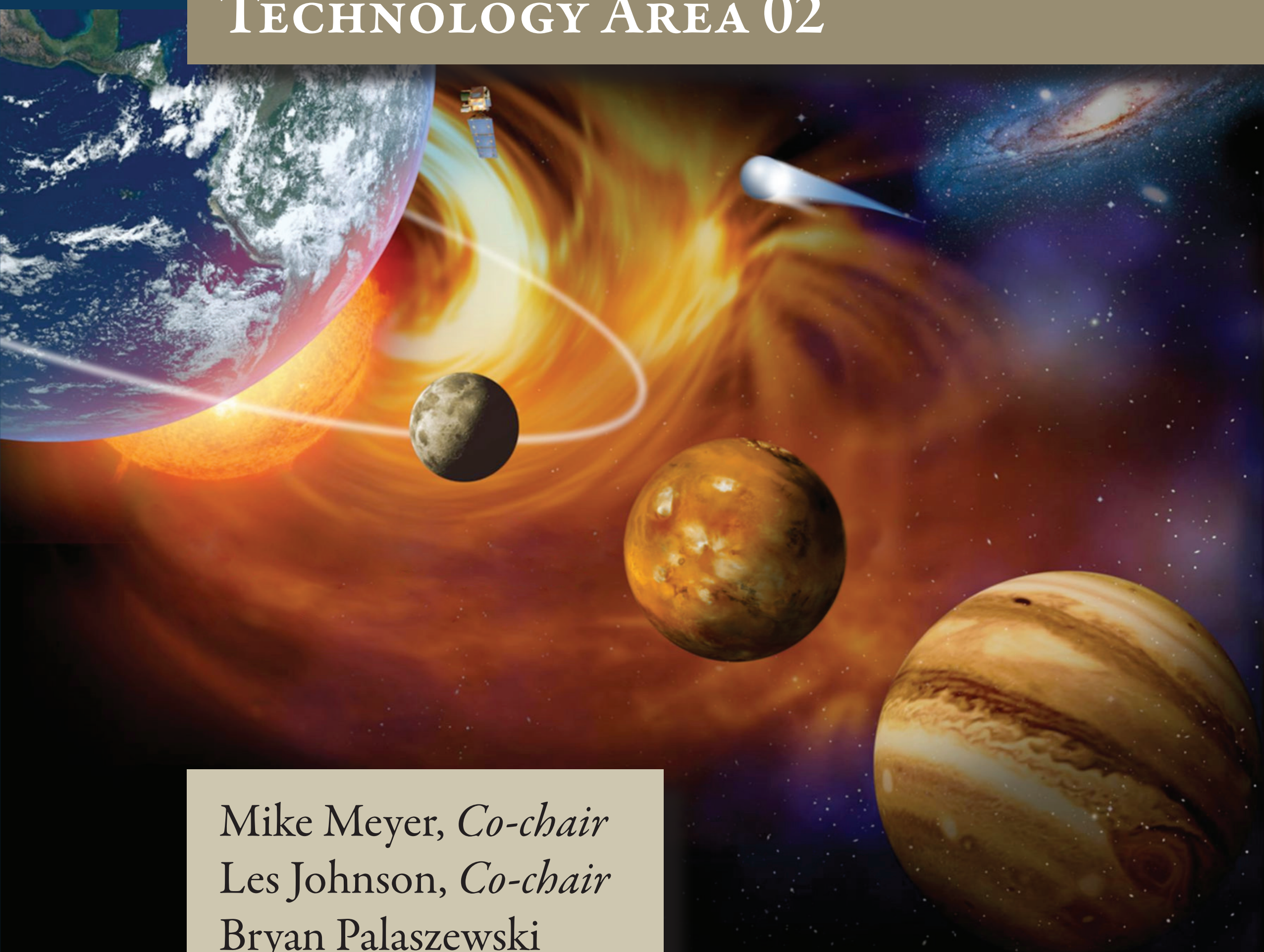
National Aeronautics and Space Administration

DRAFT In-Space Propulsion Systems Roadmap

Technology Area 02



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 02 input: In-Space Propulsion Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

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 a 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 (I_{sp}, thrust per mass flow rate of propellant). A significant improvement (>30%) in I_{sp} 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. 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. 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.

Development of technologies within this TA will result in technical solutions with improvements in thrust levels, I_{sp}, 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.

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) Non-chemical 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 meritous 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 be-

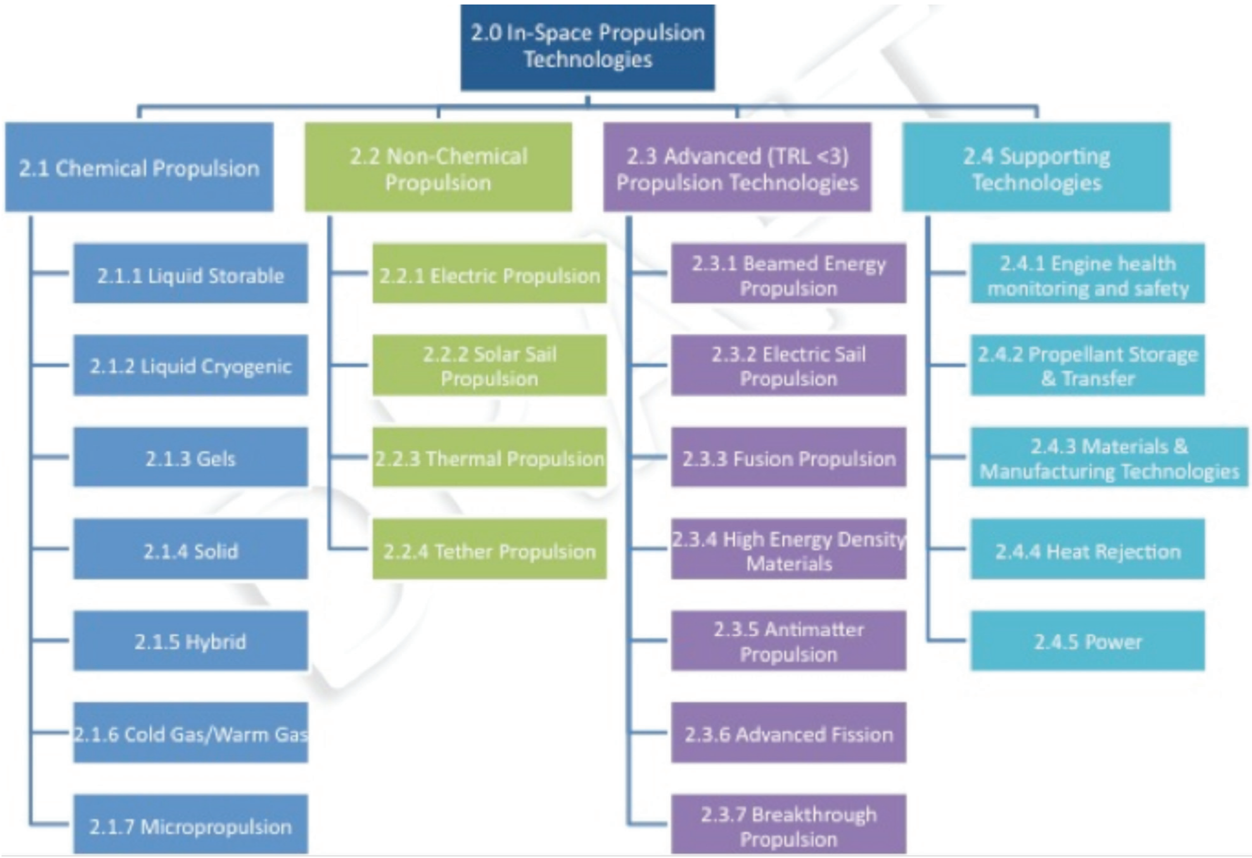


Figure 1. *In-Space Propulsion Technology Area Breakdown Structure*

tween 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/non-NASA missions.

