In-Space Chemical Propulsion Systems Roadmap

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Abstract 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.

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 the destinations" with greater reliability and safety. With wide range of possible missions and candidate propulsion technologies, the question of which technologies are "best" for future missions is a difficult one. A portfolio of propulsion technologies should be developed to provide optimum solutions for a diverse set of missions and destinations. A large fraction of the rocket engines in use today are chemical rockets; that is, they obtain the energy needed to generate thrust by chemical reactions 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 (Is, or thrust per mass flow rate of propellant).

A significant improvement (>30%) in Is can be obtained by using cryogenic propellants, such as liquid oxygen and liquid hydrogen, for example. Historically, these propellants have not been applied beyond upper stages.

Keywords chemical propulsion, in-space propulsion, specific impulse, oxidizers, fuels, monopropellants, bipropellants, cryogenic propellants, advanced propellants

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Acronyms

AHMS	Advanced Health Management System
AMPM	Agency Mission Planning Model
ARC	Ames Research Center
ATP	Authority to Proceed
CFM	Cryogenic Fluid Management
ClF_3	Chlorine Trifluoride
ClF_5	Chlorine Pentafluoride
DRM	Design Reference Mission
ECLS	Environmental Control and Life Support
EHS	Environmental Health System
GRC	Glenn Research Center
GTO	Geostationary Transfer Orbit
HEDM	High Energy Density Materials
HmNT	Hydrazine milli-Newton Thruster
HTPB	Hydroxyl-Terminated Polybutadiene
IMLEO	Initial Mass in Low-Earth Orbit
ISHM	Integrated System Health Management
ISPSTA	In-Space Propulsion Systems Technology Area
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JAXA	Japanese Aerospace Exploration Agency
JSC	Johnson Space Center
KSC	Kennedy Space Center
LST	Life Support Technologies
MMOD	Micro-Meteoroid/Orbital Debris
MMH	Monomethylhydrazine
MSFC	Marshall Space Flight Center
OF_2	Oxygen Difluoride
ProSEDS	Propulsive Small Expendable Deployer System
RCS	Reaction Control System
SDI	Strategic Defense Initiative
SOA	Hydrazine
TA	Technology Area
TABS	Technology Area Breakdown Structure
TRL	Technology Readiness Level
ZBO	Zero Boil-Off

1.Introduction

Space exploration is about getting somewhere (reduced transit times), getting a lot of 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.

Development of technologies within this technology area (TA) will result in technical solutions with improvements in thrust levels, Is, 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 TA 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 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. Furthermore, numerous concepts for advanced propulsion technologies, such as electric propulsion, are commonly used for station keeping on commercial communications satellites and for prime propulsion on some scientific missions because they have significantly higher values of specific impulse.

However, they generally have very small values of thrust and therefore must be operated for long durations to provide the total impulse required by a mission. Several of these technologies offer performance that is significantly better than that achievable with chemical propulsion. This 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.

Figure 1 is a graphical representation of the In-Space Propulsion Technology Area Breakdown Structure (TABS). The TABS is divided into four basic groups: (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 its technical maturity. There may be credible meritorious in-space propulsion concepts not foreseen or captured in this document that may be shown to be beneficial to future mission applications. Care should be taken when implementing future investment strategies to provide a conduit through which these concepts can be competitively engaged to encourage continued innovation.

Figure 2 is the roadmap for the development of advanced in-space propulsion technologies showing their traceability to potential future missions. The roadmap makes use of the following set of definitions and ground rules. The term “mission pull” defines a technology or a performance characteristic necessary to meet a planned NASA mission requirement. Any other relationship between a technology and a mission (an alternate propulsion system, for example) is categorized as “technology push.” Also, a distinction is drawn between an in-space demonstration of a technology versus an in-space validation. A space demonstration refers to the spaceflight of a scaled version of a particular technology or of a critical technology subsystem; a space validation would serve as a qualification flight for future mission implementation. A successful validation flight would not require any additional space testing of a particular technology before it can be adopted for a science or exploration mission. The graphical roadmap provides suggested technology pursuits within the four basic categories, and ties these efforts to the portfolio of known and potential future NASA or non-NASA missions.

