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2018 NASA Green Propulsion Technology Development Roadmap

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LIST OF ACRONYMS AND SYMBOLS

ACO	Announcement of Collaborative Opportunity
ADN	ammonium dinitramide
AES	Advanced Exploration Systems
AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
CAN	Cooperative Agreement Notice
CEA	Chemical Equilibrium Analysis
CFD	computational fluid dynamics
CPSM	Chemical Propulsion Subcapabilities Management
DLA	Defense Logistics Agency
DoD	Department of Defense
ECAPS	Ecologically Advanced Propulsion System
ESPA	Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter
GCD	Game Changing Division
GMAH	Green Monopropellant Alternatives to Hydrazine
GPIM	Green Propellant Infusion Mission
GPWG	Green Propulsion Working Group
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HAN	hydroxylammonium nitrate
HEOMD	Human Exploration and Operations Mission Directorate
HPGP	high-performance green propulsion
HQ	Headquarters

LIST OF ACRONYMS AND SYMBOLS (Continued)

Ir	iridium
IRAD	Internal Research and Development
JANNAF	Joint Army-Navy-NASA-Air Force
JPL	Jet Propulsion Laboratory
KPP	key performance parameters
MDA	Missile Defense Agency
MilSpec	military specification
MSFC	Marshall Space Flight Center
N_2H_4	hydrazine
OCT	Office of Chief Technologist
PMD	propellant management device
Re	rhenium
SAA	Space Act Agreement
SBIR	Small Business Innovative Research
SMC	Space and Missile Command
SNSB	Swedish National Space Board
SOA	state of the art
SSTIP	Strategic Space Technology Investment Plan
STMD	Space Technology Mission Directorate
TDA	Technology Development Area
TDM	Technology Demonstration Mission
TIM	Technical Interchange Meeting
USAF	United States Air Force

TECHNICAL MEMORANDUM

2018 NASA GREEN PROPULSION TECHNOLOGY DEVELOPMENT ROADMAP

1. INTRODUCTION

The NASA Green Propulsion Working Group (GPWG) was tasked by the NASA Chemical Propulsion Subcapabilities Management (CPSM) with the development of this NASA Green Propulsion Technologies Development Roadmap, herein referred to as the Green Propulsion Roadmap, or simply the Roadmap, to provide guidance to NASA through the CPSM on green propulsion technology development. Other agencies or commercial partners may refer to this roadmap as well.

It is envisioned that the synthesis of various Center-based activities and knowledge repositories will result in a cumulative knowledge gain, and will provide capabilities beyond the sum contribution of individual Centers. Ultimately, a well-defined roadmap of technology investment path, the enhanced coordination and alignment of activities among NASA Centers and other Federal Agencies, and a well-supported green propulsion community will facilitate the path towards the broader infusion of green propulsion technologies for science and human exploration missions, as well as a deeper understanding of the fundamental behaviors and characteristics of these systems that is on par with other historically used monopropellant propulsion systems, such as hydrazine.

2. PURPOSE

To make the next steps in green propulsion technology advancement and infuse that technology into NASA missions, it will be necessary to enhance coordination within the Agency, focus energies and resources to prioritize tasks that address identified technology gaps, and reduce unnecessary duplication of efforts between NASA Centers and projects. The purpose of the Green Propulsion Roadmap is to provide technology development guidance to NASA Mission Directorates, Centers, and projects.

3. SCOPE

This Roadmap focuses on ionic liquid propellants and related technologies that are seen as direct or near-direct replacements for hydrazine, heritage monopropellants, or hypergolic bi-propellants, and often referred to as ‘green propellants,’ ‘nontoxic propellants,’ or ‘reduced toxicity propellants.’ Cryogenic green propellants such as methane or oxygen, except when used as reactants with the ionic liquids, are specifically excluded from this scope of work.

As part of its chartered role of developing and maintaining a list of ongoing green propulsion development efforts, the GPWG seeks awareness of the objectives, task management, resources, and schedule of all such projects for the purposes of achieving its strategic objectives. The Green Propulsion Roadmap does not supersede any existing Agency or Center funded activities, multilateral agreements, and/or ongoing projects of any Center started prior to the development of the Green Propulsion Roadmap.

4. BACKGROUND

4.1 Green Propulsion Working Group

As part of the NASA Capabilities Leadership Team model, the CPSM recognizes that the development of green propulsion technologies have progressed to a point where a more focused roadmap and investment strategy is needed to further advance those technologies. The CPSM created the GPWG, a technical guidance working group.

The GPWG was specifically chartered with (1) developing and maintaining an Agency Green Propulsion Roadmap to address technological gaps within green propulsion, (2) developing and maintaining a list of green propulsion technology development efforts being pursued by members' respective Centers or Agencies, and (3) identifying and maintaining an assessment of green propulsion test facilities and Center competencies related to green propulsion for the Agency. Figure 1 shows the relationship of the GPWG within the NASA CLT model.

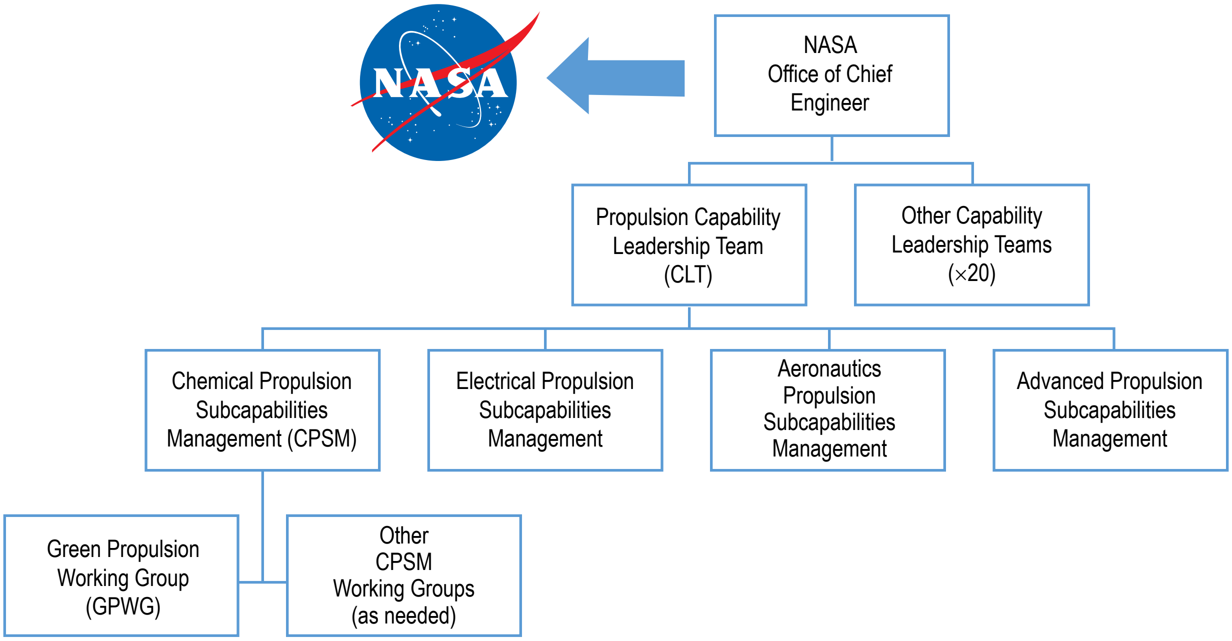


Figure 1. Relationship of Green Propulsion Working Group within the NASA Capabilities Leadership Team model.

4.2 Strategic Goals of the Green Propulsion Working Group

In order to maximize the Agency's return on investment in green propulsion technologies, this GPWG seeks to establish the strategic goals outlined in sections 4.2.1 through 4.2.3.

4.2.1 Strategic Goal 1—Establish Agency Vision for Green Propulsion

To date, there has not been a singular, defined Agency vision for green propulsion within NASA. Efforts thus far have been randomly applied to varying thrust classes and technologies from Mission Directorates, Centers, or individual grants/partnerships (e.g., Small Business Innovative Research (SBIR) efforts), largely without well-defined technology advancement goals beyond 'flight demonstration.' While these investments certainly do advance the state of the art (SOA) and do provide overall development benefits, without a clear forward vision each technology development effort fails to support the next in a clear and meaningful way. Thus, there can be overlaps and duplications of effort, leading to slower overall progress. In order to provide this focussed vision, this Roadmap was created. This Green Propulsion Roadmap lays out a course of investment, defined in a set of Technology Development Areas (TDAs), and focuses upon a step-wise plan to systematically advance the SOA with each step contributing to the next while simultaneously providing for the greatest return on investment.

