



Green Propulsion: A NASA GSFC Assessment

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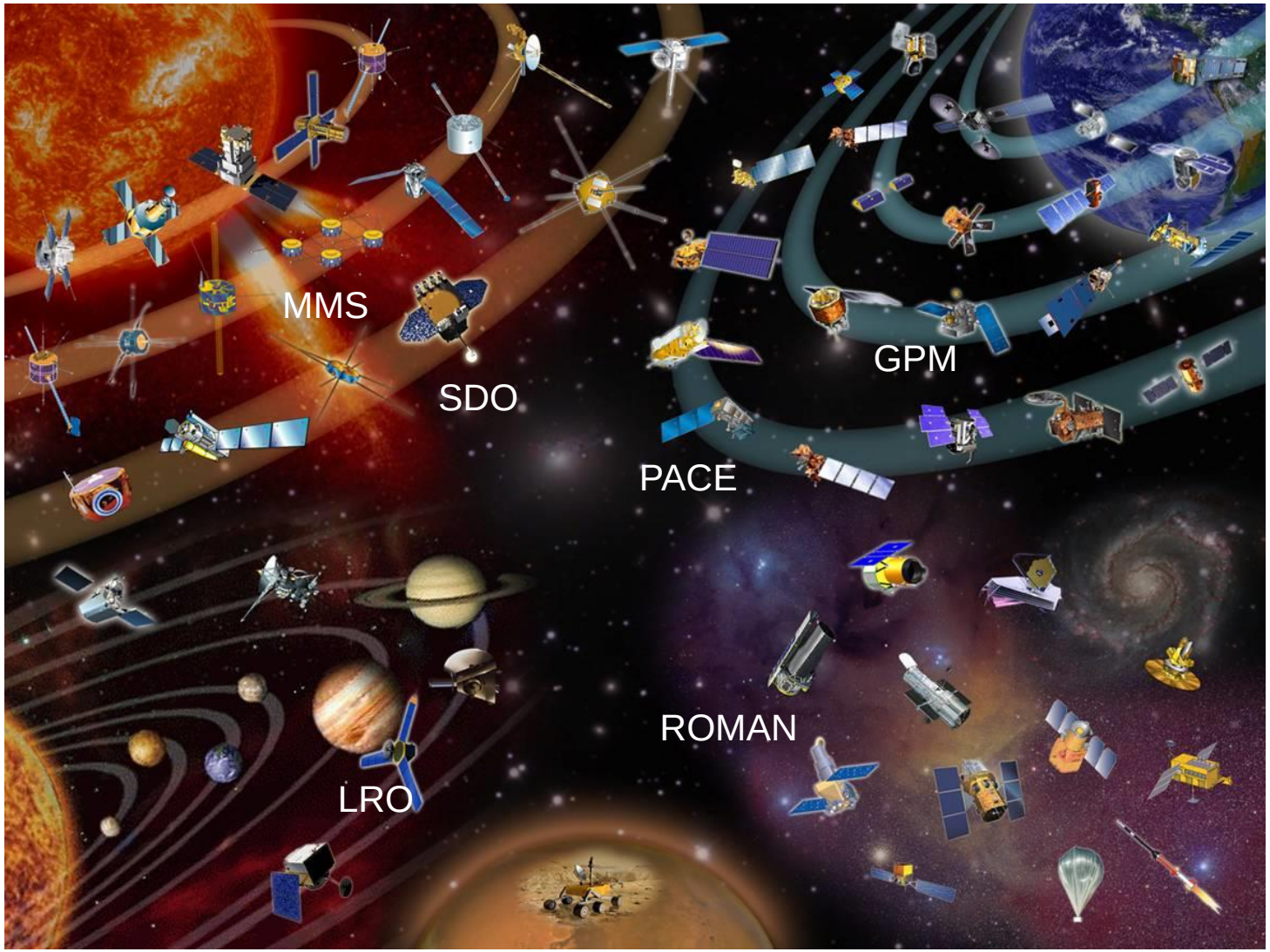
Space Propulsion 2024
Glasgow, Scotland
SP2024_00239

Goddard Space Flight Center



Named for rocketry pioneer Dr. Robert H. Goddard
NASA established the center as its first space flight complex in 1959.
The center studies Earth, the Sun, our Solar System and the Universe.

