An Analysis of Green Propulsion Applied to NASA Missions

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The advantages of green propulsion for five mission classes are examined, including a Low Earth Orbit (LEO) mission (GPM), a Geosynchronous Earth Orbit (GEO) mission (SDO), a High Earth Orbit (HEO) mission (MMS), a lunar mission (LRO), and a planetary mission (MAVEN). The propellant mass benefits are considered for all five missions, as well as the effects on the tanks, propellant loading, thruster throughput, thermal considerations, and range requirements for both the AF-M315E and LMP-103S propellants.

Nomenclature

ACS	=	Attitude Control System
CDR	=	Critical Design Review
ECAPS	=	Ecological Advanced Propulsion Systems
GEO	=	Geosynchronous Orbit
GSFC	=	Goddard Space Flight Center
GPIM	=	Green Propellant Infusion Mission
GPM	=	Global Precipitation Measurement
HEO	=	High Earth Orbit
IA	=	International Agreement
Isp	=	Specific Impulse (s)
LEO	=	Low Earth Orbit
LRO	=	Lunar Reconnaissance Orbiter
m_f	=	Spacecraft final (or dry) mass
m_i	=	Spacecraft initial (or wet) mass
MAVEN	=	Mars Atmosphere and Volatile Evolution mission
ME	=	Main Engine (for SDO)
MMH	=	Monomethyl Hydrazine
MMS	=	Magnetospheric Multi Scale mission
NASA	=	National Aeronautics and Space Administration
NOFBX	=	Nitrous Oxide Fuel Blend
NTO	=	Nitrogen Tetroxide
PRISMA	=	Prototype Research Instruments and Space Mission Advancement
R_E	=	Earth Radii
SCAPE	=	Self-Contained Atmospheric Protective Ensemble
SDO	=	Solar Dynamics Observatory
SNSB	=	Swedish National Space Board
STMD	=	Space Technology Mission Directorate
TDRSS	=	Tracking and Data Relay Satellite System
TRL	=	Technology Readiness Level

I. Introduction

Interest in green propulsion has rekindled in recent years due to the ultimate success of catalytic ignition systems for multiple high-performance formulations. These technologies present performance benefits such as reduced launch mass, increased scientific payload mass, and/or extending on-orbit lifetimes. The advantages are further reinforced due to the significant reduction in health risks encountered during launch site and ground handling operations.

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There are two primary green propulsion candidate technologies, AF-M315E and LMP-103S, that align with the needs of historical Goddard Space Flight Center (GFSC) missions. Each candidate propulsion technology offers increased performance over hydrazine monopropellant propulsion, reduces personnel and environmental hazards, and simplifies transport and handling for ground operations. Other technologies such as Nitrous Oxide Fuel Blend (NOFBX) or hydrogen peroxide either do not improve performance, or do not reduce safety concerns.

In 2010, the Prototype Research Instruments and Space Mission technology Advancement (PRISMA) mission, an SNSB mission, flew and demonstrated 1 N thrusters with 5.5 kg of LMP-103S propellant[1]. LMP-103S will also fly on the SkyBox Imaging spacecraft. The NASA Space Technology Mission Directorate (STMD) awarded the Green Propellant Infusion Mission (GPIM) in 2013. GPIM conducted CDR in March of 2014, and is scheduled for launch in late 2015. GPIM is using an AF-M315E propulsion system that includes four 1N thrusters and one 22N thruster, and will demonstrate 14 kg of total throughput for the mission[2].

A study was conducted by NASA GSFC to examine the practical inclusion of these technologies into NASA GSFC missions. Five different missions were examined, covering the entire range of NASA GSFC missions, including Low Earth Orbit (LEO), geostationary, High Earth Orbit (HEO), lunar, and planetary missions. The Global Precipitation Measurement (GPM) mission is a rainfall radar mission orbiting at a 407-km altitude that launched in February of 2014[3]. The Solar Dynamics Observatory (SDO) is a geosynchronous mission constantly imaging the Sun that uses a bipropellant propulsion system[4]. The 1026 kg listed in Table 1 for SDO is the amount of bipropellant used so far in the mission. The Magnetospheric Multi-Scale (MMS) mission is a constellation of 4 spacecraft looking at the magnetopause in a highly elliptical (1.2 x 25 R_E) orbit scheduled to launch in March 2015[5]. The Lunar Reconnaissance Orbiter (LRO) launched in 2009 and delivered pictures of the Apollo landing sites and a wealth of information for a future return to our only natural satellite[6]. The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, NASA GSFCs first Mars mission, launched in late 2013.