4.2.2 Strategic Goal 2—Provide Guidance to Focus Energies and Resources

With the increased attention to green propulsion, many different facilities, Centers, and partners are seeking to contribute to the overall technology advancement. Without effective oversight, this can lead to duplication and wasted efforts. The GPWG is tasked with continuously monitoring green propulsion technology efforts for awareness and serve in an advisory role to direct and support Agency efforts to advance green propulsion technologies. The GPWG will identify Agency capabilities and provide recommendations to the best utilization of those capabilities. If new capabilities need to be added to the Agency, the GPWG will advise to the most suitable location for those capabilities to be developed. The GPWG will also work to provide guidance to Mission Directorates, Program Offices, Centers, projects, and Agency investments in order to best utilize the resources available.

4.2.3 Strategic Goal 3—Knowledge Archiving, Distribution, and Utilization

There has already been a large trove of documents and reports created related to green propulsion technologies. This can include not just technical reports and documents, but also policy guidance, best practices, mishap reports, and/or evaluations. Ensuring that the largest audience permissible has access to this wealth of knowledge is important in minimizing duplicative efforts, poor performance, and/or wasted resources. Thus, a database of available documentation should be established to provide an easy-to-access resource for knowledge transfer and guidance among NASA and partnering satellite and vehicle manufacturers. A centralized Agency-controlled green propulsion technologies repository should be constructed. The GPWG should be tasked with the development and continual update of such a repository, and serve as a go-to resource of knowledge in green propulsion technology.

4.3 Definition of Green Propulsion

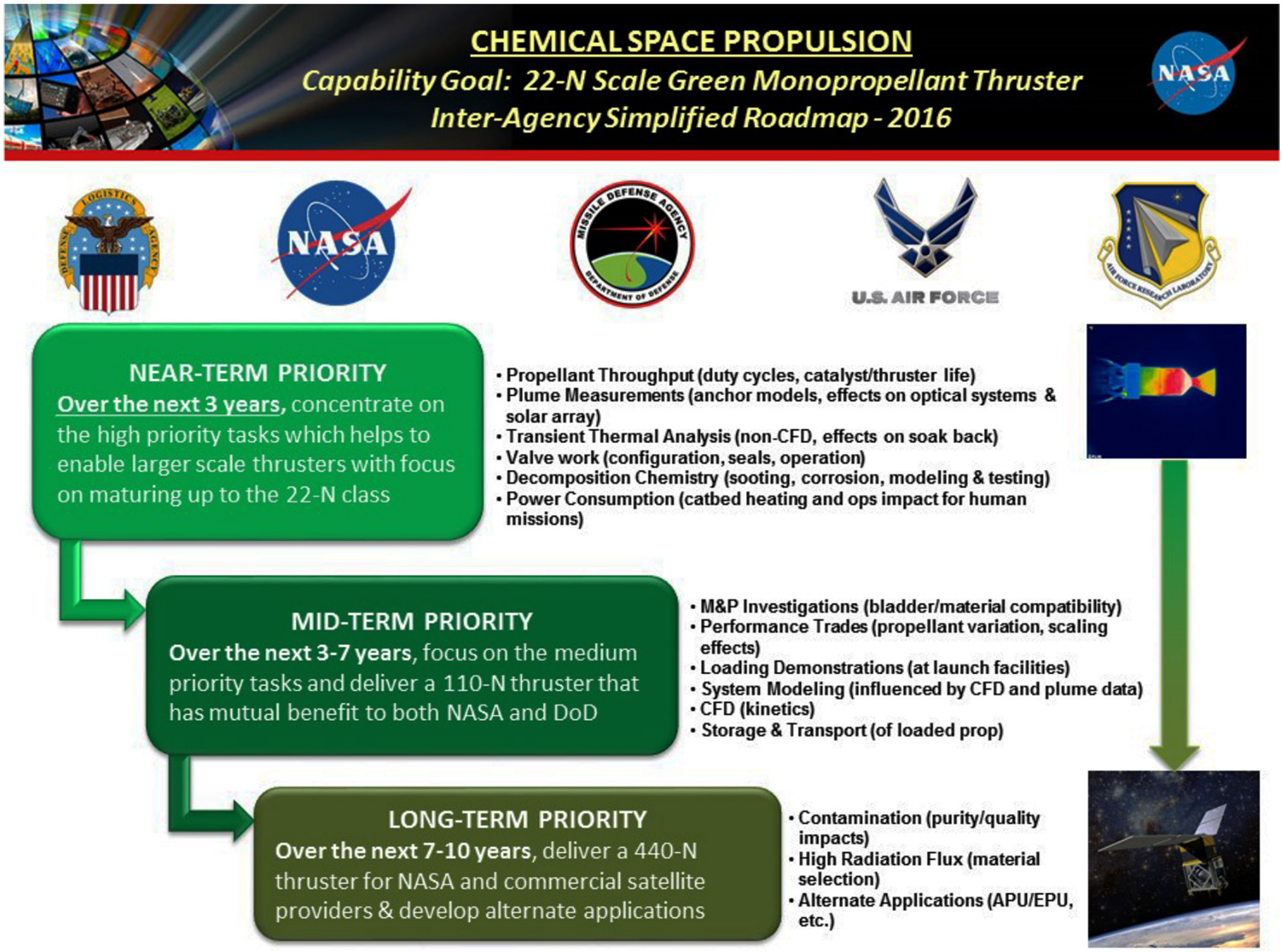
Green propellants are characterized by their relatively benign handling characteristics relative to hydrazine, and their benign exhaust products. The Green Propulsion Roadmap focuses on ionic liquid propellants and related technologies (e.g., catalysts, thrusters, etc.) which are seen as direct or near-direct replacements for hydrazine, hereafter also referred to as 'green propellants.' The ionic liquids are typically a blend of a salt oxidizer dissolved into some form of liquid fuel, and further diluted with water. These include various blends of hydroxylammonium nitrate (HAN) and ammonium dinitramide- (ADN-) based formulations, and shall include both monopropellant and bipropellant applications. Despite being referred to as 'monopropellants,' these blends do have an actual fuel/oxidizer combustion process. The ionic liquids are frequently referred to as monopropellants out of convention, however, because they are reacted over a catalytic surface similar to more conventional hydrazine or hydrogen peroxide systems. While monopropellant applications are the current focus of this Roadmap and most development efforts, applications to bi-propellant systems are also considered of interest to the Agency and technology needs for those systems will be addressed similarly.

4.4 2016 Green Monopropellant Alternatives to Hydrazine

In 2015, the Joint Army-Navy-NASA-Air Force (JANNAF) organization hosted a Technical Interchange Meeting (TIM) on Green Monopropellant Alternatives to Hydrazine (GMAH). Following presentations by government and commercial companies, a government-only session was held to identify and prioritize recognized technology gaps in green propulsion. A government Inter-Agency Working Group then took inputs from the government-only session to develop an informal technology development roadmap.

Advancements were broken down into near-, mid-, and long-term priority tasks, which were specifically defined as technologies that need to be addressed within 3 years, 3 to 7 years, and 7 to 10 years, respectively. Participants in the 2016 GMAH effort included NASA (Marshall Space Flight Center (MSFC), Glenn Research Center (GRC), and Goddard Space Flight Center (GSFC)), the United States Air Force (USAF) and Air Force Research Laboratory (AFRL), the Missile Defense Agency (MDA), and the Defense Logistics Agency (DLA).

The GMAH Roadmap is shown in figure 2, and was first presented to the larger community in 2016. More details of the 2016 Roadmap and how technology development areas were defined are included in section 5. This Roadmap was built on that foundation, including those technology gaps first identified during the 2015 GMAH TIM, and updated to include newly identified technology gaps as well as to provide a prioritize framework to address those gaps.



CHEMICAL SPACE PROPULSION

Capability Goal: 22-N Scale Green Monopropellant Thruster

Inter-Agency Simplified Roadmap - 2016

NEAR-TERM PRIORITY

Over the next 3 years, concentrate on the high priority tasks which helps to enable larger scale thrusters with focus on maturing up to the 22-N class

- Propellant Throughput (duty cycles, catalyst/thruster life)
- Plume Measurements (anchor models, effects on optical systems & solar array)
- Transient Thermal Analysis (non-CFD, effects on soak back)
- Valve work (configuration, seals, operation)
- Decomposition Chemistry (sooting, corrosion, modeling & testing)
- Power Consumption (catbed heating and ops impact for human missions)

MID-TERM PRIORITY

Over the next 3-7 years, focus on the medium priority tasks and deliver a 110-N thruster that has mutual benefit to both NASA and DoD

- M&P Investigations (bladder/material compatibility)
- Performance Trades (propellant variation, scaling effects)
- Loading Demonstrations (at launch facilities)
- System Modeling (influenced by CFD and plume data)
- CFD (kinetics)
- Storage & Transport (of loaded prop)

LONG-TERM PRIORITY

Over the next 7-10 years, deliver a 440-N thruster for NASA and commercial satellite providers & develop alternate applications

- Contamination (purity/quality impacts)
- High Radiation Flux (material selection)
- Alternate Applications (APU/EPU, etc.)