GSFC Science Missions



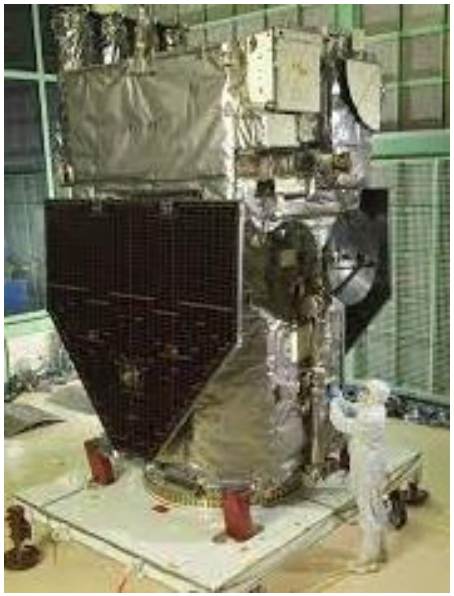
~ 300 successful scientific missions have been flown since 1959

GSFC In House Missions

LRO: Lunar Reconnaissance Orbiter
Launched: 2009
Dry Mass: 951 kg
Propellant Mass: 835 kg
Propellants: Hydrazine
Thrust Class: 22N / 90N
Propellant Throughput: 225 kg/ 450 kg
Delta-V: 1293 m/s



SDO: Solar Dynamics Observatory
Launched: 2010
Dry Mass: 1565 kg
Propellant Mass: 1409 kg
Propellants: MMH/MON-3
Thrust Class: 22N / 440N
Propellant Throughput: 450 kg/ 3000 kg
Delta-V: 1280 m/s



GPM: Global Precipitation Measurement
Launched: 2014
Dry Mass: 3305 kg
Propellant Mass: 545 kg
Propellants: Hydrazine
Thrust Class: 22N
Propellant Throughput: 214 kg
Delta-V: 227 m/s



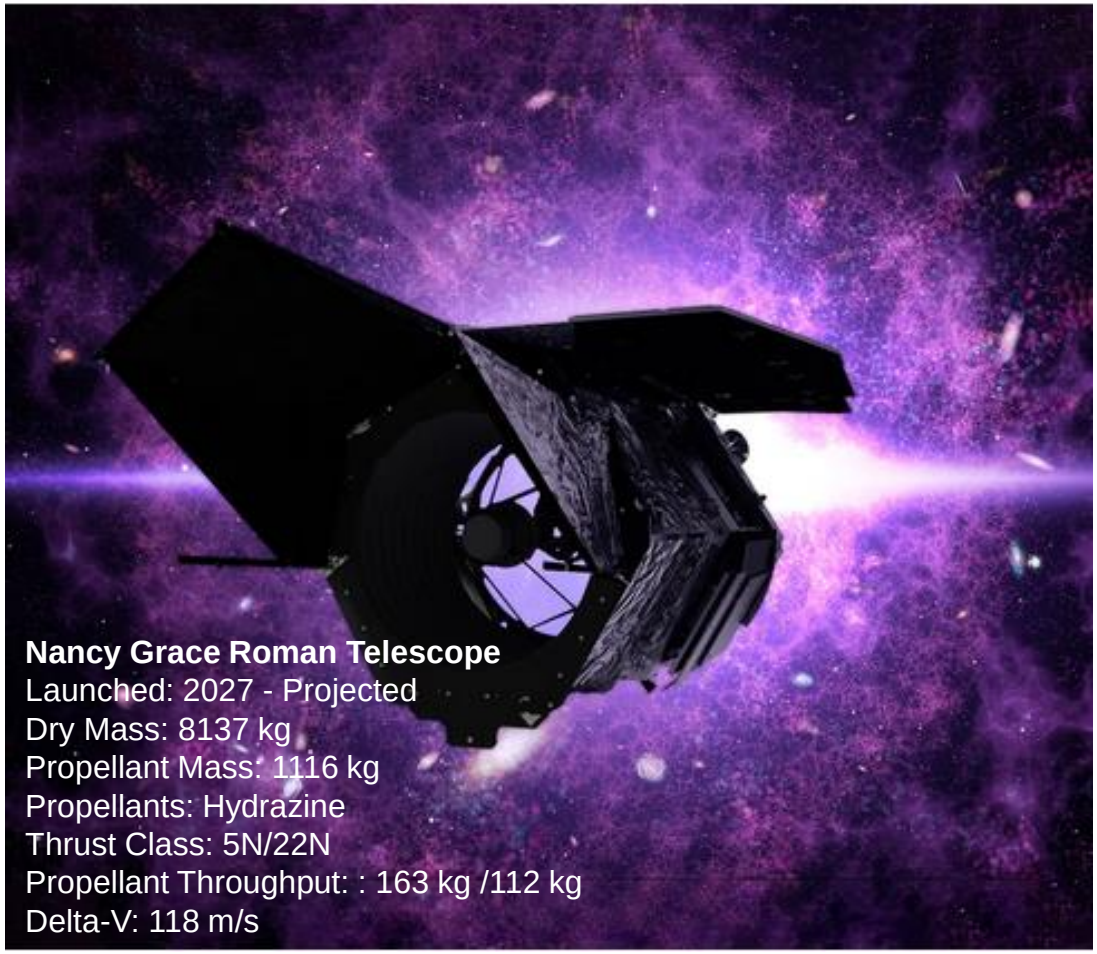
MMS: Magnetospheric Multiscale
Launched: 2015
Dry Mass: 1351 kg
Propellant Mass: 410 kg
Propellants: Hydrazine
Thrust Class: 5N /18N
Propellant Throughput: 47 kg /84 kg
Delta-V: 490 m/s



