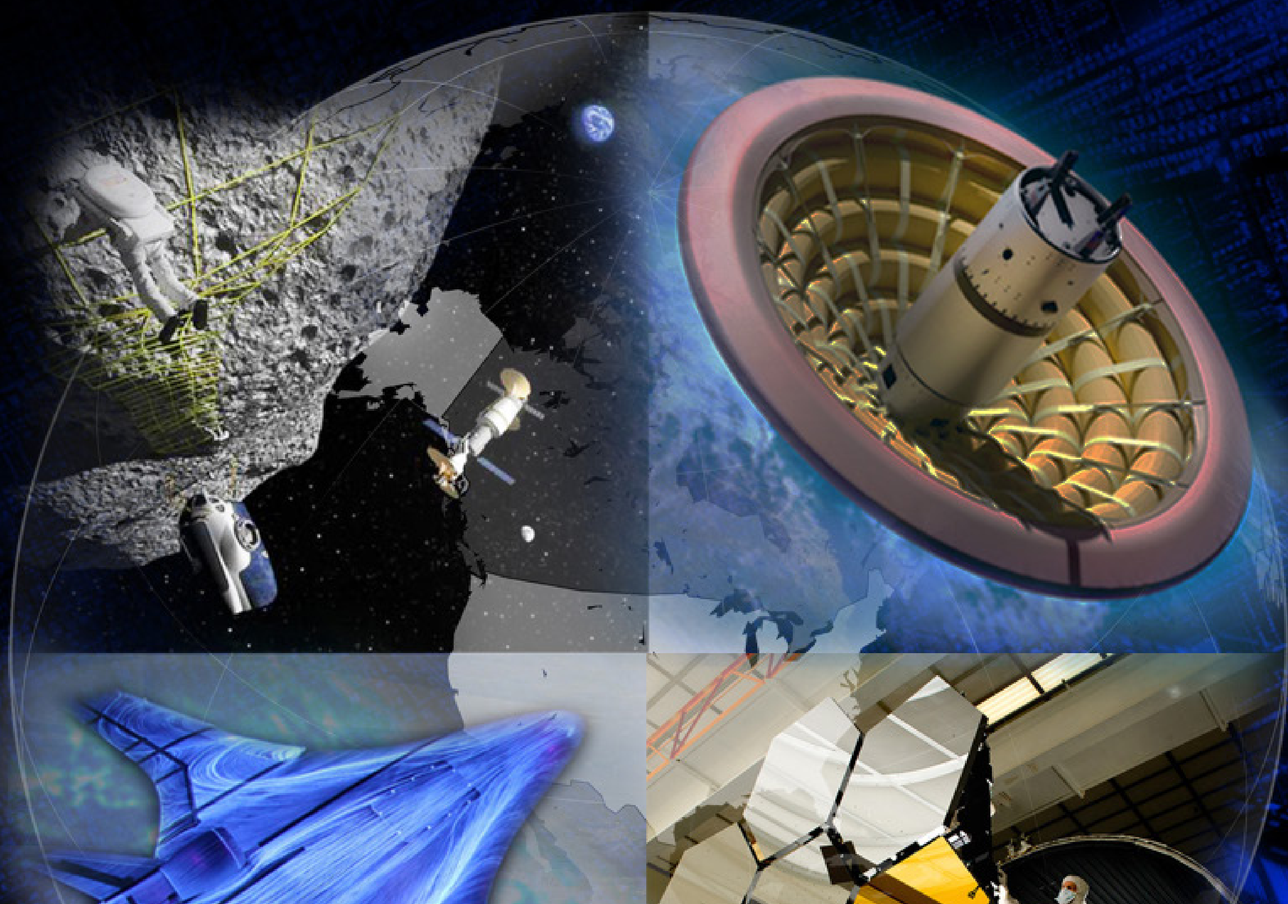
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 10: Nanotechnology



May 2015 Draft

Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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Executive Summary

This is Technology Area (TA) 10: Nanotechnology, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on "applied research" and "development" activities.

Nanotechnology involves the manipulation of matter at the atomic level to impart materials or devices with performance characteristics that far exceed those predicted for bulk materials and single atoms or molecules. This roadmap is focused on areas where such phenomena can provide solutions to technical challenges. For example, quantum confinement in nanoscale semiconductor particles, quantum dots, gives rise to novel optical behavior, making it possible to tune the color of their fluorescence simply by changing their diameter. Nanoscale texturing of surfaces can allow for control of adhesion properties, leading to biomimetic (Gecko-foot) self-healing adhesives and self-cleaning surfaces. The unusual combination of superior mechanical, electrical, electronic, and thermal properties of carbon-based nanostructured materials can change the design paradigm of future aerospace systems by enabling lightweight, multifunctional structures. Although nanomaterials are typically considered emerging systems with performance payoffs in the far future, several of these technologies have already proven to be beneficial in applications relevant to aerospace needs. Recent advances in nanotechnologies warrant an expansion of opportunities to evaluate their performance in environments that will permit their integration into NASA missions. Accelerated maturation and insertion of these nanotechnologies in many relevant aerospace applications can be realized more efficiently and rapidly by coupling experiments with computational analysis.

Goals

Areas where nanotechnologies have the greatest potential to impact NASA mission needs include: a) engineered materials and structures, b) power generation, energy storage and power distribution, c) propulsion and propellants, and d) sensors, electronics, and devices. In these applications, nanotechnologies are projected to replace state of the art materials used in aerospace vehicle components, including primary and secondary structures, propulsion systems, power systems, avionics, propellant, payloads, instrumentation, and devices. Maximum benefits can approach overall vehicle mass reductions of up to 50 percent, making space access more affordable while enhancing safety. Aircraft fuselage structural weights can be reduced by 15 percent without drag penalties, while enabling new concepts in efficient vehicle designs.

Overall reduction in mass while enhancing efficiency and performance is achieved by taking advantage of the properties offered by nanomaterials and by developing nanomanufacturing methods that optimize such tailorable properties. For example, net shape fabrication of multifunctional structures permit the integration of sensors and devices within structures that enable self-sensing and self-repairing systems that are not attainable with conventional materials or manufacturing methods in current use. Such integration of hierarchical structures permits the design of embedded functions in systems to enhance efficiencies and provide routes for meeting mass reduction targets without sacrificing safety and reliability. Performance enhancements can also be achieved by integrating power generation, energy storage, and power distribution systems with up to 50 percent efficiencies. Smaller, lighter, but more sensitive devices are possible by taking advantage of nanoelectronics and nanosensors in instrumentation with increased functionality packaged in significantly reduced volume.

Table 1. Summary of Level 2 TAs

10.0 Nanotechnology	Goals:	Provide an overall reduction in vehicle mass while enhancing efficiency, performance, and safety
10.1 Engineered Materials and Structures	Sub-Goals:	Improve performance, damage tolerance, and safety of materials and structures while reducing mass.
10.2 Energy Storage, Power Generation, and Power Distribution	Sub-Goals:	Increase performance and efficiency of power systems while reducing mass.
10.3 Propulsion	Sub-Goals:	Improve performance and safety while reducing mass and launch costs.
10.4 Sensors, Electronics, and Devices	Sub-Goals:	Increase performance and environmental durability while reducing mass, power consumption, and size.

Benefits

Nanotechnology can have a broad impact on NASA missions and programs in aeronautics, planetary science, and exploration. This technology has benefits principally in the following areas: reduced vehicle mass; improved functionality and durability; enhanced power generation and energy storage; increased propulsion performance; improved astronaut health management; and higher-efficiency advanced electronics and sensors.

Technology Area 10
Nanotechnology 1 of 4

Enabling Technology Candidates Mapped to the Technology Need Date

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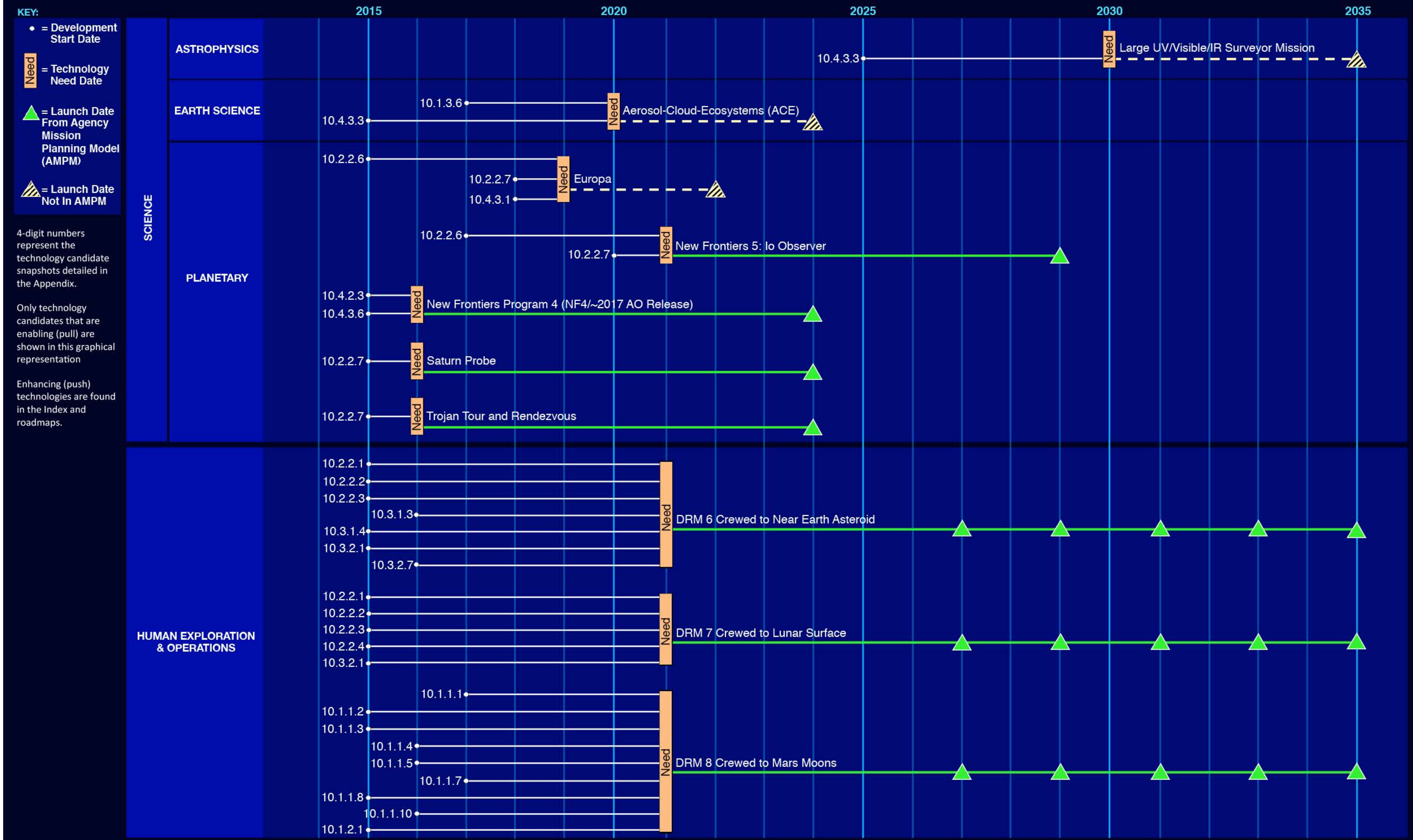


Figure 1. Technology Area Strategic Roadmap

Technology Area 10

Nanotechnology 2 of 4

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

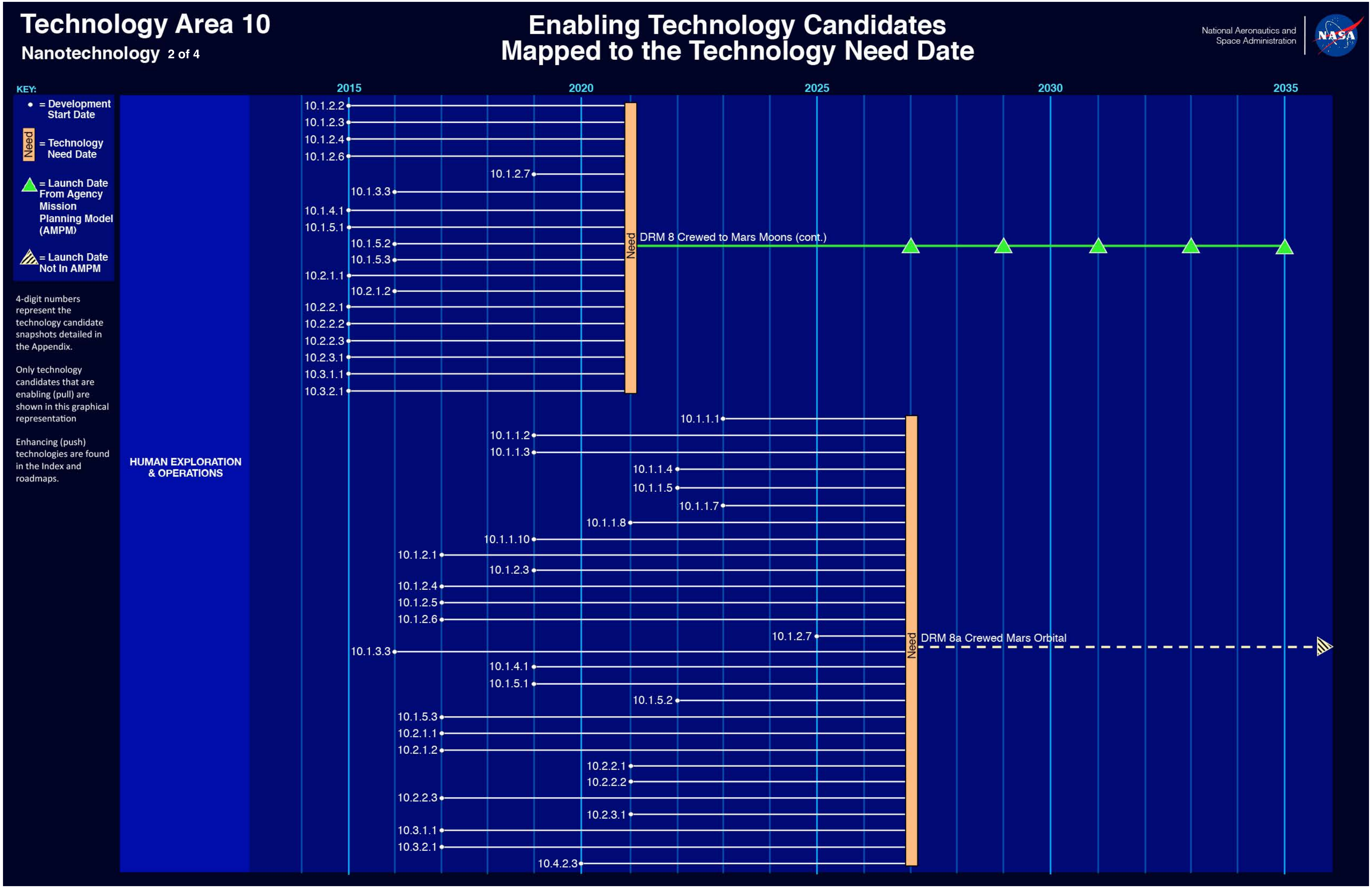


Figure 1. Technology Area Strategic Roadmap (Continued)

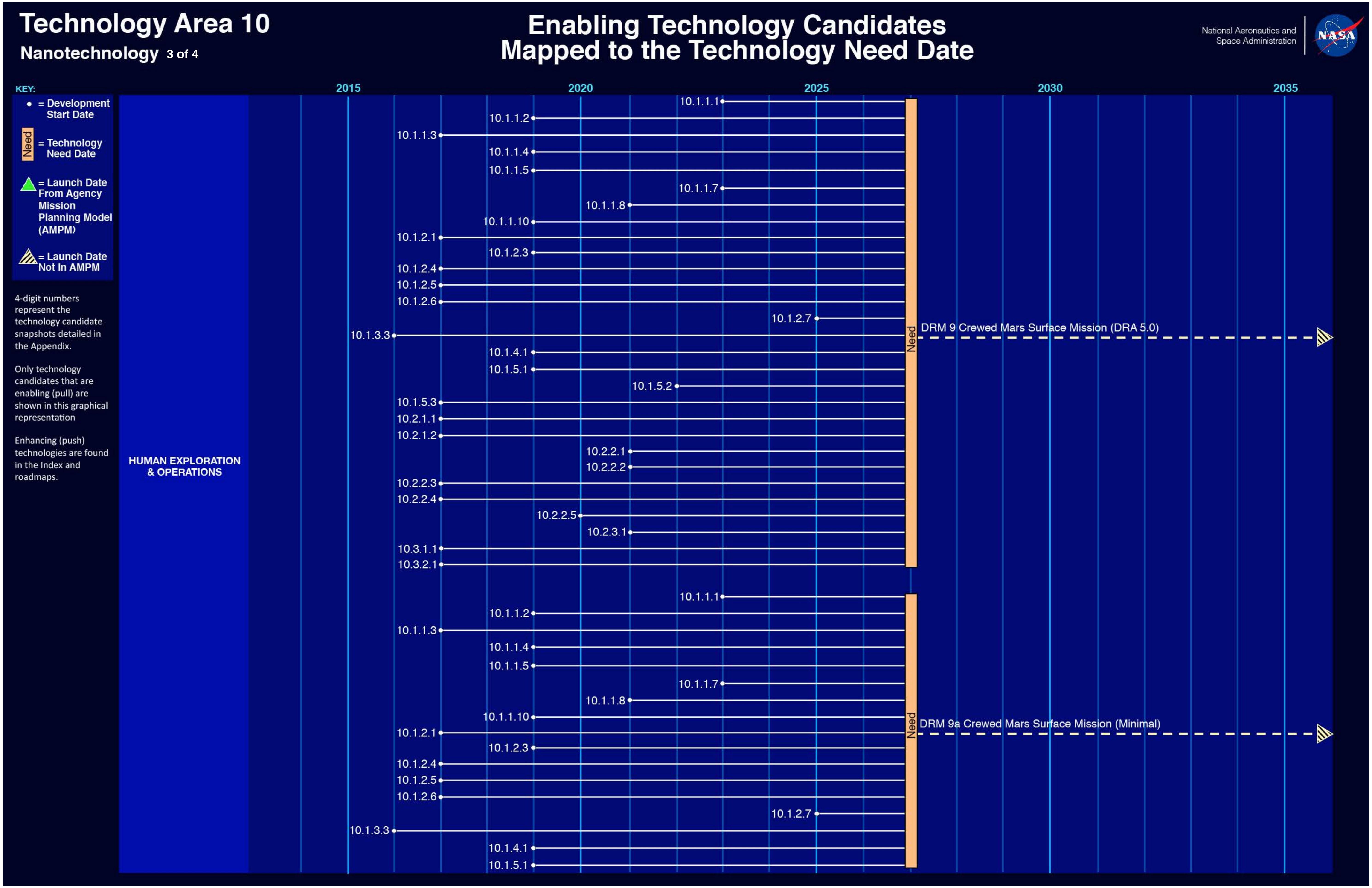


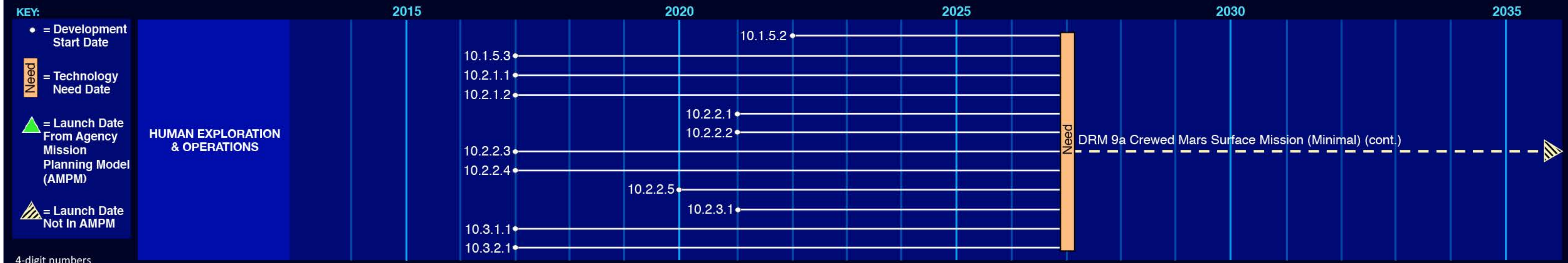
Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 10

Nanotechnology 4 of 4

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

The chart below shows the Technology Area Breakdown Structure (TABS) for Nanotechnology. The technology is divided into four major areas. Although these areas are also covered in other technology area roadmaps, the Nanotechnology roadmap is focused on solutions for technical challenges that benefit from taking advantage of nanoscale phenomena not accessible in bulk materials.

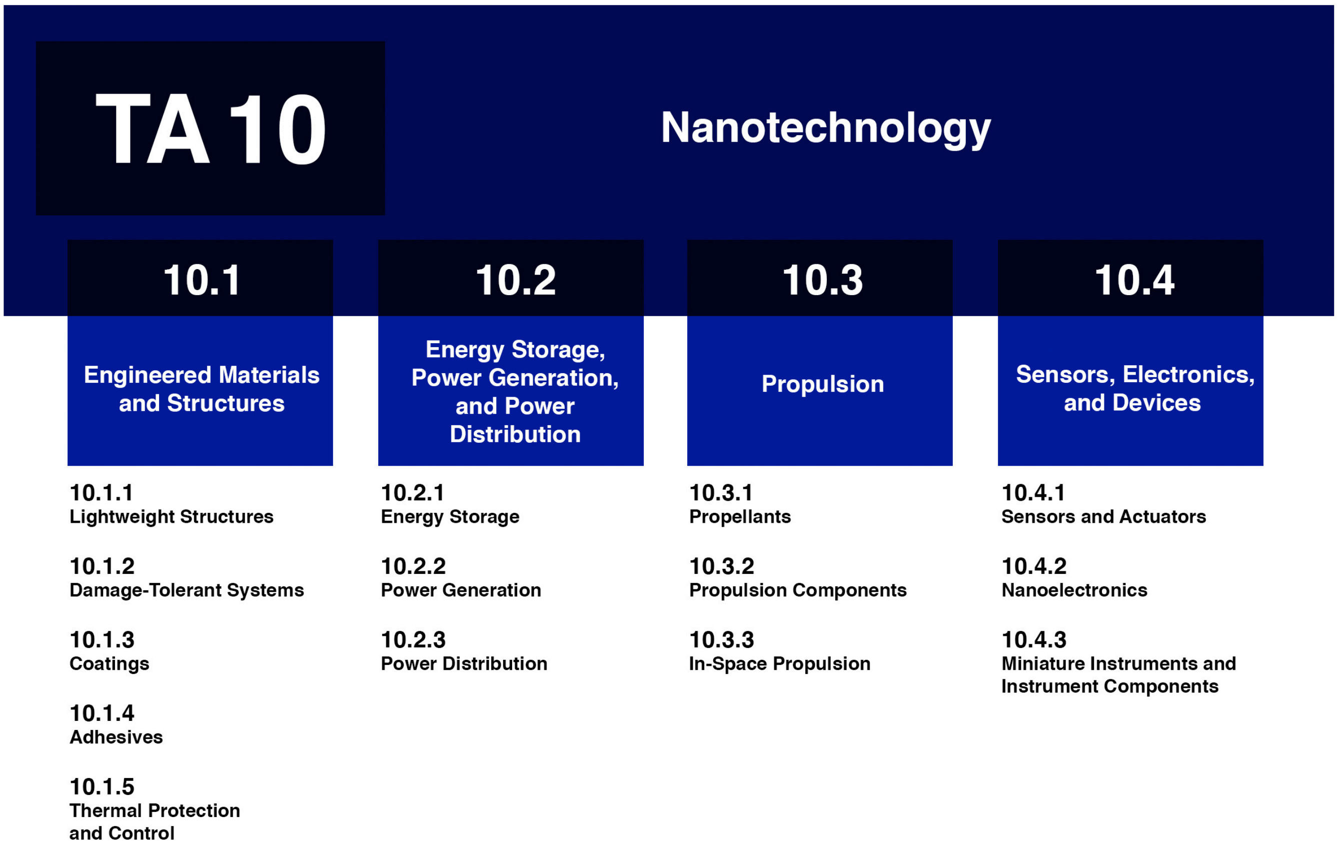


Figure 2. Technology Area Breakdown Structure Technology Areas for Nanotechnology

10.1 Engineered Materials and Structures

Nanomaterials typically possess properties that permit manipulation of material functionalities not accessible with conventional materials. This characteristic opens up the design space to enable systems concepts currently possible only by post-fabrication integration of various components. The ability to tailor component design and performance at much smaller dimensions provides routes to engineer systems with increased functionality, enhanced efficiency, and improved performance in lighter-weight structures and smaller devices.

The section for engineered materials and structures is broken into five areas:

- **10.1.1 Lightweight Structures:** Lightweight structures encompass nanomaterials with structural and functional properties that permit the reduction of overall system weight by enabling lighter weight and higher-efficiency system components. These components include lightweight, durable structural systems and high-efficiency data cables, wiring, and devices.

- **10.1.2 Damage-Tolerant Systems:** Damage-tolerant systems are comprised of nanoscale approaches to enhance system robustness through improved interlaminar interfaces, health monitoring, and repair mechanisms. Damage can be sustained in hostile environmental conditions, including extreme temperature exposure and high-impact events.
- **10.1.3 Coatings:** Coatings provide very thin, engineered surface barriers that offer protection from environmental hazards such as dust, fouling, icing, and ionizing radiation. These coatings can also be used to tailor a system's thermal response.
- **10.1.4 Adhesives:** Reversible adhesives provide a lightweight mechanism to support operational functions like satellite servicing, robotic inspection of spacecraft, orbital debris grappling, low-precision rendezvous and docking, astronaut extravehicular activity (EVA), and in-space assembly.
- **10.1.5 Thermal Protection and Control:** Thermal management solutions provide lightweight approaches to protect systems from damage due to extreme temperatures and uncontrolled cycling between thermal extremes.