Figure 2. 2016 GMAH Technology Development Areas for green propellants (graphical format).

4.5 Alignment to NASA Technology Roadmaps

This Green Propulsion Roadmap aligns and supports NASA Technology Roadmaps,[1] which provide a broad framework on anticipated NASA mission needs and technology development goals. Technologies of interest to NASA should align to these roadmaps in order to justify investment. Green propulsion is no exception. When justifying investment, alignment to a specific mission is often cited. Technologies are described as either 'enabling,' meaning the technology brings a significant improvement to a mission in terms of performance, cost, or schedule, but is not necessarily required for mission success. However, technologies can also be described more broadly to a class of missions. The terms enabling or enhancing are sometimes still used in this context to describe a capability brought to a technology area. These capabilities are a little fuzzier in definition, but generally they describe a significant added capability not otherwise available with other SOA systems.

Green propulsion is primarily an in-space propulsion technology, therefore Technology Roadmap TA-02 provides the best alignment for these new systems. Within TA-02, the following sub-goals (capabilities) within Technical Area 2.1, Chemical Propulsion, are identified as being enabled or enhanced by green propulsion technologies:

- TA-02—2.1 Chemical Propulsion

2.1.1 Liquid Storable

2.1.1.1 Monopropellants: Green propulsion technologies are seen as direct replacements for hydrazine monopropellant engine systems. Studies to date have shown both enhancing and enabling performance for missions requiring this class of thruster.[2–4] TA-02 specifically calls out "Monopropellant technologies require the development of non-toxic variants from 1 Newton to 500 Newton thrusters" and lists a series of missions identified as enhanced by monopropellant technologies.

2.1.1.2 Bi-Propellants: The performance gains shown by green propulsion systems are approaching the performance of traditional space-storable hypergolic systems. Green propulsion could be enabling for simplified system architectures to achieve similar mission profiles of traditional hypergolic bi-propellant systems. Additionally, it is envisioned that as a hydrazine replacement, there is like-wise an analogous, enhancing bi-propellant propellant combination with existing green propellants which could offer even greater performance gains. TA-02 specifically calls out "Bipropellant technologies require the development of non-toxic variants from 220 N to 30,000 N engines to achieve I_{sp}, throttle capacity, lifetime, and reliability performance comparable to or increased from the state of the art (SOA), along with improved safety and handling efficiency for use as reaction control thrusters and orbital maneuvering engines."

2.1.7 Micropropulsion

2.1.7.3 Monopropellant Micropropulsion: Micropropulsion systems, such as those flown on CubeSats, are seen as an enabling technology. Green propulsion systems could potentially provide enough delta-V to enable meaningful CubeSat missions which have been elusive to date. TA-02 specifically calls out monopropellant micropropulsion needs in stating "Monopropellant microthrusters require the development of small catalyzer beds, small high-speed flow control valves, thermal control techniques, and non-toxic alternative propellants." NASA also published a "Small Spacecraft Technology State of the Art" report, which includes details on SOA chemical propulsion systems for small satellites.

Green propulsion meets all of these technology areas, specifically in providing a 'non-toxic' variant or alternative. However, while green propulsion provides enhancing features to In-Space Chemical Propulsion, in order to further advance and utilize the green propulsion capabilities themselves, other roadmaps and sub-goals may apply. The following list includes possible investment areas which would be enabling for green propulsion (not fully inclusive).

- TA-02—2.4 Supporting Technologies: Supporting Technologies, within TA-02, are those technologies that support an in-space propulsion system or subsystem but are not themselves a propulsion system. Supporting technologies specifically aim to "improve the capability of propulsion systems to increase the efficiency and flexibility of exploration and science missions." In order to improve the capability of green propulsion systems, a number of supporting technologies need to be developed as well. This may include improved sensors, advanced system modeling, and/or more robust materials technology. These supporting technologies include aspects that may be found in several other Technical Areas (i.e., TA-11 Modeling, Simulation, Information Technology, and Processing; TA-12 Materials, Structures, Mechanical Systems, and Manufacturing; TA-14 Thermal Management Systems).

2.4.1 Engine Health Monitoring and Safety: Green Propulsion systems often have a 'life' component to them, meaning that over time, the performance of the system degrades to an unusable or undesirable level. The ability to monitor and adapt to the changes in performance will lead to longer life systems and a more steady range of performance over time. Refined thermal and decomposition models will be required for more robust analysis and predictive design tools. Sensors and diagnostic techniques which can survive the high-temperature combustion environment, will also be required to better monitor combustor life. TA-08 provides details on SOA with respect to sensing technologies while TA-11 provides details on SOA with respect to modeling and simulation.

2.4.3 Materials and Manufacturing Technologies: Green propulsion systems often utilize special materials, such as the refractory metals iridium (Ir) or rhenium (Re), to survive the high temperature and/or oxidative combustion environment. The hardware designs utilizing these materials typically have longer and/or more expensive fabrication methods associated with them. Improved manufacturing methods are required to minimize impacts to costs associated with using these materials. TA-12 provides details on the SOA with respect to materials and manufacturing technologies.

2.4.4 Heat Rejection: Green propulsion systems, due to the high combustion temperatures experienced, often have a critical need for adequate heat rejection and management. More robust thermal models and designs are needed to understand impacts to spacecraft and to effectively manage and distribute heat generated by this class of thrusters. This may include heat rejection/management by the spacecraft impacted by the thrusters. TA-14 provides details on SOA methods of heat rejection.

4.6 Investments to Date

NASA and other government agencies have a long history of investment into green propulsion systems. Efforts in the early to mid-1990's focused on early formulations of HAN-based propellants, insensitive munitions, and liquid gun propellant systems. In the recent timeframe (2010's to present), NASA has supported a number of investment opportunities. Table 1 lists some known investments in green propulsion technology from 2010 to 2017.

Table 1. List of select green propulsion investments (~2010–2017).

Project	Funding Organization	Year Funded	Lead PI Organization	Supporting Organizations	Key Technology	Propellant
Green Propellant Infusion Mission (GPIM)	NASA STMD/TDM	2012	Ball Aerospace	GRC, MSFC, GSFC, AFRL, SMC, Aerojet Rocketdyne	1-N and 22-N thrusters first on-orbit AF-M315E demo	AF-M315E
Announcement of Collaborative Opportunity (ACO)	NASA STMD/GCD	2015	Aerojet Rocketdyne	GRC GSFC	GPIM 1-N rev. 2 design	AF-M315E
Announcement of Collaborative Opportunity (ACO)	NASA STMD/GCD	2015	Busek Co.	GRC MSFC	5-N thrusters	AF-M315E
Announcement of Collaborative Opportunity (ACO)	NASA STMD/GCD	2015	Orbital ATK	MSFC	440-N thrusters	LMP-1035
Tipping Point/Pathfinder Technology Demonstration (PTD)	NASA STMD/GCD	2015	Aerojet Rocketdyne	GRC	MP5-130 CubeSat propulsion system	AF-M315E
Multiple Awards in Various Subtopics	NASA STMD/SBIR	2010–present	Various	GRC GSFC MSFC	Various	Various
Green Propellant Loading Demonstration (GPLD)	NASA GSFC	2013–present	NASA/SNSB through IA	GSFC ECAPS	First U.S. loading demo of LMP-1035	LMP-1035
International Arrangement (IA)	NASA GSFC	2013–present	NASA/SNSB	ECAPS GSFC	U.S. development and demo of 5-N and 22-N HPGP	LMP-1035
Center IRAD	NASA MSFC	2015	MSFC	ECAPS	Hot-fire demonstration of 5-N and 22-N HPGP	LMP-1035
Lunar Flashlight	NASA HEOMD AES	2015	JPL	MSFC VACCO	6U CubeSat four 100-mN thrusters	LMP-1035
Advanced AF-M315E Monopropellant Engines (AAME) Broad Agency Announcement (BAA)	USAF AFRL	2017	TBD	AFRL	Qualification of 1-N and 22-N thrusters and proto-qual 100-N thrusters	AF-M315E
Advanced Monopropellant Development (AMD)	USAF AFRL	2014–2018	AFRL	Busek Aerojet Rocketdyne	Development and modeling efforts of 500-mN, 1-N, 5-N, and 22-N thrusters	AF-M315E AF-M315Q etc.
Advanced Manufacturing & Propulsion Solutions for MoonBEAM & Other Interplanetary CubeSat Missions	NASA MSFC	2017	MSFC	Various	GP propulsion modules for 3U and 6U CubeSats	AF-M315E LMP-1035
Center IRAD	NASA MSFC	2017	MSFC	Various	0.5-N and 1-N thrusters	AF-M315E LMP-1035

Among the Agency investments to date, in 2012, NASA funded a Technology Demonstration Mission (TDM) known as the Green Propellant Infusion Mission (GPIM). This mission represented the first major NASA investment into a green propulsion system, with the intent of a space flight demonstration. The stated goals of GPIM follow:

(1) Demonstrate the on-orbit performance of a complete AF-M315E propulsion system suitable for an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter- (ESPA-) class spacecraft.

