National Aeronautics and Space Administration

# ELV Payload Safety Program Workshop
# Green Propulsion Update

marshall

Joel Robinson / MSFC
Dec 3-4, 2014

# 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

| System | Mission |
|---|---|
| FltSatCom | Communications |
| STARDUST | Deep Space Probe |
| INTELSAT | Communications |
| HEAO-B | X-Ray Astronomy |

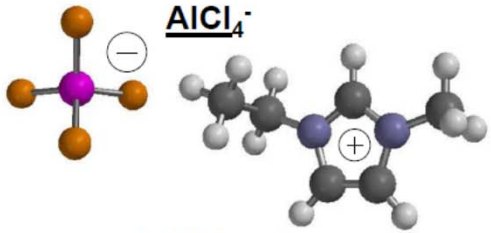
- Hundreds of Satellites Use Hydrazine for RCS & ACS

2011 Tommy Hawkins/AFRL Briefing to Partners in Environmental Technology Conference

# Hawkins Cont'd

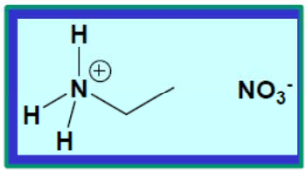
## Energetic Ionic Liquids
### Avenues to Lower Toxicity & Higher Performance

- **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




**EMIM cation**
(1-ethyl-3-methylimidazolium)

- **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




**Liquid propellants:**
Spacecraft thrusters
DACS/ACS
Booster engines

# Hawkins cont'd



## '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

| Constituents | Weight % |
|---|---|
| ADN | 60-65 |
| Methanol | 15-20 |
| Ammonia | 3-6 |
| $H_2O$ | balance |

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

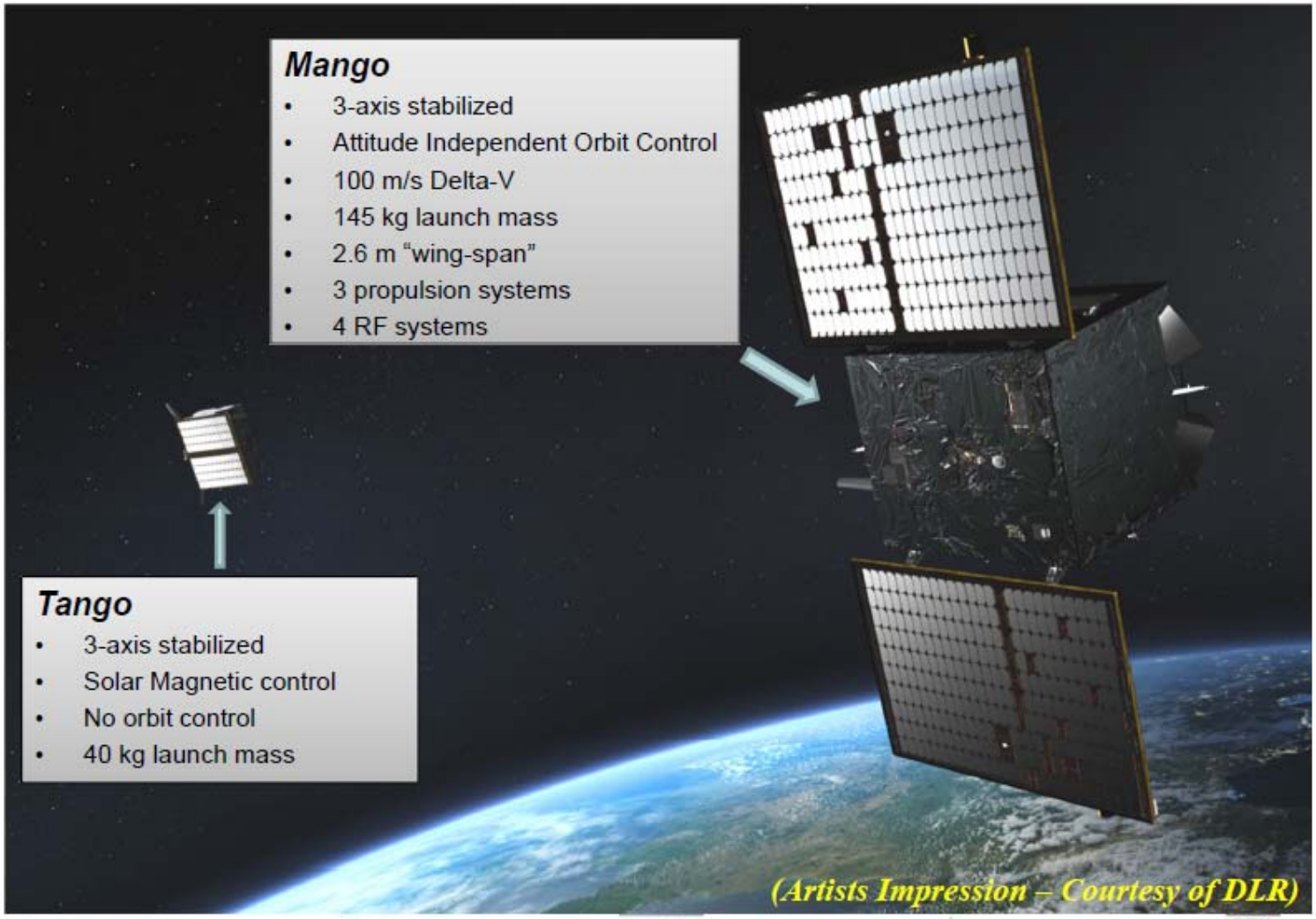
| Properties | LMP-103S | AF-M315E | Hydrazine |
|---|---|---|---|
| $Isp_{vac}$, lbf sec/lbm (e = 50:1 Pc = 300 psi) | 252 (theor.) 235 (del) | 266 (theor.) ~ 250 (del) | 242 (theor.) |
| Density , g/cc | 1.24 | 1.465 | 1.01 |
| Vapor Pressure (torr) | Ammonia Methanol $H_2O$ | <0.1 (w/o $H_2O$) | 14.3 |