GSFC In House Missions

Europa Clipper
Launched: 2024 - Projected
Dry Mass: 3241 kg
Propellant Mass: 2750 kg
Propellants: MMH/MON-3
Thrust Class: 27N
Propellant Throughput: 674 kg
Delta-V: 1593 m/s





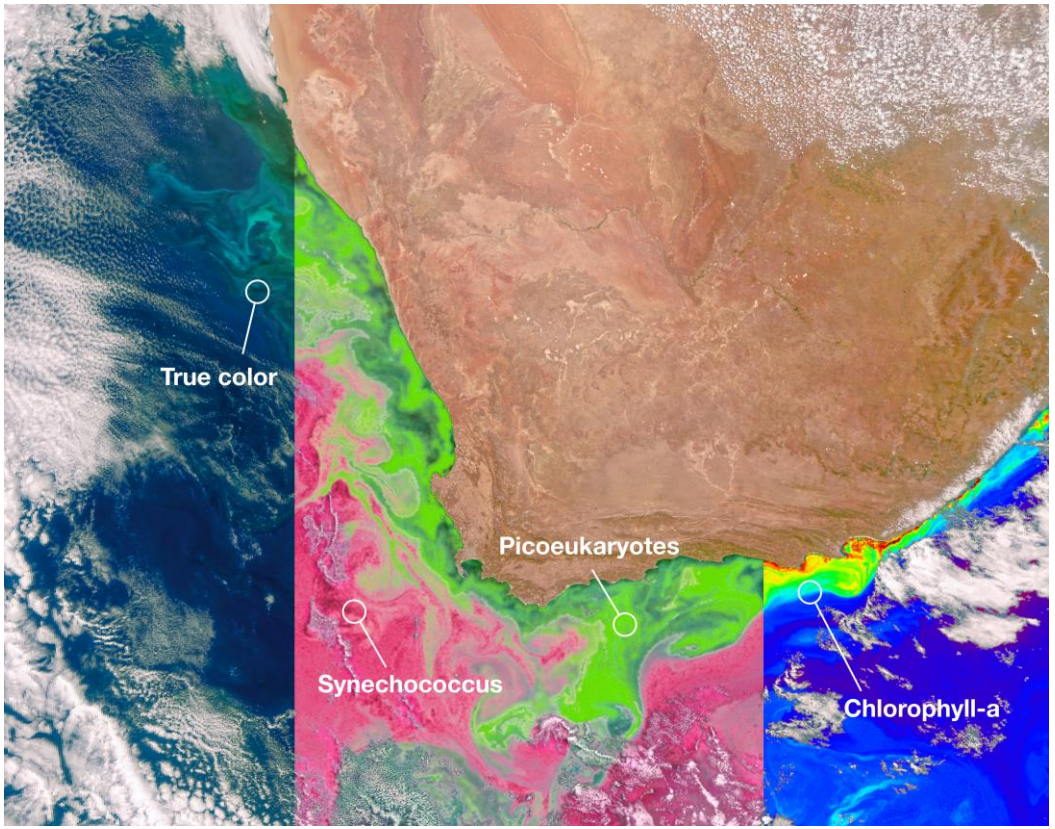
Nancy Grace Roman Telescope
Launched: 2027 - Projected
Dry Mass: 8137 kg
Propellant Mass: 1116 kg
Propellants: Hydrazine
Thrust Class: 5N/22N
Propellant Throughput: : 163 kg /112 kg
Delta-V: 118 m/s

These details are provided to illustrate GSFC's experience assembling medium to large scientific observatories with moderate to high Delta V requirements.

PACE Mission and Science

PACE: Plankton Plankton Aerosol Cloud ocean Ecosystem
Launched: 2024
Dry Mass: 1198 kg
Propellant Mass: 235 kg
Propellants: Hydrazine
Thrust Class: 22N
Propellant Throughput: 118 kg
Delta-V: 251 m/s





This first image released from OCI identifies two different communities of these microscopic marine organisms in the ocean off the coast of South Africa on Feb. 28, 2024. The central panel of this image shows *Synechococcus* in pink and picoeukaryotes in green. The left panel of this image shows a natural color view of the ocean, and the right panel displays the concentration of chlorophyll-a, a photosynthetic pigment used to identify the presence of phytoplankton.



