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TECHNOLOGY AREA ROADMAP FOR IN-SPACE PROPULSION TECHNOLOGIES

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ABSTRACT

NASA's Office of Chief Technologist assembled fifteen civil service teams to support the creation of a NASA integrated technology roadmap. The Aero-Space Technology Area Roadmap is an integrated set of technology area roadmaps recommending the overall technology investment strategy and prioritization for NASA's technology programs. The integrated set of roadmaps will provide technology paths needed to meet NASA's strategic goals. This roadmap was drafted by a team of subject matter experts from within the Agency and then independently evaluated, integrated and prioritized by a National Research Council (NRC) panel.

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

1. INTRODUCTION

In-space propulsion systems perform 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.

For exploration and science missions, increased efficiencies of future propulsion systems are critical to reduce overall life-cycle costs and, in some cases, enable missions previously considered impossible. Continued reliance on conventional chemical propulsion alone will not enable the robust exploration of deep space – the maximum theoretical efficiencies have almost been reached and they are insufficient to meet needs for many ambitous science missions currently being considered.

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 Isp. 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.

There is no single propulsion technology that will benefit all missions or mission types. The requirements for in-space propulsion vary widely depending upon the intended application [1 – 2]. The technologies described herein will support everything from small satellites and robotic deep space exploration to space stations and human missions to Mars and beyond.

2. GENERAL OVERVIEW

2.1 Technical Area Breakdown Structure

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 within a 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.

The technical area breakdown structure (TABS), shown in Figure 1, organizes credible in-space propulsion concepts 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.

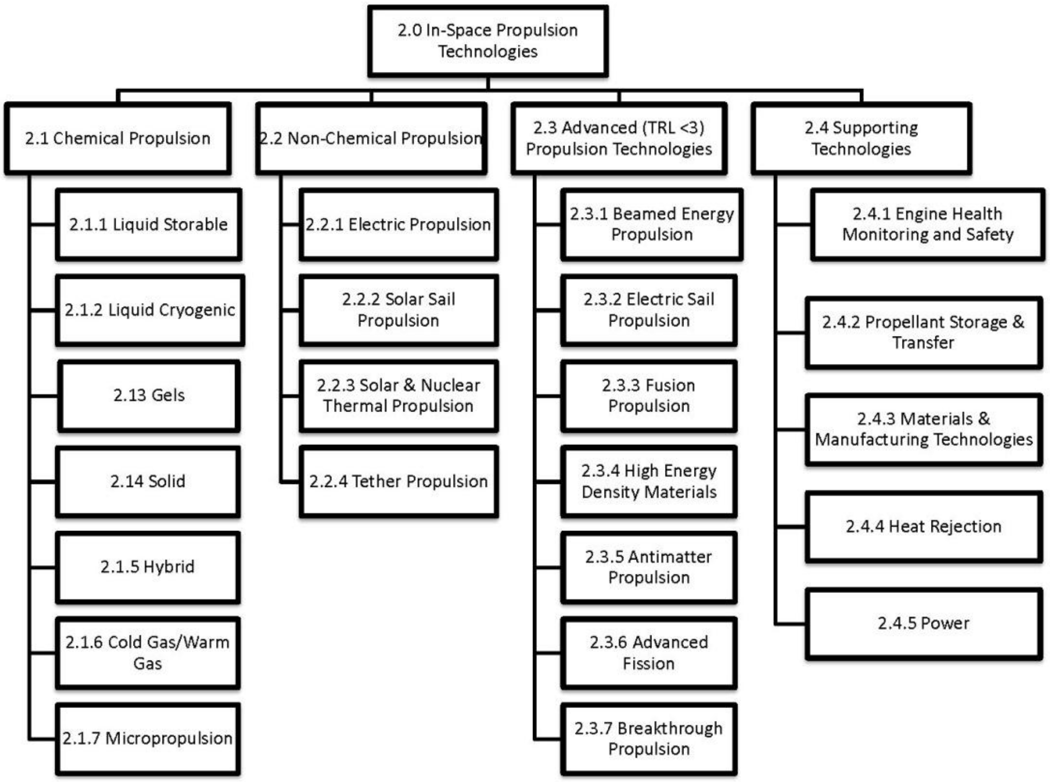

Fig. 1: Technology Area Breakdown Structure for In-Space Propulsion Technologies.

2.2 Benefits

In-space propulsion is a category of technology where developments can benefit a number of critical figures of merit for space exploration. Space exploration is about getting somewhere safely (mission enabling), getting there quickly (reduced transit times), getting a lot of mass there (increased payload mass), and getting there cheaply (lower cost).

Development of new in-space propulsion technologies will result in technical solutions with improvements in thrust levels, Isp, power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, durability, and of course, cost. In some instances, development of new technologies will result in mission-enabling breakthroughs that will revolutionize space exploration.

3. PRIORITIZING THE TOP PROPULSION CHALLENGES

The top ten technical challenges for in-space propulsion systems were identified and prioritized by NASA based on perceived mission need or potential impact on future in-space transportation systems and can be found in Table 1. 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 Technology Readiness Level (TRL) 6 is expected to be achieved. NASA's TRL is measure of a technology's relative maturity. A

TRL 1 technology is one in which the basic principles have been observed and reported; TRL 6 is typically a system level demonstration conducted on the ground; TRL 9 technologies have been successfully used in space [3]. It is likely that support of these technologies would need to begin well before the listed time horizon.

Table 1: The recommended "Top 10" in-space propulsion technologies as defined by the NASA team prior to NRC review.

Rank	Description	Need Timeframe
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems	present to 2016
2	Long-term in-space cryogenic propellant storage and transfer	2017–2022
3	High power (e.g. 50–300 kW) class Solar Electric Propulsion scalable to mega-watt (MW) class Nuclear Electric Propulsion	2017–2022
4	Advanced in-space cryogenic engines and supporting components	2017–2022
5	Developing and demonstrating micro-electro-mechanical systems (MEMS) fabricated electrospray thrusters	present to 2016
6	Demonstrating large (over 1000 m^2) solar sail equipped vehicle in space	present to 2016
7	Nuclear Thermal Propulsion (NTP) components and systems	2023–2028
8	Advanced space storable propellants	2017–2022
9	Long-life (>1 year) electrodynamic tether propulsion system in low earth orbit (LEO)	present to 2016
10	Advanced In-Space Propulsion Technologies (TRL <3) to enable a robust technology portfolio for future missions.	2023–2028

TRL 6 readiness dates were determined by considering stated mission need dates (technology “pull”), 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.