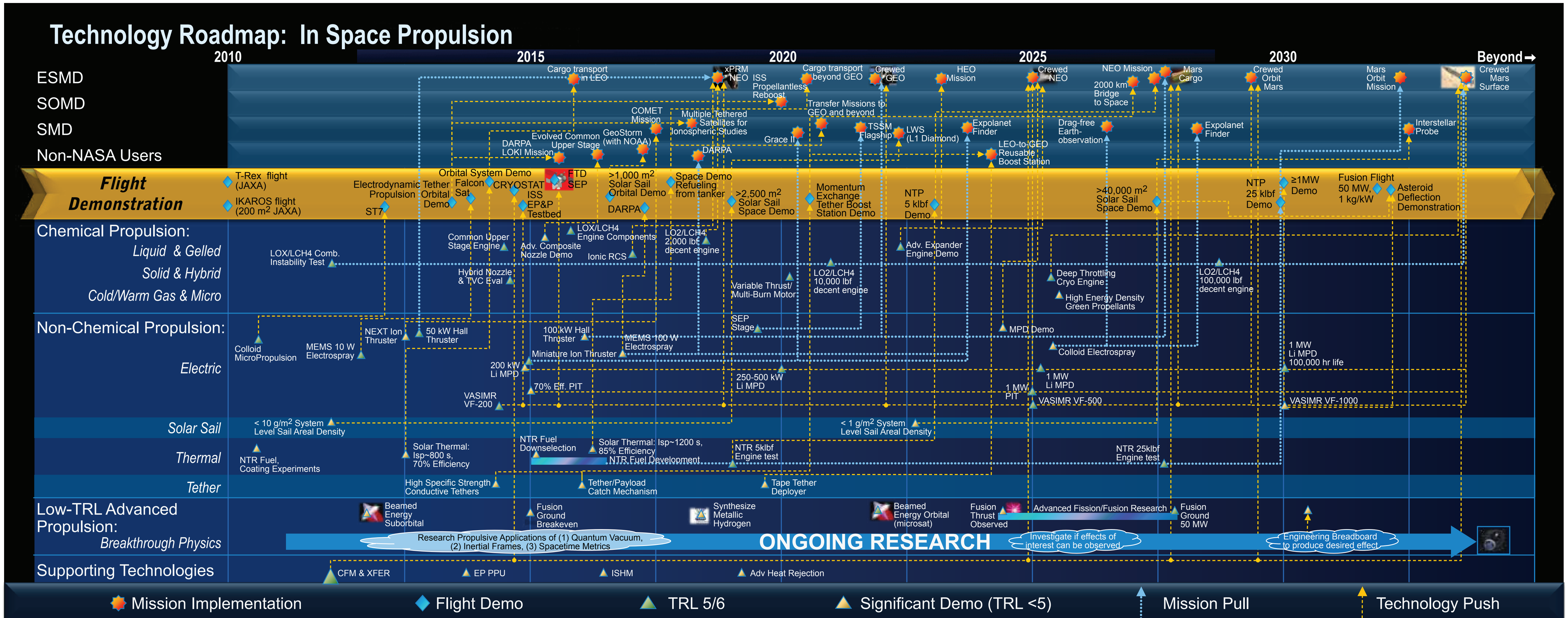
1. GENERAL OVERVIEW

1.1. Technical Approach

For both human and robotic exploration, traversing the solar system is a struggle against time and distance. The most distant planets are 4.5–6 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

Figure 2: *In Space Propulsion Technology Area Strategic Roadmap (TASR)*



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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.

1.2. 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, I_{sp}, 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.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, 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 SMD Decadal Surveys, past Design Reference Missions, Design Reference Architectures, historical mission studies, In-Space Propulsion Technology concept studies, and internal ISS utilization studies. Appendix B contains references for reports and studies identifying missions used for categorizing pull and push technology designations.

1.4. 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 con-

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. 50–300 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

sidering stated mission pull (for example, 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.

2. DETAILED PORTFOLIO DISCUSSION

The roadmap for this technical area is divided into four basic groups: (1) 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 following table on the right.

Within each section of the following tables there are three columns. The left-most column provides a summary description of a particular technology, explaining its governing physics and method of operation. The middle column identifies at a high-level the technical challenges that must be overcome to raise its maturity. The right-most column for Sections 2.1, 2.2, and 2.4 describes the significant milestones to be reached for a given technology to attain TRL-6. In Section 2.3 this column describes the milestones required for attaining TRL >3.

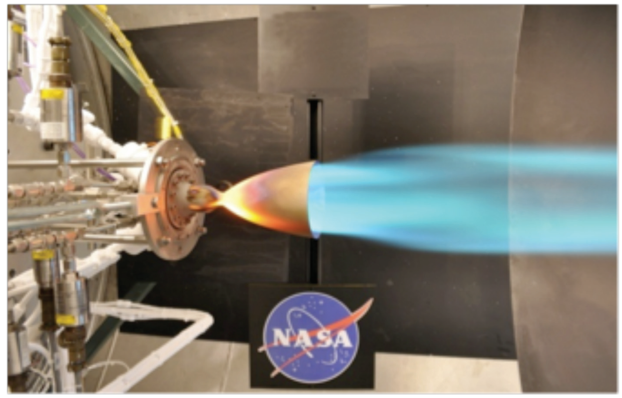
This roadmap makes use of the following set of definitions and ground rules. The term "mission pull" defines a technology or a performance characteristic necessary to meet a planned NASA mission requirement. Any other relationship between a technology and a mission (an alternate propulsion system for 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 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 representation (Fig. 2, p. 3/4) 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.

Improvement Results		
Icon	**Designator**	**Description**
	T	Decreased transit times
	M	Increased payload mass
	C	Reduces cost/system complexity/improved system reliability
	E	Enable missions to new science and exploration targets
	R	Provide potential propulsion breakthroughs that will revolutionize space exploration

2.1. 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.



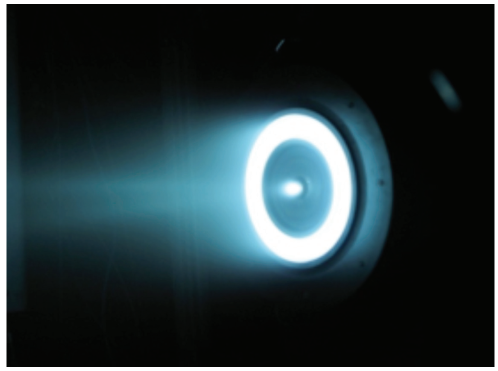
2.1 CHEMICAL PROPULSION		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.1.1 Liquid Storable		
2.1.1.1 Monopropellants		
Hydrazine thrusters use a catalytic decomposition reaction to generate high temperature gas for thrust. Hydrazine is SOA. Spacecraft reaction control system (RCS) performance is near I_{sp} 228 sec. Lander engines have higher Isp (238 secs). Freezing point is 3 °C.	Catalyst life, inability for cold starts. Increased thrust and Isp performance with pumped systems. Reduction of freezing point from 3 °C needed without compromising the performance.	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).
2.1.1.2 Bipropellants		
Bipropellant thrusters use the chemical reaction, typically hypergolic, to generate high temperature gas that is expanded to generate thrust. Nitrogen Tetroxide (NTO)/Hydrazine (N_2H_4) is SOA with I_{sp} 326 secs for fixed thrust (450 N) planetary main engine.	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.	Develop and qualify pumped bi-propellant system. Develop and qualify throttleable bi-propellant valve/system. Recapture XLR-132 NTO/MMH pump-fed engine technology.
2.1.1.3 High-Energy Propellants		
Bipropellant thrusters use the chemical reactions to generate high temperature gas that is expanded to generate thrust. One of the two may be cryogenic fluid and may also require spark ignition systems. LO_2/N_2H_4 is a hypergolic option has comparable performance to LO_2/LCH_4. Higher thrust levels needed for SMD missions.	No cryogenic engines have flown other than RL10 for <24 hrs. Cryogenic storage and operation for long duration space based missions have not been demonstrated. Valve leakage, boiloff management and thermal environment significant challenge.	Develop and qualify pump fed LO_2/MMH engine. Demonstrate operation and performance and qualify long-term storage of LO2 for space application (see Section 2.4.2).
2.1.1.4 High-Energy Oxidizers		
High-energy oxidizers such as fluorinated compounds include chlorine trifluoride (ClF3), chlorime pentafluoride (ClF5) and & oxygen difluoride (OF2). 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.	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.	The stage development for this technology was designed for SDI, etc. Recapturing the handling and upper stage ground processing methods is needed.
2.1.2 Liquid Cryogenic		
2.1.2.1 LO2, CH4		
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 LO_2 and LCH_4 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.	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.	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.