2. General Overview

2.1 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 kilometers from the Sun and to reach them in any reasonable time requires much more capable propulsion systems than conventional chemical rockets. Rapid inner solar system missions with flexible launch dates are difficult, requiring propulsion systems that are beyond today's current state of the art. 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, more efficient propulsion systems can be used to reduce total mission propellant mass requirements.

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.

2.2 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). 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. Simply put, without a propulsion system, there would be no mission. Development of technologies within this TA will result in technical solutions with improvements in thrust levels, specific impulse (Is), 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 technology area (TA) will result in mission enabling breakthroughs that will revolutionize space exploration.

2.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, and DRAs

The In-Space Propulsion Roadmap team used the NASA strategic goals and missions detailed in the following reference materials in the development of this report: Human Exploration Framework Team products to extract reference missions with dates, the Science Mission Directorate (SMD) Decadal Surveys, past Design Reference Missions (DRM), Design Reference Architectures (DRA), historical mission studies, In-Space Propulsion Technology concept studies, and internal ISS utilization studies. The references identify missions used for categorizing pull and push technology designations.

2.4. Top Technical Challenges

The major technical challenges for In-Space Propulsion Systems Technology Area (ISPSTA) were identified and prioritized through team consensus based on perceived mission need or potential impact on future in-space transportation systems. These challenges were then categorized into near- (present to 2016), mid- (2017– 2022), and far-term (2023–2028) time frames, representing the point at which TRL 6 is expected to be achieved. It is likely that support of these technologies would need to begin well before the listed time horizon. TRL-6 readiness dates were determined by considering stated mission pull (for example, Human Exploration Framework Team (HEFT) or Decadal Surveys stating mission need dates, etc.), the state-of-the-art for specific technologies that could be matured to the point of quickly enabling missions of interest to potential users (technology push), and the need for a breadth of technology- enabled capabilities across all timeframes.

3. Detailed Portfolio Discussion

The roadmap for this technical area is divided into four basic groups:

- Chemical Propulsion,
- (2) Nonchemical Propulsion,
- (3) Advanced Propulsion Technologies, and
- (4) Supporting Technologies.

The first two categories are grouped according to the governing physics. Chemical Propulsion includes propulsion systems that operate through chemical reactions to heat and expand a propellant (or use a fluid dynamic expansion, as in a cold gas) to provide thrust. Propulsion systems that use electrostatic, electromagnetic, field interactions, photon interactions, or externally supplied energy to accelerate a spacecraft are grouped together under the section titled Nonchemical Propulsion. The third section, Advanced Propulsion Technologies, is meant to capture technologies and physics concepts that are at a lower TRL level (< TRL3). The fourth section, Supporting Technologies, identifies the pertinent technical areas that are strongly coupled to, but are not part of, in-space propulsion, such that focused research within these related areas will allow significant improvements in performance for some in-space propulsion technical areas. In addition, development of some advanced forms of chemical propulsion will have modeling challenges to better understand and predict dynamic instability during combustion, and electric propulsion technologies require the enhancement and validation of complicated life models to shorten life qualification testing.

Development of technologies within this TA will result in technical solutions with improvements in thrust levels, specific impulse, power, specific mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, and durability. The benefits to be derived from each technology in the TABS will be identified with one of the icons as described in the list of technologies.

