GREEN PROPULSION : A NASA GSFC ASSESSMENT

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ABSTRACT:

In the ever-changing paradigm of efficient and capable spacecraft design, scientific missions continue pushing spacecraft subsystems to deliver effective solutions to meet challenging new mission/spacecraft applications. From an in-space storable liquid chemical propulsion perspective, monopropellant hydrazine is a dependable propellant. Bi-propellant architectures offer even superior performance, but add the complexity of a hypergolic fuel (hydrazine/ mono-methyl hydrazine) and oxidizer (Nitrogen Tetroxide/ mixed oxides of nitrogen) dual tank combination. These propulsion system designs (mono-propellant and bi-propellant) have high heritage, high propellant throughput qualified engines, widely tested material compatibility, qualified fluid delivery commercial-off-the-shelf components, known handling practices, and repeatable performance in successfully delivering on mission requirements.

NASA and the broader propulsion community have historically selected hypergolic propellants for most mission applications. The space propulsion community has learned to successfully handle these highly toxic and hazardous materials, navigate the regulated use and the associated safety protocols, personnel protective equipment, and unique training standards – all requisite for loading spacecraft propulsion systems with hypergolic propellants. The question now arises as to what is next for in-space chemical propulsion? Is there an alternative, or even replacement, to the reliable hypergolic fluids, or propellant alternatives that promise increased mission benefits?

With the evolution and proven advancements in innovative in-space green propellant technologies capable of delivering benefits to scientific missions, concern over the reliability and infusibility of this higher performing and safer to handle class of propellants is waning. As NASA science missions move forward with the potential flight infusion of green propulsion, NASA and the broader propulsion community are working to address remaining gaps in hardware development, reliability, performance, unique operational considerations, and risk mitigations for high value scientific assets.

1. NOMENCLATURE

ADN = *Ammonium dinitramide*
AFRL = *Air Force Research Laboratory*
ASCENT = *Advanced Spacecraft Energetic Non-Toxic*
COTS = *Commercial Off The Shelf*
CRES = *Corrosion Resistant Steel*
ECAPS = *ECological Advanced Propulsion Systems*
FOI = *Swedish Defence Research Agency*
GPIM = *Green Propellant Infusion Mission*
GPLD = *Green Propulsion Loading Demonstration*
GPM = *Global Precipitation Measurement*
GRC = *Glenn Research Center*
GSFC = *Goddard Space Flight Center*
HAN = *Hydroxylammonium nitrate*
HPGP = *High Performance Green Propulsion*
IA = *Implementing Arrangement*
IHPRPT = *Integrated High Payoff Rocket Propulsion Technology*
KSC = *Kennedy Space Center (NASA)*
LMP-103S = *Liquid Monopropellant 103S*
LRO = *Lunar Reconnaissance Orbiter*
MMH = *Mono-methyl hydrazine*
MMS = *Magnetospehric Multi-Scale*
MSFC = *Marshall Space Flight Center (NASA)*
NASA = *The National Aeronautics and Space Administration*
NTO/MON = *Nitrogen Tetroxide/Mixed Oxides of Nitrogen*
OCI = *Ocean Color Instrument*
PACE = *Plankton, Aerosol, Cloud, ocean Ecosystem*
PMD = *Propellant Management Device*
PRISMA = *Prototype Research Instruments and Space Mission*
ROMAN = *Nancy Grace Roman Space Telescope*
SDO = *Solar Dynamics Observatory*
SMD = *Science Mission Directorate*
SNSA = *Swedish National Space Agency*
SSC = *Swedish Space Cooperation*
STMD = *Space Technology Mission Directorate*

2. INTRODUCTION

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) has a long history in managing and constructing robotic scientific missions for the NASA Science Mission Directorate (SMD). The Earth Science, Heliophysics, Planetary, and Astrophysics Divisions are GSFC's most common SMD customers, with a projected 300 successful missions flown since GSFC became an official center in 1959. A large portion of these missions are out-of-house collaborations, meaning the mission is built by NASA contractors under GSFC management. A smaller percentage of missions are GSFC in-house missions that are managed, manufactured, built, tested, loaded, and operated by GSFC. Figure 1 illustrates the diverse GSFC mission portfolio across the SMD divisions [1]. In the illustration, the upper left is Heliophysics, upper right is Earth Science, lower left is Planetary, and lower right is Astrophysics. This summary highlights the proven capability and significant history of GSFC mission success.

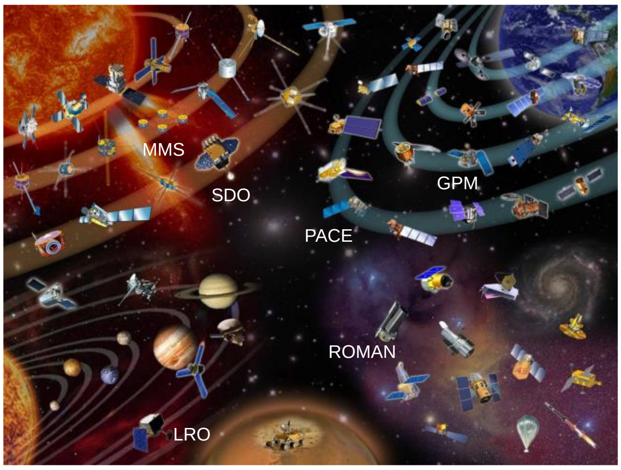

Figure 1. GSFC SMD Missions

GSFC systems engineering work with the world renowned GSFC scientists in maturing SMD science objectives into successful missions. These engineering experts examine mission needs collectively to establish the Level-1 requirements to deliver compelling science for NASA. Once the science case is made, the high-level implementation Level-2 requirements are structured to define instrument payload selection and the vehicle systems required to deliver the compelling science. The mission needs are then portioned into relevant lower-level spacecraft bus requirements (Levels 3 - 4) for discipline engineering (e.g. Propulsion, Command & Data Handling, Power, etc.) to design subsystems to enable the mission.