* Hawkins et.al., Proc. 4th International Association for the Advancement of Space Safety, Huntsville AL, 19 May 2010; Hawkins et.al., Proc. Fourth International Conference on Green Propellants for Space Propulsion, Noordwijk, The Netherlands, 20-22 June 2001.

# 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




OHB SWEDEN ECAPS DLR cnes DTU

# Blended ADN Propellant

## LMP-103S

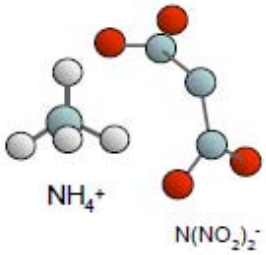
*ADN-Based Liquid Storable "Green" Monopropellant*

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

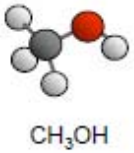
**Reduced personal and environmental hazards:**
- Low sensitivity
- Low toxicity
- Non carcinogenic

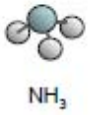
**Simpler to transport and handle:**
- SCAPE not required
- Approved for air transportation

**ADN + Solvent + Fuel + Stabilizer**

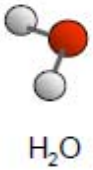


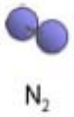





**Exhaust species**







www.sscspace.com/ecaps

ECAPS

# 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

**Loading PRISMA with LMP-103S**

**Loading PRISMA with Hydrazine**

www.sscspace.com/ecaps

- 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:

| Hydrazine | HPGP |
|---|---|
| 470 kg toxic waste | 3 kg *non-toxic* waste |
| 29 kg propellant waste | 1 kg propellant waste |

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

SSC 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

Dec 2011

ATK

Alliant Techsystems Operations LLC
Propulsion and Controls
55 Thiokol Road
Elkton, MD 21921
Tel 410-392-1000
Fax 410-392-1592
EMERGENCY: CHEMTREC 1-800-424-9300
CCN202541

**MATERIAL SAFETY DATA SHEET**

MSDS No. 416C
Date Issued: 07/25/2011
Date Revised: 12/19/2011

Approved By: _____
A. Ignatz

**I. PRODUCT IDENTIFICATION**

A. Trade Name and Synonyms: LMP-103S, Liquid monopropellant

B. DOT Description and Shipping Classification: As yet unclassified. Shipped in quantities of not more than 25 grams under DOT-SP 13481 special permit as UN0471, Articles, explosive, n.o.s. (Ammonium dinitramide), 1.4E. Special permit shipping authorization expires May 31, 2013.

C. DOT Description and Shipping Classification: For the purpose of shipping the samples of LMP-103S in Special Packaging for examination only, the following tentative shipping description and classification is assigned: Propellant, liquid, UN0495, 1.3C, CA-1999080005.

