National Aeronautics and Space Administration

NASA Strategic Technology Investment Plan

2017

National Aeronautics and Space Administration

Headquarters
Washington, DC

NASA's Office of the Chief Technologist is responsible for being the Agency's trusted authority for technology strategy and advocacy, leading NASA's technology analysis and innovation to enable future missions, advance the economic competitiveness of the United States, and benefit the Nation.

The 2017 NASA Strategic Technology Investment Plan is a comprehensive document that helps prioritize technologies essential to the pursuit of NASA's missions and achievement of national goals.

NASA recognizes that ambitious science and exploration require innovative technology—technology drives exploration.

This plan was created following the development of NASA’s 2015 Technology Roadmaps. The plan provides guidance for NASA's technology investments during the coming years.

The plan uses an analytical approach, reflecting input from each NASA Mission Directorate and ongoing challenges in secure systems, to categorize technology investments and provide guidance for balanced investments across NASA's technology portfolio.

We look forward to working with our commercial partners and academia to grow our aerospace technological base while also enabling our scientific understanding of the universe and advancing human and robotic exploration.

I encourage you to read NASA's Strategic Technology Investment Plan, and join us on our journey of discovery and exploration.

Douglas Terrier
NASA Chief Technologist
http://www.nasa.gov/oct

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Foreword

For more than a century, the National Aeronautics and Space Administration (NASA) and its predecessor the National Advisory Council for Aeronautics (NACA) have advanced our Nation's most ambitious and challenging technological endeavors. Through innovative technology development programs, NASA has enabled science and space exploration missions that have extended, in profound ways, our knowledge of the Earth, our solar system, and the universe beyond. NASA technology development programs have shaped our understanding of aeronautics and strengthened the aviation systems that sustain global transportation and commerce. To continue and guide this legacy of innovation, and to help ensure future missions and national goals are achieved, the Agency has developed the 2017 NASA Strategic Technology Investment Plan (STIP).

This STIP is an important element in the Agency-wide technology portfolio management process. It provides guiding principles for investment in the technologies detailed in the 2015 NASA Technology Roadmaps. The STIP process begins with the Agency Strategic Goals that ultimately drive the requirements for technology development that NASA must support over the next 20 years. The STIP uses an analytical approach, reflecting direct input from each NASA Mission Directorate, to categorize technology investments and provide guidance for balanced investments across the portfolio. Guiding principles, detailed below, align with the Agency's commitment to optimize technology investments while providing transparency and the maximum benefit to the Nation. Together, the goals, investment categories, and guiding principles outline an actionable plan to help NASA and its stakeholders drive technology development and innovation over the next two decades.

NASA's Definition of Technology:

A solution that arises from applying the discipline of engineering science to synthesize a device, process, or subsystem, to enable a specific capability.

Background

The 2017 STIP is a major update to the 2012 Strategic Space Technology Investment Plan. The updated STIP reflects advances in technology and evolving Agency needs and relies upon the updated 2015 NASA Technology Roadmaps. The updated roadmaps are organized around 15 key Technology Areas shown in Figure 1, which now include aeronautics. The roadmaps summarize the technologies that the Agency could develop. However, the roadmaps catalog many more technologies than can be funded in the technology portfolio. Consequently, the Agency must understand how each technology benefits its missions and the needs of the Nation and carefully allocate its technology investments.

The STIP provides high-level strategic guidance for investment in technology research and development across NASA, defining guidelines to calibrate the Agency's technology portfolio. NASA's Office of the Chief Technologist conducts an annual analytical assessment of the portfolio and compares the year's investments against the guidelines in the STIP. The results of this assessment are reviewed by the Mission Directorates and Offices via NASA's Technology

Figure 1: The Technology Areas from the 2015 NASA Technology Roadmaps.

Executive Council (NTEC).[1] As appropriate, NTEC may recommend realignment of the portfolio to meet the Agency's goals.

NASA’s Mission Directorates and Offices define and implement the specific content of the Agency’s technology portfolio through their programs. These programs (shown in Table 1) drive technology development across the Agency, innovating at all NASA Centers, in partnership with other Government agencies, industry, and academia. While some of the activities are within NASA’s focused technology development programs, research and technology development activities also take place as part of NASA’s many programs focused on specific missions. NASA’s technology research and development activities strive to be responsive and adapt to the changing needs of missions and the Agency.

Each year the Agency’s technology portfolio is assessed against the guiding principles for the investment categories identified in the STIP. NASA’s technology portfolio includes all of the technology development and related research activities underway across the Agency, found in NASA’s technology development programs, as components of larger mission programs, and as foundational engineering activites. For reference, Table 1 below shows a snapshot of the programs included in NASA’s 2016 technology portfolio assessment.

NASA’s future success will be determined largely by the investments and innovations made in scientific research and technology development. NASA’s focus has always been to discover, invent, and demonstrate new technologies that enable space exploration and scientific research, advance aeronautics, and improve life on Earth. This passion and purpose is what drives NASA’s vision and mission.

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[1] NTEC is NASA’s senior technology advisory body and helps to inform decisions on NASA’s technology capabilities, gaps, and investments. NTEC’s activities include, “Adjusting priorities based upon mission needs and technology development progress”; coordinating focus areas among Mission Directorates; and “balancing near-term, mid-term and far-term investments” (NASA Technology Executive Council Charter NC 1000.38).

Table 1: Snapshot of programs included in NASA's 2016 technology portfolio assessment.

Mission Directorate / Office	Program
Human Exploration and Operations Mission Directorate	Advanced Exploration Systems
	Human Research Program
	International Space Station
	Orion Spacecraft
	Space Biological and Physical Research Program
	Space Communications and Navigation Program
	Space Launch System Program
Science Mission Directorate	Advanced Component Technology
	Advanced Information Systems Technology
	Astrophysics Research and Analysis Program (APRA)
	Heliophysics - Technology and Instrument Development for Science (H-TIDeS)
	Homesteader (Europa Technology)
	In-Space Validation of Earth Science Technologies
	Instrument Incubator
	Mars Technology
	Maturation of Instruments for Solar System Exploration
	Nancy Grace Roman Technology Fellowships
	Planetary Instrument Concepts for the Advancement of Solar System Observations
	Planetary Science and Technology Through Analog Research
	Radioisotope Power Systems Technologies
	Strategic Astrophysics Technology
	Studies / Advanced Technology Initiatives
Space Technology Mission Directorate	Centennial Challenges Program
	Center Innovation Fund Program
	Flight Opportunities Program
	Game Changing Development Program
	NASA Innovative Advanced Concepts Program
	Small Business Innovation Research / Small Business Technology Transfer
	Small Spacecraft Technology Program
	Space Technology Research Grants Program
	Technology Demonstration Missions Program
Aeronautics Research Mission Directorate	Advanced Air Vehicles Program
	Airspace Operations and Safety Program
	Integrated Aviation Systems Program
	Transformative Aeronautics Concepts Program
Office of Safety and Mission Assurance	Nondestructive Evaluation Program
Office of the Chief Information Officer	IT Innovation Challenge Series

Developing the 2017 STIP

The 2017 STIP reflects the analysis performed on the 2015 NASA Technology Roadmaps and is part of the Agency's technology portfolio management process depicted in Figure 2. This portfolio process complements the internal budget and project selection process of the Mission Directorates by providing guidance from an integrated, Agency-wide perspective. To accomplish the STIP analysis, NASA gathered information from sources beyond the roadmaps, including a recent roadmap analysis by the National Academies of Sciences National Research Council (NRC).[2] The NRC reviewed and prioritized the technologies in the updated NASA roadmaps and identified technologies that are top priority, high priority, or low/medium priority. Top- and high-priority technologies were determined by the NRC to clearly support objectives for NASA's space science, Earth science, or exploration missions. Low/medium-priority technologies were identified where the NRC determined it is unclear how technical hurdles can be overcome, related technology has already been demonstrated, or NASA could more easily incorporate outside technical developments.

The NRC is one of the several inputs NASA uses to determine the initial categorization for the STIP. The NRC's independent prioritization are different from NASA's categorization because the Agency's categorization reflects different analysis criteria and direct input from the Mission Directorates. In addition, information from key documents, including the U.S. Space Policy and NASA's Strategic Plan, are a key input to the STIP analysis. This combined set of inputs was used to develop an initial categorization of the technologies, providing the basis from which the STIP leadership team—with representation from the NASA Mission Directorates, Center Technology Council, and Offices of the Chief Scientist, Engineer, Technologist and Information Officer—came to consensus on the final technology categorization. Technologies were reviewed for balance across technology maturity, capability objectives, and the pursuit of Agency technology investment goals.

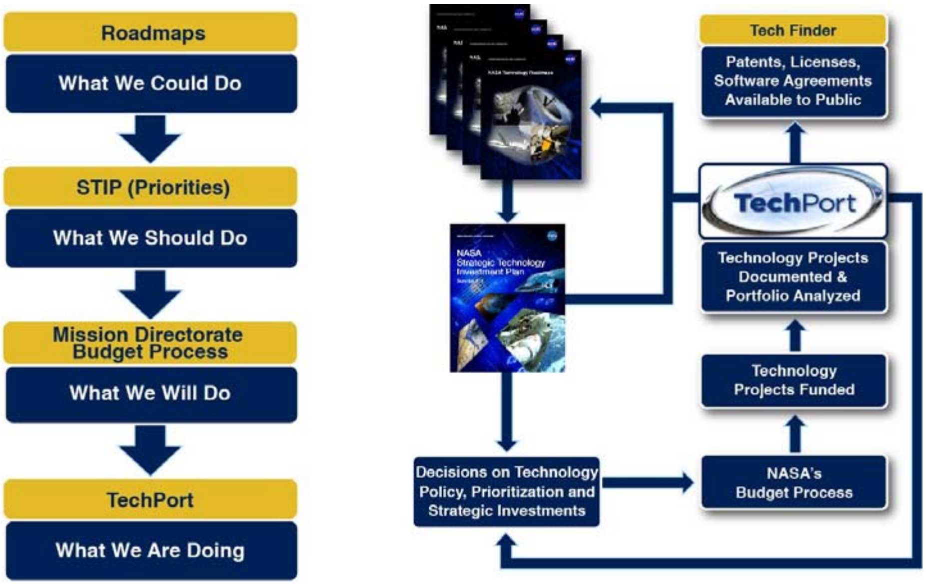

Figure 2: NASA technology portfolio management process.

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[2] National Academies of Sciences, Engineering, and Medicine. 2016. NASA Space Technology Roadmaps and Priorities Revisited. Washington, DC: The National Academies Press. doi: 10.17226/23582.

Strategic Goals To Drive Technology Development

NASA’s 2014 Strategic Plan details three broad goals: Expand the frontiers of knowledge, capability, and opportunity in space; advance understanding of Earth and develop technologies to improve the quality of life on our home planet; and serve the American public and accomplish our Mission by effectively managing our people, technical capabilities, and infrastructure. Inspired by these broad Agency goals, the STIP includes four goals to guide NASA’s technology portfolio, shown in Figure 3.

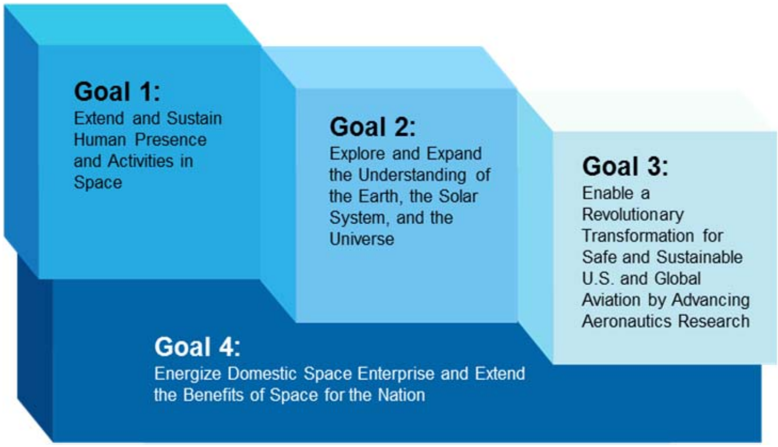

Figure 3: The four Strategic Goals To Drive Technology Development encompass the capabilities needed for NASA’s aeronautics, science, and exploration missions.

Goal 1: Extend and Sustain Human Presence and Activities in Space

Innovation is necessary to overcome the many challenges associated with long-duration, deep space human exploration. The capability to safely and reliably carry and sustain crew beyond low-Earth orbit is fundamental to the future of human space exploration and will rely on innovation across many systems, from propulsion to environmental control.

Goal 2: Explore and Expand the Understanding of the Earth, the Solar System, and the Universe

Expanding our scientific knowledge of the Earth, solar system, and universe will be the basis for many future human exploration missions. Importantly, science missions will provide the knowledge needed for understanding the Earth and the challenges linked with our climate and environment. Technological innovations that strengthen human exploration also support our most ambitious science missions.

Goal 3: Enable a Revolutionary Transformation for Safe and Sustainable U.S. and Global Aviation by Advancing Aeronautics Research

Long-term aeronautics research has provided the basis for new concepts leading to industry innovation and societal benefits. The future holds new challenges for the aviation system, including continuing growth to meet emerging global demand, integration of unmanned aircraft systems, and development of other innovative vehicle concepts to serve a myriad of needs.[3]

Goal 4: Energize Domestic Space Enterprise and Extend the Benefits of Space for the Nation

NASA is continuously working to strengthen the commercial space sector through productive partnerships with industry and other Government agencies. NASA’s efforts help expand knowledge and foster innovation across the space enterprise, and the Agency benefits from the expertise and capabilities sustained in a thriving commercial sector.

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[3] This Strategic Technology Development Goal is aligned with the Aeronautics Research Mission Directorates’ Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy.

Guiding Principles for Implementation

The following principles help guide NASA's technology investment strategy and portfolio execution. These principles are especially useful as the Agency performs ongoing analyses of the technology portfolio to maintain alignment with strategic objectives.