Once the Top Technical Challenges were identified, the NRC panel then moved on to prioritization of specific technologies. A quality function deployment (QFD) process was used to rank the technologies, and the panel verified that the results were consistent with the Top Technical Challenges they had previously identified. The NRC report identified four technologies from the In-Space Propulsion Systems technology roadmap as “high priority” and that were supportive of the four Top Technical Challenges [4]. In priority order, these were:

3.1 Electric Propulsion

Development phased by power is recommended beginning with high power solar electric propulsion (SEP) (~100 kW to ~ 1 MW) and continuing toward an ultimate goal of multimegawatt nuclear electric propulsion (NEP) capability. These high power SEP and NEP systems can enable larger scale, faster, or more efficient space transportation systems.

3.2 Long-term in-space propellant storage and transfer

The NRC identified cryogenic propellant storage and transfer as a technology at the “tipping point”. In other words, investment in this technology can quickly move it into position for infusion into flight development of in-space transportation elements. “Propellant storage and transfer is a game changing technology for a wide range of applications because it enables long-duration, high-thrust, high-ΔV missions for large payloads and crew and can be implemented within the next 3 decades.”).

3.3 Nuclear Thermal Propulsion

Nuclear Thermal Rockets are a high thrust, high Isp propulsion technology. The state of the art ground demonstrated engine, Nuclear Engine for Rocket Vehicle Applications (NERVA) demonstrated thrusts (in the 1970s) comparable to chemical propulsion (7,500 to 250,000 lbf of thrust with specific impulses of 800 to 900 seconds, double that of chemical rockets). “Critical NTR technologies include the nuclear fuel, reactor and system controls, and long-life hydrogen pumps, and technology development will also require advances in ground test capabilities, as the open-air approach previously used is no longer environmentally acceptable.”

3.4 Micropropulsion Systems

Micropropulsion addresses the needs of both micro-satellites and precision pointing and positioning for certain NASA Science Mission Directorate missions. Micropropulsion encompasses the development of miniaturized versions of chemical and non-chemical propulsion systems.

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

4. CONCLUSIONS

As part of a NASA Office of the Chief Technologist effort to develop an integrated set of Space Technology roadmaps, a draft In-Space Propulsion Systems Technology Area roadmap was developed. This draft was provided to the NRC for evaluation and for prioritization of the technologies. This paper provides a summary of that roadmap document prior to the incorporation of the input from the NRC. The NRC report identified four Top Technical Challenges for the In-Space Propulsion Systems technology roadmap as "high priority": High-Power Electric Propulsion Systems; Cryogenic Storage and Transfer; Microsatellites; and Rapid Crew Transit. The key technologies In-Space Propulsion Systems Technology Area roadmap team to support the NRC Top Technical Challenges include: Electric Propulsion; Propellant Storage and Transfer; (Nuclear) Thermal Propulsion, and Micropropulsion. The integrated roadmaps will be valuable for the Agency going forward providing NASA with strategic guidance and recommendations that inform the investment decisions of NASA's space technology activities.

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[3] Matloff, G., L., Johnson, L., and Bangs, C., Living off the Land in Space: Green Roads to the Cosmos, pp. 105 – 117, Copernicus Books, New York, New York, USA, 2007.

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Technology Area Roadmap for In Space Propulsion Technologies

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“We're all pilgrims on the same journey - but some pilgrims have better road maps.”
- Nelson DeMille

Technology Area Overview

- For both human and robotic exploration, traversing the solar system is a struggle against time and distance.
- ***Advanced In-Space Propulsion technologies will enable much more effective exploration of our Solar System.***
  - Mission designers will be able to plan missions to "fly anytime, anywhere and complete a host of science objectives at the destinations" with greater reliability and safety and, potentially, deliver much more payload to its desired destination.
- There is no "one size fits all" in-space propulsion system that will satisfy the needs of all future missions.
  - A portfolio of technologies should be developed so as to allow optimum propulsion solutions for a diverse set of missions and destinations.

This roadmap describes the portfolio of in-space propulsion technologies that can meet future space science and exploration needs.

Benefits

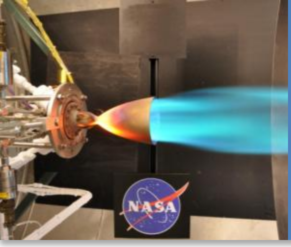
- Development of technologies within this TA will result in technical solutions with improvements in thrust levels, specific impulse, power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability and durability.
- These types of improvements will
  - Yield decreased transit times
  - Increased payload mass
  - Decreased costs
  - Enable missions to new science/exploration targets
  - Provides a potential propulsion breakthrough that will revolutionize space exploration.

Traceability to NASA Strategic Goals

- The In-Space Propulsion Roadmap team used the NASA strategic goals and missions detailed in the following reference materials in the development of the roadmap:
  - Human Exploration Framework Team products to extract reference missions with dates
  - SMD Decadal Surveys
  - Past Design Reference Missions, Design Reference Architectures, and historical mission studies
  - In-Space Propulsion Technology Program concept studies
  - Internal ISS utilization studies.