10.2 Energy Storage, Power Generation and Power Distribution

Because power generation and energy storage rely heavily on processes that occur on the molecular and atomic levels, it is not surprising that there can be major advantages in using materials that are designed and built from the atomic level up. These technologies are grouped into three areas:

- **10.2.1 Energy Storage:** Energy storage systems, primarily batteries and ultracapacitors, with high energy and power density provide power for a variety of mission applications. These systems must have the ability to sustain reliable functionality in harsh environments (extreme temperatures, radiation, reactive atmospheres). Nanotechnology can improve the efficiency of these devices by providing electrode materials with enhanced reactivity and electrolytes with better transport properties over a wide temperature range.
- **10.2.2 Power Generation:** Power generation through photovoltaics and thermophotovoltaics can provide large amounts of power for spacecraft and habitats. Energy harvesting devices, such as thermoelectric and piezoelectric devices, provide small amounts of power by converting heat or vibration into electrical energy. Nanotechnology can improve the efficiency of these devices by providing mechanisms to enhance conversion of sunlight, heat, or vibration into electrical power.
- **10.2.3 Power Distribution:** Power distribution systems include wiring, buses, and harnesses for power management and distribution in spacecraft and aircraft. Nanotechnology can enable significant reductions in the mass and volume of these systems and lead to improved durability by providing lighter weight, more durable conductive materials and insulation for wiring, and improving thermal management in energy distribution systems.

10.3 Propulsion

Propulsion technologies under this technology area (TA) focus on enhancing existing, or enabling new, capabilities using nanotechnology. Based on this, the propulsion technologies are sub-divided further into three main categories:

- **10.3.1 Propellants:** Nanoparticle-derived propellants provide a less toxic and easier to handle alternative to conventional propellants (hypergolics and cryopropellants). Use of these alternative propellants would eliminate the need for cryogenic propellant storage, simplify propellant transfer, and reduce the health and safety risks associated with hypergolics. This would greatly reduce ground operations, launch costs, and complexity.

- **10.3.2 Propulsion Components:** The use of nanomaterials with improved strength, thermal conductivity, and durability will enable the development of lighter, more efficient, longer-life propulsion systems and components for spacecraft and aircraft.
- **10.3.3 In-space Propulsion:** Propellant-less approaches, such as lightweight solar sails or tethers, offer alternatives to conventional active propulsion systems for use in robotic space exploration. Nanoemitter-based thrusters provide low power and low propellant demand propulsion for nano-, pico-, and femto-satellites.

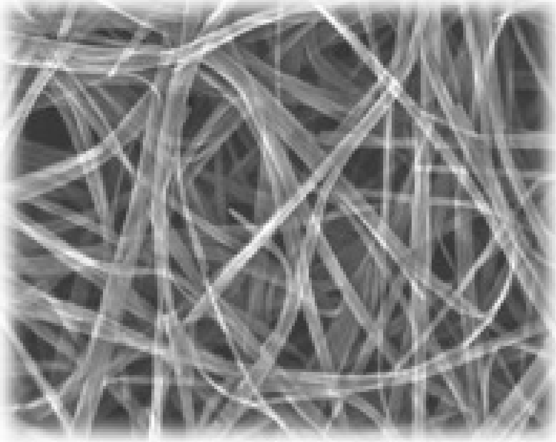
10.4 Sensors, Electronics, and Devices

Nanosensors and nanoelectronics are applications that directly benefit from advantages afforded by nanoscale features. Advantages include better performance, lower power requirements, greater packing efficiency due to smaller volumes, and radiation hardness. Sensors, electronics, and devices can be further subdivided into three areas:

- **10.4.1 Sensors and Actuators:** Nanotechnology-based sensors include systems for the detection of chemical and biological species to support planetary exploration and astronaut health, in addition to state (temperature, pressure, strain, damage) sensors for use in vehicle health management. Nanotechnology can lead to low-volume, less invasive sensors and actuators with better performance and lower power demand for new designs of morphing vehicle control surfaces, rovers, and robotic systems.
- **10.4.2 Nanoelectronics:** Nanoelectronics includes logic and memory devices for communication, data storage, and processing systems that can improve the performance of high-speed signal and control devices, such as field emission based electronics. Nanotechnology has the ability to reduce power demand while improving the performance and radiation hardness of these devices.
- **10.4.3 Miniature Instruments and Instrument Components:** Nanotechnology-derived emission sources (lasers, emitters), detectors, and optical components can reduce the volume and weight of spectrometers while increasing their efficiency for use in future science and exploration missions.

TA 10.1: Engineered Materials and Structures

While the ultimate goal of developing continuous, single-wall carbon nanotube (CNT) fibers has yet to be realized, considerable effort has been devoted to high-volume manufacturing of CNT materials. These materials are now commercially available in large sheets and continuous fiber formats suitable for the evaluation of their utility in aerospace applications. The electrical conductivity of these commercially available CNT sheets has proven to be effective for electrostatic charge dissipation and electromagnetic interference shielding, as demonstrated on the Juno satellite launched in 2011. These materials have also been tested for data cables and are in development by commercial entities for lightweight wiring. Their use in such applications is far more mature than those in structural applications where the bulk tensile strength and modulus of these carbon nanotube assemblages are significantly lower than predicted values measured on the nanoscale.



State of the art for lightweight structures, purified carbon nanotubes.

Table 2. Summary of Level 10.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
10.0 Nanotechnology	Goals:	Provide an overall reduction in vehicle mass while enhancing efficiency, performance, and safety.
Level 2		
10.1 Engineered Materials and Structures	Sub-Goals:	Improve performance, damage tolerance, and safety of materials and structures while reducing mass.
Level 3		
10.1.1 Lightweight Structures	Objectives:	Enable up to 30% reduction in the overall mass of launch vehicles and spacecraft for affordable and reliable access to space. Enable up to 15% reduction in aircraft structural weight with enhanced performance for environmentally responsible terrestrial mobility.
	Challenges:	Reliable, high volume manufacturing of high quality CNT assemblages. Test methodologies that assess the multifunctional properties. Net shape fabrication methods that exploit the potential of these materials.
	Benefits:	Reduces space vehicle and aircraft weight significantly by replacing state of the art materials used for structures, wiring, and devices with lighter weight nanomaterials and nanoporous materials.
10.1.2 Damage-Tolerant Systems	Objectives:	Improve impact damage robustness to enable up to 30% reduction in lightweight structural design and enhanced safety.
	Challenges:	Manufacturing and post processing methods for carbon nanotube to carbon fiber adhesion. Toughness of conventional ceramics for extreme temperature applications.
	Benefits:	Reduces weight by up to 30% less than current systems. Provides greater reliability and safety.

Table 2. Summary of Level 10.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
10.1.3 Coatings	Objectives:	Develop thin, lightweight barrier protection from environmental hazards that include dust, fouling, icing, and radiation to enhance systems performance.
	Challenges:	Optimization of formulations for durability and ease of application.
	Benefits:	Increases the life of materials at extreme temperatures and improves the wear resistance of materials. Reduces drag and minimizes the accretion of ice, dust, and biological fouling on surfaces thus increasing fuel efficiency.
10.1.4 Adhesives	Objectives:	Provide lightweight mechanisms to support operational functions such as grappling, docking, and mobility.
	Challenges:	Mass of the object that can be captured, types of surfaces amenable to attachment (i.e. non-flat), increasing directionality of successful attachments, ability to function in extreme atmospheric and temperature environments, and cost effective mass production.
	Benefits:	Increases functionality in the space environment, low cost servicing and inspection of spacecraft, and grappling capabilities for capturing targets.
10.1.5 Thermal Protection and Control	Objectives:	Provide lightweight thermal protection and more efficient thermal control technologies to enable safe operation in extreme environments.
	Challenges:	Qualification of high temperature materials for space vehicles in ground testing facilities accurately simulating aerothermal environment.
	Benefits:	Reduces system mass and increases system reliability. Reduces spacecraft weight, thereby increasing performance and payload capacity through nanocomposite ablators.

TA 10.1.1 Lightweight Structures

Ongoing work at NASA to advance the fabrication of structural nanocomposites has confirmed earlier published results that suggest nanocomposite-specific moduli can be competitive with conventional epoxy based carbon-fiber-reinforced polymers (CFRPs). Recent findings are beginning to shed some light on factors necessary for CNTs to effectively carry loads to enable superior specific strength properties at the macroscale. However, a full understanding of fundamental differences between structural carbon fiber composites and structural CNT nanocomposites remains elusive. Multiscale modeling and molecular simulation of these materials, coupled with experimental testing of nanocomposites, should yield a better understanding of CNT characteristics. This understanding will enable the realization of the superior properties for these nanomaterials at the macroscale, where such property improvements over CFRPs can reduce overall launch vehicle weights by as much to 30 percent, which can be equivalent to hundreds of thousands of pounds.

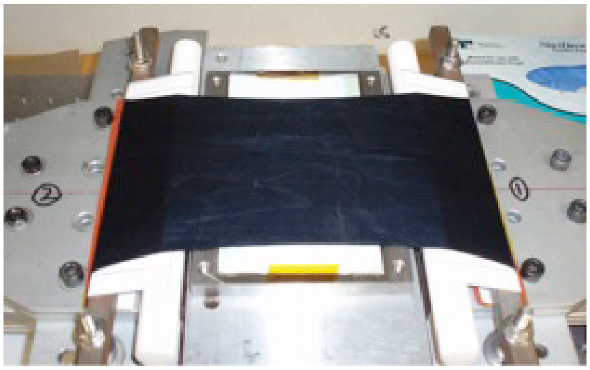


Image of large carbon nanotube sheet

Technology gaps for lightweight structures include the reliable, high-volume manufacturing of high-quality CNT assemblages; the development of structural design technologies tailored to exploit the unique set of properties offered by CNTs and other nanoreinforcements; the development of test methodologies that assess multifunctional properties; and net shape fabrication methods that exploit the potential of these materials to enable a shift in the design paradigm for advanced, lightweight structural systems. Closing these gaps can be accelerated by the development of tools to enable computational guidance for materials development.

Technical Capability Objectives and Challenges

This technology area is comprised of four types of nanostructured materials to support applications spanning lightweight structural concepts and high-performance devices.

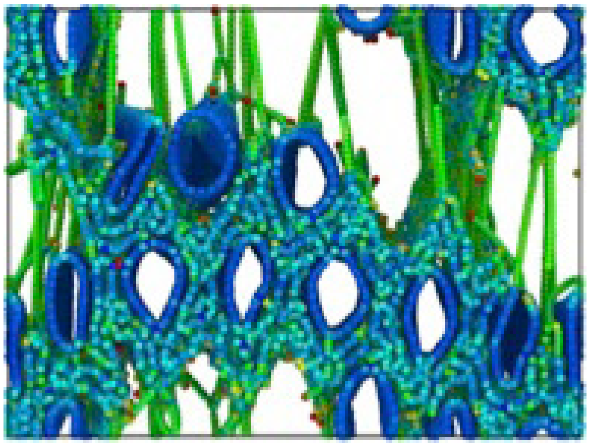
Nanoreinforcements, such as carbon nanotubes, are available in assemblages like sheets and yarns that can be fabricated into nanocomposites with mechanical properties double those of state of the art carbon fiber composites. In this form, structural weight of vehicle components can be reduced by up to 50 percent, resulting in overall launch vehicle weight reduction of 30 percent. The major challenge in this application is the need to retain the mechanical properties of these nanoscale reinforcements in the macroscale structures. Maximum benefit can be achieved if nanomanufacturing methods are developed to permit the integration of functionalities into these structures to eliminate parasitic methods currently employed.

Nanomaterials also have excellent electrical properties, with current carrying capabilities better than copper at 1/3rd of the density. This enables the use of these materials in data cables, In combination with nanoporous materials for lightweight structural insulation, overall weight reduction of up to 90 percent is possible for cabling in avionic systems. Some of these materials are in the commercialization stage, but testing for specific applications needs to be carried out. For example, recent NASA research has led to the development of polyimide aerogels that have dielectric constants lower than that of conventional polytetrafluorethylene (PTFE) insulation and densities 1/10th that of PTFE. Major challenges in advancing these technologies revolve around the scale-up of manufacturing methods to enable the evaluation of larger components in the relevant environment.

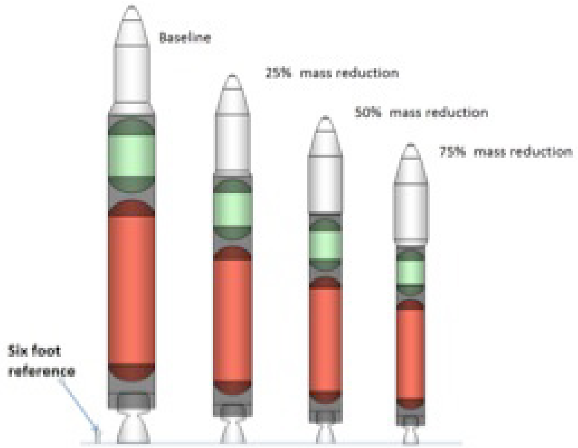
Much lower density nanofibers can also be tailored for use in environmental remediation and biomedical applications to support crew health. Methods to produce the filtration systems need to be scaled up and the technology needs to be tested in relevant use environments.

Coupling computational modeling and simulation with experimentation has the potential to significantly accelerate the development of solutions to overcome the stated challenges above. However, computational modeling tools designed specifically for use on nanomaterials need to be advanced. This can be achieved more efficiently if modeling efforts are more closely aligned to realistic experimental systems.

Flexible Aerogel Insulation



Example of computational modeling of CNT composite



Systems analysis of weight benefit savings to launch vehicle size

Benefits of Technology

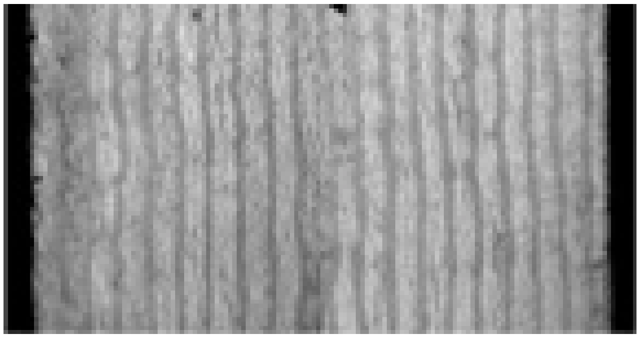
The major benefit of lightweight materials and structures is the potential for overall vehicle weight reduction. Nanomaterials can be used to replace state of the art materials used for structures, wiring, and devices to achieve this weight reduction. Specific areas that have the biggest payoff are the dry weight structures, where a 30 percent reduction in structural component weight is possible. Wiring and harnesses constitute a significant portion of vehicle systems. Replacement of these components with lighter weight nanomaterials and nanoporous materials can reduce systems weight by up to 90 percent. Overall, by designing such systems to take advantage of the performance offered by nanomaterials, a 50 percent launch vehicle weight reduction can be achieved. This reduction is sufficient to permit alternative design concepts that are not currently possible. This potential reduction in mass becomes more critical for deep-space missions where the fuel mass required to propel a vehicle to Mars orbit and back can be as much as 300 times the vehicle mass.

Table 3. TA 10.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
10.1.1.1	Nanotube Reinforced Structural Composite	Provides high-strength, high-stiffness multifunctional material for lightweight structures.
10.1.1.2	Nanolattice	Provides high-strength, high-stiffness, tough nanoporous material for lightweight structures.
10.1.1.3	Nanomanufacturing Method for Multifunctional Structures	Provides a net shape fabrication method to produce topologically-optimized lightweight multifunctional structures with inherently integrated sensors.
10.1.1.4	Low Permeability Nanocomposites	Provides lighter weight alternatives to metal liners in cryogenic propellant tanks and composite overwrap pressure vessels to reduce propellant loss.
10.1.1.5	Nanoporous Thermal Insulation	Provides high-strength nanoporous insulation at cryogenic temperatures for reliable operation of sampling systems.
10.1.1.6	Graphene Sheets	Provides high electrical and thermal conductivity through a strong, lightweight matrix.
10.1.1.7	Low Density Data Cables	Provides accurate data transmission across a strong, lightweight matrix.
10.1.1.8	Lightweight Cable Insulation	Provides electrical insulation for wires and cables at 10% the density of conventional polytetrafluorethylene (PTFE) insulation.
10.1.1.9	Low Density Nanofiber	Provides a high-strength, low-areal-density matrix suitable for membranes that can be chemically tailored for lightweight fluid or air filtration to remove toxins and particulates.
10.1.1.10	Nanomaterials Modeling and Simulation	Provides computational guidance for understanding and optimizing the properties of nanoscale materials.

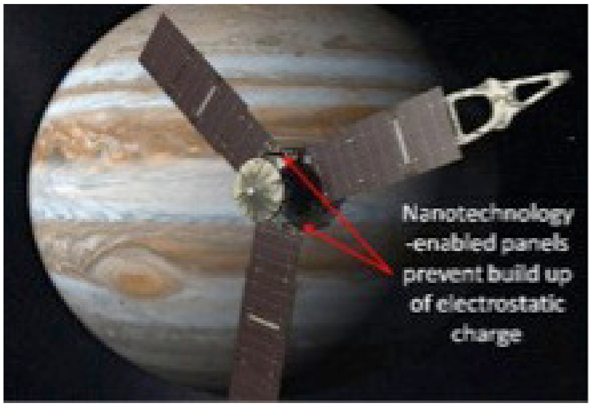
TA 10.1.2 Damage-Tolerant Systems

Significant improvements in the durability and damage tolerance of polymers and nanocomposites relative to CFRPs cannot be realized solely by low-level doping of engineering matrices with nanofillers like carbon nanotubes and graphene. Nanostitching, using “fuzzy fibers” produced by the growth of carbon nanotubes onto the surface of commercial carbon fibers, may enable enhanced toughness and damage tolerance in composites. Evaluation of the effectiveness of this approach for interlaminar property enhancements needs to be assessed on a large scale using tests like double cantilever beam and compression after impact. These methods would determine the efficacy of carbon nanotube to carbon fiber adhesion and guide the development of post-processing methods needed



Optical micrograph of carbon fiber and carbon nanotube hybrid composite, SOA for damage tolerant systems

to address this challenge. Two-fold improvement in the interlaminar toughness of composites is deemed attainable in the near future. Damage tolerance can also be realized through the use of self-healing repair mechanisms. Various approaches currently under study at universities also involve integrated sensing, which will require significant maturation for practical use in micrometeoroid and orbital debris (MMOD) environments, where self-sensing systems can assist in damage sensing and mitigation. Increased toughness in ceramics has been realized using nanoscale features similar to those found in nacre, or mother of pearl, which makes up the inner wall of seashells. Further development of this concept should make it possible to enhance the toughness of conventional ceramics for extreme temperature applications.



Juno spacecraft, which included CNT for shielding and electrostatic discharge protection

Technical Capability Objectives and Challenges

Nanomaterials can provide impact and radiation damage tolerance. Incorporating nanoreinforcements in structural systems enhances interlaminar properties and improves robustness to impact damage through structural design. A modest 15 percent improvement in damage tolerance can contribute to weight reduction on the order of 25 percent. A longer-term damage tolerance approach is the integration of nanosensors in structural systems that not only sense the damage, but also have the ability to repair such systems. The former is a near-term solution that can augment state of the art composite systems to enable lighter weight, more damage-tolerant structures with minimal changes in tooling required to manufacture these structures. The latter approach would have the biggest impact in missions where damage repair would be challenging, offering improved reliability by more efficient systems design. This application is less mature and requires the development of the appropriate nanosensors. The maximum benefit from such nanosensors can be realized with the development of manufacturing methods that integrate these sensors seamlessly into structural components.

Harmful radiation can also be mitigated by taking advantage of the inherent radiation tolerance and electrical conductivity of graphene. Incorporating graphene into parts requiring electrostatic charge dissipation is a passive and more reliable means of reducing damage caused by radiation-induced static charging than achievable by thin film coatings. Nanocomposites made with two-dimensional (2D) fillers can also be used as multifunctional structures with built-in radiation shielding characteristics, which may outperform bulkier and heavier solutions like polyethylene. These applications can be advanced by maturing large-scale manufacturing methods that consistently yield good-quality nanofillers.

Benefits of Technology

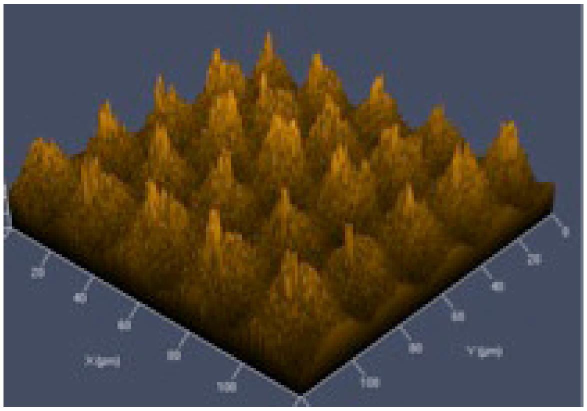
The improved damage tolerance described above has the potential to contribute to lighter structures that weigh up to 25 percent less than current systems. In addition, reliability and safety are greatly enhanced.

Table 4. TA 10.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
10.1.2.1	Damage Sensing Nanocomposite	Provides integrated damage sensing in lightweight structures.
10.1.2.2	Self-healing Nanocomposite	Provides self-repair of structural materials at locations that may be hard to access for manual repair.
10.1.2.3	Nanotoughened Composite with Improved Interlaminar Properties	Provides high interlaminar properties in lightweight structures.
10.1.2.4	Self-sensing, Self-healing Nanocomposite	Provides integrated detection and repair of damage in lightweight structures.
10.1.2.5	Impact Damage Resistant Ceramic Nanocomposite	Provides tough, lightweight structures that can survive high-velocity debris impact generated during launch.
10.1.2.6	Multifunctional Radiation Shielding Nanocomposite	Improve mechanical properties of structures while providing lightweight radiation shielding.
10.1.2.7	Electrically Conductive Nanocomposites	Nanoreinforced composites with sufficient bulk electrical conductivity to dissipate electrostatic charging.

TA 10.1.3 Coatings

Nanoengineered surfaces have proven promising in laboratory testing for applications like mitigating ice and dust accretion, as well as reducing insect residue accretion. Nanocomposite coatings can extend the life of materials at high temperatures by providing a barrier to oxidation, improving the wear resistance of materials, and enabling controlled spectral properties to increase detector performance. However, practical insertion of these systems into aerospace applications needs to be evaluated under relevant flight environments to truly assess their durability and utility in NASA missions.



Engineered surface to prevent insect residue adhesion

Technical Capability Objectives and Challenges

Nanostructured coatings permit the engineering of surfaces to provide thin, lightweight barriers for environmental hazards like bacterial fouling, icing, static charging, corrosion, and thermal oxidation. Surfaces can also be designed to possess spectral properties that contribute to enhanced detection capabilities. Surface designs need to be tailored to respond to the hazards that require mitigation. This can require different compositions and topographies tailored to specific conditions. Challenges include optimization of formulations for durability and ease of application. Advantages offered by engineered surfaces need to be evaluated in relevant environments.

Benefits of Technology

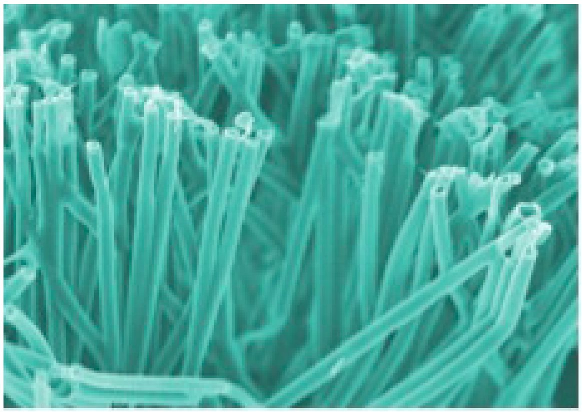
Nanostructured coatings enhance the life of materials at extreme temperatures by providing a barrier to oxidation and can improve the wear resistance of materials. Nanotexturing of surfaces can impart superfine topographical characteristics to reduce drag and minimize the accretion of ice, dust, and biological fouling. The fouling medium determines the chemical composition required for the surface because adhesion characteristics are determined by the chemical interaction between the fouling medium and the surface. Benefits of surface engineering impact crewed missions, as well as aeronautics objectives in drag reduction and fuel efficiency.

Table 5. TA 10.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
10.1.3.1	Nanostructured Coatings	Provides lightweight thermal oxidation and corrosion barriers for structures subjected to extreme temperatures.
10.1.3.2	Biological Fouling Resistant Surfaces	Provides surfaces topologically designed to prevent fouling by biological liquid contaminants to reduce drag and increase fuel efficiency.
10.1.3.3	Microbial Mitigation Surfaces	Provides surfaces designed to prevent bacterial fouling.
10.1.3.4	Anti-icing Surfaces	Provides surfaces that prevent ice and frost build-up.
10.1.3.5	Tailored Thermal Emittance	Provides mechanism for enhanced detector performance.
10.1.3.6	Optical Blacks	Provides absorption of stray radiation to enhance detector sensitivity.

TA 10.1.4 Adhesives

Biomimetically inspired reversible adhesives patterned after the nanoscale features found in gecko feet can provide a lightweight mechanism to support satellite servicing, robotic inspection of spacecraft, orbital debris grappling, low-precision rendezvous and docking, astronaut EVA, and in-space assembly. Adhesion on-off operation has been demonstrated on spacecraft surfaces under laboratory conditions, indicating that gecko adhesive designs have to overcome directionality of adhesion to find practical utility Adhesion to non-flat surfaces needs to be addressed to maximize use in the envisioned applications. Conventional adhesives, such as epoxies, may also be doped with nanoparticles to impart multifunctionality at the bondline by enhancing electrical, thermal, and optical properties in this region.



Micrograph of gecko feet like surface texture

Technical Capability Objectives and Challenges

Nanostructured adhesives are reversible, lightweight, and multifunctional for a range of applications. Application of this technology has been proven in the laboratory environment. The major challenges of reversible “Gecko-like” adhesives include mass of the object that can be captured, types of surfaces amenable to attachment (i.e. non-flat), increasing directionality of successful attachments, ability to function in extreme atmospheric and temperature environments, and cost effective mass production.

Benefits of Technology

The benefits of reversible adhesives include functionality in the space environment, low-cost servicing and inspection of spacecraft, and grappling capabilities for capturing targets. Vacuum and space environmental effects reduce the reliability of traditional adhesives; reversible adhesives show potential for temperature and pressure conditions in space applications. These shortcomings need to be addressed to maximize the benefit of this technology in robotic missions.

Table 6. TA 10.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
10.1.4.1	Biomimetic Adhesive (Gecko Feet)	Provides lightweight reversible adhesion for increased mobility of mechanisms and manipulators for in-space operations.