NASA Will Balance Investments Across All 15 Technology Areas in the Roadmaps

The 15 Technology Areas focus on anticipated mission-capability needs and provide details on each of the associated technology development needs. Investing appropriately in all Technology Areas ensures a well-rounded and robust technology portfolio. Guidelines for the level and focus of investment in these 15 Technology Areas are outlined in the STIP and will be refined, as needed, by the Mission Directorates and NTEC.

NASA Will Balance Investments Across All Levels of Technology Readiness

Technology Readiness Level (TRL) ranges from TRL 1 to TRL 9. At TRL 1, information learned from basic research is moving from an idea toward a particular technology application. At TRL 9, the technology is fully operational, incorporated into the complete system, and proven to work as designed with suitable reliability. Sustaining investments across all TRLs ensures a robust pipeline of new capabilities while also fulfilling immediate technology needs. To help maintain this balance and ensure longer-term innovations remain a priority, NASA will focus at least ten percent of the total technology investment (across Critical, Enhancing, Transformational categories) on TRL 1 and 2 technologies, as recommended by the NRC.

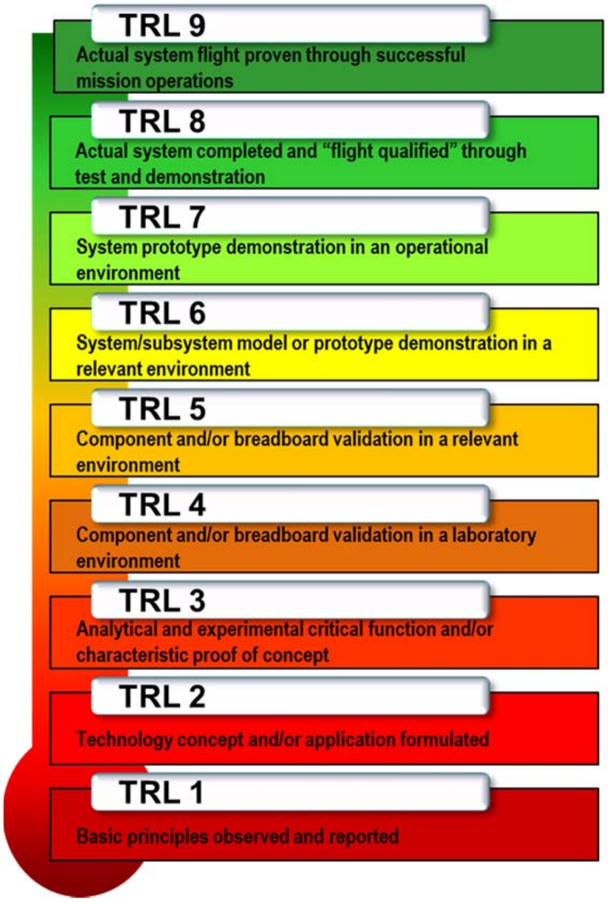

Figure 4: Technology readiness levels (source: NPR 7123.1 B).

NASA Will Balance Investments Across All 3 Investment Categories The STIP analysis defines three investment categories to guide future technology expenditures. These investment categories are Critical, Enhancing, and Transformational. The Agency will balance investment across these three categories as discussed in detail in the next section. Supporting each of these technology categories are foundational engineering tools, methods, and physical assets that NASA must develop to pursue planned and projected missions. Foundational engineering creates deeper expertise and knowledge and improves the prediction, analysis, and design of engineered systems. Foundational engineering is not identified in the STIP as a separate category—it is considered cross-cutting, and it is part of the balanced investment across Critical, Enhancing, and Transformational technologies.

NASA Will Provide Transparency to the Public

The Technology Portfolio System, TechPort, is NASA’s comprehensive resource for locating information about NASA-funded technology development activities. By providing insight into NASA’s ongoing activities, TechPort provides academia, industry, and the public the opportunity to evaluate the portfolio of technology projects, research their own specific areas of interest, compare the portfolio against NASA’s Technology Roadmaps and priorities, identify future opportunities of interest, and identify potential partnership opportunities in technology development. TechPort makes technology development information easy to find, accessible, and usable, helping NASA fuel entrepreneurship, innovation, and scientific discovery.

NASA's Advanced Exploration Systems (AES) division is pioneering innovative approaches and public-private partnerships to rapidly develop prototype systems, advance key capabilities, and validate operational concepts for...

Figure 5: TechPort homepage.

Characterizing NASA’s Investments

The Critical, Enhancing, and Transformational categories are used to group the technologies in the 2015 Roadmaps based on the STIP analytical criteria and the STIP leadership team’s inputs. The categories are devised to help allocate NASA’s technology investments. The STIP advocates a 70/20/10 balance and targets investment levels of 70 percent for Critical, 20 percent for Enhancing, and 10 percent for Transformational. It is important to recognize that these allocations for each category are notional and represent a starting point from which the Agency can assess balance across the portfolio. The complete table categorizing each technology is included in Appendix A, and specific target values for technology performance parameters can be found in the 2015 NASA Technology Roadmaps.

Critical Technologies

These technologies are Agency-critical and **necessary for planned and projected missions.**[4] Critical technologies often enable multiple missions and provide significant risk-reduction. These technologies are needed to fulfill near-term requirements or for developing capabilities with long development lead times. In many cases, Critical technology developments represent NASA unique technologies**.**

Enhancing Technologies

Enhancing technologies are those that **significantly improve mission performance**. These technologies generally represent performance improvements to existing technologies or capabilities. Enhancing technologies can strengthen return on investment, safety, or reliability. Performance improvements gained by Enhancing technologies can alleviate constraints on other technology systems, thereby, providing large benefits to the overall mission design.

Transformational Technologies

Transformational technologies are revolutionary, over-the-horizon technologies that can provide new capabilities that are important for future missions. Transformational technology developments address complex or previously unsolved problems. A reliable solution may take

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[4] NASA’s planned and projected missions are detailed in the Agency Mission Planning Model (AMPM), and other projected mission needs are considered by the individual Mission Directorates.

many iterations and require longer development time. Solutions addressing these needs are generally high risk but equally high return. They are often less mature and represent unique alternatives over current solutions. These technologies also generally have potential for a very high impact on cost, safety, or reliability.

The STIP also identifies ancillary technologies that provide incremental performance improvements to existing technologies and are required to support Critical and Enhancing developments. Although individual ancillary technologies are invested in as needed throughout the portfolio, they do not require assessment from a strategic perspective.

The investment categorization in the STIP ensures NASA is prioritizing the technologies needed for planned, near-term scientific discovery, human exploration, and aeronautics missions, while developing technologies that will be fundamental to its future missions.

Critical Technology Investments

NASA has identified ten broad investment areas containing Critical technologies. These areas group the Critical technologies from one or more of the 2015 NASA Technology Roadmap areas. Critical technologies identified in the 2015 NASA Technology Roadmaps are generally cross-cutting, meet more than one mission-specific need, and provide significant risk reduction. Critical technologies also include aeronautics research thrusts. NASA's investment in Critical technologies will comprise approximately 70 percent of the Agency's technology development portfolio. These technologies have a crucial enabling role for NASA's scientific, robotic, and human exploration missions. The ten Critical technology investment areas are:

1. Propulsion and Launch Systems
2. Human Health, Life Support, and Habitation
3. Destination Systems
4. Robotics and Autonomous Systems
5. Scientific Instruments, Sensors, and Optical Communications
6. Lightweight Space Structures and Materials
7. Entry, Descent, and Landing
8. Space Power Systems
9. Advanced Information Systems
10. Aeronautics

Technologies within these areas were identified by the STIP Leadership Team as Critical to implementing NASA's investment strategy. Each of the critical technologies in the STIP are characterized as either near or mid-term, based on the needed timing of initial investments. **Near-term Critical technologies** require investments in the technology starting now (or continuing current investments) in order to fulfill requirements for planned and projected missions.   In contrast, **mid-term Critical technologies** can delay their investment start dates three years or more from today.   Related technologies that potentially represent additional investments could be considered for future efforts. The following sections highlight technical challenges and NASA's approach to solving these challenges in addition to impacts to NASA and the Nation related to these technologies. The primary source for technical information within this section was NASA's 2015 Technology Roadmaps with additional information retrieved from the Agency's technology database, TechPort, and provided by the Mission Directorates.

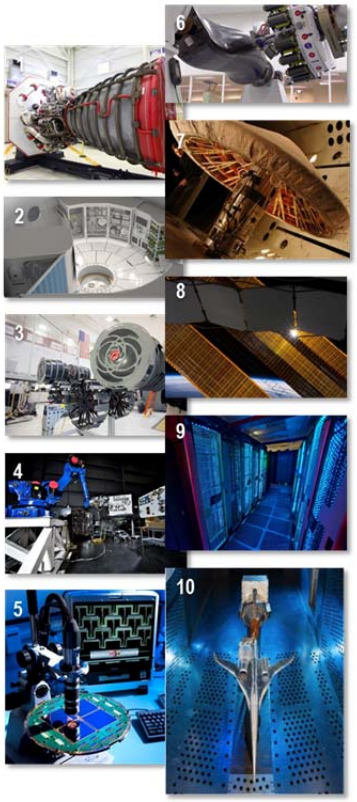

Figure 6: 10 areas within the Critical technology category.

🟧 Propulsion and Launch Systems

Propulsion and launch systems include the technologies necessary for NASA transport missions into and through space. Critical technologies within this area include solid and liquid rocket propulsion technologies for launching human and robotic payloads to orbit, in-space chemical and nonchemical propulsion technologies, and supporting technologies such as propellant gauging and thermal control. This Critical area also includes high-priority, related ground systems including testing facilities. These technologies are from the following roadmap technology areas:

Table 2: Critical technologies in propulsion and launch systems.

Technology Area – Level 3
1.1.1 Propellants
1.1.6 Integrated Solid Motor Systems
1.2.1 LH2/LOX Based
1.2.2 RP/LOX Based
1.4.3 Launch Abort Systems
2.1.2 Liquid Cryogenic
2.2.1 Electric Propulsion
2.2.3 Thermal Propulsion
2.4.2 Propellant Storage and Transfer
14.1.2 Active Thermal Control
14.2.3 Heat Rejection and Energy Storage

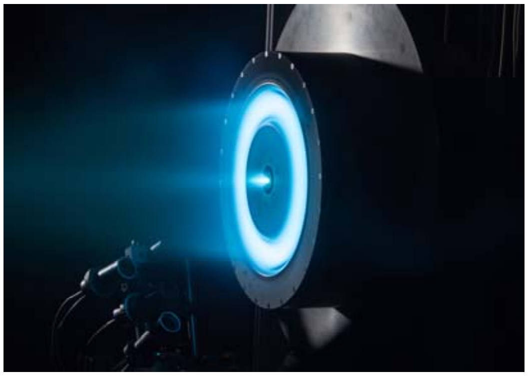

Figure 7: Solar Electric Propulsion (SEP).

Technical Challenges and Approach

Safe, reliable, and affordable access to and through space continues to be the goal of NASA’s investment in propulsion and launch system technologies. The Agency has made great strides in developing heavy lift launch capabilities, leveraging the commercial launch sector, improving highly-efficient electric in-space propulsion, and exploring emerging propulsion concepts with the potential to revolutionize space transportation.

NASA will invest in technologies to enhance performance, improve manufacturability, and reduce cost for engines, including advanced liquid oxygen/kerosene high-thrust engines, as well as more affordable upper stage engines. These technologies are augmented by advances in solid rocket boosters and feed into NASA’s heavy lift program.

NASA’s investments in in-space propulsion will aim to improve existing chemical propulsion systems and continue to mature nuclear thermal propulsion and high-power electric propulsion technologies, as well as sub-kW electric propulsion for small spacecraft and CubeSat science missions. This area includes a range of critical supporting technologies. A particular challenge for chemical in-space propulsion is the storage, measurement, maintenance, and transfer of cryogenic liquid propellants.

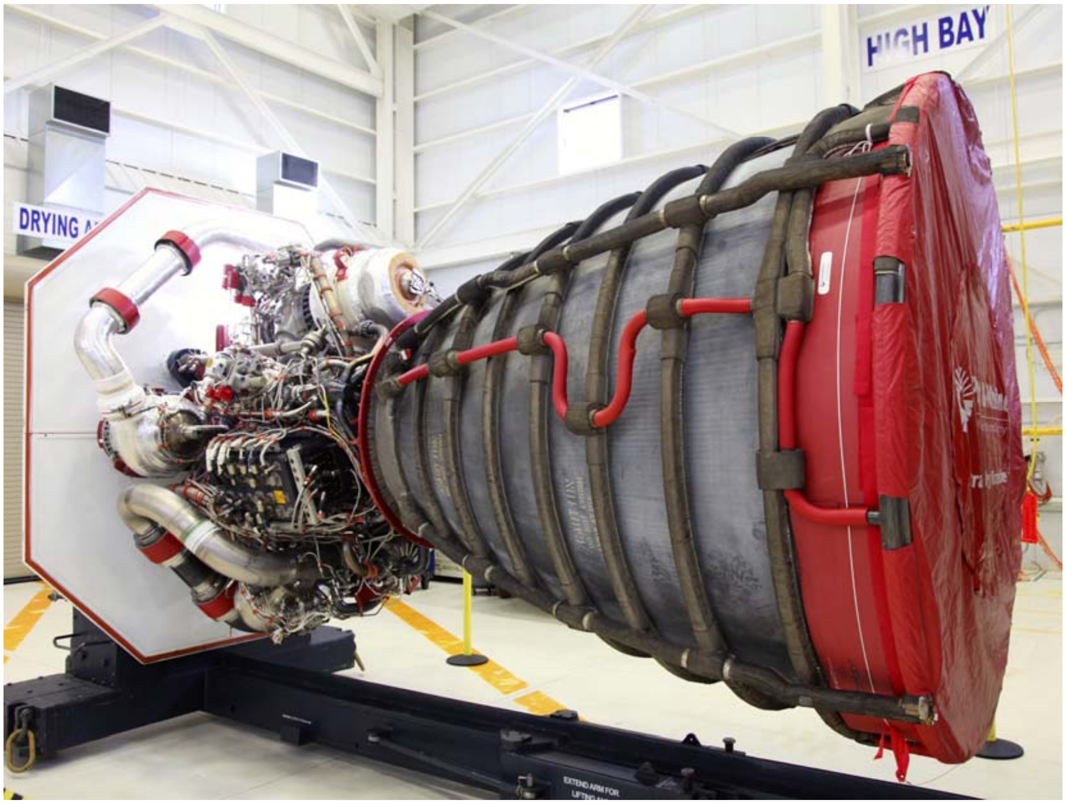

Figure 8: RS-25D engine awaits shipment to Stennis Space Center in Mississippi.

