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NASA Space Technology Roadmaps and Priorities Revisited

Committee on NASA Technology Roadmaps

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

A Report of

The National Academies of
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Preface

The NASA Authorization Act of 2010 directed NASA to create a program to maintain its research and development base in space technology. In response, NASA created a set of 14 draft space technology roadmaps to guide the development of space technologies. These roadmaps were the subject of a comprehensive external review by the National Academies of Sciences, Engineering, and Medicine,[1] which in 2012 issued the National Research Council report *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.[2] NASA then began a reexamination and updating of its 2010 draft technology roadmaps, resulting in a new set of 2015 roadmaps. A significant aspect of the updating has been the effort to assess the relevance of the technologies by showing their linkage to a set of mission classes and design reference missions (DRMs) from the Human Exploration and Operations Mission Directorate and the Science Mission Directorate. The new set of roadmaps also includes a roadmap that addresses aeronautical technologies. In the spring of 2015, the updated roadmaps were released to the public for review and comment.

Also in 2015, the Academies were asked to assemble a committee to evaluate the technologies in the updated set of 14 space technology roadmaps. Per the statement of task, the aeronautics roadmap is not included in the present study, because the 2012 NRC report, which serves as a baseline for it, has no such aeronautics roadmap. The full statement of task appears in Appendix A of this report. Specific elements of the statement of task include identifying technologies in NASA's 2015 roadmaps that were not evaluated by the 2012 NRC report, prioritizing those technologies using the same process documented in the 2012 NRC report, and recommending a methodology for future independent reviews of NASA's technology roadmaps.

In response to this latest request, the NRC appointed the 14-member Committee on NASA Technology Roadmaps. For the sake of continuity, many members of the committee were veterans of the study that led to the 2012 NRC report. The committee met four times: in September and November 2015, in Washington, D.C.; in January 2016, in Irvine, California; and in March 2016 in Washington, D.C.

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before that date.

[2] National Research Council, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* The National Academies Press, Washington, D.C.

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Kenneth M. Baldwin, University of California, Irvine,
Ellen J. Bass, Drexel University,
Mark Devlin, University of Pennsylvania,
Bill Gibson, World View Enterprises,
Alastair M. Glass, Tyndall National Institute of Ireland,
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Alfred U. MacRae, MacRae Technologies,
Michael Norman, University of California, San Diego,
Stephen M. Rock, Stanford University,
George W. Sutton, Analysis and Applications, and
Daniel Weihs, Technion-Israel Institute of Technology.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Steven J. Battel, Battel Engineering, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

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Summary

Historically, the United States has been a world leader in aerospace endeavors in both the government and commercial sectors. A key factor in aerospace leadership is continuous development of advanced technology, which is particularly critical to U.S. ambitions in space, including a human mission to Mars. NASA is executing a series of aeronautics and space technology programs using a roadmapping process to identify technology needs and improve the management of its technology development portfolio. In 2010 NASA created a set of 14 draft technology roadmaps to guide the development of space technologies. These roadmaps were the subject of a comprehensive external review by the National Academies of Sciences, Engineering, and Medicine.[1] That review was documented in the 2012 National Research Council (NRC) report *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.[2] As noted in that report, "As the breadth of the country's space mission has expanded, the necessary technological developments have become less clear, and more effort is required to evaluate the best path for a forward-looking technology development program."[3]

In 2015, NASA issued a revised set of roadmaps. A significant new aspect of the update has been the effort to assess the relevance of the technologies by listing the enabling and enhancing technologies for specific design reference missions (DRMs) from the Human Exploration and Operations Mission Directorate and the Science Mission Directorate.[4] Also in 2015, the Academies were asked to assess the priority of space technologies in the 2015 roadmaps that were not assessed in the 2012 NRC report.[5] The Committee on NASA Technology Roadmaps, which was organized to undertake these assessments, was also tasked with recommending a methodology for conducting independent reviews of future updates to NASA's technology roadmaps, which are expected to occur every 4 years.

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before that date.

[2] NRC, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* The National Academies Press, Washington, D.C.

[3] NRC, 2012, *NASA Space Technology Roadmaps and Priorities*, p. 11.

[4] NASA, 2015, *Technology Roadmaps, Introduction, Crosscutting Technologies, and Index*, Washington, D.C., July, pp. i-61 to i-67.

[5] This study is not reviewing aeronautics technologies. They appeared for the first time in the 2015 roadmaps, so the 2012 NRC report provides no baseline for comparison.

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TECHNOLOGY AREA BREAKDOWN STRUCTURE

The content of the 2015 NASA roadmaps is organized using a four-level technology area breakdown structure (TABS). Level 1 represents the technology area (TA), which is the title of the roadmap:

- TA 1, Launch Propulsion Systems
- TA 2, In-Space Propulsion Technologies
- TA 3, Space Power and Energy Storage
- TA 4, Robotics and Autonomous Systems
- TA 5, Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- TA 6, Human Health, Life Support, and Habitation Systems
- TA 7, Human Exploration Destination Systems
- TA 8, Science Instruments, Observatories, and Sensor Systems
- TA 9, Entry, Descent, and Landing Systems
- TA 10, Nanotechnology
- TA 11, Modeling, Simulation, Information Technology, and Processing
- TA 12, Materials, Structures, Mechanical Systems, and Manufacturing
- TA 13, Ground and Launch Systems
- TA 14, Thermal Management Systems
- TA 15, Aeronautics

Each roadmap describes level 2 technology subareas, level 3 technologies, and level 4 research tasks. The 2012 NRC report focused its review on the level 3 technologies. The TABS for the 2010 draft NASA roadmaps contained 320 level 3 technologies. The modified TABS recommended in the 2012 NRC report contained 295 level 3 technologies. The TABS for the 2015 NASA roadmaps now contains 340 level 3 technologies. The net increase in the number of technologies in the various TABS is due to many factors: Technologies have been added, deleted, revised, merged, and so on. A detailed comparison of the technologies in the 2010, 2012, and 2015 TABS (see Appendix B) revealed that 42 technologies met the criteria for review in this report as "new" technologies. The distribution of these new technologies by TA is as follows:

- TA 1, Launch Propulsion Systems (11 new technologies)
- TA 4, Robotics and Autonomous Systems (11 new technologies)
- TA 5, Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (4 new technologies)
- TA 7, Human Exploration Destination Systems (1 new technology)
- TA 9, Entry, Descent, and Landing Systems (3 new technologies)
- TA 11, Modeling, Simulation, Information Technology, and Processing (8 new technologies)
- TA 13, Ground and Launch Systems (3 new technologies)
- TA 14, Thermal Management Systems (1 new technology)

HIGH-PRIORITY TECHNOLOGIES

Based on the committee's review of the new technologies, which used the prioritization process documented in the 2012 NRC report, five of the new technologies have been ranked as a high priority.

Finding 1. Based on the review and analysis of the 42 new level 3 technologies that appear in the 2015 NASA roadmaps, 5 of those 42 new technologies have been added to the list of 83 high-priority technologies from the 2012 NRC report (listed in numerical order):

- 4.3.7, Grappling
- 4.4.8, Remote Interaction

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- 9.2.7, Terrain-Relative Sensing and Characterization
- 9.2.8, Autonomous Targeting
- 14.3.2, Thermal Protection System Modeling and Simulation

Technology 4.3.7, Grappling

Grappling systems are ranked as a high priority because they enable the physical capture of small asteroids and asteroid-sourced boulders, the attachment of said objects to robotic spacecraft, and the capture of free-flying spacecraft. Grappling technology would thereby support the transport of asteroids from their natural orbit to a lunar orbit, the human collection and return of samples from a boulder in lunar orbit, orbital debris mitigation, the protection of Earth from small planetary bodies, and the assembly of large spacecraft in orbit for future exploration missions. Potential commercial uses include securing boulder-sized asteroid samples for detailed sampling or processing in commercial space resources operations and securing dead satellites for return, disposal, salvage, or repair. The recent signing of the U.S. Commercial Space Launch Competitiveness Act, which entitles U.S. citizens to any asteroid or space resource obtained (or grappled and returned) from an asteroid may spur interest in commercial asteroid mining. Even so, NASA's development of grappling technology is a high priority because related work by other government organizations and industry is unlikely to meet NASA-specific needs, especially in light of the Asteroid Retrieval Mission schedule.

The content of technology 4.3.7, Grappling, overlaps somewhat with 4.6.3, Docking and Capture Mechanisms and Interfaces. Technology 4.6.3, Docking, however, focuses on the docking of one spacecraft with another, whereas 4.3.7, Grappling, also includes interactions with natural objects, such as asteroids and boulders from asteroids. Asteroids are massive tumbling targets with unstructured physical properties, and new grappling technologies will be needed to capture either a small asteroid or a boulder from a larger asteroid.

The capture, preloaded manipulation, and retrieval of samples from a boulder transported from the surface of an asteroid represent an unprecedented set of tasks for a NASA robotic or human mission. There is not much to borrow from with respect to developments by the Department of Defense or other organizations involved in aerospace research and development. Development of grappling technologies to enable the robust physical capture and preload of a boulder, other natural bodies, and spacecraft would greatly simplify the robotic control demands of an overall grappling system. The lack of detail in the TA 4 roadmap for this technology is a concern. Only a single level 4 research task was proposed, and its description provides little additional detail compared to the level 3 description. Another level 4 research task could be nonrigid approaches to grappling these large, spinning objects (e.g., looking at grapples attached to adjustable tethers) for de-spinning and securing objects to the spacecraft (or securing the spacecraft and its engines to the object).

Technology 4.4.8, Remote Interaction

Remote Interaction is assigned a high priority because it is defined as providing control and communication methods that enable humans to remotely operate otherwise autonomous systems and robots. Supervisory control incorporates techniques necessary for controlling robotic behaviors using higher-level goals instead of low-level commands, thus requiring robots to have semiautonomous or autonomous behaviors. This technology will support the design of game-changing science and exploration missions, such as new robotic missions at remote locations and simultaneous robotic missions with reduced human oversight. Remote Interaction also includes technology for enabling manual control of remote systems and for enabling operators to monitor system status, assess task progress, perceive the remote environment, and make informed operational decisions, such as tactical plans.

Technology 9.2.7, Terrain-Relative Sensing and Characterization

NASA successfully completed the survey of our solar system with the recent New Horizons mission to Pluto. NASA is continuing planetary exploration with a new era of increased surface exploration. This technology would produce "high-rate, high-accuracy measurements for algorithms that enable safe precision landing near areas of

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high scientific interest or predeployed assets."[6] As a result, 9.2.7 would help enable many critical missions in this new era and would likely lead to many surprising new discoveries. Terrain-Relative Sensing and Characterization is the most promising of the TA 9 level 3 technologies reviewed. It is a game-changing technology that could enable important new missions not currently feasible for the next 20 years. It impacts multiple missions in multiple mission areas, both human and robotic. It also has a broad impact across the aerospace community and is already influencing commercial and military autonomous vehicles, such as the rapid advancement of unmanned air vehicles.

Technology 9.2.8, Autonomous Targeting

Autonomous Targeting, which is highly coupled to 9.2.7, Terrain-Relative Sensing and Characterization, is also ranked as a high priority because it is a potentially game-changing technology that would enable important new missions, such as several of the New Frontier missions. By improving the ability of vehicles to assess and characterize the terrain they are facing for landing and exploration, this technology would enable the next step of autonomous targeting, which could be critical when interplanetary distances make remote guidance difficult or impossible. Even if a vehicle is piloted for a human mission, this technology could be critical to help assure a safe landing. Like technology 9.2.7, this technology will have a moderate impact across the aerospace community but mostly on commercial and military autonomous vehicles.

Technology 14.3.2, Thermal Protection Systems Modeling and Simulation

Thermal Protection Systems (TPS) Modeling and Simulation is ranked as a high priority because uncertainties in the modeling of strong radiative shocks are a major limitation in the design of effective heat shields for high-speed entry into the atmospheres of Earth, Mars, and other bodies. Early TPS design was largely empirical, based on extensive direct (and expensive) testing in Earth's atmosphere. Testing in ground test facilities is also difficult and expensive because of the extreme environments associated with atmospheric entry. Computational methods employing physics-based models, including modeling of materials, are improving to the point that with validation via laboratory and flight testing and verification of TPS, they can more reliably predict TPS performance. However, further development is required to build confidence that design margins can be substantially reduced and that weight savings will be realized. Major challenges remain in increasing the accuracy and precision of physics-based modeling of entry shocks, thermal radiation, and their interaction with an ablating heat shield, challenges that are addressed by this technology. Currently, uncertainties are +80 percent to −50 percent for Mars return missions; missions to other destinations have different uncertainty ranges.[7] The goal of proposed research for technology 14.3.2 is to reduce uncertainty below 25 percent for all planetary missions. This reduction in uncertainty would enable the use of heat shields that weigh less, thereby reducing spacecraft weight and/or increasing allowable payload weight. This technology couples closely with the 2012 highly ranked crosscutting technology of X.5, Entry, Descent, and Landing TPS, which includes both rigid and flexible systems. For that technology to advance and realize its potential, the modeling must improve. As noted in the roadmap for TA 14, "a significant challenge facing the development of this technology is the limitations in the available flight and ground test data" (p. TA 14-93).

HIGHEST-PRIORITY TECHNOLOGIES

The 2012 NRC report defines the highest-priority technologies in terms of their ability to support three technology objectives:

- Technology Objective A, Human Space Exploration: Extend and sustain human activities beyond low Earth orbit. This objective is focused on human missions.

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[6] NASA, 2015, *NASA Technology Roadmaps: TA 9 Entry, Descent, and Landing Systems*, Washington, D.C., p. TA 9-25.
[7] NASA, 2015, *Technology Roadmaps, TA 14: Thermal Management Systems*, p. TA 14-32.

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- Technology Objective B, In Situ Measurements: Explore the evolution of the solar system and the potential for life elsewhere. This objective includes both robotic and human missions.
- Technology Objective C, Remote Measurements: Expand our understanding of Earth and the universe in which we live. This objective is focused on robotic missions.

These three objectives encompass the full breadth of NASA's endeavors in space science, Earth science, and exploration. The 2012 NRC report does not assess or comment on the relative priority of these technology objectives.

The 2012 report includes a list of the 16 highest-priority technologies. However, 5 of the 16 were groups of related technologies, designated X.1 through X.5. Altogether, the top 16 (individual and grouped) technologies comprised 31 individual technologies.[8]

The committee added three of the five new technologies ranked as high priority to the list of highest-priority technologies from the 2012 NRC report. The new list of grouped technologies, which includes two additional technologies from the TABS in the 2012 NRC report, appears below, and the new list of the highest-priority technologies appears in Table S.1. In both the list and the table, new items are shaded.

X.1, Radiation Mitigation for Human Spaceflight
- 6.5.1, Radiation Risk Assessment Modeling
- 6.5.2, Radiation Mitigation[9]
- 6.5.3, Radiation Protection Systems
- 6.5.4, Radiation Prediction
- 6.5.5, Radiation Monitoring Technology

X.2, Lightweight and Multifunctional Materials and Structures
- 10.1.1, (Nano) Lightweight Materials and Structures
- 12.1.1, Materials: Lightweight Structures
- 12.2.1, Structures: Lightweight Concepts
- 12.2.2, Structures: Design and Certification Methods
- 12.2.5, Structures: Innovative, Multifunctional Concepts

X.3, Environmental Control and Life Support System (ECLSS)
- 6.1.1, ECLSS: Air Revitalization
- 6.1.2, ECLSS: Water Recovery and Management
- 6.1.3, ECLSS: Waste Management
- 6.1.4, ECLSS: Habitation

X.4, Guidance, Navigation, and Control (GN&C)[10]
- 4.6.2, Relative Guidance Algorithms (for Automation Rendezvous and Docking)[11]
- 5.4.3, Onboard Autonomous Navigation and Maneuvering (for Position, Navigation, and Timing)
- 9.2.7, Terrain-Relative Sensing and Characterization (for Descent and Targeting)
- 9.2.8, Autonomous Targeting (for Descent and Targeting)

X.5, Entry, Descent, and Landing (EDL) Thermal Protection Systems (TPS)
- 9.1.1, Rigid Thermal Protection Systems
- 9.1.2, Flexible Thermal Protection Systems
- 14.3.1, Ascent/Entry TPS

X.6, Grappling, Docking, and Handling
- 4.3.6, Sample Acquisition and Handling (formerly Robotic Drilling and Sample Handling)
- 4.3.7, Grappling
- 4.6.3, Docking and Capture Mechanisms and Interfaces

[8] The relative priority of the individual and grouped technologies varies from one technology objective to another, as shown in Table S.1.
[9] Renamed Radiation Mitigation and Biological Countermeasures in the 2015 TABS.
[10] Technology 9.4.7, GN&C Sensors and Systems (for entry, descent, and landing), which was an element of group X.4 in the 2012 NRC report, has been deleted because it has no technical content in the 2015 roadmap for TA 9.
[11] Renamed GN&C Algorithms in the 2015 TABS.