The GSFC Propulsion Branch delivers expertise in spacecraft propulsion design, analysis, fabrication, assembly, integration, test, propellant loading, launch, and on-orbit operations. In Figure 1, the Magnetospheric MultiScale (MMS), Solar Dynamics Observatory (SDO), Lunar Reconnaissance Orbiter (LRO), Global Precipitation Measurement (GPM), Plankton Aerosol Cloud ocean Ecosystem (PACE), and Nancy Grace Roman Space Telescope (ROMAN) are highlighted as examples of GSFC in-house missions. For each of these, the propulsion system was designed, tested, and delivered by GSFC Propulsion [2-5].

Of these GSFC in-house missions, PACE is the most recent to launch in early 2024, with ROMAN up next, scheduled to launch in 2027. The MMS, GPM, PACE and ROMAN propulsion systems implement hydrazine monopropellant blowdown architectures. LRO employs a pressure regulated hydrazine monopropellant system, and SDO is a high performance bi-propellant system (MMH/MON 3). GSFC Propulsion has significant experience in hypergolic propellant handling to perform spacecraft loading and equipment decontamination operations. GSFC Propulsion managed and conducted the MMS, SDO, LRO, GPM, and PACE (and will perform for ROMAN) propellant loading at the launch range.

Table 1, below, shows the spacecraft and propulsion system dry mass, the mission required Delta-V, the propellant load, and the required propellant throughput per engine thrust class for these missions. Since ROMAN has not launched yet, the masses listed are the expected current best estimates. These details are provided to illustrate GSFC's experience assembling medium to large scientific observatories with moderate to high Delta V requirements.

Table 1. GSFC MISSIONS [2-5]

Mission	SC/PROP Dry Mass	Delta-V	Propellant Load	Propellant Throughput
	kg	m/s	kg	kg
MMS	1351 107	490	410	5N: 47 18N: 84
GPM	3305 81	227	545	22N: 214
PACE	1198 40	251	235	22N: 118
ROMAN	8137 250	118	1116	5N: 163 22N: 112
LRO	951 142	1293	835	22N: 225 90N: 450
SDO	1565 156	1280	1409 MMH: 539 MON-3: 870	22N: 450 kg 440N: 3000 kg

Spacecraft dry mass and mission specific Delta- V needs drive the propulsion subsystem design and, ultimately, determine the required spacecraft propellant mass. Buried inside the high-level mission needs are more detailed propulsion subsystem requirements that define the engine thrust class, propellant throughput, and many other details such as the mechanical, electrical, thermal, and on-orbit operational propulsion subsystem interface requirements.

As shown in Table 1, many GSFC missions expect substantial propellant throughput and, as such, the team implements propulsion subsystems with the expectation that the engines are qualified (or will be qualified) for this level of use. Further, the engines proven operational box should be large enough to allow for a specific GSFC mission use case to easily meet a “qualification by similarity” approach, meaning the engine hardware is qualified for the mission and requires no formal re-qualification program or, at most, minimal protoflight testing. Even with the long history of numerous hydrazine engines tested and broad operational utility, there are still mission use cases that are just different enough to warrant delta-qualification testing. For LRO, a delta-qualification was undertaken to demonstrate increased throughput for end-of-life performance [4]. For MMS, a spinner spacecraft design, the upper and lower deck thrusters operated at unique and dissimilar pulse width modulations, requiring two (2) different hydrazine engine qualification campaigns [6]. For both LRO and MMS, the operation was beyond the historically tested envelope, and as such, mission specific qualification was performed on flight class engine hardware.

Each of the missions listed in Table 1 used engines in the 5-22N thrust class range, with SDO adding a 440N class main engine for the transfer to Geosynchronous Orbit. As part of a systems level investigation to green propulsion, a survey was conducted to assess relevant thrust class sizing for SMD and GSFC missions. It was determined that the 5N and 22N thrust class were the most utilized [7].

Based on extensive in-house propulsion subsystem experience and work with community partners, GSFC Propulsion follows, supports, and aids efforts in propulsion subsystem and new propellant/propulsion advancements. Technology maturation and infusion at GSFC is tied to scientific, or mission level improvement. Propulsion technology maturation is no different and must be related to a science or mission gain. 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?

To proactively address the challenges around infusing new propulsion technology into a culturally risk-averse community, NASA continues working to address risk reduction for the top two candidate green propellants: Advanced Spacecraft Energetic Non-Toxic or ASCENT (AF-M315E rebranded) and LMP-103S with associated High Performance Green Propulsion (HPGP). Over the past thirty (30) years much work has matured these two propellants with expectations to field into operational NASA missions.

Collected herein is a summary of the top candidate green propellants history, trade studies, risks, and investigation into future prospects for green propellant operational infusion into GSFC robotic science missions.

3. 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 [8-9]. 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. Significant research has been invested towards identifying appropriate propellant candidates to accomplish this goal. The two (2) most advanced and operationally mature green propellant technologies today are stable pre-mixed bi-propellant blends (ASCENT and HPGP). In addition to widely touted ASCENT and HPGP safety benefits, propellant performance is higher owed to the increased density impulse when compared to monopropellant hydrazine. This metric is the product of the propellant’s specific impulse and density, or more simply the delivered impulse per propellant unit volume.

The ASCENT propellant was developed by the U.S. Air Force, through goals set forth in the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. The U.S. Army’s successful experiences with Hydroxylammonium nitrate (HAN) based propellants showed potential in both performance and safety [8-9] and the IHPRPT program pushed for the development of a propellant technology that is a ~50% density impulse increase as compared to hydrazine [10]. The ASCENT HAN based liquid propellant delivers ~5% higher specific impulse and 46% higher density [11] over hydrazine. Finalized in 1998, the ASCENT propellant is a mixture of HAN, water, and a highly hygroscopic fuel [12].