Impact to NASA

NASA's technology investments will target improved performance and reliability, reduced manufacturing costs, and new approaches to enable a diverse set of new missions. Advances in domestic liquid oxygen and rocket propellant engine technologies would reduce or eliminate the Nation's reliance on foreign suppliers for access to space. Oxygen-rich staged combustion engines could significantly increase lift capacity and enable human missions to Mars. Advanced propellant management extends spacecraft lifetimes and could eliminate the need for multiple propellants and associated plumbing, significantly reducing the cost and complexity of NASA missions. Innovations for in-space propulsion technologies also provide advantages, including high-power extensibility using electric thrusters (Hall effect, ion, and other concepts) as well as nuclear thermal propulsion, which could enable fast transit, deep space missions at lower overall mission cost.

Impact to Nation and Partners

Other Government agencies have identified liquid oxygen and rocket propellant engines, in-space propulsion, and propellant storage and transfer as high priorities for national development. These technologies align with the Nation's space policy that calls on NASA to "conduct research and development in support of next-generation launch systems, including new U.S. rocket engine technologies," and several of these technologies are explicitly stated in the NASA Authorization Act. Commercial organizations identified solid rocket motor systems, liquid rocket engines, and propellant storage and transfer as having important benefits to the space industry. In addition, in-space propulsion technologies are potential areas for partnership. NASA's investment in these Critical propulsion and launch system technologies will have an expanding impact on our national goals and economic development.

■ Human Health, Life Support, and Habitation Systems

NASA is progressing on the Journey to Mars and other deep space and planetary destinations. To enable these missions, NASA will invest in technologies to protect, sustain, accommodate, and connect our astronauts, as well as keep them healthy. NASA is currently developing a suite of human health and performance technologies for use in deep space. Critical technologies in this area also include Environmental Control and Life Support Systems (ECLSS), radiation protection, advanced space suits, and countermeasures to use on long space missions. The technologies in this Critical area are found in the following roadmap technology areas:

Table 3: Critical technologies in life support and habitation systems.

Technology Area – Level 3
6.1.1 Air Revitalization
6.1.2 Water Recovery and Management
6.1.3 Waste Management
6.1.4 Habitation
6.2.1 Pressure Garment
6.2.2 Portable Life Support System
6.2.3 Power, Avionics, and Software
6.3.1 Medical Diagnosis and Prognosis
6.3.2 Long-Duration Health
6.3.3 Behavioral Health
6.3.4 Human Factors
6.4.1 Sensors: Air, Water, Microbial, and Acoustic
6.4.2 Fire: Detection, Suppression, and Recovery
6.4.4 Remediation
6.5.1 Risk Assessment Modeling
6.5.2 Radiation Mitigatoin and Biological Countermeasures
6.5.3 Protection Systems
6.5.4 Space Weather Prediction
6.5.5 Monitoring Technology

Figure 9: Z-2 Extravehicular Activity (EVA) suit with Portable Life Support System (PLSS).

Technical Challenges and Approach

NASA is currently overcoming the challenges associated with sustaining life for long-duration missions in space. The Agency is developing technologies to maintain and revitalize habitat atmospheres, recycle water, and manage waste. These systems must work reliably, be easy to maintain, and use fewer consumables than the current ISS ECLSS.

NASA matures EVA systems that are critical to every foreseeable human exploration mission, including a launch, entry, and abort (LEA) suit system that protects the crew from launch to transition for planetary excursions. EVA systems include hardware and software that span multiple assets in a given mission architecture and interfaces with many vehicle systems.

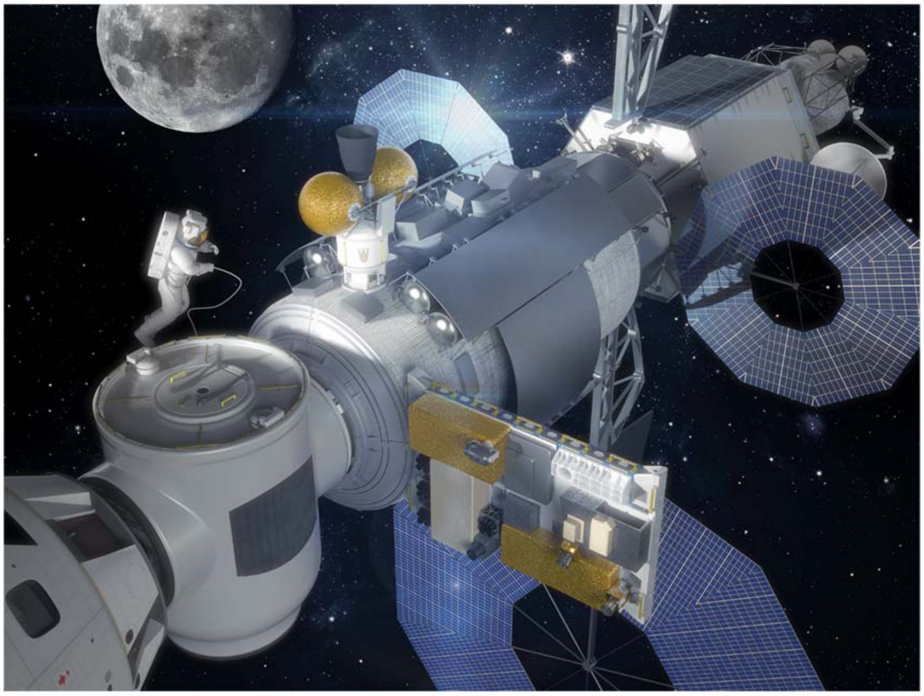

Figure 10: Deep space habitat concept.

NASA is addressing key challenges within the habitat for maintaining the physical and mental health of astronauts and detecting and diagnosing illness, cognitive/performance degradation, or trauma. NASA is developing tools to model, understand, and predict radiation risk and develop countermeasures and protection systems. NASA develops technologies that ensure crew health and safety by protecting against spacecraft hazards and by providing for an effective response should an accident occur. Specifically, NASA enhances sensors to monitor air, water, and microbial environments; provides for fire detection, suppression, and recovery; and enables remediation by providing the crew with the ability to clean the habitable environment of the spacecraft in the event of an off-nominal situation. Each of these technologies is critical to a successful mission that achieves its objectives and returns the astronauts home safely.

Impact to NASA

Technologies within this focus area work together to enable NASA to successfully conduct human missions into deep space and to Mars. These technologies will be incorporated in the next generation of deep space vehicles after proven through ground and ISS testing to support future development for Mars missions. These technologies will help decrease the mass and cost of future missions while increasing the reliability and safety of all crewed missions.

Impact to Nation and Partners

Many of the international partners NASA is working with have identified these technologies as instrumental to their own exploration plans. Several of the human health and human factor technologies have applications in other transportation systems such as aviation, and other Government agencies have identified partnership opportunities in these areas. From the commercial perspective, several of these technologies encourage ambitious efforts to expand low-Earth orbit operations and develop new space markets, including space resources. Commercial companies with terrestrial applications identified some of these critical technologies (such as brine processing, medical devices, and environmental sensors) as areas of interest.

Destination Systems

Future human and robotic exploration missions will be enabled by destination systems that provide the technologies needed for long-duration operations away from Earth, whether orbiting another planet or landing a rover. NASA's Critical technologies in the destination systems area will provide the capabilities for in-situ resource utilization (ISRU), autonomous operations, food production, crew mobility, and protection from destination hazards. The development of these Critical technologies will significantly shape the overall mission architecture, from volume and mass constraints to extending science and exploration activities and ensuring crew safety. The technologies in this Critical area are found in the following roadmap technology areas:

Table 4: Critical technologies in destination systems.

Technology Area – Level 3
7.1.2 Resource Acquisition
7.1.3 Processing and Production
7.2.1 Autonomous Logistics Management
7.2.4 Food Production, Processing, and Preservation
7.3.1 EVA Mobility
7.5.3 Integrated Flight Operations Systems
7.6.1 Particulate Contamination Prevention and Mitigation

Figure 11: Mars Oxygen ISRU Experiment (MOXIE).

Technical Challenges and Approach

From low-Earth orbit to deep space habitats, NASA is investing in the technologies that will allow crew to operate safely and sustainably at their mission destination. ISRU technologies are an enabler for space exploration: They are needed to dramatically reduce overall mission mass and, thereby, enable missions to other planets. ISRU technologies can provide destination systems building materials, consumables for propulsion systems, and habitat life support systems. ISRU systems for material acquisition, processing, and production must be tailored to the destination environment and must integrate with other exploration systems.

Optimizing the storage and use of consumables at destinations, including food, is another challenge for NASA. The Agency is investing in automated logistics management as well as production and processing techniques to better manage these challenges at mission destinations. To sustain operations at destinations, and to extend the capabilities of science and exploration missions, crew will require advanced technologies for extravehicular activity (EVA) mobility. NASA is working to develop EVA mobility tools and designs supporting safe egress and ingress for crew.

The complex challenges facing crew on long-duration, deep space missions will also require capabilities for crews to operate autonomously from ground systems on Earth. Advanced situational awareness software will be key to providing crew with integrated flight operations. NASA is working to develop the systems needed to support the thousands of procedures that are executed during mission operations, from environmental control and life support system operation to detection, isolation, and recovery from system faults. Dust and particulate contamination are among the many hazards that could threaten crew environments and damage vital equipment at mission destinations. NASA is working to understand the soils and dust plumes to effectively mitigate dust and protect equipment and crew.

Figure 12: NASA's Regolith Advanced Surface Systems Operations Robot 2.0.

Impact to NASA

Technologies within this Critical area will ensure NASA can sustain human operations in space and reach destinations far from Earth. NASA's investment in ISRU technologies will ensure development of processing capabilities that require less power and maintenance and fit within mission size and mass constraints. ISRU capability will reduce mission risk and extend exploration capabilities for longer durations. Autonomous logistics management and integrated flight systems will reduce reliance on ground systems and help optimize performance. Food production technology will impact NASA by sustaining crew for long-duration missions. EVA mobility will not only extend exploration capabilities, it will provide crew with critical situational awareness, allowing crews to work outside their vehicle to analyze and maintain the various destination systems.

Impact to Nation and Partners

NASA's investment in destination systems has the potential for large impacts beyond the Agency. International space agencies have suggested that the development of ISRU technologies could be a potential partnership opportunity supporting their own exploration missions. Internatonal space agencies have also expressed interest in potential partnership opportunities for other Critical destination systems, including technologies that support autonomy from ground systems on Earth and systems for food production. NASA's investment in Critical destination systems will pave the way for future commercial operations in low-Earth orbit and beyond.

■ Robotics and Autonomous Systems

Future NASA missions will be enabled by the development of Critical technologies in the robotic and autonomous systems area. Robotic systems will extend our ability to gather scientific data, function as precursors to human destinations, and work alongside crews on human exploration missions. Autonomous systems will enable many of the complex functions associated with missions that travel farther into the solar system and must operate independently from ground systems on Earth. Critical technologies include objective mapping and recognition, extreme-terrain mobility, sample acquisition, and onboard systems needed to continuously monitor and detect spacecraft faults and failures. Other Critical technologies in this area include sensors and cameras for inspection and navigation, dexterous manipulation for tending dormant facilities and sample collection, and human augmentation with wearable helmets and other gear. The technologies that NASA are prioritizing to support robotics and autonomous systems are associated with the following roadmap technology areas:

Table 5: Critical technologies in robotics and autonomous systems.

Technology Area – Level 3
4.1.3 Onboard Mapping
4.1.4 Object, Event, and Activity Recognition
4.2.1 Extreme-Terrain Mobility
4.3.6 Sample Acquisition and Handling
4.3.7 Grappling
4.4.8 Remote Interaction
4.5.1 System Health Management
4.5.2 Activity Planning, Scheduling, and Execution
4.5.8 Automated Data Analysis for Decision Making
4.6.1 Relative Navigation Sensors
4.6.2 GN&C Algorithms
4.6.3 Docking and Capture Mechanisms and Interfaces
4.7.2 Verification and Validation of Complex Adaptive Systems

Figure 13: Concept image of the Orion spacecraft docking with SEP-powered vehicle.

Technical Challenges and Approach

NASA missions require advanced robotic and autonomous systems, as well as human-machine teaming solutions, in order to overcome many different challenges. Extreme terrains with craters, gullies, ice, and canyons are mobility challenges that NASA is evaluating with rappelling, drilling, flying, and other novel system concepts. Human exploration missions that predeploy assets ahead of human arrival pose new challenges for robotic inspection, maintenance, repair, and autonomous operations, both in space and on the surface. Simulations of robot dynamics are also important tools that support NASA's efforts to improve a wide range of robotic capabilities.

System-level autonomy targets NASA's need to reduce reliance on crew and ground-support personnel. A major challenge for this area is developing adequate onboard computational and data storage capabilities for the verification and validation of complex models. NASA's approach requires strengthened systems health management and various systems required for onboard, automated decision making.