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TABLE S.1 The Committee's Final 2016 List of Highest-Priority Technologies, Ranked by Technology Objective, Comprising 17 Individual and Grouped Technologies, with Up to 9 per Technology Objective

Highest-Priority Technologies for Technology Objective A, Human Space Exploration	Highest-Priority Technologies for Technology Objective B, In Situ Measurements	Highest-Priority Technologies for Technology Objective C, Remote Measurements
Radiation Mitigation for Human Spaceflight (X.1)	GN&C (X.4)	Optical Systems (Instruments and Sensors) (8.1.3)
Long-Duration Crew Health (6.3.2)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)	High-Contrast Imaging and Spectroscopy Technologies (8.2.4)
ECLSS (X.3)	Electric Propulsion (2.2.1)	Detectors and Focal Planes (8.1.1)
GN&C (X.4)	Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)
(Nuclear) Thermal Propulsion (2.2.3)	EDL TPS (X.5)	Active Thermal Control of Cryogenic Systems (14.1.2)
Lightweight and Multifunctional Materials and Structures (X.2)	In Situ Instruments and Sensors (8.3.3)	Electric Propulsion (2.2.1)
Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)	Solar Power Generation (Photo-voltaic and Thermal) (3.1.3)
EDL TPS (X.5)	Extreme Terrain Mobility (4.2.1)	
Grappling, Docking, and Handling (X.6)	Grappling, Docking, and Handling (X.6)	

Finding 2. Based on the review and analysis of the five new level 3 technologies that have been added to the list of high-priority technologies, three of the technologies (4.3.7, 9.2.7, and 9.2.8), along with two other technologies (4.3.6 and 4.6.3) that previously appeared in the interim list of highest-priority technologies in the 2012 NRC report, have been added to the list of the 16 highest-priority technologies, as follows:

- Technology group X.4, Guidance, Navigation, and Control, has been expanded to include 9.2.7, Terrain-Relative Sensing and Characterization (for Descent and Targeting), and 9.2.8, Autonomous Targeting (for Descent and Targeting). Technology 9.4.7, GN&C Sensors and Systems (for Entry, Descent, and Landing), which has no technical content in the 2015 roadmap for TA 9, has been deleted.
- A new technology group has been created: X.6, Grappling, Docking, and Handling. This group consists of 4.3.6, Sample Acquisition and Handling (formerly Robotic Drilling and Sample Handling); 4.3.7, Grappling; and 4.6.3, Docking and Capture Mechanisms and Interfaces. Group X.6 has been added to the list of highest-priority technologies for Technology Objective A, Human Space Exploration, and Technology Objective B, In Situ Measurements.

FUTURE INDEPENDENT REVIEWS

This report recommends a methodology for conducting independent reviews of future updates to NASA's space technology roadmaps. This methodology takes into account the extent of changes expected to be implemented in the roadmap from one generation to the next and the time elapsed since the most recent comprehensive independent review of the roadmaps. This methodology is summarized in the following four recommendations.

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PROPOSED METHODOLOGY FOR FUTURE INDEPENDENT REVIEWS

Recommendation 1. Independent reviews of the roadmaps should be conducted whenever there is a significant change to them. NASA's technology roadmap revision cycle is expected to be performed every 4 years, but significant changes in NASA direction may necessitate more frequent reviews. The reviews should be one of two types: either a comprehensive review of the complete set of roadmaps (including TA 15), such as the one performed in 2012, or a focused review, such as the one in this report. Focused reviews can be conducted using more limited resources because they address only a subset of the total technology portfolio. In making recommendations about the review methodology, each future independent review should focus on the methodology to be used for the subsequent review rather than on a long-range plan covering multiple reviews.

Recommendation 2. Before the next independent review, the NASA Technology Executive Council and the Center Technology Council (NTEC/CTC), in accordance with their charters, should prioritize the technologies that will be examined in the review. The NTEC/CTC should present the results and rationale for the priorities to the next independent review committee. The prioritization process should take into account the factors included in the prioritization process described in Appendix C. It should also be supported by additional factors such as linkage of technologies to a concise list of design reference missions (DRMs), including an assessment of the technologies as enabling or enhancing; the use of systems analysis to establish the technology's benefit to the mission relative to the benefit of alternative technologies; and correlation of technology priorities with both expected funding and required development schedule.

Recommendation 3. As part of its prioritization process, NTEC/CTC should classify each technology to be examined by the next independent review (at TABS level 3 or level 4) as Lead, Collaborate, Watch, or Park. In addition, the Office of the Chief Technologist (OCT) should update NASA's electronic technology database, TechPort, so that it, too, indicates for each technology whether NASA is pursuing it as Lead, Collaborate, Watch, or Park. For collaborative efforts, OCT should include in TechPort details on the nature of the collaboration, including facilities, flight testing, and the development of crosscutting technologies.

Recommendation 4. The next independent review should be a comprehensive review if there have been major changes to the roadmaps and/or the DRMs, or it should be a focused review and cover only new technologies if the number of new technologies in the next version of the roadmaps once again constitutes a small percentage of the total number of technologies. The scope of the review should include the following:

- **The prioritization of technologies previously completed by the NTEC/CTC and the process used to conduct the prioritization.**
- **Roadmap for TA 15 Aeronautics.**
- **The first volume of the technology roadmaps, TA 0 Introduction, Crosscutting Technologies, and Index.**
- **The relevance of technologies to the DRMs as either enabling or enhancing.**
- **Recommendation for the methodology to be used for the review that in turn follows it.**

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1

Introduction

Historically, the United States has been a world leader in aerospace endeavors in both the government and commercial sectors. A key factor in aerospace leadership is continuous development of advanced technology, which is critical to U.S. ambitions in space, including a human mission to Mars.

While movies like *The Martian* have excited the public about a possible human mission to Mars and led to a record number of 18,300 applicants for NASA's astronaut class of 2017 (significantly higher than the previous record of 8,000 in 1978), the fundamental technologies to accomplish many NASA missions are not keeping pace with the interest. Key technology challenges for a human mission to the Mars surface include mitigating the effects of space radiation; improving in-space propulsion and power systems; developing the ability to land heavy payloads on the surface of Mars; improving the reliability of environmental control and life support systems and closing the water, air, and food cycles; and providing the necessary spacesuits, rovers, human–machine interfaces, in situ resource utilization, and other engineering systems that can operate for an extended mission in the challenging environments in space and on the surface of Mars.

Human spaceflight is not the only NASA activity that requires new technology to remain viable. NASA successfully completed the survey of our solar system with the recent New Horizons mission to Pluto, again stimulating public interest and delivering surprising scientific results. To take the next steps in robotic exploration of the solar system, advanced technologies are needed to improve the ability of vehicles to travel to and navigate with greater autonomy in a wide range of gravitational, environmental, surface, and subsurface conditions at great distances from Earth.

Knowledge of the universe beyond our solar system is gained by missions like the James Webb Space Telescope, which will carry on the legacy of the Hubble Space Telescope and other historic space science missions. In order for future missions to maintain a steady cadence of new discoveries, investments must be made in key technologies, especially those related to scientific measurement technologies and the spacecraft that support the instruments.[1]

Commercial space ventures in recent years have been proliferating, with investments coming from the traditional aerospace industry, from new aerospace companies, and from nonaerospace companies such as Amazon and Google. These commercial space ventures are creating important new opportunities for NASA collaboration. NASA's authorizing legislation, the National Aeronautics and Space Act of 2010, Sec. 20102(c), directs it to "seek and encourage, to the maximum extent possible, the fullest commercial use of space." NASA has provided markets both for commercial crew and cargo delivery to the International Space Station (ISS) and for space

[1] See, for example, Appendix C, Table C.9, last column: Highest-Priority Technologies for Technology Objective C: Remote Measurements.

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launch services for other missions. Even so, NASA could do more to create "a proactive and sustained partnership between NASA and industry that goes beyond treating the private sector as a contractor, which is typically the case when NASA funds industry to achieve NASA goals."[2]

To continue to achieve progress, NASA is currently executing a series of aeronautics and space technology programs using a roadmapping process to identify technology needs and improve the management of its technology development portfolio. The NASA Authorization Act of 2010, signed into law on October 11, 2010, directed NASA to create a program to maintain its research and development base in space technology:

> It is critical that NASA maintain an agency space technology base that helps align mission directorate investments and supports long term needs to complement mission-directorate funded research and support, where appropriate, multiple users, building upon its Innovative Partnerships Program and other partnering approaches. (National Aeronautics and Space Act of 2010, Sec. 904)

In response, NASA established a stand-alone, crosscutting space technology mission directorate and created the Space Technology program with the goal of rapidly developing, demonstrating, and infusing revolutionary, high-payoff technologies for the benefit of NASA missions, the aerospace industry, government agencies, and other national needs. NASA also created a set of 14 draft technology roadmaps in 2010 to guide the development of space technologies. These roadmaps were the subject of a comprehensive independent review by the National Research Council (NRC), which issued a report in 2012 entitled *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.[3] Among other things, that report succinctly identified a fundamental issue facing NASA today:

> The technologies needed for the Apollo program were generally self-evident and driven by a clear and well defined goal. In the modern era, the goals of the country's broad space mission include multiple objectives, extensive involvement from both the public and private sectors, choices among multiple paths to different destinations, and very limited resources. As the breadth of the country's space mission has expanded, the necessary technological developments have become less clear, and more effort is required to evaluate the best path for a forward-looking technology development program.[4]

NASA has been addressing this issue. Major effort has gone into characterizing its technology portfolio and improving the roadmapping process since the 2012 NRC report. The appointment of a chief technologist at NASA (which took place before the 2012 study), the creation of a Strategic Space Technology Investment Plan (SSTIP), and the development of the TechPort database are all positive steps toward improving the understanding of NASA's more than 1,400 diverse space technology projects with an annual cost of nearly $1 billion.[5]

In 2015, NASA took another important step by updating the 2010 draft technology roadmaps, resulting in a new set of roadmaps. The 2015 roadmaps assess the relevance of the technologies by showing their linkage to a set of mission classes and design reference missions (DRMs) from the Human Exploration and Operations Mission Directorate and the Science Mission Directorate. The 2015 roadmaps also include a new roadmap for aeronautics. The relevance of the new aeronautics technologies is indicated by their linkage to a set of aeronautic thrusts from the Aeronautics Research Mission Directorate that could be executed in the next 20 years. In the spring of 2015, the updated roadmaps were released to the public for review and comment.[6]

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[2] National Research Council (NRC), 2009, *America's Future in Space: Aligning the Civil Space Program with National Needs*, The National Academies Press, Washington, D.C., pp. 56 and 57.

[3] NRC, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* The National Academies Press, Washington, D.C.

[4] NRC, 2012, *NASA Space Technology Roadmaps and Priorities*, pp. 10 and 11.

[5] NASA Office of the Inspector General, 2015, *NASA's Efforts to Manage Its Space Technology Portfolio,* Report No. IG-16-008, Washington, D.C.

[6] NASA, 2015, *NASA Technology Roadmaps: Introduction, Crosscutting Technologies, and Index,* Washington, D.C., July. (In addition to this introductory volume, there are 15 additional volumes, one for each technology area. All are available at http://www.nasa.gov/offices/oct/home/roadmaps/index.html; accessed May 14, 2016.)

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Also in 2015 the National Academies of Sciences, Engineering, and Medicine were asked to assemble a committee to prioritize new technologies in the 2015 NASA roadmaps for TA 1-14 (that is, technologies in the 2015 roadmaps for TA 1-14 that had not been assessed in the 2012 NRC report). Per the study statement of task (see Appendix A), the new technologies have been prioritized using the same process and criteria that were used in the 2012 NRC report. The aeronautics roadmap is not included in this review because it uses the 2012 NRC report as a baseline, and there was not an aeronautics roadmap for the prior study to review. This review did not revisit the prioritization of the technologies already assessed in the 2012 NRC report, nor did it consider whether any technologies should be added to or dropped from the 2015 NASA roadmaps.

The committee was also tasked with recommending "a methodology for conducting independent reviews of future updates to NASA's space technology roadmaps, which are expected to occur every 4 years. The recommended methodology takes into account the extent of changes expected to be implemented in the roadmap from one generation to the next and the amount of time since the 2012 comprehensive NRC independent review of the roadmaps."

The 2012 NRC report included 11 findings and recommendations related to observations and general themes (see Appendix E). This study was not tasked either with reviewing those findings and recommendations or assessing NASA's response to them. However, some of the topics addressed by these findings and recommendations are mentioned in some of the recommendations in this report.

TECHNOLOGY AREA BREAKDOWN STRUCTURE

The content of the 2015 roadmaps is organized using a four-level technology area breakdown structure (TABS). Level 1 represents the technology area (TA), which is the title of the roadmap:

- TA 1, Launch Propulsion Systems
- TA 2, In-Space Propulsion Technologies
- TA 3, Space Power and Energy Storage
- TA 4, Robotics and Autonomous Systems
- TA 5, Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- TA 6, Human Health, Life Support, and Habitation Systems
- TA 7, Human Exploration Destination Systems
- TA 8, Science Instruments, Observatories, and Sensor Systems
- TA 9, Entry, Descent, and Landing Systems
- TA 10, Nanotechnology
- TA 11, Modeling, Simulation, Information Technology, and Processing
- TA 12, Materials, Structures, Mechanical Systems, and Manufacturing
- TA 13, Ground and Launch Systems
- TA 14, Thermal Management Systems
- TA 15, Aeronautics

Each roadmap describes level 2 technology subareas, level 3 technologies, and level 4 research tasks. The 2012 NRC report focused its review on the level 3 technologies. The TABS for the 2010 draft NASA roadmaps contained 320 level 3 technologies. The modified TABS recommended in the 2012 NRC report contained 295 level 3 technologies. The TABS for the new 2015 roadmaps contains 340 level 3 technologies. The net change in the number of technologies in the various TABS arises from many factors: Technologies have been added, deleted, revised, merged, and so on. A detailed comparison of the technologies in the 2010, 2012, and 2015 TABS (see Appendix B) revealed that 42 technologies met the criteria for review in this report.

The 2012 NRC report was based on a comprehensive review that considered all 320 level 3 technologies in the NASA's 2010 draft roadmaps (TA 1 through TA 14). The review established evaluation criteria (also used in this study), identified gaps, and recommended priorities for the technologies (see Appendix C). NASA augmented each of the draft 2010 roadmaps with a new section that summarized the NRC's recommendations and comments and

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released a final version of the roadmaps to the public in April 2012. The NRC's guidance also heavily influenced the technology priorities presented in the NASA 2013 Strategic Space Technology Investment Plan.

ORGANIZATION OF THIS REPORT

Chapters 2 and 3 describe the new technologies addressed in this report and their prioritization by the committee. Also presented is where the new technologies fit with respect to the previous prioritization of technologies in the list of 83 high-priority technologies and the list of 16 highest-priority technologies in the 2012 report.

Chapter 4 describes a recommended methodology for conducting independent reviews of future updates to NASA's technology roadmaps. This methodology takes into account the improved process that NASA used to generate the 2015 roadmaps and the value that independent reviews can bring.

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2

High-Priority Technologies

INTRODUCTION

As noted in Chapter 1, 42 level 3 technologies in the 2015 roadmaps meet the criteria for review in this report. Thirty-nine of these technologies are new: They do not appear in either the 2010 or the 2012 TABS. The other three appear by number in NASA's 2015 TABS and the TABS recommended in the 2012 National Research Council (NRC) report,[1] but there has been a major change to the naming and content of these technologies, so they are being evaluated again. The 42 technologies evaluated by this study are listed below by technology area (TA) and technology subarea:

TA 1, Launch Propulsion Systems (11 new technologies)
- 1.1, Solid Rocket Propulsion Systems
  - 1.1.6, Integrated Solid Motor Systems
  - 1.1.7, Liner and Insulation
- 1.6, Balloon Launch Systems
  - 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

TA 4, Robotics and Autonomous Systems (11 new technologies)
- 4.2, Mobility
  - 4.2.5, Surface Mobility
  - 4.2.6, Robot Navigation

[1] NRC, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*, The National Academies Press, Washington, D.C.

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- 4.2.7, Collaborative Mobility
- 4.2.8, Mobility Components
- 4.3, Manipulation
  - 4.3.7, Grappling
- 4.4, Human–System Interaction
  - 4.4.3, Proximate Interaction
  - 4.4.8, Remote Interaction
- 4.5, System-Level Autonomy
  - 4.5.8, Automated Data Analysis for Decision Making
- 4.7, Systems Engineering
  - 4.7.3, Robot Modeling and Simulation
  - 4.7.4, Robot Software
  - 4.7.5, Safety and Trust

TA 5, Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (4 new technologies)
- 5.1, Optical Communications and Navigation
  - 5.1.6, Optical Tracking
  - 5.1.7, Integrated Photonics
- 5.7, Orbital Debris Tracking and Characterization Systems
  - 5.7.1, Tracking Technologies
  - 5.7.2, Characterization Technologies

TA 7, Human Exploration Destination Systems (1 new technology)
- 7.4, Habitat Systems
  - 7.4.4, Artificial Gravity

TA 9, Entry, Descent, and Landing Systems (3 new technologies)
- 9.2, Descent and Targeting
  - 9.2.6, Large Divert Guidance
  - 9.2.7, Terrain-Relative Sensing and Characterization
  - 9.2.8, Autonomous Targeting

TA 11, Modeling, Simulation, Information Technology, and Processing (8 new technologies)
- 11.2, Modeling
  - 11.2.6, Analysis Tools for Mission Design
- 11.3, Simulation
  - 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, Information Processing
  - 11.4.6, Cyber Infrastructure
  - 11.4.7, Human–System Integration
  - 11.4.8, Cyber Security

TA 13, Ground and Launch Systems (3 new technologies)
- 13.1, Operational Life Cycle
  - 13.1.4, Logistics
- 13.2, Environmental Protection and Green Technologies
  - 13.2.5, Curatorial Facilities, Planetary Protection, and Clean Rooms

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13.3, Reliability and Maintainability
13.3.8, Decision-Making Tools

TA 14, Thermal Management Systems (1 new technology)
14.3, Thermal Protection Systems
14.3.2, TPS Modeling and Simulation

There are no new technologies in the following technology areas:

- TA 2, In-Space Propulsion Technologies
- TA 3, Space Power and Energy Storage
- TA 6, Human Health, Life Support, and Habitation Systems
- TA 8, Science Instruments, Observatories, and Sensor Systems
- TA 10, Nanotechnology
- TA 12, Materials, Structures, Mechanical Systems, and Manufacturing

All of the technologies in the roadmap for TA 15 Aeronautics are new, because the 2010 and 2012 TABS did not include aeronautics. As noted in Chapter 1, however, TA 15 is outside the scope of this study.