TA 10.1.5 Thermal Protection and Control

Enhancements in the thermal conductivity of materials, in particular polymers, have been shown through the addition of CNTs and graphene. Theoretical studies have indicated that incorporation of “fuzzy fibers” into polymer matrices can lead to enhanced through-the-thickness thermal conductivity of these materials. Nanostructured materials with compositions known to have high bulk thermal conductivity may provide a path for nanocomposites with thermal conductivities twice that of diamond. These nanocomposites could find application in lightweight radiators and heat exchangers for vehicles and habitats and could also be used for thermal management in electrical circuits and spacecraft buses. Control of thermal expansion in composites used in satellites and antennas is critical, since thermally-induced expansion and contraction of composite structures can lead to distortions that can negatively affect pointing accuracy. Addition of CNTs and graphene has been shown to reduce the coefficient of thermal expansion in composites.

Technical Capability Objectives and Challenges

Extreme temperatures are encountered especially in the entry and descent phases of several NASA missions. Overcoming this challenge requires a range of approaches that can take advantage of properties offered by nanomaterials. Thermal protection and control to keep spacecraft parts within acceptable temperature ranges during all mission phases require systems that can efficiently dissipate heat. This technology can be divided into three areas: (1) lightweight thermal protection systems (TPS), (2) high-temperature, flexible thermal insulation, and (3) thermal load control.

Char formation and stabilization are important for ablative materials used in rocket nozzles and TPS, since the char acts as thermal protection for the underlying ablative material. Poor mechanical integrity of the char results in spalling, leading to high erosion rates for these materials. Reducing spallation or erosion of the char can enable use of less ablative materials, thereby reducing nozzle or TPS weight. Addition of CNTs and nanofibers has been shown to improve the mechanical integrity of polymers and could be used to develop nanocomposite TPS with half the weight of conventional carbon-phenolic ablators. Nanostructured carbides can provide a path for lightweight, extreme-temperature structural materials that enable structural concepts not currently available. New, more flexible aerogels could be made into inflatable insulation that are packed away at the start of a mission and later deployed into lightweight heat shields or decelerators. CNT array-based heat sink designs that could potentially provide cooling for detector systems are being studied in universities and government labs.

The major challenges associated with re-entry materials include high cost, availability of ground-based testing facilities, and long sustainability of certification limits. For aerothermal applications, surface temperatures in excess of 4,000° F with extreme thermal gradients represent challenges with respect to ablation, thermal stress, and in-depth conduction to lower-temperature substrates. The qualification of high-temperature materials for space vehicles in ground testing facilities in the correct aerothermal environment is challenging. Simulated combined loads, temperature, and flight conditions may not be easily reproduced in a single facility. Arcjet facilities may provide the best simulation of the TPS environment, but have limitations since they are not capable of simulated convective and radiative heating. Test conditions achievable in current arcjet facilities result in either over or under testing.

Benefits of Technology

The primary benefits of thermal protection and control systems are enabling missions, reducing system mass, and increasing system reliability. Advancements in thermal protection technology could enable inflatable TPS for large-mass payload delivery to Mars, heat pipes for hypersonic cruise vehicles; nanostructured thermal sinks to cool detectors; and stowable, inflatable insulation. Nanocomposite ablators would save precious spacecraft weight, thereby increasing performance and payload capacity.

Table 7. TA 10.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
10.1.5.1	Nanostructured Thermal Sink	Provides cooling for detector systems.
10.1.5.2	Flexible Aerogel	Provides high-temperature thermal insulation for use in inflatable aeroshells.
10.1.5.3	Nanocomposite Ablators	Provides thermal protection in aerothermal applications involving translunar return velocities where surface temperatures can exceed 4,000° F.

TA 10.2: Energy Storage, Power Generation, and Power Distribution

Every space mission requires power, and as missions last longer and go farther from Earth, improvements in power generation, energy storage, and power distribution become critical. Nanotechnology has the potential to provide improvements, including greater efficiency, reduced weight, and increased durability. Challenges still exist for realizing nanotechnology-based energy systems, although progress is being made in industrial devices that have a wide range of commercial uses. Aerospace requirements are more rigorous than many commercial applications, largely due to reduced mass, extreme environments, and reliability requirements. Advancements in power generation and energy storage enabled by nanomaterials can potentially increase the capabilities of current missions and enable new science. Miniaturized power systems can enable small satellites and improve impact tolerance.

Table 8. Summary of Level 10.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
10.0 Nanotechnology	Goals:	Provide an overall reduction in vehicle mass while enhancing efficiency, performance, and safety.
Level 2		
10.2 Energy Storage, Power Generation, and Power Distribution	Sub-Goals:	Increase performance and efficiency of power systems while reducing mass.
Level 3		
10.2.1 Energy Storage	Objectives:	Develop high specific energy batteries with long cycling life and capable of operation at temperatures as low as -70° C. Develop less toxic alternatives to liquid electrolytes for human-rated batteries.
	Challenges:	Enhanced battery performance at wider temperature range under cyclic loading. Large-scale production of electrolyte materials with reliable performance characteristics. Testing of batteries fabricated from these materials under conditions necessary to support space missions.
	Benefits:	Provides battery technologies with significant enhancement of specific energies at use temperatures that align with space mission requirements.
10.2.2 Power Generation	Objectives:	Develop flexible photovoltaics with 50% efficiencies. Develop high efficiency solid oxide fuel cells that can operate below 500° C.
	Challenges:	Methods to controllably produce nanomaterials such as carbon nanotubes and quantum dots that enable enhanced organic photovoltaic performance. Better fabrication methods to produce organic polymeric solar cells with controlled interfaces. Space radiation tolerance of organic polymeric photovoltaics needs to be determined.
	Benefits:	Provides high efficiency power generation technologies with the long-term performance and durability necessary for space environments.
10.2.3 Power Distribution	Objectives:	Develop high conductivity carbon nanotube wiring and ultra-lightweight insulation to enable a 50% reduction in the mass of power cables, data, and control harnesses.
	Challenges:	Scalable fabrication methods to apply insulation to CNT wires. Increasing electrical conductivity and current carrying capacity of carbon nanotube conductors.
	Benefits:	Provides significant reductions in vehicle weight enabled by very durable, thin gage wiring.

TA 10.2.1 Energy Storage

Lithium ion batteries were used on the Mars Exploration Rovers and have operated without incident for more than 10 years. However, future science missions will require batteries with higher energy densities and specific energy. In addition, the development of solid electrolytes for lithium batteries would provide safer, less toxic alternatives to liquid electrolytes for use in human-rated batteries. Further work in electrolyte development is needed to enable operation of batteries over a wider temperature range. Recent developments in nanostructured electrode materials have led to lithium ion batteries with specific energies as high as 200 Wh/kg, which is 20 percent higher than that of the Mars Rover batteries. However, these materials have not been produced in quantities larger than laboratory scale, and batteries fabricated with these materials have not been qualified for space missions yet. The state of the art in solid polymer electrolytes is poly(ethylene oxide), PEO. While lithium-PEO batteries are used extensively in terrestrial commercial applications, lithium ion transport, essential for battery performance, is greatly reduced below room temperature and these batteries are not suitable for many space applications. Research at NASA led to the development of block copolymer membranes that showed better lithium ion conductivity than PEO. However, further improvements in membrane chemistries are needed to enable better conductivities at temperatures as low as -70° C. Recent work in directed self-assembly of block copolymers for use in fabrication of nanoelectronics devices could provide one potential approach to developing these needed electrolytes. This approach would need to be further developed for electrolyte materials.

Technical Capability Objectives and Challenges

There is a strong need for future NASA missions to have enhanced energy storage methods as missions become longer and more self-contained. The objective of this technology area is to develop batteries with high specific energy, power density, long cycling life, and the ability to operate at extreme temperatures. Conventional lithium ion batteries, such as those employed on the Mars Rovers, use a liquid electrolyte. While these batteries are suitable for most robotic missions, concerns about the toxicity and flammability of liquid electrolytes do not make these batteries attractive for human-rated missions. An alternative approach is to use solid polymer electrolytes. However, one issue with using solid electrolytes is poor lithium ion mobility and ionic conductivity at low temperatures. Prior work at NASA demonstrated that block co-polymers consisting of an ion conducting block and a rigid non-conducting block undergo phase separation to produce regions within the film that facilitate ion transport and conduction. The resulting films have better ionic conductivity than conventional solid polymer electrolytes at room temperature. Further work is needed to enhance conductivity at lower temperatures through a combination of processing improvements aimed at directed self-assembly and blending with nanoscale additives. Investigation of the long-term performance of batteries constructed from these electrolytes under cyclic loading is also needed.

Battery electrode performance may be improved with nanostructures and nanoarchitectures due to their large surface area, short diffusion length, enhanced ionic and electronic conductivity, improved safety, fast power capability, and improved mechanical robustness. Nanostructured materials based on carbon allotropes, alloys, metal oxides, and metal sulfides/nitrides have been explored as electrodes for next-generation lithium ion batteries. However, nanostructures often require complex synthetic processes and yield lower volumetric energy density due to reduced packing of nanoparticles or particle agglomeration. Fundamental understanding of the mechanism for chemical and energy transformation processes associated with complex nanostructured electrodes is lacking and has limited their development.

Although lithium batteries with both nanostructured electrodes and solid polymer electrolytes are relatively safer than liquid electrolytes, safe usage remains a concern. Safety characteristics are often determined by the composition, morphology, and microstructure of the electrode materials. Enhancing safety by designing compounds and structures to produce stable by-products upon oxidation need to be explored.

Ultracapacitors based on nanomaterials, particularly graphene, are another promising technology. Capacitors offer high power density and excellent cyclability, but have relatively low energy storage capability compared to batteries. Ultracapacitors made with nanostructured materials have the potential to provide significantly enhanced energy density without compromising their inherent advantages. In particular, electrode materials that exploit physical adsorption or redox reactions of electrolyte ions are being studied for improved performance. Major challenges that hamper the development of nanostructured ultracapacitors include large-area graphene production, capacitor cell design, and electrolyte development.

Flywheels based on nanomaterials are also being considered for energy storage. Flywheel devices store energy in a high-speed rotor levitated by mechanical or magnetic bearings. They are low maintenance and have the ability to charge and release substantial amounts of energy in a short period of time. Improvements in flywheel performance and safety can be achieved by using higher-strength reinforcements in the composite rotor. CNT reinforcements, currently under development by NASA and other Federal agencies, have the potential to produce composites with higher strength and lower density than existing composites. However, the mechanical properties of these nanotube-reinforced composites need further improvement before these materials are suitable for use in flywheels. In addition, more work is needed in the scale-up of CNT reinforcements to improve materials consistency.

There is a strong need for alternatives to rare-Earth magnets for power generation and energy storage in future NASA missions. In response to rare-Earth element supply shortages, technologies for novel, lightweight, non-rare-Earth nanocomposite based magnets are needed. However, methods to scale up the formation of magnetic nanoparticles need to be developed and their long-term performance needs to be studied.

Benefits of Technology

Nanomaterial-based energy storage systems can enhance the capabilities of current missions and enable new science and exploration missions by increasing efficiency, reducing weight, and improving durability. High-performance lithium batteries with solid polymer electrolytes will offer greater safety, due to lower flammability and toxicity than conventional lithium batteries. In addition, nanostructured electrodes will offer higher power density and mechanical robustness. Graphene ultracapacitors will offer high energy density, as well as high power density. Finally, flywheels made of CNT composites will offer greater safety and performance than traditional counterparts.

Table 9. TA 10.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
10.2.1.1	Lithium (Li) Battery Solid Polymer Electrolytes	Offers a robust packaging and safer device than liquid electrolytes. Li ions move back and forth between solid electrodes as the battery is charged and discharged.
10.2.1.2	Nanostructured Electrodes for Thermal Galvanic Cell	Provides high electrochemically-accessible surface area and fast redox-mediated electron transfer to make more efficient thermo-eletrochemical cells.
10.2.1.3	Nanotube Composite Flywheel	Provides flywheels that can be spun at very high velocity, storing energy at a density comparable to fossil fuels.
10.2.1.4	Nanostructured Electrode for Lithium (Li) Ion Battery	Offers very high surface-to-volume ratio for increased battery efficiency.
10.2.1.5	Nanostructured Supercapacitors	Provides high surface area for the deposition of conducting polymer or metal oxide that facilitates efficient ion diffusion, increasing the specific capacitance.
10.2.1.6	Lightweight Nanocomposite Magnets	Provides lightweight nanocomposite magnets for power generation and energy storage. Eliminates or mitigates reliance on rare-Earth elements supplied outside of the United States.

TA 10.2.2 Power Generation

The state of the art for photovoltaic devices that have been used on space missions are Gallium Indium Phosphide (GaInP)/Gallium Arsenide (GaAs)/Germanium (Ge) multijunction cells with efficiencies on the order of 30 percent. However, these solar cells are not flexible, are relatively fragile, and can be quite heavy. While organic polymer photovoltaics offer a lighter weight, more flexible alternative, the highest reported efficiency for an organic photovoltaic device is on the order of 10 percent. Increased performance in flexible, organic photovoltaics can be achieved through the use of CNTs and graphene to improve charge transport and quantum structures (dots and rods) to harvest more of the solar spectrum. Technical challenges that need to be addressed include the development of methods to controllably produce metallic single wall CNTs, improved methods for the production of quantum dots, synthesis and processing of large-area graphene, and better fabrication methods to produce organic polymer solar cells with controlled interfaces. In addition, the space radiation tolerance of organic polymer photovoltaics needs to be determined. These technologies are expected to lead to the development of conformal, radiation-hard photovoltaic materials with efficiencies in excess of 30 percent by 2030. These improved solar cells could be incorporated into the outer structure of a habitat or rover and provide additional power to charge onboard batteries.

Energy scavenging through the use of thermoelectric and piezoelectric materials can convert thermal or mechanical energy into electricity. Thermoelectric materials generate current based upon a temperature gradient in the materials. High-temperature thermoelectric materials, such as Lead Telluride (PbTe) and Lead Tin Telluride (PbSnTe), have been successfully used in radioisotope thermoelectric generators in NASA missions including the Mars Science Laboratory. These conventional materials have a thermoelectric figure of merit (zT) of 1. Recent advances in nanotechnology have led to the development of PbTe and Strontium Telluride (SrTe) nanocomposite with a thermoelectric figure of merit of 2.2. However, these materials have not been qualified in a space environment.

Fuel cells have been used extensively as energy sources in NASA human exploration missions as far back as Apollo. Solid oxide fuel cells (SOFCs) offer the possibility of higher power and efficiency than alkaline fuel cells and can also be used in reverse to generate oxygen from mixtures of carbon monoxide (CO) and carbon dioxide (CO_2). However, SOFCs require operating temperatures above 700° C, which limits their utility. Improvements in operating efficiencies at lower temperatures can be achieved by improving material transport through the fuel cell. Recently, nanoporous electrolytes have been developed that enable operation of SOFCs at temperatures as low as 500° C. These materials have not been scaled up or evaluated in SOFCs for space power applications.

Technical Capability Objectives and Challenges

This technology area has two objectives: (1) Develop flexible, radiation-hard photovoltaics with 50 percent efficiency, and (2) Reduce the operating temperature of SOFCs to below 500° C.

The development of flexible, high-efficiency solar cells will require advances in both nanostructured materials and nanomanufacturing to better harvest incident solar light and enhance charge generation and transport. Organic polymer-based solar cells, currently under development by other Federal agencies, only have efficiencies of about 10 percent. Enhanced light capture through the use of quantum dots and other nanostructures to better harvest unused portions of the solar spectrum, and semiconductor nanopillars to redirect reflected light back into the solar cell have both been shown to lead to enhancements in solar cell efficiency. Developing high-surface-area interfaces between junction materials has been shown to lead to enhanced charge transport and higher efficiencies. However, these approaches have not been integrated and optimized. In addition, work is needed to understand the effects of space radiation on the long-term performance and stability of these devices.

Improvements in the efficiency and reductions in the required operating temperatures of SOFCs have been made by improving material and electron transport through the use of nanoporous electrodes and electrolyte materials. To date, the operating temperature of SOFCs has been reduced to 500° C by using these approaches. Further work is needed in electrode and electrolyte chemistries and fabrication methods to enable the development of improved electrolyte and electrode materials. Operation of fuel cells in a microgravity environment presents a challenge in that materials transported away from the fuel cell electrodes are reduced in the absence of gravity. An in-depth study of the effects of microgravity on the operational performance of SOFCs is needed to not only determine their suitability for use in future NASA missions, but to also identify any deficiencies that could be addressed through better electrode, electrolyte, and fuel cell design.

Thermionic power generation devices can provide a safe and clean energy source. They convert heat directly into electrical energy using thermionic electrons. Nanomaterials can be used to greatly increase the power conversion efficiency of these thermionic devices. However, the realization of nanomaterial-based thermionic devices requires tailoring of nanomaterial properties and maximizing electron flow in the material and the system.

Benefits of Technology

The development of flexible, high-efficiency photovoltaics will provide conformal solar cell technology that can be incorporated into outer structures to provide power at reduced mass and volume requirements. SOFCs with lower operating temperature requirements will increase the number of applications where they can be applied.

Table 10. TA 10.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
10.2.2.1	Light Trapping and Harvesting Nanostructures (Quantum Structures, Nanophotonic Optical Surfaces) for Enhanced Photovoltaics (PVs)	Provides high-efficiency, low-weight photovoltaics for power generation by enhancing solar energy capture and conversion of solar spectrum into useful light.
10.2.2.2	Hierarchically Engineered Photovoltaics (PVs)	Provides high-efficiency, low-weight photovoltaics for power generation by enhancing charge separation and distribution.
10.2.2.3	Flexible, Rad Hard Photovoltaic (PV)	Provides flexible photovoltaics for space-radiation-resistant power generation.
10.2.2.4	Nanoporous Solid Oxide Fuel Cell (SOFC) Electrolytes	Provides for enhanced SOFC specific power at lower operating temperatures by increasing mass transport and charge generation.
10.2.2.5	Nanoporous Solid Oxide Fuel Cell (SOFC) Electrodes	Provides lower mass for solid oxide fuel cell cathodes.
10.2.2.6	Photon-Enhanced Thermionic Emission (PETE)	Enables greater efficiency by increasing the number of electrons that are boiled off the surface.
10.2.2.7	Thermionic Power Cells - Large Emission Surface	High-temperature emitter “boils” electrons off the surface, resulting in electron flow to the collector.
10.2.2.8	Piezoelectrics	Provides a route to generate power by harvesting energy from ambient sources, such as environmental vibrations.

TA 10.2.3 Power Distribution

Energy distribution systems constitute a significant fraction of the mass of an aerospace vehicle. There are over 4,000 pounds of copper wiring in a Boeing 777. The Space Shuttle had over 200 miles of data and power cables. Significant weight savings can be realized by replacing metallic conductors in data and power cables with lighter weight wiring from nanomaterials, such as CNTs and graphene. Work supported by other Federal agencies has demonstrated that replacement of the copper core and radio-frequency (RF) cladding in co-axial data cables with CNT yarns and sheets can reduce cable mass by between 30 and 70 percent, depending upon cable design. Because CNT yarns are more ductile than copper wiring, these cables can be made much thinner and are more durable than conventional co-axial cables. These cables have been flown on satellite missions and are available commercially from one vendor.

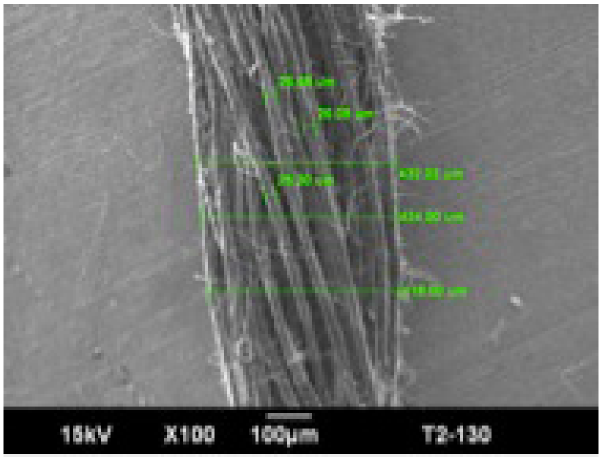


Image of CNT yarn being developed for wiring

Technical Capability Objectives and Challenges

The objective of this technical area is to develop high-conductivity CNT wiring and ultra lightweight insulation to enable a 70 percent reduction in the mass of power cables, data, and control harnesses for spacecraft to meet needs identified in the Mars 2033 and Beyond reference mission.

Replacement of copper and other metallic conductors with CNT sheets and yarns reduces cable mass. However, CNT conductors do not yet have the right electrical characteristics (conductivity and current-carrying capacity) to enable their use in power cables. Some recent progress has been made in increasing the conductivity of CNT wires through intercalation and doping with halogens like iodine and bromine. However, the highest conductivity achieved to date has been about 80 kS/cm. Further work is needed to develop approaches that lead to additional increases in conductivity.

Even more weight savings can be realized if the insulation used on CNT wiring can be made from porous aerogels. With the combination of CNT wiring and aerogel insulation, up to 70 percent weight savings relative to copper power cables can be achieved.

Benefits of Technology

Replacement of heavy copper wiring and power harnesses with wiring that is 50 percent lighter would lead to significant reductions in vehicle weight. In addition, CNT wires are inherently more ductile than copper, making it possible to make very durable, thin gauge wiring. Further weight reductions can be realized with the use of aerogel-based wiring insulation.

Table 11. TA 10.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
10.2.3.1	Carbon Nanotube Based Power and Avionics Cables	Provides power distribution for aerospace vehicles at <1/2 the mass.

TA 10.3: Propulsion

The goal of these propulsion technologies is to enable or significantly enhance a mission by achieving a level of efficiency in propulsion systems that is made possible by nanotechnology. The efficiency of a propulsion system can be significantly enhanced by increasing the efficiency of propellant consumption or by adapting structural and component enhancements that allow higher temperature tolerance, longer lifetime, and more robust propulsion systems. Alternately, new capabilities can be enabled by developing propulsion systems that are unconventional in propellant usage, miniaturization, or even in the way they are implemented on a spacecraft.

Major technological advancements are needed in the manufacturing process of nanopropellants; boron nitride nanotubes and ceramic structural nanocomposites; nanocomposite ablators; flexible, durable aerogel cryotank insulation; high thermal conductivity metallic nanocomposite nozzle liners; and high-temperature, stable nanoceramics to realize stable, superior properties in nano-based materials. The manufacturing processes may involve enhancing the interface properties; the nanoparticle stability; and uniformity of thermal, mechanical, and electrical properties from batch to batch synthesis.

Regarding the development of propulsion components, some components are more dependent upon material development, as described in the above paragraph, while the others, such as nanoemitter-based coulomb propulsion and nanoemitter thrusters for electropropulsion, are dependent upon integration and operational stability. The nanoemitter components mostly need to be readied for system-level miniaturization to preserve their dimensional advantage while ensuring on-demand operation, long operational lifetime, operational and structural stability, and harsh environment survivability.

The in-space propulsion technology development path involves achieving fabrication of ultrathin, monolithic, or woven nanofiber-based sail material, or ultra-long tether material potentially with integrated sensors, steerability, and multifunctionality. The order of development starts with the demonstration of robust, nanofiber-based, engineered sail material, followed by introduction of different stage complexities to make it “smart.”

Table 12. Summary of Level 10.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
10.0 Nanotechnology	Goals:	Provide an overall reduction in vehicle mass while enhancing efficiency, performance, and safety.
Level 2		
10.3 Propulsion	Sub-Goals:	Improve performance and safety while reducing mass and launch costs.
Level 3		
10.3.1 Propellants	Objectives:	Develop safer, easier handling of propellants.
	Challenges:	Maintaining stability in safe, large scale manufacturing methods while tailoring reactant characteristics to control burn rate. Extend the temperature range at which adsorption and desorption of hydrogen on nanostructured materials is the most efficient.
	Benefits:	Simplifies ground and mission operations since they would not require cryogenic storage and handling. Minimizes safety and health risks.

Table 12. Summary of Level 10.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
10.3.2 Propulsion Components	Objectives:	Develop robust, long-life and lower mass propulsion system components.
	Challenges:	Large-scale production of boron nitride nanotubes for incorporation into product forms to permit evaluation of the long-term durability and mechanical characteristics of these ceramic composites. Enhance thermal conductivity through improved metal to carbon nanoparticle interfaces in metal nanocomposites.
	Benefits:	Reduces propulsion component mass thus reducing vehicle weight.
10.3.3 In-Space Propulsion	Objectives:	Develop low mass solar sail membranes and tethers for propellant-less propulsion, and nanoemitter micropropulsion systems for small satellites.
	Challenges:	Scale-up for large area nanofiber membranes to permit the evaluation of their utility in solar sails. Assessment of the long-term durability of electrospun membrane materials in a space environment. Evaluation of microthrusters built from nanomaterials is required.
	Benefits:	Reduces mass of solar sails and tethers with improvements in durability and performance.

TA 10.3.1 Propellants

Overall launch cost can be reduced with the use of high-efficiency propellants that provide higher performance per unit mass. Depending upon their size and surface roughness, nanoscale particles can have surface areas in excess of 2,000 m^2/gram, roughly one-third the area of a football field. This high surface area gives rise to high surface reactivity, and the ability to adsorb large quantities of liquids or gases. Researchers in academia demonstrated that a slurry of nanoscale aluminum in ice provided enough thrust to propel a small rocket to a height of 1,300 feet. The addition of nanoscale particles (metals and aerogels) has been shown to gel liquid hydrogen and hydrocarbon jet fuels. These nanopropellants have better handling characteristics than conventional cryogenic propellants and are less toxic than hypergolic fuels. However, in order for these materials to be suitable propellant replacements, passivation chemistries and synthesis methods must be developed to prevent premature oxidation of the nanoparticles. Self-assembly-based techniques are also needed to tailor the shape and size of the nanoparticles in order to control burn rate.

Nanostructured materials have also been investigated as a safe means for hydrogen storage. There is an active program in this area within the Federal government with an objective of developing hydrogen storage materials with a sorption capacity of greater than 5.5 weight percent by 2015 and an ultimate objective of greater than 8 weight percent. One challenge remains to extend the temperature range at which adsorption and desorption of hydrogen is the most efficient.

Technical Capability Objectives and Challenges

Nanopropellants, mixtures of nanoscale metal particles in an oxidizing matrix, are needed with controllable combustion and specific thrusts equivalent to that of conventional cryogenic and hypergolic propellants. Due to their high surface areas, nanoscale metal particles are susceptible to rapid oxidation at room temperature and can spontaneously combust. Passivation approaches are needed to inhibit spontaneous combustion at room temperature while not adversely affecting their combustion behavior at elevated temperatures. New synthesis methods are needed to produce nanoparticles with controlled size and shape to improve specific thrust. Higher combustion efficiency with enhanced reaction control of lower mass propellants offer lightweight, high-energy-density alternatives to cryogenic propellants, such as liquid oxygen and hydrogen. Challenges in this technology include maintaining stability in safe, large-scale manufacturing methods while tailoring reactant characteristics to control burn rate.