GSFC Propulsion and Science

- The GSFC Propulsion Branch delivers expertise in spacecraft propulsion design, analysis, fabrication, assembly, integration, test, propellant loading, launch, and on-orbit operations
- LRO, SDO, GPM, MMS, and Europa Clipper, Roman and PACE are highlighted as examples of GSFC in-house missions.
- GSFC missions expect substantial propellant throughput and implements propulsion subsystems with the expectation that the engines are qualified (or will be qualified) for this level of use
- Technology maturation and infusion at GSFC is tied to scientific, or mission level improvement
  - Missions require persuasive rationale to consider and implement novel (i.e non-hypergolic) propellant technologies into GSFC science missions
- Why should a mission take a risk on propulsion technology, when there is a low-risk high heritage application to meet the science objectives?

Make More Compelling Science Possible!

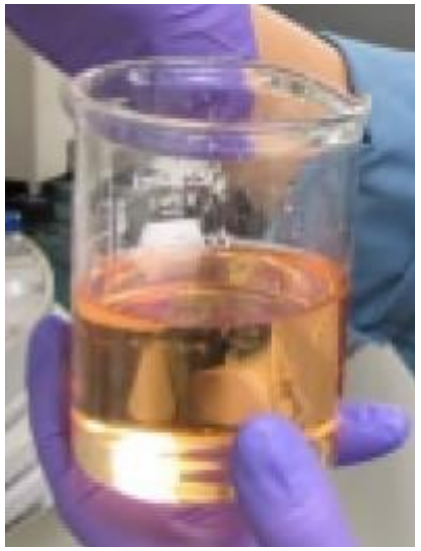


Green Propulsion

- Meaning
  - Low toxicity, reduced hazardous propellants
  - Increased performance and density over hydrazine
  - Easier and safer handling compared to hydrazine

- Benefits
  - **Reduce propellant mass and wet mass**
  - **Increase ΔV**
  - **Increase payload mass capability**
  - **Reduce tank volume requirements**
  - **Range processing simplification**
    - **Significant reduction in effort**

- Challenge:
  - To profit from the improved performance, the thrusters must demonstrate higher throughputs than currently shown
  - High Value Scientific Asset Infusion - programmatic risk



ASCENT Propellant



LMP-103S Propellant



Green Propulsion - Background

- Green propulsion, or more specifically higher performing, lower toxicity, safer to handle propellant formulations have drawn attention from the propulsion community since the 1990s

- As described then, and still true today, there is a strong desire to identify a propellant, or propulsion technology, that delivers increased performance while being safer to handle than monopropellant hydrazine or other hypergols

- The two most advanced and operationally mature green propellant technologies are pre-mixed bi-propellant blends
  - Advanced Spacecraft Energetic Non-Toxic (ASCENT) – AF-M315E rebranded
    - Hydroxylammonium nitrate (HAN) mixed with water and fuel
  - LMP-103S and associated High Performance Green Propulsion (HPGP)
    - Ammonium DiNitramide, methanol, water and ammonia

- Key green propulsion spacecraft implementation operational and design characteristics
  - Cannot be cold started: preheat temperatures ~300-400 C
    - Drives propulsion system power
  - Burn quite hot: 1600 - 1800C
    - Dictates high temperature materials
  - These propellants are safer and indeed lower toxicity propellants
    - Significant reduction in range processing