D. DOT Description and Shipping Classification: For the purpose of shipping the samples of LMP-103S in Special Packaging for examination only, the following tentative shipping description and classification is assigned: Substances, explosive, n.o.s. (ammonium dinitramide, methanol), UN0475, 1.1D, CA-1999080005.

**II. PHYSICAL DATA**

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

B. Volatiles: Methanol, Ammonia



Apr 2013

**MATERIAL SAFETY DATA SHEET**
**AIR FORCE RESEARCH LABORATORY**
**RQRP/AREA 1-30**
**EDWARDS AFB, CALIFORNIA 93524 - 5000**
**(661) 275 - 5787**

**April 17, 2013**

**SECTION I - MATERIAL IDENTIFICATION**

**Proper Shipping Name: AF-M315E**
**Hazard Class: Class "C" Explosive (1.3)**
**Description: Liquid Monopropellant**

**SECTION II - HAZARDOUS INGREDIENTS**

**Hazardous Contents: Hydroxylammonium nitrate (HAN)-based propellant**

**SECTION III - PHYSICAL DATA**

| | |
|---|---|
| **Description:** | **Translucent, light Yellow-Orange Liquid** |
| **Appearance:** | **Liquid** |
| **Color:** | **light yellow-orange** |
| **Odor:** | **No Discernible Odor** |
| **Specific Gravity:** | **1.46** |
| **Freezing Point:** | **Does not freeze; glasses at -80°C** |
| **Reactivity in Water:** | **None** |

**SECTION IV - FIRE AND EXPLOSION**

**Flash Point : Not Applicable**
**Autoignition Temperature: 140 C (runaway temperature onset for slow cook-off)**
**Flammable Limits in Air (% by Volume),**
**Lower: Not Applicable**
**Upper: Not Applicable**

Apr 2008

ECAPS
ECOLOGICAL ADVANCED PROPULSION SYSTEMS

Program Identification Number
Version: 3

**SPACECRAFT PROPULSION SYSTEM**
Contractual Document

| | | | |
|---|---|---|---|
| Title of Document: | Propellant LMP-103S MSDS | | |
| Registration Number: | DOX-RBS-#63054 | Issue Date: | 2008-04-21 |
| Contract: | ESA Phase 3 | | |
| Work Package Number: | WP2200 | | |

| | | |
|---|---|---|
| Prepared | Peter Thormählen | Date: 2008-04-17 |
| Approved | Kjell Anflo | Date: 2008-04-18 |
| Released | Börje Åstrand | Date 2008-04-21 |

**COMPANY CONFIDENTIAL**



Distribution, SSC: BOA, KAN, THO, GBE, TOH, RMO

Distribution:

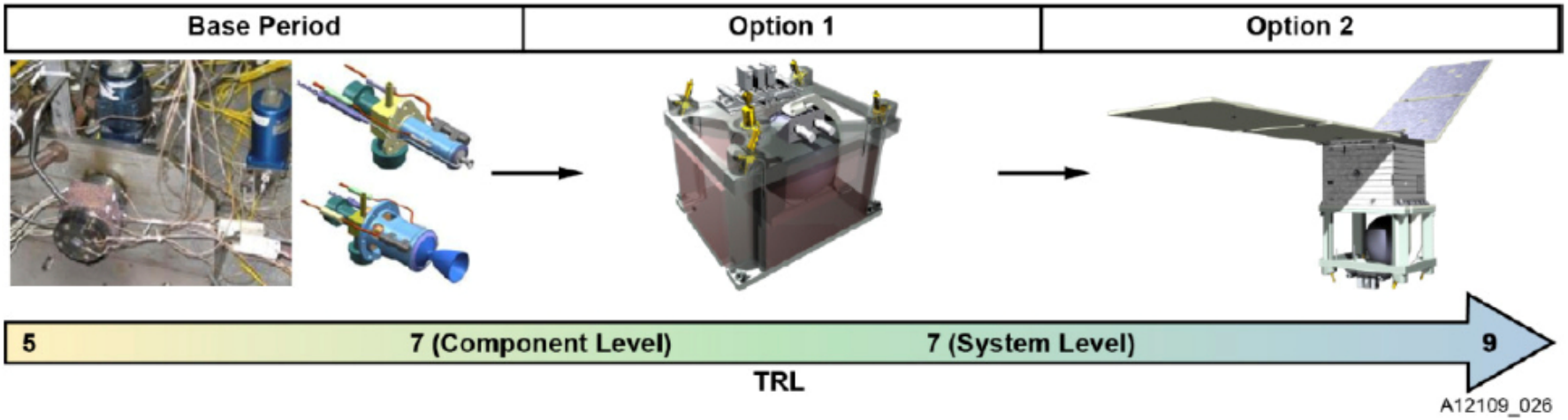
# TDM Solicitation

- 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.