Technology Area Breakdown Structure

- 2.0 In-Space Propulsion Technologies
  - 2.1 Chemical Propulsion
    - 2.1.1 Liquid Storable
    - 2.1.2 Liquid Cryogenic
    - 2.1.3 Gels
    - 2.1.4 Solid
    - 2.1.5 Hybrid
    - 2.1.6 Cold Gas/Warm Gas
    - 2.1.7 Micropropulsion
  - 2.2 Non-Chemical Propulsion
    - 2.2.1 Electric Propulsion
    - 2.2.2 Solar Sail Propulsion
    - 2.2.3 Thermal Propulsion
    - 2.2.4 Tether Propulsion
  - 2.3 Advanced (TRL <3) Propulsion Technologies
    - 2.3.1 Beamed Energy Propulsion
    - 2.3.2 Electric Sail Propulsion
    - 2.3.3 Fusion Propulsion
    - 2.3.4 High Energy Density Materials
    - 2.3.5 Antimatter Propulsion
    - 2.3.6 Advanced Fission
    - 2.3.7 Breakthrough Propulsion
  - 2.4 Supporting Technologies
    - 2.4.1 Engine health monitoring and safety
    - 2.4.2 Propellant Storage & Transfer
    - 2.4.3 Materials & Manufacturing Technologies
    - 2.4.4 Heat Rejection
    - 2.4.5 Power



2.1 Chemical Propulsion

- Chemical Propulsion involves chemical reaction of propellants to move or control spacecraft.
  - Example technologies include:
    - **Liquids** - rocket systems using mono/bipropellants, high energy oxidizers, cryogenics (LO2/LH2 & LO2/CH4) as propellant.
    - **Gels** - fuels that are thixotropic that provide higher density, reduced sloshing, and leak resistance.
    - **Solids** - fuels that premix oxidizer and fuel and are typically cast formed.
    - **Hybrids** - technology that combines benefits of solids and liquids.
    - **Cold/Warm Gas** - uses expansion of inert cold/warm gas to generate thrust.
    - **Micropropulsion** - subset of above technologies (solids, gas, monopropellants) applied to small/microsatellite applications.

- Applications include primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering.

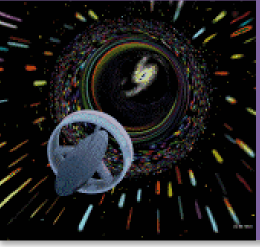
- Technology Development in this area will result in improvements in thrust levels, volume, system mass, system complexity, operational complexity, and commonality with other spacecraft systems.

2.2 Non-chemical Propulsion

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

- Similar to Chemical, applications include primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering.

- Technology Development in this area will result in improvements in thrust levels, specific impulse, power, specific mass (or specific power), and system mass.



2.3 Advanced Propulsion (<TRL3)

- Advanced Propulsion Technologies use chemical or non-chemical physics to produce thrust, but are lower technical maturity (TRL< 3) than those described in 2.1 and 2.2.
  - Example technologies include:
    - **Beamed Energy** - systems that use beamed laser or RF energy from ground source to heat propellant to generate thrust (e.g. lightcraft)
    - **Electric Sail** - system that uses a number of long/thin high voltage wires to interact with solar wind to generate thrust.
    - **Fusion** - systems that use fusion reactions indirectly (fusion power system to drive EP), or directly (fusion reaction provides kinetic energy to reactants used as propellant)
    - **High Energy Density Materials** - materials with extremely high energy densities to greatly increase propellant density and potential energy.
    - **Antimatter** – system that converts large percentage of fuel mass into propulsive energy through annihilation of particle-antiparticle pairs.
    - **Advanced Fission** – enhanced propulsion ideas that utilize fission reactions to provide heat to propellants (and in some cases utilize magnetic nozzles)
    - **Breakthrough Propulsion** – area of fundamental scientific research that seeks to explore and develop deeper understanding of nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomenon with objective of developing advanced propulsion applications.

- Predominant applications are in the area of primary propulsion, but some areas may also be applicable to reaction control, station keeping, precision pointing, and orbital maneuvering.

- Technology Development in this area will result in improvements in thrust levels, specific impulse, power, specific mass (or specific power), volume, system mass.

Interdependency with Other TA

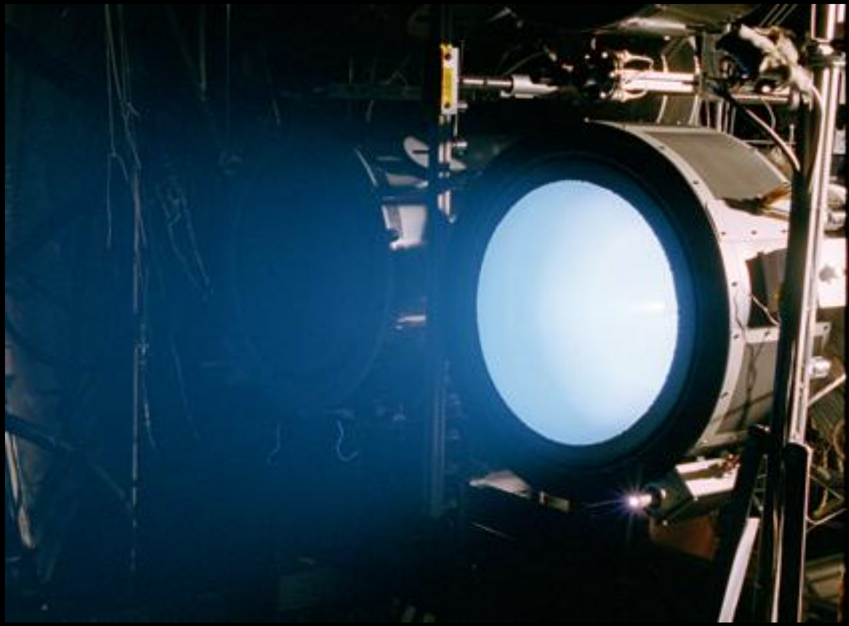
	LAUNCH PROPULSION SYSTEMS	SPACE POWER AND ENERGY STORAGE SYSTEMS	ROBOTICS, TELE-ROBOTICS, AND AUTONOMOUS SYSTEMS	COMMUNICATION AND NAVIGATION SYSTEMS	HUMAN HEALTH, LIFE SUPPORT AND HABITATION SYSTEMS	HUMAN EXPLORATION DESTINATION SYSTEMS	SCIENTIFIC INSTRUMENTS, OBSERVATORIES, AND SENSOR SYSTEMS	ENTRY, 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
	TA1	TA3	TA4	TA5	TA6	TA7	TA8	TA9	TA10	TA11	TA12	TA13	TA14
Relationship with TA2: In-Space Propulsion	S	F	F	F	T	T		T	S	F	F	T	F