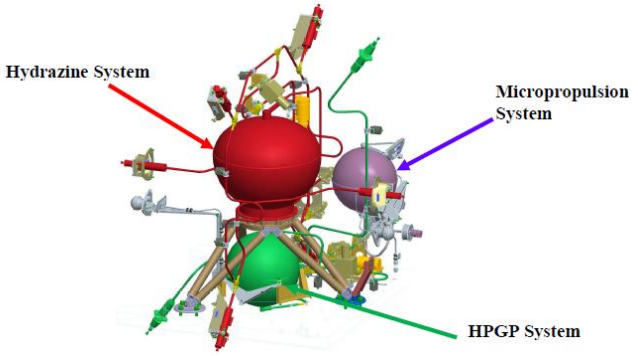
Green Propulsion Metrics

Metric	Hydrazine	ASCENT	LMP-103S
Performance	228 - 236 s	190 - 250 s	226 - 255 s
Density	1.004 g/cc	1.460 g/cc	1.240 g/cc
Life	1N: 102 kg 4N: 122.5 kg 22N: 260 kg	≥ 3% of hydrazine capability	≥ 20% of hydrazine capability
Power	----	≥ 10-20% due to single valve	≥ 20-30% due to dual seat valve
Materials Compatibility	Titanium CRES Teflon	Titanium Teflon Silica Free Diaphragms	Titanium CRES Teflon Silica Free Diaphragms
Vapor Pressure	0.2 bar @ 25 C	NONE	0.136 bar @ 25C
pH	10.1-10.7	3.7-4.0	9.1
Explosive Class	---	1.4C	1.4S
Hazard Statements ---------- Toxicity/ Exposure	1) Flammable liquid and Vapor 2) Toxic if swallowed 3) Fatal in contact with skin or if inhaled 4) Causes severe skin burns and eye damage 5) May cause an allergic skin reaction 6) May cause cancer 7) Very toxic to aquatic life with long lasting effects ---------- Toxic by ingestion and inhalation. Highly toxic by dermal contact. LD50 (Oral, Rat) = 60 mg/kg LD50 (Dermal, Rabbit) = 91 mg/kg LD50 (Inhalation, Rat) = 4 h 747 mg/m^3 TWA-PEL: 0.01 ppm	1) Fire or projection hazard 2) Toxic if swallowed – may cause genetic defects 3) Harmful with prolonged skin or eye contact – can cause irritation and dermititis 4) Toxic by ingestion, aspirating or absorbed through skin ---------- LD50 (Oral, Rat) = 550 mg/kg Skin Irritation (Rabbit) = Slight	1) Fire or Projection Hazard ---------- LMP-103S Mixture Estimates: LD50 (Oral) = 877 - 966 mg/kg LD50 (Dermal) = 40217 mg/kg LD50 (Inhalation) = 4 h 18707 mg/m^3 ADN: LD50 (Oral, Rat) = 617 mg/kg Methanol: LD50 (Oral, Rat) = 5628 mg/kg LD50 (Dermal, Rabbit) = 20 g/kg LD50 (Inhalation, Rat) = 4 h 45224 mg/m^3 TWA-PEL: 200 ppm Ammonium Hydroxide: LD50 (Oral, Rat) = 4050 mg/kg LD50 (Dermal, Rabbit) = 1 g/kg LD50 (Inhalation, Rat) = 4 h 4673 mg/m^3 TWA-PEL: 20 ppm



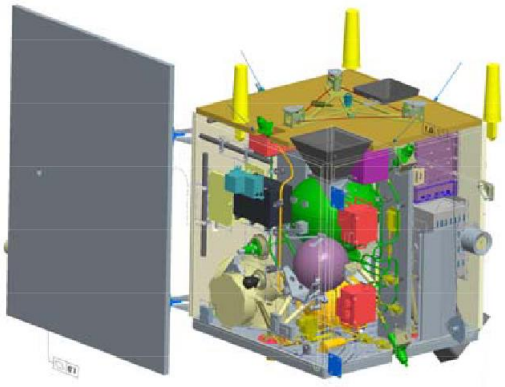
Early Green Flight Missions

- Prototype Research Instruments and Space Mission (PRISMA)
  - Launched 2010 / Mission Life: 5 years operational
  - PRISMA was a technology demonstration mission with several primary objectives in autonomous formation flying, rendezvous, and proximity operation.
  - HPGP propulsion system was a secondary mission objective
- PRISMA contained two liquid chemical propulsion systems (monopropellant hydrazine and HPGP)
- The HPGP propulsion system demonstrated over 5.5 kg of throughput and over 50,600 pulses shared by the two (2) HPGP 1N thrusters over 450 firing sequences
- The HPGP 1N engines proved increased performance at 6-12% higher specific impulse and 30-39% higher density impulse over the hydrazine system across the blowdown operation

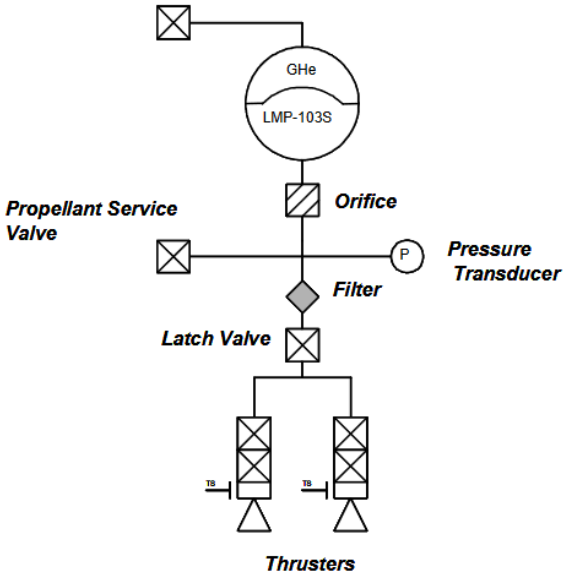


PRISMA Propulsion Systems

PRISMA HPGP COMPONENTS	
Component	**Material/Vendor**
Tubing/Fittings	CRES
Service Valves	Moog Inc.
Pressure Transducer	Bradford
Filter	Sofrance
Latch Valve	Moog Inc.
Orifice	Moog Inc.
Tank	Rafael
Flow Control Valves	Moog Inc
Thrusters	SSC/ECAPS



