NASA/TM—2012-217641

Roadmap for In-Space Propulsion Technology

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October 2012

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Prepared for the
Space Propulsion 2012
sponsored by the AAAF, ESA, and CNES
Bordeaux, France, May 7–10, 2012

National Aeronautics and
Space Administration

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Cleveland, Ohio 44135

October 2012

Level of Review: This material has been technically reviewed by technical management.

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Abstract

NASA has created a roadmap for the development of advanced in-space propulsion technologies for the NASA Office of the Chief Technologist (OCT). This roadmap was drafted by a team of subject matter experts from within the Agency and then independently evaluated, integrated and prioritized by a National Research Council (NRC) panel. The roadmap describes a portfolio of in-space propulsion technologies that could meet future space science and exploration needs, and shows their traceability to potential future missions. Mission applications range from small satellites and robotic deep space exploration to space stations and human missions to Mars. Development of technologies within the area of in-space propulsion will result in technical solutions with improvements in thrust, specific impulse (Isp), power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, durability, and of course, cost. These types of improvements will yield decreased transit times, increased payload mass, safer spacecraft, and decreased costs. In some instances, development of technologies within this area will result in mission-enabling breakthroughs that will revolutionize space exploration. There is no single propulsion technology that will benefit all missions or mission types. The requirements for in-space propulsion vary widely according to their intended application. This paper provides an updated summary of the In-Space Propulsion Systems technology area roadmap incorporating the recommendations of the NRC.

Introduction

In the summer of 2010, the NASA Office of the Chief Technologist (OCT) initiated an integrated technology roadmap development activity, and small teams of Agency subject matter experts were established to develop draft roadmaps in each of 14 Space Technology Areas (TA). The 14 teams were focused on strategically identified areas where significant technology investments are anticipated and where substantial enhancements in NASA mission capabilities are needed. Together, the fourteen roadmaps represent NASA's integrated Space Technology Roadmap. Once the TA roadmaps were drafted by the small teams, an extensive examination of the roadmaps was conducted. At the completion of a thorough NASA internal review, the roadmaps were considered "draft" status. These drafts were then provided to the National Research Council (NRC), who through an open process of community engagement, gathered input, integrated and prioritized each individual Space Technology Area Roadmap, providing NASA with strategic guidance and recommendations that will inform the technology investment decisions of NASA's space technology activities. One of these fourteen technology areas, TA02, was In-Space Propulsion Systems. This paper provides an updated summary of the In-Space Propulsion Systems technology area roadmap (Ref. 1) incorporating the recommendations of the NRC (Ref. 2).

Technology Area Scope

In-space propulsion begins where the launch vehicle upper stage leaves off, performing the functions of primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering. The main engines used in space provide the primary propulsive force for orbit transfer, planetary trajectories and extra planetary landing and ascent. The reaction control and orbital maneuvering systems provide the propulsive force for orbit maintenance, position control, station keeping, and spacecraft attitude control.

The In-Space Propulsion Systems technology area roadmap describes the portfolio of in-space propulsion technologies that could meet future space science and exploration needs. In-space propulsion represents technologies that can significantly improve a number of critical metrics. Space exploration is about getting somewhere safely (mission enabling), getting there quickly (reduced transit times), getting the maximum mass there (increased payload mass), and getting there cheaply (lower cost). The simple act of "getting" there requires the employment of an in-space propulsion system, and the other metrics are modifiers to this fundamental action.

There is no single propulsion technology that will benefit all missions or mission types. The requirements for in-space propulsion vary widely due according to their intended application. The technologies described herein will support everything from small satellites and robotic deep space exploration to space stations and human missions to Mars. Figure 1 is a graphical representation of the In-Space Propulsion Technology Area Breakdown Structure (TABS). The TABS is divided into four basic elements: (1) Chemical Propulsion, (2) Nonchemical Propulsion, (3) Advanced Propulsion Technologies, and (4) Supporting Technologies, based on the physics of the propulsion system and how it derives thrust as well as technical maturity. The NRC panel recommended several changes to the fourth element. The "draft" roadmap included four additional technologies that support propulsion, but these significantly overlapped with other Technology Areas and have been removed for this final version.