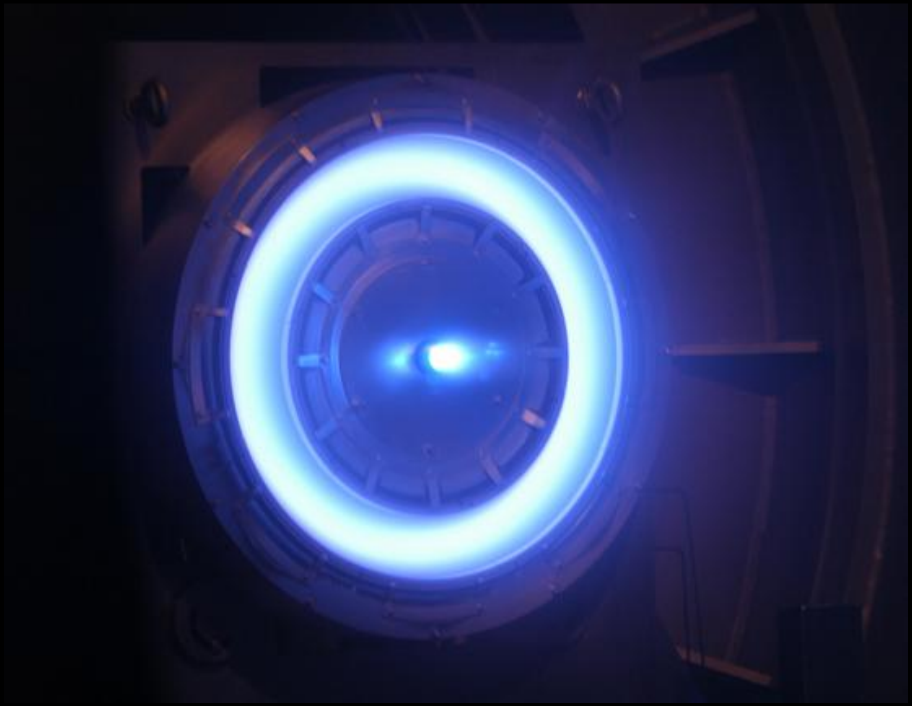
(green)	Extensive
(blue)	Limited

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

- Interdependencies were identified with several other Technology Area road maps
  - The relationships were categorized as synergistic with technologies in another TA (S), dependent on technologies in another TA (F-from), or supporting technologies in another TA (T-to)

#1 Power Processing Units for Ion, Hall and Other Electric Propulsion Systems





Benefit	Alignment	Technical Risk
Enhancing	NASA Objective Non-NASA Needs NASA Capability Aligned	Low Risk Near-Term Need Low Effort

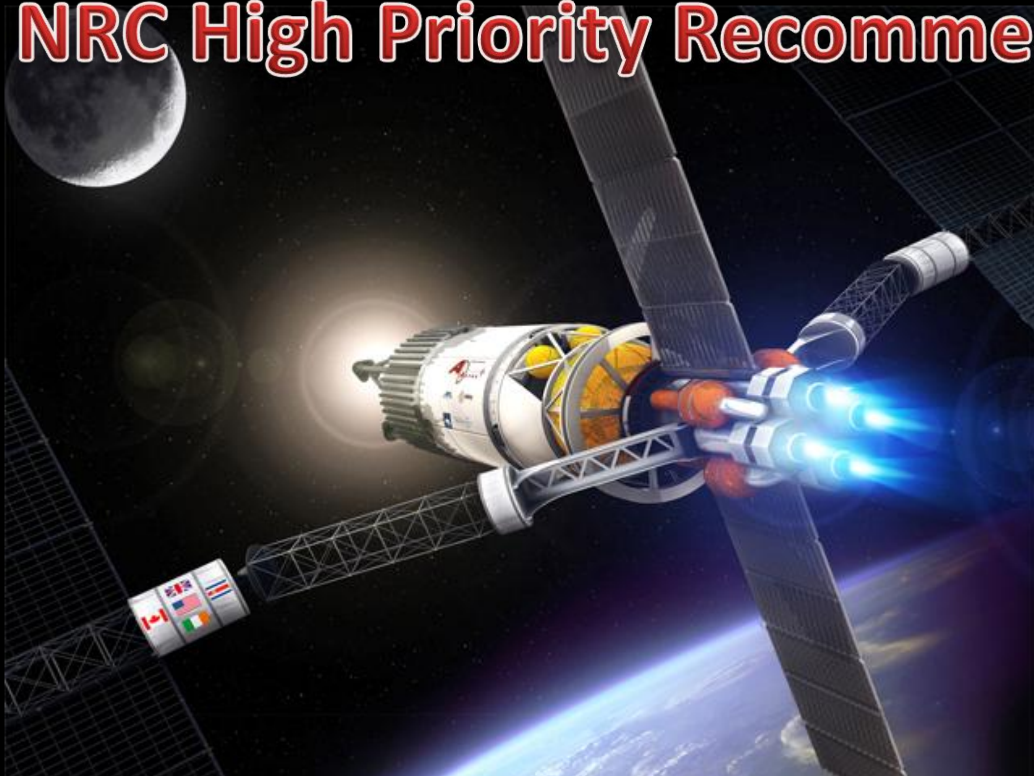
#2 Long-Term Cryogenic Propellant Storage and Transfer