This chapter describes the results of the committee's effort to prioritize the 42 new (or heavily revised) technologies using the same prioritization process that the NRC used in developing the 2012 report. As described in the following sections, the committee added 5 of the 42 to the list of 83 high-priority level 3 technologies from the 2012 NRC report.[2] The five technologies (listed in order of the technology number) are as follows:

4.3.7, Grappling
4.4.8, Remote Interaction
9.2.7, Terrain-Relative Sensing and Characterization
9.2.8, Autonomous Targeting
14.3.2, TPS Modeling and Simulation

In the discussion of technologies below, the greatest detail is provided for these five high-priority technologies, and the least amount of detail is provided for those technologies that are ranked as a low priority. For all of the technologies, additional information is available in the 2015 NASA Technology Roadmaps.[3]

Table 2.1 provides the complete list of 88 technologies that the committee determined are a high priority: 83 from the 2012 NRC report plus the 5 listed above, which are shaded.

UNDERSTANDING THE TABLES

In each of the sections that follow, there is a table that shows the scores for each technology that were used to determine its priority. These tables were created by taking the corresponding table from the 2012 NRC report and inserting the new technologies evaluated in this report. The first column lists the technologies. The last two columns show the score and the priority (high, medium, or low) assigned to each technology. Appendix C, in the section 2012 NRC Report: Process to Identify the High-Priority Technologies, provides a detailed explanation of the intervening columns and the quality function deployment (QFD) process that formed the basis for the scoring.

In the tables and figures, the priority of each technology is designated as L (low priority), M (medium priority), H (high priority), or H* (high priority, QFD override). As described in Appendix C, the steering committee and panels who authored the 2012 NRC report had the option of ranking key technologies as a high priority even

[2] NRC, 2012, *NASA Space Technology Roadmaps and Priorities*.
[3] NASA, "2015 NASA Technology Roadmaps," Washington, D.C., available at http://www.nasa.gov/offices/oct/home/roadmaps/index.html, accessed June 20, 2016.

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TABLE 2.1 The 88 High-Priority Level 3 Technologies—83 from the 2012 NRC Report[a] and 5 More from This Report, Which Are Shaded

TA 1 Launch Propulsion Systems	
1.3.1	Turbine Based Combined Cycle (TBCC)
1.3.2	Rocket Based Combined Cycle (RBCC)
TA 2 In-Space Propulsion Technologies	
2.2.1	Electric Propulsion
2.4.2	Propellant Storage and Transfer
2.2.3	(Nuclear) Thermal Propulsion
2.1.7	Micro-Propulsion
TA 3 Space Power and Energy Storage	
3.1.3	Solar Power Generation (Photovoltaic and Thermal)
3.1.5	Fission Power Generation
3.3.3	Power Distribution and Transmission
3.3.5	Power Conversion and Regulation
3.2.1	Batteries
3.1.4	Radioisotope Power Generation
TA 4 Robotics, TeleRobotics, and Autonomous Systems	
4.6.2	Relative Guidance Algorithms
4.6.3	Docking and Capture Mechanisms/Interfaces
4.5.1	Vehicle System Management and FDIR[b]
4.3.7	Grappling
4.3.2	Dexterous Manipulation
4.4.2	Supervisory Control
4.2.1	Extreme Terrain Mobility
4.3.6	Robotic Drilling and Sample Processing
4.4.8	Remote Interaction
4.2.4	Small Body/Microgravity
TA 5 Communication and Navigation	
5.4.3	Onboard Autonomous Navigation and Maneuvering
5.4.1	Timekeeping and Time Distribution
5.3.2	Adaptive Network Topology
5.5.1	Radio Systems
TA 6 Human Health, Life Support, and Habitation Systems	
6.5.5	Radiation Monitoring Technology
6.5.3	Radiation Protection Systems
6.5.1	Radiation Risk Assessment Modeling
6.1.4	Habitation
6.1.3	Environmental Control and Life Support System (ECLSS) Waste Management
6.3.2	Long-Duration Crew Health
6.1.2	ECLSS Water Recovery and Management
6.2.1	Extravehicular Activity (EVA) Pressure Garment
6.5.4	Radiation Prediction
6.5.2	Radiation Mitigation
6.4.2	Fire Detection and Suppression
6.1.1	Air Revitalization
6.2.2	EVA Portable Life Support System
6.4.4	Fire Remediation
TA 7 Human Exploration Destination Systems	
7.1.3	In Situ Resource Utilization (ISRU) Products/Production
7.2.1	Autonomous Logistics Management
7.6.2	Construction and Assembly
7.6.3	Dust Prevention and Mitigation
7.1.4	ISRU Manufacturing/Infrastructure Emplacement
7.1.2	ISRU Resource Acquisition
7.3.2	Surface Mobility
7.2.4	Food Production, Processing, and Preservation
7.4.2	Habitation Evolution
7.4.3	Smart Habitats
7.2.2	Maintenance Systems
TA 8 Science Instruments, Observatories, and Sensor Systems	
8.2.4	High-Contrast Imaging and Spectroscopy Technologies
8.1.3	Optical Systems (Instruments and Sensors)
8.1.1	Detectors and Focal Planes
8.3.3	In Situ Instruments and Sensors
8.2.5	Wireless Spacecraft Technology
8.1.5	Lasers for Instruments and Sensors
8.1.2	Electronics for Instruments and Sensors
TA 9 Entry, Descent, and Landing (EDL) Systems	
9.4.7	GN&C[c] Sensors and Systems (EDL)
9.2.7	Terrain-Relative Sensing and Characterization
9.2.8	Autonomous Targeting
9.1.1	Rigid Thermal Protection Systems
9.1.2	Flexible Thermal Protection Systems
9.1.4	Deployment Hypersonic Decelerators
9.4.5	EDL Modeling and Simulation
9.4.6	EDL Instrumentation and Health Monitoring
9.4.4	Atmospheric and Surface Characterization
9.4.3	EDL System Integration and Analysis
TA 10 Nanotechnology	
10.1.1	(Nano) Lightweight Materials and Structures
10.2.1	(Nano) Energy Generation
10.3.1	Nanopropellants
10.4.1	(Nano) Sensors and Actuators
TA 11 Modeling, Simulation, Information Technology, and Processing	
11.1.1	Flight Computing
11.1.2	Ground Computing
11.2.4a	Science Modeling and Simulation
11.3.1	Distributed Simulation
TA 12 Materials, Structures, Mechanical Systems, and Manufacturing	
12.2.5	Structures: Innovative, Multifunctional Concepts
12.2.1	Structures: Lightweight Concepts
12.1.1	Materials: Lightweight Structure
12.2.2	Structures: Design and Certification Methods
12.5.1	Nondestructive Evaluation and Sensors
12.3.4	Mechanisms: Design and Analysis Tools and Methods
12.3.1	Deployables, Docking, and Interfaces
12.3.5	Mechanisms: Reliability/Life Assessment/Health Monitoring
12.4.2	Intelligent Integrated Manufacturing and Cyber Physical Systems
TA 14 Thermal Management Systems	
14.3.1	Ascent/Entry Thermal Protection Systems
14.3.2	TPS Modeling and Simulation
14.1.2	Active Thermal Control of Cryogenic Systems

continiued

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NASA Space Technology Roadmaps and Priorities Revisited

TABLE 2.1 Continued

[a] National Research Council, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*, The National Academies Press, Washington, D.C.

[b] Fault detection, isolation, and recovery.

[c] Guidance, navigation, and control.

NOTES:

1. Technologies are listed by roadmap/technology area (TA 1 through TA 14; there are no high-priority technologies in TA 13). Within each technology area, technologies are listed in descending order by the quality function deployment (QFD) score assigned by the panels that helped to author the 2012 report. This sequencing may be considered a rough approximation of the relative priority of the technologies within a given technology area.

2. Except for the five new technologies, the name of each technology in this table is as it appears in the original list of 83 high-priority technologies in the 2012 NRC report. In some cases, the names have been slightly revised for the 2015 TABS (see Appendix B). Two technologies have been deleted and do not appear in the 2015 TABS: 8.2.4, High Contrast Imaging and Spectroscopy Technologies, and 8.2.5, Wireless Spacecraft Technologies. Three technologies have been renumbered: 5.4.3, 11.2.4a, 12.5.1, above, have been renumbered as 5.4.2, 11.2.4, and 12.4.5, respectively, in the 2015 TABS.

if they did not have a numerical score that corresponded to a high priority rank. These override technologies were deemed by the panels to be high priority irrespective of the numerical scores. In the tables and figures for each technology area in this chapter, the override technologies are designated by an "H*".

TA 1, LAUNCH PROPULSION SYSTEMS

In the 2012 NRC report, TA 1 included all propulsion technologies required to deliver space missions from the surface of Earth to Earth orbit or Earth escape, including solid rocket propulsion systems, liquid rocket propulsion systems, air breathing propulsion systems, ancillary propulsion systems, and unconventional/other propulsion systems. The 2015 NASA technology roadmaps for TA 1 expanded the scope to include suborbital balloon technologies. Table 2.2 shows how the new technologies fit into the TA 1 TABS. The scoring and ranking of all TA 1 technologies are illustrated in Figures 2.1 and 2.2.

TABLE 2.2 TA 1, Launch Propulsion Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
1.1 Solid Rocket Propulsion Systems	1.1.6 Integrated Solid Motor Systems
	1.1.7 Liner and Insulation
1.2 Liquid Rocket Propulsion Systems	None
1.3 Air-Breathing Propulsion Systems	None
1.4 Ancillary Propulsion Systems	None
1.5 Unconventional and Other Propulsion Systems	None
1.6 Balloon Systems (new)	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

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NASA Space Technology Roadmaps and Priorities Revisited

Technology Name	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
	Benefit	Alignment			Risk/Difficulty				
1.1.1. (Solid Rocket) Propellants	1	3	3	0	3	-1	-1	70	L
1.1.2. (Solid Rocket) Case Materials	1	3	3	1	3	-1	-1	72	L
1.1.3. (Solid Rocket) Nozzle Systems	1	3	3	0	3	-3	-1	62	L
1.1.4. Hybrid Rocket Propulsion Systems	1	3	3	0	3	-3	-3	54	L
1.1.5. Fundamental Solid Propulsion Technologies	1	9	3	0	3	-3	-1	92	M
1.1.6 Integrated Solid Motor Systems	3	3	3	0	3	-3	-1	116	M
1.1.7 Liner and Insulation	3	3	3	1	3	-1	-1	126	M
1.2.1. LH2/LOX Based	1	9	9	0	3	1	-3	112	M
1.2.2. RP/LOX Based	1	9	9	0	3	1	-3	112	M
1.2.3. CH4/LOX Based	1	3	3	0	3	-3	-3	54	L
1.2.4. Detonation Wave Engines (Closed Cycle)	1	3	3	0	3	-3	-3	54	L
1.2.5. (Liquid Rocket) Propellants	1	9	3	1	3	-3	-1	94	M
1.2.6. Fundamental Liquid Propulsion Technologies	1	9	3	1	3	-3	-1	94	M
1.3.1. TBCC	3	9	9	0	3	-3	-3	150	H
1.3.2. RBCC	3	9	9	0	3	-3	-3	150	H
1.3.3. Detonation Wave Engines (Open Cycle)	1	3	3	0	3	-3	-3	54	L
1.3.4. Turbine Based Jet Engines (Flyback Boosters)	1	3	1	0	3	-3	-3	50	L
1.3.5. Ramjet/Scramjet Engines (Accelerators)	1	0	3	0	3	-3	-3	39	L
1.3.6. Deeply Cooled Air Cycles	1	3	3	0	3	-3	-1	62	L
1.3.7. Air Collection and Enrichment System	1	3	1	0	3	-3	-1	58	L
1.3.8. Fundamental Air Breathing Propulsion Technologies	1	3	3	1	3	-1	-3	64	L
1.4.1. Auxiliary Control Systems	1	9	3	0	3	-1	-1	100	M
1.4.2. Main Propulsion Systems (Excluding Engines)	1	9	3	0	3	-1	-1	100	M
1.4.3. Launch Abort Systems	3	3	1	0	3	-1	-3	112	M
1.4.4. Thrust Vector Control Systems	1	9	3	0	3	-1	-1	100	M
1.4.5. Health Management & Sensors	1	9	3	1	3	-1	-1	102	M
1.4.6. Pyro and Separation Systems	1	9	3	0	3	-1	-1	100	M
1.4.7. Fundamental Ancillary Propulsion Technologies	1	9	3	0	3	-3	-1	92	M
1.5.1. Ground Launch Assist	1	3	3	1	3	-3	-3	56	L
1.5.2. Air Launch / Drop Systems	1	3	3	0	3	-3	-3	54	L
1.5.3. Space Tether Assist (for launch)	0	3	1	0	1	-3	-3	3	L
1.5.4. Beamed Energy / Energy Addition	1	3	1	1	1	-3	-3	32	L
1.5.5. Nuclear (Launch Engines)	0	0	0	0	1	-3	-9	-38	L
1.5.6. High Energy Density Materials/ Propellants	1	3	3	1	1	-3	-1	44	L
1.6.1 Super-Pressure Balloon	3	9	3	1	1	-1	-1	136	M
1.6.2 Materials	1	9	3	1	1	-1	0	86	L
1.6.3 Pointing Systems	1	9	3	1	1	-1	-1	82	L
1.6.4 Telemetry Systems	1	9	3	1	1	-1	-1	82	L
1.6.5 Balloon Trajectory Control	3	9	1	0	3	-3	-1	142	M
1.6.6 Power Systems	1	9	3	1	1	-1	0	86	L
1.6.7 Mechanical Systems: Launch Systems	1	3	3	1	1	-1	-1	52	L
1.6.8 Mechanical Systems: Parachute	1	3	3	1	1	-1	0	56	L
1.6.9 Mechanical Systems: Floatation	1	3	3	1	1	-3	-1	44	L

FIGURE 2.1 Scoring matrix for TA 1. H, high priority; M, medium priority; L, low priority; TBCC, turbine-based combined cycle; RBCC, rocket-based combined cycle.

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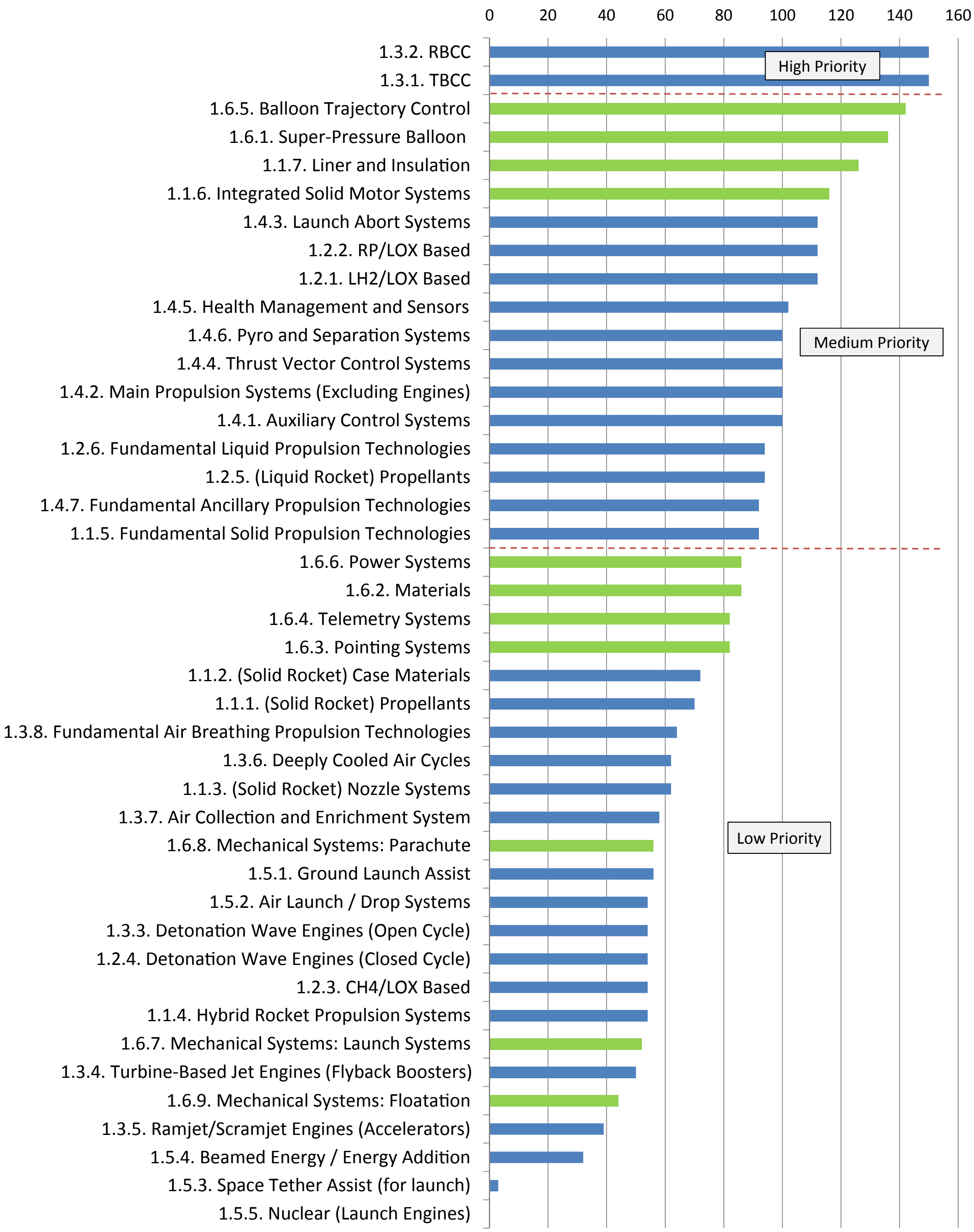

FIGURE 2.2 TA 1 level 3 technologies ranked by QFD score. The new technologies evaluated in this study are indicated in green. TBCC, turbine-based combined cycle; RBCC, rocket-based combined cycle.