(2) Demonstrate AF-M315E steady-state performance of delivered volumetric impulse of at least 40% greater than hydrazine.

(3) Demonstrate stable performance of a flight-weight attitude control thruster for at least 10,000 total pulses.

(4) Demonstrate stable performance of a flight-weight primary propulsion thruster for propellant throughput of at least 7 kg.

(5) Demonstrate three-axis spacecraft attitude control with a pointing accuracy of less than 6 degrees.

(6) Produce a detailed report comparing all aspects of ground and on-orbit propellant operations for AF-M315E and hydrazine.

Details on the programmatic goals and development of GPIM may be found in the public literature.[5,6] While the overarching goal of GPIM is to conduct a flight demonstration of a green propulsion system, much work still remains to address all known technology gaps and challenges associated with these new propulsion systems. For instance, GPIM was originally intended to fly four 1-N attitude control thrusters and a 22-N primary thruster, but the 22-N thruster was changed to a fifth 1-N thruster due to technical challenges experienced delivering a flight-qualified 22-N thruster. Technical challenges not addressed or resolved by GPIM include applications of other green propellants such as LMP-103S, novel noncatalytic ignition methods, propellant management devices (PMDs), as well as many other identified technical gaps.

The Agency has also focused recently on public-private partnerships, relying on the development through private industry while providing some limited resources to help advance the technology. While these are NASA solicitations, it is expected that industry will define goals and lead the development efforts in partnership with NASA, rather than starting from a NASA-defined mission or goal, as a means to foster private development of the technologies.

In 2015, NASA issued a solicitation titled, “Utilizing Public-Private Partnerships to Advance Emerging Space Technology System Capabilities” (NNH15ZOA001K), commonly referred to as an Announcement of Collaborative Opportunity (ACO). This solicitation mechanism provided private companies access to NASA expertise and facilities in return for the private company’s development investment through a no-cost exchanged Space Act Agreement (SAA). Several topic areas were addressed within this solicitation, of which green propulsion was included. The green propulsion technology topic area sought to support industrial partners in furthering their green propellant thruster developments by providing technical expertise and access to NASA test facilities. Investments were limited in duration (24 months), and total investment to NASA facilities (2 FTE (man-year) labor/$1M in total funding, including labor). Again, due in part to the limited number and size of awards, not all identified technology gaps could be addressed through this arrangement.

A second type of public-private partnership was also released at the same time, "Utilizing Public-Private Partnerships to Advance Tipping Point Technologies" (NNH15ZOA001N). Similar in intent to the ACO, this partnership provided NASA investment matching dollars with the intent to advance these new capabilities to a point (a 'tipping point') where industry would then complete and qualify them for market without further government investments. While green propulsion was not a specific topic area identified, it was one area that could support several of the topic areas within the Tipping Point solicitation. One partnership was identified to develop a green propulsion small satellite (CubeSat) propulsion system. This system was for a commercial 'point solution' and product development and was not meant to specifically address the overall technical challenges seen in green propulsion.

While the investments noted above are advancing green propulsion technologies, they have focused around 'point solutions' to advancing an industry developed product for flight infusion and commercialization, rather than through systematic and broader investment around generalized research and development to address broader technical issues. The public-private partnership model appears to be the preferred Agency mechanism of funding green propulsion for the foreseeable future. This roadmap provides a systematic, integrated technology development approach that can be consulted in the formulation of future NASA solicitations and the needs and plans of the broader technical community.

5. GREEN PROPULSION TECHNOLOGY DEVELOPMENT AREAS

Significant progress toward meeting the technology and infusion challenges for green propulsion over the next 10 years hinges on addressing high-priority TDAs. In 2015–2016, an Inter-Agency Working Group sought to develop a technology development roadmap based on presentations and discussion following the JANNAF-sponsored GMAH TIM. The Inter-Agency Working Group included members from NASA (GRC, MSFC, and GSFC), USAF (AFRL and Space and Missile Command (SMC)), MDA, and the DLA. That roadmap, shown in figure 2 is expanded on in table 2, and is further expanded and described in subsequent subsections.

Table 2. 2016 GMAH Technology Development Areas for green propulsions.

	Near-Term Priority	**Mid-Term Priority**	**Long-Term Priority**
Timeframe	Over next 3 years	3–7 years	7–10 years
Thrust class target	Up to 22 N	Up to 110 N	Up to 440 N and alternative applications
Primary technology advancement areas	• Propellant throughput (duty cycles, catalyst/thruster life) • Plume measurements (anchor models, effects on spacecraft optical systems, or solar arrays) • Transient thermal analysis (non-CFD, effects on soak-back temperatures) • Valve work (configurations, seals, operation) • Decomposition chemistry (sooting, corrosion, modeling, and testing) • Power consumption (catbed heating, operational impacts for human missions)	• Materials and property investigations (bladder/material compatibility) • Performance trades (propellant variations, scaling effects) • Loading demonstrations (at launch facilities) • System modeling (influenced by CFD and plume data) • CFD (kinetics) • Storage and transport (of loaded propellant)	• Contamination (purity/quality impacts) • High radiation flux (material selections) • Alternate applications (auxiliary power units, electrical power units, etc.)

The Inter-Agency Working Group identified a series of technology gaps after presentations by various government and industry partners during the main portion of the GMAH TIM. Those technology gaps identified were as follows (* = highest priority gaps):

- Ignition power and techniques*—Catalyst systems can be heavier in mass than noncatalytic systems and require significant power to utilize.

- Throughput*—Existing green propellant thrusters have only demonstrated a fraction of lifetime compared to existing SOA hydrazine thrusters. The hotter combustion environment, steep thermal transients, and corrosive intermediate species of combustion are believed to reduce overall thruster and catalyst lifetimes.

- Plume modeling*—Impact of continuum and rarified flow effects, effluents of thrusters/propellants, and impact on nearby spacecraft surfaces are not well understood.

- Materials properties—Material and thermal property data on Ir, Re, and/or other refractory metals, particularly at the elevated temperatures experienced by green propellant thrusters, is lacking. Material compatibility, particularly for soft-goods, is not well understood.

- Response time—Required preheat times and ignition delays seen in SOA green propellant thrusters are longer than SOA hydrazine thrusters.

- New propellant formulations—Other higher performing formulations of green propellants are being developed, and have not been evaluated to the same degree as AF-M315E or LMP-103S. The trade between combustion temperature (and thereby thruster/catalyst life) and performance by altering the blend ratios of propellants is not well understood. Comprehensive standards for how propellants are made/blended (similar to existing propellant MilSpecs) are nonexistent.

- Manufacturing techniques and cost—Current material systems used in green propulsion systems are expensive and difficult to come by. Manufacturing methods are more expensive relative to hydrazine thruster systems.

- Propellant performance modeling—Analysis codes for more predictive analysis of behavior and decomposition/combustion process are lacking or nonexistent.

- Propellant supply—Current propellant formulations are either foreign sourced or contain constituents that are foreign sourced. No dedicated logistical supply chain exists.

The Inter-Agency Working Group ranked and prioritized the needs after identifying the above technical gaps. Specific areas of advancement (i.e., primary technology advancement areas) were identified to address one or more of the technical gaps. Additionally, a step-wise advancement approach was considered, meaning near-term advancements were identified that could feed into later advancements. Advancements were broken down into near-, mid- and long-term priority tasks, which were specifically defined as technologies that could/need to be addressed within 3 years, 3 to 7 years, and 7 to 10 years, respectively. Additionally, the high, medium, and low priority tasks were also applied, in a general sense, to a set of thrust classes with scaling in mind, with the high priority (near term) being up to 22-N class, mid term up to 110-N class, and long term being up to 440-N class and alternate applications (such as auxiliary power units). This roadmap was presented to the community in a graphical format. Table 2 lists the 2016 GMAH technology advancement areas (also shown in its graphical form in fig. 2).

The GPWG reviewed the work of the 2016 Inter-Agency Working Group, and concurs that the identified technical gaps and technology development areas are still relevant and necessary to see green propulsion technology advanced. The 2016 Roadmap presents a good variety of TDAs to address known technology gaps, recognizes a logical step-wise approach to the technology development and scaling to larger thrust classes, and is supportive of potential public-private partnership opportunities. Thus, the GPWG recommends the 2016 Roadmap be adopted as baseline, with some additions.