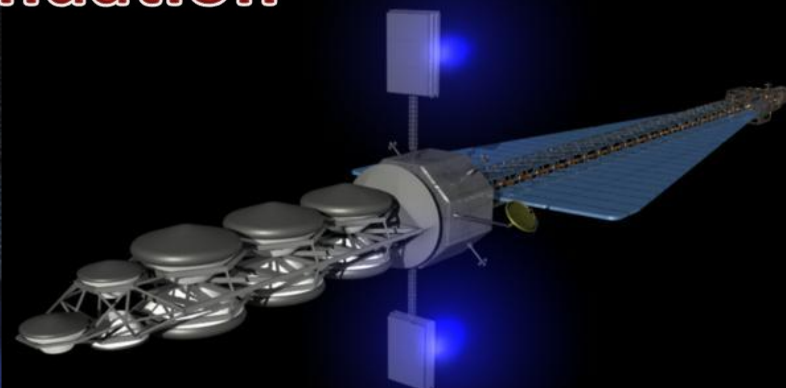
NRC High Priority Recommendation

Benefit	Alignment	Technical Risk
Enabling	NASA Objective NASA Capability Aligned	Medium Risk Mid-Term Need Medium Effort

#3 High Power Solar Electric Propulsion Systems Scaleable to MW-Class Nuclear Electric Propulsion

NRC High Priority Recommendation





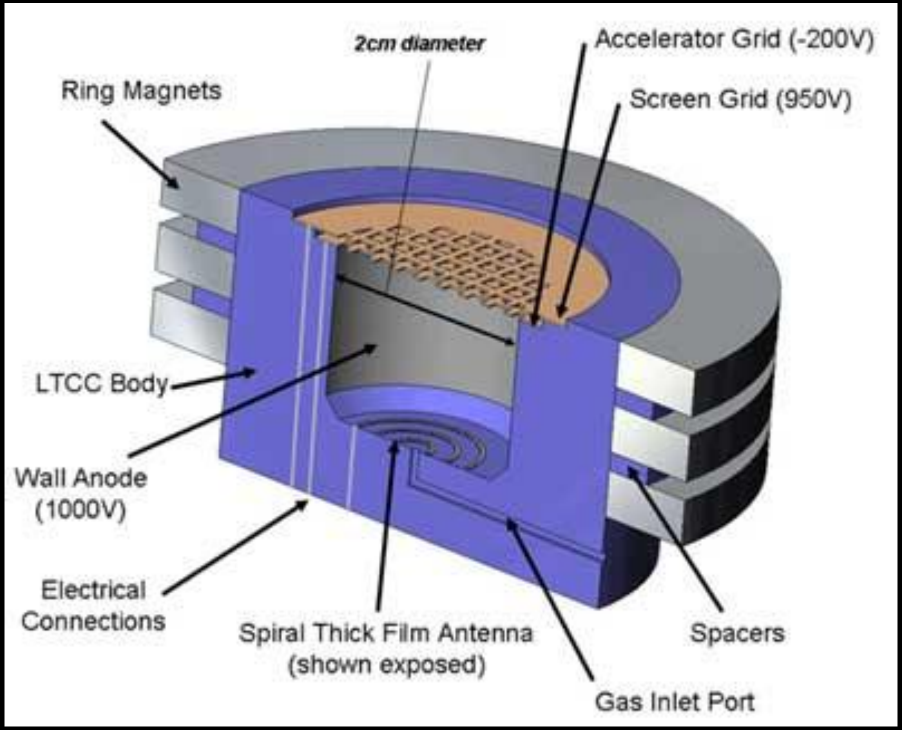
Benefit	Alignment	Technical Risk
Enhancing	NASA Objective NASA Capability Aligned	Medium Risk Mid-Term Need Medium Effort

#4 Advanced In-Space Cryogenic Engines

Benefit	Alignment	Technical Risk
Enhancing Enabling	NASA Objective NASA Capability Aligned	Medium Risk Mid-Term Need Medium Effort

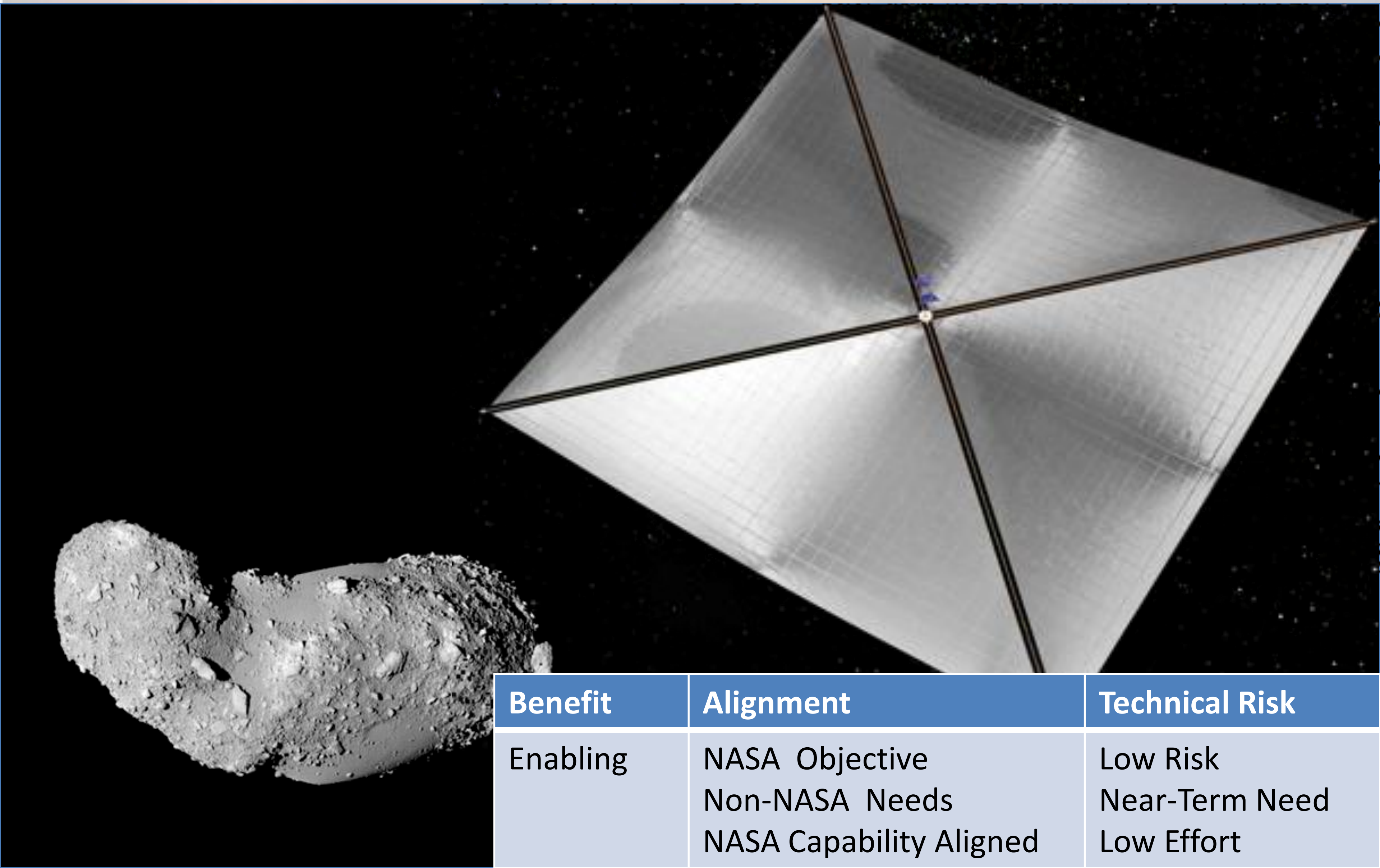
#5 Developing and Demonstrating MEMS-Fabricated Micropropulsion Thrusters