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Technology 1.1, Solid Rocket Propulsion Technologies

Two new technologies in solid rocket propulsion systems were evaluated, and both were ranked as a medium priority.

Technology 1.1.6, Integrated Solid Motor Systems

A new five-segment advanced solid rocket booster is being developed for the Space Launch System (SLS) Block 1, which is derived from the Space Shuttle's four-segment solid rocket booster. An advanced booster option for SLS Blocks 1b and 2 is necessary to meet the payload requirement of 130 metric tons. Three options exist to meet this need, one of which is an advanced solid rocket booster.

Technology for integrated solid motor systems is fairly mature, and relatively minor improvements are needed. However some improvements are enabling for applicable missions. Also, the level 4 research task Nano Launch Vehicle Solid Motor Stage looks promising for a wide variety of missions. This technology is ranked as a medium priority.

Technology 1.1.7, Liner and Insulation

Health concerns and supply issues have mandated that nonasbestos liners and insulation be developed for solid rocket systems. While there are existing "green" Kevlar-based liners and insulations, they do not meet NASA's requirements. This problem can and must be solved for the applicable missions. A material (polybenzimidazole acrylonitrile butadiene rubber, or PBI NBR) has been identified, and the path forward is clear. This technology is ranked as a medium priority.

Technology 1.6, Balloon Launch Systems

The Science Mission Directorate has a stable of flight options, one of which is provided by the NASA Balloon Program. Currently operational balloons support large payload volumes, payload masses up to 3,600 kg, and flights of up to 60 days at altitudes over 30 km. Nine technologies to improve balloon capabilities were reviewed.

Medium-Priority Balloon Launch Technologies

Technologies 1.6.1, Super-Pressure Balloon, and 1.6.5, Balloon Trajectory Control, were ranked as a medium priority because they enable ultralong-duration balloon flights that would increase the scientific value of NASA's balloon program. Super-pressure balloons as well as super-pressure in combination with zero-pressure balloon vehicles offer the possibility of much longer flights (up to 100 days) and flights at a larger variety of latitudes. However, much of the technical risk has been alleviated because a smaller super-pressure balloon has already flown. Balloon trajectory control may be required to enable longer duration flights at midlatitudes by helping to avoid overflight of populated areas and to reach safe termination locations, thereby avoiding the need to prematurely terminate flights.

Low-Priority Balloon Launch Technologies

Technologies 1.6.2, Materials; 1.6.3, Pointing Systems; 1.6.4, Telemetry Systems; 1.6.6, Power Systems; 1.6.7, Mechanical Systems: Launch Systems; 1.6.8, Mechanical Systems: Parachute; and 1.6.9, Mechanical Systems: Floatation were ranked as a low priority because they primarily address engineering problems (that is, implementing identified technical solutions) rather than technology challenges (that is, developing new technical solutions). As a result, these technologies have a lower priority than other elements of the technology roadmaps that more directly address technology challenges.

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TA 4, ROBOTICS AND AUTONOMOUS SYSTEMS

TA 4 includes 11 new level 3 technologies. Many of these technologies are categorized as new as a result of a new organization of the TA 4 technologies from the previous roadmaps. Table 2.3 shows how the new technologies fit into the TA 4 TABS. The scoring and ranking of all TA 4 technologies are illustrated in Figures 2.3 and 2.4.

While all of the new TA 4 technologies are important to robotics, 2 of the 11 new technologies were ranked as high priority (4.3.7, Grappling, and 4.4.8, Remote Interaction), 5 were ranked as a medium priority (4.2.5, Surface Mobility; 4.2.6, Robot Navigation; 4.2.8, Mobility Components; 4.7.4, Robot Software; and 4.7.5, Safety and Trust), and 4 were ranked as a low priority (4.2.7, Collaborative Mobility; 4.4.3, Proximate Interaction; 4.5.8, Automated Data Analysis for Decision Making; and 4.7.3, Robot Modeling and Simulation).

Technology 4.3.7, Grappling

Grappling systems are ranked as a high priority because they enable the physical capture of small asteroids and asteroid-sourced boulders, the attachment of said objects to robotic spacecraft, and the capture of free-flying spacecraft. Grappling technology would thereby support the transport of asteroids from their natural orbit to a lunar orbit, the human collection and return of samples from a boulder in lunar orbit, orbital debris mitigation, the protection of Earth from small planetary bodies, and assembly of large spacecraft in orbit for future exploration missions. Potential commercial uses include securing boulder-sized asteroid samples for detailed sampling or processing in commercial space resources operations and securing dead satellites for return, disposal, salvage, or repair. The recent signing of the U.S. Commercial Space Launch Competitiveness Act, which entitles U.S. citizens to any asteroid or space resource obtained (or grappled and returned) from an asteroid may spur interest in commercial asteroid mining. Even so, NASA's development of grappling technology is a high priority because related work by other government organizations and industry is unlikely to meet NASA-specific needs, especially in light of the Asteroid Retrieval Mission schedule.

The content of technology 4.3.7, Grappling, overlaps somewhat with 4.6.3, Docking and Capture Mechanism/Interfaces. The focus of technology 4.6.3, however, is focused on docking of one spacecraft with another, whereas the scope of 4.3.7 also includes interactions with natural objects, such as asteroids and boulders from asteroids. Asteroids are massive tumbling targets with unstructured physical properties, and new grappling technologies will be needed to capture either a small asteroid or a boulder from a larger asteroid.

The alignment of technology 4.3.7 to NASA's needs is very high because NASA is developing the first robotic mission to visit a large near-Earth asteroid. The goal of the mission is to grapple and collect a multi-ton boulder

TABLE 2.3 TA 4, Robotics and Autonomous Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
4.1 Sensing and Perception	None
4.2 Mobility	4.2.5 Surface Mobility 4.2.6 Robot Navigation 4.2.7 Collaborative Mobility 4.2.8 Mobility Components
4.3 Manipulation	4.3.7 Grappling
4.4 Human–System Interaction	4.4.3 Proximate Interaction 4.4.8 Remote Interaction
4.5 System-Level Autonomy	4.5.8 Automated Data Analysis for Decision Making
4.6 Autonomous Rendezvous and Docking	None
4.7 Systems Engineering	4.7.3 Robot Modeling and Simulation 4.7.4 Robot Software 4.7.5 Safety and Trust

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	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	**27**	**5**	**2**	**2**	**10**	**4**	**4**		
	0/1/3/9	**0/1/3/9**	**0/1/3/9**	**0/1/3/9**	**1/3/9**	**-9/-3/-1/1**	**-9/-3/-1/0**		
Technology Name	**Benefit**	**Alignment**			**Risk/Difficulty**				
4.1.1. Vision (including active illumination)	3	9	3	3	3	-3	-1	152	M
4.1.2. Tactile Sensing	3	3	1	1	3	-3	-1	114	M
4.1.3. Natural Feature Image Recognition	1	3	1	1	3	-3	-1	60	L
4.1.4. Localization and Mapping	3	3	3	1	3	-3	-1	118	M
4.1.5. Pose Estimation	1	3	1	0	3	-3	-1	58	L
4.1.6. Multi-Sensor Data Fusion	3	9	9	9	3	-3	-1	176	M
4.1.7. Mobile Feature Tracking and Discrimination	1	3	1	1	3	-3	-1	60	L
4.1.8. Terrain Classification and Characterization	3	3	1	1	3	-3	-3	106	M
4.2.1. Extreme Terrain Mobility	3	9	0	1	9	-3	-3	194	H
4.2.2. Below-Surface Mobility	3	3	0	1	3	-9	-3	80	L
4.2.3. Above-Surface Mobility	3	3	1	0	3	-3	-1	112	M
4.2.4. Small Body / Microgravity Mobility	3	3	1	0	3	-3	-1	112	H*
4.2.5 Surface Mobility	3	9	1	3	3	-9	-3	116	M
4.2.6 Robot Navigation	3	9	9	9	1	-9	-3	124	M
4.2.7 Collaborative Mobility	0	0	1	9	1	-9	-3	-18	L
4.2.8 Mobility Components	3	9	1	9	3	-9	0	140	M
4.3.1. Robot Arms	1	3	1	1	3	-3	-1	60	L
4.3.2. Dexterous Manipulators (including robot hands)	3	9	1	3	9	-3	-1	208	H
4.3.3. Modeling of Contact Dynamics	1	3	1	1	3	-3	-1	60	L
4.3.4. Mobile Manipulation	1	3	1	1	9	-3	-1	120	M
4.3.5. Collaborative Manipulation	3	3	1	3	9	-3	-1	178	M
4.3.6. Robotic Drilling and Sample Handling	3	9	0	1	9	-3	-3	194	H
4.3.7 Grappling	3	9	1	0	9	-1	-1	210	H
4.4.1. Multi-Modal Human–Systems Interaction	3	9	3	3	3	-3	-3	144	M
4.4.2. Supervisory Control (incl time delay supervision)	3	9	3	3	9	-3	-3	204	H
4.4.3 Proximate Interaction	1	3	0	3	3	-3	-1	62	L
4.4.4. Intent Recognition and Reaction	1	3	1	3	3	-3	-3	56	L
4.4.5. Distributed Collaboration	3	9	3	3	3	-3	-3	144	M
4.4.6. Common Human–Systems Interfaces	1	3	1	3	3	-3	-1	64	L
4.4.7. Safety, Trust, and Interfacing of Robotic/Human Proximity Operations	3	9	3	9	3	-3	-3	156	M
4.4.8 Remote Interaction	3	9	9	3	3	1	-1	180	H
4.5.1. Vehicle System Management & FDIR	3	9	3	9	9	-3	-3	216	H
4.5.2. Dynamic Planning & Sequencing Tools	3	9	3	3	3	-3	-1	152	M
4.5.3. Autonomous Guidance & Control	3	9	3	3	3	-1	-1	160	M
4.5.4. Multi-Agent Coordination	3	3	3	9	3	-3	-3	126	M
4.5.5. Adjustable Autonomy	3	9	3	9	3	-3	-1	164	M
4.5.6. Terrain Relative Navigation	3	3	3	3	3	-3	-1	122	M
4.5.7. Path and Motion Planning with Uncertainty	1	3	1	3	3	-3	-1	64	L
4.5.8 Automated Data Analysis for Decision Making	1	3	3	3	3	-9	-1	44	L
4.6.1. Relative Navigation Sensors	3	9	1	0	3	-3	-1	142	M
4.6.2. Relative Guidance Algorithms	9	9	1	0	3	-3	-1	304	H
4.6.3. Docking and Capture Mechanisms/Interfaces	9	9	1	0	3	-3	-1	304	H
4.7.1. Modularity / Commonality	3	9	1	1	3	-3	-1	144	M
4.7.2. V&V of Complex Adaptive Systems	3	9	9	9	3	-3	-3	168	M
4.7.3. Onboard Computing	3	9	9	1	3	1	-1	176	L
4.7.3 Robot Modeling and Simulation	1	9	1	1	3	-3	-1	90	L
4.7.4 Robot Software	3	3	3	3	3	-3	-1	122	M
4.7.5 Safety and Trust	3	9	3	9	3	-3	-3	156	M

FIGURE 2.3 Scoring matrix for TA 4. H, high priority; H*, high priority (QFD override); M, medium priority; L, low priority.

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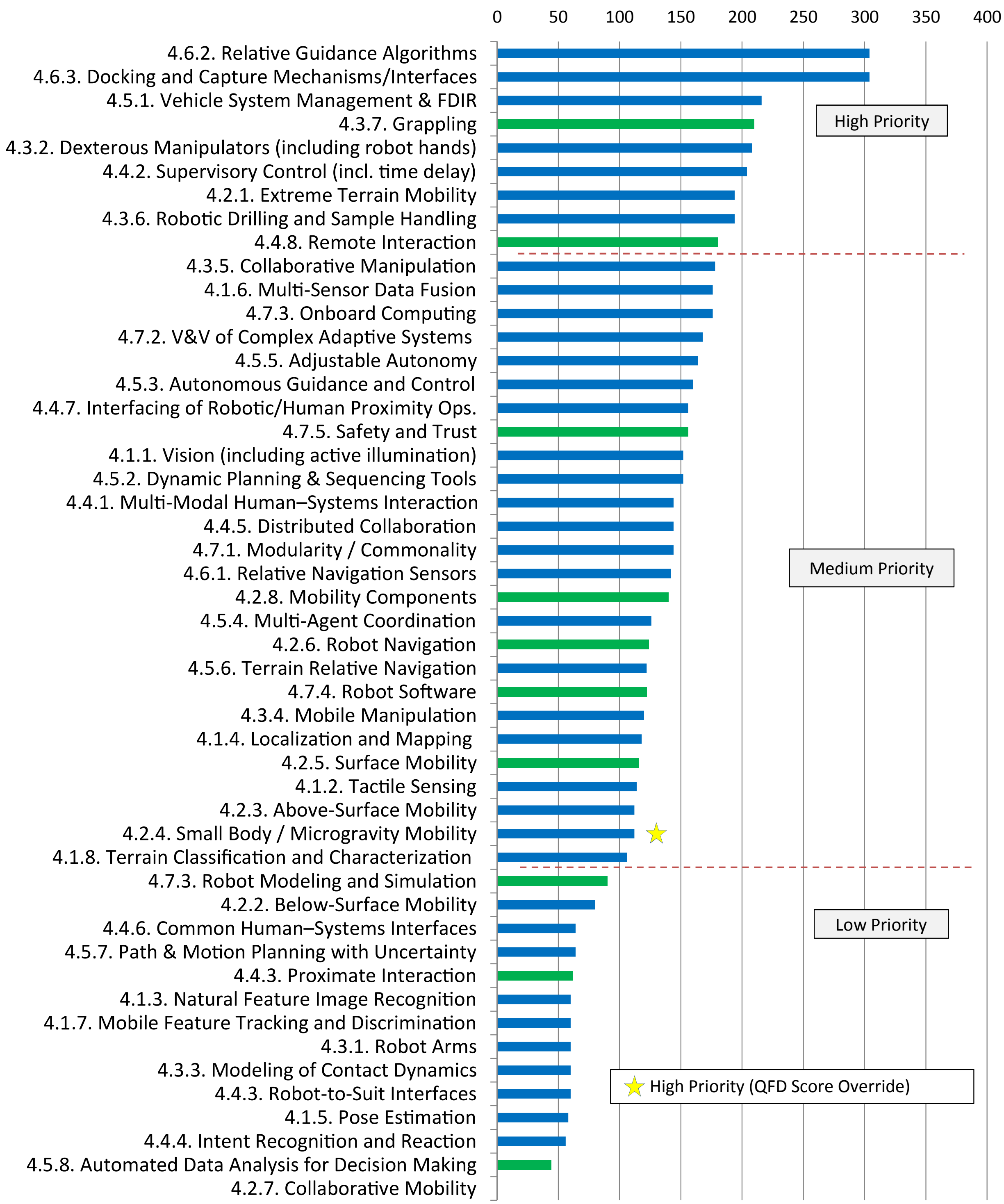

FIGURE 2.4 The TA 4 level 3 technologies ranked by QFD score. The new technologies evaluated in this study are indicated in green.

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from its surface and redirect the boulder into a stable orbit around the moon. Once there, astronauts would again employ grappling technologies to explore the boulder and return to Earth with samples in the 2020s.

The International Space Station (ISS) could be an effective platform for evaluating and testing the performance of the electromechanical elements of grappling systems. Reliability testing of the grappling capture and preload systems could be conducted inside or outside the ISS.

The lack of detail in the TA 4 roadmap for this technology is a concern. Only a single level 4 research task was proposed, and its description gives little additional detail over the level 3 description. A potential level 4 research task of interest would be nonrigid approaches to grappling large, spinning structures. For example, grapples attached to adjustable tethers could perhaps be used to immobilize a spinning object and secure it to the spacecraft (or secure the spacecraft to the object).

Technology 4.4.8, Remote Interaction

Remote Interaction is a high-priority technology because it would provide control and communication methods that enable humans to remotely operate otherwise autonomous systems and robots. Control includes teleoperation, supervisory control, and other control strategies. Remote Interaction includes supervisory control technology, which is ranked as a high priority in the 2012 NRC report.[4] As stated in the 2012 report, supervisory control incorporates techniques necessary for controlling robotic behaviors using higher-level goals instead of low-level commands, thus requiring robots to have semiautonomous or autonomous behaviors. Supervisory control increases the number of robots a single human can simultaneously supervise, reducing costs. This technology also reduces the impacts of time delays on remotely supported robotic teams, improving the synergy of combined human–robot teams, and facilitating teams of distributed robots. This technology will support the design of game-changing science and exploration missions, such as new robotic missions at remote locations and simultaneous robotic missions with reduced human oversight.

In addition to supervisory control, 4.4.8, Remote Interaction, also includes technology to enable manual control of remote systems and to enable operators to monitor system status, assess task progress, perceive the remote environment, and make informed operational decisions. These technologies are compatible and complementary to supervisory control technologies, and successful systems for remote operations must integrate all these technologies. Appropriate visualization, interfaces, and decision support for situation assessment are necessary to enable smooth transitions between supervisory and manual control, as required by the task. This capability to transition between modes is particularly important in performing novel tasks or in responding to unanticipated situations. Technology for remote operations that integrate supervisory control, manual control, and effective interfaces will enable realization of efficient and productive remote operations.