Table 1 Input Data[3,4,5,6]

Mission	Hydrazine Load (or Equivalent)	Isp	Tank Volume	Tank Mass	ΔV	m_f	m_i
	kg	*s*	*in^3*	*kg*	*m/s*	*kg*	*kg*
GPM	545	220	46,823	53.5	227.4	3305	3850
SDO	1026	305.5	78,510	54.16	1280	1948	2974
MMS	410	220	42,800	51.72	490	1351	1761
LRO	894.9	220	56,288	68.95	1293	951	1846
MAVEN	1638.10	226	107,805	75.19	2093.4	780	2419

II. Analysis

The performance benefits of the AF-M315E and LMP-103S propellants can be examined in different ways – to decrease the propellant mass, to increase the ΔV, or to increase the payload mass. A wide range of other aspects are also considered for all of these missions and both propellants, including the effects on the tanks, propellant loading, thruster throughput, thermal considerations, and range requirements. The specific impulses used for all of the analyses are 250 seconds for AF-M315E, and 246 seconds for LMP-103S. AF-M315E is 50% denser, and LMP-103S is 30% denser than hydrazine propellant.

A. Propellant Mass

The first analysis performed considered reducing the propellant mass for the same mission ΔV and dry mass. The propellant load requirements show significant reductions when compared to the equivalent hydrazine masses, depending on the mission. Figure 1 shows the results for propellant mass, and Figure 2 shows the results for the spacecraft wet mass. These masses were calculated using the ΔV and dry masses shown in Table 1. The mass differences between the required green, hydrazine, and bipropellant MMH/NTO propellant masses range from 100 kg for MMS to over 500 kg for MAVEN. The SDO bipropellant system requires 300 kg less than the green propellants. This analysis does not include the mass benefit or penalty to hold either more or less propellant than the baseline. The benefits shown here only reflect the increase in specific impulse for the green propellants.

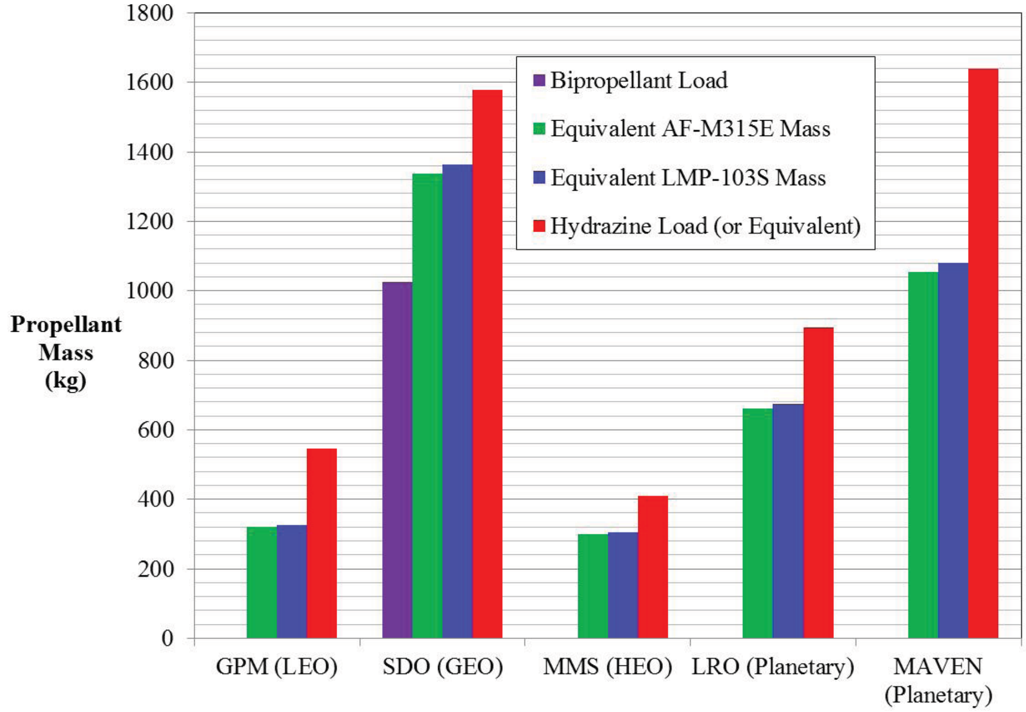

Figure 1 Propellant mass.