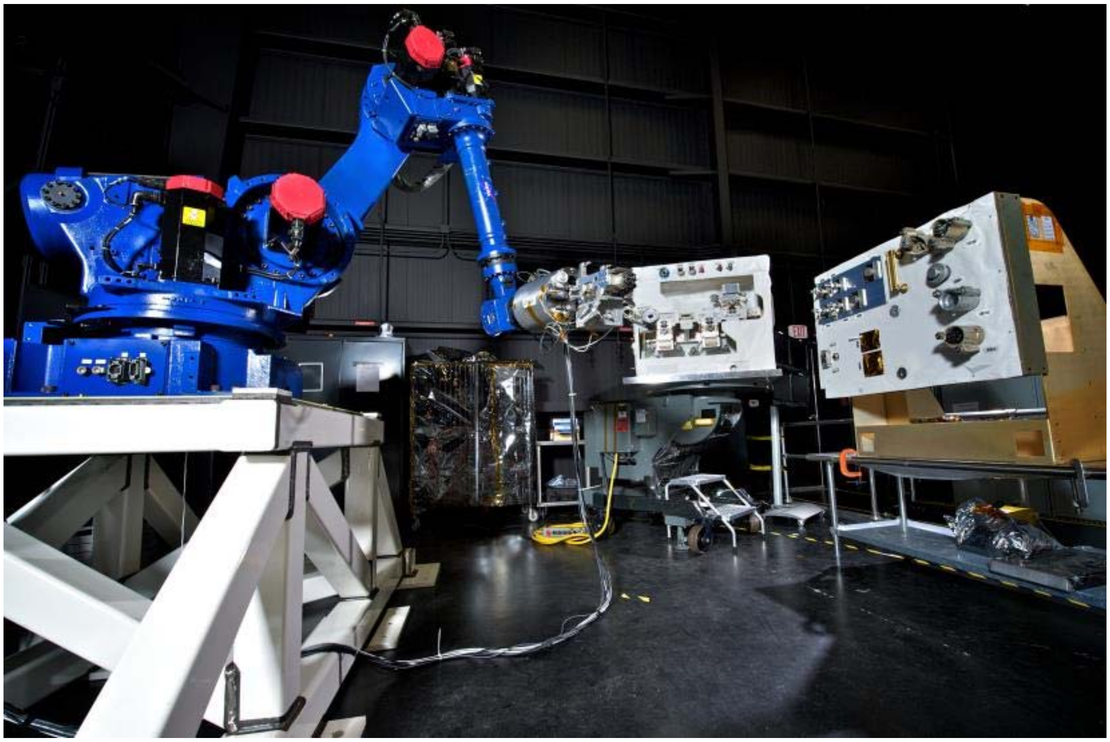

Figure 14: Practice for the Robotic Refueling Mission at NASA Goddard Space Flight Center.

NASA is also working to advance the performance of relative navigation sensors needed for rendezvous and docking. These sensors include three-dimensional imaging, visible-wavelength cameras, and long-wave infrared cameras.

Impact to NASA

Critical technologies in the robotic and autonomous systems area will enable many of NASA's future missions. Robotic missions that face challenging communication constraints or are carried out in environments that are only partially understood, such as Titan and Venus, will rely on systems-level autonomy. Rendezvous and docking, enabled by improved sensors and mechanisms, will support missions that explore asteroids, moons, and, eventually, missions to Mars. Lunar and Martian exploration will involve complex systems predeployed and left dormant for months or years, significantly reducing mission costs of robotics and autonomous systems maintaining the facilities when no crew is present.

Impact to Nation and Partners

NASA's robotic and autonomous system capabilities align with the needs beyond the Agency. System-level autonomy and relative navigation sensors have applications for other Government agencies that develop and operate robotic systems. Mobile, safe, dexterous, and autonomous systems are also needed by the Department of Energy with challenges in environmental management and response preparedness. Wearable robotic and cognitive support for crew have merit in terrestrial applications with workers in dangerous environments. Additionally, technologies related to autonomous capabilities could also strengthen advanced manufacturing, which has been identified as a national technology priority.

Scientific Instruments, Sensors, and Optical Communications

Many NASA missions would be impossible without the technology advancements in scientific instruments and sensors included in this Critical area. Critical technologies include particle detectors and focal planes for more precise and accurate imaging and advanced laser technology for atmospheric sounding and light detection and ranging (LIDAR). Optical communication technologies are also critical to meet the demand for higher data rates from the instrumentation and sensors carried on NASA science missions and to ensure safe, timely, effective mission operations. The technologies that NASA are prioritizing are associated with the following roadmap technology areas:

Table 6: Critical technologies in scientific instruments, sensors, and optical communications.

Technology Area – Level 3
5.1.1 Detector Development
5.1.2 Large Apertures
5.1.3 Lasers
5.1.4 Acquisition and Tracking
5.1.5 Atmospheric Mitigation
5.1.6 Optical Tracking
5.1.7 Integrated Photonics
5.4.1 Timekeeping and Time Distribution
8.1.1 Detectors and Focal Planes
8.1.2 Electronics
8.1.4 Microwave, Millimeter-, and Submillimeter-Waves
8.1.5 Lasers
8.3.3 In-Situ (other)

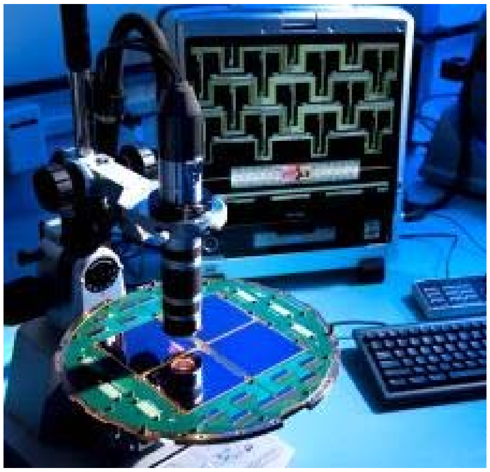

Figure 15: Focal plane array device developed at NASA's Jet Propulsion Laboratory to measure cosmic microwave background radiation.

Technical Challenges and Approach

NASA missions have resulted in stunning new discoveries from ancient architecture on Earth to water on Mars, and these discoveries were only possible through advances in instrument and sensor technologies. Critical remote sensing instruments include advanced detectors and focal plane technologies to enable large format arrays, increased sensitivity, and increased operating temperatures. In addition, laser and LIDAR sensors have become a critical tool for measuring planetary surfaces, atmospheric conditions and compensation, and performing Doppler measurements for wind speed and weather prediction.

NASA science missions require remote sensing instruments for Earth observation and planetary exploration. New technologies are necessary for low-noise, high-speed, and low-power detector arrays. NASA science missions require laser instruments that are lightweight and efficient, high in output power, and tunable across a wide range of wavelengths necessary for scientific observations. The identified Critical technologies will help detect life on Mars, Europa, Titan, and Enceladus, and characterize atmospheres, oceans, magnetospheres, and the Sun's heliosphere. NASA's approach includes space qualifiable immunoassay-based, electrochemical, and gas chromatograph mass spectrometer sensors for life detection; efficient magnetometers and charged particle detectors; and neutral mass spectrometers. Technical challenges include constraints on size, mass, and power, and instrumentation must be robust against radiation and temperature extremes. Better instruments and sensors for near-Earth and deep space missions will be supported by optical communication technologies that increase

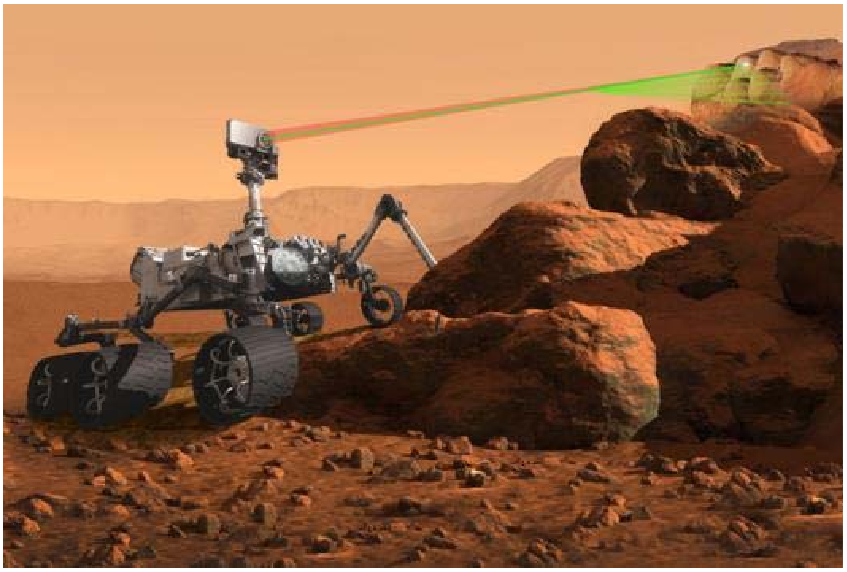

Figure 16: Concept image of the SuperCam instrument for Mars 2020 Rover.

data rates. Optical communication challenges include the development of larger detectors that are efficient and radiation tolerant as well as higher power lasers with better DC-to-optical efficiency.

Impact to NASA

In the physical sciences, human knowledge is limited by what we can see and measure. Consequently, advances in scientific knowledge go hand in hand with new technologies for perceiving our world. NASA scientific instrument and sensor technologies enable new mission concepts and experiment designs that are not possible today. Optical communications will increase data rates far beyond the performance of existing radio frequency systems, providing capabilities needed for deep space missions. The technologies within this Critical investment area provide reduced size, mass, and power requirements and increased sensitivity, accuracy, environmental tolerance, and communication capabilities, allowing us to see more, obtain superior measurements, and operate in new environments.

Impact to Nation and Partners

Scientific instruments and sensors have far-reaching applications. Science missions are frequently international efforts, and our partners rely on NASA technology to meet mission objectives. NASA’s partners identified several of the detector and laser technologies as potential partnership areas for future missions. In addition to probing the secrets of the universe, these technologies benefit national security, weather prediction, and land management. Other Government agencies are particularly interested in NASA laser technology and infrared sensors for Earth observations, as well as optical communication capabilities. Additionally, many commercial imaging companies are adapting NASA technologies to provide remote sensing data services. Although the operating environment may differ for NASA instruments and sensors, the function and performance are often similar to terrestrial requirements. Consequently, NASA instrument technologies can be leveraged for medical diagnostics and hospitals, battlefields and other hostile environments, port and border security, and other applications.

Lightweight Space Structures and Materials

NASA’s investments in lightweight space structures and materials will enable missions and greatly extend capabilities for exploration and scientific research. NASA’s Critical technologies for lightweight structures and materials will have major impacts on the constraints and challenges for spacecraft systems. Lightweight structures and material directly improve launch costs for NASA and commercial partners by reducing structure weight and increasing payload mass fraction. NASA Critical technologies include advanced composites for tanks and other structures, materials and designs to enable very large solar arrays, and capabilities for additive manufacturing and composites manufacturing. The Critical technologies for lightweight space structures and materials are associated with the following roadmap technology areas:

Table 7: Critical technologies in lightweight structures and materials.

Technology Area – Level 3
10.1.1 Lightweight Structures
12.1.1 Lightweight Structural Materials
12.1.5 Special Materials
12.2.2 Design and Certification Methods
12.3.2 Mechanism Life Extension Systems
12.4.1 Manufacturing Processes
12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems
12.4.5 Nondestructive Evaluation and Sensors

Technical Challenges and Approach

NASA will invest in a variety of lightweight structural concepts, including designs that save weight using fewer joints, less massive joints where joints are needed, and affordable, large-scale composites. Lightweight structures and materials technologies are needed for a variety of subsystems, and NASA is developing Critical technologies for larger composite components, composite cryogenic tanks, inflatable habitats, expandable structures, very large solar arrays, and structures for landers and surface habitats.

NASA is also developing the technology needed to enable mechanisms to function reliably in extreme and harsh environments. NASA’s approach includes design, materials, lubricants, and relubrication systems to help bearings operate reliably in dusty conditions. Actuators for cryogenic valves and couplings must also be improved to ensure long life in extreme thermal conditions. NASA’s future missions rely on mechanisms that must work for extended periods of time while subject to extreme radiation, pressure, and temperature, and must be robust enough to survive shocks and impacts.

Manufacturing innovations are needed to enable many of the technology developments for lightweight space structures and materials. NASA will invest in Critical technologies for metallic materials, including sold state joining and additive manufacturing, as well as processes that allow for larger polymer matrix composites and ceramic matrix composites. To help lower costs and reduce development time, NASA is pursuing technology with capabilities for digital and model-based manufacturing systems. Manufacturing innovations supporting production of higher efficiency photovoltaic cells and tools for nondestructive evaluation are important to NASA’s development of lightweight space systems. Finally, NASA is exploring a variety of applications for nanomaterials, including structural composites, data cables, tank liners, and thermal and electrical insulators.

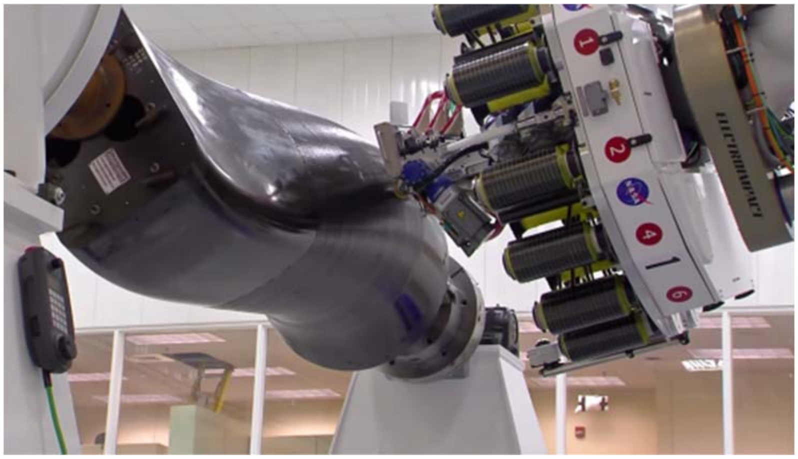

Figure 17: Advanced robotic manufacturing and composites are technology areas critical to NASA missions in exploration, science, and aeronautics.

Finally, NASA needs to develop accurate assessment of the as-built state correlated to performance to ensure safety and reliability during ever increasing mission durations. Assessing and maintaining vehicle integrity with minimal human intervention is critically important. Accurate characterization of structural integrity requires in-situ sensor arrays to rapidly interrogate large areas and detect anomalies. Deployable NDE devices are used to perform accurate local assessments of these anomalies. Such sensor systems must be capable of detecting precursors of global degradation, as well as rapidly identifying and locating suddenly occurring mission threatening damage. This capability enables early mitigation against critical conditions to maintain integrity.