Within each section of the technology descriptions there are three elements. The first element provides a summary description of a particular technology, explaining its governing physics and method of operation. The second element identifies at a high-level the technical challenges that must be overcome to raise its maturity. The third element for Sections 3.1, 3.2, and 3.4 describes the significant milestones to be reached for a given technology to attain TRL-6. In Section 3.3 this element describes the milestones required for attaining TRL >3. This roadmap makes use of the following set of definitions and ground rules. The term "mission pull" defines a technology or a performance characteristic necessary to meet a planned NASA mission requirement. Any other relationship between a technology and a mission (an alternate propulsion system for example) is categorized as “Technology Push.” Also, a distinction is drawn between an in-space demonstration of a technology versus an in-space validation. A space demonstration refers to the space flight of a scaled version of a particular technology or of a critical technology subsystem; a space validation would serve as a qualification flight for future mission implementation. A successful validation flight would not require any additional space testing of a particular technology before it can be adopted for a science or exploration mission. The graphical Roadmap representation (Fig. 2) provides suggested technology pursuits within the four basic categories, and ties these efforts to the portfolio of known and potential future NASA/non-NASA missions. Most of the near-term content on the graphic is based on actual plans while the out years can be considered to have larger uncertainties bars on the placement of items within the timeline. Tables I and II provide the final ranking on all of the in-space propulsion technologies and their linkages to related supporting technology areas.

3.1. Chemical Propulsion

Chemical Propulsion involves the chemical reaction of propellants to move or control a spacecraft. Chemical propulsion system functions include primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering. The main engines 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.

Monopropellants

State of the art

Hydrazine thrusters use a catalytic decomposition reaction to generate high temperature gas for thrust. Hydrazine is SOA. Spacecraft reaction control system (RCS) performance is near Is = 228 s. Lander engines have higher Is (238 s). Freezing point is 3 °C.

Challenges

Catalyst life, inability for cold starts. Increased thrust and Is performance with pumped systems. Reduction of freezing point from 3 °C needed without compromising the performance.

Milestones to TRL 6

Evaluate alternate propellants such as NOFB, and AF315E. Develop thrusters to operate in pulse and continuous operation with new propellant. Qualify propellants, components (valves, filters, regulators etc.).

Bipropellants

State of the art

Bipropellant thrusters use the chemical reaction, typically hypergolic, to generate high temperature gas that is expanded to generate thrust. Nitrogen Tetroxide (NTO)/Hydrazine (N2H4) is SOA with Is = 326 s for fixed thrust (450 N) planetary main engine.

Challenges

Increased thrust with improved packaging for landers & orbit insertion. Throttle capability for planetary landers. Pumped systems desirable for planetary spacecraft vs. pressure fed systems. Mixture-ratio control and propellant gauging to reduce residuals & improve performance.

Milestones to TRL 6

Develop and qualify pumped bi-propellant system.

Develop and qualify throttleable bi-propellant valve /system.

Recapture XLR-132 NTO/MMH pump-fed engine technology

3.2 High-Energy Oxidizers

High-energy oxidizers such as fluorinated compounds include chlorine trifluoride (ClF_3), chlorine pentafluoride (ClF_5) and & oxygen difluoride (OF_2). These oxidizers have a long history of testing with most recent testing in the 1980s under the Strategic Defense Initiative (SDI). Stages for interceptors were created for flight testing using hydrazine/ClF5.

Challenges

Fluorinated propellants have safety issues (high reactivity), but the upper stage processing methods to isolate ground support personnel from the oxidizers have been developed. These processing methods have not been exercised since the 1980s.

Milestones to TRL 6

The stage development for this technology was designed for SDI, etc. Recapturing the handling and upper stage ground processing methods is needed.

3.3 Liquid cryogenic propellants

Oxygen / methane propulsion

SOA is MMH/NTO at TRL 9 for Reaction Control System (RCS) and orbital maneuvering propulsion, which are integrated. LOX/Methane is proposed to enable higher performance, space storability, pressure-fed and pump-fed options, common LO2 and LCH4 components (lower cost), application to In-Situ Resource Utilization (ISRU) for Mars, and higher density for improved packaging. LOX/Methane is TRL 4-5 in that Cryogenic Fluid Management (CFM), feed systems, RCS, main engine, & components have been tested in vacuum environments.