Internationally, extensive work on an ammonium dinitramide (ADN) based propellant started in 1997 through a collaborative venture between the Swedish Space Cooperation (SSC), ECological Advanced Propulsion Systems (ECAPS) and the Swedish Defense Research Agency (FOI). The LMP-103S mixture developed through this High Performance Green Propulsion (HPGP) maturation effort is 63.0% ADN, 18.4% Methanol, 4.6% Ammonia, and water to balance (~ 14%) [13]. The ADN salt is dissolved in the methanol, water, and ammonia mixture, with methanol serving as the fuel component, water tempering the combustion temperature, and the ammonia as a stabilizer [14]. LMP-103S delivers ~6% higher specific impulse and 30% higher density [15].

ASCENT and HPGP thruster designs drive key spacecraft implementation operational and design characteristics that are atypical to hydrazine monopropellant architectures. The most notable difference to on-orbit operations is that ASCENT and HPGP engines cannot be cold started, dictating that operations require pre-heat before use. This can be constraining to a mission due to the nominal pre-heat temperatures required (315°C for ASCENT

[11] and 350°C [16] for HPGP), which levies requirements on the spacecraft power system to achieve these high pre-heat temperatures. While hydrazine engines are typically pre-heated to maximize engine life, it is to a much lower start temperature at (70-90°C). Hydrazine engines can be cold started for emergency maneuvering applications and the engine designs are qualified for a discrete number of cold starts.

The ASCENT and LMP-103S propellant formulations also burn quite hot, at ~1800C for ASCENT [17], and ~1600 for LMP-103S [16]. For comparison, monopropellant hydrazine engines operate at ~ 900°C and ~1300 C for a bi-propellant (MMH/(NTO/MON)) combination. The ASCENT and HPGP engine designs need a suitable selection of high temperature (and generally more expensive) materials, to successfully operate and survive.

Table 2, below, lists a summary of parameters for the ASCENT and LMP-103S propellant as compared to monopropellant hydrazine. This list is specific to propulsion design characteristics for construction and operation. In addition, in the handling aspects for and ground testing and Range campaign. The ASCENT and LMP-103S hazard statements readily demonstrates that green propellants are safer and indeed lower toxicity materials. However, each have fundamental hazards to mishandling and require a healthy respect and proper training.

4. EARLY GREEN PROPULSION FLIGHT MISSIONS

4.1. PRISMA

The in-space propulsion community experienced a green propulsion rekindling initiated through the Prototype Research Instruments and Space Mission (PRISMA) launched in 2010, which demonstrated HPGP performance in space. PRISMA was a technology demonstration mission with several primary objectives in autonomous formation flying, rendezvous, and proximity operation. PRISMA's HPGP propulsion system was a secondary mission technology maturation objective [26]. The PRISMA mission pushed boundaries in terms of green propellant technology advancement to date and provided the path to an on-orbit operational mission.

PRISMA was developed by the SSC with funding from a European collaboration of partner states [26]. The PRISMA spacecraft and propulsion system, shown in Figure 2, contained two (2) liquid chemical propulsion systems (monopropellant hydrazine and HPGP), each operated in blowdown mode. The hydrazine system used six (6) 1N thrusters with a 11 kg propellant load. The HPGP system used two (2) 1N thrusters with a 5.5 kg LMP-103S propellant load. The propulsion subsystems were contained and tightly packaged inside the spacecraft structure as shown in Figure 2.

Table 2. Propellant Metrics [18-25]

Metric	Hydrazine	ASCENT	LMP-103S
Performance	228 - 236 s [20-21]	190 - 250 s [22]	226 - 255 s [16, 24]
Density	1.004 g/cc	1.460 g/cc	1.240 g/cc
Life	1N: 102 kg [20] 4N: 122.5 kg [20] 22N: 260 kg [21]	≥ 3% of hydrazine capability [22,11]	≥ 20% of hydrazine capability [16,24]
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

The HPGP fluid schematic is identical to historical blowdown hydrazine monopropellant architectures. The hydrazine and HPGP propulsion systems were assembled from standard hydrazine commercial-off-the-shelf (COTS) fluid components and typical corrosion resistant (CRES) stainless steel tubing. The propellant tank and system filter went through a delta-qualification specific for the implementation of a silica free diaphragm material, and filter fluid interface geometry [27]. A listing of the PRISMA propulsion fluid components (material/vendor) is provided in Table 3, below.

The PRISMA propulsion subsystem design was of particular interest due to having the dual systems, allowing for the direct comparison between hydrazine and HPGP. On-orbit operations, performance, and the dissimilar pre-launch range processing constraints were evaluated. A similar type of performance characterization mission was conducted in the 1960s to operationally compare hydrogen peroxide and hydrazine [12]. In this comparison, the newer propellant hydrazine's performance was higher than hydrogen peroxide. This is analogous to the PRISMA comparison, to which HPGP proved superior to hydrazine. Since PRISMA was HPGP's first use on-orbit, and a secondary mission objective, considerable work was performed to characterize and define the mechanical, thermal, and electrical interface requirements, and potential spacecraft plume interactions [28].

The PRISMA Mission was launched on 15 June 2010, and after a 5-year extended mission, was decommissioned in 2015 [29]. 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 [29].

4.2. GPIM

The inaugural ASCENT mission was the Green Propellant Infusion Mission (GPIM). GPIM was a Technology Demonstration Mission awarded in 2012 by NASA's Space Technology Mission Directorate (STMD) to Marshall Space Flight Center (MSFC). The GPIM program construct is shown in Figure 3, outlining the cross cutting, collaborative, and collective GPIM implementation approach [30].