Impact to NASA

Lightweight space structures and materials will have major impacts on NASA missions. Lightweight structures allow for increased payloads to orbit, and longer-life mechanisms ensure NASA systems work as intended for long-duration missions in harsh environments. NASA's investment in advanced manufacturing processes will provide important benefits across the Agency by saving time and reducing costs. Overall, improved manufacturing processes are needed to fully realize the performance benefits of advanced structural concepts and materials.

Impact to Nation and Partners

The technologies identified as most important for advancing lightweight space structures and materials have the potential to more broadly impact the Nation and NASA's partners. Critical technologies for additive manufacturing and composites for cryogenic tanks align with key military needs for spacecraft and launch vehicles. Other Government agencies have identified benefits from technologies in this area relating to advanced manufacturing. These capabilities support other Government agency needs for improved performance in aviation systems and satellites. International space agency partners have identified potential opportunities for collaboration for many of the Critical technologies in this area. For example, advanced composites structures could offer mass savings across many applications that are valuable to international partners. Finally, nearly all technologies align with priorities highlighted in NASA's Authorization Act, supporting the Space Launch System (SLS), the Orion spacecraft, or composite materials for aeronautics.

■ Entry, Descent, and Landing

Future missions for science and space exploration require entry, descent, and landing (EDL) technologies that allow spacecraft to slow from high speeds, transit atmospheres, and land on solar system bodies, while managing extreme thermal conditions. NASA's Critical technologies for EDL will ensure the Agency meets these needs. NASA will invest in technologies for rigid ablative decelerators, deployable decelerators, instrumentation for measuring EDL design parameters, and critical materials. These technologies are associated with the following roadmap technology areas:

Table 8: Critical technologies in entry, descent, and landing.

Technology Area – Level 3
9.1.1 Thermal Protection Systems for Rigid Decelerators
9.1.2 Thermal Protection Systems for Deployable Decelerators
9.1.3 Rigid Hypersonic Decelerators
9.1.4 Deployable Hypersonic Decelerators
9.2.3 Supersonic Retropropulsion
9.2.7 Terrain-Relative Sensing and Characterization
9.2.8 Autonomous Targeting
9.4.5 Modeling and Simulation
9.4.6 Instrumentation and Health Monitoring
14.3.1 Ascent/Entry TPS
14.3.2 TPS Modeling and Simulation
14.3.3 TPS Sensors and Measurement Systems

Figure 18: Deployable hypersonic decelerator technology.

Technical Challenges and Approach

NASA will invest in technologies that enable EDL for larger human exploration systems and for exploration in extreme environments, including Venus and the outer planets and their moons. To enable these capabilities, NASA's Critical technologies include materials for rigid ablative decelerators and deployable decelerators. Accompanying these are technologies to develop instrumentation and modeling capabilities that will help optimize the design of EDL systems.

NASA technologies in this area will improve the performance of thermal protection systems (TPS) for rigid decelerators. NASA is focused on lower-mass ablative TPS materials that can handle the increased heat rates and heat loads that result from heavier spacecraft entering atmospheres at higher velocities than ever before. A major challenge is developing environmentally friendly materials that can be affordably manufactured and demonstrate resistance to impact damage. For hypersonic entry, deployable concepts must overcome several challenges related to scalability using lightweight, high-temperature materials and aerodynamic stability.

Improved instrumentation and health monitoring is critical for advanced EDL systems. Measuring surface temperature and pressure for TPS materials along with atmospheric and flight parameters will allow NASA to gather data, validate engineering models, and optimize EDL performance. Distributed, miniaturized sensor networks that can operate effectively in the forebody and aftbody of EDL systems will allow in-situ measurement for both rigid and deployable systems.

Figure 19: Orion capsule heatshield instrumentation, shown from inside the aeroshell.

Impact to NASA

Innovations for advanced EDL systems enable many of NASA's future science and human exploration missions. Technologies for rigid decelerators with higher-performance TPS materials will protect robotic spacecraft exploring Venus and Saturn, and they will be needed to reliably return crew from human missions to asteroids and Mars. Deployable decelerator technologies help increase aeroshell surface area, which would otherwise be constrained by the launch vehicle, providing EDL capabilities for larger-mass payloads. Better instrumentation and health monitoring will have impacts across NASA's EDL systems by providing data needed to improve designs and performance, assess risk, and reduce cost.

Impact to Nation and Partners

The technologies NASA are developing to support advanced EDL systems are important for the Nation and NASA's partners. Commercial partners share interest in TPS technologies, such as advanced materials, high-temperature seals and barriers, flexible/deployable systems, and NASA-developed computational modeling tools. These are critical capabilities for any spacecraft facing the extreme conditions of returning through the Earth's atmosphere. Other Government agencies supporting these commercial efforts have identified benefits of NASA EDL technologies. International space agencies working to develop their own EDL capabilities have also identified potential partnership opportunities aligned with each of NASA's Critical technologies, including tools for nondestructive evaluation, advanced instrumentation, and EDL modeling.

🟧 Space Power Systems

NASA Critical technologies in space power systems will satisfy future missions’ requirements for the highest possible specific power and energy density with the durability to support longer missions farther away from Earth. These technologies are associated with the following roadmap technology areas:

Table 9: Critical technologies in space power systems.

Technology Area – Level 3
3.1.3 Solar
3.1.5 Fission
3.2.1 Batteries
3.2.3 Regenerative Fuel Cells
3.3.3 Distribution and Transmission
3.3.5 Conversion and Regulation

Technical Challenges and Approach

Photovoltaic arrays are an important space power system. NASA’s Critical technologies will improve photovoltaics to support solar electric propulsion (SEP) and planetary missions with challenging solar intensity and temperature requirements. For missions farther from the Sun, technologies provide improvements needed for low-intensity, low-temperature photovoltaic cells. Inner-planet missions, like to Venus, require high-intensity, high-temperature, and acid-resistant solar cells. These challenges, in addition to radiation tolerance, make the existing solar arrays expensive and difficult to manufacture. Another challenge is demonstrating solar arrays that can be packaged with greater efficiency at lower cost while remaining durable to extreme space environments.

Small and medium scale nuclear fission, another technology in this area, could support in-situ resource utilization, deep space robotic electric propulsion, and other science and exploration mission needs. Challenges for fission power systems are application specific and focus on integration and design for safety, reliability, and affordability. Higher-temperature fuels, materials, and components will help enable future performance improvements.

NASA seeks to qualify high specific energy, high energy density batteries for the space environment. Batteries are needed that are tolerant to electrical, thermal, and mechanical abuse with no fire or thermal runaway. Batteries that can safely store very large amounts of energy in small, low-mass packages enable the next generation of deep space EVA suits that require advanced life support, communications, and computing equipment. All other missions are enhanced by having additional electrical power available without a mass penalty.

Fuel cells are another energy storage technology needed to provide capabilities for long-duration upper stages, space habitats, landers, rovers, and in-situ resource utilization. Fuel cell systems are attractive for space missions that require large-scale energy storage on the order of several MWh. This capability is especially important for applications like space habitats and planetary surface systems requiring tens of kilowatts of electrical power.

Future space power systems will require improved management, distribution conversion, and regulation technologies. NASA’s Critical technologies provide capabilities for autonomous management of power systems and semiconductors and other components that tolerate both high-voltage and extreme radiation.

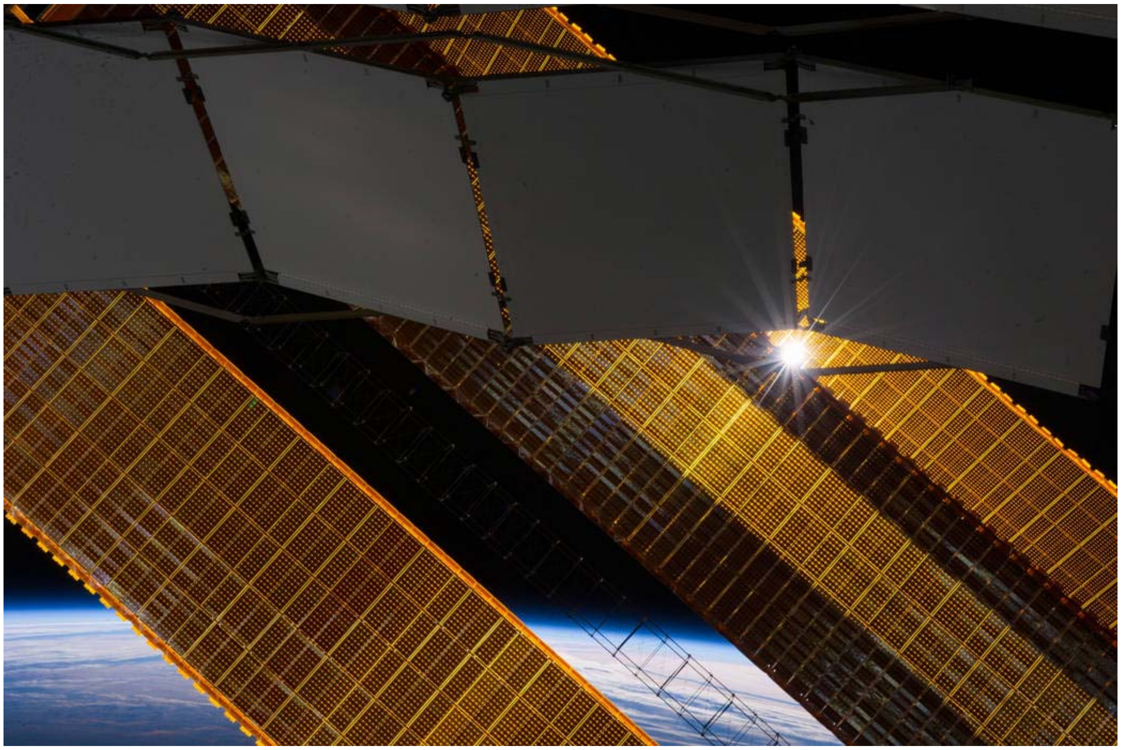

Figure 20: Primary solar array and radiator panel on the International Space Station.

Impact to NASA

Innovations that improve the performance of space power systems are critical for all missions, especially long-duration missions into deep space. Technologies that enable large-scale arrays for SEP will be an important step to develop the capabilities needed for the journey to Mars. Technologies that make solar cells and arrays more efficient and more durable will further enable ambitious science missions. Energy storage technologies will have broad impacts on many NASA missions by reducing mass, and they will be particularly valuable for next-generation, deep space extravehicular activity (EVA) suits that must power communications and life support systems. Batteries for extreme environments and nuclear fission will enable future lunar and Mars surface missions. Finally, power management and distribution technologies will support NASA's goals for high-power electric propulsion and low-power science operations in extreme environments.

Impact to Nation and Partners

Critical technologies supporting space power systems have broad applications and impacts. Other Government agencies have acknowledged a number of benefits from NASA's technologies supporting solar power and battery performance. Low-cost deployable solar arrays impact the performance of communications satellites and other commercial space applications, and universities rely on low-cost reliable power technologies for cubesats. Internationally, other space agencies and organizations have expressed interest in a potential partnership opportunity that aligns to NASA's technologies in solar arrays and cells, primary and secondary batteries, and advanced power management and distribution components. The commercial sector has specified benefits and partnership opportunities associated with NASA's technologies for high-voltage, high-temperature power management and distribution.

Advanced Information Systems

All of NASA's missions rely on information systems to perform critical functions from the formulation of mission designs to end-of-life operations. Advances in information systems support capabilities for everything from flight computing and ground computing to mission design. As NASA works to develop spacecraft that carry scientific instruments, robotic systems, and cargo and crew further into the solar system, the burden on information systems increases significantly. For example, autonomous systems, which will support many functions on future missions, must process large amounts of data to make informed decisions. Technologies that support high performance flight software and networks as well as science modeling tools are needed for several applications. Fundamental to all of NASA's information systems are the cyber security technologies needed to ensure safe, reliable operations. The Critical technologies for advanced information systems are associated with the following roadmap technology areas:

Table 10: Critical technologies in advanced information systems.

Technology Area – Level 3
11.1.1 Flight Computing
11.1.2 Ground Computing
11.2.4 Science Modeling
11.4.8 Cyber Security

Technical Challenges and Approach

Flight computing systems face challenging constraints in extreme space environments, and NASA will invest in technologies to improve the necessary processors, memory, and software. NASA's Critical flight computing technologies will provide improvements that are needed to increase autonomy for onboard operations and to allow for collection and on-board processing of larger volumes of data. NASA's approach includes developing components and systems that are radiation hardened, support low-power requirements, and incorporate capabilities for fault tolerance. An example is NASA's work with other Government agencies to develop a next-generation spaceflight computer with multiple cores on a chip in a connected, scalable architecture. NASA's approach is to develop general purpose technologies, such as flight processors, rather than specialized computing solutions bundled with other flight systems. This approach will provide flexibility and help ensure solutions stay within cost and schedule requirements.

NASA will make investments to overcome challenges related to ground computing and science modeling. Critical technologies for ground computing will support high-impact work requiring big data processing and advanced analytics. NASA is working to advance the scale, reliability, and efficiency of ground computing systems. Science modeling is another critical part of the Agency's investment in advanced information systems. From Earth system modeling to heliophysics, NASA science modeling challenges require advanced tools using assimilation and simulations to model and solve multiscale problems.

NASA's information systems must also keep pace with rapidly evolving cyber security threats. This Critical technology must eliminate unauthorized access to NASA data, provide flexibility for updates and broad application across systems, and effectively detect and control anomalous behavior. Cyber sercurity is a Critical technology for NASA because it undergirds the many systems and operations NASA relies upon for mission success.