PRISMA Spacecraft

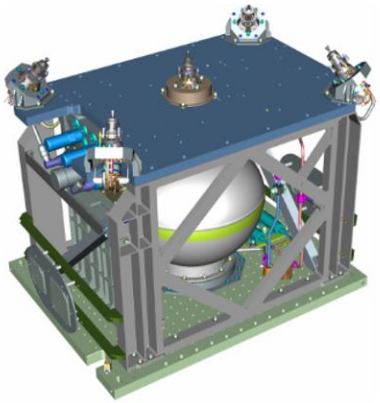


PRISMA Fluid System

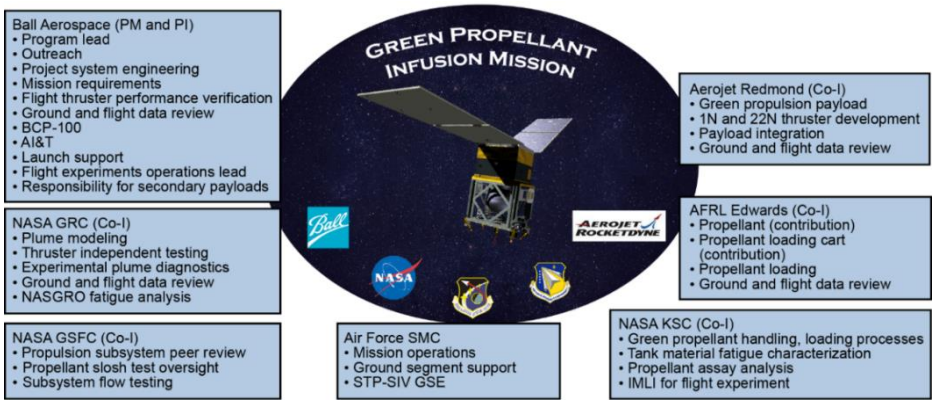
Early Green Flight Missions

- Green Propellant Infusion Mission (GPIM)
  - Awarded in 2012, Completed in 2015, Launched in 2019
    - Launch delay due to STP-2 vehicle readiness
  - Mission Life: 15 month operational
- Structured to advance ASCENT to the point of direct infusion
- The GPIM top-level requirements were targeted to:
  - Propulsion system architecture and performance
  - Holistic propellant operations assessment
- GPIM program pulled together the community stakeholders
- The GPIM mission demonstrated ~2% higher specific impulse increased performance relating to an estimated ~ 48% increased density impulse

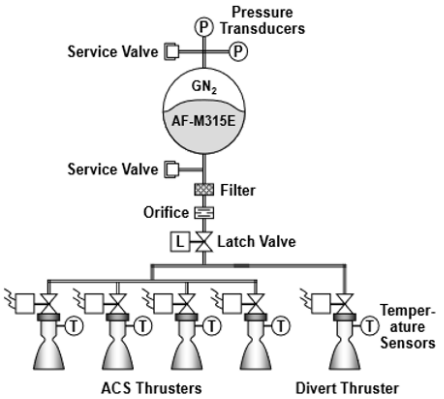
GPIM ASCENT COMPONENTS	
Component	**Material/Vendor**
Tubing/Fittings	Titanium
Service Valves	Vacco
Pressure Transducer	Tavis
Filter	Vacco
Latch Valve	Vacco
Orifice	Aerojet
Tank	Northup Grumman
Flow Control Valves	Aerojet
Thrusters	Aerojet