Technical Approach

For both human and robotic exploration, traversing the solar system is a struggle against time and distance. The most distant planets are 4.5 to 6 billion km from the Sun and to reach them in any reasonable time requires much more capable propulsion

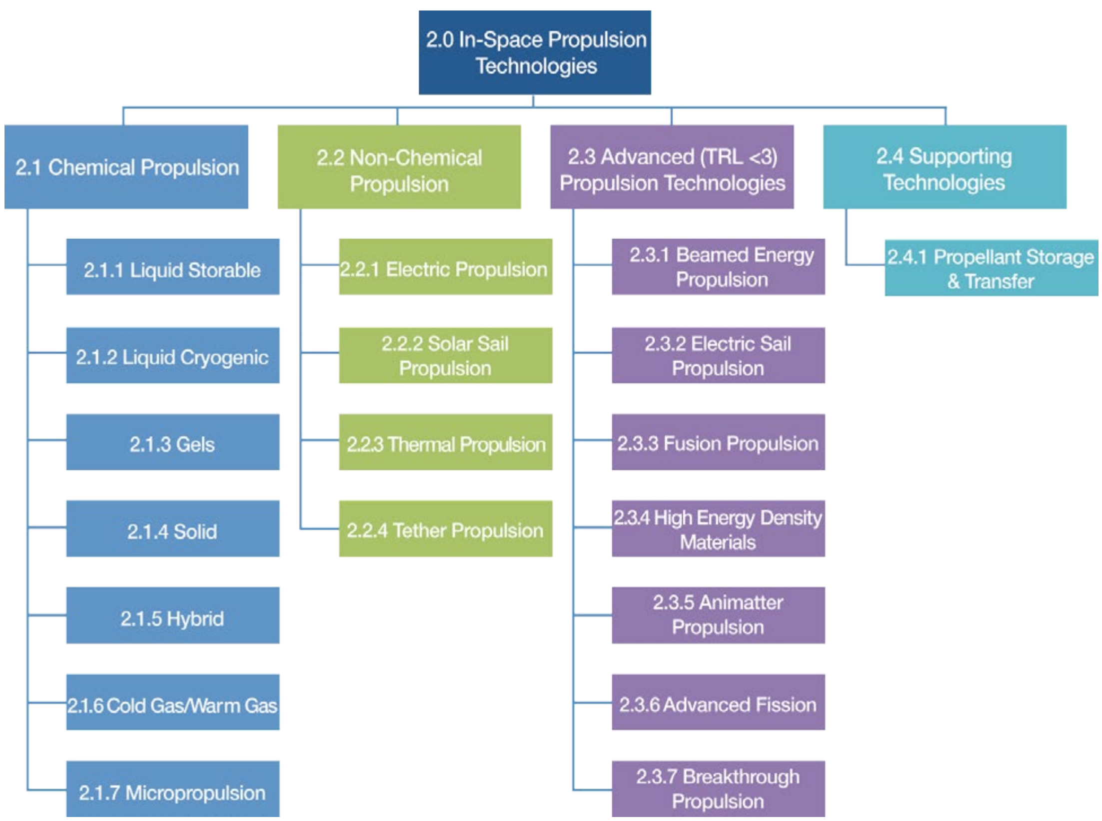

Figure 1.—Technology Area Breakdown Structure (TABS) for Technology Area 02, In-Space Propulsion Technologies. This TABS has been updated incorporating recommendations from the National Research Council.

systems than conventional chemical rockets. The logistics, and therefore the total system mass required to support sustained human exploration beyond Earth to destinations such as the Moon, Mars or Near Earth Objects, are daunting unless more efficient in-space propulsion technologies are developed and fielded.

With the exception of electric propulsion systems used for commercial communications satellite orbit positioning and station-keeping, and a handful of lunar and deep space science missions, all of the rocket engines in use today are chemical rockets; that is, they obtain the energy needed to generate thrust by combining reactive chemicals to create a hot gas that is expanded to produce thrust. A significant limitation of chemical propulsion is that it has a relatively low specific impulse (thrust per unit of mass flow rate of propellant). Numerous concepts for advanced in-space propulsion technologies have been developed over the past 50 years. While generally providing significantly higher specific impulse compared to chemical engines, they typically generate much lower values of thrust. Thrust to weight ratios greater than unity are required to launch from the surface of the Earth, and chemical propulsion is currently the only propulsion technology capable of producing the magnitude of thrust necessary to overcome Earth's gravity. However, once in space, new higher Isp propulsion systems can be used to reduce total mission propellant mass requirements.