As noted in the 2012 NRC report, limited supervisory control has been deployed for the Mars rovers, so that the basic capabilities have a high TRL (9) but the advanced capabilities have a relatively low TRL (2-3). The alignment to NASA's needs is high due to the impact of reducing the number of personnel required to supervise robotic missions and the number of science and exploration missions to which the technology can be applied. Remote interaction generally has applications across the government agencies, including the Departments of Defense, Energy, and Homeland Security. For example, submersible unmanned vehicles can encounter time delays while under water; although the range of time delays of interest for submersible unmanned vehicles is different than the range of time delays of interest to space applications. Thus, NASA is uniquely positioned to lead the maturation of this technology to TRL 6. There may also be opportunities on some aspects of this technology for NASA to collaborate with both industry and international partners, such as Japan, France, and Germany.

The alignment with other aerospace and national needs is considered to be moderate, since the results can impact remote interaction for any robotic system. The risk is assessed as moderate to high, based on the fact that providing for remote interaction is a systems engineering problem. Thus development of the technology is highly

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[4] Supervisory Control is technology 4.4.2 in the TABS recommended by National Research Council, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* The National Academies Press, Washington, D.C.

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dependent on the development of underlying robotic and human–machine interaction capabilities. The program will need to leverage existing NASA and DOD capabilities to ensure timely development of various related technologies, such as robust, autonomous behaviors.

Medium-Priority TA 4 Technologies

Technologies 4.2.5, Surface Mobility; 4.2.6, Robot Navigation; 4.2.8, Mobility Components; 4.7.4, Robot Software; and 4.7.5, Safety and Trust, were ranked as a medium priority. All have the potential to make major improvements in robotic technology applicable to multiple missions. The factors that kept them from being high priority were primarily that (1) there was not a clear plan for addressing their technical hurdles, (2) NASA has already successfully demonstrated some relevant technology on flight missions, and/or (3) there is substantial work being done in these areas outside of NASA that could easily be incorporated by NASA. Thus it is not a high priority for NASA to have a leading role in these areas. Tremendous amounts of work related to 4.2.5, Surface Mobility; 4.2.6, Navigation; 4.7.4, Robot Software; and 4.7.5, Safety and Trust, are under way outside of NASA, although terrestrial use requirements differ from NASA's requirements. Technology 4.2.8, Mobility Components, while more NASA unique, had a mix of level 4 research tasks that either had already been largely achieved (e.g., wheels for planetary surfaces) or were lacking a clear plan for achievement.

Low-Priority TA 4 Technologies

Technologies 4.2.7, Collaborative Mobility, and 4.5.8, Automated Data Analysis for Decision Making, were ranked as low priority because the proposed level 4 research tasks did not seem likely to provide significant improvement to robotics technology or they are not on the critical path for the design reference missions (DRMs). These general categories are all important, but substantial work is being done in these areas outside of NASA. The proposed work was either not critical to the DRMs or not NASA specific and thus could be taken from similar work being done by industry or other agencies.

Technology 4.4.3, Proximate Interaction, is a technology area of great interest to robotics, particularly with regard to industrial, service, and assistive technology applications where robots interact with humans. However, this technology was ranked as low priority because the proposed level 4 work did not appear to be NASA specific. The DRMs do not appear to require proximate interaction technology beyond the capabilities already demonstrated by NASA. The improvement in NASA operations to extend proximate operations into new areas of NASA operations did not appear to be of great benefit during the time frame of this roadmap. It may be important to transfer and adapt technology from the technology robotics domain in the future, but this is not an urgent requirement.

Technology 4.7.3, Robot Modeling and Simulation, was ranked as a low priority. While modeling and simulation are critical, the proposed level 4 research tasks are not NASA specific and are actively being pursued by the Department of Agriculture, DOD, and other agencies. The NASA-specific aspects would be using the simulation in remote operations, but all of the proposed work is basically supercomputer-level simulations. Thus the methods and types of models are not specific to NASA and the benefit of a NASA effort in this domain is not a high priority.

TA 5, COMMUNICATION, NAVIGATION, AND ORBITAL DEBRIS TRACKING AND CHARACTERIZATION SYSTEMS

The 2015 NASA roadmap for TA 5 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems expands the scope of this technology area from that presented in the TABS in the 2012 NRC report by adding a new level 2 technology subarea, 5.7, Orbital Debris Tracking and Characterization. This new technology subarea incorporates two new level 3 technologies: 5.7.1, Tracking Technologies, and 5.7.2, Characterization Technologies. Two other level 3 technologies have been added: 5.1.6, Optical Tracking, and 5.1.7, Integrated Photonics. Table 2.4 shows how the new technologies fit into the TA 5 TABS. The scoring and ranking of all TA 5 technologies are illustrated in Figures 2.5 and 2.6.

All four of the new TA 5 level 3 technologies were evaluated to be of medium priority.

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TABLE 2.4 TA 5, Communications, Navigation, and Orbital Debris Tracking and Characterization Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
5.1 Optical Communications and Navigation	5.1.6 Optical Tracking 5.1.7 Integrated Photonics
5.2 Radio Frequency Communication	None
5.3 Internetworking	None
5.4 Position, Navigation, and Timing	None
5.5 Integrated Technologies	None
5.6 Revolutionary Concepts	None
5.7 Orbital Debris Tracking and Characterization Systems (new)	5.7.1 Tracking Technologies 5.7.2 Characterization Technologies

Technology 5.1.7, Integrated Photonics

Technology 5.1.7, Integrated Photonics, is ranked as a medium priority, although it is the most promising of the new level 3 technologies in TA 5. It has wide applicability for shorter range intersatellite communications links for near-Earth applications and networked communications to planetary orbiters with deep space communications capabilities. It may also offer marginal integration and test improvements for deep space communications systems requiring large optical power amplifiers. Moreover, the range of NASA applications goes beyond communications to include sensors such as LIDARs for docking and autonomous landing and active science instruments for wind measurements, particle characterization, vibrometry, and so on.

The overall QFD ranking is consistent with rankings from the previous study for similar and related technologies such as 5.1.3, Lasers (144), and 5.1.1, Detector Development. Unlike the very specialized development required for observatory and science instruments, there are substantial outside development efforts in integrated photonics driven by the terrestrial fiber optic network. An international community of telecommunications companies and government consortia are investing heavily in 5.1.7, reducing the development risk for NASA. As a result, 5.1.7, Integrated Photonics, is ranked as a medium-priority technology. This is not to say that NASA should not be investing as well, but this investment could be more focused on NASA-unique aspects, in particular on reliability and radiation tolerance of telecom products operating in various space environments. There may also be program/science requirements for integrated photonics operating at wavelengths or waveforms other than those used for terrestrial fiber-optic systems.

Technology 5.7.1, Tracking Technologies

Technology 5.7.1, Tracking Technologies, is also considered to be relatively important within the set of medium-priority technologies. This is largely driven by increasing awareness of the problem that orbital debris poses for NASA space operations, particularly in low Earth orbit, where the ISS or Earth-sensing satellites can be exposed to debris with considerable differential velocities. Addressing this problem will require development of new, low-TRL approaches to deal with the challenging problems of searching, tracking, and cataloging a dynamic debris environment ranging over several magnitudes in size. The committee notes that the proposed set of level 4 research tasks currently does not adequately reflect these challenges. Nonetheless, while the problem is potentially significant, the committee chose to rank this as a medium priority for NASA investment given extensive efforts by other U.S. government organizations and the European Space Agency. Explicitly referencing these efforts in NASA's roadmap would facilitate coordination.

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Technology Name	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
	Benefit	Alignment			Risk/Difficulty				
5.1.1. Detector Development	3	9	3	1	3	-3	-1	148	M
5.1.2. Large Apertures	3	9	1	0	3	-3	-3	134	M
5.1.3. Lasers	3	9	1	1	3	-3	-1	144	M
5.1.4. Acquisition and Tracking	3	9	1	0	3	-3	-1	142	M
5.1.5. Atmospheric Mitigation	3	9	1	1	3	-3	-3	136	M
5.1.6 Optical Tracking	1	9	0	1	3	-1	0	100	M
5.1.7 Integrated Photonics	3	9	3	3	3	-1	-1	160	M
5.2.1. Spectrum-Efficient Technologies	1	9	3	0	3	-3	-1	92	M
5.2.2. Power-Efficient Technologies	1	9	9	3	3	1	-1	126	M
5.2.3. Propagation	1	9	1	1	3	-9	-3	58	L
5.2.4. Flight and Ground Systems	1	9	3	1	3	-3	-1	94	M
5.2.5. Earth Launch and Reentry Communications	1	9	1	0	3	-9	-3	56	L
5.2.6. Antennas	3	9	3	0	3	-3	-1	146	M
5.3.1. Disruptive Tolerant Networking	3	9	3	3	3	1	-1	168	M
5.3.2. Adaptive Network Topology	3	9	3	3	9	-9	-1	188	H
5.3.3. Information Assurance	1	9	9	0	1	-9	-3	52	L
5.3.4. Integrated Network Management	3	9	3	0	3	-1	-1	154	M
5.4.1. Timekeeping and Time Distribution	3	9	9	3	9	-9	-1	200	H
5.4.3. Onboard Autonomous Navigation and Maneuvering	3	9	3	0	9	-3	-1	206	H
5.4.4. Sensors and Vision Processing Systems	3	9	3	0	3	-3	-1	146	M
5.4.5. Relative and Proximity Navigation	3	9	3	0	3	-3	-1	146	M
5.4.6. Auto Precision Formation Flying	3	3	1	0	9	-3	-1	172	M
5.4.7. Auto Approach and Landing	3	3	1	0	3	-3	-1	112	M
5.5.1. Radio Systems	3	9	3	9	3	-3	-1	164	H*
5.5.2. Ultra Wideband Communications	3	3	1	0	9	-9	-1	148	M
5.5.3. Cognitive Networks	3	3	3	3	3	-9	-3	90	M
5.5.4. Science from the Communication System	1	3	0	0	3	-3	-1	56	L
5.5.5. Hybrid Optical Communication and Navigation Sensors	1	3	1	0	3	-3	-1	58	L
5.5.6. RF/Optical Hybrid Technology	1	9	3	1	3	-9	-1	70	L
5.6.1. X-Ray Navigation	0	3	0	0	1	-9	-3	-23	L
5.6.2. X-Ray Communications	0	0	0	0	1	-9	-3	-38	L
5.6.3. Neutrino-Based Navigation and Tracking	0	0	0	0	1	-9	-9	-62	L
5.6.4. Quantum Key Distribution	0	3	1	0	1	-9	-3	-21	L
5.6.5. Quantum Communications	0	3	1	0	1	-9	-9	-45	L
5.6.6. SQIF Microwave Amplifier	1	3	3	1	1	-9	-3	12	L
5.6.7. Reconfigurable Large Apertures Using Nanosat Constellations	1	3	0	0	1	-9	-3	4	L
5.7.1 Tracking Technologies	3	9	3	1	3	-3	-1	148	M
5.7.2 Characterization Technologies	1	9	3	0	3	-3	0	96	M

FIGURE 2.5 Scoring matrix for TA 5. H, high priority; H*, high priority (QFD override); M, medium priority; L, low priority.

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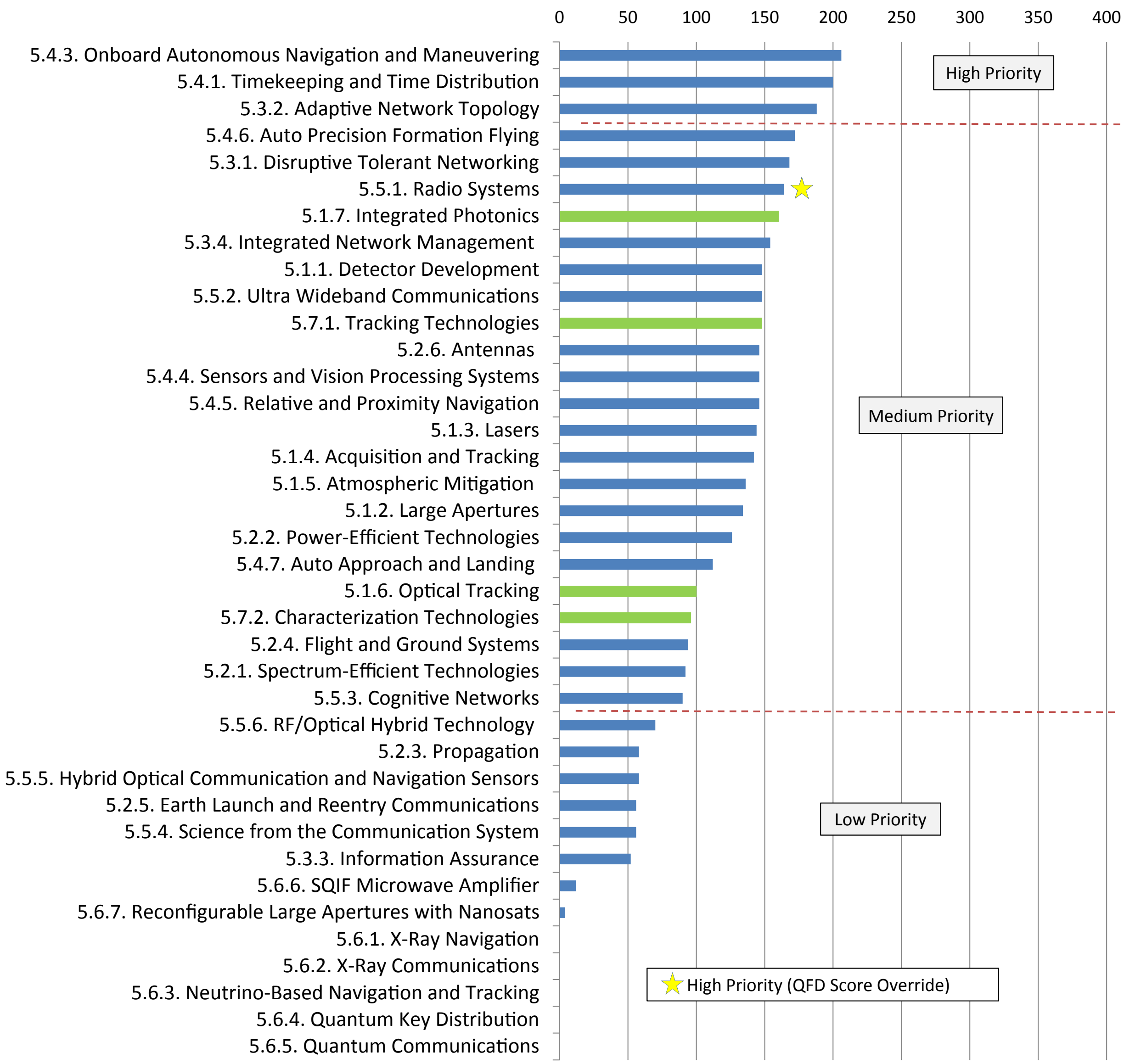

FIGURE 2.6 The TA 5 level 3 technologies ranked by QFD score. The new technologies evaluated in this study are indicated in green.

Technologies 5.1.6, Optical Tracking, and 5.7.2, Characterization Technologies

Although 5.1.6, Optical Tracking, and 5.7.2, Characterization Technologies, were both ranked as a medium priority, they scored substantially lower than two other new TA 5 technologies, above. Technologies needed to implement optical tracking are covered by other level 3 technologies, such as low-jitter focal plane arrays that can count individual photons (5.1.1), large apertures (5.1.2), and exquisite timing (5.4.1). No technical challenges were identified for 5.7.2, Characterization Technologies, which focuses on modeling the debris environment. Coordination of NASA's efforts in this area with other organizations would prevent duplication and validate the results of NASA's research.

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TABLE 2.5 TA 7, Human Exploration Destination Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
7.1 In Situ Resource Utilization	None
7.2 Sustainability and Supportability	None
7.3 Human Mobility Systems	None
7.4 Habitat Systems	7.4.4 Artificial Gravity
7.5 Mission Operations And Safety	None
7.6 Cross-Cutting Systems	None

There is high likelihood that investment from other organizations outside NASA could overshadow any potential NASA investments in three of the new TA 5 technologies: 5.1.7, Integrated Photonics; 5.7.1, Tracking Technologies; and 5.7.2, Characterization Technologies. Given this situation, NASA's limited resources could be better applied elsewhere.

TA 7, HUMAN EXPLORATION DESTINATION SYSTEMS

The 2015 NASA draft roadmap for technology area TA 7, Human Exploration Destination Systems, adds one new level 3 technology: 7.4.4, Artificial Gravity. Table 2.5 shows how this technology fits into the TA 7 TABS. The scoring and ranking of all TA 7 technologies are illustrated in Figures 2.7 and 2.8.

Technology 7.4.4, Artificial Gravity

Artificial gravity (7.4.4) was determined to be a low-priority technology with the current understanding of the potential of other gravity countermeasures outlined in technology 6.3.2 Long-Duration (Crew) Health. NASA is investigating approaches to mitigate the risks of long-duration exposures to microgravity environments through exercise and other countermeasures that would cost much less than developing spacecraft with artificial gravity. Artificial gravity uses centripetal forces to simulate gravitational forces either by rotating the crew on a centrifuge within a spacecraft or by rotating the spacecraft as a whole (Figure 2.9). Apparatuses that rotate individuals and that do not impact the overall design of the spacecraft fall within the scope of TA 6, Human Health, Life Support, and Habitation Systems (specifically, research task 6.3.2.1, Artificial Gravity), which is evaluated in the 2012 NRC report.

The greatest technical challenges to artificial gravity involve understanding (1) spacecraft design modifications required to accommodate rotation and (2) the positive and negative impacts of artificial gravity. A key prerequisite is understanding the degree and duration of partial gravity necessary to counteract various human health issues associated with long-term exposure to zero or microgravity.[5] Full development of artificial gravity technology would require one or more full-scale in-space demonstrations, and it might require a requalification of all other vehicle systems. This endeavor will likely remain a low priority unless and until currently proposed microgravity countermeasures prove ineffective.