2.1 CHEMICAL PROPULSION		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.1.2.2 LO_2, LH_2		
SOA is MMH/NTO at TRL 9 for Reaction Control Systems (RCS) and orbital maneuvering propulsion, which are integrated. Development of LOX/LH_2 RCS (liquid propellants) allows integration with an upper stage that uses LOX/LH_2. An O_2/H_2 RCS typically involves taking low-pressure propellants from the main tanks, pumping to higher pressure, turning liquid to a gas, and then storing in a gas accumulator. The TRL is 4-5 with engines having been tested, dating back to 1970 for early shuttle designs. Throttleable LO_2/LH_2 main engines for planetary descent are at TRL 4 with recent CECE engine testing. LOX/LH_2 for primary in-space propulsion trades well for some mission applications.	For integrated RCS, reducing system complexity and dry mass. For throttle-able main engine, developing deep throttling capability with good performance. Cryogenic fluid management issues must also be addressed.	Develop components (pumps, heat exchangers, accumulators) for the O_2/H_2 feed system and perform integrated system level tests. Develop and test LO_2/LH_2 throttleable main engine for crewed descent.
2.1.3 Gelled & Metalized-Gelled Propellants		
Gelled and metallized fuels are a class of thixotropic (shear thinning) fuels which improved the performance of rocket and airbreathing systems in several ways: increased rocket specific impulse, increased fuel density, reduced spill radius in an accidental spill, lower volatility during low pressure accidental propellant fires, reduced fuel sloshing, and lower leak potential from damaged fuel tanks (due to higher propellant viscosity). Military systems have sought gelled fuels for all of these reasons. NASA systems have studied gelled fuels analytically and experimentally for lunar and Mars missions, upper stages, interplanetary robotic missions, and launch vehicle applications. Increased fuel density and increased engine specific impulse are the primary benefits. Missile flight tests, 1999, 2001, with Earth-storable propellants: Inhibited Red Fuming Nitric Acid for the oxidizer, and gelled-MMH/Carbon for the fuel.	Gelled cryogenic propellants have only been tested in laboratory experiments and have not yet flown in a space representative environment. One potential issue to be addressed would be boil-off and a corresponding shift in gellant-loading in the fuel. Cryogenic fluid management issues must also be addressed. Storable NTO/MMH/Aluminum, Oxygen/RP-1/Aluminum, and Cryogenic Oxygen/Hydrogen/Aluminum are the primary candidates to be investigated. The primary challenges are with gelling the fuels with the aluminum particles.	Recapture gelled hydrogen/cryogenic fuel work from 1970s. Cryogenic fluid management issues must also be addressed. Large scale (500-1000 lbs thrust) RP-1/Aluminum, and Hydrogen/Aluminum engine and component testing must be conducted.
2.1.4 Solid Rocket Propulsion Systems		
Solid propellants are usually pre-mixed oxidizer and fuel that are then formed into a particular shape, so that when the surface is ignited the surface area burns at a predetermined & tailored burn rate to generate the thrust and duration required for the mission. I_{sp} values are normally less than 300 secs. For space-based solids, Hydroxyl-Terminated Polybutadiene (HTPB) propellant has been used exclusively in apogee kick-motors & upper stages. Thrust vectoring is controlled by gimballing or gaseous/liquid injection.	Increase Isp by using nano-particles to increase surface burning area. Improve durability of thrust vector control system to withstand long-term exposure to space environment. Improve pointing accuracy in thrust vector control. Maintaining pressure in chamber to ensure ignition (covers, purge systems) is required for use in space. Long-term storage issues in space may not yet be well understood.	Develop and hot-fire test formulations with nano-particles included in solid propellant mix. Develop and qualify propellant for long-duration space applications.
2.1.5 Hybrid		
Hybrid rockets utilize a solid fuel and liquid oxidizer. They are potentially safer and have a higher I_{sp} than solid rockets, and are less complex and cheaper than liquid rockets. Hybrid rockets are generally larger in volume than solid rockets due to the lower density of its propellants. Also, for most hybrid fuels the regression rate is much less than solids, which requires more burning surface for an equivalent thrust. For simple grain shapes, they are restrained to high length/diameter ratios, which translate to long, thin motors. Hybrid motors have been demonstrated at the 250K thrust level. Recent funded investments in hybrid technology development has resulted in significant progress reducing technology risk, with long burn duration firings at 20K thrust level.	Further fundamental fuel/oxidizer/additives/ propellant-web design investigations combined with burn rate additives, paraffin, different oxidizer flows, and multiport multilayer configurations need to be conducted. re-start/ multiple firing use for upper stage is needed. For in-space propulsion, in general, higher mass-fraction and higher I_{sp} ranges are critical design issues, and optimization trade studies are required.	System studies on large upper stages and apogee kick-motors must be conducted over the range of technology options. The most promising candidates (Aluminum-loading, high regression fuel, paraffin, additives, vortex, multiport/multi-layer configuration, etc.) should be tested at larger thrust levels to determine propulsion scaling and combustion efficiency. Subscale testing and analysis is needed to prepare candidate system(s) for enhanced component demonstrations at 250,000 lbs thrust. For future missions/applications, requirements, system studies and development of components will be needed.

2.1 CHEMICAL PROPULSION		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.1.6 Cold Gas/Warm Gas		
Cold Gas systems have been flying in space since the 1950's with thrust levels from fractions of a pound to 10s of pounds. Warm gas systems have been used in flight systems for pressurization, but not for main propulsion. The principal advantage of the warm gas version of a cold gas system is a ~ 50% reduced tank volume. Gas propulsion systems are typically used for small delta-V or when small total impulse is required. Generally inexpensive and very reliable, inert gases are inherently non-toxic and most of the residual risk lies with the high-pressure storage tanks, although good design provides ample margin for safety. Cold gas systems are TRL 9; warm gas TRL5/6.	Getting a flight demonstration of a warm gas system is the next challenge. Thruster development and development of a combination isolation valve/regulator is an important improvement for packaging the system, and such a combination component could be used for other systems (such as pressurization).	Definition of a specific mission, or thrust class to drive the required applications engineering is important for a technology demonstration. Thruster development and development of a combination isolation valve/regulator is required. Other alternative catalyst options need to be evaluated.
2.1.7 Micropropulsion		
2.1.7.1 Solids		
Solid motor microthrusters are simply miniature versions of large solid-booster rockets. There are many solid motor options that are flight ready for micropropulsion applications.	Determine minimal size and thermal scaling for given applications.	Off-the-shelf designs are already at TRL > 6, and ready for flight demonstration. Definition of a specific mission and thrust class to drive applications engineering is needed.
2.1.7.2 Cold Gas/Warm Gas		
Micropropulsion cold/warm gas thrusters are miniature versions of these devices described earlier. There are many off-the shelf small cold gas thrusters that are flight ready for micropropulsion applications, some with flight heritage. Smaller thruster systems based on "liquified gas" (e.g. butane) have been developed for inspector spacecraft and cubesat application, and MEMS based thrusters have been developed. Most of these thrusters are awaiting flight demonstration.	Very few technical challenges exist other than flight demonstration.	These types of thrusters are already at TRL>6 and require flight demonstration.
2.1.7.3 Hydrazine or Hydrogen Peroxide Monopropellant		
Microthrusters using monopropellants such as N2H4 (and others) are very small engines that produce low thrust levels and minimum impulse bits for reaction control systems (RCS). Hydrazine micro-thrusters are used for primary propulsion on small sats (~100 kg class). SOA Performance for an MR-103H(TRL 9) is thrust: 1.07 N, I_{sp}: 220 s, Power 6.5 W, Min. Ibit: 5000 uNs, Mass: 195 g. A TRL 4-5 Hydrazine milli-Newton Thruster (HmNT) is under development that produces thrust: 129 mN, I_{sp}: 150 s, Power (valve): 8.25 W, Min. Ibit: 50 uNs, Mass: 40 g. Under development (TRL 2-3) are MEMS fabricated versions, but no performance data is available yet.	Challenges include the development of small catalyzer-beds, small high-speed flow control valves and thermal control techniques.	Successful testing and performance measurements need to be made on these devices to elevate the TRL to 5. Qualification and long-duration testing need to be conducted to reach TRL 6.

2.2. Nonchemical Propulsion

Nonchemical Propulsion serves the same set of functions as chemical propulsion, but without using chemical reactants. Example technologies include: systems that accelerate reaction mass electrostatically and/or electromagnetically (Electric Propulsion), systems the energize propellant thermally (Solar or Nuclear Thermal Propulsion), and those that interact with the space environment to obtain thrust electromagnetically (Solar Sail and Tether Propulsion).



2.2 Nonchemical Propulsion		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.2.1 Electric Propulsion		
2.2.1.1 Electrothermal		
2.2.1.1.1 Resistojets		
Resistojets use an electrically heated element in contact with the propellant to increase the enthalpy prior to expansion through a nozzle. Additional heat may be added chemically, with hydrazine propellant for example. Resistojets are a mature (TRL 9) technology with hundreds of thrusters in operation on commercial communications satellites for station keeping, orbit insertion, attitude control, and de-orbiting. Off-the-shelf resistojets with power levels ranging from 467-885 W are available. Low power (<50 W) resistojets that operate on xenon, nitrogen or butane have been developed and flown on over 20 spacecraft. A multipropellant resistojet designed to operate on waste gases from the ISS was developed, but never flown. Applications for xenon resistojets are attitude control or proximity operations near small bodies that might benefit from longer life and higher performance.	Challenges are in scaling technology to much smaller sizes and power levels for use on microspacecraft, including microfabrication techniques, high temp materials, low-leak rate microfabricated valves for small gas-fed systems, achieving high performance with low Reynolds number nozzles, and lifetime of high-temp components.	Demonstrate scalability to very small sizes, microfabrication of thruster components, and verification of thruster performance and life.
2.2.1.1.2 Arcjets		
Arcjets use an electric arc to heat the propellant prior to expansion through a nozzle. Additional heat may be added chemically, with hydrazine propellant for example. Arcjets are a mature (TRL 9) technology with hundreds of thrusters in operation on commercial communications satellites, primarily for station keeping. Off-the shelf hydrazine arcjet systems have power levels of 1670 to 2000 W. Lower power hydrazine arcjets (~500 W) have achieved TRL 5-6. Ammonia arcjets at 30 kW were flight-qualified (TRL 7). Laboratory model hydrogen arcjets have power levels ranging from 1 to 100 kW, but did not progress beyond ~TRL 4.	Minor product improvements are being made on existing products, but there is little mission pull for more advanced arcjets.	No immediate applications that require advanced arcjets.