NRC High Priority Recommendation



Benefit	Alignment	Technical Risk
Enabling	NASA Objective Non-NASA Needs NASA Capability Aligned	Medium Risk Near-Term Need Low Effort

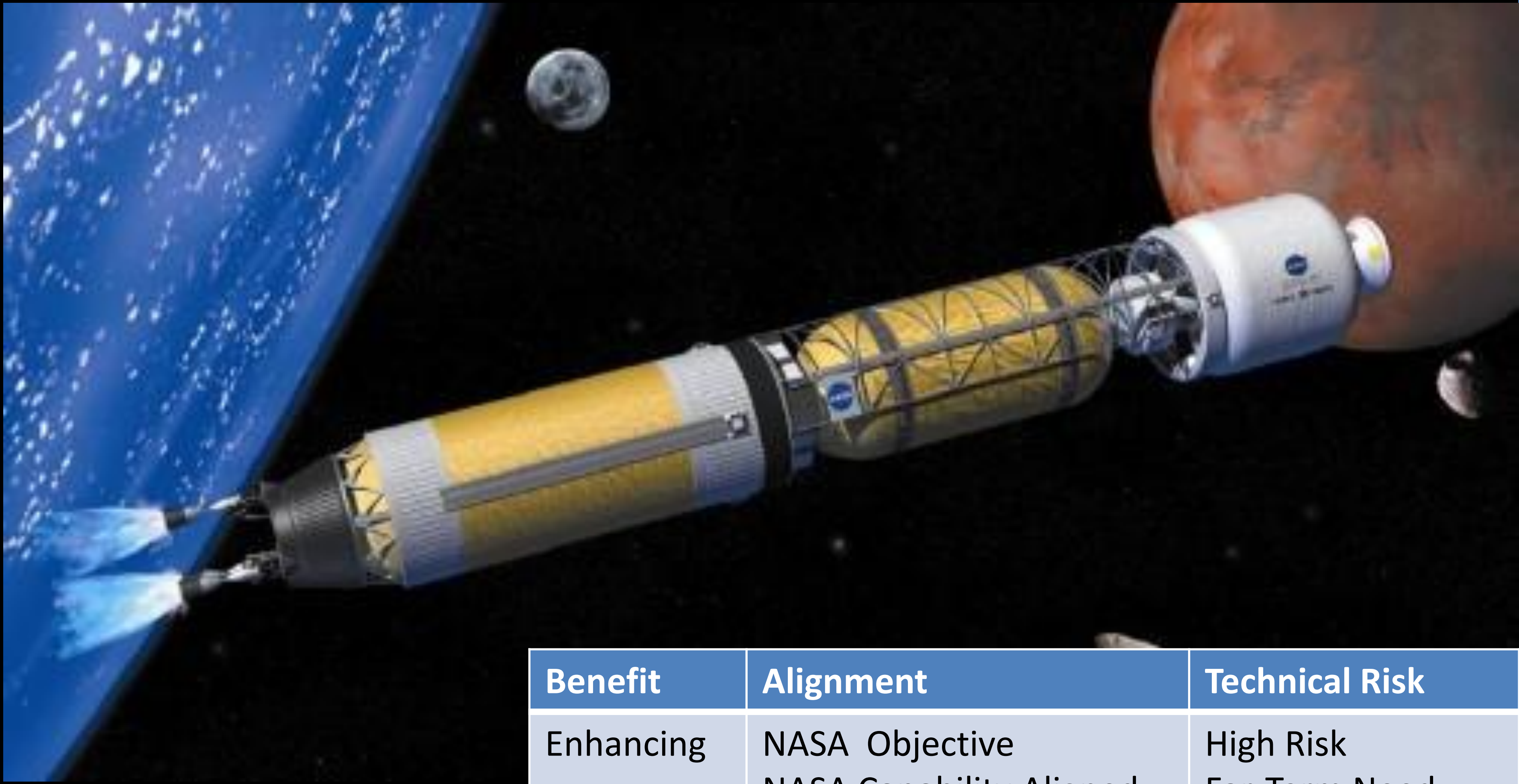
#6 Demonstrate Large Solar Sail In-Space



Benefit	Alignment	Technical Risk
Enabling	NASA Objective Non-NASA Needs NASA Capability Aligned	Low Risk Near-Term Need Low Effort