# Green Propellant Infusion Mission (GPIM)
# NASA STMD Technology Demonstration Mission

**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

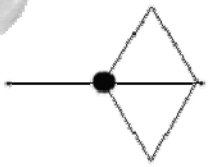


# MSFC approach to future

- 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



International

ISS

Lunar

Lagrange Point

Asteroid

Mars

WE ARE HERE!

**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.*

**2014**

**Current actvities:**

- *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.*

**2016**

**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.

**2018**

**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.

**2020-25**

*Lunar, Lagrange*

- APU application
- Landers
- HEOMD thrusters
- SMD missions

**2025**

Asteroids

**Future implementation**

→ SLS

→ Asteroid/Mars

→ Replace bi-prop up to 200 lbf

**2030 - 40**

*Mars*

***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

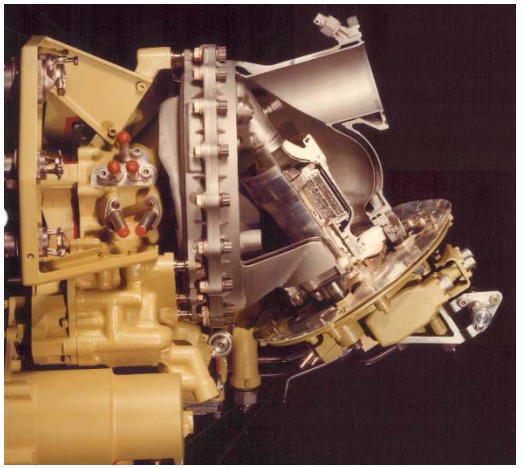
Phase 1 Feasibility Testing

Phase 2 Gas Generator Testing

SRB GG5116

Phase 3 System Testing

Orbiter APU Engineering Test Unit S/N-008



spares

spares

Additional hardware being excessed from SLS Core Stage:
- 9 gas generators
- 2 gas generator valve modules