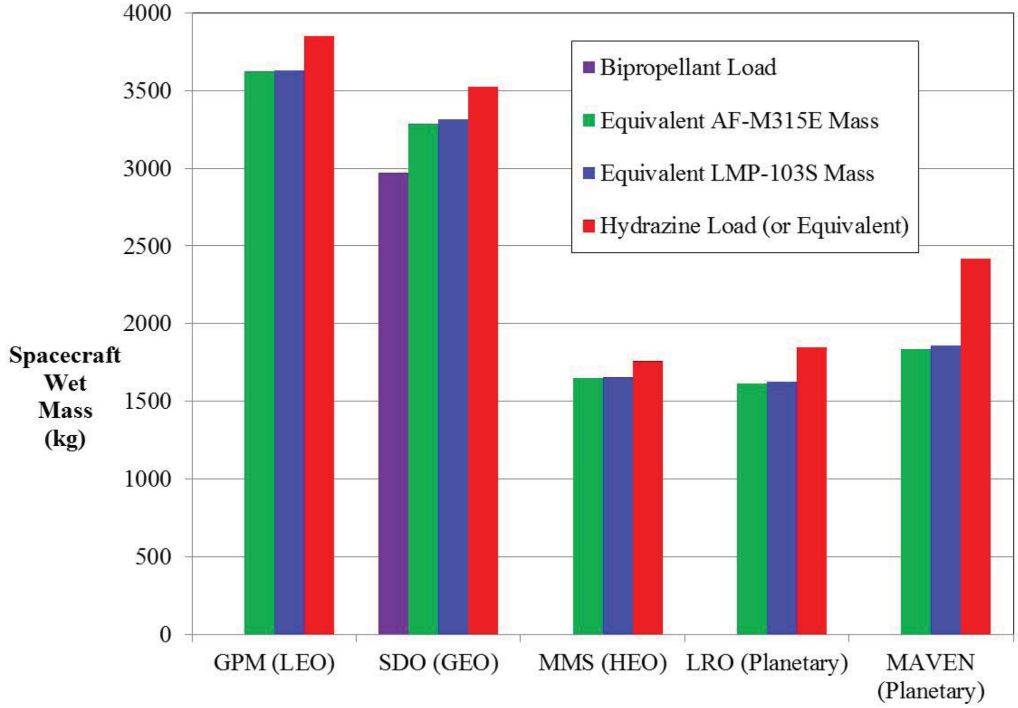

Figure 2 Spacecraft wet mass.

B. ΔV Benefits

The added ΔV available from a green propellant system was considered in two scenarios – first, where the same propellant volume as the baseline system was used, and second, where the same propellant mass was used.

The analysis for the ΔV based on propellant volume assumes that there are no changes to the spacecraft – the same tank is used. This ignores the fact that the tank would carry heavier loads and be heavier, but includes the benefit of the propellant density. In addition, the launch mass is significantly more, and assumes there is additional launch vehicle capability. The results for this analysis are shown in Figure 3, showing significant benefits for all considered mission classes.

In the case of SDO, the ΔVs were computed assuming the same propellant volume as the bipropellant system. Figure 3 shows the baseline bipropellant system as well.

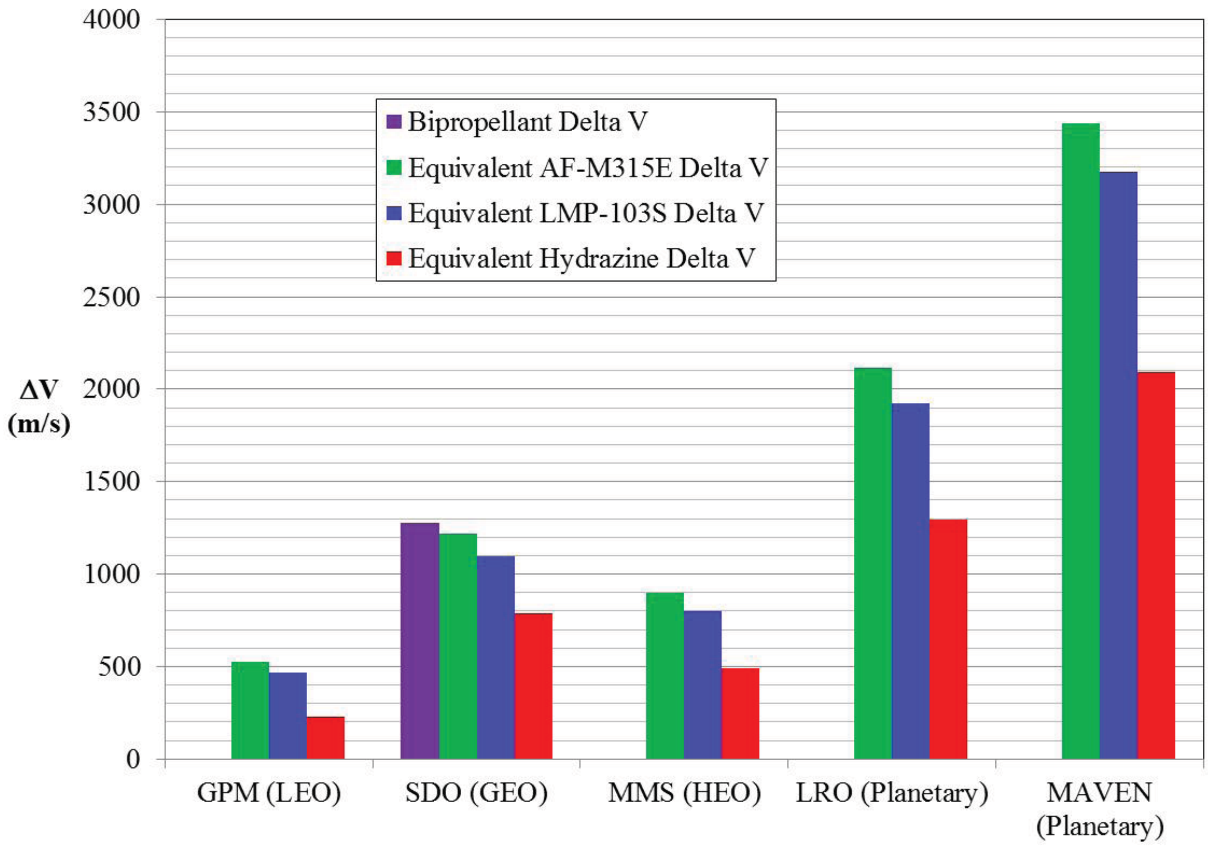

Figure 3 ΔV differences for the same tank volumes.