Benefits

In-space propulsion is a category of technology where developments can benefit a number of critical Figures of Merit (metrics) for space exploration. Space exploration is about getting somewhere safely (mission enabling), getting there quickly (reduced transit times), getting a lot of mass there (increased payload mass), and getting there cheaply (lower cost). Development of technologies within this TA will result in technical solutions with improvements in thrust levels, Isp, power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, durability, and of course, cost. These types of improvements will yield the desired decreased transit times, increased payload mass, safer spacecraft, and decreased costs. In some instances, development of technologies within this TA will result in mission-enabling breakthroughs that will revolutionize space exploration. Advanced in-space propulsion technologies will enable much more effective exploration of our Solar System and will permit mission designers to plan missions to fly anytime, anywhere, and complete a host of science objectives at their destinations. A wide range of possible missions and candidate chemical and advanced in-space propulsion technologies with diverse characteristics offers the opportunity to better match propulsion systems for future missions. Developing a portfolio of in-space propulsion technologies will allow optimized propulsion solutions for a diverse set of missions and destinations. The portfolio of concepts and technologies described in this roadmap are designed to address these future space science and exploration needs.

Top Technical Challenges and Technology Priorities

The In-Space Propulsion Systems technology roadmap team identified specific technologies to enable new missions, as shown in Figure 1. This suite of options represents a balance of near-term and longer-range infusion opportunities and a balance of "mission pull" and "push" technologies. The draft roadmaps were created without budget constraints and therefore would require substantially more technology development resources than NASA is planning to invest in the near term. For this reason, it is important to prioritize the technologies with in the roadmap. As shown in Table I, the NASA In-Space Propulsion Systems technology roadmap team provided an initial (internal) assessment of the top ten Technical Challenges. For this assessment, prioritizing *Technical Challenges* was interpreted as identifying the most important challenges within the technology development suite. Table I includes technologies applicable to a range NASA missions and includes technologies with near- (present to 2016), mid- (2017 to 2022), and far-term (2023 to 2028) time frames, representing the point at which achieving TRL 6 could be expected.

TABLE I.—INITIAL (NASA INTERNAL) ASSESSMENT OF THE TOP TEN TECHNICAL CHALLENGES FOR IN-SPACE PROPULSION TECHNOLOGY DEVELOPMENT.
[N, near-term (present to 2016), M, mid-term (2017–2022), and F, far-term (2023–2028) timeframe achievement of TRL 6 is anticipated.]

Rank	Description	
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems	N
2	Long-term in-space cryogenic propellant storage and transfer	M
3	High power (e.g., 50 to 300 kW) class Solar Electric Propulsion scalable to MW class Nuclear Electric Propulsion	M
4	Advanced in-space cryogenic engines and supporting components	M
5	Developing and demonstrating MEMS-fabricated electrospray thrusters	N
6	Demonstrating large (over 1000 m^2) solar sail equipped vehicle in space	N
7	Nuclear Thermal Propulsion (NTP) components and systems	F
8	Advanced space storable propellants	M
9	Long-life (>1 year) electrodynamic tether propulsion system in LEO	N
10	Advanced In-Space Propulsion Technologies (TRL <3) to enable a robust technology portfolio for future missions.	F

The NRC was given the more challenging task to prioritize the technology investment considering current budgetary constraints and further to prioritize across the fourteen TAs. In their review, the NRC used a multi-step approach. First they identified the Top Technical Challenges, which, for their process, describe broader capabilities, rather than specific technologies. These challenges then helped guide the NRC panel's prioritization of specific technologies. The following four Top Technical Challenges for in-space propulsion were identified in the NRC's final report:

1. ***High-Power Electric Propulsion Systems:*** *Develop high power electric propulsion systems technologies to enable high ΔV missions with heavy payloads.*
2. ***Cryogenic Storage and Transfer:*** *Enable long-term storage and transfer of cryogens in space and reliable cryogenic engine operation after long dormant periods in space.*
3. ***Microsatellites:*** *Develop high performance propulsion technologies for high-mobility microsatellites (<100 kg).*
4. ***Rapid Crew Transit:*** *Establish propulsion capability for rapid crew transit to/from Mars.*

Once the Top Technical Challenges were identified, the NRC panel then moved on to prioritization of specific technologies. A quality function deployment (QFD) process was used to rank the technologies, and the panel verified that the results were consistent with the Top Technical Challenges they had previously identified. The NRC report identified four technologies from the In-Space Propulsion Systems technology roadmap as "high priority" and that were supportive of the four Top Technical Challenges. In priority order, these were:

- ***Electric propulsion***
  - Development phased by power is recommended beginning with high power solar electric propulsion (SEP) (~100 kW to ~ 1 MW) and continuing toward an ultimate goal of multimegawatt nuclear electric propulsion (NEP) capability. These high power SEP and NEP systems can enable larger scale, faster, or more efficient space transportation systems.
- ***Propellant storage and transfer***
  - The NRC identified cryogenic propellant storage and transfer as a technology at the "tipping point". In other words, investment in this technology can quickly move it into position for infusion into flight development of in-space transportation elements. "Propellant storage and transfer is a game-changing technology for a wide range of applications because it enables long-duration, high-thrust, high-ΔV missions for large payloads and crew and can be implemented within the next 3 decades."
- ***(Nuclear) Thermal propulsion***
  - Nuclear Thermal Rockets are a high thrust, high Isp propulsion technology. The state of the art ground demonstrated engine, Nuclear Engine for Rocket Vehicle Applications (NERVA) demonstrated thrusts (in the 1970s) comparable to chemical propulsion (7,500 to 250,000 lbf of thrust with specific impulses of 800 to 900 seconds, double that of chemical rockets). "Critical NTR technologies include the nuclear fuel, reactor and system controls, and long-life hydrogen pumps, and technology development will also require advances in ground test capabilities, as the open-air approach previously used is no longer environmentally acceptable."
- ***Micropropulsion systems***
  - Micropropulsion addresses the needs of both microsatellites and precision pointing and positioning for certain NASA Science Mission Directorate missions. Micropropulsion encompasses the development of miniaturized versions of chemical and non-chemical propulsion systems.

The first three technologies were separated as high priority by the QFD scoring assessment of the NRC; the NRC panel decided to elevate micropropulsion systems to a medium-high priority "to highlight the importance of developing propulsion systems that can support the rapidly developing micro-satellite market, as well as certain large astrophysics spacecraft." The NRC also noted that these four technologies were consistent with their Top Technical Challenges.

Discussion

The NASA internal TA02 roadmap team was in general agreement with the NRC prioritization, and there is good overlap with the original internal assessment by the NASA internal team (Table I). However, it is important to recognize that the In-Space Propulsion Systems Technology Roadmap includes many additional technologies beyond the four identified as high priority. In fact, the NRC report noted that, "In an unconstrained funding environment, the TA02 roadmap presents a reasonable approach, particularly when focus is placed on the high-priority technologies listed above." In addition, the NRC panel recognized the value of investing modest resources in low TRL technologies that may provide the seedling for future technology development. The TABS 2.3 Advanced Propulsion Technologies area is ideally suited to make the most benefit from such an investment.

Conclusion

As part of a NASA Office of the Chief Technologist effort to develop an integrated set of Space Technology roadmaps, a draft In-Space Propulsion Systems Technology Area roadmap was developed (Ref. 1). This draft was provided to the NRC for evaluation and for prioritization of the technologies. This paper provides a summary of that roadmap document and the salient recommendations of the NRC were discussed. The NRC input (Ref. 2) has been incorporated with the draft roadmap to create an updated version. The NRC report identified four Top Technical Challenges for the In-Space Propulsion Systems technology roadmap as "high priority": High-Power Electric Propulsion Systems; Cryogenic Storage and Transfer; Microsatellites; and Rapid Crew Transit. The key technologies In-Space Propulsion Systems Technology Area roadmap team to support the NRC Top Technical

Challenges include: Electric Propulsion; Propellant Storage and Transfer; (Nuclear) Thermal Propulsion, and Micropropulsion. The integrated roadmaps will be valuable for the Agency going forward providing NASA with strategic guidance and recommendations that inform the investment decisions of NASA's space technology activities.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE *(DD-MM-YYYY)* 01-10-2012	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Roadmap for In-Space Propulsion Technology

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Meyer, Michael; Johnson, Les; Palaszewski, Bryan; Coote, David; Goebel, Dan; White, Harold

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 432938.08.01.03.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-18195-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2012-217641

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 20
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
Cryogenic rocket propellants; Cryogenic storage; Chemical propulsion; Electric propulsion; Micro rocket; Spacecraft propulsion; Low thrust propulsion; Solar sails; Nuclear thermal propulsion; Nuclear electric propulsion

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	12	**19b. TELEPHONE NUMBER** ***(include area code)*** 443-757-5802