Benefits of Technology

Use of nanopropellants in place of conventional cryogenic propellants would greatly simplify ground and mission operations, since they would not require cryogenic storage and handling. They are also less toxic than hypergolic propellants, thereby minimizing safety and health risks.

Table 13. TA 10.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
10.3.1.1	Nanopropellants	Provides fuel materials with the potential for higher combustion efficiency, enhanced reaction control, and lower mass.
10.3.1.2	Nanostructures for Hydrogen Storage (Nanotubes, Nanoporous Materials, and Metal-Organic Frameworks (MOFs))	Provides storage of readily-accessible hydrogen without the need for cryogenic cooling, the associated storage energy costs, and loss due to boil off.
10.3.1.3	Low Density Nanogelled Propellants	Provides lightweight and high-energy-density propellants in the form of a nanogel that may enable variable thrust control.
10.3.1.4	"Smart" Propellants	Provides highly-efficient propellants with ignition and combustion characteristics that can be altered with an applied external stimulus (electric or magnetic field, light) to provide variable thrust.

TA 10.3.2 Propulsion Components

Recent NASA research has led to the development of new polymer clay nanocomposites that have 60 percent lower permeability and better microcrack resistance than conventional toughened epoxies. University researchers have produced polymer clay films with 1,000-fold lower permeability. Multifunctional polymer-reinforced silica aerogels with thermal conductivities (<20 mW/ mK) and mechanical properties suitable for use as replacements for multi-layer insulation have been developed. These can potentially eliminate the need for external foam. Use of nanocomposites and aerogel insulation, along with new high-performance carbon fibers, is expected to enable the development of composite cryotanks that are 30 percent lighter and more damage tolerant than today's tanks.

Technical Capability Objectives and Challenges

The mass and performance of propulsion system components can be improved by the use of nanostructured materials. The objective of this technology area is to develop advanced materials to enable a 30 percent reduction in the mass and a doubling of the life of propulsion components for launch vehicles, spacecraft, and aircraft. Weight reduction can be achieved via the development of lightweight composites with higher thermal stability and mechanical strength enabled by inorganic nanofiller reinforcements. Structural components like nozzle liners can benefit from the enhanced thermal conductivity and strength imparted by such nanofillers. In addition, more efficient, highly-porous thermal insulation provides an alternative to multi-layer insulation (MLI) currently used in fuel tanks.

Additions of organically-modified clays and functionalized graphene have been shown to lead to nanocomposites with improved strength, toughness, durability, and higher temperature stability than the base polymer. However, nanoparticle addition is limited to concentrations below about 5 percent due to agglomeration at higher concentrations and significant increases in viscosity with the addition of these nanoparticles. This limits the extent of improvements that can be achieved in mechanical properties and thermal stability.

Boron nitride nanotubes (BNNT) have been shown to have better high-temperature stability than CNTs with equivalent mechanical properties. The addition of BNNTs to ceramics has led to increased toughness and improved mechanical properties. The major technical challenges facing use of BNNTs in ceramic nanocomposites is producing these nanotubes on a large scale, in product forms such as fiber and fabrics, that can be readily used as reinforcements for ceramic matrix composites. Recent work by NASA researchers demonstrated that BNNTs can be grown onto the surface of ceramic fibers typically used in ceramic matrix composites to produce “fuzzy” fibers and preforms. A silicon carbide ceramic matrix composite reinforced with a “fuzzy” three-dimensional (3D) silicon carbide fiber preform was shown to have a three-fold higher strength than the corresponding composite made with a conventional 3D preform. Scale-up of these materials is needed, along with more extensive work on characterizing their long-term durability and mechanical behavior.

Improvements in the thermal conductivity of metals can enable the development of lighter-weight rocket nozzle liners. CNTs and graphene both have high thermal conductivities. While graphene and CNTs have been successfully incorporated into copper, aluminum, and other metals, the thermal conductivity of the resulting nanocomposites has not been very high. This has been attributed to poor thermal conductance at the metal-to-carbon nanoparticle interface. New processing methods and other approaches are needed to better tailor this interface and enhance thermal conductivity.

Benefits of Technology

The development of propulsion components using nanostructured components can reduce component mass and overall vehicle weight.

Table 14. TA 10.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
10.3.2.1	Nanocomposite Ablators (High Strength Char)	Provides more durable, longer-life ablatives by inclusion of nanoscale additives to strengthen the char materials.
10.3.2.2	Boron Nitride Nanotubes (BNNT)/Ceramic Structural Nanocomposites	Provides lightweight composites with high thermal stability and mechanical strength that can be used for a wide range of high temperature propulsion applications.
10.3.2.3	Flexible, Durable Aerogel Cryotank Insulation	Provides ultra-lightweight (99.8% porous) materials engineered for thermal insulation for propulsion fuel tanks.
10.3.2.4	High Thermal Conductivity, Metallic Nanocomposite Nozzle Liners	Provides enhanced thermal conductivity, strength, and lightweight nozzle liners.
10.3.2.5	High Temperature Stable Nanoceramics	Provides improved fracture toughness and wear resistance material for use in extreme thermal environments.
10.3.2.6	Nanoemitter for Coulomb Spacecraft Propulsion	Provides propellant-less propulsion system for in-space relative motion and control of small satellites by building coulomb forces between spacecraft using nanostructures for electrical charging.
10.3.2.7	Nanoemitter Based Thrusters (Includes Field Extraction Thrusters)	Provides high I_{sp} and delta-V for small spacecraft (pico/femto/chip sats), as well as for fine movements of large space structures.

TA 10.3.3 In-Space Propulsion

Technical Capability Objectives and Challenges

The objective of this technology area is to provide efficient, low-mass propulsion for satellites and spacecraft. Recent advances in nanomaterials and nanomanufacturing offer potential approaches to reducing the mass and improving the durability and performance of solar sails. Electrospinning has been shown to produce low-density nanofiber mats that could be used as ultra lightweight membranes to replace conventional polymer films in solar sails. Improvements in the strength and resistance to the space environment (atomic oxygen, radiation) could be made through the use of nanoscale material additives, such as CNTs, clay, or graphene. Incorporation of adaptive nanocomposites in the electrospun nanofibers could enable the development of self-steering solar sails.

Technical challenges related to the development of nanofiber membranes include scale-up to produce large-area membranes, the development of bonding techniques to attach the membranes to solar sail struts, and assessment of the long-term durability of electrospun membrane materials in a space environment. Use of high-strength and high-electrical-conductivity CNT fibers in tethers could enable significant reductions in tether weight and improvements in durability. However, current CNT yarns and fibers have specific tensile strengths about half that of carbon fiber and Kevlar, and have electrical conductivities several orders of magnitude less than copper. High-volume manufacturing methods to reliably produce CNT fibers with much improved mechanical and electrical properties need to be developed. This will allow the testing of these materials to assess the effects of long-term exposure to the space environment on their mechanical and electrical properties. Some of this work is being done at NASA and at other Federal agencies.

CNTs are currently being evaluated for use in microthrusters at NASA and by other Federal agencies. Due to their better high-temperature stability, BNNT offer the possibility of making longer-life microthrusters than those made from CNTs. Recent studies indicate that the field emission behavior of BNNTs decreases with increasing number of emission cycles and suggest that the BNNTs degrade under high electrical fields. Further research is needed to understand this phenomenon and develop strategies to improve the durability of BNNTs under high electrical fields.

Benefits of Technology

Solar sails, tethers, and microthrusters offer viable propulsion solutions for small satellites. Use of nanomaterials and nanomanufacturing methods can enable significant reductions in the mass of solar sails and tethers, and improvements in durability and performance.

Table 15. TA 10.3.3 Technology Candidates – not in priority order

TA	Technology Name	Description
10.3.3.1	Low Areal Density, High Strength and Stiffness Nanofiber Solar Sails (Passive)	Provides a passive thrust, strong and lightweight nanofiber that uses solar radiation pressure for propulsion.
10.3.3.2	Adaptive Nanofibers for Steerable Solar Sails	Provides nanofiber-based materials that have adaptive capabilities as a mechanism to steer a spacecraft.
10.3.3.3	Nanotube Based Space Tether	Provides a strong, low-mass, potentially electrically-conductive tether material.

TA 10.4: Sensors, Electronics, and Devices

Nanosensors, electronics, and devices have the potential to enhance many NASA missions by providing greatly increased sensitivity and performance while minimizing weight, size, and power consumption. Challenges in reliable manufacturing and reproducible operations exist. For example, improvements in batch-to-batch synthesis and controllable assembly and orientation of nanomaterials are not yet possible. In addition, challenges in standardizing device-to-device performance and calibration exist. Continued development by Federal agencies in the area of sensors, electronics, and devices will improve reliability in fabrication and device performance and allow these technologies to transition from laboratory demonstrations to NASA missions.

Table 16. Summary of Level 10.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
10.0 Nanotechnology	Goals:	Provide an overall reduction in vehicle mass while enhancing efficiency, performance, and safety.
Level 2		
10.4 Sensors, Electronics, and Devices	Sub-Goals:	Increase performance and environmental durability while reducing mass, power consumption, and size.
Level 3		
10.4.1 Sensors and Actuators	Objectives:	Provide increased sensitivity and selectivity with reduced mass, power consumption and a smaller overall footprint.
	Challenges:	Long-term reliability. Control the structure of CNTs, or separate various types of CNTs.
	Benefits:	Provides in-situ and real-time monitoring with greatly improved sensitivity.
10.4.2 Nanoelectronics	Objectives:	Develop logic and electronic components with increased efficiency that are capable of operating in extreme environments.
	Challenges:	Reliable mass fabrication of electronics. Stability, precision, and reliability in the fabrication and performance of nanoelectronics.
	Benefits:	Provides greater operating efficiencies at extreme temperature and in radiation environments.
10.4.3 Miniature Instruments and Instrument Components	Objectives:	Develop ultrasensitive instruments with reduced mass, power consumption and reduced overall footprint.
	Challenges:	Desired resolution and selectivity for analysis with miniaturized instrumentation having reduced weight, size, and power requirements and components need to be proven.
	Benefits:	Increases sensitivity, reduces mass, size and power consumption to science instrumentation.

TA 10.4.1 Sensors and Actuators

Nano-scale sensors are highly tailorable and can achieve single-photon sensitivity and single-molecule detection while operating at µW or nW levels. They can be made from a wide variety of nanoengineered segments of deoxyribonucleic acid (DNA) and other biological molecules. They are also readily integrated with sensor electronics to produce very compact, highly "intelligent" instruments. The rate of progress in this area is very rapid. NASA successfully flew a Nano ChemSensor Unit (NCSU) on a U.S. satellite in 2007. This NCSU, the first example of a nanotechnology-based sensor system in space, was capable of detecting trace amounts of nitrogen dioxide. In 2008, NASA flew a compact trace gas sensor system comprised of a main nanoparticle-impregnated polymer sensor and an auxiliary CNT-based chemical sensor on the International Space Station (ISS). It is anticipated that such sensor systems can achieve sensitivity in the parts per billion level with precise selectivity through the use of appropriate chemical functionalization.

Nanochemsensor flown on the ISS

The electrical behavior (conducting, semiconducting, or insulating) of CNTs depends upon their structure (chirality and diameter). Therefore, creating the abilities to control the structure or, alternatively, the ability to sort various types of CNTs is a challenge. Recently, a small business developed a process to make 99 percent pure semiconducting single-wall nanotubes (SWNTs) and 99 percent pure metallic SWNTs. These pure CNTs have been used by NASA to make an array-based sensor system.

A suite of sensors for state sensing (temperature, pressure, and humidity), autonomous distributed sensors for chemical sensing, biological sensing, and water quality monitors for human and robotic exploration could be available by 2020. One of the main developments required for these sensor systems is the sampling, sensor cleaning or replacement, and waste rejection schemes that make them autonomous systems. When integrated with nanoelectronics and embedded in "smart" materials, an intelligent chemical, biological, and radiation sensing system is projected to be available by 2025.

Technical Capability Objectives and Challenges

Desired technical capabilities include sensors for vehicle health monitoring, radiation dosage measurement, sensitive gas phase and liquid phase sensors for chemical and biomolecule or organism analysis, and tactile sensors to function as sensing skin. Challenges in long-term reliability exist for many of these technologies.

Benefits of Technology

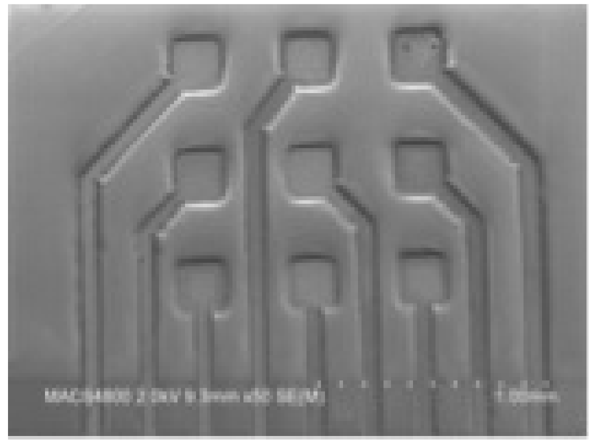
These technologies will enhance many missions by providing in-situ and real-time monitoring with greatly improved sensitivity.

Table 17. TA 10.4.1 Technology Candidates – not in priority order

TA	Technology Name	Description
10.4.1.1	Embedded State Sensors	Provides efficient in-situ means to map strain and temperature of structures.
10.4.1.2	High Performance Radiation Sensors	Provides rapid detection of ultraviolet (UV), gamma and neutron radiation.
10.4.1.3	Autonomous, Distributed Sensors	Provide means for communication in autonomous swarms and embedded chemical sensing in planetary probes.
10.4.1.4	Gas and Vapor Sensors	Provides highly sensitive means to detect fuel leaks and monitor cabin air.
10.4.1.5	Water Quality Monitoring Sensors	Provides various mechanisms to monitor water quality with improved.
10.4.1.6	Tactile Sensors	Provides means to measure surface pressure variations and mechanical deformation.

TA 10.4.2 Nanoelectronics

With recent advances in graphene and other 2D conductive nanomaterials, nanowire technologies, and a deeper understanding of CNTs, a clearer path towards achieving less than 10 nm feature sizes and junction areas is projected by 2025. Such developments are expected to use either e-beam direct write or lithography-free, direct synthesis techniques. Graphene has shown great promise as the next-generation electronics material with electron mobility of ~ 200,000 cm^2 V^{-1} s^{-1} and is conducive for large-area synthesis in tune with traditional foundry processes. Recent demonstration of 300 GHz transistors using graphene supports the projection of developing high-speed devices that operate at THz levels by 2020, with potential to develop fully-functional high-speed circuits that can be employed in future missions.



Multiplex nanobiosensor chip

Both graphene and embedded nanowires allow development of flexible and stretchable electronics. Graphene, with its breaking strength of 100 GPa and ability to be a single atomic thickness sheet, offers extraordinary material choice to develop flexible, transparent electronics that can potentially shrink the entire avionics and system electronics volume by an order of magnitude. Nanomaterial-based electronics are uniquely suitable for space applications, as they tend to be highly resistant to radiation (due to their small target cross-section) or can be made radiation tolerant without special processing and fabrication methods. Additionally, a new class of vacuum nanoelectronics components demonstrated recently is both insensitive to radiation and tolerant to extremely high temperatures (>700° C), making them suitable for extreme environment applications. These devices use nanotubes or nanowires integrated with microstructures and, together with nanoelectronics, should be available for fault-tolerant, extreme-environment electronics and memory applications between 2020 and 2025.

The above mentioned materials help decrease device dimensions beyond what is directly possible using standard semiconductor processing techniques. As device dimensions approach that of an atom, the performance enhancement of these charge-transport-based devices reaches a fundamental limit, referred to in the literature as "the end of the silicon roadmap." A relatively new approach, spintronics, uses an electron's spin rather than its charge to define logic states. While in its infancy, spintronics holds the promise of significantly enhanced performance over conventional architectures.

Technical Capability Objectives and Challenges

Desired technical capabilities for nanoelectronics include moldable electronics to fit on any surface, low-power and radiation-hard logic, electronics that can operate in extreme environments, and sub-optical wavelength-scaled electrical components and circuits. Challenges exist in reliable mass fabrication of electronics.

Benefits of Technology

These technologies will greatly enhance and possibly enable missions with extreme temperature and radiation environments, including robotic and human planetary exploration.

Table 18. TA 10.4.2 Technology Candidates – not in priority order

TA	Technology Name	Description
10.4.2.1	Flexible, Stretchable Electronics	Provides electronics that can be tethered to any shape of surface.
10.4.2.2	Nanoelectronics Based Adaptive Logic	Provides low power adaptive logic based upon one-dimensional (1D) or 2D nanostructures.
10.4.2.3	Nanoelectronics Based Memory Devices	Provides low-power-demand memory (including nonvolatile) and switches for computing and communications.
10.4.2.4	Advanced Architectures (e.g. Spintronics)	Provides alternative to charge-based electronics by exploiting electron spin that is immune to radiation.
10.4.2.5	2D Nanomaterials Based Electronics	Provides electron mobility of ~200,000 $cm^2 V^{-1} s^{-1}$ to enable the next generation of high-speed electronics.
10.4.2.6	1D Nanoelectronics	Provides novel component level technology and architectures to potentially produce systems 100-1,000X denser at constant power with embedded redundancy; small size for radiation tolerance; time-dependent nano-micro electronic interconnects for functional adaptation.
10.4.2.7	Nanolithography	Provides scanning probe approaches to displace resists, deposit materials, or chemically change the substrate surface with nanoscale features.
10.4.2.8	Seamless 1D Schottky Diode	Provides high speed, robust Schottky diode with wide-band gap 1D single material for nanoelectronics.
10.4.2.9	Nanoscale Vacuum-tube Electronics	Provides high-speed digital electronics and amplifiers for harsh environments.

TA 10.4.3 Miniature Instruments and Instrument Components

Miniature instruments and components include payload subsystems whose mass can be decreased by one to two orders of magnitude; performance in terms of measurement resolution, sensitivity, signal to noise (S/N) ratio, and power consumption can be enhanced from double to up to an order of magnitude using nanotechnology. High-impact developments include miniaturization of spectroscopic instruments for remote and in-situ exploration. Development of high-current-density (1 A/cm^2 to 100 A/cm^2) cold electron sources that can operate reliably for thousands of hours with <10 percent degradation can enable the realization of photon sources at different wavelengths (e.g., X-ray, UV, THz, mm-waves) for spectroscopy. It should be possible to develop a cluster of miniature spectroscopic tools that operate from mm-wave to X- rays to accomplish a variety of science measurements between 2015 and 2025. Specific developments include mW to tens of W, 3 to 5 percent band-tunable THz sources for remote sensing, 10^9-10^{12} photons/s flux efficient X-ray tubes, sub 250 nm- UV lasers, and mW-level mass ionizers.

Technical Capability Objectives and Challenges

Desired technical capabilities for nanoelectonics include mass analysis with reduced weight and size, mineral and chemical detection with reduced power, high-pixel microscopy without the use of traditional lenses, lasers that require less power, and highly-sensitive and fully-autonomous integrated crew health monitoring systems. The objective of these instruments is to increase sensitivity, lower background noise, and increase radiation hardness. It is also desirable to have instruments that deliver increased analytical capability, such as high mass resolution, chirality measurements, and high selectivity.

Benefits of Technology

These technologies will greatly benefit robotic and human exploration missions where sensitivity, mass, size, and power consumption are critical to science instrumentation.

Table 19. TA 10.4.3 Technology Candidates – not in priority order

TA	Technology Name	Description
10.4.3.1	Miniature Mass Spectrometer	Provides complete mass analysis function on a chip or at least 100x smaller than SOA, saving weight and power consumption.
10.4.3.2	Gigapixel Optoelectronic Array	Provides a lens-free holographic imaging technique that is compact and low power.
10.4.3.3	Nanolasers	Provides lasing in UV, visible and near infrared (NIR),spectra.
10.4.3.4	Nanostrucutred Emitter for Miniature X-Ray Spectrometer	Provides high-efficiency electron emission to enable smaller size X-ray tube for chemical and mineral analysis.
10.4.3.5	Portable Integrated Medical Diagnosis Tool for Long-Duration Human Spaceflight	Provides means to monitor bodily functions through breath and fluid analyses with portable, highly-sensitive tools.
10.4.3.6	Portable Microimaging Raman Spectrometer	Provides method with enhanced sensitivity for molecular finger printing.
10.4.3.7	Nano-electrospray	Provides an efficient means to disperse liquid as fine particle aerosol.

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Appendix

Acronyms

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
BNNT	Boron Nitride Nanotubes
CFRP	Carbon Fiber Reinforced Polymer
CMOS	Complementary Metal-Oxide-Semiconductor
CNT	Carbon Nanotubes
DIAL	Differential Absorption Lidar
DNA	DeoxyriboNucleic Acid
DRM	Design Reference Mission
EVA	ExtraVehicular Activity
I_{sp}	Specific Impulse
IRVE	Inflatable Reentry Vehicle Experiment
ISS	International Space Station
LEO	Low-Earth Orbit
MLI	Multi-Layer Insulation
MMOD	MicroMeteoroid and Orbital Debris
MOF	Metal-Organic Framework
OCT	Office of the Chief Technologist
NASA	National Aeronautics and Space Administration
NCSU	Nano ChemSensor Unit
NEA	Near Earth Asteroid
NIR	Near InfraRed
PEO	Poly(Ethylene Oxide)
PTFE	PolyTetraFluorEthylene
PV	PhotoVoltaic
QTC	Quantum Tunneling Composite
RBO	Reduced Boil-Off
RF	Radio Frequency
SERS	Surface-Enhanced Raman Scattering
SOA	State Of the Art
SOFC	Solid-Oxide Fuel Cell
STIP	Strategic Technology Investment Plan
SWNT	Single Wall NanoTube
TA	Technology Area
TABS	Technology Area Breakdown Structure
TPS	Thermal Protection System
TRL	Technology Readiness Level
UV	UltraViolet
ZBO	Zero Boil-Off

Abbreviations and Units

Abbreviation	Definition
%	Percent
amu	Atomic Mass Unit
°C	Celsius
cc	Cubic centimeter
cm^2	Square centimeter
°F	Fahrenheit
g	Grams
GaAs	Gallium Arsenide
GaInP	Gallium Indium Phospide
Ge	Germanium
GHz	GigaHertz
gm	Grams
GPa	GigaPascal
Gy	Gamma
hrs	Hours
Hz	Hertz
I_{sp}	Specific Impulse
K	Kelvin
kg	Kilograms
kHz	KiloHertz
kJ	KiloJoules
km	Kilometers
L	Liter
lbf	Pounds force
m^2	Square meters
m^3	Cubic meters
Mbar	Megabar
MeV	Megaelectron Volts
mg	MilliGrams
MHz	Megahertz
mJ	MilliJoules
mK	MilliKelvin
mL	MilliLiter
mmol	Milli Mol
mN	MilliNewton
MPa	MilliPascal
mSv	MilliSieverts

Abbreviation	Definition
mW	MilliWatts
ng	Nanograms
nm	Nanometer
nW	NanoWatts
PbTe	Lead Telluride
PbSnTe	Lead Tin Telluride
pL	Petaliter
ppb	Parts per billion
ppm	Parts per million
S or sec	Seconds
SrTe	Strontium Telluride
V	Velocity
W	Watt
Wh	Watt Hours
x	Times
y	Year
Δ	Change/Delta
μW	MicroWatts
Ω	Ohms

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Technology Candidate Snapshots

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.1 Nanotube Reinforced Structural Composite

TECHNOLOGY

Technology Description: Provides high-strength, high-stiffness multifunctional material for lightweight structures.

Technology Challenge: Carbon nanotubes (CNTs) need to be manufactured in large sheets or yarn amenable to continuous processing to yield higher specific tensile strength, CNT-reinforced composites than state of the art (SOA) carbon fiber reinforced polymers (CFRPs). Retaining nanoscale mechanical properties in large demonstration articles.

Technology State of the Art: Large sheets and continuous CNT yarns are commercially available in large quantities. NASA program targeting CNT nanocomposites with double CFRP specific tensile properties.

Parameter, Value:

Specific tensile strength of CNT nanocomposite: ~1.6 GPa/g/cc; Specific modulus: ~80 GPa/g/cc

TRL 3

Technology Performance Goal: 30% reduction in overall vehicle weight.

Parameter, Value:

Specific tensile strength: 2.0 GPa/g/cc;

Specific modulus: 80 GPa/g/cc;

Yield ~30% overall vehicle weight savings

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultralightweight structural components.

Capability Description: Enables lighter weight components for aircraft and spacecraft to reduce launch and flight costs.

Capability State of the Art: Structural component SOA is carbon fiber composite (i.e, CFRP).

Parameter, Value:

Specific tensile strength: 0.8 GPa/g/cc;

Specific modulus: 36 GPa/g/cc

Capability Performance Goal: Weight savings of 30% lighter than carbon fiber reinforced polymer composites. Larger diameter structures manufacturing methods developed.

Parameter, Value:

Specific tensile strength: 2.0 GPa/g/cc;

Specific modulus: 80 GPa/g/cc

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.2 Nanolattice

TECHNOLOGY

Technology Description: Provides high-strength, high-stiffness, tough nanoporous materials for lightweight structures.

Technology Challenge: A route for fabrication scale-up needs to be developed.

Technology State of the Art: Laboratory-scale demonstrations have been published for both ceramic and metallic lattices.

Parameter, Value:

Specific tensile strength: 2 GPa

TRL

3

Technology Performance Goal: Double specific mechanical properties of carbon fiber reinforced polymers.

Parameter, Value:

Specific Ttnsile strength: 2x greater than conventional intermediate modulus carbon fibers;

Weight: 30% lighter than carbon fiber reinforced polymer composites

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultralightweight structural components.

Capability Description: Enables lighter weight components for aircraft and spacecraft to reduce launch and flight costs.

Capability State of the Art: Carbon fiber reinforced composites.

Parameter, Value:

Specific tensile strength: 0.8 GPa/g/cc;

Specific modulus: 36 GPa/g/cc

Capability Performance Goal: Material fabrication needs to be scaled up and resulting nanolattice structural components need to be evaluated under relevant conditions.