For the second ΔV analysis, the same propellant mass as the baseline system was used. This assumes the same launch mass and dry mass, but neglects any decrease in tank volume, and equivalent tank mass decrease. The results for this analysis are shown in Figure 4, and demonstrate less of an increase than Figure 3, but still significant increases, in particular for MAVEN and GPM.

For SDO, all of the systems used a propellant mass of 1026 kg. Figure 4 shows the ΔV of the baseline bipropellant system as well as a hydrazine system, but the bipropellant numbers use much smaller tanks.

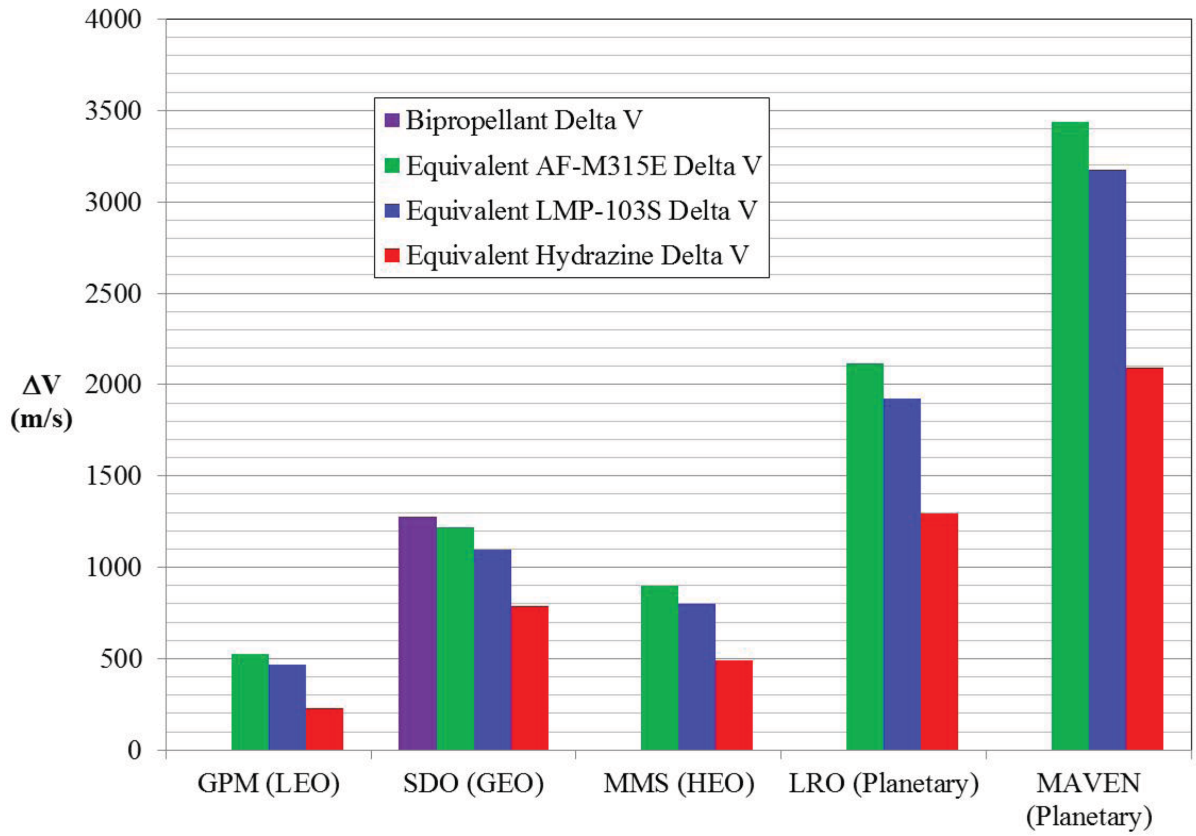

Figure 4 ΔV differences for the same propellant masses.

C. Payload Mass

The propellant benefits can also be used to include increased payload mass. This analysis assumes that the same initial mass is launched, and the difference between the baseline hydrazine mass (or hydrazine mass equivalent) is made up with payload. The hydrazine mass equivalent was calculated for SDO using the same ΔV and final spacecraft mass as the bipropellant system. This analysis ignores the differences in payload mass on dry mass. Assuming the same initial mass is launched, the analysis in Figure 5 shows that a significant amount of payload mass can be added to all of the missions.

All of the results in Figure 5 are comparisons to the hydrazine system. For SDO, less payload mass could be carried than with the bipropellant propulsion system (310 kg less with AF-M315E, and 340 kg less with LMP-103S).