The focus of the 2016 GMAH Roadmap was primarily on the thruster technology. The Agency must also invest in understanding the broader propulsion system-level technology gaps in parallel. Knowledge of how to model and integrate these new propellants, as well as thruster components, is required. Understanding physical characteristics of the propellants, and helping to complete propellant property databases, should also be included as a near- to mid-term goal to maximize infusion potential to NASA missions.

While the 2016 GMAH Roadmap does identify general timeframes when a technology is needed, the GPWG also recognizes that some development efforts will take more time and may need to start in the more near term. Thus, timeframes are considered suggested from a priority standpoint, but are also flexible as some efforts will need to occur in the nearer term or concurrently in order to meet specific mission requirements. Also, the GPWG recommends expanding the definition of near-, mid-, and long-term development from 3-, 7-, 10-year increments to 5-, 10-, 15-year increments, given the public-private partnership model most likely to be utilized in investing in technology development.

The GPWG sees small satellites (those spacecraft with mass below 180 kg, including the class of small satellites known as CubeSats) to have tremendous promise in being a flight platform for addressing many of the identified TDAs. This is especially true within the realities of constrained budget environments, where larger demonstration-only missions could be cost prohibitive. Thus, small satellite flights and demonstrations are encouraged where feasible to advance identified TDAs. This can be co-beneficial, as it will also provide small satellites a capability (propulsion) that is currently lacking for that class of spacecraft.

Additionally, the GPWG recognizes the constraints of recent government budgetary environments and the highly proprietary nature of private industry investments. Thus, the working group recommends identified TDAs be advanced through public-private partnership as much as feasible. The GPWG believes the government has several unique areas of expertise and facilities to support advanced modeling and test capabilities, which can bolster and aid private development efforts. The public-private partnerships are best served through intra- and inter-Agency coordination. By partnering and teaming, both among government agencies as well as with private industry, the greatest value of development can be achieved.

To provide greater detail to the technology advancement areas identified in the 2016 Roadmap, specific recommendations to advancing TDAs is provided in the following sections, grouped around major development categories: thruster hardware development, modeling development, materials and properties, and propellant development. Since the technology development areas span a range of thrust classes, it is difficult to specify specific advancement metrics as they are very thrust class dependent. As an example, the total lifetime (propellant throughput) of a thruster will be very different at 1-N scales versus 100-N scales. However, any technology development effort proposed should identify key performance parameters (KPPs) of the SOA and provide some quantifiable metric of improvement in that KPP being offered. KPPs include parameters such as (not all inclusive) propellant throughput (in terms of kg or total impulse), specific impulse/density specific impulse ($I_{sp}/\rho I_{sp}$), heating requirements (W) or preheat time (minutes), material/hardware costs ($ or % reduction), model accuracy (% uncertainty), ignition delay (ms), etc.

Note the GPIM mission identified some KPPs relative to 1-N thrusters as part of its objectives. As a minimum rule of thumb, since this class of thruster is seen as a direct replacement for hydrazine-based systems, development efforts should demonstrate comparable or better performance/metrics to hydrazine systems or identify how the technology effort is leading to that goal. Where specific green propellant SOA metrics exist, efforts should demonstrate how they are improving upon those metrics. It is recommended that development efforts progress from smaller thrust classes (100 mN to 22 N) in the near term to the larger thrust classes (>100 N) in the mid- and far-term, as technology development advancements and risk reduction efforts identified to make smaller thrust classes commercially viable and flight qualified will cascade into and be utilized by larger thrust classes.

5.1 TDA-01—Thruster Hardware Development

With respect to thruster hardware development, the GPWG recommends the following areas of advancement:

TDA-1.1 Improve propellant throughput (near term):
- Seek efforts to demonstrate lifetime (propellant throughput) equivalent to SOA hydrazine systems. This can be terms of life in minutes or total impulse, as a function of thrust class.
- Develop catalyst systems to withstand hotter combustion temperatures, steeper thermal transients, and corrosive surrogate chemical species known to reduce life of SOA catalyst systems.

TDA-1.2 Reduce ignition power requirements (near term):
- Identify novel methods for reducing preheat power requirements, such as unique catalyst bed heating configurations or modes of thruster operation.
- Investigate noncatalytic methods or alternative methods for ignition.
- Investigate methods to reduce ignition delay (whether through reaction or preheat).

TDA-1.3 Develop supporting hardware (near to mid term):
- Develop improved valves for use with green propulsion systems, including variable position valves, other configurations, seals, operation, etc.
- Develop green propellant specific storage and management devices (tanks, bladders, LADs, PMDs).

TDA-1.4 Improve manufacturing techniques and cost (mid term):

- Develop chamber designs which adapt material and manufacturing methods to reduce overall engine system cost.
- Identify manufacturing methods for refractory materials that reduces overall production costs.
- Investigate methods of manufacturing unique catalyst structures and geometries.

5.2 TDA-02—Modeling and Tools Development

Computational models and tools provide engineers with the capability to predict performance, analyze and diagnose system anomalies, and provide partners with design tools to reduce overall development costs. The GPWG recommends the following models and tools be developed:

TDA-2.1 Plume models (near term):

- Understand continuum and rarefied flow effects, effluents of thrusters, and impact on nearby spacecraft surfaces. Use hot-fire test data to help anchor and corroborate models.

TDA-2.2 Catalytics and decomposition chemistry (near term):

- Develop physics-based models based on a priori understanding, utilizing test data to anchor and corroborate models.
- Characterize pressure drops and heat exchange rates of various gas and fluid media through alternative catalyst bed structures, such as monolithic foam catalysts, for higher fidelity modeling and simulation at varying temperatures.
- Identify kinetics of reaction for higher fidelity modeling and simulation.
- Identify potential life-limiting combustion processes (such as sooting/corrosion).

TDA-2.3 Transient thermal analysis (near term):

- Thermal analysis (via computational fluid dynamics (CFD) or similar) and review of test data of various engine designs for different operational modes, including the identification of potential thermal issues such as heat soak-back into sensitive regions of thruster hardware.
- Develop a simplified geometry/mesh of a thruster, including catalyst bed for specified support structures to aid designers predicting thermal loads during operation.

TDA-2.4 Propellant performance modeling (mid to long term):

- Identify impacts of scaling (higher thrust classes) to performance and combustion/thermal environment.
- Develop, refine, and anchor codes with test data (e.g., Chemical Equilibrium Analysis (CEA) type) for more predictive analysis.
- Investigate alternate propellant formulations to identify performance versus combustion or thermal environment trades.
- Identify and refine chemical process assumptions in fluid properties and/or combustion modeling codes, such as CEA or REFPROP codes.

5.3 TDA-03—Materials Properties and Compatibility

A complete understanding of materials and compatibility considerations are enabling to lower cost systems and necessary for thorough evaluation of structural limitations of designs. The GPWG recommends development of the following databases:

TDA-3.1 Identify and increase system material compatibility database, including compatible 'soft goods' (e.g., seals, bladders, etc.) (near to mid term):
- Expand thermal and mechanical database on Ir, Re, and Ir/Re systems, particularly at higher temperatures.
- Expand thermal and mechanical database on weld and joining data for superalloy (e.g., nickel-based alloys) and refractory metals (e.g., Ir/Re/platinum).
- Expand database on material compatibility for many common materials of interest including soft goods (e.g., stainless steels, nickel alloys, EPDM, Viton, PTFE, etc.).

TDA-3.2 Generate a green propulsion database, such as inclusion of data into NASA's Materials and Processes Technical Information System database (mid term).

TDA-3.3 Identify impacts of high radiation flux onto system components (long term).

5.4 TDA-04—Propellant Development

In order to have a robust technology, a complete and thorough understanding of the properties of the propellant itself needs to be addressed. While the propellants have been tested for a number of physical and thermal properties, many properties' data are lacking or unavailable. These properties will help mission planners recognize potential risks to mission success as system architectures are developed, and will aid a number of the computational models described above in TDA-02. Additionally, the current propellant supply base is unable to provide long-term quantities of propellant without further investment and development in the supply chain. The GPWG recommends the following assessments be undertaken regarding propellant development and supply:

TDA-4.1 Improve and develop propellant supply base (near term):
- Identify domestic suppliers of blended propellants as well as propellant constituents.
- Identify logistical handling, transport, and procurement of propellants.
- Develop MilSpec-type standards for propellant blends.
- Define more comprehensive propellant specifications (help to establish appropriate MilSpecs).

TDA-4.2 Quantify and expand database of propellant properties (near to mid term):
- Identify impacts of purity/quality (including gas or water absorption) on propellant performance.
- Assess impact of radiation tolerance and effects on propellant performance.
- Understand thermal stability due to thermal soak-back and impacts on performance.
- Increase database on thermal and physical properties of propellant over a range of temperatures.

TDA-4.3 Explore new propellant formulas (mid to long term):

- Evaluate alternate formulations of propellant blends to understand impacts to performance and combustion temperatures, with implications to overall system costs.