Parameter, Value:

Specific tensile strength: 2.0 GPa/g/cc;

Specific modulus: 80 GPa/g/cc

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.3 Nanomanufacturing Method for Multifunctional Structures

TECHNOLOGY

Technology Description: Provides a net shape fabrication method to produce topologically-optimized lightweight multifunctional structures with inherently integrated sensors.

Technology Challenge: Metallic parts need means of inspection quality assurance in applications beyond non-load bearing secondary structures. Plastic components can only be fabricated from non-aerospace-grade material systems.

Technology State of the Art: Three-dimenstional (3D) printing of homopolymeric materials for consumer use is rapidly growing. However, 3D printing of aerospace-grade components using nanomaterials is in its infancy.

Parameter, Value: Nanocomposite feedstock are now commercially available. This technology is more advanced in the area of 3D printed electronics, which uses ink containing nanomaterials.

TRL: 3

Technology Performance Goal: Advanced manufacturing/processes/materials to reduce recurring hardware production cost while maintaining highly reliable aerospace systems is essential for meeting affordability and sustainability requirements. Develop manufacturing method to take advantage of lightweight multifunctional materials in topologically optimized structural designs. In-space manufacturing.

Parameter, Value: Integrated functions for CubeSat with mass range 1-20 kg. Demonstrated performance of manufactured components in relevant applications.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultralightweight structural components.

Capability Description: Enables lighter weight components for aircraft and spacecraft to reduce launch and flight costs.

Capability State of the Art: 3D printing only available for homogeneous polymers, metals mostly powder technology. Plastic disposable parts can be made for terrestrial applications. Metallic parts have been produced and used in secondary parts for aircraft. 3D printing demonstrated in microgravity on the International Space Station (ISS).

Parameter, Value: Homogeneous material systems with non-optimal mechanical properties. No nano enabled functions integrated.

Capability Performance Goal: Manufacturing methods and component evaluation under realistic aerospace environments required.

Parameter, Value: Integrated functions for CubeSat with mass range 1-20 kg. Demonstrated performance of manufactured components in relevant applications.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.4 Low Permeability Nanocomposites

TECHNOLOGY

Technology Description: Provides lighter weight alternatives to metal liners in cryogenic propellant tanks and composite overwrap pressure vessels to reduce propellant loss.

Technology Challenge: Challenges include developing scalable manufacturing methods and techniques needed to bond film to composite tank and long-term durability under static and cyclic cryogenic propellant loading.

Technology State of the Art: Clay/polymer nanocomposites. Cellulose nanocomposite.

Parameter, Value:
Clay/epoxy nanocomposite films with 1,000 lower permeability than neat epoxy. Films made from cellulosic nanofibrils with low oxygen permeability.

TRL
4

Technology Performance Goal: Low permeability and good ductility over a wide temperature range.

Parameter, Value:
Permeabilty, toughness.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultralightweight structural component.

Capability Description: Provides lightweight, structurally durable material for cryogenic tanks.

Capability State of the Art: Metallic liners.

Parameter, Value:
Gas permeability.

Capability Performance Goal: Improved adhesion to composite cryotank surface.

Parameter, Value:
Permeability, toughness, adhesion.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.5 Nanoporous Thermal Insulation

TECHNOLOGY

Technology Description: Provides high-strength nanoporous insulation at cryogenic temperatures for reliable operation of sampling systems.

Technology Challenge: Challenges include developing scalable manufacturing methods and evaluating long-term durability and performance under a simulated space environment (thermal, radiation, mechanical loads).

Technology State of the Art: Polyimide aerogel insulation.

Parameter, Value:
Polyimide aerogel films with densities as low as 0.1 g/cc;
Thermal conductivities as low as 14 mW/mK

TRL 5

Technology Performance Goal: Advanced multi-layer insulation to reduce head leak; reduced boil-off (RBO) applications are to reduce propellant loss and zero boil-off (ZBO) application are to eliminate boil-off.

Parameter, Value:
From 3,510 lbf to 4,792 lbf;
20 watt/m^2;
RBO reduction: 66%;
ZBO reduction: 100%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultralightweight structural component.

Capability Description: Provides lightweight, structurally durable material for cryogenic tanks.

Capability State of the Art: Silica aerogel on Mars rovers.
Thermal protection: Inflatable Reentry Vehicle Experiment (IRVE).

Parameter, Value:
Thermal conductivity: liquid hydrogen tank heat leak per unit area: 0.21 W/m^2

Capability Performance Goal: Long-term durability in space environment.

Parameter, Value:
From 3,510 lbf to 4,792 lbf;
20 watt/m^2;
RBO reduction: 66%;
ZBO reduction: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.6 Graphene Sheets

TECHNOLOGY

Technology Description: Provides high electrical and thermal conductivity through a strong, lightweight matrix.

Technology Challenge: Challenges include growing high-quality, defect-free graphene on a large scale to verify device performance.

Technology State of the Art: Laboratory-scale demonstrations have been plentiful, as evidenced by the abundance of literature information. However, scale-up to high volumes of high-quality graphene remains a challenge.

Parameter, Value:
4-layer graphene sheet demonstrated to have in-plane sheet resistance equivalent to Indium Tin Oxide (ITO), but has poorer transparency (between 92 and 98%) relative to ITO.

TRL
3

Technology Performance Goal: Lightweight reinforcement for manufacturing of components requiring electrostatic and electromagnetic shielding.

Parameter, Value:
Sheet resistance (in-plane): 30 Ω/square or better

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight devices.

Capability Description: Provides conductive, transparent materials required for displays, organic light emitting diodes emi shielding, photovoltaic electrodes, and antistatic coatings.

Capability State of the Art: ITO is the material used for applications listed in the capability description.

Parameter, Value:
Sheet resistance (in-plane): 30 Ω//square

Capability Performance Goal: In-plane electrical conductivity at least equivalent to ITO.

Parameter, Value:
Sheet resistance (in-plane): 30 Ω//square or better

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years
Earth Systematic Missions: Three-Dimensional Tropospheric Winds from Space-based Lidar (3D Winds)	Enhancing	--	2030*	2025	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.7 Low Density Data Cables

TECHNOLOGY

Technology Description: Provides accurate data transmission across a strong, lightweight matrix.

Technology Challenge: Prototype cable needs more extensive testing; larger-volume supplies of higher-quality carbon nanotubes (CNTs) need to be available on a more consistent basis. There is currently only one high-volume supplier of CNT material suitable for cable manufacture.

Technology State of the Art: Data cable prototypes have been demonstrated. Full potential for lightweight cabling and wiring design that take advantage of CNT fatigue resistance and strength has yet to be realized and is under development.

Parameter, Value: All-CNT wiring for cables demonstrated to be 69% lighter compared to regular cable

TRL: 3

Technology Performance Goal: Cable mass reduction for data transmission. Communication delay tolerant power management.

Parameter, Value: 25% mass reduction; 50% mass reduction, > 6 seconds

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight devices.

Capability Description: Provides highly conductive, lightweight material for data transmission.

Capability State of the Art: Carbon nanotube data cables/wiring have been demonstrated in space.

Parameter, Value: Frequency dependent electrical conductivity, reliability of data transmission.

Capability Performance Goal: Cable mass reduction.

Parameter, Value: 50% mass reduction, > 6 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.8 Lightweight Cable Insulation

TECHNOLOGY

Technology Description: Provides electrical insulation for wires and cables at 10% the density of conventional polytetrafluorethylene (PTFE) insulation.

Technology Challenge: Prototype cable with aerogel insulation needs more extensive testing.

Technology State of the Art: Data cable prototypes have been demonstrated. Full potential for lightweight cabling and wiring design that take advantage lightweight insulation has yet to be realized and is under development.

Parameter, Value: All-carbon nanotube (CNT) wiring for cables demonstrated to be 69% lighter compared to regular cable

TRL: 3

Technology Performance Goal: Cable mass reduction for data transmission. Communication delay tolerant power management.

Parameter, Value: Cable mass reduction versus state of the art: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight devices.

Capability Description: Provides highly conductive, lightweight material for data transmission.

Capability State of the Art: Data cables/wiring have been demonstrated in space.

Parameter, Value: Cable weight

Capability Performance Goal: Cable mass reduction.

Parameter, Value: 70% mass reduction

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	6 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.9 Low Density Nanofiber

TECHNOLOGY

Technology Description: Provides a high-strength, low-areal-density matrix suitable for membranes that can be chemically tailored for lightweight fluid or air filtration to remove toxins and particulates.

Technology Challenge: Electrospun materials need to be tailored to function as required and tested in relevant environment.

Technology State of the Art: Electrospun nanofibers have been studied for various membrane applications.

Parameter, Value:	TRL
17.5 mmol CO_2/g sorbent	2

Technology Performance Goal: Particulate control for 4-person crew up to 1 month in NEA. More efficient and durable sorbents and filtration systems to enable higher efficiency and less maintenance.

Parameter, Value:	TRL
2 ppm CO_2; 3 years before maintenance/failure; 11.9 mg/g at < 1 ppm	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight membranes.

Capability Description: Provides reliable, durable, low-density materials for environmental revitalization and biomedical applications to support crew health.

Capability State of the Art: Zeolites and amine-based sorbent beds are currently used on the International Space Station (ISS). High Efficiency Particulate Air (HEPA) filters are in use for particulate filtration.

Parameter, Value:

1.77 ppm CO_2;

0.5 year between maintenance/failure;

Amine-based sorbent: 11.9 mg/g at < 1 ppm

Capability Performance Goal: Higher efficiency, low maintenance particle control.

Parameter, Value:

2 ppm CO_2;

3 years before maintenance/failure;

11.9 mg/g at < 1 ppm

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years

10.1 Engineered Materials and Structures
10.1.1 Lightweight Structures

10.1.1.10 Nanomaterials Modeling and Simulation

TECHNOLOGY

Technology Description: Provide computational guidance for understanding and optimizing the properties of nanoscale materials.

Technology Challenge: Challenges include enabling the design and property prediction for nanostructured composite materials. Theory and algorithmic advances are required to address the mesoscale structure and properties.

Technology State of the Art: Typical simulations treat 10^6 – 10^7 particles.

Parameter, Value:

Simulations for 10^7 particles

TRL 3

Technology Performance Goal: Develop computational tools to model systems representing 10^{12} atoms.

Parameter, Value:

Simulations for 10^{12} particles, with many atoms represented by coarse-grained particles

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: 11.3.5 Exascale Simulation and 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation.

CAPABILITY

Needed Capability: Accurate materials simulation techniques across all length scales relevant to macroscopic material performance.

Capability Description: Theory and algorithmic advances are required to address the mesoscale structure and properties that determine many macroscopic material properities.

Capability State of the Art: Well-developed methods exist for predicting properties on length scales below ~10 nm and above ~1 μm.

Parameter, Value:

Within 10% of experiment in most cases

Capability Performance Goal: Develop computational tools to address scales between 10 nm and 1 μm.

Parameter, Value:

Accuracy comparable to state of the art for shorter- and longer-length scales

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.1 Damage Sensing Nanocomposite

TECHNOLOGY

Technology Description: Provides integrated damage sensing in lightweight structures.

Technology Challenge: Sensor/structure component design concepts are still in their infancy. Developing methods to interrogate systems and interpret massive data being transmitted will be required.

Technology State of the Art: Technology currently at coupon demonstration level.

Parameter, Value: Nanosensor demonstrated but will need to be integrated into relevant composite structures

TRL: 2

Technology Performance Goal: Robustness to micrometeoroid and orbital debris (MMOD) damage. Ability to detect MMOD strikes on critical aerospace vehicle components.

Parameter, Value: 120 hours useful operation/MMOD strike; autonomous

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved damage tolerance.

Capability Description: Enhanced robustness of structural components through health monitoring and repair mechanisms.

Capability State of the Art: Current structures have parasitic sensors. Fiber optic sensors on satellites range from mapping strain and temperature distribution to monitoring spacecraft attitude. A foreign space agency has been investigating fiber optic sensors for several years, and the first operational spaceflight demonstrations are under development. NASA developed embedded acoustic emission sensors (not nano) for impact monitoring, which flew on the Space Shuttle for impact detection in wing leading edge.

Parameter, Value: Detected particle impact on Space Shuttle leading edge

Capability Performance Goal: Sensor integration into relevant composites, damage-tolerant sensor.

Parameter, Value: 120 hours useful operation/MMOD strike; autonomous

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.2 Self-Healing Nanocomposite

TECHNOLOGY

Technology Description: Provides self-repair of structural materials at locations that may be hard to access for manual repair.

Technology Challenge: Scale-up of laboratory-scale prototypes needs to be initiated. Testing at micrometeoroid and orbital debris (MMOD) velocities is also needed. Other challenges include the inherent brittleness of the epoxy matrix, which is prone to microcrack formation either from exposure to cryogenic conditions or from impact from different sources, and the fact that microcracks increase gas permeation and leakage.

Technology State of the Art: Self-repairing systems include microencapsulation, vascular networks of reactive resins, and puncture-healing polymeric matrices. Nanoreinforced polymeric matrices with sufficient conductivity to enable healing sufficient to support self-repair.

Parameter, Value: Composites made with self-healing matrices are too resin-rich to have equivalent properties as state of the art composites

TRL: 3

Technology Performance Goal: Robustness to MMOD damage.

Parameter, Value: 120 hours useful operation/MMOD strike

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved damage tolerance.

Capability Description: Enhanced robustness of structural components through improved interlaminar interfaces, health monitoring, and repair mechanisms.

Capability State of the Art: Epoxy composites that need to be repaired post mission.

Parameter, Value: Structural property retention

Capability Performance Goal: MMOD damage tolerance.

Parameter, Value: 120 hours useful operation/MMOD strike

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.3 Nanotoughened Composite with Improved Interlaminar Properties

TECHNOLOGY

Technology Description: Provides high interlaminar properties in lightweight structures.

Technology Challenge: A proof-of-concept via realistic testing is required to optimize design for aerospace applications. Micrometeoroid velocities relative to a spacecraft in orbit average 10 kilometers per second (22,500 mph) is also a challenge.

Technology State of the Art: Coupon-level demonstrations at universities and start-up companies.

Parameter, Value: $G1c = 2\ kJ/m^2$

TRL: 3

Technology Performance Goal: Robustness to micrometeoroid and orbital debris (MMOD) damage. Improved abrasion/cut/puncture resistance. 60% increase in number of launch exposures the refractory material can withstand before damage occurs and repairs are necessary.

Parameter, Value: 120 hours useful operation/MMOD strike

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved damage tolerance.

Capability Description: Enhanced robustness of structural components through health monitoring and repair mechanisms.

Capability State of the Art: Epoxy carbon fiber composite.

Parameter, Value:
977-3/IM7: CAI: 193 MPa;
Open hole compression: 322 MPa

Capability Performance Goal: MMOD damage tolerance.

Parameter, Value:
120 hours useful operation/MMOD strike

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.4 Self-Sensing, Self-Healing Nanocomposite

TECHNOLOGY

Technology Description: Provides integrated detection and repair of damage in lightweight structures.

Technology Challenge: Scale-up of laboratory-scale prototypes needs to be initiated. Testing at micrometeoroid and orbital debris (MMOD) velocities is also needed. Other challenges include the inherent brittleness of the epoxy matrix, which is prone to microcrack formation either from exposure to cryogenic conditions or from impact from different sources, as well as the fact that microcracks increase gas permeation and leakage.

Technology State of the Art: Self-repairing systems include microencapsulation, vascular networks of reactive resins, distributed carbon nanotube (CNT) network, and puncture-healing matrices.

Parameter, Value:

Composites made with self-healing matrices are too resin-rich to have equivalent properties as state of the art composites. Sensor functionality has to be demonstrated in relevant nanocomposites.

TRL

3

Technology Performance Goal: Robustness to MMOD damage.

Parameter, Value:

120 hours useful operation/MMOD strike

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved damage tolerance.

Capability Description: Enhanced robustness of structural components through health monitoring and repair mechanisms.

Capability State of the Art: Epoxy composites that need to be repaired post mission. Current structures have parasitic sensors such as fiber optic sensors on satellites that range from mapping strain and temperature distribution to monitoring spacecraft attitude. A foreign space agency has been investigating fiber optic sensors for several years and the first operational spaceflight demonstrations are under development. NASA developed embedded acoustic emission sensors (not nano) for impact monitoring which flew on the Space Shuttle for impact detection in wing leading edge.

Parameter, Value:

Structural property retention and parasitic sensors that are commercially available

Capability Performance Goal: MMOD damage tolerance.

Parameter, Value:

120 hours useful operation/MMOD strike

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.5 Impact Damage Resistant Ceramic Nanocomposite

TECHNOLOGY

Technology Description: Provides tough, lightweight structures that can survive high-velocity debris impact generated during launch.

Technology Challenge: Challenges include developing nanoceramics with the required toughness without sacrificing hardness.

Technology State of the Art: Laboratory-scale demonstration of spark plasma sintered nanoceramics have good mechanicals.

Parameter, Value:

Insufficient fracture toughness due to challenges in manufacturing method to yield high toughness without losing hardness.

TRL: 2

Technology Performance Goal: Robustness to foreign object debris propelled during launch. Requires refractory material that can withstand more strikes before damage occurs and repairs are necessary.

Parameter, Value:

0.2 to 0.5 inches erosion under maximum exposure conditions.

Reduce time required between replacement of launch pad components.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved damage tolerance.

Capability Description: Enhanced robustness of structural components through health monitoring and repair mechanisms.

Capability State of the Art: Launch pads currently use Fondue Fire brick in highest-temperature location and Fire brick in lower-temperature locations. Ha-Flex composite materials with epoxy at other facilities.

Parameter, Value:

0.2 to 0.5 inches erosion under maximum exposure conditions.

Capability Performance Goal: Erosion resistance, low maintenance.

Parameter, Value:

0.2 to 0.5 inches erosion under maximum exposure conditions;

Reduce time required between replacement of launch pad components

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.6 Multifunctional Radiation Shielding Nanocomposite

TECHNOLOGY

Technology Description: Improve mechanical properties of structures while providing lightweight radiation shielding.

Technology Challenge: Tests need to be developed to guide the design of more effective shielding materials.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Nanomaterials-filled composites are being evaluated for radiation shielding efficacy in the lab.			
Parameter, Value: Nanocomposites only tested at coupon level to determine point doses and do not account for internal secondary particle showers in human body.	2	**Parameter, Value:** 150 mSv total career equivalent dose.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight radiation protection.

Capability Description: Provides radiation protection for astronauts.

Capability State of the Art	Capability Performance Goal
Polyethylene sheets on the International Space Station (ISS).	Reduced long-term radiation exposure.
Parameter, Value: Annual limit 500 mSv/y to BFO.	**Parameter, Value:** 150 mSv total career-equivalent dose.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.1 Engineered Materials and Structures
10.1.2 Damage-Tolerant Systems

10.1.2.7 Electrically Conductive Nanocomposites

TECHNOLOGY

Technology Description: Nanoreinforced composites with sufficient bulk electrical conductivity to dissipate electorstatic charging.

Technology Challenge: Ensuring the consistency of material properties for scaled-up production is a challenge. Opportunities to test materials in realistic environments with in-situ data collection are limited.

Technology State of the Art: Qualified for space use based on June flight. Large sheets and continuous carbon nanotube (CNT) yarns are available. Extensive literature documenting enhanced electrical conductivity of lightly CNT doped matrices of polymers.

Parameter, Value:

10^8 ohms/sq;

Specific conductivity:S*cm^2/g;

Yarn: DC / 1 MHz 2.0x 10^4 18.2 x 10^4;

Sheet: DC / 1 MHz 0.55 x 10^4 1.7 x 10^4;

PANI CNT Composite DC-electrical conductivity of 621 S/cm

TRL 9

Technology Performance Goal: Sufficient conductivity of lightweight structures to mitigate radiation-induced electrostatic charge.

Parameter, Value:

10^8 ohms/sq

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight radiation protection.

Capability Description: Provides mitigation of radiation-induced surface charging and internal electrostatic discharge (IESD).

Capability State of the Art: CNT-reinforced polymer nanocomposite was flown on Juno mission for electrostatic charge dissipation in 2011.

Parameter, Value:

Specific conductivity:S*cm^2/g;

Yarn: DC / 1 MHz 2.0 x 10^4 18.2 x 10^4;

Sheet: DC / 1 MHz 0.55 x 10^4 1.7 x 10^4

Capability Performance Goal: Electrostatic charge dissipation.

Parameter, Value:

10^8 ohms/sq

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	2 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	2 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	2 years

10.1 Engineered Materials and Structures
10.1.3 Coatings

10.1.3.1 Nanostructured Coatings

TECHNOLOGY

Technology Description: Provides lightweight thermal oxidation and corrosion barriers for structures subjected to extreme temperatures.

Technology Challenge: Tailored nanostructure designs and methods required to controllably achieve such engineered surfaces, including environmental durability of nanostructures and robust adhesion to the substrate, need to be developed.

Technology State of the Art: Nanostructured thermal barrier coatings.

Parameter, Value:

Alumina-titania nanostructured coatings have been evaluated for mechanical and high-temperature wear behavior in university labs. Nanostructured coatings of other compositions have been produced by spray coating of nano-sized powders. Improved wear and corrosion resistance were attributed to formation of semi molten nano zones in these coatings.

TRL 3

Technology Performance Goal: Durability at high temperatures. Adhesion to substrate.

Parameter, Value:

> 3,000° F

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engineered surface barriers.

Capability Description: Provides thin, lightweight surface protection from extreme environments.

Capability State of the Art: Thermal barrier coatings are used extensively in the hot sections of aircraft engines and are under development for use in rocket nozzles.

Parameter, Value:

Thermal oxidative stability, temperature capability, and thermal shock resistance.

Capability Performance Goal: Durability at high temperatures.

Parameter, Value:

> 3,000° F

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

10.1 Engineered Materials and Structures
10.1.3 Coating

10.1.3.2 Biological Fouling Resistant Surfaces

TECHNOLOGY

Technology Description: Provides surfaces topologically-designed to prevent fouling by biological liquid contaminants to reduce drag and increase fuel efficiency.

Technology Challenge: Formulations need to be optimized for durability and ease of application.

Technology State of the Art: Engineered surfaces tested in the lab, wind tunnel and flown on small aircraft. EcoDemonstrator flight tests scheduled in Spring 2015.

Parameter, Value:

Ideally, no insect residue adhesion. Currently, reduced insect residue adhesion, reduced insect residue height and area.

TRL 4

Technology Performance Goal: Anti-contamination coatings/dust control. Contaminant-tolerant cooling for extravehicular activity (EVA) (potable water).

Parameter, Value:

gm/cm^2-day;

Drag;

Iceophobics;

Adhesion/abhesion;

Friction and wear

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engineered surface barriers.

Capability Description: Provides thin, lightweight surface protection from environmental hazards.

Capability State of the Art: Flight tests of engineered surfaces on Proteus and Falcon Aircraft.

Parameter, Value:

Insect residue adhesion prevention;

Reduced insect residue height

Capability Performance Goal: Contamination resistance.

Parameter, Value:

gm/cm^2-day;

Drag;

Iceophobics;

Adhesion/abhesion;

Friction and wear

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vertical Life Vehicle Efficiency and Environmental Performance in 2035	Enhancing	--	--	2035	5 years

10.1 Engineered Materials and Structures
10.1.3 Coatings

10.1.3.3 Microbial Mitigation Surfaces

TECHNOLOGY

Technology Description: Provides surfaces designed to prevent bacterial fouling.

Technology Challenge: Nanoscale, high-surface-area catalysts need to be tested for this application.

Technology State of the Art: Nanosilver is currently used in consumer products.

Parameter, Value:	TRL
0.4 ppm silver found to be effective as biocide	3

Technology Performance Goal: Microbial control that requires minimal crew time/effort, does not produce unpleasant-tasting water, and is reusable for longer missions.

Parameter, Value:	TRL
gm/cm²-day	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engineered surface barriers.

Capability Description: Provides thin, lightweight surface protection from environmental hazards.

Capability State of the Art: Existing microbial control methods depend on iodine or ionic silver biocides, physical disinfection, and point-of-use steriiization filters. UV light emitting diodes and surface passivation methods are being explored.

Parameter, Value:
Cells/L

Capability Performance Goal: Antimicrobial surface, reusability.

Parameter, Value:
gm/cm²-day

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

10.1 Engineered Materials and Structures
10.1.3 Coatings

10.1.3.4 Anti-Icing Surfaces

TECHNOLOGY

Technology Description: Provides surfaces that prevent ice and frost build-up.

Technology Challenge: Nanoengineered surfaces have been effective at preventing ice formation, but durability for practical application must be optimized.

Technology State of the Art: Nanoengineered surfaces are currently being tested in laboratories with ice chambers.

Parameter, Value:
Lab demonstrations of anti-icing surfaces have been reported. Durability testing in progress.

TRL 3

Technology Performance Goal: Surfaces prevent ice and frost formation.

Parameter, Value:
No ice adhesion.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engineered surface barriers.

Capability Description: Provides thin, lightweight surface protection from environmental hazards.

Capability State of the Art: Anti-icing fluid used to clean aircraft prior to take-off.

Parameter, Value:
No ice formation.

Capability Performance Goal: Environmental icephobic surface.

Parameter, Value:
No ice adhesion.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Safe, Efficient Growth in Global Operations: Improved Efficiency and Hazard Reduction within NextGen Operational Domains	Enhancing	--	--	2025	5 years
Ultra-Efficient Commercial Vehicles: Achieve Community Goals for Improved Vehicle Efficiency and Environmental Performance in 2025	Enhancing	--	--	2025	5 years
Achieve Community Goals for Improved Vertical Life Vehicle Efficiency and Environmental Performance in 2035	Enhancing	--	--	2035	5 years

10.1 Engineered Materials and Structures
10.1.3 Coatings

10.1.3.5 Tailored Thermal Emittance

TECHNOLOGY

Technology Description: Provides mechanism for enhanced detector performance.

Technology Challenge: The durability of adaptive surfaces under space environment needs to be demonstrated.

Technology State of the Art: Carbon nanotube (CNT) arrays are currently under investigation for use as superblack surfaces.

Parameter, Value:

Absorption of stray radiation across a wide range of wavelengths required.

TRL

3

Technology Performance Goal: Controlled thermal emittance over a broad wavelength range.

Parameter, Value:

Thermal emittance greater than 0.89.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Radiative surfaces.

Capability Description: Provides controlled spectral properties.

Capability State of the Art: Space-qualified super black paint AZ 1000-ECB has been flown on the Optical Properties Monitor (OPM), the Mir Environmental Effects Payload (MEEP) Passive Optical Sample Assembly (POSA)-I experiment, and the Materials International Space Station Experiment (MISSE).