2.2 Nonchemical Propulsion		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.2.1.2 Electrostatic		
2.2.1.2.1 Ion Thrusters		
Ion thrusters employ a variety of plasma generation techniques to ionize a large fraction of the propellant. High voltage grids then extract the ions from the plasma and electrostaticly accelerate them to high velocity at voltages up to and exceeding 10 kV. Ion thrusters feature the highest efficiency (60 to >80%) and very high specific impulse (2000 to over 10,000 sec) compared to other thruster types. Over 130 ion thrusters have flown in space on over 30 spacecraft in both primary propulsion and satellite station keeping applications. The propellant presently used is xenon for its high atomic mass, easy storage on spacecraft and lack of contamination issues, although other propellants can be used. Flight thrusters operate at power levels from 100 W to 4.5 kW. Various ion thrusters are at TRL 9 (13cm XIPS, 25cm XIPS, NSTAR, T5 Kaufman Thruster, RIT10, 10 ECR, and ETS-8). The 7.2 kW NEXT ion thruster is already at TRL6 and requires flight demonstration or mission application.	Ion thruster performance and life is determined by the grids. Thrusters operate at voltages of 750 V - 10,000 V, and voltage breakdown of closely space multi-aperture grids is an important issue. Improve-ments in low-erosion grid materials and longer life cathodes are needed for future deep space missions. Improvements in efficiency based on better plasma generator design is needed. Improved modeling & model-based design & life predictions are also needed for future ion thruster development.	Ion thrusters require development to produce higher I_{sp} and longer life by utilizing advanced grid materials. High power ion thrusters developed at JPL and GRC in the 20 to 30 kW range are at TRL4 and require environmental testing and life qualification to achieve TRL6.
2.2.1.2.2 Hall Thrusters		
Hall thrusters are electrostatic thrusters that utilize a cross-field discharge described by the Hall effect to generate the plasma. An electric field perpendicular to the applied magnetic field accelerates ions to high exhaust velocities, while the transverse magnetic field inhibits electron motion that would tend to short out the electric field. Hall thruster efficiency and specific impulse is somewhat less than that achievable in ion thrusters, but the thrust at a given power is higher and the device is much simpler. Over 240 xenon Hall thrusters have flown in space since 1971 with a 100% success rate. Commercially developed flight Hall thrusters operate between 0.2 and 4.5 kW with 50% efficiency, thrust densities of 1 mN/cm^2, and Isp of 1200–2000 secs. Hall thrusters have been demonstrated from 0.1 to 100 kW with efficiencies of 50-70%. Recent research has demonstrated operation with alternative propellants and I_{sp} increases to 3000–8000 secs.	Scaling to high-power and achieving sufficient lifetime are central challenges. Scaling to higher power (>10 kW) normally results in increased specific mass (kg/kW), but provides longer lifetime due to greater amounts of wall material inherent in larger designs. A major challenge is to capitalize on recent breakthroughs on reducing wall erosion rates to realize very long life and throughput (>1000 kg) and increase I_{sp}. Life validation of high-power, long-life thrusters requires development of physics-based models of the plasma & erosion processes.	Hall thruster power level must progress from thrusters capable of 10's of kW of power to systems of multiple thrusters capable of the order of 1 MW [ref. HEFT study]. Key milestones for high power Hall thrusters are demonstration of long-life technology on large thrusters (10's to 100's of kW), development of 100 kW or multi-100kW thrusters with demonstration of performance and life, and development of associated power processing units (PPUs). The10-20-kW class thrusters developed by AFRL must be leveraged to achieve TRL6 within 3-5 years as a steppingstone to higher power thrusters. Larger thrusters operating at power levels of 50 kW and higher require performance demonstration at Isp from 2000 to 3000 sec, environmental testing and life qualification to achieve TRL6.
2.2.1.3 Electromagnetic		
2.2.1.3.1 Pulsed Inductive Thruster		
The Pulsed Inductive Thruster (PIT) is an electromagnetic plasma accelerator that creates its plasma by inductive breakdown of a layer of gaseous propellant transiently puffed onto the surface of an induction coil. Energy stored in a bank of capacitors switched into the coil produces an azimuthal electric field generates a flat ring of current that provides a piston against which the rising magnetic field acts, entraining and ionizing the balance of the propellant and ejecting it along the thruster axis. The PIT has demonstrated efficiency of greater than 50%, and an I_{sp} of 2000-9000 secs in a single pulse. New pulsed inductive concepts have operated at much lower stored energy (100 J versus 2-4 KJ of the high-power PIT) and provides a >3x smaller thruster operating at 20-40x less energy than the larger variant.	Demonstration of the life of propellant valves and solid-state switches, and continuous operation at fixed performance. For ISRU, continuous operation with H_2O without loss in performance is needed. Similar challenges exist for the scaled-down versions of the PIT. Sustained power levels of 200 kW$_e$ at efficiencies of 70% or higher with I_{sp} of 3000-10000 secs are required.	The key milestones to TRL 6 include demonstration of switch and valve life >1010 pulses (>3yrs @100pps, >6yrs @50pps), and demonstration of >70% thrust efficiency and I_{sp} in the range of 4,000 to 10,000 sec during continuous operation. Continuous operation with ammonia and/or water for in situ propellant utilization must be demonstrated and the life verified.

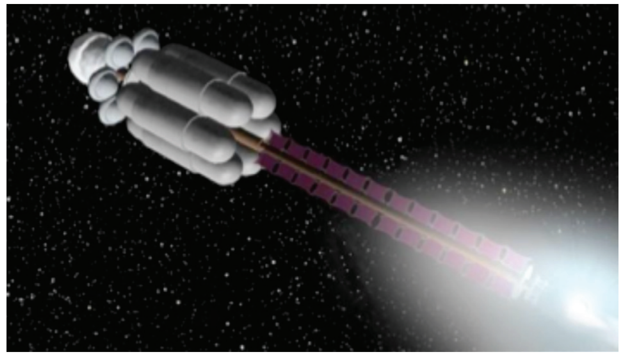
2.2 Nonchemical Propulsion		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.2.1.3.2 Magnetoplasmadynamic Thruster		
Magnetoplasmadynamic (MPD) thrusters employ the interaction of high currents with either applied magnetic fields or the self-induced magnetic field to accelerate ionized propellant. MPD thrusters offer high efficiency and very high power processing capability in a small volume, and have been demonstrated at steady state power levels up to 1 MW_e. There are three variants on the MPD thruster: steady state self-field engines, steady state applied-field engines, and quasi-steady thrusters. MPD thrusters show that they can achieve efficiencies over 50% at I_{sp}'s greater than 10,000 secs and thruster power levels of multi-MW_e. State-of-the-art laboratory model (TRL 3-4) lithium applied field thrusters have demonstrated efficiencies greater than 50% at 4,000 secs in a 200 kW_e device and modeling indicates they can achieve over 60% efficiency at power levels of 250 kW_e and above.	Challenges are component lifetime, thermal management, and performance limitations due to the "onset" phenomenon. The cathode must operate at high temperatures for sufficient emission current densities. Reduction in the cathode operating temperature by lowering the work function, passive radiative and/or active cooling must be demonstrated. Approaches to improving thruster performance by increasing the onset current must be understood theoretically and experimentally verified.	MPD thruster power levels must progress from thrusters capable of 100's of kW to the order of 1 MW or higher. Near-term milestones to achieve TRL6 at 200 to 250 kW_e are demonstration of lithium applied-field thruster performance at 60% efficiency at I_{sp} of 6,000 sec and long life cathodes with anode thermal management and thruster life validated in long duration (10,000 hrs) wear tests. Mid-term milestones for TRL6 thrusters at 1 MW include demonstration of lithium self-field thruster performance at >50% efficiency, long cathode life and anode thermal management, technologies for raising the onset current, and verification of thruster life. In the far term, very high power hydrogen-fueled thrusters must be developed and demonstrated.
2.2.1.3.3 Variable Specific Impulse Magnetoplasma Rocket		
The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a high power electric space propulsion engine capable of Isp/thrust modulation at constant input power. Plasma is produced by helicon discharge with energy added by ion cyclotron resonant heating (ICRH). Axial momentum is obtained by adiabatic expansion of plasma in a magnetic nozzle. Thrust/specific impulse ratio control achieved by partitioning RF power and propellant flow between helicon and ICRH systems. The most advanced VASIMR prototype to date is the VX-200 device that uses 35 kW helicon source to generate argon plasma, 170 kW ICRH section to heat plasma, and an adiabatic magnetic nozzle to produce exit plume. The VX-200 leverages commercially developed solid-state RF generators with efficiencies of 98 % & specific mass less than 1 kg/kW. It uses a cryogen-free low-temperature supercon-ducting magnet to produce fields approaching 1 Tesla required for helicon and ICRH sections. The VX-200 has been operated at power levels of up to 200 kW & with performance data estimates of 5,000 sec I_{sp} and 60% efficiency for 5 sec pulses.	The current technical challenges are the cryogen-free low-temperature superconducting magnet, the magnetic nozzle performance and lifetime (from sputtering) and the high temperature heat rejection system required to extend the pulse length. Future technical challenges include specific mass, heat rejection and thermal control, interactions of the divergent plume with the spacecraft, and life qualification.	Subsystem: continue cryo-cooler testing and characterization for use with superconducting magnets, trade 60kW pumped fluid system (uses ISS PVTCS pump with Downtherm-J) performance against titanium-H_2O Loop Heat Pipe system (interdependency with TA14), complete verification plan for 200kW Nautel amplifer. System: Test VF-200 in a large vacuum chamber (e.g., Space Power Facility) to collect plume characteristics data for additional modelling validation. Measure & quantify RF nature of VF-200 plume to ensure compliance with NASA spaceflight hardware requirements. Perform testing of the VF-200 system to meet qualification & acceptance environmental testing requirements. Demonstrate operation of VF-200 on ISS at 200kW power level for 15-min firing duration, ~5 N thrust, I_{sp} of 4000-6000 secs, and efficiency of ~50-55%. Collect on-orbit plume characteristics data.
2.2.1.4 Micropropulsion		
2.2.1.4.1 Microresistojets		
See description on resistojets earlier. Microresistojets are smaller versions of conventional resistojets and generally have an overall lower TRL because of a lack of flight hardware development and demonstration. Small thruster systems based on "liquified gas" (e.g., butane) have been developed for Inspector spacecraft and Cubesat applications and are ready to be flight demonstrated. MEMS based resistojet thrusters have also been developed primarily for small-sat applications.	Conventional butane-based microresistojet thrusters require flight demo. For MEMS based designs, there are issues associated with microfabrication techniques, wall losses, and thermal design of the smaller thruster volumes. Additionally, the small nozzle dimensions generally reduce the efficiency of these devices and designing MEMS based miniature flow-control valves has proven difficult.	Butane thrusters are at TRL 5-6 and ready for flight demonstration. For MEMS based devices, demonstration is needed of the scalabiity to very small sizes, microfabrication of thruster components, and verification of thruster performance and life.
2.2.1.4.2 Microcavity Discharge, Teflon		
Microcavity discharge thrusters are similar to arcjects (see description above), except that the dimensions are much smaller and the TRLs are lower (no flight development to date). MEMS fabrication has been used along with smaller more conventional techniques. In these exceedingly small scaled down versions of arc-jets, the arc is concentrated in a very small volume at lower power to maintain the life of the single thruster, or configured in arrays one thruster can be used if another fails.	Challenges are MEMS-fabrication techniques, reliability of arc electrodes, array design, and thermal issues.	Demonstrate scalability to very small sizes, microfabrication of thruster components, and verification of thruster performance and life.