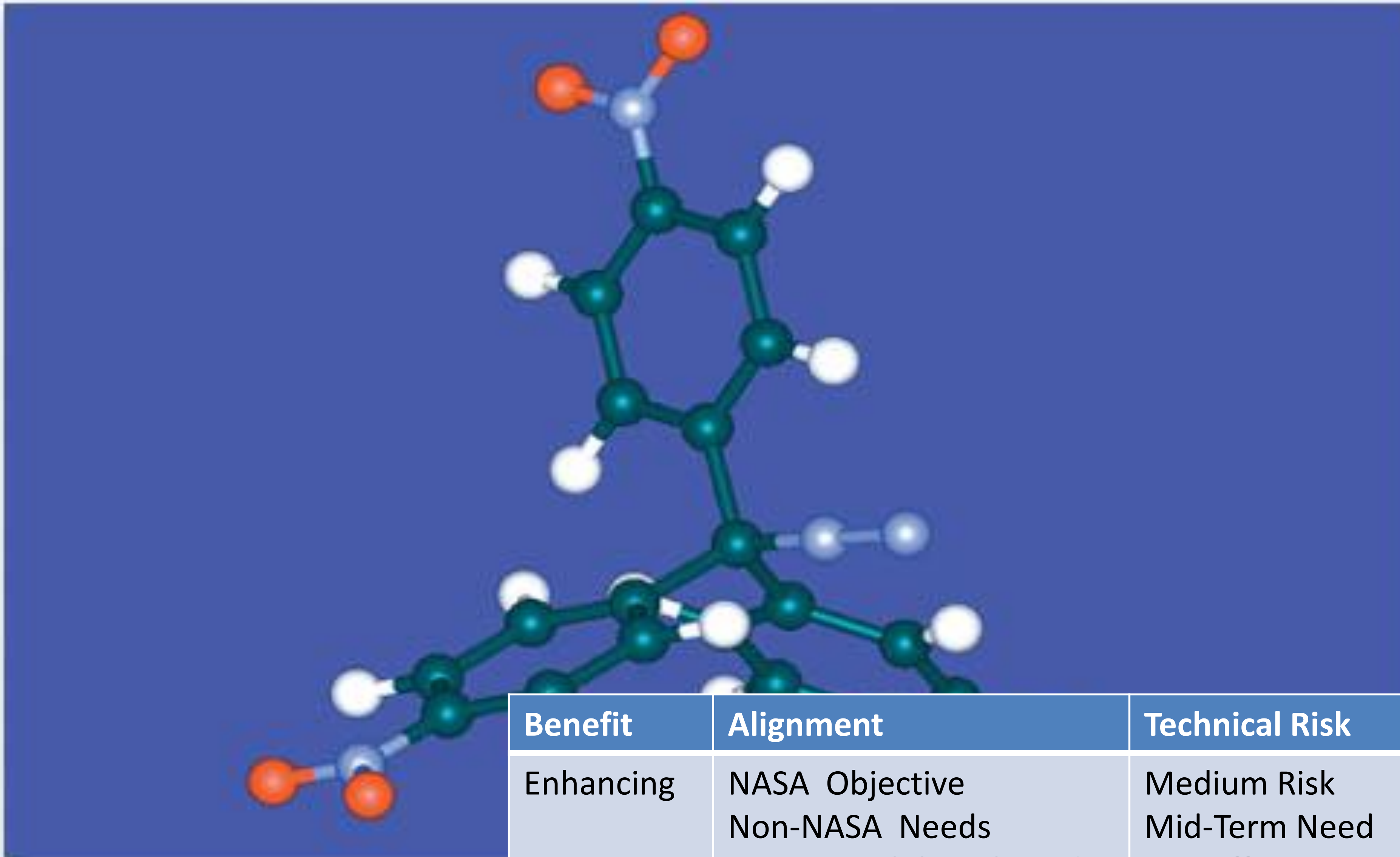
#7 Nuclear Thermal Propulsion Components and Systems

NRC High Priority Recommendation



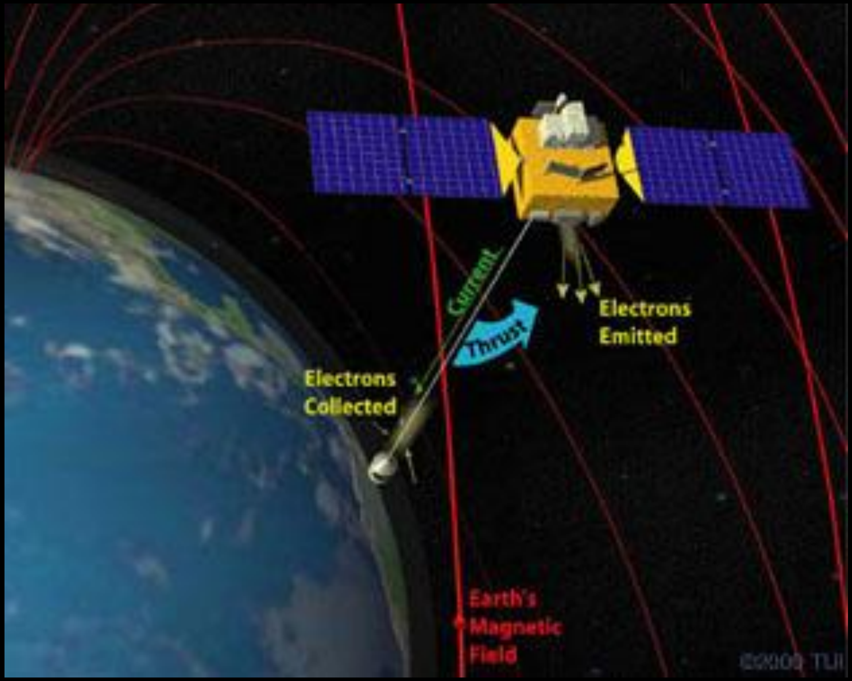
Benefit	Alignment	Technical Risk
Enhancing	NASA Objective NASA Capability Aligned	High Risk Far-Term Need High Effort

#8 Advanced High-Performance Space Storable Propellants



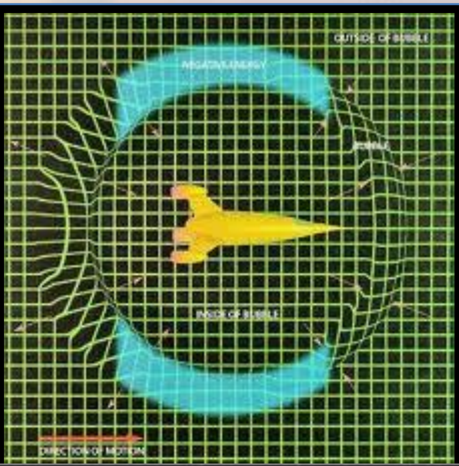
Benefit	Alignment	Technical Risk
Enhancing	NASA Objective Non-NASA Needs NASA Capability Aligned	Medium Risk Mid-Term Need Low Effort