The GPIM program pulled together a consortium of NASA, U.S. Air Force, and commercial propulsion community stakeholders throughout the U.S. to leverage key technical expertise in ASCENT propulsion technology maturation. GPIM Level-1 requirements were explicitly linked to the ASCENT propellant and propulsion technology. Structured to advance ASCENT to the point of direct infusion into suitable propulsion applications, the GPIM top-level requirements were all targeted to the propulsion system architecture, propellant performance, attitude control thruster (engine pulsing characteristics and pointing accuracy), and orbital maneuvering thruster performance. The final top-level deliverable was a propellant operations assessment [30].

The GPIM mission was led by Ball Aerospace as the Principal Investigator, and Ball also provided the GPIM spacecraft bus. The original GPIM construct included four Co-investigators: Aerojet, NASA Glenn Research Center (GRC) and Kennedy Space Center (KSC), and the Air Force Research Laboratory (AFRL) [31].

Aerojet was responsible for the GPIM propulsion subsystem delivery to Ball Aerospace, the spacecraft bus integrator. Aerojet's responsibility was the complete development and qualification of the 1N and 22N ASCENT engines. NASA GRC's major contribution to GPIM was the ASCENT engine plume testing and modelling [32]. Plume characterization is a crucial propulsion to spacecraft interaction that must be characterized to ensure that thruster plumes will not contaminate or impinge on sensitive spacecraft surfaces (e.g. solar arrays, instrument optics).

NASA KSC provided GPIM the historical expertise in propellant storage, handling, and assay operations. NASA KSC also facilitated and performed propellant tank material stress intensity testing as is mandatory for damage tolerance crack growth assessments for propellant tank loading and pressurization at U.S. Ranges [33].

The AFRL is the world expert in ASCENT propellant and the HAN-based formulations and provided GPIM guidance on all propellant related aspects of the mission. AFRL also contributed the ASCENT propellant for each developmental risk reduction ground test activity, flight propellant, and executed the GPIM propellant loading and pressurization operations [34].

NASA GSFC was brought on shortly into the GPIM program start as the final Co-investigator responsible to provide propulsion subsystem and component expertise to the GPIM program [35]. As a direct contribution, GSFC performed ASCENT propellant cold flow and surge testing and managed the propellant tank slosh testing.

Figure 4 illustrates the GPIM propulsion system and fluid schematic. The GPIM propulsion system is equivalent to historical blowdown hydrazine architectures that have been flown in the past with great success. The flight GPIM propulsion systems were assembled from space industry standard hydrazine COTS fluid components and titanium tubing. The GPIM propulsion fluid components and associated vendor listings are documented in Table 3 [30]. The ASCENT propellant is not compatible with iron-based materials, so the fluid components used are heritage titanium 6Al-4V COTS [22]. The latch valve used on GPIM contained a stainless-steel component that would not be compatible for long term ASCENT operation [30] but was judged to be acceptable within the scope of the GPIM mission goals.

Table 3. PROPULSION SUBSYSTEM COMPONENTS

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
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

For the GPIM program, both the 1N and 22N thrust class engines were matured with the original intent to fully qualify and fly each for flight on the GPIM. Delays in the flight readiness of the 22N thrust class engine forced the difficult decision to implement 1N engines in all locations [22], both for ACS and Divert applications. Post this decision, Aerojet continued with the 22N engine design maturation efforts in parallel, ultimately demonstrating 7.5 kg propellant throughput in ground testing, meeting a key GPIM program requirement [11].

The GPIM mission launched on 25 June 2019 as a secondary payload on the Air Force STP-2 Falcon Heavy launch vehicle. It should be noted that the GPIM spacecraft was completed in 2015 but remained in storage until 2019 due to delays in the STP-2 primary payload launch readiness. GPIM was loaded with 14.2 kg of ASCENT propellant and pressurized to 30.3 Bar(a). The GPIM mission lifetime was 15 months and demonstrated ~2% higher specific impulse increased performance over the mission life, relating to an estimated ~ 48% increased density impulse [30].

5. FOLLOW ON MISSIONS & EFFORTS

5.1. HPGP

HPGP 1N systems, using LMP-103S propellant, have seen success on several post-PRISMA follow-on missions. This began in 2013 with the first SkySat- 3, with the identical propulsion subsystem design implemented on eighteen (18) additional spacecraft (SkySat-3 to -21) [13, 36-37]. The SkySat design, shown in Figure 2, used four (4) HPGP 1N engines, similar fluid components as for PRISMA, and an LMP-103S propellant load of 10.5 kg. One key difference is in the SkySat tanks delivered propellant using a Propellant Management Device (PMD) as opposed to the diaphragm configuration on PRISMA. On-orbit comprehensive performance of the first eleven (11) SkySat spacecraft has been documented to date [36]. Beyond SkySat, a total of thirty (30) spacecraft have implemented HPGP 1N systems [38].

Both the SkySat constellation and Astroscale ELSA-D 1N HPGP systems have experienced some technical issues associated with thruster non-fire anomalies [13, 36,39]. For the SkySat systems, the issues consisted of a combination of 1N flow control valve design, propellant, and unregulated bus voltage. The Astroscale mission anomaly was identified as a “system issue” [39]. The SkySat issues were recoverable, however, the Astroscale anomaly was not recoverable.

The HPGP 1N systems, and LMP-103S propellant, have been processed at eight (8) different Launch Ranges across the planet. SkySat 16-21 were all loaded at the same time in May 2020 due to multiple factors involving the COVID pandemic. SkySAT 16-18 launched from KSC in June 2020, while the 19-21 stayed stored fully loaded for ~2 months at Astrotech Space Operations in Titusville, Florida before launching in August 2020 [37].

In addition to the 1N engines, additional thrust class HPGP engines have also made strides. The ArgoMoon mission includes an HPGP 100mN engine on a VACCO CubeSat propulsion module [16]. 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 [16].

5.2. ASCENT

Post GPIM, 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 [40-41]. An ASCENT propulsion module flew on the Lunar Flashlight mission to demonstrate 100 mN thrust class engines (see Figure 4) [41-42]; however, the mission ended pre-maturely due to propulsion subsystem anomalies [43].