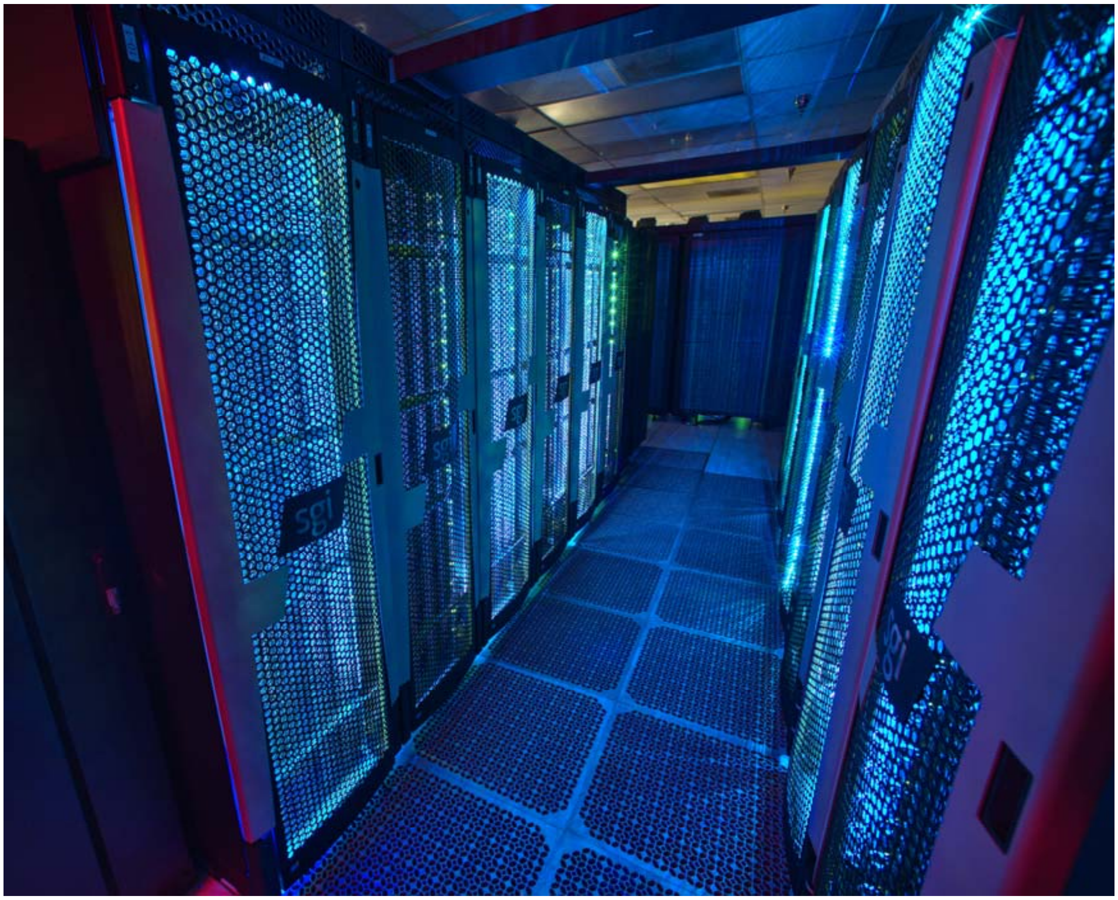

Figure 21: NASA Center for Climate Simulation (NCCS) Discovery Supercomputer.

Impact to NASA

NASA’s technologies for advanced information systems will enable the autonomous capabilities required for long-duration, complex missions. Critical technologies support more capable scientific instruments that gather and process more data about the universe and the solar system. Flight systems will rely on high-performance computers for landing, hazard avoidance, autonomous rendezvous and docking, and many other complicated functions. Advanced ground computing and science modeling technologies will help to ensure NASA has the tools required to process, analyze, and manage big data. Finally, cyber security technologies ensure all of these information systems function reliably and without compromising NASA data.

Impact to Nation and Partners

NASA’s investments to advance information system technologies have many potential impacts outside the Agency. Other Government agencies have identified mutual benefits for each of NASA’s Critical technologies, including the ability to model the cost of complex missions. NASA’s investments in these systems support other Government agency needs for information system hardware and software suited to the design constraints of space operations. Satellites and other systems used by government agencies benefit, for example, from better radiation tolerance and low power operation for components. Each of these technologies aligns with international space agency opportunities and priorities specified by international partners. Finally, NASA’s advanced computing efforts support National Technology Priorities, and commercial benefits have been identified for the advanced processors and memory.

🟧 Aeronautics

NASA’s aeronautics research is formulated under six Strategic Thrusts that act as the link between its strategic vision and its research plans. In combination, these Strategic Thrusts respond to the needs of aviation to 2035 and beyond. The Strategic Thrusts are used to define the technology areas in the Aeronautics roadmap, including the following Critical areas:

Table 11: Critical technologies in aeronautics.

Technology Area – Level 3*
15.1.1 Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1)
15.1.2 Full NextGen Integrated Terminal, En Route, Surface, and Arrivals/Departures Operations to Realize Trajectory-Based Operations (ATM+2)
15.2.1 Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise
15.3.1 Aircraft meet economic and environmental demands of airlines and the public and are on a defined path to fleet-level carbon neutral growth
15.3.2 Aircraft meet economic demands of airlines and the public with revolutionary improvements in community noise and energy efficiency to achieve fleet-level carbon neutral growth relative to 2005
15.3.3 Aircraft meet economic demands of airlines and the public with transforming capabilities in community noise and energy efficiency enabling a 50 percent reduction in fleet-level carbon output relative to 2005
15.3.4 Increased capability of vertical lift configurations that promote economic benefits and improve accessibility for new and current markets
15.4.1 Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems
15.5.1 Domain Specific In-Time Safety Monitoring and Alerting Tools

*The Aeronautics Technology Areas shown here are updated from those appearing in the 2015 NASA Roadmaps.

Technical Challenges and Approach

NASA’s efforts to support growth in global aviation include research and development across many areas. NASA’s technologies in this area advance operational concepts including improving the flow of aircraft arriving and departing airports, improved weather and system hazard awareness, real-time environment assessments, and the development of requirements and operational standards for unmanned aerial systems (UAS) operations in the National Airspace System (NAS).

For commercial supersonic aircraft, NASA’s Critical technologies include demonstrating the results of NASA research into reducing sonic boom noise and utilizing this demonstration aircraft to support the development of overland sonic boom standards. To advance ultra-efficient commercial vehicles, NASA’s technologies include tools to enable new airframe configurations with high levels of aerodynamic performance, lower structural weight, and innovative approaches to noise reduction. Improvements in propulsion, airframe, and other subsystem components are being investigated to achieve noise reduction. Technology supporting the tools to reduce turbofan thrust specific fuel consumption (TSFC), noise, and emissions align with this approach. Other technologies include methods to reduce perceived noise and aircraft fuel consumption through integrated airframe-engine concepts.

Critical technologies to advance the transition to low-carbon propulsion will characterize alternative fuels, combustor concepts, and their integration requirements. Efforts in this area also include methods to increase the efficiency of engines and transmissions and reduce the noise of vertical lift vehicles to support future operations in dense urban areas. Technologies are also being investigated to enable electrified aircraft propulsion to facilitate the transition to alternative power and propulsion.

NASA's technologies to enable real-time, system-wide safety assurance include several areas of work. NASA is developing technical approaches for integrating sensitive data from heterogeneous sources to build base models of nominal and off-nominal system performance and improve accuracy of detection and prediction tools. NASA is working to improve performance of detection, analysis, and prognostic tools as well as integrate threat prognosis, alerting, and guidance systems. NASA is exploring human-machine teaming solutions to maximize safety and mitigation of aviation risks. In the area of autonomy, NASA is looking at working with its partners to develop methods and standards for introducing increasingly autonomous systems into the NAS.

Impact to NASA

NASA's Critical aeronautics technology supporting growth in global aviation will improve air traffic efficiency in all phases of operations using an integrated approach to surface operations, weather rerouting, and en route operations. NASA's aeronautics technologies will provide criteria and technology for future overland supersonic flight and validated analysis tools for advanced supersonic technologies. Benefits for next generation commercial vehicles include reduced noise, emissions, and low life cycle carbon fuel consumption. NASA's aeronautics technologies will significantly impact the use of fuels and new propulsion systems. The Agency's safety assurance technologies will increase system safety of the NAS and provide near-real-time discovery and corrective actions of safety threats as well as self-protecting and self-healing air traffic systems.

Impact to Nation and Partners

Partnerships with other Government agencies, industry, academia, and foreign aeronautics agencies leverage the Aeronautics Research Mission Directorate investments through joint efforts that benefit the Nation's citizens and industries, complement NASA's internal capabilities. These joint efforts also provide access to a wide range of technologies beyond the traditional aeronautics portfolio and facilitate technology transfer to more mature states of development and eventual implementation. Integrated technology demonstrations typically include selected industry or government partners who contribute their own funding or knowledge to sufficiently advance highly beneficial technologies to where they can be fielded into the system benefiting the flying public. These partnerships give ARMD deep insight into the goals and needs of the aviation community while providing user feedback and facilitating industry engagement early in the technology development cycle.

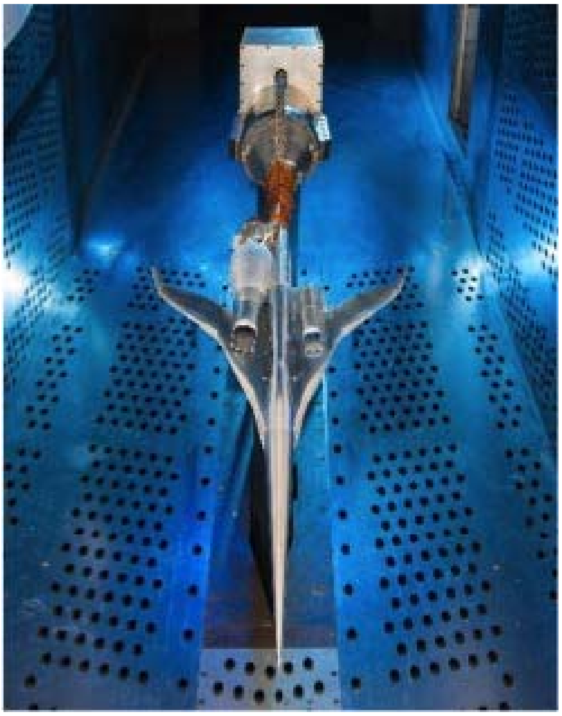

Figure 22: Wind tunnel design validation of sonic boom signatures, inlet, and nozzle effects.

Enhancing Technology Investments

Enhancing technologies in the 2017 STIP focus on improving mission performance. Enhancing technologies will comprise approximately 20 percent of the Agency's technology development portfolio. Investments in Enhancing technologies are integral to supporting the strategy outlined by the STIP. Enhancing technologies represent enhancements to existing technologies or capabilities and offer increased performance, safety, reliability, which in turn can reduce system risk.

Enhancing technologies cover a breadth of technology development needs. Examples include radioisotope and chemical power generation, mobility components for robotic systems, optical components for scientific instruments, and test tools and methods for structures. Enhancing technologies have been prioritized by international and other Government agencies in addition to being prioritized by NASA. For example, other U.S. government agencies and international space agencies are interested in partnering on Enhancing technologies related to chemical sensors, miniaturized remote sensing, habitats and advanced manufacturing. Commercial industry is interested in medical diagnosis and prognosis technologies, passive thermal control technologies, and mechanisms for cryogenic fluid transfer. Overall, Enhancing technologies help NASA to meets its four strategic technology investment goals by providing improved capabilities for identified mission needs.

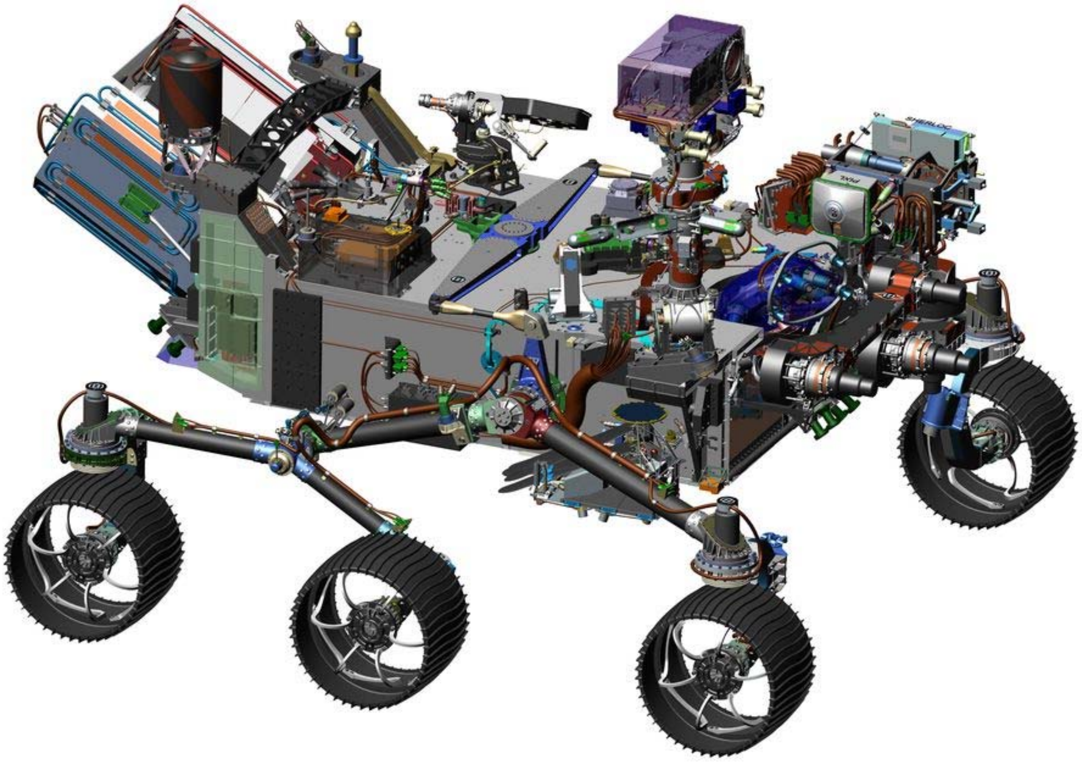

Figure 24: The Mars 2020 rover will carry a radioisotope power system to operate its many electrical components.