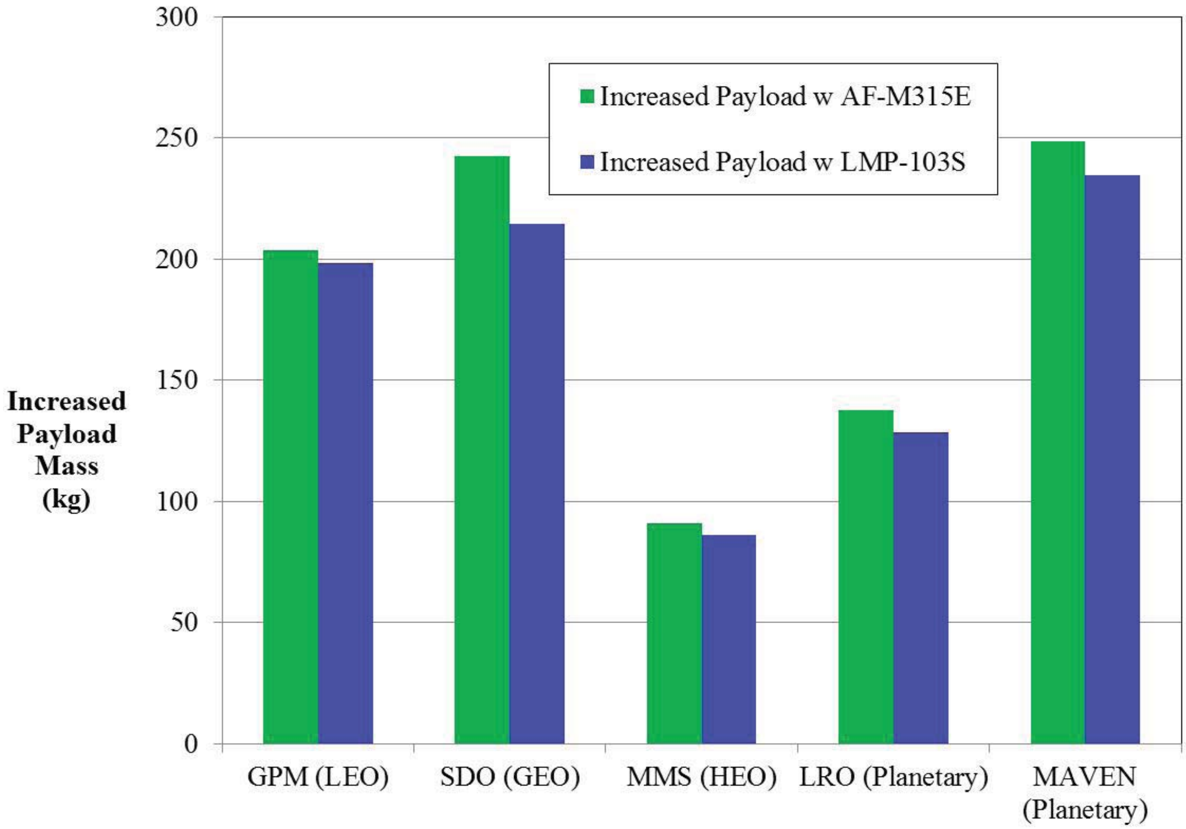

Figure 5 Additional payload mass for the same initial wet mass and delta V.

D. Propellant Tanks

The tank dimensions also play a significant role. The AF-M315E and LMP-103S propellants are 50% and 30% more dense than hydrazine, respectively. This significantly reduces the overall tank size for the same amount of propellant. For a spherical tank, dimensions can be reduced by an additional 14.5 % for AF-M315E, and 9.1% for LMP-103S.

An analysis was completed to examine the ΔV capability for AF-M315E and LMP-103S in comparison to hydrazine for volumes ranging from 0.0082 m^3 (500 in^3) to 1.80 m^3 (110000 in^3). Given a specific volume and the propellant densities, a mass of propellant was determined. The ΔV was then calculated using a spacecraft dry mass of 1000 kg and 4000 kg. Figure 6 shows the ΔV comparison results. The Tracking and Data Relay Satellite System (TDRSS) tank volume is also highlighted along the each curve. For each of the spacecraft dry mass cases, AF-M315E and LMP-103S displays an average of 35.6% and 24.9% increased ΔV capability over hydrazine, respectively.