2.2 Nonchemical Propulsion		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.2.1.4.3 Micropulse Plasma		
Pulsed plasma thrusters (PPTs) use capacitively or inductively coupled plasma discharge to accelerate conductive gas, liquid, or solid at high powers (kW to MW in discharge) for very short pulses (<1 msec). Typical PPTs ablate teflon using a surface discharge to provide the propellant. Pulsing allows average power consumption to be very low but requires energy storage and switching. Small PPTs were first flown onboard Russian Zond 2 spacecraft in 1964 and several other missions. PPTs offer very small impulse bits, solid propellant storage, modularity, and proven operation. Recent advances in PPT miniaturization have been achieved. The Vacuum Arc Thruster (VAT) is another ablative pulse plasma type that uses metal electrodes and an arc discharge. A VAT module has been developed for Cubesat.	Miniaturization of PPT technology must focus on mass reduction of the supporting power electronics (in particular on lighter capacitors and switches). The thruster itself faces challenges during miniaturization in the tailoring of discharge energy to the decreased fuel rod cross sectional area. If the discharge energy becomes too small, carbon neutrals in the plasma arc can return to the fuel surface & result in charring, which ultimately can lead to shorting of the thruster electrodes.	Demonstrate scalability to very small sizes, microfabrication of thruster components, and verification of thruster performance and life.
2.2.1.4.4 Miniature Ion/Hall		
These are scaled down versions of ion and Hall thrusters described earlier. Miniature ion and Hall engines have recently been developed for formation flying applications of future space telescopes (the 100-W NASA MiXI ion thruster) and for small satellites orbit maneuvering (the 200-W = Miniature Hall thruster). Use of inert, noncontaminating xenon propellant near sensitive optical surfaces, as well as ability to smoothly modulate thrust amplitude have made miniature electric engines attractive. Ion Thruster On a Chip (ITOC) concepts have been investigated that included subcomponent developments including microfabricated accelerator grids and field emission based cathodes for discharge generation and neutralization. A 4-cm diameter RF ion thruster was developed in Europe and is slated for upcoming ESA earth-observing missions, and miniature ion thrusters based on Electron Cyclotron Resonance (ECR) plasma production at microwave frequencies are under development in Japan and in US universities.	In addition to the challenges of reducing the size of engines (associated with lower efficiencies due to higher surface losses and voltage breakdown in small gaps), other required subsystems have to be equally miniaturized including the feed system and the power processing unit (PPU). Off-the shelf solutions feed systems and power supplies used in conventional thrusters could be adapted for micro-ion/Hall engines based on present performance. A key challenge to the thruster design is to scale appropriately the applied magnetic fields in the smaller sized ion and Hall thrusters, and the development of miniature hollow cathode technology.	Develop microfabrication techniques for the thruster and subsystem components, scalability to very small sizes, and demonstrate subsystem performance, life and integration with spacecraft in demonstration missions.
2.2.1.4.5 MEMS Electrospray		
Electrospray thrusters use a conductive fluid and electrostatic fields to extract and accelerate charged droplets, clusters of molecules, and/or individual molecules or ions. The ion-emission pointed-tips are on the order of microns which lends to MEMS based fabrication to produce large arrays of emitters. The SOA in electrospray thrusters is a 5-30 uN precision thruster (TRL6) planned for stabilization and solar pressure compensation, which is awaiting a flight demonstration on ST7/Laser Interferometer Space Antenna Pathfinder. Other designs are under development. Using MEMS techniques, closely packed emitter tips are used to decrease the system volume while increasing the number of emitters (and hence the thrust). MEMS fabricated electrospray thrusters in development in US laboratories and in Europe are at TRL 3, and have demonstrated high efficiency (>80%). This high efficiency removes many thermal issues, and the lack of a plasma discharge or confinement requirements simplifies the construction and voltage holdoff.	Challenges are MEMS fabrication of large tip arrays, microfluidics for distributing propellant to all the tips, cleanliness, power-processing, thruster testing, and lifetime. To date, the challenges of demonstrating microfabcation and microfluidics to feed the arrays with propellant in the laboratory have prevented a space-qualifiable protoype demonstration.	Milestones to TRL 6 include flight of the ST-7/LISA Pathfinder that will demonstrate colloid thruster performance, demonstration of a MEMS fabricated prototype array, and performance measurements, flight demonstration and successful life test of MEMS fabricated arrays.

2.2 Nonchemical Propulsion		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.2.2 Solar Sail Propulsion		
Solar sails are large, lightweight reflective structures that produce thrust by reflecting solar photons and thus transferring much of their momentum to the sail. The state-of-the-art solar sails were produced for the NASA In Space Propulsion 20 meter Ground System Demonstrations (GSD) in 2005. The JAXA funded Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS), launched in May, 2010, deployed its sail in June and has since demonstrated both photon acceleration and attitude control. IKAROS has a square sail that is approximately 14 meters long on each side, 7.5 micrometers thick and used a spin deployment method to deploy its sail.	System level integration and test of the component technologies for >1,000-m^2 sail using existing materials and technologies are needed. Gravity offload and deployment tests of the large sail are needed.	Due to the constraints of gravity, solar sail propulsion performance will not be totally demonstrated to TRL 6 on the ground. A space flight demonstration will be required to fully achieve TRL 6.
2.2.3 Thermal Propulsion		
2.2.3.1 Solar Thermal		
Solar Thermal Propulsion (STP) heats the propellant with concentrated sunlight inside an absorber cavity and provides a very high specific impulse (~500–1200 seconds). The solar energy is concentrated and focused inside either a direct gain or thermal storage type engine configuration. The solar concentrator is may be rigid, segmented or inflatable. The engine would be fabricated from ultra high temperature materials and operated as a heat exchanger with the propellant. A variety of propellants have been considered (e.g., hydrogen, methane, ammonia). The thrust level for this system would be on the order of 1.0 lbf. The L'Garde flight experiment in 1996 demonstrated the deployment of a large inflatable concentrator (TRL6). The 30-day LH_2 storage with controlled boil-off was demonstrated in 1998-1999 (TRL5). Various engine concepts have been made and fabricated from Rhenium, Tungsten/Rhenium, and Rhenium coated graphite (TRL4). A new Ebeam manufacturing process has been demonstrated to fabricate complex STP engine designs. In addition, a new ultra-high temperature material (tri-carbide) has the potential to allow greater I_{sp} than 1000 seconds.	Challenges are optical concentrator accuracy and performance (from 50-60% to 85-90%), system/stage packaging, sun pointing (sub-arcsec accuracy in flat, 1 cm by 1 cm packages), inflatable deployment, controlled cryogenic boil-off, and engine performance. An integrated overall system test has never been performed. STP is limited by payload shroud volume when considering liquid hydrogen LH_2. Options to overcome this hurdle include the use of high temperature carbides with melting point ~4200K. At temperatures above 3200K and pressures ~25 psia.	Perform experiments with inflatable or rigid concentrators to increase the optical performance to 85-90% efficiency. Demonstrate the pointing capabilities of dual concentrators to keep the focuses on target during all expected spacecraft orientations with the sun. Demonstrate the propulsion performance of a high temperature carbide thruster manufactured with modern material processing techniques, which allow complex geometries to be fabricated. Ground test the performance of more dense propellants (e.g., methane, ammonia). In addition, demonstrate the utilization of deployable LH_2 tanks.
2.2.3.2 Nuclear Thermal		
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 1970's) comparable to chemical propulsion (7,500 to 250,000 lbs of thrust with specific impulses of 800 to 900 seconds, double that of chemical rockets). Vehicles with solid-core NTR engines have been considered for human missions to Mars as their high Isp allows reductions of the initial mass in low earth orbit (IMLEO) from 12 to 7 heavy lift launch vehicle with 200 metric ton payloads.	The NERVA program matured the technology to a TRL 6 level in the 1970s. The current challenge is to capture the engineering and technical knowledge base of the NERVA program. New fuel elements with longer life is another technical challenge to be addressed by future efforts.	Complete fuel tests – select primary & backup fuel/element design; design Ground & Flight Technology Demonstration engines; complete borehole gas injection tests - detailed design of ground test facility begins – "Authority to Proceed" (ATP); complete small (5 klbf) ground technology demonstration engines tests; conduct 5 klbf NTP Flight Technology demonstrator (FTD) mission; develop engine scale-up design for crewed Mars missions.