Examples of Enhancing Technologies:

Radioisotope (TA 3.1.4)
Radioisotope power systems (RPS) have been in use for decades and are configured to provide power for sophisticated NASA science missions. Deep space mission, for example, rely on the long life and reliability of RPS for operation in environments where conventional power systems are not feasible. A key goal for this enhancing technology is increased overall power conversion efficiency and reduced degradation for increased performance at destination. Higher power systems (200-500W) will be required for future missions, and improvements in thermoelectric and dynamic power conversion systems will be essential to reduce the overall use of plutonium 238. In addition, the development of compact mW power sources will enable the use of distributed sensor systems for the exploration of surface phenomenon on icy moons and other bodies of interest.

Force and Tactile Sensing (TA 4.1.5)
Force and tactile sensing provides feedback to help spacecraft and other robotic platforms interact more effectively with each other and with their environment. These types of sensors are increasingly common for terrestrial robotics applications, and space-qualified versions will have significant value for NASA’s missions. These sensors will help to improve general object grabbing tasks in space. The ability to reduce the size and cost of these senors will help to increase their availablity and possible applications.

Power Efficient Technologies (TA 5.2.2)
Spacecraft power systems must provide sufficient power for radio frequency communications. Power-efficient technologies that reduce the power required for radio frequency communication can help benefit other spacecraft systems and the overall missions design. Efficiency improvements for traveling wave tube amplifiers and solid-state power amplifiers will help reduce power demand. Data compression, coding, and modulation are other ways this enhancing technology can help achieve requirements for lower power demand.

Destination Reconnaissance, Prospecting, and Mapping (TA 7.1.1)
Destination reconnaissance, prospecting, and mapping will be needed for in-situ resource utilization at future destinations. Technologies are needed that can provide improved characterization of geotechnical and physical properties, mineralogy, and chemistry at exploration destinations. By improving characterization of mission destinations, mission planners can minimize risks and better optimize the performance of various destination systems.

Flexible Material Systems (TA 12.1.3)
Various types of flexible materials are being explored to provide benefits and improved capabilities for missions. Flexible materials can help with storage and deployment of systems and may offer advantages over ridged metal or composite structures. Structural textiles and lightweight flexible materials must provide reliability and integrity for long-duration missions.

Transformational Technology Investments

Transformational technologies identified in the 2017 STIP are an investment in over-the-horizon technologies that offer revolutionary capabilities for future missions. NASA’s investment in these technologies will comprise approximately 10 percent of the Agency’s investment in technology development. Transformational developments are often less mature and represent unique alternatives over current solutions. Transformational investments are generally higher risk than others but offer equally high return while providing significant improvements on cost, safety, reliability, or capabilities. Transformational technologies keep NASA at the frontier of innovation, from in-space propulsion to revolutionary concepts for communication and navigation to nanotechnologies.

Revolutionary concepts for communication and navigation, including x-ray and quantum technologies, may develop into valuable alternatives to state-of-the art optical and radio systems. These technologies are less developed than current communication and navigation systems. However, sustained investments in these areas keep this Transformational technology moving forward, helping the Agency to better understand and demonstrate potential for future communication and navigation capabilities that may revolutionize NASA missions.

NASA’s investments in autonomous aviation systems for the National Airspace System represents another Transformational technology with broad potential impacts. Methods developed for verification, validation, and certification will support trusted, joint human-machine systems for autonomous applications. By investing in these Transformational technologies in parallel with more mature technologies, NASA can effectively balance high-risk, high-return technology development.

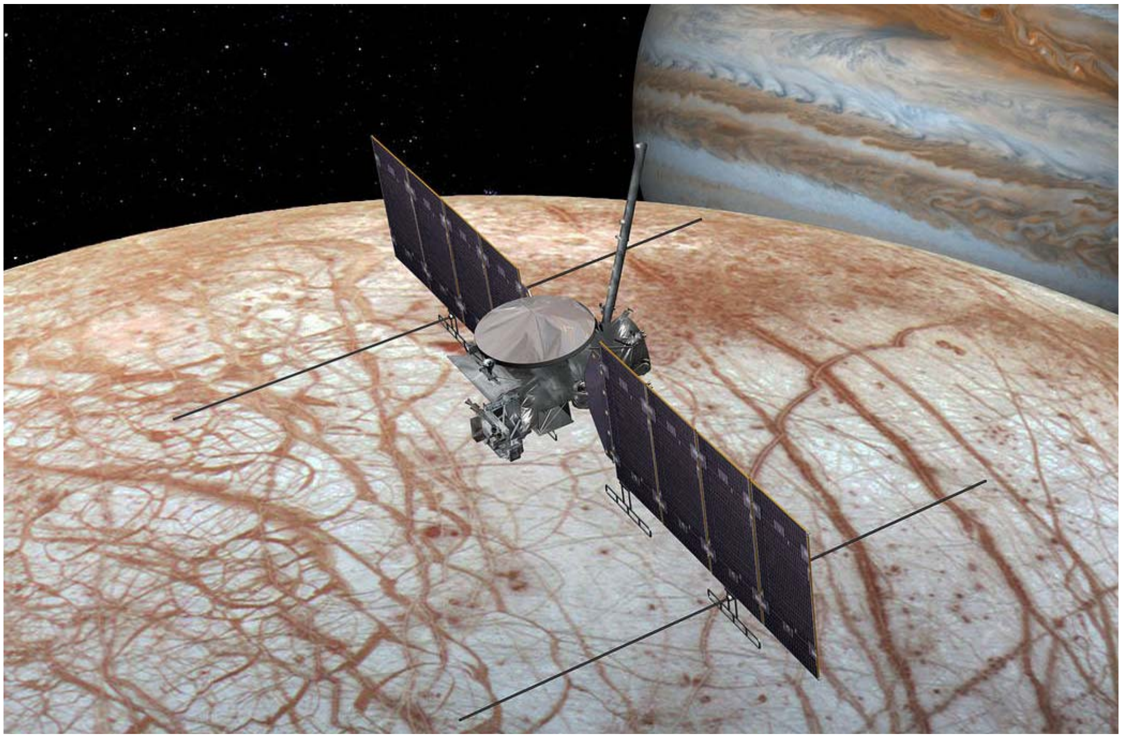

Figure 23: Transformational technologies such as quantum communications and exascale simulation could open up new possibilities for future missions, like NASA’s future Europa mission depicted above.

Examples of Transformational Technologies:

Advanced Fission (TA 2.3.6)
Advanced fission aims to understand alternatives to solid core nuclear thermal propulsion, which may offer greater specific impulse. These alternative concepts include gas and liquid cores, fission-fragment systems, and external-pulsed plasma propulsion. More analytical work is required to understand the challenges associated with containment, startup, shutdown, cooling, and other issues, but these concepts could offer higher thrust and two to three times the specific impulse, greatly reducing in-space trip times.

Quantum Communications (TA 5.6.5)
Quantum communications use the phenomena of entagled photons to achieve secure, high data rate, long-range communications across space. Quantum communication technology has not yet been demonstrated at a scale suitable for NASA missions. However, this technology could reduce reliance on large antennas, broadcast power, and line of sight. By integrating quantum and optical systems, NASA could improve communication efficiency for future missions.

Damage-Tolerant Systems (TA 10.1.2)
The nanoscale approaches advancing damage-tolerant systems could significantly improve engineered materials and structures. NASA is investigating various approaches for manufacturing and post-processing of polymers and composite materials that can sustain performance after impact damage or in extreme temperature conditions. Two examples include the growth of carbon nanotubes to increase material toughness and mimicking nanoscale features of seashells to improve ceramics. These approaches are intended to not only improve reliability and safety but also reduce weight by up to 25 percent.

Collaborative Science and Engineering (TA 11.4.4)
Collaborative science and engineering tools will enable geographically-dispersed teams to come together for real-time collaboration in an integrated environment where the tools, data, and people span multiple institutions. This capability supports development of multidisciplinary solutions and new understanding of scientific phenomena as well as discovery of the interrelationships between phenomena to an extent that would otherwise not be possible. This capability includes immersive sight, sound, and touch virtual reality to enable real-time, continuous collaboration.

Initial Introduction of Alternative Propulsion Systems (TA 15.4.2)
This Transformational technology includes hybrid electric propulsion systems and other alternatives to conventional, petroleum based fuels. While the Agency works to improve conventional propulsion technologies, the Agency is also advancing this transformational area by exploring ways to improve power density and systems for onboard electricity generation. Initial testing with small aircraft will help assess the benefits associated with reduced operating cost and environmental impact for a 5-10 MW hybrid gas-electric concept.

Conclusion

This STIP recommends guidelines for investments in NASA technology development resources, starting from the technologies identified in the 2015 NASA Technology Roadmaps. The STIP advocates for a balanced portfolio of investments across the 15 roadmaps and a 70/20/10 balance in relative expenditure between Critical, Enhancing, and Transformational technologies. This balance ensures that technologies required for planned and projected missions are developed while investments are reserved for technologies that improve mission performance as well as revolutionary, over-the-horizon technologies.

Alignment between the STIP and NASA’s technology portfolio will be reviewed yearly by NTEC, representing the Mission Directorates and the Offices of the Chief Technologist, Chief Engineer, Chief Scientist, Chief Information Officer, and Chief Health and Medical Officer. NTEC can recommend a realignment of the portfolio or elevate topics to the Agency Executive Council, if necessary. Alternately, based on tracking progress against the guidelines over successive years, NTEC may recommend adjusting the guidelines in the STIP, as needed.

This approach will allow NASA to realize the greatest benefit from its technology investments and achieve its strategic goals for the benefit of the Nation.

Appendix A: Technology Categories

The category definitions are provided on pages 7 and 8.

Near Critical Near-Term Mid Critical Mid-Term 🟦 Enhancing 🟩 Transformational ⬜ Ancillary

TA1 Launch Propulsion Systems

Near	1.1.1 Propellants
🟦	1.1.2 Case Materials
🟦	1.1.3 Nozzle Systems
⬜	1.1.4 Hybrid Rocket Propulsion Systems
⬜	1.1.5 Fundamental Solid Propulsion Technologies
Near	1.1.6 Integrated Solid Motor Systems
🟦	1.1.7 Liner and Insulation
Near	1.2.1 LH2/LOX Based
Mid	1.2.2 RP/LOX Based
⬜	1.2.3 CH4/LOX Based
⬜	1.2.6 Fundamental Liquid Propulsion Technologies
⬜	1.4.1 Auxiliary Control Systems
⬜	1.4.2 Main Propulsion Systems (Excluding Engines)
Near	1.4.3 Launch Abort Systems
⬜	1.4.4 Thrust Vector Control Systems
⬜	1.4.6 Pyro and Separation Systems
⬜	1.4.7 Fundamental Ancillary Propulsion Technologies
⬜	1.5.2 Air Launch and Drop Systems
🟩	1.5.4 Beamed Energy and Energy Addition
🟦	1.6.1 Super-Pressure Balloon
🟦	1.6.2 Materials
🟦	1.6.3 Pointing Systems
⬜	1.6.4 Telemetry Systems
🟦	1.6.5 Balloon Trajectory Control
⬜	1.6.6 Power Systems
🟦	1.6.7 Mechanical Systems: Launch Systems
⬜	1.6.8 Mechanical Systems: Parachute
⬜	1.6.9 Mechanical Systems: Floatation

TA2 In-Space Propulsion Technologies

🟦	2.1.1 Liquid Storable
Mid	2.1.2 Liquid Cryogenic
⬜	2.1.3 Gels
🟦	2.1.4 Solids
🟦	2.1.5 Hybrid
🟦	2.1.6 Cold Gas/Warm Gas
🟦	2.1.7 Micropropulsion
Near	2.2.1 Electric Propulsion
🟦	2.2.2 Solar and Drag Sail Propulsion
Mid	2.2.3 Thermal Propulsion
🟩	2.2.4 Tether Propulsion
🟩	2.3.1 Beamed Energy Propulsion
🟩	2.3.2 Electric Sail Propulsion
🟩	2.3.3 Fusion Propulsion
🟩	2.3.4 High-Energy-Density Materials
🟩	2.3.5 Antimatter Propulsion
🟩	2.3.6 Advanced Fission
🟩	2.3.7 Breakthrough Propulsion
Near	2.4.2 Propellant Storage and Transfer

TA3 Space Power and Energy Storage

🟩	3.1.1 Energy Harvesting
🟦	3.1.2 Chemical
Near	3.1.3 Solar
🟦	3.1.4 Radioisotope
Mid	3.1.5 Fission
🟩	3.1.6 Fusion
Near	3.2.1 Batteries
⬜	3.2.2 Flywheels
Mid	3.2.3 Regenerative Fuel Cells
⬜	3.2.4 Capacitors
🟦	3.3.1 Fault Detection, Isolation, and Recovery
🟦	3.3.2 Management and Control
Near	3.3.3 Distribution and Transmission
🟩	3.3.4 Wireless Power Transmission
Near	3.3.5 Conversion and Regulation

TA4 Robotics and Autonomous Systems

🟦	4.1.1 3D Sensing
🟦	4.1.2 State Estimation
Mid	4.1.3 Onboard Mapping
Near	4.1.4 Object, Event, and Activity Recognition

Near Critical Near-Term Mid Critical Mid-Term 🟦 Enhancing 🟩 Transformational ⬜ Ancillary