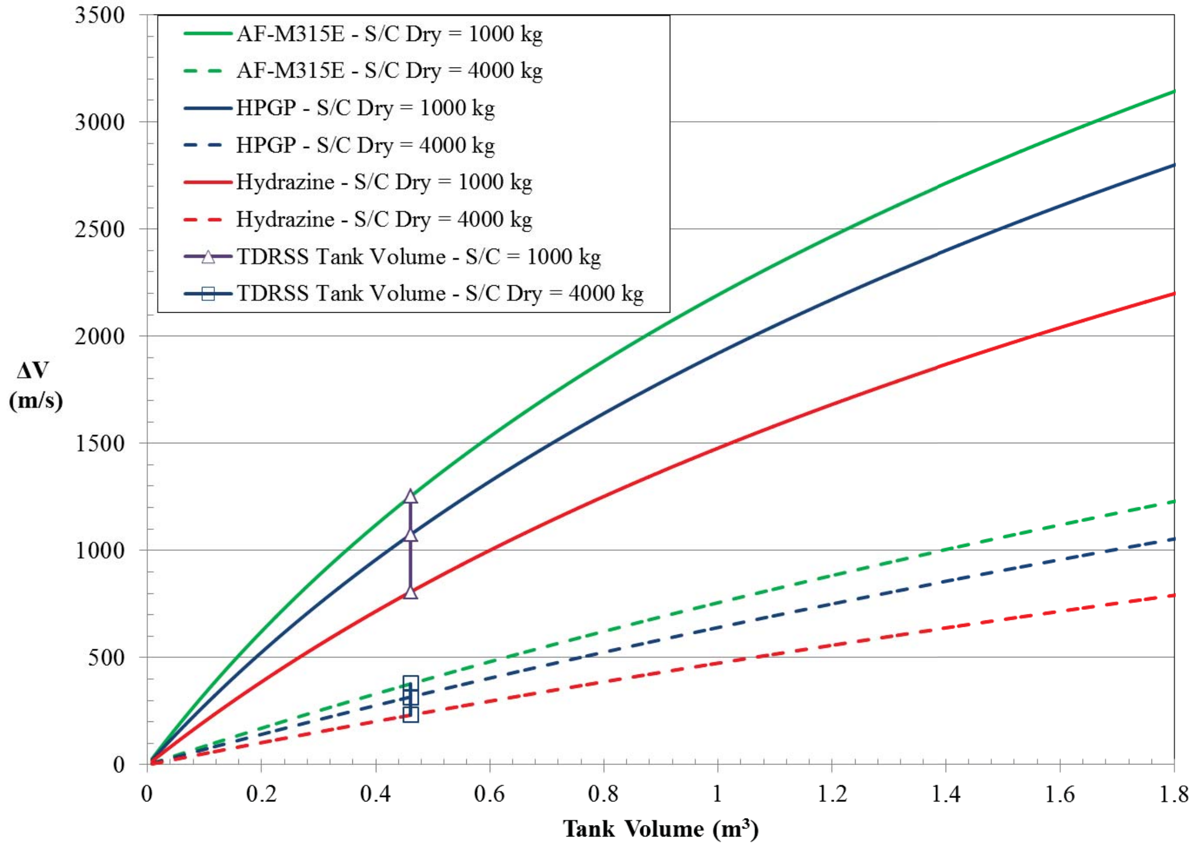

Figure 6 ΔV vs propellant volume for a generic spacecraft and tank.

E. Thruster Type and Throughput

The current green technology limitation to several of these GSFC missions is that they require substantial insertion-class engines. LRO, MAVEN, and SDO all have insertion engines with thrust levels greater than those being demonstrated by either PRISMA or GPIM, although development engines exist for both propellants.

Thruster throughput requirements for all of the missions were also considered. For SDO, 71% of the propellant is used by the Main Engine (ME). The worst case propellant throughput for the SDO comparison is for the propellant mass analysis in Section A, where the same ΔV and dry mass are used, because the baseline is a bipropellant system. The ME throughput requirement for AF-M315E and LMP-103S, respectively, are 949 and 969 kg. The Attitude Control System (ACS) requirements are much more modest on SDO; assuming a complement of 8 ACS thrusters are used evenly, the throughput requirements for AF-M315E and LMP-103S, respectively, are 48 and 49 kg. These numbers do not include a factor of 2 that is typically used for thruster qualifications.

While the SDO mission bounds the ME throughput requirements, the ACS engine requirements are actually much higher for the spacecraft that do not have an ME (MMS and GPM), so all of the propellant goes through the ACS engines. For the maximum usage, the maximum throughput would come from the case where the same propellant volumes are used in Section B. This is very conservative, because these cases have significantly more ΔV capability, but they make full use of the benefits of the propellant. Assuming the propellant is throughput evenly between all of the thrusters for the two missions that only have ACS thrusters, MMS and GPM, the throughout requirements are shown in Table 2, not including a factor of 2. For the analysis where the same propellant mass is used, the propellant throughput requirement would be the same as hydrazine. For the case where the propellant mass is used to produce the same ΔV as hydrazine, the throughput requirement is much lower than hydrazine.

Table 2 Throughput Requirements

	Throughput for Same Propellant Volume (kg)		Throughput for Same ΔV (kg)		
	AF-M315E	LMP-103S	AF-M315E	LMP-103S	Hydrazine Throughput (kg)
MMS	49.9	44.4	24.9	25.4	34.2
GPM	66.3	59.0	26.8	27.2	45.4

The masses for the GPM mission are the throughput drivers for all of these cases. The AF-M315E and LMP-103S engines have not currently demonstrated the GPM throughput requirements. Current hydrazine thrusters easily meet these throughput requirements.