5.3. SUMMARY

ASCENT and HPGP propulsion subsystems have achieved successes. Even with the accomplishments of these identified programs, challenges remain to broader green propulsion mission infusion to high value scientific missions.

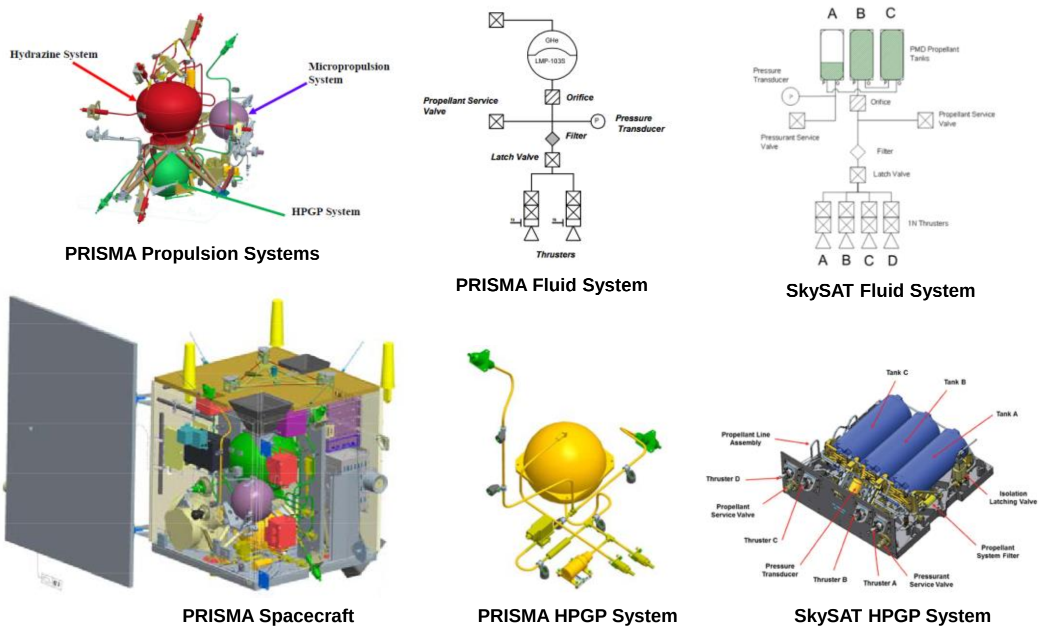

Figure 2. PRISMA/SkySAT HPGP Propulsion System

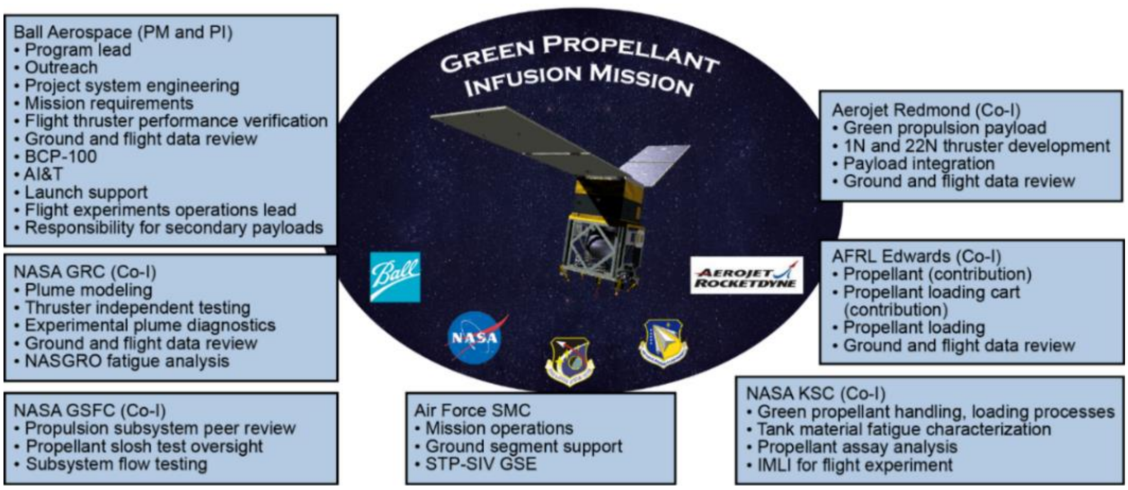

Figure 3. GPIM Program Construct

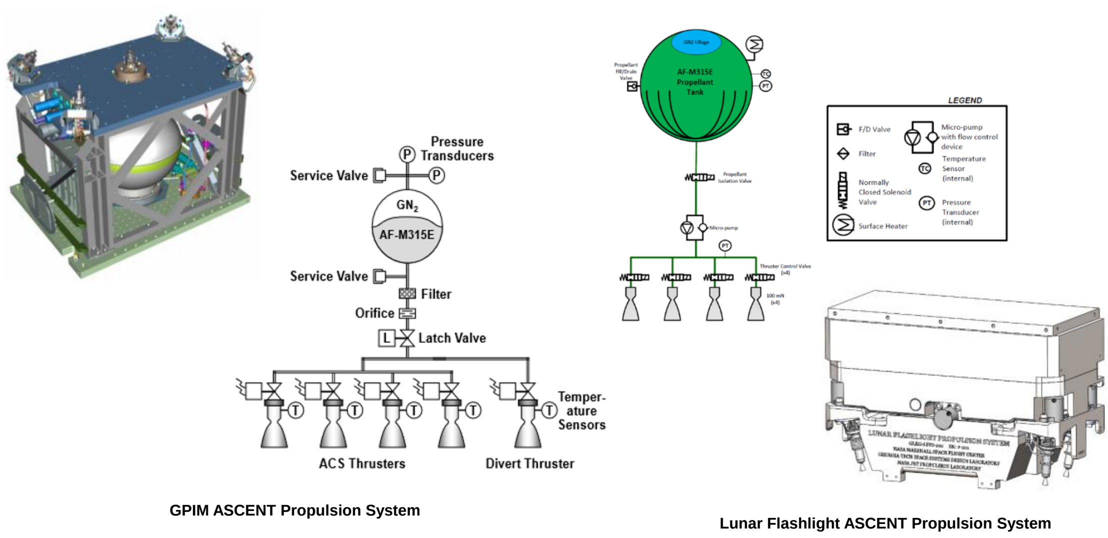

Figure 4. GPIM and Lunar Flashlight Propulsion System

6. MISSION TRADE STUDIES

Mission requirements drive propulsion subsystem design, performance parameters, and life expectations. Mission trade studies are performed during the design phase to ensure appropriate technology selection and components for a given mission paradigm. ASCENT and HPGP system trade studies have been evaluated against historical GSFC missions: GPM, SDO, MMS, LRO, and MAVEN [44] to investigate designs and potential benefits. Further, HPGP systems have been evaluated for the PACE and ROMAN missions due to the HPGP 5N and 22N technology maturations in parallel with the early mission designs [45]. These missions represent a diverse set of requirements, as each have dissimilar scientific objectives and orbits.

In each mission example evaluated in these trade studies, the performance of the propulsion subsystem technically benefited from green propulsion architecture due to the increased performance and propellant density, as expected. This potential performance enhancement was weighed against the current maturity state of the ASCENT and HPGP technologies. The results clearly indicate that the ASCENT and HPGP engines could not be baselined in current and near future GSFC missions without further investment due to the lack of demonstrated propellant throughput levels necessary to meet the identified 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 meet the needs of the science mission community.

The following section provides a detailed breakdown of the green propulsion mission trade study conducted for NASA's PACE mission.

6.1. PACE HPGP MISSION TRADE

6.1.1. MISSION BACKGROUND

NASA's PACE observatory launched at 01:33 EST from Space Launch Complex-40 on Cape Canaveral Space Force Base on 8 February 2024. As described previously, PACE is a NASA GSFC in-house mission. The scientific data collected through the PACE mission focuses on two fundamental science goals: 1) To extend key systematic ocean color, aerosol, and cloud data records for the Earth system and climate studies, and 2) to address new and emerging science questions using its' advanced instruments, surpassing the capabilities of previous missions [46]. The PACE mission is advancing the assessment of ocean health with measurements of the distribution of phytoplankton, tiny plants, and algae that sustain the marine food web. In addition, PACE will continue the systematic records of key air quality and Earth's climate variables.