TA 9, ENTRY, DESCENT, AND LANDING SYSTEMS

The 2015 NASA roadmap for TA 9, Entry, Descent, and Landing Systems, realigned many level 3 technologies that appeared in the TABS in the 2012 NRC report. The 2015 TA 9 roadmap reports that the only work to support 7 of the 17 level 3 TA 9 technologies in the TABS recommended by the 2012 NRC report now falls under other

[5] The long-term effects of partial gravity on the surface of the Moon or Mars are also unknown, but this issue is outside the scope of technology 7.4.4.

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	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	**27**	**5**	**2**	**2**	**10**	**4**	**4**		
	0/1/3/9	**0/1/3/9**	**0/1/3/9**	**0/1/3/9**	**1/3/9**	**-9/-3/-1/1**	**-9/-3/-1/0**		
Technology Name	**Benefit**	**Alignment**			**Risk/Difficulty**				
7.1.1. (ISRU) Destination Reconnaissance, Prospecting, and Mapping	3	9	3	1	9	1	-1	224	M
7.1.2. (ISRU) Resource Acquisition	9	9	1	0	9	1	-3	372	**H**
7.1.3. ISRU Products/Production	9	9	3	3	9	1	-1	390	**H**
7.1.4. (ISRU) Manufacturing and Infrastructure Emplacement	9	9	3	0	9	1	-3	376	**H**
7.2.1. Autonomous Logistics Management	9	9	3	3	9	1	-1	390	**H**
7.2.2. Maintenance Systems	3	9	9	9	9	-3	-3	228	**H***
7.2.3. Repair Systems	3	9	9	9	1	1	-9	140	L
7.2.4. Food Production, Processing and Preservation	9	9	3	9	3	1	-1	342	**H**
7.3.1. EVA Mobility	3	9	0	1	9	1	0	222	M
7.3.2. Surface Mobility	9	9	1	1	9	-3	-3	358	**H**
7.3.3. Off-Surface Mobility	3	3	0	0	9	-1	-3	170	L
7.4.1. Integrated Habitat Systems	3	9	3	9	3	-9	-1	140	L
7.4.2. Habitat Evolution	9	9	1	0	9	-1	-9	340	**H**
7.4.3. Smart Habitats	9	3	1	9	3	-3	-3	284	**H**
7.4.4 Artificial Gravity	3	9	0	0	9	-9	-9	144	L
7.5.1. Crew Training	1	9	9	1	3	1	-1	122	L
7.5.5. Integrated Flight Operations Systems	3	9	3	3	3	1	-1	168	L
7.5.6. Integrated Risk Assessment Tools	3	9	9	9	3	1	-1	192	M
7.6.2. Construction and Assembly	9	9	3	3	9	1	-1	390	**H**
7.6.3. Dust Prevention and Mitigation	9	9	3	1	9	1	-1	386	**H**

FIGURE 2.7 Scoring matrix for TA 7. H, high priority; H*, high priority (QFD override); M, medium priority; L, low priority.

technologies, which in many cases belong to other TAs. Of particular note, technology 9.4.7, Guidance, Navigation, and Control (GN&C) Sensors and Systems, was the highest ranked TA 9 technology in the 2012 NRC report, and it was designated as one of the 16 highest priority technologies. The 2015 TA 9 roadmap, however, reports that there is no system-level work proposed for 9.4.7, though some contributing technology is being proposed under two preexisting technologies (9.1.3, Rigid Hypersonic Decelerators, and 9.1.4, Deployable Hypersonic Decelerators) and three new technologies (9.2.6, Large Divert Guidance; 9.2.7, Terrain-Relative Sensing and Characterization; and 9.2.8, Autonomous Targeting). These three new technologies were the subject of the committee's evaluation, and Table 2.6 shows how they fit into the TA 9 TABS. The scoring and ranking of all TA 9 technologies are illustrated in Figures 2.10 and 2.11.

Two of the three new level 3 technologies were evaluated to be of high priority (9.2.7 and 9.2.8), which is consistent with the 2012 NRC report that ranked GN&C as a high priority. Technology 9.2.6 was ranked as low priority.

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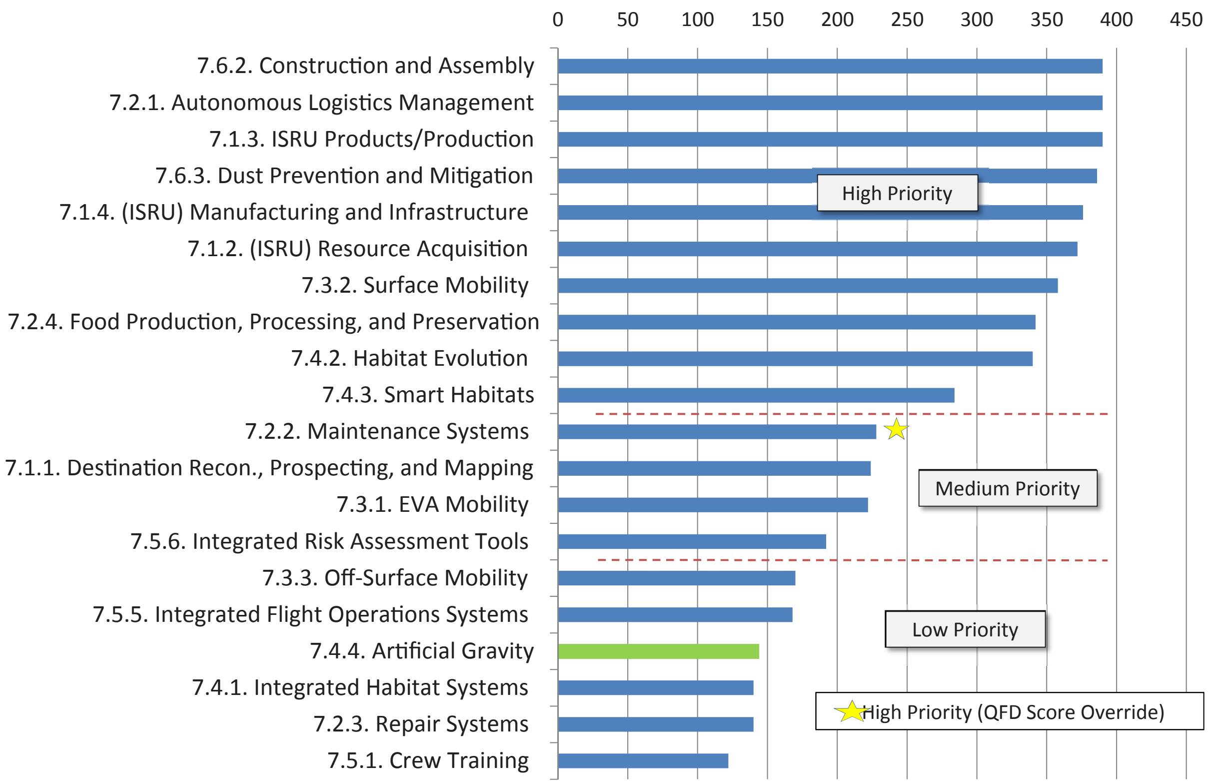

FIGURE 2.8 The TA 7 level 3 technologies ranked by QFD score. The new technology evaluated in this study is indicated in green.

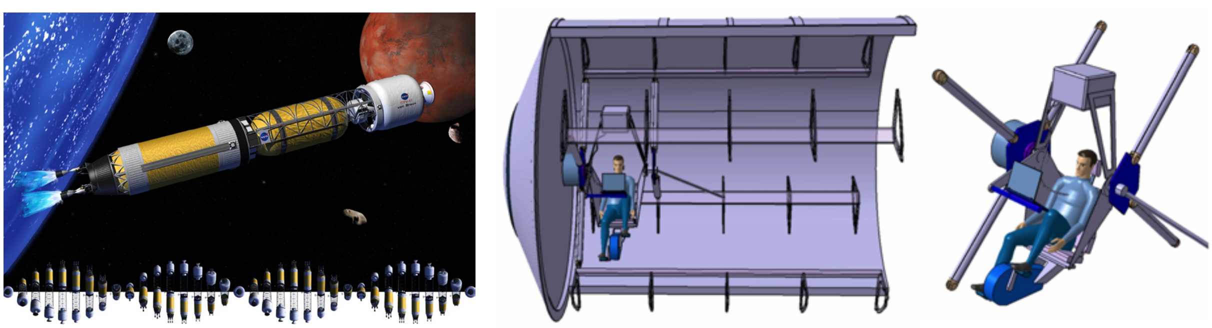

FIGURE 2.9 Examples of using artificial gravity through either rotation of the entire spacecraft or an internal centrifuge. SOURCE: *Left:* S.K. Borowski, D.R. McCurdy, and T.W. Packard, 2014, "Conventional and Bimodal Nuclear Thermal Rocket (NTR) Artificial Gravity Mars Transfer Vehicle Concepts," Paper AIAA-2014-3623 presented at the 50th Joint Propulsion Conference and Exhibit, American Institute of Aeronautics and Astronautics, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140017461.pdf; courtesy of NASA. *Right:* European Space Agency, "Artificial Gravity with Ergometric Exercise (AGREE)—Accommodation Feasibility Study," European Space Research and Technology Centre, August 2011.

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TABLE 2.6 TA 9, Entry, Descent, and Landing Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
9.1 Aeroassist and Atmospheric Entry	None
9.2 Descent and Targeting	9.2.6 Large Divert Guidance 9.2.7 Terrain-Relative Sensing and Characterization 9.2.8 Autonomous Targeting
9.3 Landing	None
9.4 Vehicle Systems	None

	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
Technology Name	Benefit	Alignment			Risk/Difficulty				
9.1.1. Rigid Thermal Protection Systems	9	9	3	1	9	1	-3	378	H
9.1.2. Flexible Thermal Protection Systems	9	9	3	1	9	-1	-3	370	H
9.1.3. Rigid Hypersonic Decelerators	3	9	1	0	3	-1	-3	142	M
9.1.4. Deployable Hypersonic Decelerators	9	9	1	0	9	-3	-3	356	H
9.2.1. Attached Deployable Decelerators	3	3	1	0	9	-1	-1	180	M
9.2.2. Trailing Deployable Decelerators	3	9	1	0	9	-1	-1	210	M
9.2.3. Supersonic Retropropulsion	1	3	1	0	3	-1	-3	58	L
9.2.6 Large Divert Guidance	1	3	0	0	1	-3	-3	28	L
9.2.7.Terrain-Relative Sensing and Characterization	9	9	9	1	9	1	-1	398	H
9.2.8 Autonomous Targeting	9	9	3	1	9	1	-1	386	H
9.3.1. Touchdown Systems	3	9	1	1	1	1	-1	140	M
9.3.2. Egress and Deployment Systems	1	3	0	0	1	1	-1	52	L
9.3.3. (EDL) Propulsion Systems (Interaction)	3	3	1	0	3	-1	-1	120	M
9.3.5. (EDL) Small-Body Systems (No Gravity)	1	3	1	0	9	-1	-1	126	M
9.4.2. (EDL) Separation Systems	1	9	3	0	1	1	-1	88	L
9.4.3. (EDL) System Integration and Analyses	3	9	3	1	9	-1	-1	216	H*
9.4.4. Atmosphere and Surface Characterization	3	9	3	3	9	-1	-1	220	H*
9.4.5. EDL Modeling and Simulation	3	9	3	1	9	1	-1	224	H*
9.4.6. (EDL) Instrumentation and Health Monitoring	3	9	3	0	9	1	-1	222	H*
9.4.7. GN&C Sensors and Systems (EDL)	9	9	9	3	9	1	-1	402	H

FIGURE 2.10 Scoring matrix for TA 9. H, high priority; H*, high priority (QFD override); M, medium priority; L, low priority.

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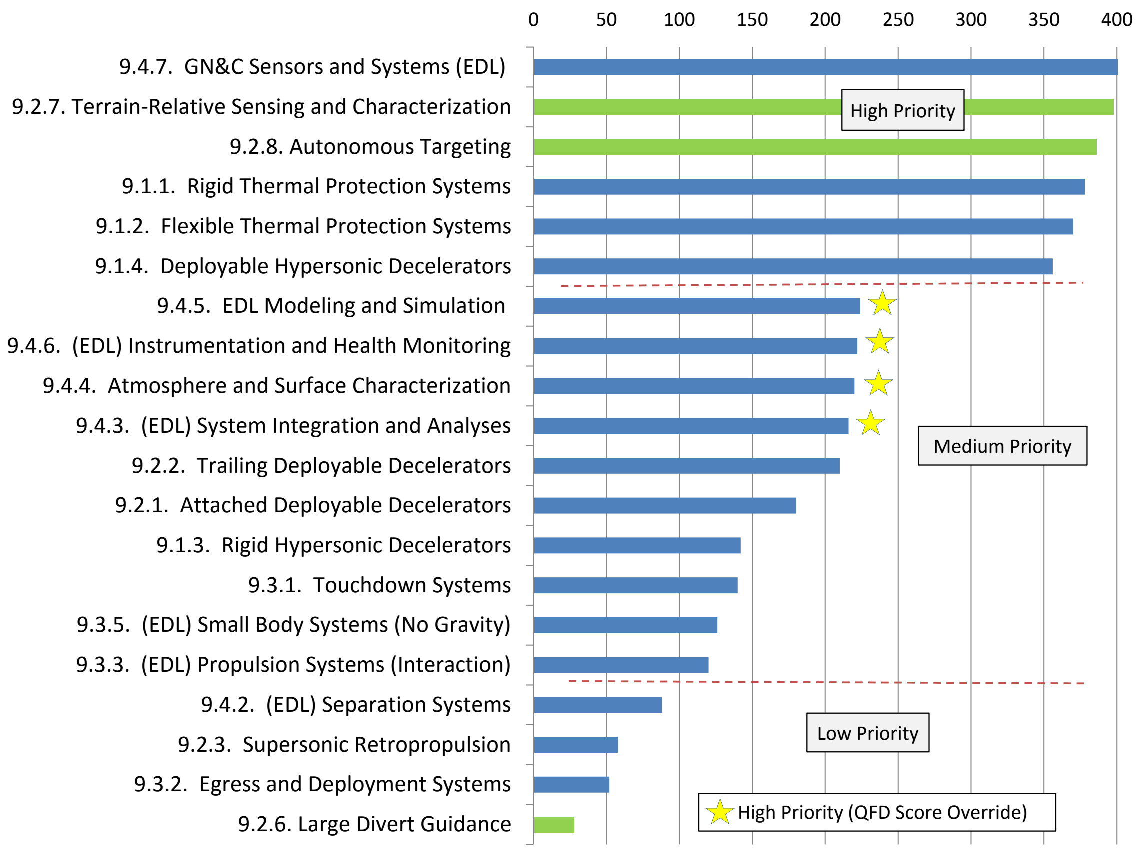

FIGURE 2.11 The TA 9 level 3 technologies ranked by QFD score. The new technologies evaluated in this study are indicated in green.

Technology 9.2.7, Terrain-Relative Sensing and Characterization

Technology 9.2.7, Terrain-Relative Sensing and Characterization, is the most promising of the new level 3 technologies. This technology would produce "high-rate, high-accuracy measurements for algorithms that enable safe precision landing near areas of high scientific interest or predeployed assets."[6] It is a game-changing technology that could enable important new missions not currently feasible in the next 20 years. It impacts multiple missions in multiple mission areas, both human and robotic. With the flyby of Pluto completing an initial remote-sensing survey of the major objects in our solar system, NASA is continuing planetary exploration with a new era of increased surface exploration. This technology will help enable many such missions in this new era, such as human and robotic Mars missions, sample return missions, and a Europa lander.

This technology also has a broad impact across the aerospace community, already influencing commercial and military autonomous vehicles, such as the rapid advancement of unmanned air vehicles. For example, this technology is helping to develop systems that allow a single operator simultaneously to oversee the operation of a distributed set of vehicles. Both this technology and 9.2.8, Autonomous Targeting, which are highly coupled, enhance autonomous capabilities by reducing the dependence of onboard systems on human operators.

The technology risk, which is moderate to high, is a good fit for a NASA technology project in terms of both time frame and feasibility, and there are well-developed plans for its execution.

[6] NASA, 2015, *NASA Technology Roadmaps: TA 9 Entry, Descent, and Landing Systems*, Washington, D.C., p. TA 9-25.

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Technology 9.2.8, Autonomous Targeting

The algorithms associated with technology 9.2.8, Autonomous Targeting, are tightly coupled to the sensors of technology 9.2.7, above. Technology 9.2.8 is likewise a game-changing technology that would enable important new missions not currently feasible in the next 20 years, such as several of the New Frontier missions. It would also enhance multiple missions in multiple mission areas, both human and robotic. By improving the ability of vehicles to assess and characterize the terrain they are facing for landing and exploration, this technology would enable the next step of autonomous targeting, which could be critical when interplanetary distances make remote guidance difficult or impossible. Even if a vehicle is piloted for a human mission, this technology could be critical for a safe landing.

This technology was ranked only slightly lower than 9.2.7 in terms of its impact on the aerospace community, where it was still expected to impact a fairly large subset. It will not have as broad an applicability as 9.2.7 since the algorithms in this area are expected to be much more specific to NASA applications, though it will still have some applicability to commercial and military autonomous vehicles. It is expected that this technology, like 9.2.7, will have less influence on nonaerospace applications. The technology risk is also moderate to high, but it is a good fit for the NASA technology projects both in time frame and feasibility, with well-developed plans for its execution.