TDA-4.4 Explore alternate applications (long term):

- Investigate uses of propellants in alternative applications, such as bi-propellant engines, aerospace auxiliary power units, or electrical power units.

6. IDENTIFICATION OF POTENTIAL NASA INFUSION OPPORTUNITIES

As with all Agency technology developments, the goal is the infusion of the technology into space flight opportunities. This infusion can sometimes present as many challenges as developing the technology in the first place, as the industry and mission planners are often reluctant to accept new technological risks unless the mission in question specifically demands the new technology.

With the exception of the 2012-funded GPIM, expected to fly mid to late 2018, the NASA flight opportunities for green propulsion in the near term are most likely going to be with NASA focused missions as well as the recently energized SmallSat/CubeSat community. For these types of missions, the thruster sizes of interest are predominantly the 100-mN to 22-N classes, with the former most applicable to CubeSat or SmallSat mission architectures and the latter for mid to large science missions (including ESPA class or larger). Figure 3 is an adapted figure from Bacha et al.,[4] illustrating the number of missions served by various thrust classes. From this figure it can be implied that development of green propulsion would be best infused where the largest number of mission opportunities exist, in this case, the lower thrust classes which also correspond to the near-term objectives identified in the TDAs. The figure also highlights that, as advancements are made at the lower thrust classes, those developments will 'cascade' into and benefit the development efforts of larger thrust classes.

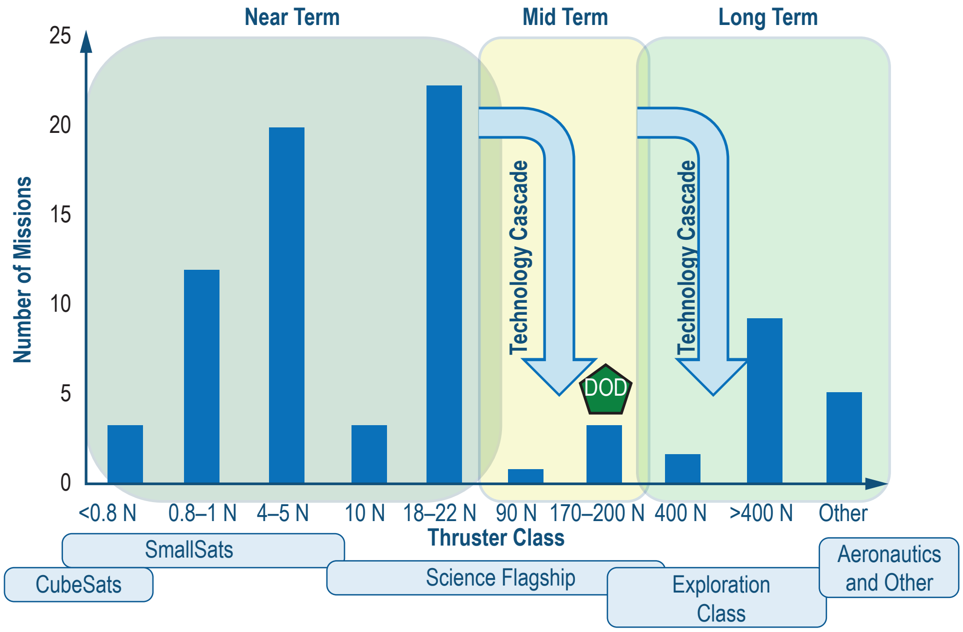


Figure 3. Thruster class distribution for NASA missions, and priority for infusion (adapted from Bacha et al., 2016).

It should be noted that the Department of Defense (DoD) and other government agencies are also interested in green propulsion development, and there are unique infusion opportunities there as well. However, there are notable differences to the applications of the technology to the missions DoD might pursue versus those that NASA might pursue. As a broad generalization, DoD interests seem focused around a system that can provide a rapid, on-demand response with a high-impulse-type maneuver. Missions are relatively short in duration (hours to months). NASA, on the other hand, is typically interested in applications that require longer hardware life, with a system ‘coasting’ for long durations in space, thus requiring a robust system that will perform without instantaneous guidance and control from Earth. They might also be more power limited depending on the spacecraft platform. These missions may be longer in duration (months to years). These applications are somewhat divergent from each other. Generally, the rapid response, high-impulse applications of DoD uses tend to require higher performance propellant blends which lead to shorter catalyst lifetimes and more exotic materials, whereas applications for NASA are more tolerant of systems that require longer preheat times and tolerant of slower response, but which need more robust components where hardware can be expected to coast for months to years between use. However, while these agency needs appear divergent, the development needed to serve each mission type is complimentary, and several TDAs contribute to advancement for both types of missions. Also, the above statements are broad generalizations: there may be very specific mission needs in one agency that are complimentary to the aims in another agency.

Additionally, in general, there are four areas of focus that can be served by green propulsion technology development. Figure 4 maps the various TDAs to these four focus areas—Lower Life-Cycle Costs, Predictive Capability, Hardware Development, and Alternative Applications. Lower life-cycle cost involves identifying opportunities to minimize overall mission costs of existing green propulsion systems; e.g., ground handling, safety, materials, etc. Hardware development involves developing specific hardware/products required for making green propulsion trades; e.g., valves, seals, catalyst/throughput, etc. Predictive capability involves development of analytical tools required to predict and plan for system performance; e.g., combustion codes, thermal models, etc. Alternative applications involves exploring other options for green propellants which would provide alternative infusions paths; e.g., aircraft APUs, dual mode electric propulsion, etc. Of course, efforts in one focus area also might benefit other focus areas, hence a Venn-type diagram is appropriate. Figure 4 provides a snapshot of where a given TDA might best serve the different focus areas, along with an idea of how near-term ready that technology can be.

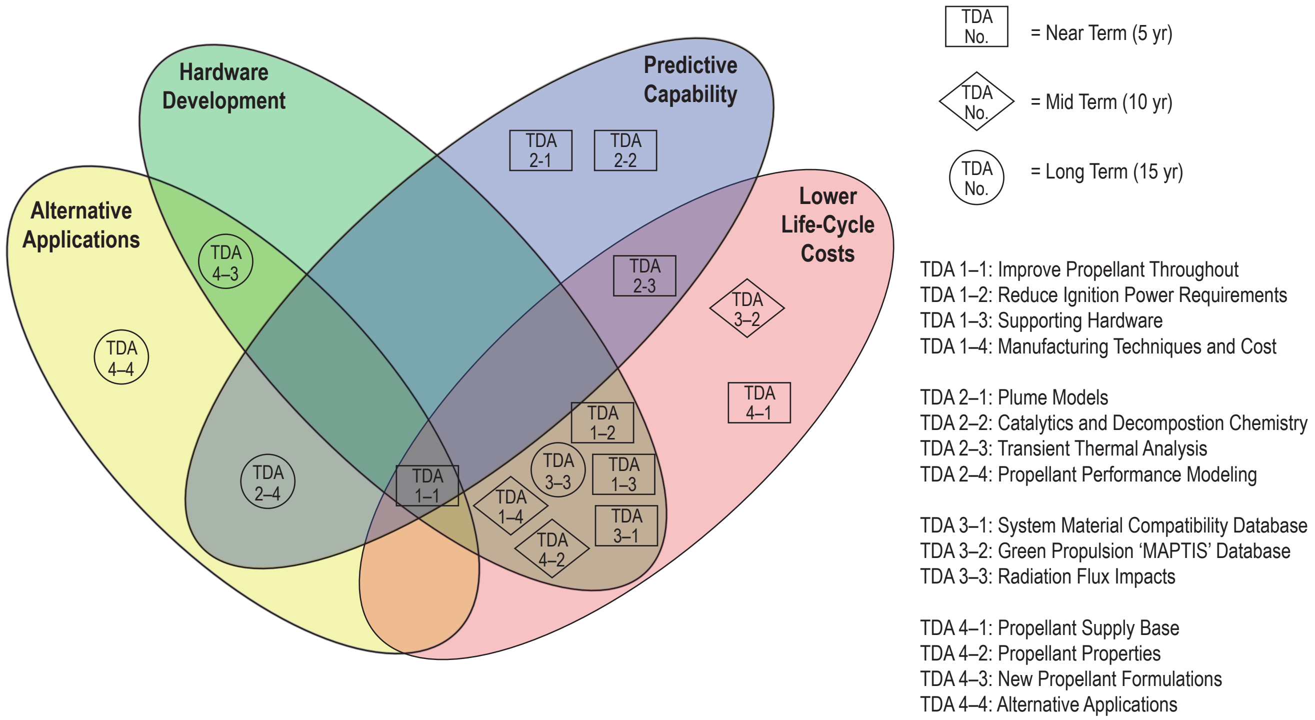


Figure 4. Illustration of Technology Development Area mapped on desired focus direction.