Challenges

System level integration and test of the component technologies are needed.

Improvement in the main engine injector performance and stability. Development

of flight-weight compact exciter, and demonstrating the ability to deliver the correct quality of propellant for repeatable engine performance are needed.

Milestones to TRL 6

Perform system-level integration and test of the component technologies.

Some component improvements are required such as to improve the main engine injector performance and stability.

Test a regeneratively cooled main engine.

3.4 Advanced (TRL <3) Propulsion Technologies

Metallic hydrogen

Metallic hydrogen is a theoretically dense energetic material (not yet produced on earth). The TRL level is not at level 1 as the characteristics are based on theoretical calculations. The estimated density at ambient conditions is 7 g/cc, 10 times LH2. Above a critical temperature, possibly 1000 K, metallic hydrogen will become unstable and recombine to the molecular phase, releasing the energy of recombination, 216 MJ/kg (for reference: H2 + O2 in the SSME releases 10 MJ/kg, LO2/ RP1 releases 6 MJ/kg). Ongoing experiments are using diamond anvil cells and short pulse laser technologies to follow the hydrogen melt line toward the conditions for the metallic state. Expected Is values are in the 500-2000 s range.

Challenges

Upgrading existing experimental equipment is required for synthesis and characterization of small quantities of metallic hydrogen. Scaling up production by many orders of magnitude is required. Engine components must be developed that are compatible with metallic hydrogen. Test engines must be developed to verify expected operations and performance with a variety of diluents and mixture ratios. Potential need for tankage that operates at millions of psi.

TRL maturation plan

Demonstrate synthesis of metallic hydrogen in laboratory.
Evaluate characteristics of metallic hydrogen in laboratory.
Develop production scaling techniques.
Develop engine components and test various diluents.
Perform propellant tankage development.
Perform tests of various engine sizes and diluents.

Atomic Boron /Carbon /Hydrogen

Atoms trapped in solid cryogens (neon, etc.) at 0.2 to 2 weight %. Atomic hydrogen, boron, and carbon fuels are very high energy density, free-radical propellants. Atomic hydrogen may deliver an Is of 600 to 1,500 s. There has been great progress in the improvement of atom storage density over the last several decades. Lab studies have demonstrated 0.2 & 2 % weight atomic hydrogen in a solid hydrogen matrix. If the atom storage were to reach 10–15 %, which would produce a specific impulse (Is) of 600–750 s.

Challenges

Storage of atoms at 10, 15, or 50 weight % is needed for effective propulsion.

TRL maturation plan

Formulate atom storage methods for high density.
Develop engine designs for recombining propellants without immediate deflagration.
Perform testing and validation of engine designs.

High Nitrogen Compounds (N4+, N5+)

These are the most powerful explosives created in history. Work was conducted under the High Energy Density Materials (HEDM) Program. Gram quantities formulated in laboratory (1999). Theoretical studies have shown that these materials may have in-space propulsion applications.

Challenges

The propellants are highly shock sensitive. Challenges include fabrication, transportation, ground processing, and personnel safety to name a few. Presently, there are no integrated vehicle designs that can make use of this possible propellant.

TRL maturation plan

Perform inhibitor research to facilitate safe scaling.
Develop high-speed deflagration/detonation engine technology.
Perform testing and validation of engine technology

Dawn of Space Commercialization

With the retirement of the Space Shuttle in the USA, new directions for space exploration have begun. While NASA is now more focused on planetary exploration with robots and humans, NASA has begun fostering commercial companies to provide the more near-Earth cargo and personnel deliveries to the International Space Station (ISS). Several companies, SpaceX, Orbital, and Boeing, are providing space vehicles that can deliver cargo, or people, or both to the ISS. SpaceX is even hoping to build a large launcher that can deliver sizable one metric ton payloads to Mars, with a modification of their Dragon Capsule. In addition, several companies such as Virgin Galactic (a venture with Great Britain and the USA), are planning for short flights in microgravity for space tourism. All of these applications can benefit from more advanced chemical propulsion: improved propellants with higher specific impulse (I_s) for space tourism, as well as higher density propellants for first stage applications.