F. Other Operational Limitations

Both green propellants have operational restrictions that do not exist for hydrazine propulsion systems. The main operational restriction for both systems, is that the thruster must be preheated. There is no cold start capability for either type of thruster. This is a significant restriction, since a common contingency requirement for hydrazine thrusters is to be able to detumble a spacecraft when it comes off the launch vehicle, and the thrusters often cannot be preheated to meet this requirement.

G. Integration and Test and Propellant Loading

Recent experience has also shown the advantage of using a green propellant during integration and testing and for propellant loading. Water is often required to be loaded into the propulsion system to simulate the propellant load during spacecraft vibration testing, which requires the hardware to be dried. This would not be required if test facilities allowed the propellant to be loaded prior to testing.

There are a significant number of elements that add cost for hydrazine systems. These elements include hydrazine spacecraft loading contracts, hazardous end-of-line sampling, offload contingency planning, spacecraft processing facility rental, the manpower to support propellant loading, medical check outs, SCAPE training, and shipping. These costs can easily exceed $1M, not including the costs to maintain the marching army of a project while hydrazine-specific activities are going on. Many of these activities can be accomplished at reduced cost, if not eliminated, by transitioning to either green propellant.

The primary benefit of green propellants is the reduced safety requirements for loading – no Self-Contained Atmospheric Protective Ensemble (SCAPE) systems are required for loading due to the non-hazardous nature of the propellants. The reduction in safety requirements can significantly benefit schedule, and hence cost, as demonstrated on PRISMA[1].

H. Thermal Requirements

The principal thermal advantage of the two green propellants is that each can go to a lower minimum temperature (-7C for LMP-103S, and -10C for AF-M315E). Even at these temperatures, the propellants do not freeze; they become highly viscous or start to precipitate crystals. Although desired operational temperatures remain similar to hydrazine, the implication of the lower survival temperature is that during non-operational times, the tanks can be allowed to cool. Figure 7 shows an analysis of the amount of extra eclipse time that the MMS and GPM mission could survive if they went to different orbits that had longer eclipses. Although the LMP-103S propellant has a higher heat capacity (AF-M315E = 2230 J/kg*K, and LMP-103S ~ 2420 J/kg*K), the AF-M315E propellant can go colder, and allows a significantly longer eclipse than the LMP-103S propellant. The thermal capacitance numbers were treated as constants for this analysis. Mission average heater power can also be reduced, but that analysis is very mission configuration specific.

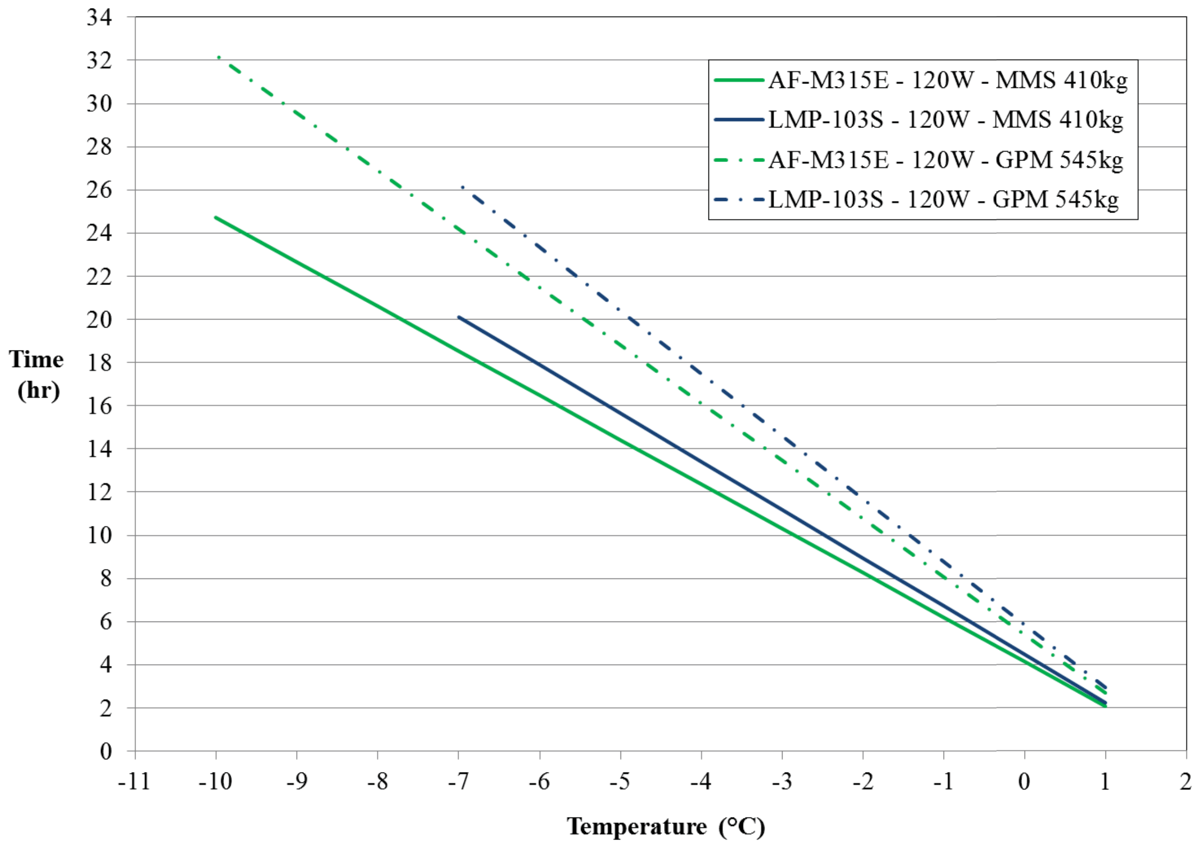

Figure 7 Added time for eclipse for MMS and GPM.

