td>
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<td>Ares I First Stage ReCS</td>
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<td>Ares I-X First Stage ReCS</td>
<td>2009</td>
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<td>PCAD LO2/LCH4 Engine</td>
<td>2008</td>
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<td>Demonstration of Automated Rendezvous Technology (DART)</td>
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<td>NGLT LO2-Ethanol thruster</td>
<td>2005</td>
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<tr>
<td>In-House 25-lb O2/CH4 Thruster</td>
<td>2005</td>
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<td>Orbital Space Plane</td>
<td>2004</td>
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<td>X-37 Orbital Vehicle (2nd version)</td>
<td>2003</td>
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<td>X-38 Deorbit Propulsion</td>
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<td>NGLT LO2-LH2 Thruster</td>
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<td>X-37 (Original version)</td>
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<td>US Prop Module (for International Space Station (ISS))</td>
<td>2000</td>
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<td>X-33 Reaction Control System (gaseous O2/CH4)</td>
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<td>Interim Control Module (ICM) for ISS</td>
<td>1998</td>
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<td>Aerosassist Flight Experiment</td>
<td>1994</td>
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<td>Combined Radiation and Release Effects Satellite</td>
<td>1991</td>
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<td>Orbital Maneuvering Vehicle (OMV)</td>
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<td>Inertial Upper Stage RCS; Transfer Orbit Stage RCS</td>
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<td>HEAO (3 spacecraft)</td>
<td>1981</td>
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<td>Skylab</td>
<td>1977</td>
<td>Yes</td>
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<tr>
<td>Saturn S-IVB Auxiliary Propulsion System</td>
<td>1973</td>
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</tbody>
</table>

*MSFC has similar, long history with solid propellants:*
- Orion LAM & ACM
- Ares-I motors (USM, BDM, FSTM, BSM)
- STAR motors
- Inertial Upper Stage
- Sounding Rockets