2.2 Nonchemical Propulsion		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.2.4 Tether Propulsion		
2.2.4.1 Electrodynamic		
An electrodynamic tether (EDT) can work as a thruster because a magnetic field exerts a force on a current-carrying wire. This force is perpendicular to the wire and to the field vector. It is this interaction that allows relatively short electrodynamic tethers to use solar power to "push" against a planetary magnetic field to achieve propulsion without expenditure of propellant. The groundwork has been laid for this type of propulsion. Important achievements include retrieval of a tether in space (TSS-1, 1992), successful deployment of a 20-km-long tether in space (SEDS-1, 1993), and operation of an EDT in space with tether current driven in both directions (PMG, 1993). The Propulsive Small Expendable Deployer System (ProSEDS) experiment was to use an EDT to achieve ~0.4 N drag thrust, thus deorbiting the stage. JAXA demonstrated in space the operation of a 300-m uninsulated tape tether anode (T-Rex, 2010). Long-life, Micro-Meteoroid/Orbital Debris (MMOD) survivable tethers and alternative technologies that could replace hollow cathode plasma contactors have been tested in the laboratory.	The critical EDT subsystems have been tested both in space and in the laboratory to TRL 5/6. To field this technology, a full-scale (multi-kilometer, multi-kW) space validation at the system level is required. The primary challenge for EDT propulsion is at the system level, not at the subsystem level. Improvements to better preclude arcing and mechanism deployment design can be pursued, but are not necessary for flight demonstration.	A space flight validation of an EDT propulsion system will be required to fully achieve TRL 6.
2.2.4.2 Momentum Exchange		
A spinning, or Momentum Exchange Tether (MET) system can be used to boost payloads into higher orbits with a Hohmann-type delta-V or as an "elevator" between two different orbits. A tether system would be anchored to a relatively large mass in LEO awaiting rendezvous with a payload delivered to orbit by a launch vehicle. The uplifted payload meets with the tether facility, which then begins a slow spin-up using electrodynamic tethers (for propellantless operation) or another low thrust, high Isp thruster. At the proper moment and tether system orientation, the payload is released into a transfer orbit – potentially to geostationary transfer orbit (GTO) or Earth Escape. Most of the achievements cited for EDT propulsion establish the state of the art for MET systems. The missing system-level validations are spin-up, multi-spacecraft interaction, orbital transfer dynamics, and rendezvous and docking with the tether tip.	There are numerous subsystem and component-level engineering challenges remaining before this capability reaches TRL-6: The development of long-life, survivable conducting and nonconducting tethers, deployers, no expellant anodes and cathodes, and a robust tether dynamics modeling capability are chief among them.	Very long (up to 100+ km), high strength-to-weight conducting & nonconducting tethers survivable in the LEO micrometeoroid, orbital debris, atomic oxygen & EUV environment. Reliable wire and/or tape tether deployers with reel-in and reel-out capability Alternative anodes and cathodes with minimal or no expellants (Field Emitter Array Cathodes, Solid Expellants, etc.) Flywheel energy storage (crossover to space power team) High-res, long-tether dynamics modeling to allow precise rendezvous between tether tip and payload. High-res, long-tether dynamics modeling to allow precision spin-up (if required, Rotovator only) orbital transfer of payloads. Rendezvous & docking of payload & tether tip for rapid payload transfer between launch vehicle (orbital or suborbital) & tether tip.

2.3. Advanced Propulsion Technologies



Advanced Propulsion Technologies are those that use chemical or nonchemical physics to produce thrust, but are generally considered to be of lower technical maturity (TRL< 3) than those described in Sections 2.1.1 and 2.1.2. Gravity Assist is often used in conjunction with In-Space Propulsion to provide the required mission Δv, but does not directly influence or impact In-Space Propulsion technologies discussed here. AeroGravity Assist (AGA) is covered in TA09.

2.3 Advanced (TRL <3) Propulsion Technologies		
Description and State of the Art	**Technical Challenges**	**TRL Maturation**
2.3.1 Beamed Energy Propulsion		
Beamed energy propulsion uses laser or microwave energy from a ground or space based energy source and beams it to an orbital vehicle which uses it to heat a propellant, with the advantage being high exit velocity of exhaust products over traditional chemical propulsion. Earth-to-Orbit laser propulsion technology has been investigated both analytically and experimentally as a first step to orbital transfer. In space applications to be demonstrated are orbit transfer and earth escape. Other in-space applications could be to de-orbit orbital debris by way of ablation.	Development of MW Free Electron Lasers. Development of novel optics/tracking and pointing systems for orbit transfers. Propellant feeds or ablative propellants will also need to be technically addressed. Development of efficient capture and transformation of beamed energy into propulsive energy (e.g., heat exchangers, direct plasma breakdown in propellant).	Demonstrate thermal rocket mode using liquid, gaseous, or Delrin ablation propellant for in space maneuvers.
2.3.2 Electric Sail Propulsion		
Consists of a number of thin, long, and conducting wires that are kept in a high positive potential by an onboard electron gun. The positively charged wires repel solar wind protons, thus deflecting their paths and extracting momentum from them. Simultaneously they also attract electrons from the solar wind plasma. A way to deploy the wires is to rotate the spacecraft and have the centrifugal force keep them stretched. By fine-tuning the electrical potentials of individual wires and thus the solar wind force individually, the attitude of the spacecraft can also be controlled. Deployment of multikilometer length wires in space has been demonstrated (see electrodynamic tether propulsion). Electron guns have also been flown in space. Other technical approaches to achieve electrostatic propulsion from the solar wind include the superconducting magsail and Mini-Magnetospheric Plasma Propulsion (M2P2), but none of these have yet been demonstrated; all propulsive effects have been only predicted in theory and modeling.	Quantification of thrust magnitudes with on-orbit data. Demonstration of noninterfering centrifugal deployment of multiple wires from a single spacecraft. Validation of current collection and electrostatic propulsion from the solar wind. Validation of electrostatic attitude control in the solar wind.	Validate physics models. Develop system level performance models. Develop control laws for attitude control using multiple wire anodes. Perform subscale space flight validation (outside of the magnetosphere).
2.3.3 Fusion Propulsion		
Fusion propulsion involves using fusion reactions to produce the energy required for the spacecraft propulsion. This can be accomplished either indirectly (with a fusion reactor producing electrical power that is in turn utilized in an electric thruster), or directly, by using the thermal/kinetic energy resulting from the fusion reactions to accelerate a propellant. This is accomplished either by creating a hot, thermal plasma that is then expelled through a magnetic nozzle to provide thrust (in the same manner as in a plasma thrusters) or using high-energy, charged particle, fusion products to create the hot, thermal plasma in the thrust chamber. The physics and related technologies are is still under investigation at the laboratory scale level. A gain (energy out of the reaction to energy into the reaction) of approximately 1 has been achieved, but for useful fusion propulsion, a gain of 100 to 1000 is needed.	Creation of a sustained fusion reaction that can drive a plasma thruster with a specific mass low enough (alpha < 4) to be competitive with advanced fission is the primary challenge. Production of a positive energy output with Deuterium-Tritium reactions has yet to be demonstrated even in ground-based Tokamak reactor concepts. Production of a thermal plasma suitable for an electric thruster from high-energy fusion products (such as would come from an aneutronic fusion reactor) is needed.	Develop plasma thruster concept capable of efficiently converting high-energy, charged particle fusion products into propellant energy. Demonstrate plasma thruster concept on the ground in space-like simulated environment. Perform testing and validation of engine technology.