PACE's primary science instrument is the Ocean Color Instrument (OCI) hyperspectral spectrometer. The PACE observatory also includes two (2) Multi-angle Polarimeters (SPEXone and HARP2) to provide detailed information on Earth's atmosphere and ocean, such as particle size and composition. The OCI instrument was a NASA GSFC in-house build, SPEXone was contributed by the Netherlands institute for Space Research, and HARP2 by the University of Maryland Baltimore Country Earth and Space Science Institute. Since launch, the PACE mission is operating nominally, and all instruments are collecting science data.

The PACE mission needs propulsion to perform required maneuvers. The 251 m/s total Delta-V requirement shown in Table 1 accounts for launch vehicle dispersions, orbit maintenance consisting of both altitude and inclination adjustments, yearly planned collision avoidance risk mitigation, and controlled re-entry maneuvers. PACE baselined a hydrazine monopropellant blowdown propulsion system employing eight 22N thrust class engines, four (4) prime and four (4) redundant (see Figure 5). The 22N thrust class engine selection was motivated by the controlled re-entry burn maneuvers, the achievable thrust across the blowdown operation, and the time requisite to achieve the segmented per-burn Delta-V.

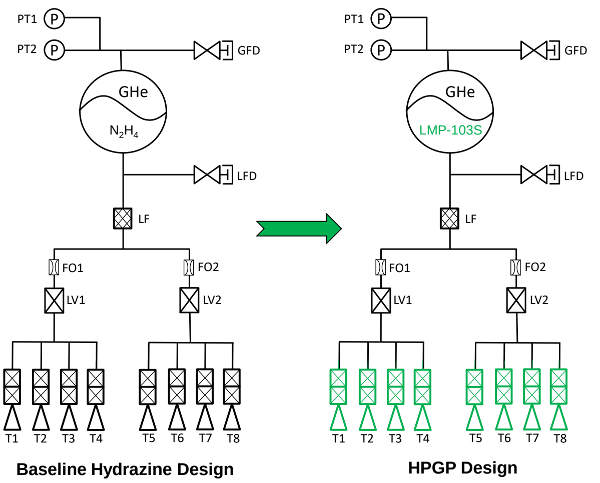

Figure 5. PACE Propulsion Design: N_2H_4 vs HPGP

6.1.2. TRADE STUDY MOTIVATION

From the PACE propulsion mission design inception cycles in 2013, HPGP was considered for infusion. As the mission phases progressed from concept studies into formulation, the PACE HPGP trade matured in parallel. The PACE project performed a trade study of the hydrazine baseline against a HPGP system to potentially: 1) increase propulsion system performance as part of risk mitigation for observatory mass growth, 2) reduce hazardous ground operations and 3) streamline range processing, reducing cost. Early in Phase-A, an initial HPGP trade was presented to the newly established PACE project management and system engineering teams. Based on the overall PACE subsystem architecture a comprehensive evaluation was performed to identify the technical, cost, schedule, on-orbit operational science and any remaining risks to implementing HPGP into the PACE mission.