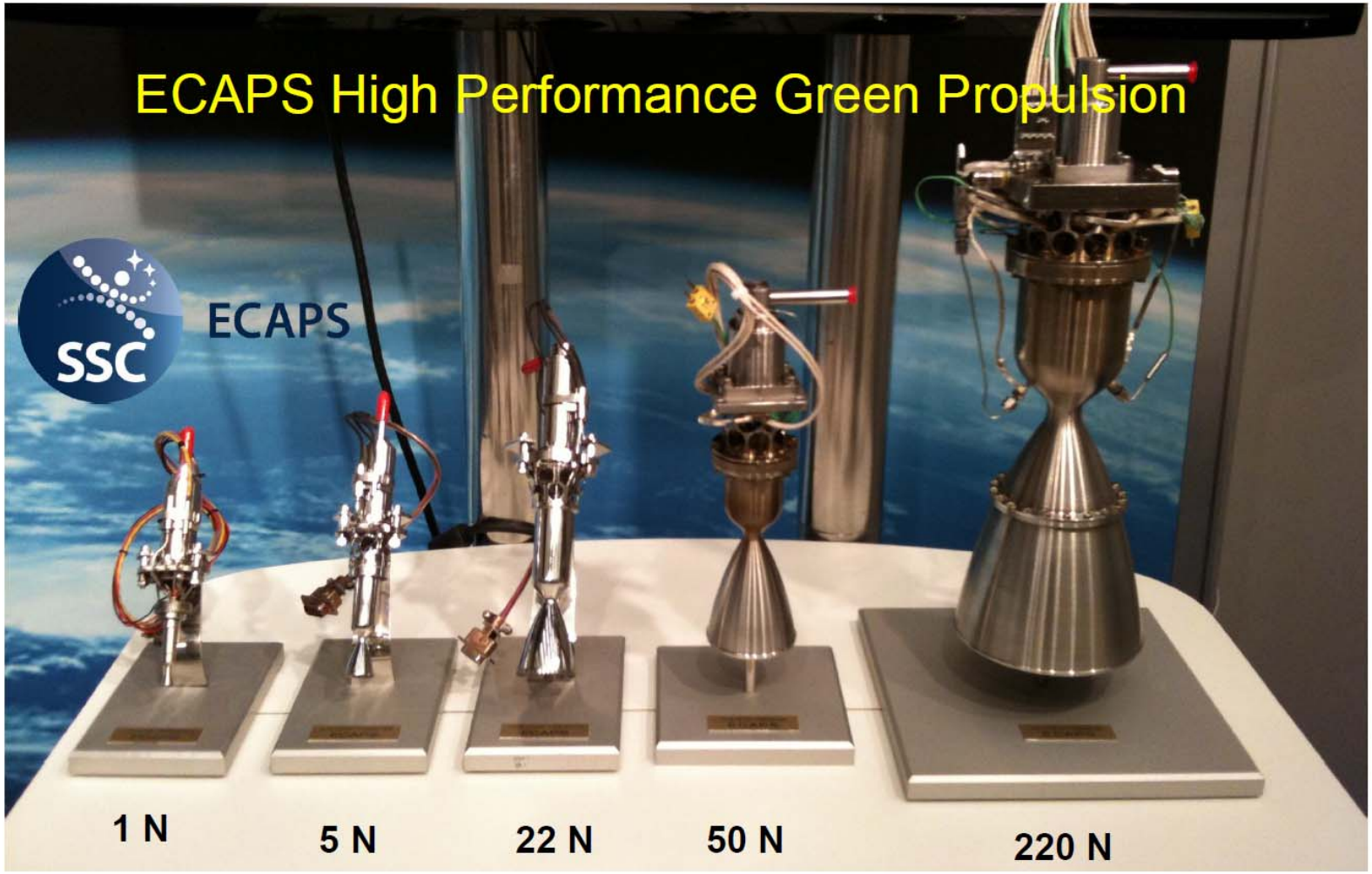
# Status of APU Feasibility testing

- 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

# ECAPS Hardware Fabricated




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

| Spacecraft or System Name | Most Recent Activity* | Human Rated | Biprop (MMH/NTO) | Mono-prop (N2H4) | Oxygen/ Methane | Hydrogen Peroxide, JP-8 | Dual Mode | Cold Gas | Non-Toxic | Cryogenic |
|---|---|---|---|---|---|---|---|---|---|---|
| Robotic Lunar Lander | Ongoing | No | ● (MMH/MON-25) | | | | | | | |
| Orion Service Module Propellant Tanks | Ongoing | Yes | ● | | | | | | | |
| Chandra | Flying | No | ● | ● | | | ● | | | |
| Ares I Upper Stage ReCS | Ongoing | Yes | | ● | | | | | | |
| Ares I First Stage RoCS | 2010 | Yes | | ● | | | | | | |
| Ares I-X First Stage RoCS | 2009 | No | ● | | | | | | | |
| PCAD LO2/LCH4 Engine | 2008 | No | | | ● | | | | | |
| Demonstration of Automated Rendezvous Technology (DART) | 2005 | No | | ● | | | | ● | | |
| NGLT LO2-Ethanol thruster | 2005 | No | | | | | | | ● | ● |
| In-House 25-lbf O2/CH4 Thruster | 2005 | No | | | ● | | | | ● | ● |
| Orbital Space Plane | 2004 | Yes | ● | ● | | | | | | |
| X-37 Orbital Vehicle (2nd version) | 2003 | No | ● | | | | | | | |
| X-38 Deorbit Propulsion | 2002 | No | | ● | | | | | | |
| NGLT LO2-LH2 Thruster | 2002 | No | | | | | | | ● | ● |
| X-37 (Original version) | 2001 | No | | | | ● | ● | | ● | |
| US Prop Module (for International Space Station (ISS)) | 2000 | Yes | ● | | | | | | | |
| X-33 Reaction Control System (gaseous $O_2/CH_4$) | 2000 | No | | | ● | | | | ● | |
| Interim Control Module (ICM) for ISS | 1998 | Yes | ● | | | | | | | |
| Aeroassist Flight Experiment | 1994 | No | | ● | | | | | | |
| Combined Radiation and Release Effects Satellite | 1991 | No | | ● | | | | | | |
| Orbital Maneuvering Vehicle (OMV) | 1990 | No | ● | ● | | | | | | |
| Inertial Upper Stage RCS; Transfer Orbit Stage RCS | 1990 | No | | ● | | | | | | |
| HEAO (3 spacecraft) | 1981 | No | | ● | | | | | | |
| Skylab | 1977 | Yes | | | | | | ● | | |
| Saturn S-IVB Auxiliary Propulsion System | 1973 | Yes | ● | | | | | | | |

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