Space tourism vehicles, such as Virgin Galactic's SpaceShipTwo, use hybrid propulsion: a solid fuel and a liquid/gaseous oxidizer. While it is touted as a safer rocket motor over a pure solid rocket motor, the issues of reliability over long periods of time may lead the designers to higher I_s liquid rocket engines. Multiple flights per day were planned for the SpaceShipTwo vehicle. Replenishing the liquid/gaseous oxidizer and refitting a new solid fuel grain on the vehicle may limit its flight rate. An all liquid rocket engine may simplify the refueling logistics and eliminate any need for solid fuel grain replacements.

In the SpaceX Falcon launch vehicle planning, the first stage is to be reused. The stage is to use its rocket engines to land softly on a robotic recovery ship. Carrying this additional retro-propulsion and landing propellant will lead to a reduction in the total payload mass to orbit. A higher I_s rocket engine would reduce or potentially alleviate this payload mass penalty.

For its Mars landing option, the SpaceX Dragon capsule would use its integrated launch abort system rocket thrusters to effect the final landing. Based on preliminary studies, these thrusters could allow a Mars landing using only supersonic retro-propulsion, and eliminate the need for a parachute landing system. The deceleration during landing would be very high, so such a landing mode would accommodate only robotic missions and would be too great of a stress on human astronauts. Higher Is rocket engines would allow higher payloads to be landed on Mars. Also, if the liquid engines could be throttled over a wider range, the capsule would be more likely to accommodate human astronauts.

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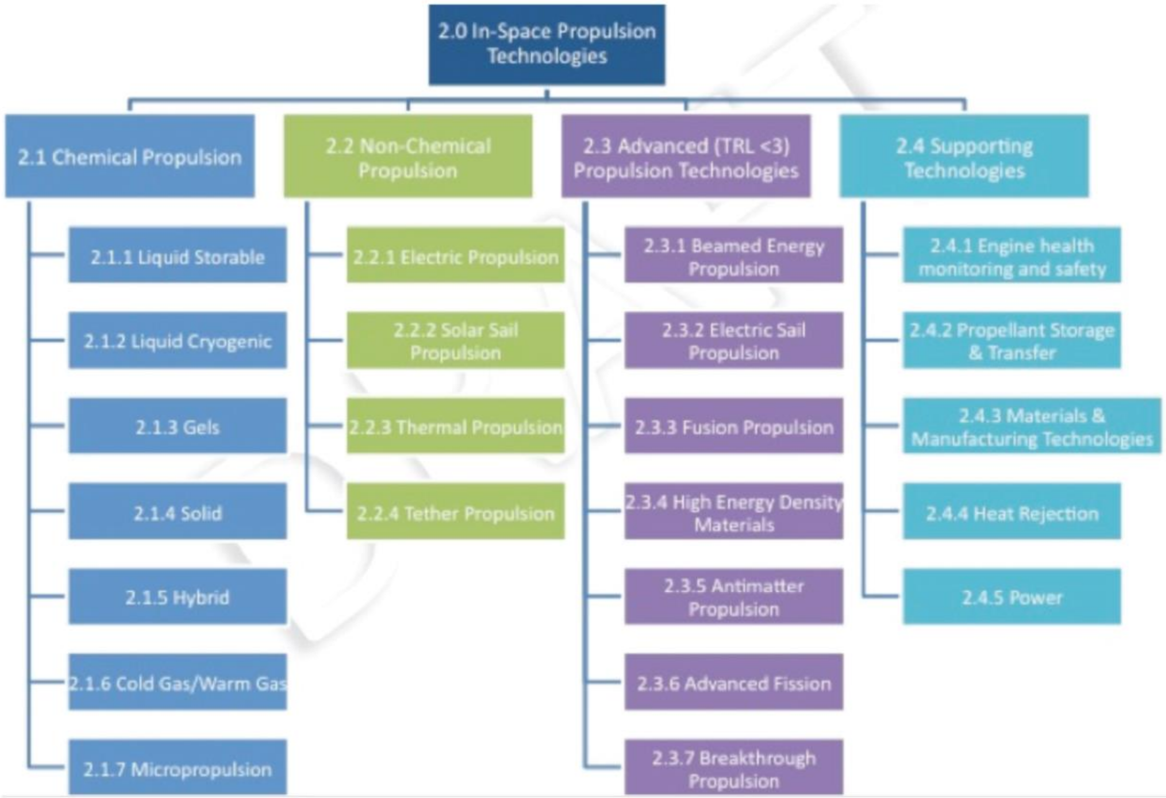