Technology 9.2.6, Large Divert Guidance

Technology 9.2.6, Large Divert Guidance, would develop new guidance algorithms to enable substantial changes in the lateral direction of a vehicle during reentry for a divert capability of 1 to 10 km. This technology is considered a low priority owing to the minimal improvement it would make in mission capability and the likely mass penalties for the divert propulsion required. The applicability of this technology is limited to a small number of missions, and large divert capability is not necessarily required for precision landing. Completing development of this technology would be a major effort with extremely high risk. The TA 9 roadmap states that a mission demonstration of a full-scale system is required before this technology would be flown on an operational mission. Plans for development of this technology also were not very well defined.

TA 11, MODELING, SIMULATION, INFORMATION TECHNOLOGY, AND PROCESSING

The 2015 NASA roadmap for TA 11, Modeling, Simulation, Information Technology, and Processing, expands the scope of this technology area beyond that presented in the TABS in the 2012 NRC report by adding eight new level 3 technologies. Table 2.7 shows how these new technologies fit into the TA 11 TABS. The scoring and ranking of all TA 11 technologies are illustrated in Figures 2.12 and 2.13.

Two of the eight new level 3 technologies (11.2.6, Analysis Tools for Mission Design, and 11.3.7, Multiscale, Multiphysics, and Multifidelity Simulation) were evaluated to be of medium priority; the other six new technologies were ranked as low priority.

TABLE 2.7 TA 11, Modeling, Simulation, Information Technology, and Processing: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
11.1 Computing	None
11.2 Modeling	11.2.6 Analysis Tools for Mission Design
11.3 Simulation	11.3.5 Exascale Simulation 11.3.6 Uncertainty Quantification and Nondeterministic Simulation 11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation 11.3.8 Verification and Validation
11.4 Information Processing	11.4.6 Cyber Infrastructure 11.4.7 Human–System Integration 11.4.8 Cyber Security

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	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
Technology Name	**Benefit**	**Alignment**			**Risk/Difficulty**				
11.1.1. Flight Computing	9	9	9	3	9	1	-3	394	H
11.1.2. Ground Computing	9	9	9	9	3	1	-1	354	H
11.2.1. Software Modeling and Model-Checking	3	9	9	9	3	-3	-1	176	M
11.2.2. Integrated Hardware and Software Modeling	3	9	9	9	3	1	-1	192	M
11.2.3. Human–System Performance Modeling	1	9	3	3	3	1	-1	114	L
11.2.4a. Science Modeling and Simulation	9	9	9	9	3	1	-1	354	H
11.2.4b. Aerospace Engineering Modeling and Sim.	3	9	9	1	3	-1	-3	160	M
11.2.5. Frameworks, Languages, Tools, Standards	1	9	3	1	1	1	-1	90	L
11.2.6 Analysis Tools for Mission Design	3	9	3	3	3	-1	-1	160	M
11.3.1. Distributed Simulation	3	9	9	9	3	1	-1	192	H*
11.3.2. Integrated System Life Cycle Simulation	1	9	1	0	3	-9	-1	64	L
11.3.3. Simulation-Based Systems Engineering	1	3	9	9	1	-1	-3	72	L
11.3.4. Sim.-Based Training and Decision Support	1	1	1	1	3	1	0	70	L
11.3.5 Exascale Simulation	1	9	9	9	3	1	-3	130	L
11.3.6 Uncertainty Quantif., Nondeterministic Sim.	1	9	3	9	3	-3	-1	110	L
11.3.7 Multiscale, Multiphysics, and Multifidelity Sim.	3	9	9	9	3	1	-1	192	M
11.3.8 Verification and Validation	1	9	9	3	3	1	-3	118	L
11.4.1. Science, Engr, and Mission Data Life Cycle	3	9	9	0	3	1	-1	174	M
11.4.2 Intelligent Data Understanding	1	3	1	0	1	-3	-1	38	L
11.4.3 Semantic Technologies	3	9	1	1	3	1	-1	160	M
11.4.4 Collaborative Science and Engineering	0	9	3	9	3	-3	-9	51	L
11.4.5. Advanced Mission Systems	3	9	9	1	9	-9	-3	188	M
11.4.6 Cyber Infrastructure	1	9	9	1	1	-1	-3	86	L
11.4.7 Human–System Integration	1	9	3	3	3	-1	-1	106	L
11.4.8 Cyber Security	1	1	0	1	3	1	-3	56	L

FIGURE 2.12 Scoring matrix for TA 11. H, high priority; H*, high priority (QFD override); M, medium priority; L, low priority.

Technology 11.3.7, Multiscale, Multiphysics, and Multifidelity Simulation

Technology 11.3.7, Multiscale, Multiphysics, and Multifidelity Simulation, is ranked as the most promising of the new TA 11 technologies. It promises the benefits of increasing the span of dimensional scales and fidelity of predictions, thereby improving the understanding, design, and optimization of physical systems that possess a hierarchical interdependence of physical processes. The TA 11 roadmap says that simulations that would be developed as part of this technology would contribute to "the development of lighter and more durable structural materials; higher performing materials for fuel cells, nuclear reactors, batteries, and solar cells; and new multi-functional materials that combine these functions. The simulations also have application to understanding reactive

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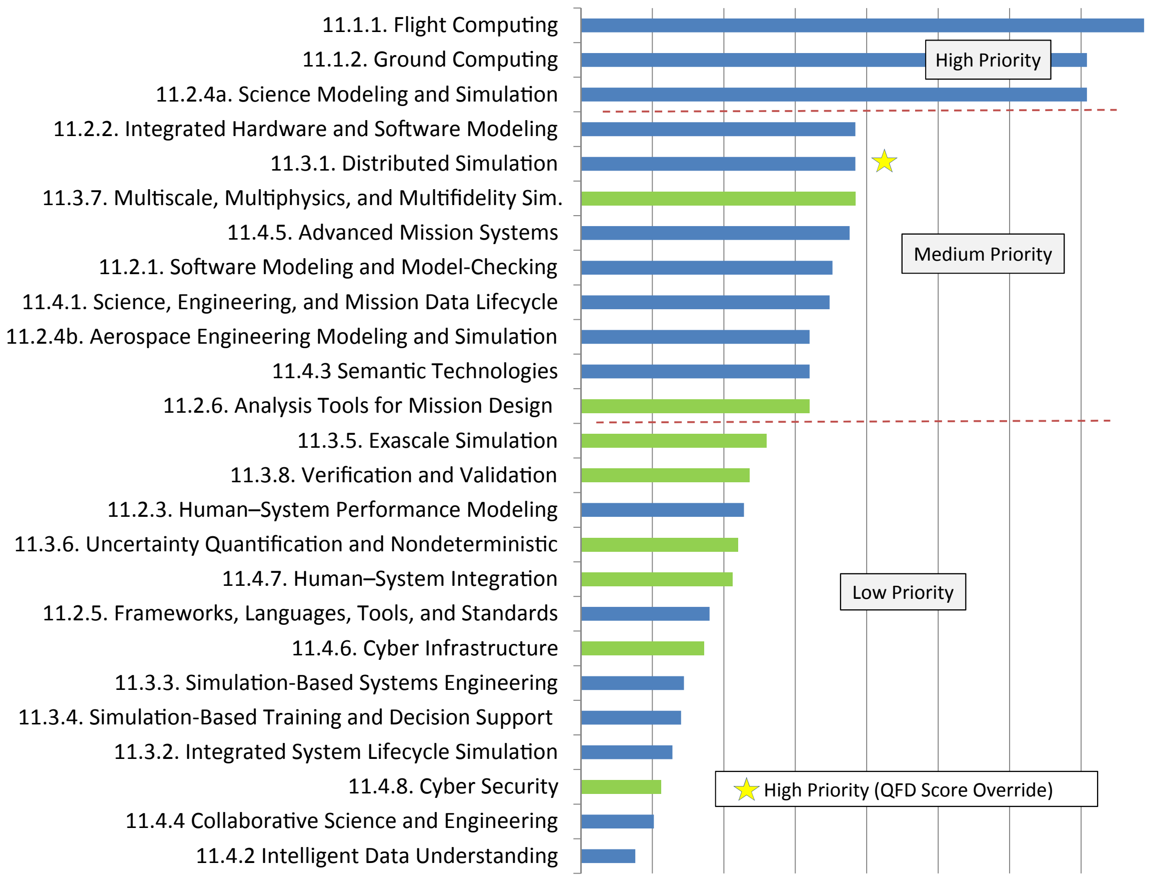

FIGURE 2.13 The TA 11 level 3 technologies ranked by QFD score. The new technologies evaluated in this study are indicated in green.

flows found within engines and surrounding airframes at hypersonic speeds."[7] The contribution that advances in this technology will make to the above applications remains to be seen. In any case, the committee did not rank 11.3.7 as a high-priority technology largely because other private and government entities are developing the underlying technologies. Although NASA can contribute to its development and pursue applications to specific problems and systems, it is not necessary for NASA to take the lead in technology development.

Technology 11.3.5, Exascale Simulation, which is ranked as a low priority, will eventually be an important component of 11.3.7 by bringing in much greater computing capacity. Exascale capability (1,000 petaflops) is being developed in laboratories in several countries and is supported by the U.S. National Strategic Computing Initiative. It is predicted to be available within the next 5 to 7 years. By closely watching developments in exascale computing, NASA would be prepared to anticipate and implement it as it becomes available. Both 11.3.5 and 11.3.7 were components of technology 11.2.4a Science Modeling and Simulation in the 2012 NRC report, which

[7] NASA, 2015, *NASA Technology Roadmaps: TA 11 Modeling, Simulation, Information Technology, and Processing*, Washington, D.C., p. TA 11-38.

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was given a high priority. Technologies 11.2.4a and 11.2.4b, Aerospace Engineering Modeling and Simulation have been merged as 11.2.4, Science Modeling, in the 2015 NASA TABS.

Technology 11.2.6, Analysis Tools for Mission Design

Technology 11.2.6, Analysis Tools for Mission Design, is also ranked as a medium priority. These tools could enhance current mission design capabilities and improve NASA's management of its technology portfolio. As missions become more complex and distributed, integrated mission design tools are better equipped to reach optimum designs than the current mixture of commercial-off-the-shelf systems and selected systems from previous missions. In addition to the benefit of optimum mission design, advanced analysis tools have the potential of improving the estimates of both cost and risk. Analysis Tools for Mission Design was not ranked as a high-priority technology largely because it represents an enhancement over current practice rather than an enabling component for new missions.

Low-Priority Technologies

The other new TA 11 technologies were all ranked as a low priority: 11.3.5, Exascale Simulation, is being developed by other private and government entities. As noted above, NASA could continue to watch advances in this area rather than becoming more involved in it. Technology 11.3.6, Uncertainty Quantification and Nondeterministic Simulation, could potentially improve the robustness of cost controls and mission by reducing uncertainties in many aspects of mission design and development. However, concepts such as mathematical descriptions of uncertainty that are consistent with the true state of knowledge of the system are still fairly abstract and in need of basic research efforts, which NASA could watch until they become more suitable for application to its own specific problems. Technology 11.3.8, Verification and Validation, as applied to software, modeling, and simulation, is already an ongoing activity and could be steadily improved. While it is important and relevant, it is not clearly in need of major investment. Improvements in technology 11.4.7, Human–System Integration, will become more important for future deep-space missions in which crew autonomy will need to increase in order to reduce dependence on ground-based control. Many different approaches have been proposed to improve human–system integration, and many concepts are already being defined in mission design activities. As focused areas of particular interest are identified, higher priority targets for significant investment will probably emerge. Technologies 11.4.6, Cyber Infrastructure, and 11.4.8, Cyber Security, were ranked as low priority because, while important to NASA, both are of vital importance to a great many organizations in government and industry. Given the level of investment that others are making, NASA is better suited to be a user rather than a developer of these technologies.

TA 13, GROUND AND LAUNCH SYSTEMS

The 2015 NASA roadmap for TA 13 Ground and Launch Systems expands the scope of this technology area from that presented in the TABS in the 2012 NRC Report by adding three new level 3 technologies: 13.1.4, Logistics; 13.2.5, Curatorial Facilities, Planetary Protection, and Clean Rooms; and 13.3.8, Decision-Making Tools. Table 2.8 shows how the new technologies fit into the TA 13 TABS. The scoring and ranking of all TA 13 technologies are illustrated in Figures 2.14 and 2.15.

TABLE 2.8 TA 13, Ground and Launch Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
13.1 Operational Life Cycle	13.1.4 Logistics
13.2 Environmental Protection and Green Technologies	13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms
13.3 Reliability and Maintainability	13.3.8 Decision-Making Tools
13.4 Mission Success	None

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	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
Technology Name	Benefit	Alignment			Risk/Difficulty				
13.1.1. Storage, Distribution, Conservation of Fluids	1	9	9	1	3	-3	-1	106	M
13.1.2. Automated Alignment, Coupling, and Assembly Systems	1	3	0	0	1	-1	-1	44	L
13.1.3. Autonomous Command and Control for Ground and Integrated Vehicle/Ground Systems	1	3	1	1	3	-3	-1	60	L
13.1.4 Logistics	1	3	3	0	3	-9	0	42	L
13.2.1. Corrosion Prevention, Detection, and Mitigation	1	3	1	9	3	1	-1	92	M
13.2.2. Environmental Remediation and Site Restoration	1	0	0	9	1	1	-1	55	L
13.2.3. Preservation of Natural Ecosystems	0	1	1	9	3	-3	-3	31	L
13.2.4. Alternate Energy Prototypes	0	1	1	3	3	-3	-3	19	L
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Room	3	3	1	1	3	-3	0	118	M
13.3.1. Advanced Launch Technologies	1	3	3	0	3	-3	-3	54	L
13.3.2. Environment-Hardened Materials and Structures	1	3	3	3	3	-3	-1	68	L
13.3.3. Inspection, Anomaly Detection, and Identification	1	9	3	1	3	-3	-1	94	M
13.3.4. Fault Isolation and Diagnostics	1	9	3	1	3	-3	-1	94	M
13.3.5. Prognostics Technologies	1	9	3	1	3	-3	-1	94	M
13.3.6. Repair, Mitigation, and Recovery Technologies	1	9	3	1	3	-3	-1	94	M
13.3.7. Communications, Networking, Timing, and Telemetry	0	9	9	0	3	-3	-1	77	M
13.3.8 Decision-Making Tools	1	3	3	0	3	-9	0	42	L
13.4.1. Range Tracking, Surveillance, and Flight Safety Technologies	1	9	9	0	3	1	-1	120	M
13.4.2. Landing and Recovery Systems and Components	1	3	1	0	3	-3	-1	58	L
13.4.3. Weather Prediction and Mitigation	0	9	9	1	3	-3	-1	79	M
13.4.4. Robotics / Telerobotics	0	9	3	1	1	-3	-1	47	L
13.4.5. Safety Systems	1	9	9	1	1	-1	-1	94	M

FIGURE 2.14 Scoring matrix for TA 13. M, medium priority; L, low priority.

As in the previous NRC review of TA 13, none of the new TA 13 technologies was ranked as high priority. Technologies 13.1.4 and 13.3.8 were ranked as a low priority primarily because the benefit of each technology would be minor. While ground and launch systems are significant contributors to mission life cycle costs, the primary innovations are being made by commercial providers for which NASA is serving as a competitive catalyst and a customer rather than as a developer. Technology 13.2.5, Curatorial Facilities, Planetary Protection, and Clean Rooms, is important to planetary surface missions in that it would facilitate ground operations and reduce the need for heat-resistant flight hardware. Planetary protection would also be a key element of a robotic Mars sample return mission or a human mission to the Mars surface. However, like the other new TA 13 technologies, 13.2.5 is not an urgently needed, game-changing technology, and it is ranked as a medium priority.