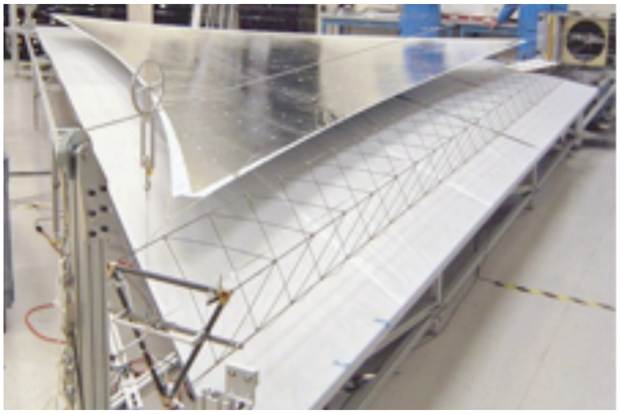
2.3 Advanced (TRL <3) Propulsion Technologies		
Description and State of the Art	**Technical Challenges**	**TRL Maturation**
2.3.4 High Energy Density Materials		
2.3.4.1 Metallic Hydrogen		
Metallic hydrogen is a theoretically dense energetic material (not yet produced on earth). The TRL level is not at level 1 as the characteristics are based on theoretical calculations. The estimated density at ambient conditions is 7 g/cc, 10 times LH_2. 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: $H_2 + O_2$ in the SSME releases 10 MJ/kg, LO_2/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 Isp values are in the 500-2000 secs range.	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.	Demonstrate synthesis of metallic hydrogen in lab. Evaluate characteristics of metallic hydrogen in lab. Develop production scaling techniques. Develop engine components and test various diluents. Perform propellant tankage development. Perform tests of various engine sizes and diluents.
2.3.4.2 Atomic Boron/Carbon/Hydrogen		
Atoms trapped in solid cryogens (neon, etc.) at 0.2 to 2 weight percent. Atomic hydrogen, boron, and carbon fuels are very high energy density, free-radical propellants. Atomic hydrogen may deliver an Isp of 600 to 1,500 secs. 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 percent atomic hydrogen in a solid hydrogen matrix. If the atom storage were to reach 10–15 percent, which would produce a specific impulse (Isp) of 600–750 secs.	Storage of atoms at 10, 15, or 50 weight percent is needed for effective propulsion.	Formulate atom storage methods for high density. Develop engine designs for recombining propellants. Perform testing and validation of engine designs.
2.3.4.3 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.	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.	Perform inhibitor research to facilitate safe scaling. Develop high-speed deflagration/detonation engine technology. Perform testing and validation of engine technology.
2.3.5 Antimatter Propulsion		
Antimatter propulsion is based on conversion of a large percentage (up to ~75%) of fuel mass into propulsive energy by annihilation of atomic particles with their antiparticles. Creation, manipulation, storage and annihilation of picogram amounts of antimatter is routine at high-energy physics laboratories such as Fermi Lab. In addition, very small amounts of positrons are routinely created, manipulated, stored and annihilated at various university labs and in hospitals. Low energy storage of small amounts of positrons and antiprotons has been demonstrated at research institutions. Many antimatter propulsion concepts have been explored analytically over the years.	The next step is experimental demonstration of these propulsion concepts. This requires a significant source of antimatter available for engineering research. Current production rates of antiprotons are not sufficient for any known propulsion applications, but could be scaled up by several orders of magnitude. Portable storage of antiprotons needs to be developed.	Develop and demonstrate proof-of-concept experiment to verify producing, controlling, and exhausting annihilation/reaction products. Develop and demonstrate thruster concept. Develop and demonstrate full-scale engine in vacuum chamber. Develop and demonstrate long-term storage and transportation systems for antiprotons.

2.3 Advanced (TRL <3) Propulsion Technologies		
Description and State of the Art	**Technical Challenges**	**TRL Maturation**
2.3.6 Advanced Fission		
2.3.6.1 Gas Core		
In gas-core rocket, radiant energy is transferred from high-temperature fissioning plasma to hydrogen propellant. Propellant temperature can be significantly higher than engine structural temperature. In some designs, propellant stream is seeded with submicron particles (~20% weight fraction) to enhance heat transfer. Both open-cycle and closed-cycle configurations have been proposed. Radioactive fuel loss and its effect on performance is a major problem with open-cycle concept. Cavity reactors for critical gas core assemblies are known to be achievable. To date, small scale, non-nuclear gas flow tests have been performed. Evaluation of critical physics and engineering aspects for integrated open cycle systems have been limited to computational studies. Closed cycle nuclear light bulb concept, whereby energy from hot reactant gas is transferred to hydrogen propellant via radiation transfer through a transparent wall, has been successfully studied in a laboratory environment to limited extent. By increasing temperature of fissioning gas, it is possible to achieve full ionization and formation of a plasma. Fissioning plasma offers superior performance potential but will require some type of electromagnetic containment system much like those encountered for magnetic fusion systems. I_{sp} values of 1500-2500 secs have been estimated.	An open-cycle engine relies on flow dynamics to control fuel loss. With both open and closed cycle concepts, cooling engine walls is a major engineering problem. It is not known whether practical means can be devised to contain nuclear fuel, adequately cool the chamber, and achieve useful thrust to weight characteristics. Experiments to demonstrate effective containment of simulated fuel particulate and effective transfer of heat from simulated fuel particulate cloud to flowing hydrogen are needed. Closed-cycle concept avoids fuel loss problem but requires development of adequate transparent wall material and effective coupling of radiation heat transfer between hot reactant gas and hydrogen propellant. Open-cycle fuel loss must be limited to less than one percent of the total flow.	Demonstrate effective solutions to technical challenges in simulated non-nuclear laboratory environment. Demonstrate breadboard system in non-nuclear environment. Demonstrate breadboard cavity reactor with sustained fissioning gas core. Demonstrate breadboard propulsion system driven with fissioning gas core. Perform testing and validation of engine technology.
2.3.6.2 Fission Fragment		
In a fission fragment engine, the thrust results from the expulsion of high velocity (~5% light speed) nuclear fission fragments produced from a high power nuclear reactor through a magnetic nozzle. Several concepts have been proposed to directly use this fission energy as part of an extremely high specific impulse rocket engine (I_{sp} ~50,000+ secs). In one concept, thin wires of a fissionable material are brought into a critical state and the fission fragments collected as they exit the wire. A somewhat similar concept utilizes uranium foils wherein the fission fragments are collected as they exit the foil. A third concept recently proposed uses a "dusty" plasma core wherein the uranium dust particles are suspended in a container and brought into a critical state. A magnetic field is used to contain the fuel and at the same time extract the thrust producing fission fragments.	The first challenge is to perform more detailed system studies to better understand the system-level technologies required for this approach to be viable. Because the fission fragments are very highly charged, they have a very short mean free path in most materials. As such, they are very difficult to collect before they interact with their surroundings, and thus lose their energy before they can be expelled through a nozzle. In addition, their extremely high energy requires extremely high magnetic fields in order to direct them out of the nozzle to produce useful thrust.	Develop and test concept to show that large portion of fission fragments are directed before interacting with surroundings. Demonstrate critical reactor configuration. Develop and demonstrate magnetic field configuration to maximize thrust.
2.3.6.3 External Pulsed Plasma Propulsion (EPPP)		
EPPP was first studied in 1950s and early-1960s for ARPA and then NASA. Known as Project Orion, the system employed small nuclear bombs to provide thrust via a large pusher plate at the rear of the spacecraft. More advanced versions of EPPP have been considered since then involving fissile fuel pellets compressed via laser or particle beams, and other concepts involving combined fission and fusion reactions. EPPP can achieve both high average accelerations (1–2 g) and high I_{sp} (~10,000–100,000 s), making it well suited for rapid interplanetary spaceflight.	Some recent ideas have pointed to approaches that could mitigate nuclear proliferation and radiation issues.	Develop practical concept that relies on decoupling of initiator/driver mechanism (e.g., laser, plasma guns) from fissile/fusionable fuel/propellant. Develop accurate computational analyses and proof-of-principle demonstrations to assess operation of key processes (e.g., driver, fuel/driver material interaction, fuel energy release/thermalization process and thrust production). Demonstration of integrated subscale system operation in secure facilities, leading to TRL 6.

2.3 Advanced (TRL <3) Propulsion Technologies		
Description and State of the Art	**Technical Challenges**	**TRL Maturation**
2.3.7 Breakthrough Propulsion		
Breakthrough Propulsion Physics is specifically looking for propulsion breakthroughs from physics. It is not looking for further technological refinements of existing methods. It is an area of fundamental scientific research that seeks to explore and develop a deeper understanding of the nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomenon with the pinnacle objective of developing advanced propulsion applications and systems that will revolutionize how we explore space. Past research efforts have yielded a number of publications in peer-reviewed literature detailing applied theoretical models and laboratory investigation results/conclusions. Fundamental scientific research in this area is a high risk/high payoff venture. Individual investigations may yield good science, but not always result in a propulsion physics breakthrough.	Challenges in this area are to develop theoretical models and high fidelity laboratory experiments for model verification /validation (coupling of gravity & electromagnetism, vacuum fluctuation energy, warp drives & wormholes, & superluminal quantum effects).	A small sustained investment is needed to identify & support affordable, near-term, & credible research that will make incremental progress toward these propulsion goals. Prioritizing and pursuing focused research to: (1) establish if an idea has propulsion applications, (2) investigate if the effect of interest can be observed in the laboratory, & (3) begin engineering breadboard development to produce the desired effect in a manner useful for spaceflight applications. Once a concept has progressed through these wickets, it should be ready to migrate beyond the TRL 3 level and could be recategorized as a game-changing technology.

2.4. Supporting Technologies

Supporting Technologies are those technologies that support an in-space propulsion system or subsystem but which are not directly propulsive. The supporting technology areas given significant consideration by the ISPSTA team included pervasive technologies (Integrated System Health Management, Materials and Structures, Heat Rejection and Power) and cryogenic fluid management (CFM) for propellants. For the pervasive technologies, technology gaps for propulsion application are identified in the preceding sections, embedded in the text of the individual propulsion technology supported. In each case, the technologies are directly or significantly addressed by the following TAs respectively: Robotics, Tele-robotics, and Autonomous Systems; Materials, Structures/Mechanical Systems, and Manufacturing; Thermal Management Systems; and Space Power and Energy Storage Systems. For cryogenic fluid management and transfer, the thermal control components are addressed in detail by the Thermal Management Systems TA, whereas micro-gravity fluid dynamics and the integration of the thermal control and fluid management technologies are covered within this road map. There is also a need for future propulsion systems to be more serviceable/maintainable as system life and reuse increase, and those requirements have been treated as embedded in the individual technologies rather than a separate supporting technology area.