Figure 1. *In-Space Propulsion Technology Area Breakdown Structure*

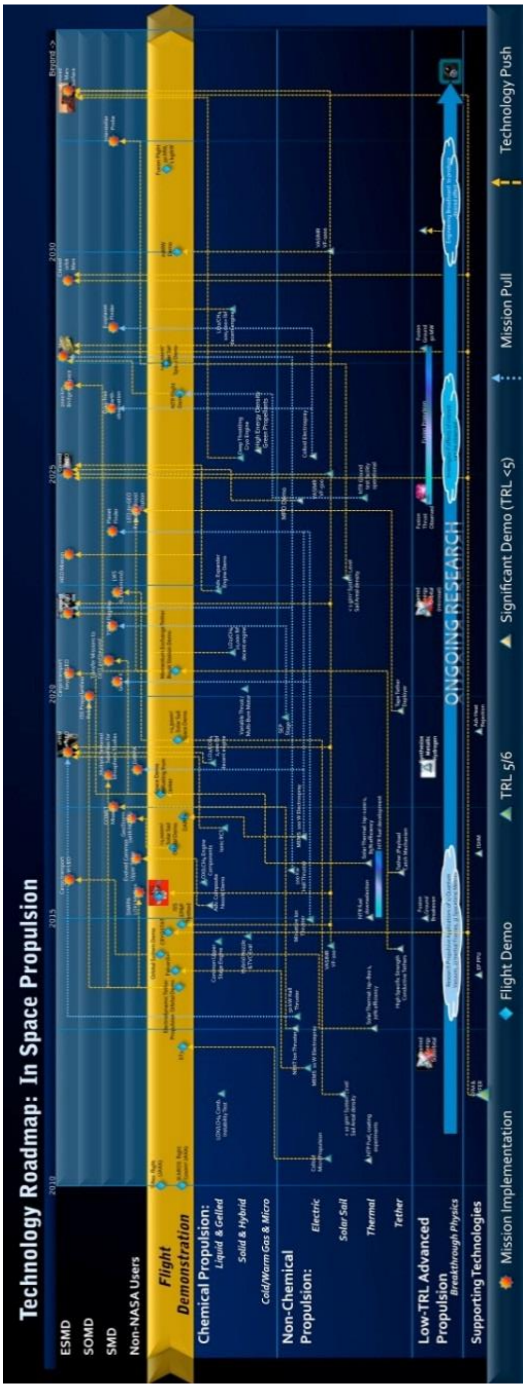

Figure 2a. TA02 technology roadmap.