Parameter, Value:

Thermal emittance greater than 0.89.

Capability Performance Goal: Controlled thermal emittance to enhance detector sensitivity.

Parameter, Value:

Thermal emittance greater than 0.89.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Wide Field Infrared Survey Telescope (WFIRST)	Enhancing	--	2025	2018	3 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enhancing	--	2024*	2020	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.1 Engineered Materials and Structures
10.1.3 Coatings

10.1.3.6 Optical Blacks

TECHNOLOGY

Technology Description: Provides absorption of stray radiation to enhance detector sensitivity.

Technology Challenge: Durability under space environment of carbon nanotube (CNT) arrays needs to be demonstrated.

Technology State of the Art: CNT arrays are currently under investigation for use as superblack surfaces.

Parameter, Value: Absorption of stray radiation across a wide range of wavelengths required.

TRL: 3

Technology Performance Goal: Absorption of solar radiation to enhance detector sensitivity.

Parameter, Value: Solar absorption greater than 0.98.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Radiative surfaces.

Capability Description: Provides controlled spectral properties.

Capability State of the Art: CNT-reinforced sheet was flown on Juno mission for electrostatic charge dissipation.

Parameter, Value: Solar absorption greater than 0.98.

Capability Performance Goal: Solar absorption, durability.

Parameter, Value: Solar absorption greater than 0.98.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Wide Field Infrared Survey Telescope (WFIRST)	Enhancing	--	2025	2018	3 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enabling	--	2024*	2020	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.1 Engineered Materials and Structures
10.1.4 Adhesives

10.1.4.1 Biomimetic Adhesive (Gecko Feet)

TECHNOLOGY

Technology Description: Provides lightweight reversible adhesion for increased mobility of mechanisms and manipulators for in-space operations.

Technology Challenge: Gecko adhesive designs have to overcome directionality of adhesion; adhesion to non-flat surfaces need to be addressed.

Technology State of the Art: Conceptual grappling technologies have been demonstrated.

Parameter, Value:
On-off operation demonstrated on over 30 spacecraft surfaces, 30,000 on-off cycles, over 1 year of continuous hold, in a thermal vacuum chamber at full vacuum down to -60° C. Ability to grapple a representative piece of 33 kg debris.

TRL 3

Technology Performance Goal: Expand grappling capabilities of robotic arm on the International Space Station (ISS) to enable capture of cooperative and non-cooperative targets.

Parameter, Value:
Mass of object that can be captured, multiple surfaces that can be grabbed, functionality in space environment.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reversible adhesives.

Capability Description: Lightweight mechanism to support operational functions, such as satellite servicing, robotic inspection of spacecraft, orbital debris grappling, low-precision rendezvous and docking, astronaut extravehicular activity (EVA), and in-space assembly.

Capability State of the Art: Shuttle grappling arm, 7-degree of freedom ISS grappling arm.

Parameter, Value:
Degree of freedom, works with cooperative targets.

Capability Performance Goal: Increase mass of object that can be captured, ability to grab surfaces in space environment.

Parameter, Value:
Mass of object that can be captured, surfaces that can be grabbed, demonstrated functionality in space environment.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.5 Thermal Protection and Control

10.1.5.1 Nanostructured Thermal Sink

TECHNOLOGY

Technology Description: Provides cooling for detector systems.

Technology Challenge: Nanostructured heat sink designs need to be developed and evaluated in realistic space environments.

Technology State of the Art: Carbon nanotuce (CNT) array-based heat sink designs are being studied in universities and government labs.

Parameter, Value:

Proof of concept that thermal interface resistance between CNTs and other components can be reduced by bridging the interface with short, covalently-bonded organic molecules. Results also significant for graphene applications.

TRL 2

Technology Performance Goal: Demonstrate increase in energy storage from 200 kJ/kg to 333 kJ/kg. Further advances in Hx configuration may reduce containment mass.

Parameter, Value:

Thermal energy storage per unit mass of phase change material (PCM) from (kJ/kg). Better-than-water-based-systems, which are projected to provide ~333 kJ/kg of PCM.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Balanced spacecraft thermal load during cyclical mission environments.

Capability Description: Provide a reliable water phase change heat exchanger with 40% less mass than state of the art wax PCM technology.

Capability State of the Art: PCM heat exchangers provide thermal storage during relatively hot portions of missions with cyclic thermal environments. Heat can later be rejected during relatively cold portions of the cycle. PCMs currently use wax as the phase change medium on Skylab and Lunar Rover.

Parameter, Value:

Thermal energy storage per unit mass of phase change material (kJ/kg). Current wax systems provide ~200 kJ/kg of phase change materials.

Capability Performance Goal: Lightweight heat exchanger.

Parameter, Value:

Provide better-than-water-based systems, which are projected to provide ~333 kJ/kg of PCM.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

10.1 Engineered Materials and Structures
10.1.5 Thermal Protection and Control

10.1.5.2 Flexible Aerogel

TECHNOLOGY

Technology Description: Provides high-temperature thermal insulation for use in inflatable aeroshells.

Technology Challenge: Improved materials chemistry, scale-up are needed.

Technology State of the Art: High-temperature polymer aerogels. Alumina/aluminosilicate aerogels.

Parameter, Value:

Polyimide and ceramic aerogels developed and tested.

TRL 9

Technology Performance Goal: Demonstrate > 300 second use time.

Parameter, Value:

Thermal conductivity; < 20 mW/mK. To provide sufficient insulation, the multi-layer insulation (MLI) requires an effective thermal conductivity of 5 mW/mK.

TRL 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight, durable thermal insulation.

Capability Description: New, more flexible aerogels could be made into inflatable insulation that is packed away at the start of a mission and later deployed into lightweight heat shields or decelerators.

Capability State of the Art: Silica aerogel blanket insulation demonstrated in Inflatable Reentry Vehicle Experiment (IRVE) missions.

Parameter, Value:

3,000° F;

Thermal conductivity;

Density;

Use temperature range;

Insulating capability

Capability Performance Goal: Increase temperature resistance.

Parameter, Value:

Thermal conductivity; < 20 mW/mK;

To provide sufficient insulation, the MLI requires an effective thermal conductivity of 5 mW/mK.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

10.1 Engineered Materials and Structures
10.1.5 Thermal Protection and Control

10.1.5.3 Nanocomposite Ablators

TECHNOLOGY

Technology Description: Provides thermal protection in aerothermal applications involving translunar return velocities where surface temperatures can exceed 4,000º F.

Technology Challenge: Reducing entry loads and significantly reducing heat shield mass by 30-40%, ground-based testing facilities for thermal protection system (TPS), high cost, and long sustainability of certification limits are challenges.

Technology State of the Art: Carbon nanotube (CNT)-phenolic composites.

Parameter, Value:
Low mass loss after 45 seconds at 1,000 w/cm^2 flux

TRL 4

Technology Performance Goal:
Ablative heat shields with slow charring, low-density materials are necessary to control system mass.

Parameter, Value:
40% reduction in areal mass, greater than 2 kW/cm^2;
Reduced cost: ~50%;
Dual heat pulse capability demonstration

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-temperature, durable, lightweight material for reentry.

Capability Description: Enhanced capability material (i.e., more durability, higher temperature capability, greater thermal shock resistance, and lower thermal conductivity) to improve thermal protection material and vehicle performance.

Capability State of the Art: Phenolic Impregnated Carbon Ablator (PICA) flown on Stardust, Dragon, and Mars Science Laboratory (MSL).

Parameter, Value: 3,000° F for PICA, 3,360° F for PICA-X, weight, low density, efficient ablative capability at high heat flux.

Capability Performance Goal: Higher velocity entries (12+ km/sec). Order of magnitude increase in multi-layer insulation (MLI) performance. Tolerance for higher entry speeds and more heating.

Parameter, Value:
40% reduction in areal mass, greater than 2 kW/cm^2;
Reduced cost ~50%;
Dual heat pulse capability demonstration

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.1 Energy Storage

10.2.1.1 Lithium (Li) Battery Solid Polymer Electrolytes

TECHNOLOGY

Technology Description: Offers a robust packaging and safer device than liquid electrolytes. Li ions move back and forth between solid electrodes as the battery is charged and discharged.

Technology Challenge: Safety and efficiency are challenges.

Technology State of the Art: Poly(ethylene oxide) and similar polymers are currently used as solid electrolytes in lithium batteries.

Parameter, Value:	TRL
Operating temperature: 60° C	4

Technology Performance Goal: The performance should not be compromised at temperatures as low as -20° C.

Parameter, Value:	TRL
Low-temperature conductivity: -20° C	4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Batteries with high specific energy that can operate at high or low temperature.

Capability Description: Batteries capable of operating at ultra low temperature.

Capability State of the Art: Primary batteries with liquid electrolytes.

Parameter, Value:

Specific energy: 90-250 Wh/kg;

Energy density: 130-500 Wh/L;

Cycle life: 1;

Operating temperature: -20° C

Capability Performance Goal: Specific energy.

Parameter, Value:

> 250 Wh/Kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.1 Energy Storage

10.2.1.2 Nanostructured Electrodes for Thermal Galvanic Cell

TECHNOLOGY

Technology Description: Provides high electrochemically-accessible surface area and fast redox-mediated electron transfer to make more efficient thermo-eletrochemical cells.

Technology Challenge: Low grade, low efficiency.

Technology State of the Art: High thermocell efficiency is achieved by using vertical forests of multiwall-carbon nanotubes (CNTs) that reduce electrical and thermal resistance at electrode/substrate junctions.

Parameter, Value:
Efficiency: 1.4%

TRL
1

Technology Performance Goal: Efficiency.

Parameter, Value:
Efficiency: > 50%

TRL
1

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Batteries with high specific energy that can operate at high or low temperature.

Capability Description: Batteries capable of operating at extreme temperature.

Capability State of the Art: Thermal galvanic cell.

Parameter, Value:
Efficiency: < 1%

Capability Performance Goal: Efficiency.

Parameter, Value:
Efficiency: > 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.1 Energy Storage

10.2.1.3 Nanotube Composite Flywheel

TECHNOLOGY

Technology Description: Provides flywheels that can be spun at very high velocity, storing energy at a density comparable to fossil fuels.

Technology Challenge: Scale up and integration are challenges.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Carbon nanotubes: CNTs can store mechanical energy with a density of 1,125 Wh/kg and power density of 144 MW/kg.		**Technology Performance Goal:** Specific energy.	
Parameter, Value: Energy density: 1,125 Wh/kg; Power density: 144 MW/kg	2	**Parameter, Value:** 175 Wh/kg; 250 Wh/L	2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Large energy storage flywheels.

Capability Description: High efficiency and specific energy, MWh-class energy storage for deep-space and surface storage applications.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Kevlar fiber composite flywheels.	**Capability Performance Goal:** Energy density.
Parameter, Value: Energy density: 120 Wh/Kg	**Parameter, Value:** Energy density: > 200 Wh/Kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	4 years
New Frontiers: Io Observer	Enhancing	--	2029	2021	4 years
New Frontiers: Trojan Tour and Rendezvous	Enhancing	--	2024	2016	1 year
New Frontiers: Saturn Probe	Enhancing	--	2024	2016	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.1 Energy Storage

10.2.1.4 Nanostructured Electrode for Li Ion Battery

TECHNOLOGY

Technology Description: Offers very high surface-to-volume ratio for increased battery efficiency.

Technology Challenge: Complex synthesis process, low volumetric energy density due to reduced packing density, undesired side reaction between electrode and electrolye.

Technology State of the Art	Technology Performance Goal
Technology State of the Art: Lithium ion batteries are currently used in cell phones, consumer electronics, and automobiles.	**Technology Performance Goal:** Higher energy densities at temperatures as low as -20° C.
Parameter, Value: Specific energy: 230 Wh/kg — **TRL** 2	**Parameter, Value:** Specific energy: 400 Wh/Kg — **TRL** 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Batteries with high specific energy.

Capability Description: Batteries capable of operating at extreme temperature.

Capability State of the Art: Primary batteries (silver oxide (Ag-Zn), lithium sulfur dioxide (Li-SO_2), lithium thionyl chloride (Li-$SoCl_2$)).

Parameter, Value:

Specific energy: 90-250 Wh/kg;

Energy density: 130-500 Wh/L;

Cycle life: 1;

Operating temperature: -20 to -60° C

Capability Performance Goal: Specific energy.

Parameter, Value:

Specific energy: > 300 Wh/kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.1 Energy Storage

10.2.1.5 Nanostructured Supercapacitors

TECHNOLOGY

Technology Description: Provides high surface area for the deposition of conducting polymer or metal oxide that facilitates efficient ion diffusion, increasing the specific capacitance.

Technology Challenge: Safety, reliability, and cost are challenges.

Technology State of the Art: Lithium ion supercapacitors have been developed for terrrestrial applications but have not been evlauted for space.

Parameter, Value:
Energy density: 50 Wh/Kg

TRL
2

Technology Performance Goal: Specific capacitance, specific energy, energy density.

Parameter, Value:
Energy density: > 100 Wh/Kg

TRL
2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Batteries with high specific energy.

Capability Description: Batteries capable of operating at extreme temperature.

Capability State of the Art: Primary batteries (silver oxide (Ag-Zn), lithium sulfur dioxide (Li-SO_2), lithium thionyl chloride (Li-$SoCl_2$)).

Parameter, Value:
Specific capacitance;
Specific energy: 90-250 Wh/kg;
Energy density: 130-500 Wh/L;
Cycle life: 1;
Operating temperature: -20 to -60° C

Capability Performance Goal: Specific energy.

Parameter, Value:
Specific energy: > 300 Wh/Kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.1 Energy Storage

10.2.1.6 Lightweight Nanocomposite Magnets

TECHNOLOGY

Technology Description: Provides lighterweight nanocomposite magnets for power generation and energy storage. Eliminates or mitigates reliance on rare-Earth elements supplied outside the United States.

Technology Challenge: Lightweight magnets needed for engineered nanomaterials for applications in energy generation and storage. Shortage of rare-Earth metals will create critical need for alternative magnets or beyond-rare-Earth magnets technologies.

Technology State of the Art: Currently, all rare-Earth permanent magnets. Supply of rare-Earth elements is critical to the U.S. and NASA.

Parameter, Value: Br Flux density 0.2 Tesla

TRL: 2

Technology Performance Goal: Non-rare Earth or at least reduction in rare-Earth content composite bonded magnets that can replace rare-Earth magnets.

Parameter, Value: Flux density 0.5 Tesla

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight engineered materials and lightweight nanocomposite magnets for energy generation and storage, motors, and flywheels.

Capability Description: Non-rare Earth composite magnets mitigate vulnerability to supply.

Capability State of the Art: Rare-Earth bonded magnets.

Parameter, Value: At flux density Br 0.9 7 Tesla

Capability Performance Goal: Non-rare Earth nanocomposite magnets that can be used as alternative magnets for such systems as flywheels.

Parameter, Value: Br 0.4-0.7 Tesla

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
New Frontiers: Io Observer	Enhancing	--	2029	2021	5 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.1 Light Trapping and Harvesting Nanostructures (Quantum Structures, Nanophotonic Optical Surfaces) for Enhanced Photovoltaics (PVs)

TECHNOLOGY

Technology Description: Provides high-efficiency, low-weight photovoltaics for energy generation by enhancing solar energy capture and conversion of solar spectrum into useful light.

Technology Challenge: Ultra high conversion efficiency in required environments.

Technology State of the Art: Cadmium selenide (CdSe)/zinc sulfide (ZnS) core shell quantum dots decorated metal organic frameworks; nanophotonics-based antireflection gratings.

Parameter, Value:

Energy transfer efficiency of 80% with quantum dots; antireflection gratings increased efficiency of crystalline silicon (c-Si) colar cell by 25%.

TRL: 2

Technology Performance Goal: Compact, high-power solar arrays; survives high inertial loads; tolerant to high mechanical frequencies and high voltage and high radiation environment.

Parameter, Value:

35 kw/m^3;

> 50 kW arrays;

Efficiency: > 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High efficiency photovoltaics.

Capability Description: Provides photovoltaic systems with low mass and high quantum conversion efficiencies.

Capability State of the Art: Gallium (Ga), indium phosphide (InP)/gallium arsenide (GaAs)/germanium (Ge) multijunction solar cells.

Parameter, Value:

Cell efficiency: 30%

Capability Performance Goal: Efficiency.

Parameter, Value:

Efficiency: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	6 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.2 Hierarchically Engineered Photovoltaics (PVs)

TECHNOLOGY

Technology Description: Provides high-efficiency, low-weight photovoltaics for energy generation by enhancing charge separation and distribution.

Technology Challenge: Ultra high conversion efficiency in required environments.

Technology State of the Art: Metal oxide nanowire arrays.

Parameter, Value:
8.6% efficiency

TRL
2

Technology Performance Goal: Compact, high-power solar arrays; survives high inertial loads; tolerant to high mechanical frequencies and high voltage and high radiation environment.

Parameter, Value:
35 kw/m^3;
> 50 kW arrays;
Efficiency: > 50%

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High efficiency photovoltaics.

Capability Description: Provides photovoltaic systems with low mass and high quantum conversion efficiencies.

Capability State of the Art: Gallium (Ga), indium phosphide (InP)/ gallium arsenide (GaAs)/germanium (Ge) multijunction solar cells.

Parameter, Value:
Cell efficiency: 30%

Capability Performance Goal: Efficiency.

Parameter, Value:
Efficiency: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	6 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.3 Flexible, Rad Hard Photovoltaics (PV)

TECHNOLOGY

Technology Description: Provides flexible photovoltaics for space-radiation-resistant power generation.

Technology Challenge: Ultra high conversion efficiency in required environments.

Technology State of the Art: Ultrathin (nanometers) photovoltaics from monolayers of graphene and MoS_2, WS_2.

Parameter, Value:
Efficiency: 1%

TRL: 2

Technology Performance Goal: Compact, high-power solar arrays; survives high inertial loads; tolerant to high mechanical frequencies and high voltage and high radiation environment.

Parameter, Value:
35 kw/m^3;
> 50 kW arrays;
Efficiency: > 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High efficiency photovoltaics.

Capability Description: Provides photovoltaic systems with low mass and high quantum conversion efficiencies.

Capability State of the Art: Gallium (Ga), indium phosphide (InP)/ gallium arsenide (GaAs)/germanium (Ge) multijunction solar cells.

Parameter, Value:
Cell efficiency: 30%

Capability Performance Goal: Efficiency.

Parameter, Value:
Efficiency: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.4 Nanoporous Solid Oxide Fuel Cell (SOFC) Electrolytes

TECHNOLOGY

Technology Description: Provides for enhanced solid oxide fuel cell (SOFC) specific power at lower operating temperatures by increasing mass transport and charge generation.

Technology Challenge: Increased specific power at lower temperatures.

Technology State of the Art: Nanoporous Yttrium-stabilized-Zirconia membranes for SOFCs.

Parameter, Value:
Power density of 1.34 W/cm² at 500° C

TRL: 3

Technology Performance Goal: Subsystem service in the designated application requires high specific power, high conversion efficiency, long life, and high reliability.

Parameter, Value:
Specific power: 400 W/kg;
Efficiency: ~60%;
Lifetime: > 10,000 hours

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solid oxide fuel cells with high specific energy and operating temperatures below 500° C.

Capability Description: SOFCs and electrolyzers capable of operating at temperatures below 500° C.

Capability State of the Art: Alkaline fuel cells used on the Space Shuttle and Apollo program.

Parameter, Value:
12 kW peak and 6 W average power;
66-450 mA/cm² current density;
2,000 hours operation life

Capability Performance Goal:
Power density at 500° C.

Parameter, Value:
2 W/cm²

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.5 Nanoporous Solid Oxide Fuel Cell (SOFC) Electrodes

TECHNOLOGY

Technology Description: Provides lower mass for solid oxide fuel cell (SOFC) cathodes.

Technology Challenge: Increased specific power at lower temperatures.

Technology State of the Art: Nanoporous platinum alloy electrodes for thin film SOFCs.

Parameter, Value:
1,037 W/cm^2 power density

TRL: 3

Technology Performance Goal: Subsystem service in the designated application requires high specific power, high conversion efficiency, long life, on/off cycle capabilities, and high reliability.

Parameter, Value:
Efficiency: ~60%;
Lifetime: > 10,000 hours

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: SOFCs with high specific energy and operating temperatures below 500° C.

Capability Description: SOFCs and electrolyzers capable of operating at temperatures below 500° C.

Capability State of the Art: Alkaline fuel cells used on the Space Shuttle and Apollo program.

Parameter, Value:
12 kW peak and 6W average power;
66-450 mA/cm^2 current density;
2,000 hours operation life

Capability Performance Goal: Power density at 500° C.

Parameter, Value:
2 W/cm^2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	7 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.6 Photon-Enhanced Thermionic Emission (PETE)

TECHNOLOGY

Technology Description: Enables greater efficiency by increasing the number of electrons that are boiled off the surface.

Technology Challenge: Limiting the space charge to maximize electron flow; decreasing work function.

Technology State of the Art: Gallium nitride (GaN), carbon nanotubes (CNTs), amorphous diamond, or other materials, coupled with nanostructured surfaces.

Parameter, Value:	TRL
Efficiency: 10-15%; Predicted: 42-60%, depending on temperature	2

Technology Performance Goal: **High efficient PETE solar collectors able to survive harsh space environment.**

Parameter, Value:	TRL
Efficiency: 45%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-efficiency energy harvesting.

Capability Description: High-efficiency energy harvesting by converting vibrations or waste heat into electric power.

Capability State of the Art: Lead Telluride (PbTe), TAGS, and lead tin telluride (PBSnTe) used on Multi-Mission Radioisotope Thermoelectic Generator (MMRTG) for the Mars Science Laboratory (MSL).

Parameter, Value:
Efficiency: 6-7%

Capability Performance Goal: Efficiency.

Parameter, Value:
Efficiency: 45%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Europa	Enabling	--	2022*	2019	4 years
New Frontiers: Io Observer	Enabling	--	2029	2021	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.7 Thermionic Power Cells – Large Emission Surface

TECHNOLOGY

Technology Description: High-temperature emitter "boils" electrons off the surface, resulting in electron flow to the collector.

Technology Challenge: Limiting the space charge to maximize electron flow; decrease work function.

Technology State of the Art: Reducing work function by nanomaterial coatings on the collector and introducing nanostructures on the surface.

Parameter, Value:
Efficiency: 10-15%

TRL 2

Technology Performance Goal: Long-life and highly-efficient thermionic cells able to maintain collector/emitter distance in harsh space environment.

Parameter, Value:
Efficiency: 40%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-efficiency energy harvesting.

Capability Description: High-efficiency energy harvesting by converting vibrations or waste heat into electric power.

Capability State of the Art: Lead Telluride (PbTe), TAGS, and lead tin telluride (PBSnTe) used on Multi-Mission Radioisotope Thermoelectic Generator (MMRTG) for the Mars Science Laboratory (MSL).

Parameter, Value:
Efficiency: 6-7%

Capability Performance Goal: Efficiency.

Parameter, Value:
Efficiency: 40%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enabling	--	2022*	2019	1 year
New Frontiers: Io Observer	Enabling	--	2029	2021	1 year
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	1 year
New Frontiers: Saturn Probe	Enabling	--	2024	2016	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.2 Power Generation

10.2.2.8 Piezoelectrics

TECHNOLOGY

Technology Description: Provides a route to generate power by harvesting energy from ambient sources, such as environmental vibrations.

Technology Challenge: Developing long-life devices that do not wear out and perform long term in harsh space environments is a challenge.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Lead zirconate titanate (PZT) ribbon and nanowires, nanostructured zinc oxide (ZnO), Polyvinylidene Fluoride (PVDF), etc.		**Technology Performance Goal:** Robust, long-life, and efficient piezoelectric nanomaterials able to withstand extreme harsh space environment.	
Parameter, Value: Efficiency: 70-90% in ideal lab environment	2	**Parameter, Value:** Efficiency: 70% in operational environment	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-efficiency energy harvesting.

Capability Description: High-efficiency energy harvesting by converting vibrations or waste heat into electric power.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Pizoelectric materials: PZT), PVDF, quartz, lead scandium titanate, lead zirconate titanat. Structural Health Monitoring, autonomous data acquisition, radio frequency identification (RFID) systems, biological data monitoring.	**Capability Performance Goal:** Efficiency.
Parameter, Value: Efficiency: 0.3-15%	**Parameter, Value:** Efficiency: > 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years

10.2 Energy Storage, Power Generation, and Power Distribution
10.2.3 Power Distribution

10.2.3.1 Carbon Nanotube Based Power and Avionics Cables

TECHNOLOGY

Technology Description: Provides power distribution for aerospace vehicles at < 1/2 the mass.

Technology Challenge: Controllable synthesis of metallic carbon nanotubes (CNTs), graphene processing techniques, improved doping chemistries, and improved fiber processing methods are needed.

Technology State of the Art: CNT wires with conductivities as high as 52 kS/cm demonstrated in the laboratory.

Parameter, Value:
Electrical conductivity: 52 kS/cm

TRL
3

Technology Performance Goal: Electrical conductivity.

Parameter, Value:
Electrical conductivity: > 100 kS/cm

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lightweight power cables and harnesses.

Capability Description: Power and data cables that are lighter and more durable.

Capability State of the Art: CNT data cables have been demonstrated in space; power distribution has not been demonstrated. Copper wiring used in satellite, aircraft, and spacecraft.

Parameter, Value:
Frequency-dependent electrical conductivity, reliability of data transmission.

Capability Performance Goal: Electrical conductivity.

Parameter, Value:
Electrical conductivity: > 100 Ks/cm

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	6 years

10.3 Propulsion
10.3.1 Propellants

10.3.1.1 Nanopropellants

TECHNOLOGY

Technology Description: Provides fuel materials with the potential for higher combustion efficiency, enhanced reaction control, and lower mass.

Technology Challenge: To achieve process stability when large-scale manufacturing is involved through successful development of passivation chemistries to prevent premature oxidation of nanoparticles in the propellant and stable synthesis methods to tailor shape and size of nanoparticles in order to control their burn rate.

Technology State of the Art: Solid propulsion technology involving nanometer-dimensioned solid propellants to enhance the burning efficiency and burning rate and, hence, propulsion performance. Demonstration of the nanopropellants involving Al nanoparticles and ice has been done in the field using miniature rockets.

Parameter, Value:	TRL
Combustion efficiency; Thrust; Specific impulse (I_{sp})	3

Technology Performance Goal: State of the art is acceptable up to DRM-6.