2.4 Supporting Technologies		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.4.1 Engine Health Monitoring and Safety		
Integrated System Health Management (ISHM) as applied to propulsion relies on the automation of interpretation, reasoning, and decision making based on data collected during the processing and operation of propulsion system to enable the following basic functionality: anomaly detection, diagnostics, prediction of future anomalies (Prognostics), and enabling intuitive and rapid integrated awareness about configuration and condition of every element in a system. Only a few health management systems have been implemented in operational mode; all are considered to provide low functional capability, and do not truly represent knowledge systems. The Space Shuttle Main Engine Advanced Health Management System (AHMS) monitors a selected number of engine sensors, detects threshold violations based on experimental models, and can activate redline conditions. See TA04 road map for more details.		

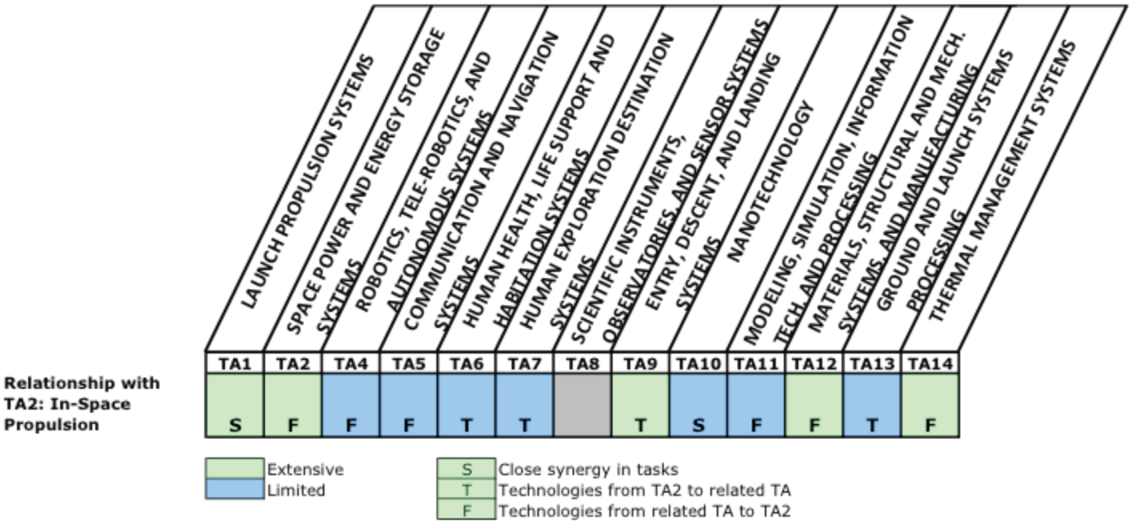
2.4 Supporting Technologies		
Description and State of the Art	**Technical Challenges**	**Milestones to TRL 6**
2.4.2 Propellant Storage, Transfer & Gauging		
Cryogenic Fluid Management (CFM) broadly describes the suite of technologies that can be used to enable the efficient in-space use of cryogens despite their propensity to absorb environmental heat, their complex thermodynamic and fluid dynamic behavior in low gravity and the uncertainty of the position of the liquid-vapor interface since the propellants are not settled. In addition to propulsion, this technology can support power reactant storage and ECLSS needs. The State of the Art is defined by commercial upper stages with a capability of up to 9 hours in space (propellant boil-off rates on the order of 30%/day) and which require propellant settling (via thruster firing to accelerate the vehicle) before performing critical functions. Many of the CFM technology elements have been matured to a TRL of near 5 through ground testing.	Enable long duration (months to years) duration in space missions with cryogens and efficient in-space transfer of propellants for tanker or depot architectures. Specific challenges to be addressed by in space demonstration before reaching TRL 6 include: - Safe and efficient venting of unsettled propellant tanks - Zero boil-off (ZBO) storage of cryogenic propellants for long duration missions -Accurate micro-g propellant gauging and fluid acquisition -Automated cryogenic fluid couplings & propellant transfer -Performance issues due to integration of components	1) Conduct ground tests in representative thermal vacuum environments of high fidelity CFM components (partial crossover with TA14 Thermal Management) and systems 3) Complete short duration cryogenic flight experiment(s) to obtain data to mature models of critical fluid/thermal physics. 4) Conduct CFM flight demonstration - Demonstrate in space long duration (>6 months) storage of LO_2 (ZBO) and LH_2 (<0.5% loss/month). Demonstrate low loss in-space transfer of LO_2 and LH_2 including automated fluid couplers. Demonstrate microgravity venting, liquid acquisition, and quantity gauging of LO_2 and LH_2. (note that methane is stored at similar temperature to LO_2 and therefore can use similar technology).
2.4.3 Materials & Manufacturing Technologies		
Structures and materials play a critical role in all in-space propulsion systems for both human and robotic missions. The reader is referred to the Technology Area 12, Materials, Structures Mechanical Systems and Manufacturing technology, road map for a State of the Art description and specific technology development recommendations. In some cases, material, structural, or manufacturing advances are required to enable propulsion technology advances, in other cases the structural/material advances are enhancing, in still others (for example composite tanks) advancements can result in a significant propulsion system improvement of their own. In general in-space propulsion desires reduced cost, lighter weight, wider operating temperatures, and robustness against in-space and propulsion system environmental conditions.		
2.4.4 Heat Rejection		
Heat rejection is a key supporting capability for several in space propulsion systems. Some examples include rejection of the waste heat generated due to inefficiencies in electric propulsion devices and rejection of the heat removed from a cryogenic propellant storage system by a cryocooler. The reader is referred to the Technology Area 14, Thermal Management Systems technology, road map for a State of the Art description and specific technology development recommendations. In general the key heat rejection system metrics for in-space propulsion are cost, weight, operating temperature, and environmental durability (e.g. radiation, MMOD).		
2.4.5 Power		
Power systems play an integral role in all in-space propulsion systems for both human and robotic missions. The reader is referred to the Technology Area 3, Space Power and Energy Storage Systems technology, roadmap for state-of-the-art description & specific technology development recommendations. In some cases, power is only required for basic functions of instrumentation and controls and technology advances are not required, but in other cases the propulsion energy of the technology is derived from electrical power generation, management and distribution, & power system technology advances are critical for the advancement of the propulsion system (e.g., high power solar or nuclear electric propulsion). In general the key power system metrics for in-space propulsion are cost, reliability, specific power, operating ranges (power and environmental), & maximum power generation.		

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

The ISPSTA team evaluated the technical content of the other fourteen technology area road maps for relationships with the content of the ISPSTA roadmap. In completing this evaluation, three types of interdependencies were identified in which either ISPSTA technology development was related to technology development in another road map, as illustrated in table below. In some cases, propulsion technology development is planned in both road maps and close synergies could were identified. In other cases, ISPSTA technology development depends on successful technology development in another TA. For example, solar power array and power management technologies are developed by the Space Power and Energy Storage road map to support high power solar electric propulsion. In the third type of dependency, another TA road map is supported by technology developed by ISPSTA. An example of this case is development of throttleable cryogenic propulsion in the IPSTA road map supporting the Entry, Descent and Landing TA road map. For all three types of relationships, significant benefit will be realized through coordination of the implementing technology development projects.

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

More capable and efficient in-space propulsion will benefit NASA, national defense, and the



commercial space industry – virtually any organization that builds or uses space satellites. Specific technologies with multi-user applicability include: Metalized Propellants for higher performance and safer missile systems; Long-Duration Cryogenic Propulsion for high-energy orbit transfer; Electric Propulsion for longer-life communications and Earth observing satellites; Solar Sails for sustained observation of the Earth's polar regions; research toward Nuclear Thermal Propulsion will lead to smaller and more efficient reactor designs; Tethers will enable lower-cost access to space and orbit transfer; and the development of new technologies from robust research and technology development will enable new missions and applications for all potential users.

ACRONYMS

AHMS	Advanced Health Management System
AMPM	Agency Mission Planning Model
ARC	Ames Research Center
ATP	Authority to Proceed
CFM	Cryogenic Fluid Management
CIF3	Chlorine Trifluoride
CIF5	Chlorine Pentafluoride
DRM	Design Reference Mission
ECLS	Environmental Control and Life Support
ECR	Electron Cyclotron Resonance
EDT	Electrodynamic Tether
EHS	Environmental Health System
GRC	Glenn Research Center
GTO	Geosta¬tionary Transfer Orbit
HEDM	High Energy Density Materials
HmNT	Hydrazine milli-Newton Thruster
HTPB	Hydroxyl-Terminated Polybutadiene
ICRH	Ion Cyclotron Resonant Heating
IKAROS	Interplanetary Kite-Craft Accelerated by Radiation Of the Sun
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
ITOC	Ion Thruster On a Chip
JAXA	Japanese Aerospace Exploration Agency
JSC	Johnson Space Center
KSC	Kennedy Space Center
LST	Life Support Technologies
MET	Momentum Exchange Tether
MMOD	Micro-Meteoroid/Orbital Debris
MPD	Magnetoplasmadynamic
MMH	Monomethylhydrazine
MSFC	Marshall Space Flight Center
NERVA	Nuclear Engine for Rocket Vehicle Applications
OF2	Oxygen Difluoride
PIT	Pulsed Inductive Thruster
PPUs	Power Processing Units
ProSEDS	Propulsive Small Expendable Deployer System
RCS	Reaction Control System
SDI	Strategic Defense Initiative
SOA	Hydrazine
TRL	Technology Readiness Level
TSS-1	Tether In Space
VASIMR	Variable Specific Impulse Magnetoplasma Rocket
VAT	Vacuum Arc Thruster
ZBO	Zero Boil-Off

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