🟦	4.1.5 Force and Tactile Sensing
Mid	4.2.1 Extreme-Terrain Mobility
🟦	4.2.2 Below-Surface Mobility
🟦	4.2.3 Above-Surface Mobility
🟦	4.2.4 Small-Body and Microgravity Mobility
🟦	4.2.5 Surface Mobility
🟦	4.2.6 Robot Navigation
⬜	4.2.7 Collaborative Mobility
🟦	4.2.8 Mobility Components
🟦	4.3.1 Manipulator Components
🟦	4.3.2 Dexterous Manipulation
🟦	4.3.4 Mobile Manipulation
🟩	4.3.5 Collaborative Manipulation
Near	4.3.6 Sample Acquisition and Handling
Near	4.3.7 Grappling
🟩	4.4.1 Multi-Modal Interaction
🟩	4.4.3 Proximate Interaction
🟩	4.4.5 Distributed Collaboration and Coordination
Near	4.4.8 Remote Interaction
Near	4.5.1 System Health Management
Near	4.5.2 Activity Planning, Scheduling, and Execution
🟩	4.5.4 Multi-Agent Coordination
Near	4.5.8 Automated Data Analysis for Decision Making
Near	4.6.1 Relative Navigation Sensors
Near	4.6.2 GN&C Algorithms
Near	4.6.3 Docking and Capture Mechanisms and Interfaces
🟦	4.7.1 Modularity, Commonality, and Interfaces
Near	4.7.2 Verification and Validation of Complex Adaptive Systems
🟦	4.7.3 Robot Modeling and Simulation
⬜	4.7.4 Robot Software
🟦	4.7.5 Safety and Trust

TA5 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Near	5.1.1 Detector Development
Near	5.1.2 Large Apertures
Near	5.1.3 Lasers
Near	5.1.4 Acquisition and Tracking
Near	5.1.5 Atmospheric Mitigation
Near	5.1.6 Optical Tracking
Near	5.1.7 Integrated Photonics
🟦	5.2.1 Spectrum-Efficient Technologies
🟦	5.2.2 Power-Efficient Technologies
🟦	5.2.3 Propagation
🟩	5.2.5 Earth Launch and Re-Entry Communications
🟦	5.2.6 Antennas
🟦	5.3.1 Disruption-Tolerant Networking
🟦	5.3.2 Adaptive Network Topology
Mid	5.4.1 Timekeeping and Time Distribution
🟩	5.4.2 Onboard Auto Navigation and Maneuver
🟩	5.4.3 Sensors and Vision Processing Systems
🟦	5.4.4 Relative and Proximity Navigation
🟩	5.4.5 Auto Precision Formation Flying
🟦	5.4.6 Autonomous Approach and Landing
🟦	5.5.1 Radio Systems
🟦	5.5.2 Ultra Wideband
🟦	5.5.3 Cognitive Networks
🟦	5.5.6 Radio Frequency and Optical Hybrid Technology
🟩	5.6.1 X-Ray Navigation
🟩	5.6.2 X-Ray Communications
🟩	5.6.3 Neutrino-Based Navigation and Tracking
🟩	5.6.4 Quantum Key Distribution
🟩	5.6.5 Quantum Communications
🟩	5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier
🟩	5.6.7 Reconfigurable Large Apertures
🟦	5.7.1 Tracking Technologies
🟦	5.7.2 Characterization Technologies

TA6 Human Health, Life Support, and Habitation Systems

Near	6.1.1 Air Revitalization
Near	6.1.2 Water Recovery and Management
Near	6.1.3 Waste Management
Near	6.1.4 Habitation
Near	6.2.1 Pressure Garment
Near	6.2.2 Portable Life Support System

Near Critical Near-Term Mid Critical Mid-Term 🟦 Enhancing 🟩 Transformational ⬜ Ancillary

Near	6.2.3 Power, Avionics, and Software
Near	6.3.1 Medical Diagnosis and Prognosis
Near	6.3.2 Long-Duration Health
Near	6.3.3 Behavioral Health
Near	6.3.4 Human Factors
Near	6.4.1 Sensors: Air, Water, Microbial, and Acoustic
Near	6.4.2 Fire: Detection, Suppression, and Recovery
🟦	6.4.3 Protective Clothing and Breathing
Near	6.4.4 Remediation
Near	6.5.1 Risk Assessment Modeling
Near	6.5.2 Radiation Mitigation and Biological Countermeasures
Near	6.5.3 Protection Systems
Near	6.5.4 Space Weather Prediction
Near	6.5.5 Monitoring Technology

TA7 Human Exploration Destination Systems

🟦	7.1.1 Destination Reconnaissance, Prospecting, and Mapping
Near	7.1.2 Resource Acquisition
Mid	7.1.3 Processing and Production
🟩	7.1.4 Manufacturing Products and Infrastructure Emplacement
Near	7.2.1 Autonomous Logistics Management
⬜	7.2.2 Maintenance Systems
🟦	7.2.3 Repair Systems
Mid	7.2.4 Food Production, Processing, and Preservation
Mid	7.3.1 EVA Mobility
🟩	7.3.2 Surface Mobility
🟦	7.3.3 Off-Surface Mobility
🟦	7.4.1 Integrated Habitat Systems
⬜	7.4.2 Habitat Evolution
🟦	7.4.3 "Smart" Habitats
🟩	7.4.4 Artificial Gravity
🟦	7.5.2 Planetary Protection
Near	7.5.3 Integrated Flight Operations Systems
Mid	7.6.1 Particulate Contamination Prevention and Mitigation
🟩	7.6.2 Construction and Assembly

TA8 Science Instruments, Observatories, and Sensor Systems

Near	8.1.1 Detectors and Focal Planes
Near	8.1.2 Electronics
🟦	8.1.3 Optical Components
Near	8.1.4 Microwave, Millimeter-, and Submillimeter-Waves
Near	8.1.5 Lasers
🟦	8.1.6 Cryogenic / Thermal
🟦	8.2.1 Mirror Systems
🟩	8.2.2 Structures and Antennas
🟦	8.2.3 Distributed Aperture
🟦	8.3.1 Field and Particle Detectors
Near	8.3.3 In-Situ (other)

TA9 Entry, Descent, and Landing Systems

Near	9.1.1 Thermal Protection Systems for Rigid Decelerators
Near	9.1.2 Thermal Protection Systems for Deployable Decelerators
Near	9.1.3 Rigid Hypersonic Decelerators
Mid	9.1.4 Deployable Hypersonic Decelerators
🟦	9.2.1 Attached Deployable Decelerators
🟦	9.2.2 Trailing Deployable Decelerators
Mid	9.2.3 Supersonic Retropropulsion
🟦	9.2.6 Large Divert Guidance
Near	9.2.7 Terrain-Relative Sensing and Characterization
Near	9.2.8 Autonomous Targeting
🟦	9.3.1 Propulsion and Touchdown Systems
Near	9.4.5 Modeling and Simulation
Near	9.4.6 Instrumentation and Health Monitoring

TA10 Nanotechnology

Near	10.1.1 Lightweight Structures
🟩	10.1.2 Damage-Tolerant Systems
⬜	10.1.3 Coatings
⬜	10.1.4 Adhesives
🟩	10.1.5 Thermal Protection and Control
🟩	10.2.1 Energy Storage
🟩	10.2.2 Power Generation
🟩	10.2.3 Power Distribution

Near Critical Near-Term Mid Critical Mid-Term 🟦 Enhancing 🟩 Transformational ⬜ Ancillary

⬜	10.3.1 Propellants
🟩	10.3.2 Propulsion Components
🟦	10.3.3 In-Space Propulsion
🟩	10.4.1 Sensors and Actuators
🟩	10.4.2 Nanoelectronics
🟩	10.4.3 Miniature Instruments and Instrument Components

TA11 Modeling, Simulation, Information Technology and Processing

Near	11.1.1 Flight Computing
Near	11.1.2 Ground Computing
🟦	11.2.1 Software Modeling and Model Checking
🟦	11.2.2 Integrated Hardware and Software Modeling
🟦	11.2.3 Human-System Performance Modeling
Near	11.2.4 Science Modeling
⬜	11.2.5 Frameworks, Languages, Tools, and Standards
🟦	11.2.6 Analysis Tools for Mission Design
⬜	11.3.1 Distributed Simulation
🟦	11.3.2 Integrated System Lifecycle Simulation
🟦	11.3.3 Simulation-Based Systems Engineering
🟦	11.3.4 Simulation-Based Training and Decision Support Systems
🟩	11.3.5 Exascale Simulation
🟦	11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods
🟦	11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation
🟦	11.3.8 Verification and Validation
⬜	11.4.1 Science, Engineering, and Mission Data Lifecycle
🟦	11.4.2 Intelligent Data Understanding
🟦	11.4.3 Semantic Technologies
🟩	11.4.4 Collaborative Science and Engineering
🟦	11.4.5 Advanced Mission Systems
🟦	11.4.6 Cyber Infrastructure
🟦	11.4.7 Human-System Integration
Near	11.4.8 Cyber Security

TA12 Materials, Structures, Mechanical Systems and Manufacturing

Near	12.1.1 Lightweight Structural Materials
🟩	12.1.2 Computationally-Designed Materials
🟦	12.1.3 Flexible Material Systems
🟦	12.1.4 Materials for Extreme Environments
Mid	12.1.5 Special Materials
🟦	12.2.1 Lightweight Concepts
Near	12.2.2 Design and Certification Methods
🟦	12.2.3 Reliability and Sustainment
🟦	12.2.4 Test Tools and Methods
🟦	12.2.5 Innovative, Multifunctional Concepts
🟦	12.2.6 Loads and Environments
🟩	12.3.1 Deployables, Docking, and Interfaces
Near	12.3.2 Mechanism Life Extension Systems
🟦	12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms
🟦	12.3.4 Design and Analysis Tools and Methods
🟦	12.3.5 Reliability, Life Assessment, and Health Monitoring
🟦	12.3.6 Certification Methods
Near	12.4.1 Manufacturing Processes
Near	12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems
🟦	12.4.3 Electronics and Optics Manufacturing Process
🟦	12.4.4 Sustainable Manufacturing
Near	12.4.5 Nondestructive Evaluation and Sensors

TA13 Ground and Launch Systems

🟦	13.1.1 On-Site Production, Storage, Distribution, and Conservation of Fluids
🟦	13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems
🟦	13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems
⬜	13.1.4 Logistics
🟦	13.2.1 Corrosion Prevention,

Near Critical Near-Term Mid Critical Mid-Term 🟦 Enhancing 🟩 Transformational ⬜ Ancillary

🟦	Detection, and Mitigation
⬜	13.2.2 Environmental Remediation and Site Restoration
⬜	13.2.3 Preservation of Natural Ecosystems
⬜	13.2.4 Alternate Energy Prototypes
⬜	13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms
⬜	13.3.1 Launch Infrastructure
⬜	13.3.2 Environment-Hardened Materials and Structures
🟩	13.3.3 On-Site Inspection and Anomaly Detection and Identification
🟦	13.3.4 Fault Isolation and Diagnostics
🟦	13.3.5 Prognostics
🟦	13.3.6 Repair, Mitigation, and Recovery Technologies
🟦	13.3.7 Communications, Networking, Timing, and Telemetry
🟦	13.3.8 Decision-Making Tools
🟦	13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies
🟩	13.4.2 Landing and Recovery Systems and Components
🟩	13.4.3 Weather Prediction and Mitigation
⬜	13.4.5 Safety Systems

TA14 Thermal Management Systems

🟦	14.1.1 Passive Thermal Control
Near	14.1.2 Active Thermal Control
🟦	14.2.1 Heat Acquisition
🟦	14.2.2 Heat Transport
Near	14.2.3 Heat Rejection and Energy Storage
Near	14.3.1 Ascent/Entry TPS
Near	14.3.2 TPS Modeling and Simulation
Near	14.3.3 TPS Sensors and Measurement Systems

*TA15 Aeronautics**

Near	15.1.1 Improved NextGen Operational Performance in Individual Domains, with Some Integration Between Domains (ATM+1)
Mid	15.1.2 Full NextGen Integrated Terminal, En Route, Surface, and Arrivals/Departures Operations to Realize Trajectory-Based Operations (ATM+2)
🟩	15.1.3 Beyond NextGen Dynamic Fully Autonomous Trajectory Services (ATM+3)
Near	15.2.1 Supersonic Overland Certification Standard Based on Acceptable Sonic Boom Noise
🟩	15.2.2 Introduction of Affordable, Low-boom, Low-noise, and Low-emission Super-sonic Transports
🟩	15.2.3 Increased Mission Utility and Commercial Market Growth of Supersonic Transport Fleet
Near	15.3.1 Aircraft meet economic and environmental demands of airlines and the public, and are on a defined path to fleet-level carbon neutral growth
Mid	15.3.2 Aircraft meet economic demands of airlines and the public with revolutionary improvements in community noise and energy efficiency to achieve fleet-level carbon neutral growth relative to 2005
Mid	15.3.3 Aircraft meet economic demands of airlines and the public with transforming capabilities in community noise and energy efficiency enabling a 50 percent reduction in fleet-level carbon output relative to 2005.
Near	15.3.4 Increased capability of vertical lift configurations that promote economic benefits and improve accessibility for new and current markets.
🟩	15.3.5 New vertical lift configurations and technologies introduced that enable new markets, increase mobility, improve accessibility, and reduce environmental impact
🟩	15.3.6 Vertical lift vehicles of all sizes used for widespread transportation and services, improved mobility and accessibility, with economic benefits and low environmental impact
Near	15.4.1 Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems
🟩	15.4.2 Initial Introduction of Alternative Propulsion Systems
🟩	15.4.3 Introduction of Alternative Propulsion Systems to Aircraft of All Sizes
Near	15.5.1 Domain Specific In-Time Safety Monitoring and Alerting Tools

Near Critical Near-Term Mid Critical Mid-Term 🟦 Enhancing 🟩 Transformational ⬜ Ancillary

- 🟩 15.5.2 Predictive Technologies with Domain Level Application Domain Level Application
- 🟩 15.5.3 Adaptive Real-time Safety Management Threat Management
- 🟩 15.6.1 Introduction of aviation systems with bounded autonomy, capable of carrying out function-level goals
- 🟩 15.6.2 Introduction of aviation systems with flexible autonomy based on earned levels of trust, capable of carrying out mission-level goals
- 🟩 15.6.3 Introduction of distributed collaborative aviation systems with assured autonomy, capable of carrying out policy-level goals

* The Aeronautics Technology Areas shown here are updated from those appearing in the 2015 NASA Roadmaps.

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