Parameter, Value:	TRL
I_{sp}: 900 seconds	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Green propellants.

Capability Description: Provide alternatives to cryogenic and hypergolic propellants that are non-toxic and do not require cryogenic storage and handling.

Capability State of the Art: Cryogenic propellants such as liquid oxygen and liquid hydrogen.

Parameter, Value:

I_{sp}: 300 to 450 seconds

Capability Performance Goal: Non-cryogenic propellants with higher combustion efficiency, enhanced reaction control, lower mass with variable thrust capability.

Parameter, Value:

I_{sp}: 900 seconds;
Wt % capacity: > 15;
Thrust: 300-6,000 N;
Combustion efficiency: 70%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.3 Propulsion
10.3.1 Propellants

10.3.1.2 Nanostructures for Hydrogen Storage (Nanotubes, Nanoporous Materials, and Metal-Organic Frameworks (MOFs))

TECHNOLOGY

Technology Description: Provides storage of readily-accessible hydrogen without the need for cryogenic cooling, the associated storage energy costs, and loss due to boil off.

Technology Challenge: Material that meets all requirements has not yet been identified. Poor reaction kinetics/thermodynamics, stability to environment is an area of research.

Technology State of the Art: Novel nanomaterials are being investigated for storage using chemi- or physisorption mechanisms. The goal is to have solid-state, high-hydrogen storage capacity that allows for easily-accessed hydrogen. Important parameters include high surface area and strong interactions with hydrogen. Early in development.

Parameter, Value:

Combustion efficiency;

Thrust;

Specific impulse (I_{sp})

TRL 2

Technology Performance Goal: Liquid oxygen/hydrogen in-space propulsion stages provide rapid transit for crew. Chemical thrusters provide lunar decent and ascent.

Parameter, Value:

Weight capacity: > 15%

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Green propellants.

Capability Description: Provide alternatives to cryogenic and hypergolic propellants that are non-toxic and do not require cryogenic storage and handling.

Capability State of the Art: Hydrogen is used as a type of rocket fuel. It is also used aboard the International Space Station (ISS) for energy.

Parameter, Value:

Energy density: 120 MJ/kg, but large losses are associated with cryogenic storage and boil-off

Capability Performance Goal: Non-cryogenic propellants with higher combustion efficiency, enhanced reaction control, lower mass with variable thrust capability.

Parameter, Value:

I_{sp}: 900 seconds;

Wt % capacity: > 15;

Thrust: 300-6,000 N;

Combustion efficiency: 70%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years

10.3 Propulsion
10.3.1 Propellants

10.3.1.3 Low Density Nanogelled Propellants

TECHNOLOGY

Technology Description: Provides lightweight and high-energy-density propellants in the form of a nanogel that may enable variable thrust control.

Technology Challenge: Achieving high energy density is a challenge.

Technology State of the Art: Nanogel materials that can store fuel are being examined as novel propellants. High energy density and stability are key to realizing this technology. Propellant:polymer:water of 94:5:1 (mass) has been reported.

Parameter, Value:

Combustion efficiency;

Thrust;

Specific impulse (I_{sp})

TRL 2

Technology Performance Goal: State of the art acceptable up to DRM-6.

Parameter, Value:

Nominal thrust: 300 to 6,000 N

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Green propellants.

Capability Description: Provide alternatives to cryogenic and hypergolic propellants that are non-toxic and do not require cryogenic storage and handling.

Capability State of the Art: Bayern-Chemie gel-based rocket propellant tested in missiles at Technology Readiness Level (TRL) 6.

Parameter, Value:

Nominal thrust: 300 to 6,000 N

Capability Performance Goal: Non-cryogenic propellants with higher combustion efficiency, enhanced reaction control, lower mass with variable thrust capability.

Parameter, Value:

I_{sp}: 900 seconds

Wt % capacity: > 15;

Thrust: 300-6,000 N;

Combustion efficiency: 70%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years

10.3 Propulsion
10.3.1 Propellants

10.3.1.4 “Smart” Propellants

TECHNOLOGY

Technology Description: Provides highly-efficient propellants with ignition and combustion characteristics that can be altered with an applied external stimulus (electric or magnetic field, light) to provide variable thrust.

Technology Challenge: Requires advanced orbital mechanics computation and centimeter precision.

Technology State of the Art: Nano and pico spacecraft are being investigated computationally for use as propellants where the ejected spacecraft eventually returns to the host spacecraft for re-use.

Parameter, Value:

Combustion efficiency;

Thrust;

Specific impulse (I_{sp})

TRL: 1

Technology Performance Goal: State of the art acceptable up to DRM-6.

Parameter, Value:

Combustion efficiency: 70%

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Green propellants.

Capability Description: Provide alternatives to cryogenic and hypergolic propellants that are non-toxic and do not require cryogenic storage and handling.

Capability State of the Art: ALICE (nanoaluminum powder and ice) has been used as rocket fuel to propel a 9 foot rocket to 1,300 feet.

Parameter, Value:

Combustion efficiency: 70%

Capability Performance Goal: Non-cryogenic propellants with higher combustion efficiency, enhanced reaction control, lower mass, with variable thrust capability.

Parameter, Value:

I_{sp}: 900 seconds

Wt % capacity: > 15;

Thrust: 300-6,000 N;

Combustion efficiency: 70%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	6 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.1 Nanocomposite Ablators (High Strength Char)

TECHNOLOGY

Technology Description: Provides more durable, longer-life ablatives by inclusion of nanoscale additives to strengthen the char materials.

Technology Challenge: Achieving property consistency that affects application efficiency and material manufacturability are challenges.

Technology State of the Art: New technology to develop nanotechnology-based materials to create non-traditional ablators. Basic properties, such as flammability, high temperature stability, manufacturability, and application to propulsion, are currently being studied. Still in early development stage.

Parameter, Value:

Combustion efficiency;

Thrust;

Specific impulse (I_{sp})

TRL 2

Technology Performance Goal: State of the art acceptable up to DRM-6.

Parameter, Value:

I_{sp}: 900 seconds

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lower density, long-life thermal protection.

Capability Description: Provide lighter weight, more durable thermal protection systems for use in aeroshells and rocket nozzles.

Capability State of the Art: Cryogenic propellants, such as liquid oxygen and liquid hydrogen.

Parameter, Value:

I_{sp}: 300 to 450 seconds

Capability Performance Goal: Lifetime.

Parameter, Value:

1,500 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.2 Boron Nitride Nanotubes (BNNT)/Ceramic Structural Nanocomposites

TECHNOLOGY

Technology Description: Provides lightweight composites with high thermal stability and mechanical strength that can be used for a wide range of high temperature propulsion applications.

Technology Challenge: Development of repeatable, scalable production of boron nitride nanotubes (BNNT) reinforcements, processing methods to incorporate BNNT into composites, and evaluation of long-term durability and performance of BNNT composites in simulated propulsion system environments.

Technology State of the Art: BNNT-decorated ceramic fibers (silicon carbide (SiC), aluminum oxide (Al2O3)), aka "fuzzy fibers", and preforms developed. BNNT fuzzy 3D SiC preform reinforced composite shown to have three times the room temperature strength of conventional SiC 3-D preform reinforced SiC composite. No testing reported at elevated temperature.

Parameter, Value:
Material strength, temperature tolerance, robustness.

TRL
3

Technology Performance Goal: Toughness, strength.

Parameter, Value:
2X increase in toughness;
10X increase in strength

TRL
7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lighter-weight, more durable, higher-efficiency propulsion components.

Capability Description: Enhance the useful life and performance and reduce the mass of propulsion components.

Capability State of the Art: For large liquid fueled rockets, engines are made of stainless steels, nickel-based superalloys, and copper alloys for their high strength and high thermal conductivity in order to cope with the stresses and extreme thermal environments. These metals are heavy, and replacement with lightweight functional composites are slowly introduced as exemplified by with Delta IV (ablative materials) and Vega (composite casing).

Parameter, Value:
[Inconel 718: nickel-based super alloy used for combustion chambers]
Tensile strength: 1,100 MPa;
Thermal conductivity: 13 x10^{-6}/K;
Operation temperature: 3,000-6,000° F (1,650-3,300° C) with cooling

Capability Performance Goal: Interlaminar toughness.

Parameter, Value:
2X that of conventional Si/SiC composite

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	6 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.3 Flexible, Durable Aerogel Cryotank Insulation

TECHNOLOGY

Technology Description: Provides ultra-lightweight (99.8% porous) materials engineered for thermal insulation for propulsion fuel tanks.

Technology Challenge: Development and demonstration of scalable production methods and evaluation of durability under simulated use conditions are challenges.

Technology State of the Art: Polyimide aerogel insulation developed for inflatable decelerator applications for entry, descent, and landing. Testing performed at elevated temperatures. However, no testing was performed for cryotank insulation. Materials have densities on the order of 0.1 g/cm^3, thermal conductivities as low as 14 mW/mK.

Parameter, Value:	TRL
Material strength, temperature tolerance, robustness.	4

Technology Performance Goal: Thermal conductivity.

Parameter, Value:	TRL
14 mW/mK	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lighter-weight, more durable, higher-efficiency propulsion components.

Capability Description: Enhance the useful life and performance and reduce the mass of propulsion components.

Capability State of the Art: Spray on foam insulation (SOFI) and multi-layer insulation (MLI).

Parameter, Value:

Fuel temperature: liquid hydrogen fuel at -253° C (-423° F) and liquid oxygen oxidizer at -182° C; (-296° F). The MLI average density: 38.4 kg/m^3 (2.4 pounds/ft^3).

Capability Performance Goal: Low density and thermal conductivity.

Parameter, Value:

Density: < 200 mg/cm^3

Thermal conductivity: < 10 mW/mK

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.4 High Thermal Conductivity, Metallic Nanocomposite Nozzle Liners

TECHNOLOGY

Technology Description: Provides enhanced thermal conductivity, strength, and lightweight nozzle liners.

Technology Challenge: Thermal conductivity at copper/nanotube interface; scalable manufacturing methods.

Technology State of the Art: Extremely strong carbon nanotube (CNT)/metal nanocomposite materials have been reported. Enhanced mechanical properties and conductivities have been demonstrated with CNT/copper nanocomposites. Other nanocomposite materials (e.g. Cu-NbC) demonstate promising characteristics.

Parameter, Value: Material strength, temperature tolerance, robustness.

TRL: 2

Technology Performance Goal: Thermal conductivities higher than copper (350 W/mK).

Parameter, Value: W/mK

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lighter-weight, more durable, higher-efficiency propulsion components.

Capability Description: Enhance the useful life and performance and reduce the mass of propulsion components.

Capability State of the Art: For large liquid fueled rockets, engines are made of stainless steels, nickel-based superalloys, and copper alloys for their high strength and high thermal conductivity in order to cope with the stresses and extreme thermal environments. These metals are heavy, and replacement with lightweight functional composites are slowly introduced as exemblified by with Delta IV (ablative materials) and Vega (composite casing).

Parameter, Value:

[Inconel 718: nickel-based super alloy used for combustion chambers];

Tensile strength: 1,100 MPa;

Thermal conductivity: 13 x 10^{-6}/K;

Operation temperature: 3,000-6,000° F (1,650-3,300° C) with cooling

Capability Performance Goal: High thermal conductivity, low density.

Parameter, Value:

Thermal conductivity: > 20 x 10^{-6}/K

Density: < 7 g/cm^3

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.5 High Temperature Stable Nanoceramics

TECHNOLOGY

Technology Description: Provides improved fracture toughness and wear resistance material for use in extreme thermal environments.

Technology Challenge: Bulk processing (e.g., agglomerated powders, fine powders, sintering) is a challenge.

Technology State of the Art: Material properties, such as thermal shock and oxidation resistance, and mechanical strength are being investigated for several types of nanoceramics.

Parameter, Value:

Material strength, temperature tolerance, robustness.

TRL

2

Technology Performance Goal: Increased operating temperature. Improved toughness and strength.

Parameter, Value:

Temperature: > 3,000° F;

Toughnesss: 2X increase;

Strength: 10X increase

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Lighter-weight, more durable, higher-efficiency propulsion components.

Capability Description: Enhance the useful life and performance and reduce the mass of propulsion components.

Capability State of the Art: For large liquid fueled rockets, engines are made of stainless steels, nickel-based superalloys, and copper alloys for their high strength and high thermal conductivity in order to cope with the stresses and extreme thermal environments. These metals are heavy, and replacement with lightweight functional composites are slowly introduced as exemplified by Delta IV (ablative materials) and Vega (composite casing).

Parameter, Value:

[Inconel 718: nickel-based super alloy used for combustion chambers];

Tensile strength: 1,100 MPa

Thermal conductivity: 13 x 10^{-6}/K;

Operation temperature: 3,000-6,000° F (1,650-3,300° C) with cooling

Capability Performance Goal: Interlaminar toughness.

Parameter, Value:

> 2X that of conventional silicon carbide (SiC)/SiC composites

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	6 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.6 Nanoemitter for Coulomb Spacecraft Propulsion

TECHNOLOGY

Technology Description: Provides propellant-less propulsion system for in-space relative motion and control of small satellites by building coulomb forces between spacecraft using nanostructures for electrical charging.

Technology Challenge: Challenging proximity of spacecrafts to achieve desired propulsion effects. Stability, lifetimes, harsh environment, and reliability are also challenges.

Technology State of the Art: Many types of nanoemitters have been studied (e.g., carbon nanotubes (CNTs), nanowires, nanotips, etc.); any emitter that has been examined for space applications is a candidate.

Parameter, Value:	TRL
Areal density; Thrust; Specific impulse (I_{sp})	3

Technology Performance Goal: The technology is still in very early stages of formulation. Technology goals used here are based on reasonable assumptions made in a simulation.

Parameter, Value:	TRL
30 mN; I_{sp}: 2,000 seconds	5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small satellite propulsion.

Capability Description: Provide propulsion alternatives suitable for small, nano- and pico-satellites.

Capability State of the Art: There is no state of the art that is equivalent to the technology being used in relevant environment (space). This technology offers a propellant-less system for Earth orbit missions. This is especially suitable for formation or swarm flying of multiple miniature space crafts to achieve mission objectives. Mostly suitable for pico/femto/chip sats.

Parameter, Value:

No state of the art

Capability Performance Goal: Miniature size, lighter weight, higher I_{sp}/thrust.

Parameter, Value:

Areal density: 12g/m^2;

I_{sp}: 2,000 seconds / 30 mN

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years

10.3 Propulsion
10.3.2 Propulsion Components

10.3.2.7 Nanoemitter Based Thrusters (Includes Field Extraction Thrusters)

TECHNOLOGY

Technology Description: Provides high specific impulse (I_{sp}) and delta-V for small spacecraft (pico/femto/chip sats), as well as for fine movements of large space structures.

Technology Challenge: Miniaturization of all components and the system while keeping the system operation efficiency > 70% and reliable on-demand operation with long life are challenges.

Technology State of the Art: The technology has been demonstrated at different laboratories showing electrospray using nanoemitters and different low-melting point metal propellants.

Parameter, Value:	TRL
Thrust; Specific impulse (I_{sp})	3

Technology Performance Goal: High I_{sp} at small volumes to suit small spacecrafts.

Parameter, Value:	TRL
200 millinewtons (mN); I_{sp}: ~ 5,000 seconds within volume of < 10 cm^3	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Electropropulsion.

Capability Description: To achieve propulsion thrust using accelerated ions.

Capability State of the Art: LISA Pathfinder (Launch in 2015) uses Cs-based electric propulsion system. Ion propulsion used on Dawn.

Parameter, Value:

150 mN;

I_{sp}: > 4,000 seconds;

5 W operation power;

Delta-V: 11 km/s;

Total impulse; 1.2×10^7 N s

Capability Performance Goal: High I_{sp} at small volumes to suit small spacecrafts.

Parameter, Value:

200 mN;

I_{sp}: ~ 5000 seconds within volume of < 10 cm^3

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years

10.3 Propulsion
10.3.3 In-Space Propulsion

10.3.3.1 Low Areal Density, High Strength and Stiffness Nanofiber Solar Sails (Passive)

TECHNOLOGY

Technology Description: Provides a passive thrust, strong and lightweight nanofiber that uses solar radiation pressure for propulsion.

Technology Challenge: Fabrication, ultrathin, deploying in space, and spacecraft control are challenges.

Technology State of the Art: Nanofiber yarns and fabrics, mainly as carbon composites with polymers, have been studied as high-strength, low-mass materials.

Parameter, Value:

Areal density;
Thrust;
Specific impulse (I_{sp})

TRL 2

Technology Performance Goal: Low-thrust, in-space propulsion characterized by large area sails whose areal densities are low enough to reduce the overall sail mass.

Parameter, Value:

Areal density: 12 g/m^2

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small satellite propulsion.

Capability Description: Provide propulsion alternatives suitable for small, nano- and pico-satellites.

Capability State of the Art: Polyimide membrane solar sails were deployed on Ikaros.

Parameter, Value:

Areal density: 80 g/m^2

Capability Performance Goal: Miniature size, lighter weight, higher I_{sp}/thrust.

Parameter, Value:

Areal density: 12g/m^2;
I_{sp}: 2,000 seconds / 30 mN

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	6 years

10.3 Propulsion
10.3.3 In-Space Propulsion

10.3.3.2 Adaptive Nanofibers for Steerable Solar Sails

TECHNOLOGY

Technology Description: Provides nanofiber-based materials that have adaptive capabilities as a mechanism to steer a spacecraft.

Technology Challenge: Reliable technique to merge sensory, multifunctional, and steerable capabilities in an engineered nanofiber-based sail material.

Technology State of the Art: Both adaptive capability as well as smart nanofiber-based material development is still ongoing and no record of clear demonstration of the two together exists at this time.

Parameter, Value:

Areal density;

Thrust;

Specific impulse (I_{sp})

TRL 7

Technology Performance Goal: Low-thrust, in-space propulsion.

Parameter, Value:

Areal density: 12 g/m^2

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small satellite propulsion.

Capability Description: Provide propulsion alternatives suitable for small, nano-, and pico-satellites.

Capability State of the Art: Polyimide solar sails were deployed on Ikaros, variable reflectance elements are used for steering.

Parameter, Value:

Areal density: 80 g/m^2

Capability Performance Goal: Miniature size, lighter weight, higher I_{sp}/thrust.

Parameter, Value:

Areal density: 12 g/m^2;

I_{sp}: 2,000 seconds / 30 mN

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years

10.3 Propulsion
10.3.3 In-Space Propulsion

10.3.3.3 Nanotube Based Space Tether

TECHNOLOGY

Technology Description: Provides a strong, low-mass, potentially electrically-conductive tether material.

Technology Challenge: Achieving uniform strength, single fiber-based, ultra-long (thousands of meters) nanotubes that can be weaved into tethers or alternate techniques of creating such long tethers without compromising the overall fiber strength is a challenge.

Technology State of the Art: Maximum tether lengths of < 2 feet have been achieved so far of pure carbon nanotubes (CNTs), and maximum tensile strengths of < 2 GPa have been achieved. However, lower-strength CNT-polymer fibers have been made much longer.

Parameter, Value:	TRL
Areal density; Thrust; Specific impulse (I_{sp})	1

Technology Performance Goal: High-strength and lightweight tether material, and the ability to produce long tethers (ropes).

Parameter, Value:	TRL
Tether strength as a function of its density	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Small satellite propulsion.

Capability Description: Provides propulsion alternatives suitable for small, nano-, and pico-satellites.

Capability State of the Art: Bare aluminum tether on T-REX mission, Steel tether on STARS, Zylon coated with Photosil Hoytether (tether structure name) on MAST.

Parameter, Value:

Mass/unit length and tensile strength: 20 kg/km;

State of the art demonstrated CNT tether strength ~40 GPa per g/cc

Capability Performance Goal: Miniature size, lighter weight, higher I_{sp}/thrust.

Parameter, Value:

Areal density: 12 g/m^2;

I_{sp}: 2,000 seconds / 30 mN

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enhancing	--	On-going	--	10 years

10.4 Sensors, Electronics, and Devices
10.4.1 Sensors and Actuators

10.4.1.1 Embedded State Sensors

TECHNOLOGY

Technology Description: Provides efficient in-situ means to map strain and temperature of structures.

Technology Challenge: Technology has to be demonstrated beyond the laboratory.

Technology State of the Art: Nanostructured fiber optic sensors to detect thermal strain under long term space environment (e.g., low-Earth orbit (LEO)). Monitoring structures with embedded nanostructured fiber-optic sensors (FOS) has found use in various applications, ranging from cryogenic fusion energy experiments over rotor blades of wind turbines to airplane and spacecraft structures. Significant amount of research in the area of carbon nanotube (CNT) sensors. Technologies like lamb waves and embedded eddy current coils are receiving significant attention.

Parameter, Value:	TRL
Strain sensing is a focus of funded activities.	1

Technology Performance Goal: Temperature range: sunlight and Earth shadow temperature cycles for temperature and thermal strain measurement.

Pressure range: 10^{-12} bar to 1 bar.

Crack size: 1 mm for structure material and 10 mm for critical flaw better than 10 microstrain.

Parameter, Value:	TRL
-145° C – 470° C for Europa mission	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Embedded state sensors.

Capability Description: Provides in-situ and real time sensing of vehicle health monitoring of temperature, pressure, and crack detection.

Capability State of the Art: FOS on satellites are used for a range of activities, from the mapping of strain and temperature distribution to monitoring spacecraft attitude. A foreign space agency has been investigating FOS for several years and currently the first operational spaceflight demonstrations are under development. NASA developed embedded acoustic emission sensors (not nano) for impact monitoring which flew on the space shuttle for impact detection in wing leading edge.

Parameter, Value:

Sunlight and Earth shadow temperature cycles. Not specifically indicated in the reference.

Capability Performance Goal: Provides in-situ and real time sensing of vehicle health monitoring of temperature, pressure, and crack detection.

Parameter, Value:

Strain sensing is a focus of funded activities.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Real-Time System-Wide Safety Assurance: Introduction of Advanced Safety Assurance Tools	Enhancing	--	--	2025	8 years

10.4 Sensors, Electronics, and Devices
10.4.1 Sensors and Actuators

10.4.1.2 High Performance Radiation Sensors

TECHNOLOGY

Technology Description: Provides rapid detection of ultraviolet (UV), gamma, and neutron radiation.

Technology Challenge: Technologies have to be demonstrated beyond the laboratory.

Technology State of the Art: Carbon nanotube (CNT) sensors for proton and gamma ray detection.

Parameter, Value:

Sensitive to 10 MeV and 30 MeV with the proton flux varied from 1.0 x 10^2 to 2.2 x 10^{11} protons cm^{-2}s^{-1} to the total fluence of 2 x 10^6 to 1 x 10^{11} protons/cm^2. The low-dose detector can provide 4 orders of magnitude change of the emission intensity in response to low dose of 0.5 Gy irradiation.

TRL: 3

Technology Performance Goal: Low-power detector system capable of monitoring a wide range of high-energy heavy ions over a spherical aspect area and highly-sensitive gamma ray and proton detection.

Parameter, Value:

100 MeV proton dose with flux of 10^7 to 10^{11} 0.5 Gy gamma irradiation.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-performance radiation sensor.

Capability Description: Provides real-time, cumulative radiation dosage measurement for manned and unmanned spaceflight.

Capability State of the Art: Bubble detector for neutron detection in the International Space Station (ISS). Full-Field Radiation detector system and Fast solid state Cherenkov detector on MISSE 7. A UNH-led Cosmic Ray Telescope for the Effects of Radiation (CRaTER) radiation detector aboard NASA's Lunar Reconnaissance Orbiter (LRO).

Parameter, Value:

Mapping of heavy ions >100 MeV/amu;

High radiation flux rates for 10+ year missions.

Capability Performance Goal: Provides real-time, cumulative radiation dosage measurement for manned and unmanned spaceflight.

Parameter, Value:

Sensitive to 10 MeV and 30 MeV with the proton flux varied from 1.0 x 10^2 to 2.2 x 10^{11} protons cm^{-2}s^{-1} to the total fluence of 2 x 10^6 to 1 x 10^{11} protons/cm^2.

The low-dose detector can provide 4 orders of magnitudes change of the emission intensity in response to low dose of 0.5 Gy irradiation.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Earth Systematic Missions: Climate Absolute Radiance and Refractivity Observatory (CLARREO)	Enhancing	--	2021*	2016	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.1 Sensors and Actuators

10.4.1.3 Autonomous, Distributed Sensors

TECHNOLOGY

Technology Description: Provide means for communication in autonomous swarms and embedded chemical sensing in planetary probes.

Technology Challenge: Technologies have to be demonstrated beyond the laboratory.

Technology State of the Art: Carbon nanotube (CNT) sensors and other nanostructured fiber optics and electronic sensors.

Parameter, Value:	TRL
Space to ground laser communication, low-cost navigation sensor network with 8 x 1.5 U CubeSats.	3

Technology Performance Goal: Fully-capable, smart 100 g satellites with formation flying capability.

Parameter, Value:	TRL
Targeted pressure sensor response and resolution (10 Hz, 2 mbar) and temperature sensor resolution ~0.1° C, and a peak power consumption of less than 3.5 W, whereas the average power required during an orbit is just 0.4 W.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous, distributed sensors.

Capability Description: Provides a self-powered, software-controlled, ad hoc, ubiquitous wireless sensor network for planetary exploration and vehicle health management.

Capability State of the Art: Nanocomposite fiber optic sensor.

Carbon nanotube sensors.

Parameter, Value:

Space-to-ground laser communication, low-cost navigation sensor network with 2 x 1.5 U CubeSats.

Capability Performance Goal: Provides a self-powered, software-controlled, ad hoc, ubiquitous wireless sensor network for planetary exploration and vehicle health management.

Parameter, Value:

Space-to-ground laser communication, low-cost navigation sensor network with 8 x 1.5 U CubeSats.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	6 years

10.4 Sensors, Electronics, and Devices
10.4.1 Sensors and Actuators

10.4.1.4 Gas and Vapor Sensors

TECHNOLOGY

Technology Description: Provides highly sensitive means to detect fuel leaks and monitor cabin air.

Technology Challenge: Reliability of measurements and the longevity of sensors are challenges.

Technology State of the Art: Carbon nanotube (CNT) sensors to form an autonomously-distributed network for chemical profiling in cabin.

Parameter, Value:

.6 ppb to 10 ppm for nitrogen dioxide (NO_2) 1-100 ppm for ammonia high ppb to low ppm for organic volatiles low ppm for hydrogen (H_2) and carbon monoxide (CO).

TRL
3

Technology Performance Goal: Reduce the power 10x and overall sensor module size 100x.