HPGP engine technology had been advancing due to ECAPS missions post-PRISMA and through the NASA SNSA IA efforts. In 2013, NASA and SNSA outlined a collaborative IA for the respective agencies to pursue increased HPGP technology maturation [47]. Since its inception, each agency has been actively engaged in advancing the IA's three main objectives: 1) design, analyse, and manufacture a fully flight-like HPGP thrusters and gather environmental and hot-fire life test data, 2) promote and advance LMP-103S Range Safety awareness and propellant handling capabilities, and 3) investigate and test LMP-103S propellant material effects and various other handling-relevant chemical properties. For PACE, the most notable element was the HPGP engine development. The other aims contributed, but the engine design and long-life testing was critical to minimizing technical risk for the high visibility Earth Science mission [44]. The IA was pushing 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.

The Green Propellant Loading Demonstration (GPLD) was the inaugural U.S. domestic LMP-103S loading operation exercise. It demonstrated safe propellant transport, storage, and handling at a U.S. Range, Wallops Flight Facility (WFF), which is part of GSFC [48]. This 2015 collaboration between NASA GSFC, SNSA, ECAPS, and Moog Inc. demonstrated a cost and schedule benefit with LMP-103S versus traditional hydrazine propellant loading and decontamination operations. NASA GSFC led this demonstration, successfully executing a 7.8 kg LMP-103S propellant load into a Moog Inc. provided titanium flight-like rolling diaphragm tank [48-49]. Post propellant loading, the tank was pressurized to 24.13 bar(a), directly followed by a tank blowdown operation. In this operation a Moog Inc. -52-265 latching isolation valve was opened to expel the LMP-103S propellant from the flight-like tank, through a network of tubing, into a catch container. Following this exercise, the loading equipment, flight-like tank, latching isolation valve, tubing, and all instrumentation were decontaminated in place using purge gas and water. Through the GPLD operation, the team managed small LMP-103S propellant leakage clean-ups and even residual ADN salt decontamination without difficulty.

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 [49]. As a result of GPLD, LMP-103S propellant achieved U.S. Range acceptance. Moreover, the institutional knowledge and practical hands-on experience gained from this pathfinder activity was documented for the benefit of the broader propulsion community [49].

The PACE HPGP propulsion trade study was enabled by the 22N engine technology maturation and the flight like loading demonstration at U.S. range, further compelled by the potential for continued observatory mass growth during development. During the trade study timeframe, GPIM started flight development efforts on their 22N ASCENT engine, but with a planned 7.0 kg throughput goal, would be insufficient to meet the PACE mission throughput requirement of 118 kg. As such, the PACE green propulsion trade focused on HPGP only.

6.1.3. PACE HPGP MISSION TRADE

As stated previously, PACE was considering the use of HPGP for the propulsion subsystem performance benefits in terms of spacecraft dry mass growth margin, the proven reduction in handling hazards, and the HPGP 22N engines recent advances and planned 2017 comprehensive test program [24]. To seriously consider HPGP for the PACE mission, the HPGP 22N engine testing had to demonstrate sufficient performance and longevity.

The PACE mission propellant budget was derived based on the GSFC Gold Rules (Technical Resource Margins, in GSFC-STD-1000G Table 1.06-1, Rules for the Design, Development, Verification, and Operation of Flight Systems). This method prescribes a series of margins that are required for each mission phase (Pre-Phase A – D). The assumptions required to be included in the generation of propellant margins are:

1) worst case observatory mass
2) -3σ low launch vehicle performance
3) -3σ low propulsion subsystem performance
4) -3σ flight dynamics error and constraints

Once the nominal mission Delta-V is defined, the additional parameter most significant to propellant allocation is the worst-case observatory mass. Designers can attain propellant margin by selecting a propellant tank volume that supports the worst-case observatory mass (with margin). Observatory mass is always a difficult to estimate and, from experience, increases throughout the mission development phases. In terms of propulsion subsystem design, the propellant allocation determines tank(s) volumetric sizing, and tank quantity. In general the propellant tank drives the structure size. A propulsion subsytem design that allows the mass to grow to the propellant tank capability offers a stability. Even with these appropriate margins outlined above implemented in the system design, PACE was struggling with high risk of mass growth and the >15% requirement heading into the mission Preliminary Design Review.

Table 3 provides the comparison between hydrazine and HPGP for PACE resulting from the trade study. For the defined 251 m/s Delta-V, the spacecraft dry mass capabilities were determined for a Northup Grumman diaphragm tank volume at 315.5 Liter. In the Northup Grumman diaphragm tank volumetric offerings, there is a gap from 186.0 Liter to 315.5 Liter, the PACE tank volume at 315.5 Liter was chosen for single tank design, and anticipated mass growth. This 315.5 Liter tank was qualified to propellent mass allocations at 250 kg.

For the trade, HPGP provided ~300 kg in spacecraft dry mass margin increase versus that supportable by the comparable hydrazine system. The 251 m/s total Delta-V incorporated the -3σ low launch vehicle performance, and flight dynamics errors and constraints. To determine the dry mass capability, a conservative -3σ low propulsion subsystem performance was used as required by gold rules.

For consideration, if the 315.5 Liter tank is filled to the entire 250 kg propellant mass capability, there remains 15% extra propellant volume capacity. Maximizing the full blowdown volume allows for a ~288 kg LMP-103S propellant load, increasing the dry mass capacity further to 2200 kg. This implementation would require at minimum tank protoflight testing, or a more likely full tank qualification to qualify the 38 kg higher propellant mass loading would meet mechanical/structural environmental requirements. Also, shown in Table 3, is the analysis for keeping a fixed 1600 kg dry mass, the HPGP design can also deliver increased Delta-V for a fixed spacecraft mass.