I. Range Requirements and Dry Mass

Safety at the launch range imposes a significant number of requirements above and beyond what is needed for loading to contain safety hazards, in particular for hypergolic systems with hydrazine. The principal benefit is the removal of one hardware inhibit to the unintentional release of propellant, which removes the need for one valve, reducing the propulsion system mass.

Using the MMS and GPM propulsion system components, a dry mass comparison was performed to discern the variances using an AF-M315E or LMP-103S propulsion system. This comparison is seen in Table 3. The green propellant systems are heavier than the monopropellant systems, but less massive than the SDO bipropellant system.

Table 3 Propulsion system dry mass comparison for MMS and GPM green propulsion systems.

	Bipropellant Propulsion System Dry Mass (kg)	Hydrazine Propulsion System Dry Mass (kg)	Propulsion System Dry Mass – AF-M315E (kg)	Propulsion System Dry Mass – LMP-103S (kg)
MMS	-	72.4	74.2	72.4
GPM	-	65.7	66.9	66.7
SDO	126.1	-	117.0	118.7

AF-M315E requires the use of all titanium components, tubing and fittings. SDO also required the use of titanium components, tubing and fittings. The SDO component masses were utilized in the propulsion system dry mass determination for MMS and GPM using an AF-M315E system. The 22N MMS and GPM hydrazine thruster masses were replaced by the AF-M315E thruster mass. Since GPIM is not flying a 5N thruster, a linear interpolation between the 1N and 22N was used to determine the 5N mass for the MMS 5N AF-M315E axial thrusters. For the AF-M315E propulsion system, the filter mass was selected from the filtration requirements and corresponding titanium construction. The AF-M315E thrusters are 56% heavier respectively than the MMS and GPM counterparts.

LMP-103S is compatible with CRES materials that are typically used in hydrazine monopropellant systems. Since this is the case, no component masses changed for the MMS and GPM propulsion system dry mass determination using a LMP-103S system except the thruster mass. The LMP-103S thrusters are 10% heavier than the MMS and GPM 22 N thrusters, and actually 20% lighter than the MMS 5N thrusters. The combination of heavier 22N thrusters and lighter 5N thrusters are what result in the same dry system mass for hydrazine and LMP-103S on MMS.

For SDO, the mass of a regulated green propulsion system was calculated for both types of green propellant, assuming redundant regulators and the same propellant tanks. Most of the mass reduction of using green propulsion comes from the removal of a significant number of components from the oxidizer side. CRES lines are also heavier for the LMP-103S system. It should be noted that this mass tally does not include the main engine. The total mass is not reduced as much as it could be based on the components because the green propulsion thrusters are more massive than the bipropellant thrusters. The green propulsion systems also greatly improve the numerical reliability of the system and reduce the integration and test complexity, since the component count goes from 63 for SDO (a complex regulated bipropellant system) to 33 for a regulated green propulsion system.

IV. Conclusions

All of these effects are of significance to future missions, but the analysis shows the benefits cannot be applied to all missions, primarily because of demonstrated throughput. One could combine some of the benefits, for example to increase both ΔV and payload mass, but the performance benefits were all analyzed independently here.

The US currently supports a large infrastructure for hydrazine. The infrastructure was sized to support the Shuttle. With the Shuttle no longer flying, spacecraft will shoulder more of the infrastructure cost. Costs such as storage, monitoring, sampling, waste disposal, and SCAPE maintenance add significant overhead costs.

Significant savings can be expected from the use of green propellant in the mission life-cycle cost. With the higher temperatures, materials in the thrusters are likely to be more expensive, driving the cost of the thrusters significantly higher than hydrazine thrusters. Although the hardware is likely more expensive, the savings for ground operations are significant. In addition, when environmental aspects of the complete life-cycle costs are considered, there are additional significant savings[7].

The recently signed NASA-SNSB Implementing Arrangement (IA) will provide increased LMP-103S technology maturation in 2014-2015. Under the IA, SNSB and ECAPS will mature the 5N (1 lbf) and 22N (5 lbf) thrusters from TRL 5 up to TRL 6, including throughput. NASA will then receive TRL 6 thrusters and LMP-103S propellant to conduct testing and evaluation of the thruster technology for mission operations. The GPIM mission will also do ground qualification of the 1N and 22N thrusters to reach TRL 6, including throughput.

Acknowledgments

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