While past investments may have focused on specific propellant solutions; i.e., one specific propellent blend, from a NASA perspective, there is no one 'right' solution between the various green propulsion systems being developed. The choice of propulsion system (and its propellant) is mission dependent (program constraints, technical risk, cost, schedule, compatibility, etc.), and the Agency focus on any given propellant to date has been largely due to availability and technology transfer issues rather than specific technical solutions. The GPWG sees green propulsion as a viable alternative for future flight missions and recommends that similar development efforts for the widest variety of system solutions and propellants be pursued to meet NASA mission needs. This will give mission planners the greatest range of technologies available and thus lead to the greatest opportunity for infusion.

7. ROLE OF PARTNERSHIPS

The current fiscal reality of government funding pushes technology development efforts towards more cooperative, partnership-based approaches. By cooperating with other government agencies, engaging in public-private partnerships, and by seeking lower cost flight opportunities (e.g., small satellites and/or CubeSats), it is possible that critical technology advancements could be made that enable the infusion of green propulsion systems into NASA spacecraft and missions.

Partnerships will be a key to success in seeking to advance development of green propulsion systems. With the goal of fostering partnerships and promoting collaboration where feasible, the GPWG intends to be a forum for communicating to and seeking subject matter experts, facilities, and institutional support across NASA and outside the Agency. These partnerships include intra-NASA partnerships (i.e., between Centers and/or Headquarters (HQ) Mission Directorates), inter-Agency partnerships (i.e., between NASA and other government agencies), and public-private partnerships (i.e., between NASA and private commercial entities). These may also include working with other advisory or collaborative bodies, such as technical societies (e.g., American Institute of Aeronautics and Astronautics (AIAA) or the JANNAF bodies). Partnerships may take many forms, both official and unofficial.

7.1 Intra-NASA Partnerships

There are a number of partnerships that can form within NASA. Such partnerships can be between Centers, such as one Center leading a development effort but using the test facilities or expertise of a partner Center. Partnerships can also exist between HQ Mission Directorates, with one Mission Directorate leading the development effort that will be infused into another Directorate's mission, such as infusing technologies into exploration or science missions. Also, the Agency's SBIR program is supported by the other Mission Directorates. The GPWG will act in an advisory role, through the CPSM, to the various Mission Directorate programs. The following are examples of intra-NASA partnerships:

- Inter-Center partnerships (between GRC, GSFC, MSFC, and others).
- Intra-Agency coordination (between Mission Directorates).
- Mission Directorate support to NASA's SBIR program (such as Human Exploration and Operations Mission Directorate (HEOMD) or science topics within SBIR).
- Fellowships and innovation grants (NASA Science Technical Research Fellowship, Center Innovation Funds, Early Career Initiative, Early Career Fellowship).

7.2 Inter-Agency Partnerships

Other government agencies have invested in green propulsion, or have unique capabilities and expertise which can aid development efforts. For example, the USAF is the developer of the green propellant AF-M315E, and has unique capabilities for testing these systems. Other agencies that lack strategic capabilities possessed by a NASA Center would benefit from a forum that provides access to those capabilities. The GPWG will work as a unique point of contact with these other government agencies, will collaborate and review with them the broader community development efforts in green propulsion, and will help make connections between agencies. This will help to foster a larger community of information exchange, and will minimize duplication of efforts across the government. Examples of inter-Agency partners include the following:

- USAF
  - AFRL
  - SMC
- Sandia National Laboratories
- MDA
- U.S. Navy
- Small Satellite Program.

7.3 Public-Private Partnerships

Private commercial entities are increasingly interested in green propulsion. Green propulsion has the potential to reduce ground costs, increase performance, and/or meet environmental concerns. However, the costs of development may be beyond the ability of some commercial entities. The government, with unique capabilities and expertise, can ‘fill in the gaps’ for these commercial entities, providing capabilities that would be cost prohibitive for the commercial entity to pursue. Additionally, commercial entities tend to be more focused on developing a sellable product. This can leave gaps in the knowledge base where technical issues are avoided or ignored in order to get a successful product to market. Partnerships with the government can help to address these technical issues and expand the knowledge base that otherwise would be skipped in an effort to market a product.

Universities and national laboratories can be capable and cost-effective partners to NASA to help dive deep into specific technical issues, and develop the industry’s future subject matter experts. Examples of partnership mechanisms are the following:

- Broad Agency Announcements
- Announcement of Collaborative Opportunities (ACOs)
- SAAs
- Collaborative Agreement Notices

7.4 Collaborative Bodies

Several collaborative bodies exist which may provide a forum for discussion of green propulsion technologies, or provide standards or guidelines to be considered while pursuing advancement in green propulsion technologies. To the greatest extent possible, the GPWG will collaborate with these bodies in order to promote the greatest amount of data sharing possible. Such collaborative bodies include the following:

- JANNAF and subcommittees
- John Hopkins University Energetics Research Group (formerly CPIAC and CADRE)
- AIAA technical committees
  - Liquid Propulsion Technical Committee
- Rocket propulsion for the 21st Century.

7.5 International Partnerships

It is recognized that international entities have a significant investment in green propulsion technologies to date. International partnerships carry with them unique challenges, such as ITAR/ Export Control restrictions, as well as opportunities. Typically, these partnerships are arranged through government agencies or bodies, within implementing arrangements. Often they are executed as no-cost exchanged arrangements. Yet pursuing these partnerships, where permissible, can add another layer of technical exchange that enhances technology development efforts. Examples of possible partnerships would include the following:

- NASA Swedish National Space Board
- NASA European Space Agency
- NASA Japan Aerospace Exploration Agency.

8. SUMMARY AND CONCLUSIONS

The GPWG, an advisory group under direction from the NASA Chemical Propulsion Subcapabilities Management team, has sought to lay out a roadmap and vision for future green propulsion technology development. Reviewing inputs from a previously developed GMAH Roadmap, and considering NASA specific interests, the GPWG defined a number of specific technology development areas to be addressed. It is the intent of this group that this roadmap serve to inform and guide future investments in green propulsion technology in a manner that addresses and aligns with NASA strategic technology investment, mission needs where they can be defined, and a vision towards growth of the technology and discipline. Additionally, this group invites other Agencies or partners to reference this roadmap for technology development programs. This Technical Publication will be periodically reviewed and new versions issued to keep updated with technology developments and changes in Agency strategies, as appropriate.

APPENDIX A—STRATEGIC TECHNOLOGY INVESTMENT GUIDES AND PLANS

NASA has several policy documents to provide guidance when considering a strategic approach to space technology investment, . These documents provide an Agency Strategic Plan for space technology development, and are frequently referenced when considering new technology efforts. Even more frequently, these are often a required reference in responses to Agency solicitations to show alignment to NASA strategic goals and plans. Outside of these Agency documents other sources also exist, which provide plans for technology development, and some provide specific advice on green propulsion technology that can be useful when putting together an overall roadmap on green propulsion technology development.

A.1 Overview of NASA Strategic Space Technology Investment Plan (2012)

The first document supporting NASA's overall plan for technology investment is the "NASA Strategic Space Technology Investment Plan."[7] First published in 2012, and described on the OCT Web site, "The NASA Strategic Space Technology Investment Plan (NASA SSTIP) is a comprehensive strategic plan that prioritizes space technologies essential to the pursuit of NASA's mission and achievement of national goals…The plan provides guidance for NASA's space technology investments during the next four years, within the context of a 20-year horizon. The plan is updated every two years, as appropriate, to meet Agency and national needs." The most current version of the plan at the time of this writing is the 2012 version.

The SSTIP itself is aligned to NASA Technology Roadmaps, a set of technology development roadmaps developed under NASA's Office of Chief Technologist, and described in appendix A.2. The SSTIP identifies the following principles of investment and execution for new technology development. NASA will:

- Balance investments across all 14 space technology areas in the roadmaps.
- Balance investments across all levels of technology readiness.
- Ensure developed technologies are infused into Agency missions.
- Develop technologies through partnerships and ensure that developed technologies are infused throughout the domestic space enterprise.
- Use a systems engineering approach when planning technology investments.
- Reach out to the public and share information about its technology investments.

Within the SSTIP are several Core Technology Investments, areas that represent focused areas of technology investment which are indispensable for NASA's present and planned future missions. One specific technology area identified was Launch and In-Space Propulsion. Within that technology area, the SSTIP specifically states that "NASA is also evaluating alternatives to chemical propellants known as 'green' or non-toxic propellants, because they have the potential to reduce risk on the ground." They also meet the goal of investing in systems to "improve the cost and operation of current systems and enhance and enable future robotic and human exploration missions." The

SSTIP notes, “Advancing chemical propulsion technologies enables much more effective exploration of our solar system and permits mission designers to plan missions that fly anytime, anywhere, and complete a host of science objectives at their destination.” The SSTIP also states, “Developing new chemical propulsion technologies will result in technical solutions with improvements in thrust levels, specific impulse, power, specific mass, volume, system mass, system complexity, operational complexity, durability, and cost.”