GPIM Propulsion System



GPIM Program Construct



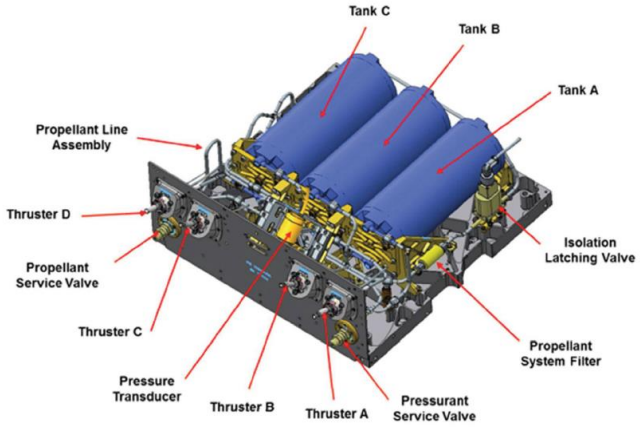
GPIM Fluid System



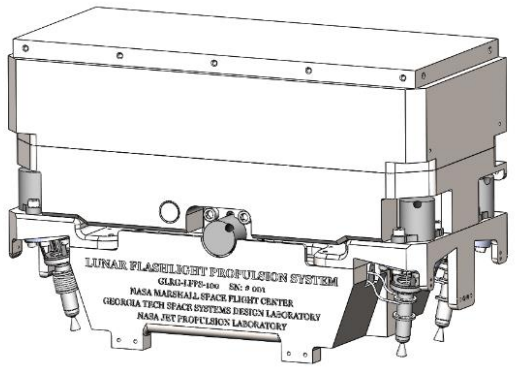
Follow On Missions & Efforts

- LMP-103S/HPGP
  - 1N systems, using LMP-103S propellant, have seen success on follow-on missions
  - SkySat identical propulsion subsystem design implemented on eighteen (18) spacecraft (SkySat-3 to -21)
  - A total of thirty spacecraft have implemented HPGP 1N systems
  - SkySat constellation and Astroscale ELSA-D 1N HPGP systems have experienced technical issues associated with thruster non-fire anomalies
  - ArgoMoon is flying a 100mN HPGP engine
  - In a push to investigate higher thrust engines (5N and 22N), NASA GSFC and the Swedish National Space Agency (SNSA) established a collaborative Implementing Arrangement (IA) for the respective agencies to support HPGP maturation

- ASCENT
  - ASCENT efforts shifted toward a focus on advancing the GPIM 1N engine design and further work for SmallSat applications with 100 mN thruster class sizing
  - An ASCENT propulsion module flew on the Lunar Flashlight mission in 2022 to demonstrate 100 mN thrust class engines;
    - The mission ended pre-maturely due to propulsion subsystem anomalies



SkySAT HPGP System



Lunar Flashlight ASCENT Propulsion System



Green Propulsion Trades

- Mission trade studies performed in the design phase ensure appropriate technology selection and subsystem readiness for a given mission paradigm

- ASCENT and HPGP system trade studies have been evaluated against GSFC missions
- In each example evaluated in these trade studies, the propulsion subsystem performance technically benefited from green propulsion architecture due to the increased performance and propellant density
- The performance enhancement is weighed against the current maturity state and incurred risk
  - Results clearly indicate that the ASCENT and HPGP engines could not be baselined in GSFC missions due to the lack of demonstrated propellant throughput levels (i.e qualification) necessary to meet the identified scientific mission needs
  - For broad application, GSFC propulsion desires ASCENT and HPGP engine designs with varying thrust classes (1N, 5N, 22N, and higher), each at high throughput levels to provide propellant alternatives to typical hypergols propulsion subsystem architectures

- The PACE project performed a trade study of the hydrazine baseline against a HPGP system to:
  - Increase propulsion system performance as risk mitigation for observatory mass growth
  - Reduce hazardous ground operations and
  - Streamline range processing, reducing cost



PACE HPGP Trade

- Motivation:
  - HPGP 22N engine technology had been advancing due to ECAPS missions post-PRISMA and through the NASA SNSA IA efforts
  - The IA is intended to achieve HPGP 5N and 22N flight engine designs and demonstrated long life testing to LMP-103S throughputs of 100 kg and 150 kg, respectively.
    - Specifically, the 2017 HPGP 22N Engineering Qual-Modlel long life test campaign
  - The Green Propellant Loading Demonstration (GPLD) was the inaugural U.S. domestic LMP-103S loading operation exercise demonstrating safe propellant transport, storage, and handling at GSFC/Wallops Flight Facility (WFF)
  - The GPLD exercise demonstrated a significant reduction in effort compared to a traditional hydrazine equivalent loading, providing empirical evidence of Range related cost and schedule savings
  - HPGP compatible with existing COTS hardware and CRES materials

- Reasoning:
  - PACE was struggling with high risk of mass growth and the >15% mass margin requirement heading into the mission Preliminary Design Review