Table 3. PACE PROPULSION MISSION 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)

The HPGP propulsion trade for the PACE mission was additionally intriguing due to the minimal changes required to the baseline propulsion subsystem design to change from hydrazine to HPGP. As seen in Figure 5, the PACE hydrazine and HPGP systems implemented identical tank volumes in a blowdown configuration, with the HPGP design using HPGP 22N engines instead of traditional hydrazine 22N engines. Additionally, due to LMP-103S compatibility with CRES materials, the tubing and other propulsion subsystem fluid components also remained similar to baseline, if not identical. For the HPGP system, the tank diaphragm material would require a change to a silica-free elastomer, but this would be less arduous than a wholesale tank architecture change. These benefits delineated in Table 3 demonstrated to the PACE mission that the HPGP option was viable to mitigate the spacecraft mass growth risk while keeping the baseline tank size and overall spacecraft mechanical design. However, none of these HPGP system benefits could be realized without a robust and fully tested HPGP 22N engine design.

Since 2013, the major IA focus was in the maturation and testing of the 22N thrust class engine. As previously discussed, this size engine class, coupled with high throughput expectations, targeted the identified use case for moderate to large NASA science mission infusion. The HPGP 22N thruster maturity progression over the 2015-2016 timeframe and the 2017 long life test campaign enabled the PACE propulsion team to keep the HPGP trade open. The HPGP 22N engine test campaign was centered around an Engineering Qualification Model that underwent a rigorous verification test program aligned to a typical NASA GSFC flight mission requirements [24]. The actual PACE mission requirements were selected as the benchmark to lay the foundational set of requirement goals for the HPGP thruster test program. This program would comprehensively test the thruster, demonstrating the maturation of the design for the IA and, at the same time, support the PACE HPGP propulsion subsystem trade study, achieving a HPGP 22N thruster mission qualification.

During the test program, at approximately 53 kilograms of propellant throughput, and off-nominal condition was detected whereby the HPGP 22 N thruster performance began to slowly fluctuate off the nominal thrust and propellant flow rate. The testing was halted and an investigation revealed the root cause as the displacement of an internal 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. Ultimately, the decision was made to fly the baseline hydrazine propulsion subsystem on the PACE mission.

6.1.4. TRADE SUMMARY

The HPGP propulsion option was seriously considered for the PACE mission and was supported as an active trade from 2013-2017. The adoption of an HPGP system was evaluated by the other spacecraft subsystems: Avionics, Power, Flight Software, Thermal, Mechanical, Safety, Safety and Mission Assurance, Guidance Navigation and Control, Integration and Test, Contamination, and ground operations.

The HPGP system required higher power than the baseline due to needing higher temperature thruster pre-heating. In addition, to retain the thruster reactor temperature at the required 350°C over low-duty cycle pulsing necessitated a regulated temperature controller. Implementation of these identified changes would be an added expense to the PACE baselined avionics suite. The cost increase was a contributing factor in PACE's decision to retain the baseline hydrazine propulsion architecture.

The higher thruster reactor start temperature and steady state operating temperature at 1600°C also posed design challenges for the spacecraft Thermal engineering team.

If a higher propellant load was selected for the HPGP design had implications to the spacecraft structural loads and resulting design.

The safety impacts of the HPGP system were all positive and had been proven throughout multiple loading operations. In terms of mission assurance, there was healthy skepticism for the new technology but a strong desire to follow the design, and testing.

The most compelling benefit of the PACE HPGP trade was an opportunity to continually engage with the project and subsystems on the potential use of an alternative propellant over the course of several years. During the trade timeframe, the first flight-like HPGP 22N thruster was designed, manufactured, and tested to a 53 kg throughput level over a wide operational envelope. This was enabling for a potential future mission infusion of the technology. Even though HPGP was not implemented on PACE, the in-house team of program managers, systems and discipline engineers all gained from the exposure.

It should be pointed out from Table 1, the PACE dry mass was 1198 kg, and was kept within acceptable growth for the hydrazine baseline to be successful and meet mission Delta-V requirements. This is not always the case, and changing tanks late in the mission flow causes significant impacts to the subsystems.

7. WAY FORWARD

Each of the efforts described throughout this paper provided advancements to the state of the art for the candidate green propellant (ASCENT and HPGP) technology for science missions. At this time, ASCENT is under continued development through AFRL, with several contracts supporting programs focused on 1N [50], and 22N and 100/110N [51] class engines. These companies are also working internally to grow their engine catalogs with work progressing on the 5N [52]. NASA MSFC-manged Green Propulsion Dual Mode will test chemical and electrospray ASCENT technology [53]. 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 [54]. The formulation has demonstrated similar performance to monopropellant hydrazine, but with the increased density impulse [54].

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. Based on the previous 22N test campaign, the HPGP thruster designs have been updated to incorporate many lessons learned. Additionally, 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.

NASA GSFC continues to push green propulsion technology development, pursue risk reduction activities to capitalize on potential infusion mission opportunities, and remain cognizant of ASCENT and HPGP performance from on-going missions and engine technology maturation.

There are remaining technical, cost, and schedule risks. For traditional hydrazine and bi-propellant applications, users have choices between different vendors. This is not necessarily the case for ASCENT and HPGP applications, posing risk to mission adoption. In general, even with the significant reduction in range related costs, these higher performing green propulsion systems are more expensive driven primarily by engine costs, or subsystem interface requirements atypical to hydrazine utilization. The green propellant itself costs more per volume and comes in smaller volume containers than heritage propellants; ASCENT in 3.78-18.92 Liter containers and LMP-103S in 5 Liter sizings. These smaller volumes complicate ground processing operations for large spacecraft propellant loads. Larger propellant source containers will require additional and expensive testing for transport classification in the U.S. and, as such, remain a future task to be completed. ASCENT and HPGP engine designs impose higher power requirements on the host spacecraft but can be largely overcome by the spacecraft bus design.

The one major focus for the future will be achieving reliable flight ASCENT and HPGP engine designs and comprehensively proving performance through testing. This is not one test, but a collection of multiple tests to demonstrate repeatable performance and establish healthy reliability for mission infusion.

8. 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.

Green propulsion technologies have demonstrated benefits to spaceflight missions. These achievements have yielded operational lessons which the community must embrace to enable successful ASCENT and HPGP mission implementation in the future. 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.

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