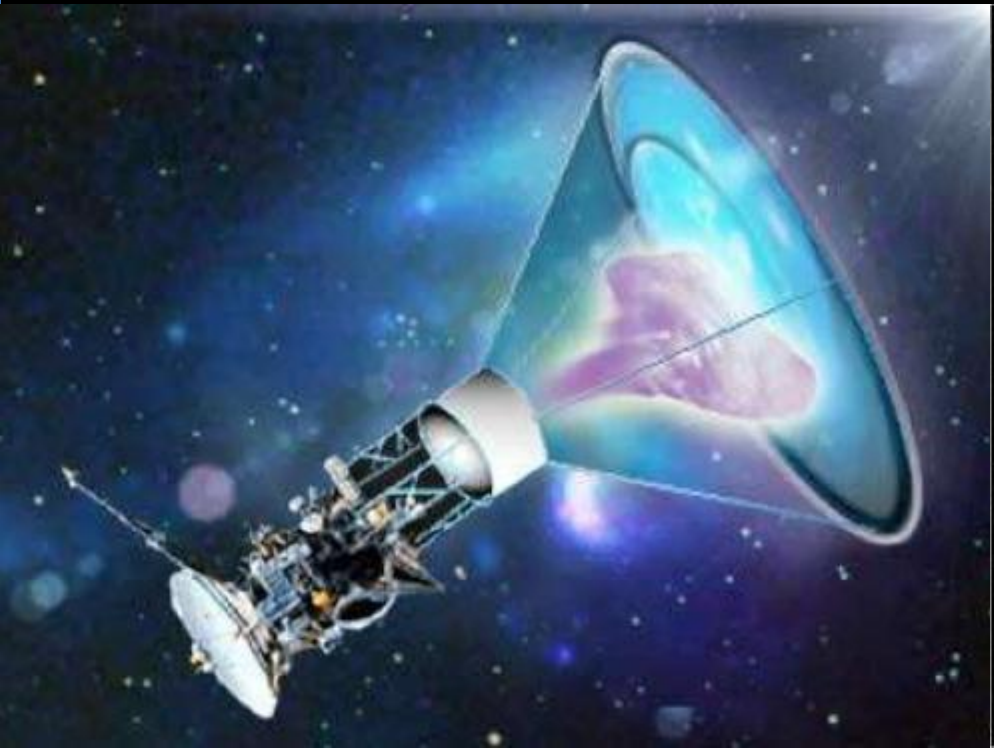
#9 Long Life Electrodynamic Tether Propulsion System in LEO

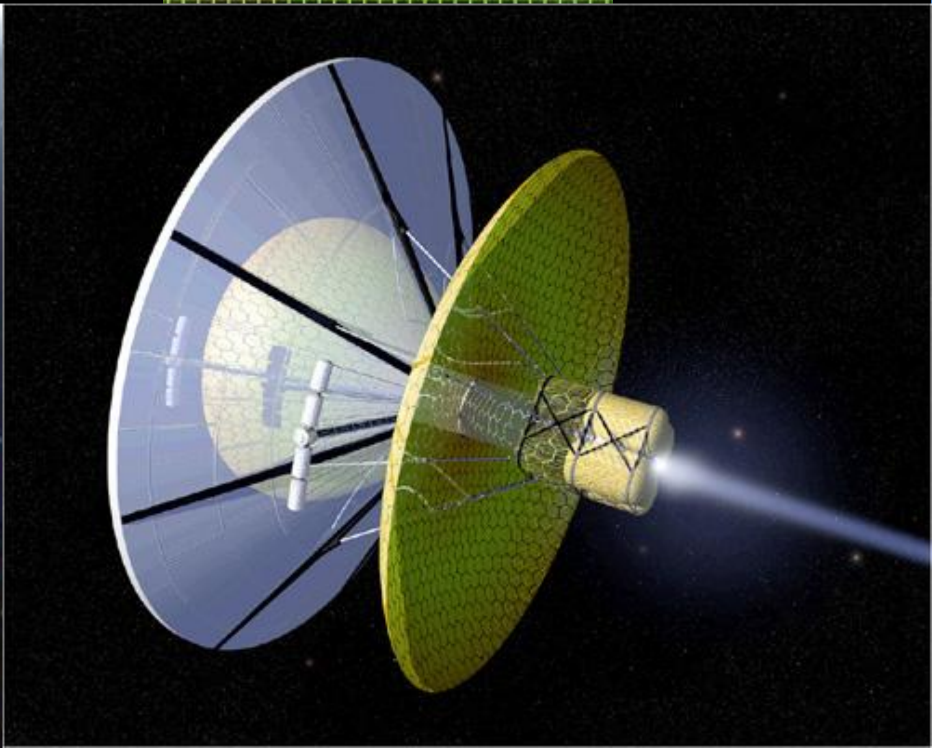


Benefit	Alignment	Technical Risk
Enabling	NASA Objective Non-NASA Needs NASA Capability Aligned	Low Risk Near-Term Need Low Effort

#10 Advanced Technologies To Enable A Robust Technology Portfolio for Future Missions







Top Technical Challenges

Rank	Description	Time
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 scaleabe to MW-class Nuclear Electric Systems	M
4	Advanced in-space cryogenic engines and supporting components	M
5	Developing and demonstrating MEMS-fabricated micropropulsion thrusters	N
6	Demonstrating large (over 1000 m^2) solar sail equipped vehicle on-orbit	N
7	Nuclear Thermal Propulsion (NTP) components and systems	F
8	Advanced, high performance, 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

N – near (present to 2016), M – mid (2017-2022), F – far (2023-2028)

(Timeframe for maturation to TRL 6)