Parameter, Value:

Target detection limit in mid- to low-ppb for gases and vapors detection using low power in < 100 mW.

TRL
7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Gas/vapor sensors with ppb to ppm sensitivity, µW power requirements.

Capability Description: Provides low-power, high-sensitive sensors that can form an autonomously-distributed network for gas/vapor, chemical or temperature detection.

Capability State of the Art: CNT chemsensors on a satellite and on the International Space Station (ISS) for NO_2, mercury (Hg), and formic acid (HCOOH). Miniaturized nanosensor in a drill string for real time and in-situ water (H_2O) detection in a chamber with a simulated Mars condition. Silcon carbide (SiC) sensors for fire detection in a cabin and for other planet exploration.

Parameter, Value:

Detection limit:

NO_2: 4.6 ppb;

Hg: 1 ppm;

HCOOH: 10 ppb;

Water vapor: 250 ppm at -45° C and 6 mbar;

Hydrogen: low ppm;

Carbon monoxide: low ppm

Capability Performance Goal: Provides low-power, high-sensitive sensors that can form an autonomously-distributed network for gas/vapor, chemical or temperature detection.

Parameter, Value:

4.6 ppb to 10 ppm for NO_2;

1-100 ppm for ammonia;

High ppb to low ppm for organic volatiles;

Low ppm for H_2 and CO

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.1 Sensors and Actuators

10.4.1.5 Water Quality Monitoring Sensors

TECHNOLOGY

Technology Description: Provides various mechanisms to monitor water quality with improved.

Technology Challenge: Going from culture plate reading or coliform test requires the development of biomaker detection system (e.g., protein, deoxyribonucleic acid (DNA), ribonucleic acid (RNA)), which is a challenge.

Technology State of the Art: Carbon nanotube (CNT)/nanofiber biosensor for strain-specific identification of bacteria. Quantum-dot-based biosensor for strain-specific identification of bacteria. Surface plasmon resonance or surface-enhanced raman scattering (SERS) nano-particle-based biosensor for strain specific identification of bacteria.

Parameter, Value:

1-organism limit of detection, strain-specific selectivity, less than 1 hour response time.

TRL 3

Technology Performance Goal: Provide species identification in-flight within 100 mL water. Reduce crew time to 1 mi. Reduce consumables to less than 1 lb/yr. Reduce response time to 1 hr. Distinguish viable vs non-viable microbes.

Parameter, Value:

Operate at μW or nW levels;

1 hour detection time;

1 organism LOD;

Strain identification

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-power, high-sensitivity water quality monitoring.

Capability Description: Monitors and identifies non-specific strain of bacteria presence.

Capability State of the Art: Coliform test, microbial culture used on the International Space Station (ISS). These tests require 1.7hr crew time 29 lbs/yr consumables 48hrs response time. Cannot distinguish viable from non-viable bacteria.

Parameter, Value:

Species identification;

Crew time;

Consumable mass;

Response time;

Microbe viability

Capability Performance Goal: Monitors and identifies non-specific strain of bacteria presence.

Parameter, Value:

1 organism limit of detection;

Strain-specific selectivity;

Less than 1 hour response time

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years

10.4 Sensors, Electronics, and Devices
10.4.1 Sensors and Actuators

10.4.1.6 Tactile Sensors

TECHNOLOGY

Technology Description: Provides means to measure surface pressure variations and mechanical deformation.

Technology Challenge: Homogeneous distribution of nanoparticles in elastomer binder.

Technology State of the Art: e-whiskers based on patterned carbon nanotube (CNT) and silver nanoparticle composite films. Gecko feet quantum tunneling composites (QTC) with nanoparticle conductor

Parameter, Value:

< 30 µW energy consumption;
13 Pa detection force;
< 17 ms response time;
1.14 kPa-1 sensitivity

TRL 3

Technology Performance Goal: Lower energy consumption. Low detection force. Fast response time. High sensitivity.

Parameter, Value:

< 30 µW energy consumption;
13 Pa detection force;
< 17 ms response time;
1.14 kPa-1 sensitivity

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Tactile sensors.

Capability Description: Provides highly-sensitive tactile sensors that function as “skin” or “whisker” in feeling touches and pressure.

Capability State of the Art: Tactile gloves using QTC on Robonaut QTC is a composite made from conductive filler particles with an elastomer binder Robonaut2 (R2) launched to the International Space Station (ISS) in 2011.

Parameter, Value:

Sensitivity, response time.

Capability Performance Goal: Energy consumption and detector parameters.

Parameter, Value:

< 30 µW energy consumption;
13 Pa detection force;
< 17 ms response time;
1.14 kPa-1 sensitivity

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.1 Flexible, Stretchable Electronics

TECHNOLOGY

Technology Description: Provides electronics that can be tethered to any shape of surface.

Technology Challenge: Consistency of the source of the nanomaterials for making the electronic device is a challenge. Developing a nano, micro fabrication process for handling flexible substrates and large quantity production is also a challenge.

Technology State of the Art: Both graphene and embedded nanowires allow development of flexible and stretchable electronics.

Parameter, Value:

Graphene has the breaking strength of 100 GPa that is capable of making a single atomic thickness sheet. The electronics' performance parameter should be equal or better than the current silicon electronics.

TRL 1

Technology Performance Goal: Equal or better than silicon electronics, radiation tolerance, and high temperature tolerance.

Parameter, Value:

THz level fast speed transistors.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Flexible, stretchable electronics.

Capability Description: Provides electronics that are tethered on any shape of surface.

Capability State of the Art: No field test yet.

Parameter, Value:

Endurance;

Strain tolerance

Capability Performance Goal: Provides electronics that are tethered on any shape of surface.

Parameter, Value:

Graphene has the breaking strength of 100 GPa that is capable of making a single atomic thickness sheet. The electronics' performance parameter should be equal or better than the current silicon electronics.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.2 Nanoelectronics Based Adaptive Logic

TECHNOLOGY

Technology Description: Provides low power adaptive logic based upon one-dimensional (1D) or two-dimensional (2D) nanostructures.

Technology Challenge: Consistency of the source of the nanomaterials for making the electronic device is a challenge. Developing a nano, micro fabrication process for handling flexible substrates and large quantity production is also a challenge.

Technology State of the Art: Nanowire-based nan-Finite State Machine (FSM).

Parameter, Value:	TRL
2-bit logic flow	2

Technology Performance Goal: Equal or better than silicon electronics, radiation tolerance, and high temperature tolerance.

Parameter, Value:	TRL
Functionally distinct 2-bit full adder with 32-set matched and complete logic output	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ultra-low power adaptive logic.

Capability Description: Provides low-power, radiation-hard, reconfigurable logic for computing and avionics.

Capability State of the Art: Fuzzy-logic systems and field-programmable gate arrays (FPGAs) in use on Mars Exploration Rover (non-nano).

Parameter, Value:
Adaptability, radiation durability

Capability Performance Goal: Provides low-power, radiation-hard reconfigurable logic for computing and avionics.

Parameter, Value:
2-bit logic flow

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.3 Nanoelectronics Based Memory Devices

TECHNOLOGY

Technology Description: Provides low-power-demand memory (including nonvolatile) and switches for computing and communications.

Technology Challenge: Evaluation of long-term radiation stability is a challenge.

Technology State of the Art: Carbon nanotube (CNT) vacuum electronics. Silicon carbide (SiC) nanoelectromechanical switches and logic gates. Nanomagnetic logic.

Parameter, Value: 1-30 Mrad, 10 uA, zero leakage power

TRL 3

Technology Performance Goal: Performance (speed > 1 THz), radiation tolerance.

Parameter, Value: 1 THz

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fault-tolerant, extreme-environment electronics and memory.

Capability Description: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Capability State of the Art: NRAM tested on STS-125 (May 2009).

Parameter, Value: Radiation-tolerant, low-power memory.

Capability Performance Goal: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Parameter, Value:
CNT vacuum electronics;
SiC nanoelectromechanical switches and logic gates;
Nanomagnetic logic.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	7 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enabling	--	2024	2016	1 year

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.4 Advanced Architectures (e.g., Spintronics)

TECHNOLOGY

Technology Description: Provides alternative to charge-based electronics by exploiting electron spin that is immune to radiation.

Technology Challenge: Consistency of the source of the nanomaterials for making the electronic device is a challenge. Developing a nano, micro fabrication process for handling large quantity production is also a challenge.

Technology State of the Art: Significant investment. Low Technology Readiness Level (TRL) work at this point.

Parameter, Value:	TRL
Equal or better than the current silicon electronics.	1

Technology Performance Goal: Radiation-tolerant and -resistant, high-speed devices.

Parameter, Value:	TRL
300 GHz to THz breaking strength of 100 GPa > 700° C with electron mobility of ~ 200,000 cm^2 V^{-1} s^{-1}	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fault-tolerant, extreme-environment electronics and memory.

Capability Description: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Capability State of the Art: Complementary metal-oxide-semiconductor (CMOS) technology with silicon electronic components.

Parameter, Value:

Feature size: 100^{-22} nm

Capability Performance Goal: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Parameter, Value:

Equal or better than the current silicon electronics.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	1 year

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.5 2D Nanomaterials Based Electronics

TECHNOLOGY

Technology Description: Provides electron mobility of ~200,000 $cm^2 V^{-1} s^{-1}$ to enable the next generation of high-speed electronics.

Technology Challenge: Consistency of the source of the nanomaterials for making the electronic device is a challenge. Developing a nano, micro fabrication process for handling large quantity production is also a challenge.

Technology State of the Art: Graphene electronics.

Parameter, Value:	TRL
Equal or better than the current silicon electronics.	1

Technology Performance Goal: Radiation-tolerant and -resistant, high-speed devices.

Parameter, Value:	TRL
300 GHz to THz breaking strength of 100 GPa > 700° C with electron mobility of ~ 200,000 $cm^2 V^{-1} s^{-1}$.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fault-tolerant, extreme-environment electronics and memory.

Capability Description: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Capability State of the Art: Complementary metal-oxide-semiconductor (CMOS) technology with silicon electronic components.

Parameter, Value:

Feature size: 100^{-22} nm

Capability Performance Goal: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Parameter, Value:

Equal or better than the current silicon electronics.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	1 year
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	8 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.6 1D Nanoelectronics

TECHNOLOGY

Technology Description: Provides novel component level technology and architectures to potentially produce systems 100-1000X denser at constant power with embedded redundancy; small size for radiation tolerance; time-dependent nano-micro electronic interconnects for functional adaptation.

Technology Challenge: Consistency of the source of the nanomaterials for making the electronic device is a challenge. Developing a nano, micro fabrication process for handling large quantity production is also a challenge.

Technology State of the Art: Carbon nanotube (CNT)-based logic devices and circuits, memory devices have been demonstrated. Wafer-level technology is very preliminary. Lack of ability to selectively grow various chiral semiconducting and metallic tubes is a major issue.

Parameter, Value:	TRL
Equal or better than the current silicon electronics.	1

Technology Performance Goal: Radiation-tolerant and -resistant, high-speed devices.

Parameter, Value:	TRL
A current gain cut-off frequency of 8 GHz has been obtained. Millipedes are non-volatile memories stored on nanoscale pits burned into the layer of a thin polymer, where data is read and written using an array of NEMS-based probes. This technique of data storage offers a density of more than 1 TB per square inch, about 20 times the density of the best magnetic storage available today.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fault-tolerant, extreme-environment electronics and memory.

Capability Description: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Capability State of the Art: CNTs as materials have been tested for radiation effects but not functional devices.

Parameter, Value:

Feature size: 100^{-22} nm

Capability Performance Goal: Provides electronics and memory that are capable of long-term operation in extreme environments (temperature, radiation).

Parameter, Value:

Equal or better than the current silicon electronics.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	8 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.7 Nanolithography

TECHNOLOGY

Technology Description: Provides scanning probe approaches to displace resists, deposit materials, or chemically change the substrate surface with nanoscale features.

Technology Challenge: In-space manufacturing and repair of electronics for long-duration human spaceflight are challenges.

Technology State of the Art: Simple electronic circuits and components have been generated, but scale up and integration not yet realized.

Parameter, Value: 20 nm resolution

TRL: 3

Technology Performance Goal: Critical dimension.

Parameter, Value: 10 nm resolution

TRL: 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced nanolithography.

Capability Description: Provides a non-optical wavelength dependent patterning by harnessing the self-assembly of polymer materials or physically printing or shaving materials.

Capability State of the Art: No relevant environment nanolithography demonstration.

Parameter, Value: Critical dimension

Capability Performance Goal: Provides a non-optical wavelength dependent patterning by harnessing the self-assembly of polymer materials or physically printing or shaving materials.

Parameter, Value: 10 nm resolution

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	1 year
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.8 Seamless 1D Schottky Diode

TECHNOLOGY

Technology Description: Provide high-speed, robust Schottky diode with wide-band gap 1D single material for nanoelectronics.

Technology Challenge: Evaluating the switching action speed is a challenge.

Technology State of the Art: Mechanical and thermal mismatch between the meal and semiconductor junction from two different materials makes the devices vulnerable to damage.

Parameter, Value:	TRL
Fabricated the electronic device that exceeds current limitations to the switching speed, mechanical, and thermal stability	1

Technology Performance Goal: High-speed/robust Schottky diode for nanoelectronics and sensitive pressure sensor in harsh environments.

Parameter, Value:	TRL
Tuning the band gap of a 1D single material (III-V and II-VI compounds) from ~6 eV to 0 eV	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-speed, mechanically-stable Schottky diode (nano-electronics).

Capability Description: The Schottky diode with band gap tuning technology will enable high-speed/robust nano-electronic devices like sensitive radiation detectors, ultra-small bioelectronics probes, and high-speed switches.

Capability State of the Art: Silicon carbide (SiC) Schottky diode is used with limited temperature operation range capability and stability.

Parameter, Value:

Harsh environment space applications with high thermal conductivity: 120 W/mK;

Operation temperature range: between 170° C and 300° C

Capability Performance Goal: Provides electronics and switches that are capable of:
1) High sensitivity (minimum work function between the semiconductor and metallic regions);
2) High mechanical stability;
3) High reverse leakage current;
4) Thermal stability;
5) Tunable rectified current, maximum peak current, and forward/reverse voltage;
6) High density, small size, lightweight device

Parameter, Value:

Better than the state of the art. High speed, minimum work function, tunable operation temperature (up to 1000° C) / rectified current / reverse voltage, high thermal conductivity (300-3,000 W/mK)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	8 years

10.4 Sensors, Electronics, and Devices
10.4.2 Nanoelectronics

10.4.2.9 Nanoscale Vacuum-tube Electronics

TECHNOLOGY

Technology Description: Provides high-speed digital electronics and amplifiers for harsh environments.

Technology Challenge: Scalable fabrication with features < 100 nm; long-term electrode stability.

Technology State of the Art: Nanoscale vacuum-channel transistors have been shown to have similar functionality as metal–oxide–semiconductor field-effect transistors (MOSFETs) made with solid gate dielectrics. By relying on field emission between shaped electrodes rather than field-modulated semiconductor charge transport, vacuum-channel transistors can be fabricated using radiation-hard, high-temperature materials such as ceramics and refractory metals. With modern-day nanoscale fabrication capabilities, the dimensions of these miniature vacuum tubes can be made sufficiently small to operate in high-pressure environments without ionizing ambient gases. Existing semiconductor-based vacuum-channel devices have already been shown to be capable of switching speeds up to 400 GHz – an order of magnitude faster than state of the art MOSFET devices.

Parameter, Value:	TRL
Single transistor devices (semiconductor-based); 400 GHz switching speed.	2

Technology Performance Goal: With modern batch fabrication processes, it is possible to imagine compact vacuum tube analogues of the various solid-state electronic devices currently used for power regulation, memory, and digital logic. Vacuum-channel transistors need to be demonstrated with reproducible electrode gap dimensions (~100 nm or less) using high-temperature materials (tungsten electrodes on ceramic substrates, for example), and these materials must be shown to be insusceptible to erosion from ionization. To create useful devices for memory and computation applications, “batch fabrication” also means reproducible dimensions over thousands or even millions of individual components on a single chip. Finally, while the switching speed of all-metal triode designs has yet to be measured, it is conceivable to optimize nanoscale vacuum tubes for high-speed operation on the order of 1 THz.

Parameter, Value:	TRL
Many (millions) of components fashioned into logic gates, memory, and low-power amplifiers (refractory metal-based); switching up to 1 THz.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development or maturation of this technology is dependent on the development/advancement of robust, batch-fabricated vacuum-tube electrodes with fabrication tolerances < 100 nm.

CAPABILITY

Needed Capability: Digital logic devices, memory, and power amplifiers compatible with harsh environments.

Capability Description: Manufacturable, high-speed, chip-scale devices capable of long-term operation in high-temperature and high-radiation environments.

Capability State of the Art: Silicon Complementary metal-oxide-semiconductor (CMOS) electronics are limited to operation < 200° C and can achieve switching speeds on the order of 40 GHz; radiation hardness requires specialized substrates, packaging, and/or logic redundancies. However, silicon integrated circuit design and manufacturing is remarkably mature.

Parameter, Value:

< 200° C, 40 GHz SOA switching speed, and maximum radiation tolerance of 1 to 10 Mrad.

Capability Performance Goal: Metal-based nanoscale triodes can in principle be used to reproduce the functionality of modern CMOS logic devices with comparable overall device size and order-of-magnitude faster switching. With proper material selection, devices can have extreme temperature and radiation tolerance; however, chip-level design and fabrication require significant advancement.

Parameter, Value:

>1,000° C possible with refractory metals on ceramic substrates, > 400 GHz possible with vacuum-channel devices, and radiation limited by mechanical damage threshold.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	1 year
New Frontiers: Saturn Probe	Enhancing	--	2024	2016	1 year
Planetary Flagship: Europa	Enhancing	--	2022*	2019	1 year
New Frontiers: Io Observer	Enhancing	--	2029	2021	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.1 Miniature Mass Spectrometer

TECHNOLOGY

Technology Description: Provides complete mass analysis function on a chip or at least 100x smaller than the state of the art, saving weight and power consumption.

Technology Challenge: Operation lifetime and demonstrating the technology in relevant environment are challenges.

Technology State of the Art: Molecular ionization from nano-emitters.

Parameter, Value:

Handheld: < 10 lbs

TRL 3

Technology Performance Goal: Reduced power, reduced mass, radiation resistance, and ability to operate in extreme environment.

Parameter, Value:

Mass range: 2-535 Da;

Sensitivity: sub ppb;

Power: 0.5 mW;

30 cm x 18 cm x 9.5 cm

TRL 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Miniature mass spectrometer.

Capability Description: Provides complete mass analysis function on a chip or at least 100x smaller than the state of the art, saving weight and power consumption based on nanoemitters.

Capability State of the Art: Quadrupole mass spec (QMS) flown on Mars Science Laboratory (MSL). QMS analyzes thermally-evolved gases from solid phase samples.

Parameter, Value:

Mass Range: 2-535 Da;

Sensitivity: sub ppb;

Detector dynamic range: > 10^{10} with pulse counting and Faraday cup;

Crosstalk: < 10^{6} adjacent unit mass channels

Capability Performance Goal: Provides complete mass analysis function on a chip or at least 100x smaller than the state of the art, saving weight and power consumption.

Parameter, Value:

Handheld: < 10 lbs

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enabling	--	2022*	2019	1 year
New Frontiers: Io Observer	Enhancing	---	2029	2021	1 year
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	1 year
New Frontiers: Saturn Probe	Enhancing	--	2024	2016	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.2 Gigapixel Optoelectronic Array

TECHNOLOGY

Technology Description: Provides a lens-free holographic imaging technique that is compact and low power.

Technology Challenge: Challenges in long-range order of self-assembled nanoparticles (size under 100 nm).

Technology State of the Art: Reach the high numeric aperture (.92) and 500 nm deflection limit. Reach far infrared (FIR).

Parameter, Value:
Nano lens array significantly enhances the signal-to-noise ratio (SNR) and refractive index.

TRL
2

Technology Performance Goal: Compact near infrared (NIR) holographic imaging using lens-free sensor array made from self-assembled nanolens array.

Parameter, Value:
100 nm resolution higher numeric aperture over 1.0 that comparable to 100x water immerse lenses from micro array to nano array (20 to 400 nm) to enhance the SNR.

TRL
2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Gigapixel optoelectronic array (e.g., FIR).

Capability Description: This is lens-free microscopy imaging technology with high numerical aperture (0.9+). The giga-pixel phase and amplitude can be assembled through "nanolenses." Multimode optical fibers are coupled with the sample plane wave to generate hologram images.

Capability State of the Art: None flown.

Parameter, Value:
Giga-pixel phase and amplitude.

Capability Performance Goal: This is lens-free microscopy imaging technology with high numerical aperture (0.9+). The giga-pixel phase and amplitude can be assembled through "nanolenses." Multimode optical fibers are coupled with the sample plane wave to generate hologram images.

Parameter, Value:
Nanolens array significantly enhances the SNR and refractive index.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: CMB Polarization Surveyor Mission	Enhancing	--	2035*	2035	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.3 Nanolasers

TECHNOLOGY

Technology Description: Provides lasing in ultraviolet (UV), visible, and near infrared (NIR) spectra.

Technology Challenge: Measuring molecular and vibrational spectroscopies is a challenge.

Technology State of the Art: Gallium arsenide (GaAs) NW NIR lasers 22 kW/cm^2 lasing threshold.

Parameter, Value:

Room temperature;
Low lasing thresholds

TRL 3

Technology Performance Goal: UV lasing and low lasing thresholds.

Parameter, Value:

< 200 nm UV < 25 kW/cm^2

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: UV lasers.

Capability Description: Provides smaller footprint and uses less power.

Capability State of the Art: Measure concentrations of ozone in the atmosphere (e.g., Differential Absorption Lidar (DIAL)).

Parameter, Value:

Ce:LiCAF tunable UV laser 282-300 nm (for DIAL) 130 to 800 mW

Capability Performance Goal: Provide smaller footprint and use less power.

Parameter, Value:

Room temperature;
Low lasing thresholds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enabling	--	2035*	2030	5 years
Earth Systematic Missions: Aerosol-Cloud-Ecosystems (ACE)	Enabling	--	2024*	2020	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.4 Nanostructured Emitter for Miniature X-ray Spectrometer

TECHNOLOGY

Technology Description: Provides high-efficiency electron emission to enable smaller size X-ray tube for chemical and mineral analysis.

Technology Challenge: Reliability and power of measurement are challenges.

Technology State of the Art: Carbon nanotube (CNT)-based X-ray tube.

Parameter, Value:	**TRL**
Thumb size.	2

Technology Performance Goal: Low-power, compact, and high-resolution detection.

Parameter, Value:	**TRL**
Specific developments include mW to tens of W, 3-5% band tunable THz sources for remote sensing, 10^9-10^{12} photons/s flux efficient X-ray tubes, sub 250 nm-UV lasers, and mW level mass ionizers.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Miniature X-ray spectrometer.

Capability Description: Provide a low-power, remote chemical and mineral detection capability.

Capability State of the Art: CheMin on NASA's Opportunity rover on Mars.

Parameter, Value:

Laptop size.

Capability Performance Goal: Provide a low-power, remote chemical and mineral detection capability.

Parameter, Value:

Thumb size.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Far Infrared Surveyor Mission	Enhancing	--	2035*	2035	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.5 Portable Integrated Medical Diagnosis Tool for Long-Duration Human Spaceflight

TECHNOLOGY

Technology Description: Provides means to monitor bodily functions through breath and fluid analyses with portable, highly-sensitive tools.

Technology Challenge: Sensor capability of all necessary health biomarkers is not readily available.

Technology State of the Art: Carbon nanotube (CNT), carbon nanofibers (CNF), and graphene electrochemical biosensor.

Parameter, Value: 9 channels

TRL 4

Technology Performance Goal: Sensitivity depends on target analyte. Reduce power by half. Reduce size by 30 times. Reduce weight by 10 times. Double recording channels.

Parameter, Value: 1 9V battery 5 cm x 2 cm x 2 cm 50 g; 32 channels

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous lab-on-a-chip system.

Capability Description: Provides an autonomous, fully-integrated crew health diagnostic system on a chip for non-invasive physiological monitoring of individuals.

Capability State of the Art: Abbot i-STAT or samples returned to ground for analysis.

Parameter, Value: 0.02 ng/mL

Capability Performance Goal: Provide an autonomous, fully-integrated crew health diagnostic system on a chip for non-invasive physiological monitoring of individuals.

Parameter, Value: 9 channels

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.6 Portable Microimaging Raman Spectrometer

TECHNOLOGY

Technology Description: Provides method with enhanced sensitivity for molecular finger printing.

Technology Challenge: Increasing the sensitivity, frequency range, and pulse power cannot be achieved as low-mass/power instruments suitable for exploration missions.

Technology State of the Art: Portable trapping and interrogating with surface-enhanced Raman scattering (SERS) active substrates.

Parameter, Value:
Portable

TRL 3

Technology Performance Goal:
Reduce detection limit by 10x. Increase number shots by 1 order magnitude. Increase frequency range by 1.5 times. Increase pulse power by 5 times.

Parameter, Value:
< 1 weight % detection;
> 10^9 shots;
40-100 kHz;
300-0.3 mJ/pulse

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Miniature aman spectrometer and microimagers.

Capability Description: Provides a Raman spectrometer for remote or in-situ imaging minerals that can identify organics.

Capability State of the Art: None flown.

Parameter, Value:
None flown.

Capability Performance Goal: Provide a Raman spectrometer for remote or in-situ imaging minerals that can identify organics.

Parameter, Value:
Portable

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enabling	--	2024	2016	1 year

10.4 Sensors, Electronics, and Devices
10.4.3 Miniature Instruments and Instrument Components

10.4.3.7 Nano-Electrospray

TECHNOLOGY

Technology Description: Provides an efficient means to disperse liquid as fine particle aerosol.

Technology Challenge: Challenges include the high variability from sample to sample.

Technology State of the Art: Chip-based nano-electrospray, coupled with mass spectroscopy (MS).

Parameter, Value: 25 pL: small volumes for MS

TRL: 1

Technology Performance Goal: Small sample volume. Low variability from sample to sample.

Parameter, Value: 25 pL

TRL: 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sample extraction, survey, and verification systems.

Capability Description: Nanomaterials’ high surface area is used to extract molecules and particles from a sample.

Capability State of the Art: No technology demonstration in relevant environment.

Parameter, Value:
None flown.

Capability Performance Goal:
Nanomaterials’ high surface area is used to extract molecules and particles from a sample.

Parameter, Value:
25 pL: small volumes for MS

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	3 years