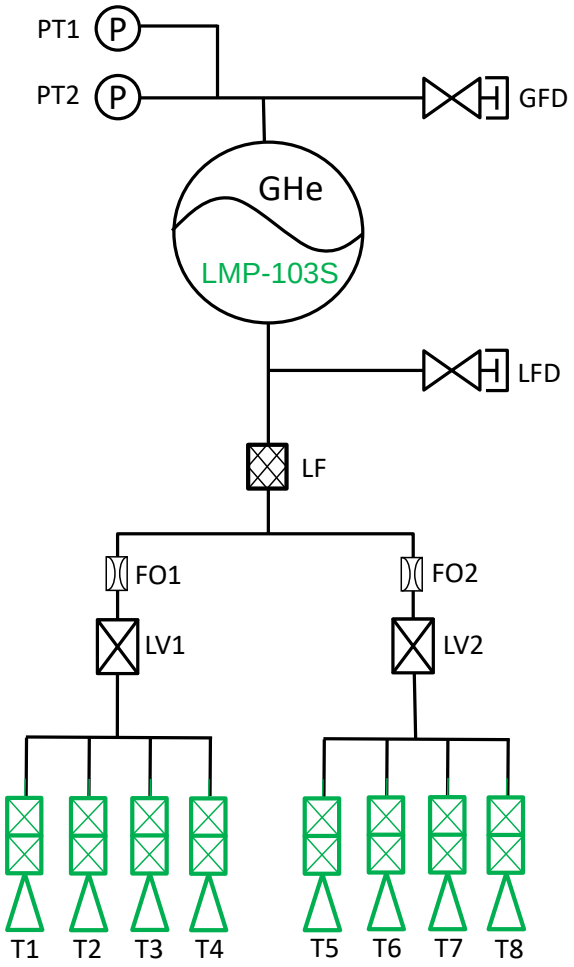
- Trade space:
  - High performance green propellant (HPGP) system (LMP-103S) versus baseline hydrazine



PACE Propulsion Trade

	N_2H_4	HPGP
Propellant	Hydrazine	LMP-103S
Tank Volume	315.5 L	
Blowdown	27.6 – 5.5 bar(a)	24 – 5.5 bar(a)
Dry Mass Capability	1600 kg	1900 kg
Propellant Load	240 kg	250 kg (Mass Limit)
Dry Mass Capability	1600 kg	2200 kg
Propellant Load (Maximizing Volume)	240 kg	288 kg (Tank Qualification)
Dry Mass	1600 kg	
Delta-V Capability (Tank Mass Limit)	251 m/s	294 m/s (250 kg propellant)
Delta-V Capability (Tank Volume Limit)		336 m/s (288 kg propellant)

HPGP System allows increased dry mass capability ~ 300 kg from Baseline



HPGP Design



PACE Propulsion Trade

- The HPGP PACE propulsion option supported as an active trade from 2013-2017

- The HPGP system was evaluated by all spacecraft subsystems to evaluate impacts:
  - Power: Higher power is requisite for increased pre-heat temperature
  - Avionics: Regulated reactor temperature controller (Low duty)
  - Thermal: Higher steady state operating temperature (1600C)
  - Structures: Higher propellant loading (if selected), and larger dry mass (if selected) would have structural implications
  - Contamination: Plume to be carefully considered
  - Safety: All positive
  - Mission Assurance: healthy scepticism for the new technology but a strong desire to follow the design, and testing

- During the 2017 HPGP 22N EQM testing, an anomaly was encountered at 53 kg throughput
  - Investigations revealed the root cause as a retainer plate during random vibration testing prior to hot fire
  - This test setback coupled with the tight PACE mission schedule made it difficult to move forward with the HPGP propulsion subsystem option

- PACE made the decision to fly hydrazine monopropellant



Way Forward

- ASCENT is under continued development, with several contracts supporting programs focused on 1N, and 22N and 100/110N class engines
- NASA MSFC-manged Green Propulsion Dual Mode mission will test chemical and electrospray ASCENT technology

- The NASA SNSA IA for HPGP maturation is still ongoing with an anticipated 5N thruster test campaign in 2024 and a 22N test campaign in 2025.
- The continued on-orbit commercial use of the ECAPS 1N thrusters has yielded improvements to manufacturing practices and efficiencies relevant to the HPGP 5N and 22N designs

There are remaining technical, cost, and schedule risks to both ASCENT and LMP-103S/HPGP high value scientific asset propulsion system adoption

- Aerojet, the GPIM ASCENT engine manufacturer, is currently developing a drop in replacement formulation for hydrazine with reduced vapor pressure and higher density in collaboration with Purdue University, the Aerospace Corporation and NASA GSFC



Conclusions

- Hydrazine and hypergolic bi-propellant subsystem architectures have operated on countless spacecraft and have a long history of successful operation
  - These propulsion systems rest upon high heritage designs and known safety critical handling practices
  - These propellants will, in practicality, continue to be selected for missions for years to come

- The evidence provided herein demonstrates that even with the multitude of successes realized for hypergolic propulsion systems, there remains a strong case and over >30 years basis for pursuing higher performing safer propellant formulations to enable mission success

- This is substantiated by vast research, successful on-orbit demonstrations, and follow-on missions.

For broader adoption into NASA GSFC missions, and to truly capitalize on the mission related benefits, the engine development is fundamental. All mission benefits are contingent on high performing long life green propulsion engine designs