In creating the Green Propulsion Technology Roadmap, the GPWG aligned with these strategic principles, and created a roadmap that is complimentary to the aims of NASA’s SSTIP.

A.2 Overview of 2015 NASA Technology Roadmaps (2015)

First developed in 2012, and revised in 2015, the NASA Technology Roadmaps[8] provide a set of 15 roadmaps/technology areas (originally 14 in the 2012 version) to guide investments and development in space technology. As stated on the OCT Web site, “The 2015 NASA Technology Roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years (2015–2035). The roadmaps focus on applied research and development activities.” Figure 5 shows a poster of all the 2015 Technology Roadmap areas.

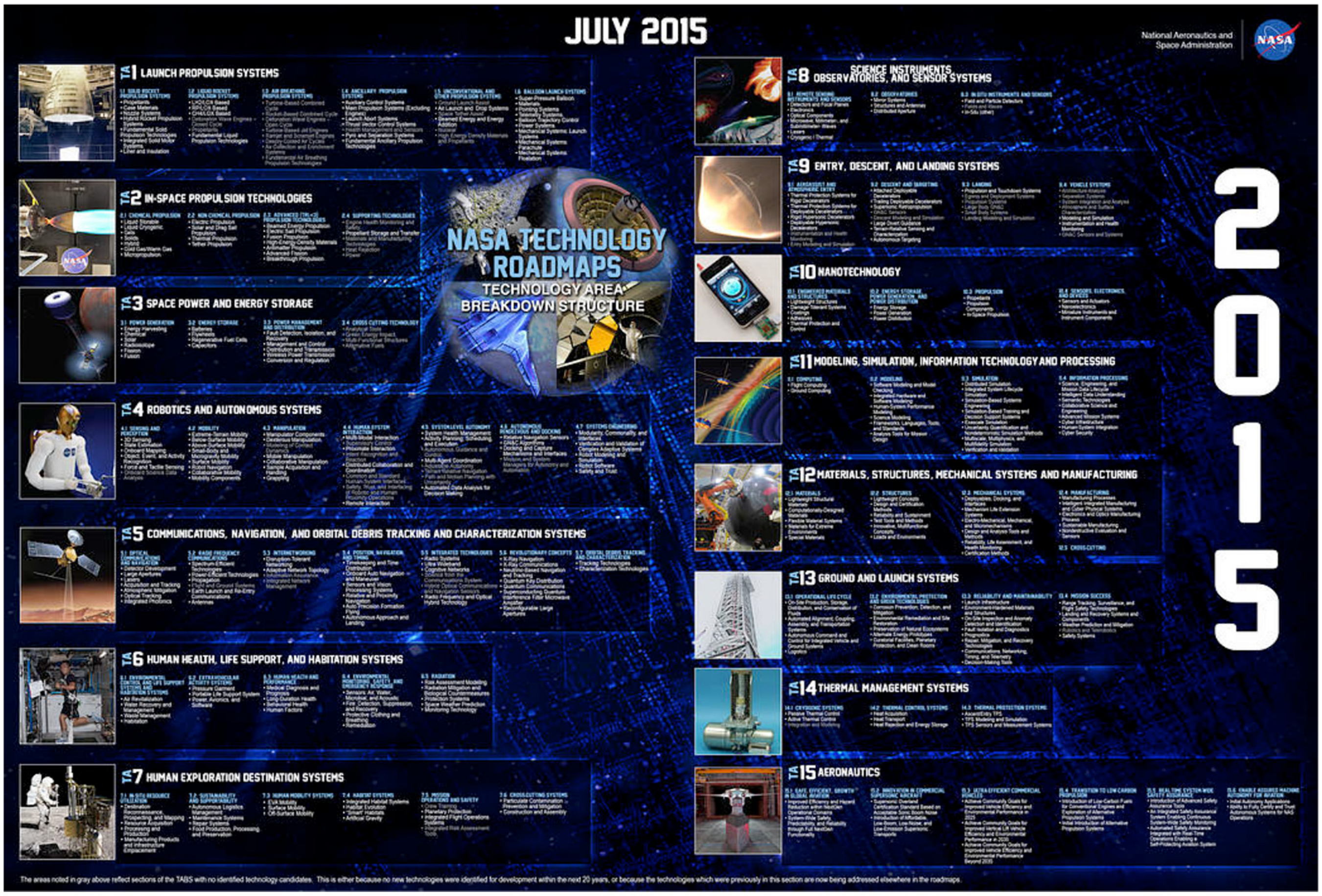


Figure 5. Poster of the 2015 Technology Roadmap areas.

Each Technology Area contains an executive summary, a set of overarching goals and challenges, a roadmap graphic, a Technology Area Breakdown Structure graphic, detailed discussions, and associated Technology Candidate snapshots.

The Technology Candidate is an individual technology nominee with the potential to support a planned or conceptual NASA Design Reference Mission(s). The Technology Candidate Snapshot includes the following information about the technology being considered:

- Technology, including a description, challenge, dependencies, SOA performance level, and a technology performance goal.
- Capability needed, including a description, SOA performance level, and a capability performance goal.
- Mission linkages, including the launch date (if determined), the technology need date, and the estimated time to mature the technology.

For each design reference mission, the technology candidate is designated as either enabling (a pull technology) or enhancing (a push technology). Enabling technology candidates satisfies a capability need for a space mission or aeronautics roadmap outcome by providing the desired performance within acceptable cost and risk. The enhancing technology candidates, on the other hand, provide significant benefits over the current SOA but are not required for a specific mission or aeronautics roadmap outcome.

In creating the Green Propulsion Technology Roadmap, the Green Propulsion Working Group reviewed the NASA 2015 Technology Roadmaps, and believes that green propulsion aligns with the goals and technology areas of the Technology Roadmaps. The specific alignments are detailed in the body of the Green Propulsion Technology Roadmap, section 4.5.

A.3 Other Supporting Technology Investment Guides

Beyond the NASA Strategic Space Technology Investment Plan and the NASA 2015 Technology Roadmaps, there are other documents that provide some guidance for NASA's strategic technology investment. One such document was the National Research Council produced "NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space."[9] As stated on the National Academies Press Web site, this document sought to support NASA OCT roadmap goals by "Reaching out to involve the external technical community, the National Research Council (NRC) considered the 14 draft technology roadmaps prepared by OCT and ranked the top technical challenges and highest priority technologies that NASA should emphasize in the next 5 years. This report provides specific guidance and recommendations on how the effectiveness of the technology development program managed by OCT can be enhanced in the face of scarce resources."

NASA's 2014 Strategic Plan[10] is an overarching and broad set of strategic goals and objectives to support NASA's vision and mission. While not specifically addressing technology investment, the Strategic Plan does provide the foundations that all other strategy guides and plans must adhere to. Both the NASA Technology Roadmaps and the Strategic Space Technology Investment Plan align to supporting NASA's Strategic Plan.

While not a NASA-specific strategic investment guide or plan, Sackheim and Masse[11] outlined several metrics related to investment in green propulsion technology. They state "…a thorough examination of the concerns driving industry, recent technical advances, and current actual capabilities of leading emergent green technologies, as well as an overview of open technical issues, may be of utility in both providing an understanding of these recent trends and setting expectations for the future." The authors present several selection criteria for monopropellants in their paper, many of which align to specific Technology Development Areas outlined in section 3.7 of this roadmap. Their conclusions state that "green propellants promise new capabilities beyond the current state of the art that should be pursued in earnest," and comment that at least for AF-M315E, its "…high density-specific impulse is mission enabling." The GPWG cautions, however, that Sackheim and Masse do not specifically call out or give priority to any one technology need, but rather weigh the pros and cons of green propulsion against SOA hydrazine systems and maturity. The belief of the GPWG is that this paper should be considered a useful resource for an overall strategy on green propulsion technology, and gives some external perspective to the technology. (The late Robert Sackheim was a former Assistant Center Director for MSFC and later a space propulsion consultant, while Robert Masse is affiliated with Aerojet Rocketdyne, one of the leading commercial entities currently developing green propulsion technologies.)

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14. ABSTRACT

The Green Propulsion Working Group (GPWG), under the Chemical Propulsion Subcapabilities Management team, is tasked with developing a Roadmap for a prioritized approach in the development of green propulsion technologies. The purpose of the Roadmap, and the GPWG, is to provide technology development investment guidance to NASA Mission Directorates, Centers, and projects. The Roadmap does not supersede any existing Agency or Center funded activities, multilateral agreements, and/or ongoing projects of any Center started prior to the effective publication of the Roadmap.

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