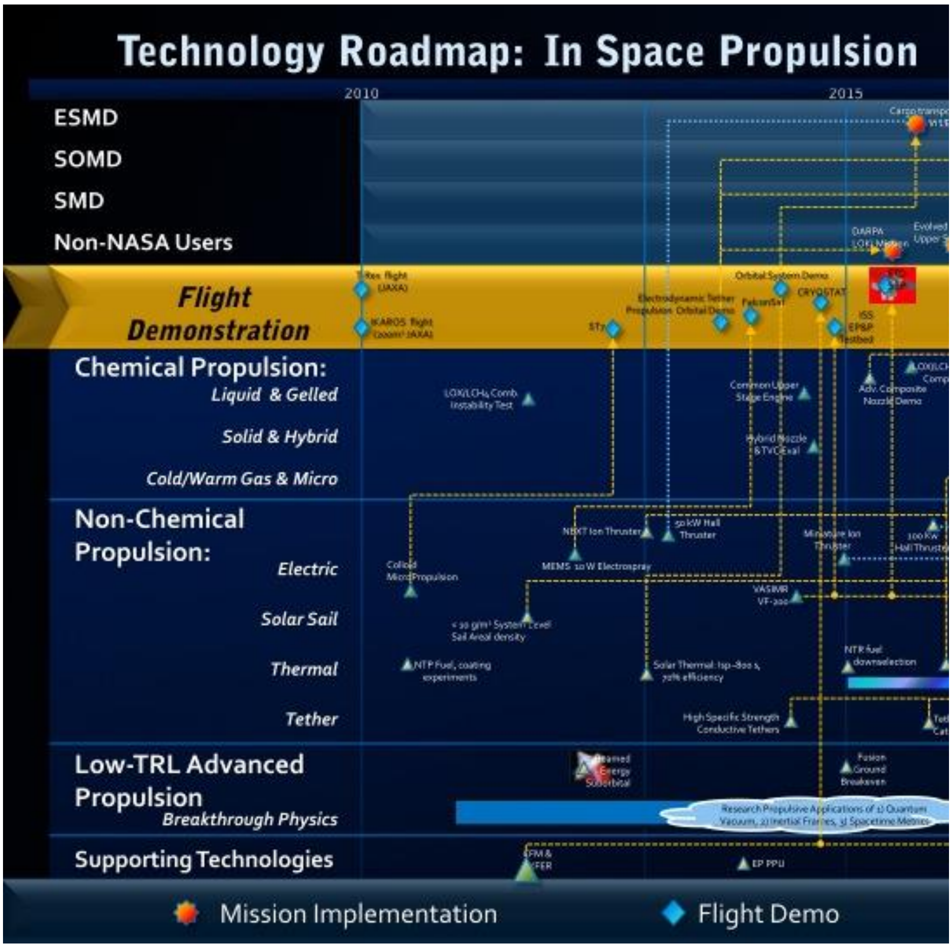

Figure 2b. TA02 technology roadmap.

Table I. Technology rankings and priorities.

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

Table II. TA02 relationships to other technology areas.

	LAUNCH PROPULSION SYSTEMS	SPACE POWER AND ENERGY STORAGE SYSTEMS	ROBOTICS, TELE-ROBOTICS, AND AUTONOMOUS SYSTEMS	COMMUNICATION AND NAVIGATION SYSTEMS	HUMAN HEALTH, LIFE SUPPORT AND HABITATION SYSTEMS	HUMAN EXPLORATION DESTINATION SYSTEMS	SCIENTIFIC INSTRUMENTS, OBSERVATORIES, AND SENSOR SYSTEMS	ENTRY, DESCENT, AND LANDING SYSTEMS	NANOTECHNOLOGY	MODELING, SIMULATION, INFORMATION TECH. AND PROCESSING	MATERIALS, STRUCTURAL AND MECH. SYSTEMS, AND MANUFACTURING	GROUND AND LAUNCH SYSTEMS PROCESSING	THERMAL MANAGEMENT SYSTEMS	AERONAUTICS
	TA1	TA2	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14	TA15
Relationship with TA2: In-Space Propulsion	🟩 S	🟩 F	🟦 F	▨	▨	▨	▨	🟩 T	🟦 S	▨	🟩 F	🟦 T	🟩 F	▨

🟩	Extensive
🟦	Limited

S	Close synergy in tasks
T	Technologies from TA2 to related TA
F	Technologies from related TA to TA2