TA 14, THERMAL MANAGEMENT SYSTEMS

The 2015 NASA draft roadmap for technology area TA 14, Thermal Management Systems, adds one new level 3 technology, 14.3.2 TPS Modeling and Simulation, which replaces a section with the same technology

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NASA Space Technology Roadmaps and Priorities Revisited

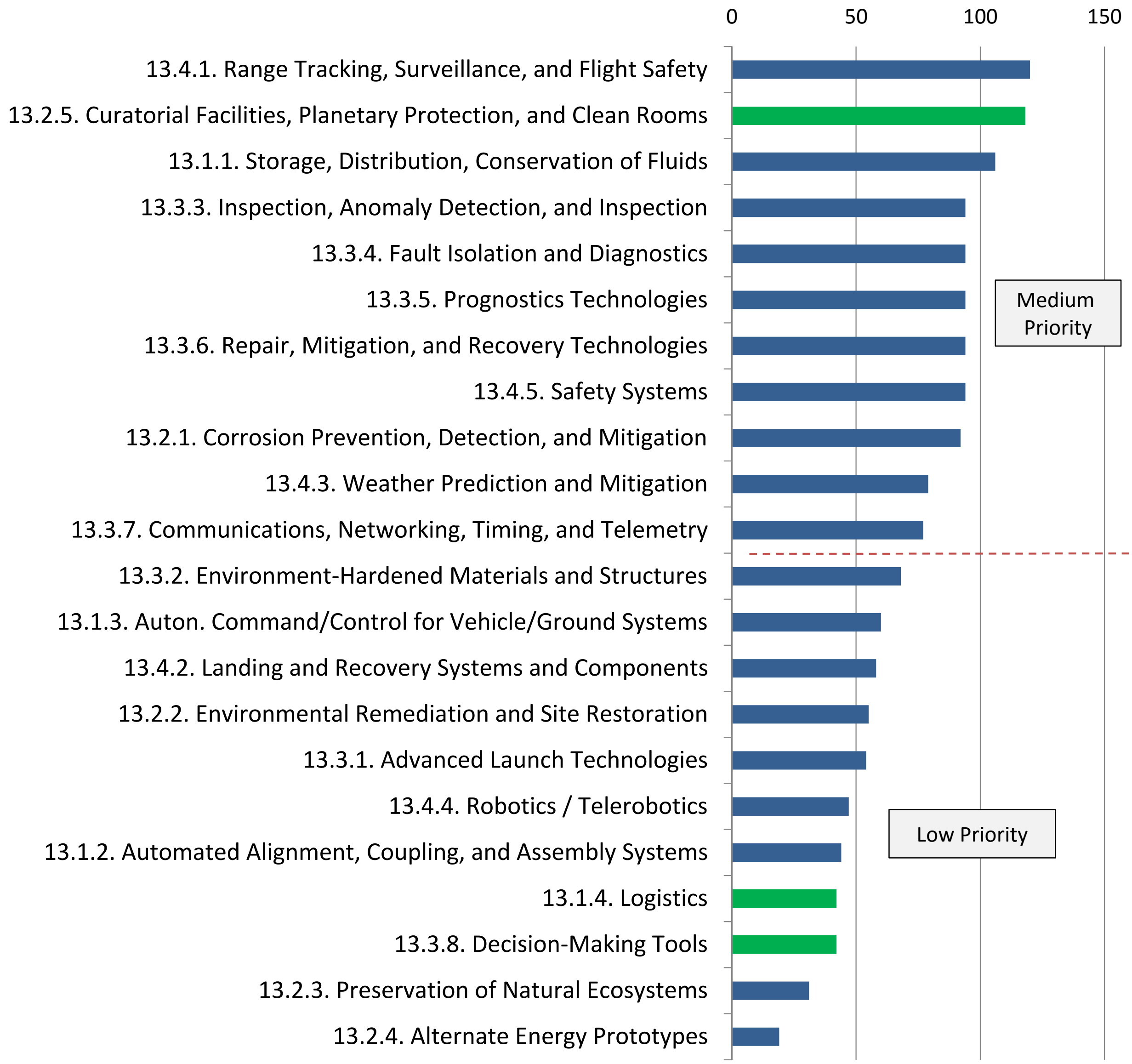

FIGURE 2.15 The TA 13 level 3 technologies ranked by QFD score. The new technologies evaluated in this study are indicated in green.

number—14.3.2 Plume Shielding (Convective and Radiative)—that appeared in the 2012 NRC TABS and the 2010 NASA TABS. Table 2.9 shows how the new technology fits into the TA 14 TABS. The scoring and ranking of all TA 14 technologies are illustrated in Figure 2.16 and 2.17.

Technology 14.3.2, Thermal Protection System Modeling and Simulation

The rationale for the new 14.3.2 TPS Modeling and Simulation is that uncertainties in the modeling of strong radiative shocks are a major limitation in the design of effective heat shields for high-speed entry into the

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NASA Space Technology Roadmaps and Priorities Revisited

TABLE 2.9 TA 14, Thermal Management Systems: Technologies Evaluated

Level 2 Technology Subarea	Level 3 Technologies Evaluated
14.1 Cryogenic Systems	None
14.2 Thermal Control System	None
14.3 Thermal Protection Systems	14.3.2 Thermal Protection System Modeling and Simulation

Technology Name	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
	Benefit	Alignment			Risk/Difficulty				
14.1.1. Passive Thermal Control	3	3	1	1	3	-3	-3	106	M
14.1.2. Active Thermal Control	3	9	3	3	3	-3	-1	152	H*
14.1.3. Systems Integration (Thermal Management)	3	9	1	1	3	-3	-3	136	M
14.2.1. Heat Acquisition	1	3	3	1	3	-3	-1	64	L
14.2.2. Heat Transfer	1	3	3	3	3	-3	-1	68	L
14.2.3. Heat Rejection and Energy Storage	3	9	1	1	3	-3	-1	144	M
14.3.1. Ascent/Entry TPS	9	9	1	1	9	-1	-3	366	H
14.3.2 TPS Modeling and Simulation	3	9	3	1	3	1	-1	164	H*
14.3.3. Sensor Systems and Measurement Technologies (Thermal Management)	1	9	3	3	3	-1	-1	106	M

FIGURE 2.16 Scoring matrix for TA 14. H, high priority; H*, high priority (QFD override); M, medium priority; L, low priority.

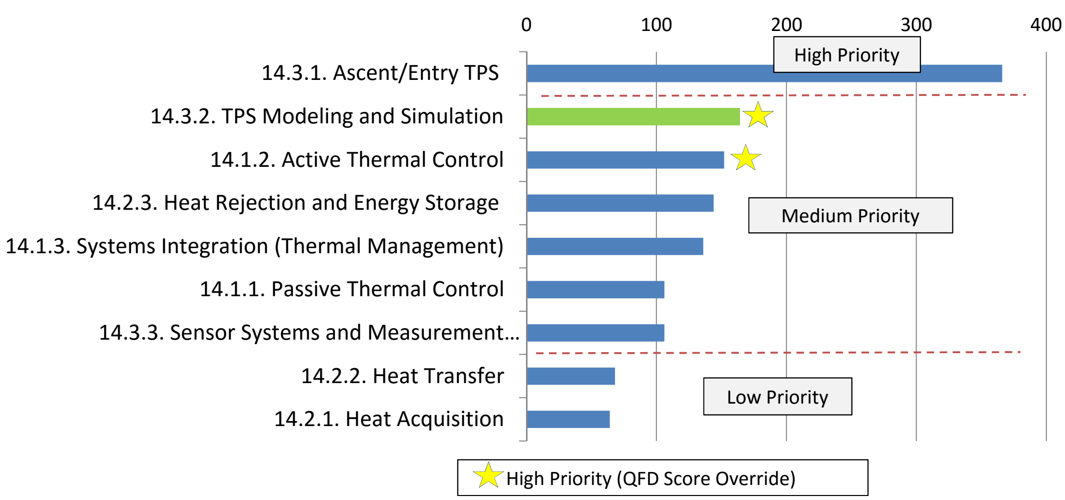

FIGURE 2.17 The TA 14 level 3 technologies ranked by QFD score. The new technology evaluated in this study is indicated in green.

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atmospheres of Earth, Mars, and other bodies. This technology would address major challenges that remain in the physics-based modeling of entry shocks, thermal radiation, and their interaction with an ablating heat shield. Early TPS design was largely empirical, based on extensive direct (and expensive) testing in Earth's atmosphere. Testing in ground test facilities is also difficult and expensive because of the extreme environments associated with atmospheric entry. Computational methods employing physics-based models are improving to the point that with validation via laboratory and flight testing and verification, they can more reliably predict TPS performance. However, further development is required to build confidence that design margins can be substantially reduced and that weight savings will be realized. Major challenges remain in increasing the accuracy and precision of physics-based modeling of entry shocks, thermal radiation, and their interaction with an ablating heat shield, challenges that are addressed by this technology. Currently, uncertainties are +80 percent to –50 percent for Mars return missions; missions to other destinations have different uncertainty ranges.[8] The goal of proposed research for technology 14.3.2 is to reduce uncertainty below 25 percent for all planetary missions. This reduction in uncertainty would enable the use of heat shields that weigh less, thereby reducing spacecraft weight and/or increasing allowable payload weight.

Although the QFD score for this technology fell within the range of medium priority scores for TA 14, it ranks as the highest scoring medium-priority technology in TA 14, and the committee concluded that this technology is a high priority and ranks it as such. This technology couples closely with the 2012 highly ranked cross-cutting technology of X.5, Entry, Descent, and Landing TPS, which includes both rigid and flexible systems. For that technology to advance and realize its potential, the modeling must improve.

As noted in the roadmap for TA 14, "a significant challenge facing the development of this technology is the limitations in the available flight and ground test data" (p. TA 14-93). The committee endorses the suggestion made by the 2012 committee and other groups that more opportunities to obtain these critical flight data should be realized to validate modeling efforts.

The QFD scores rank this level 3 technology only at the medium level. However, the committee classified 14.3.2 as a high-priority override technology given that the technology is very important to any NASA mission that includes atmospheric entry and given the rate of advancement in the multiphysical modeling of shockwave phenomena. The development of this technology would benefit from increased collaboration by NASA with outside organizations. For example, some U.S. research universities are employing high-end computing systems to solve highly complex, multiphysical problems with the support of the National Science Foundation, the Department of Energy's Office of Science, and other government agencies. Several multi-university collaborations have been established to tackle these advanced modeling and simulation challenges employing advanced algorithms, software, working data storage, and user–machine interfaces. Research into shock wave phenomena and plasma processes is included in the topics under study.

> **Finding 1.** Based on the review and analysis of the 42 new level 3 technologies that appear in the 2015 NASA roadmaps, 5 of those 42 new technologies have been added to the list of 83 high-priority technologies from the 2012 NRC report (listed in numerical order):
>
> - 4.3.7, Grappling
> - 4.4.8, Remote Interaction
> - 9.2.7, Terrain-Relative Sensing and Characterization
> - 9.2.8, Autonomous Targeting
> - 14.3.2, Thermal Protection System Modeling and Simulation

As shown in Chapter 3, technologies 9.2.7, 9.2.8, and 4.3.7 have been included in the list of the highest-priority level 3 technologies.

[8] NASA, 2015, *NASA Technology Roadmaps: Thermal Management Systems*, Washington, D.C., July, http://www.nasa.gov/offices/oct/home/roadmaps/index.html.

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3

Highest-Priority Technologies

As detailed in Chapter 2, the committee added 5 of the 42 technologies assessed in this report to the list of 83 high-priority level 3 technologies from the 2012 NRC report. The 5 technologies (listed in order of the technology number) are as follows:

4.3.7, Grappling
4.4.8, Remote Interaction
9.2.7, Terrain-Relative Sensing and Characterization
9.2.8, Autonomous Targeting
14.3.2, TPS Modeling and Simulation

As summarized below, the 2012 report also determined which of the 83 high-priority technologies should be given the highest priority. Of the five new high-priority technologies listed above, this chapter describes how the first three have been integrated into the initial group of highest-priority technologies.

TECHNOLOGY OBJECTIVES

As described in Appendix C, the highest-priority technologies were identified based largely on their correlation with three technology objectives, as follows:

Technology Objective A, Human Space Exploration: Extend and sustain human activities beyond low Earth orbit.

This objective includes a major part of NASA's mission to send humans beyond the protection of the Van Allen belts, mitigate the effects of space radiation and long exposure to the microgravity environment, enable the crew to accomplish the goals of the mission (contained in Technology Objective B), and then return to Earth safely. This objective includes using the International Space Station (ISS) for technology advancement to support future human space exploration, providing opportunities for commercial companies to offer services to low Earth orbit and beyond, and developing the launch capability required for safe access to locations beyond low Earth orbit. Supporting technologies would enable humans to survive long voyages throughout the solar system, get to their chosen destination, work effectively, and return safely.

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Technology Objective B, In Situ Measurements:
Explore the evolution of the solar system and the potential for life elsewhere.

This objective is concerned with the in situ analysis of planetary bodies in the solar system. It includes the detailed analysis of the physical and chemical properties and processes that shape planetary environments and the study of the geologic and biological processes that explain how life evolved on Earth and whether it exists elsewhere. It involves development of instruments for in situ measurements and the associated data analysis. This objective includes all the in situ aspects of planetary science; measurement of interior properties, atmospheres, particles, and fields of planets, moons, and small bodies; and methods of planetary protection. Supporting technologies would enable humans and robots to perform in situ measurements on Earth and on other planetary bodies (astrobiology).

Technology Objective C, Remote Measurements:
Expand our understanding of Earth and the universe in which we live.

This objective includes astrophysics research; stellar, planetary, galactic, and extragalactic astronomy; particle astrophysics and fundamental physics related to astronomical objects; solar and heliospheric physics; and magnetospheric physics and solar–planetary interactions. This objective also includes space-based observational Earth-system science and applications aimed at improving our understanding of Earth and its responses to natural and human-induced changes. This objective includes all space science activities that rely on measurements obtained remotely from various observational platforms. Supporting technologies would enable remote measurements from platforms that orbit or fly by Earth and other planetary bodies, and from other in-space and ground-based observatories.

GROUPED TECHNOLOGIES

In the process of developing the final list of the highest-priority technologies, the 2012 steering committee first developed an interim list (Table 3.1).[1]

In additional to individual technologies (designated by a three-digit identifier from the Technology Area Breakdown Structure for the 2010 draft roadmaps), the table also includes five grouped technologies (designated by a two-digit identifier starting with "X"). The 2012 steering committee had determined that, in several instances, technologies on the original list of 83 high-priority technologies that were highly ranked in the final prioritization process were also highly coupled. During the prioritization process, these highly coupled technologies were grouped together and considered as one unit, as follows: There are a total of five grouped technologies (designated X.1 through X.5). Each one consists of 3 to 5 original technologies as follows:

- X.1, Radiation Mitigation for Human Spaceflight
  - 6.5.1, Radiation Risk Assessment Modeling
  - 6.5.2, Radiation Mitigation[2]
  - 6.5.3, Radiation Protection Systems
  - 6.5.4, Radiation Prediction
  - 6.5.5, Radiation Monitoring Technology
- X.2, Lightweight and Multifunctional Materials and Structures
  - 10.1.1, (Nano) Lightweight Materials and Structures
  - 12.1.1, Materials: Lightweight Structures
  - 12.2.1, Structures: Lightweight Concepts
  - 12.2.2, Structures: Design and Certification Methods
  - 12.2.5, Structures: Innovative, Multifunctional Concepts

[1] The derivation of this interim list is described in Appendix C.
[2] Renamed Radiation Mitigation and Biological Countermeasures in the 2015 TABS.

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TABLE 3.1 Interim List of Highest-Priority Technologies, Ranked by Technology Objective, Comprising 27 Individual and Grouped Technologies, with 11 to 13 per Technology Objective

Highest-Priority Technologies for Technology Objective A, Human Space Exploration	Highest-Priority Technologies for Technology Objective B, In Situ Measurements	Highest-Priority Technologies for Technology Objective C, Remote Measurements
Radiation Mitigation for Human Spaceflight (X.1)	GN&C (X.4)	Optical Systems (Instruments and Sensors) (8.1.3)
Long-Duration (Crew) Health (6.3.2)	Electric Propulsion (2.2.1)	High-Contrast Imaging and Spectroscopy Technologies (8.2.4)
ECLSS (X.3)	Solar Power Generation (Photo-voltaic and Thermal) (3.1.3)	Detectors & Focal Planes (8.1.1)
GN&C (X.4)	In Situ (Instruments and Sensor) (8.3.3)	Lightweight and Multifunctional Materials and Structures (X.2)
Thermal Propulsion (2.2.3)	Fission Power Generation (3.1.5)	Radioisotope (Power) (3.1.4)
Fission (Power) (3.1.5)	Extreme Terrain Mobility (4.2.1)	Electric Propulsion (2.2.1)
Lightweight and Multifunctional Materials and Structures (X.2)	Lightweight and Multifunctional Materials and Structures (X.2)	Solar Power Generation (Photo-voltaic and Thermal) (3.1.3)
EDL Thermal Protection System (TPS) (X.5)	Radioisotope (Power) (3.1.4)	Science Modeling and Simulation (11.2.4a)
Atmosphere and Surface Characterization (9.4.4)	Robotic Drilling and Sample Handling (4.3.6)[a]	Batteries (3.2.1)
Propellant Storage and Transfer (2.4.2)	EDL TPS (X.5)	Electronics (Instruments and Sensors) (8.1.2)
Pressure Garment (6.2.1)	Docking and Capture Mechanisms/ Interfaces (4.6.3)	Active Thermal Control of Cryogenic Systems (14.1.2)
		(Mechanisms) Reliability / Life Assessment / Health Monitoring (12.3.5)
		Vehicle System Management and FDIR (4.5.1)

[a] Technology 4.3.6 has been renamed Sample Acquisition and Handling in the 2015 roadmap for TA 4, Robotics, Telerobotics, and Autonomous Systems.

NOTE: Shaded items do not appear in the 2012 report's final list of highest-priority technologies.

- X.3, Environmental Control and Life Support System (ECLSS)
  - 6.1.1, ECLSS: Air Revitalization
  - 6.1.2, ECLSS: Water Recovery and Management
  - 6.1.3, ECLSS: Waste Management
  - 6.1.4, ECLSS: Habitation
- X.4, Guidance, Navigation, and Control (GN&C)
  - 4.6.2, Relative Guidance Algorithms (for Automation Rendezvous and Docking)[3]
  - 5.4.3, Onboard Autonomous Navigation and Maneuvering (for Position, Navigation, and Timing)
  - 9.4.7, GN&C Sensors and Systems (for Entry, Descent, and Landing)
- X.5, Entry, Descent, and Landing (EDL) Thermal Protection Systems (TPS)
  - 9.1.1, Rigid Thermal Protection Systems
  - 9.1.2, Flexible Thermal Protection Systems
  - 14.3.1, Ascent/Entry TPS

[3] Renamed GN&C Algorithms in the 2015 TABS.

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FINAL RANKING OF THE NEW HIGH-PRIORITY TECHNOLOGIES

Technologies 9.2.7 and 9.2.8

In deciding whether to add one or more of the five new high-priority technologies to the list of highest-priority technologies, the committee first examined the new technologies in the context of the above list of grouped technologies. As indicated above, group X.4 contains three technologies: 4.6.2, 5.4.3, 9.4.7. The new 2015 roadmap for TA 9, however, has essentially deleted technology 9.4.7, because it no longer has any technical content. All of the research previously included in 9.4.7 has been moved into the following technologies:

- 9.1.3, Rigid Hypersonic Decelerators
- 9.1.4, Deployable Hypersonic Decelerators
- 9.2.6, Large Divert Guidance
- 9.2.7, Terrain-Relative Sensing and Characterization
- 9.2.8, Autonomous Targeting

Given this situation, the committee had to decide which of the above technologies (if any) to move into group X.4 to take the place of 9.4.7. Two of these five technologies, 9.1.3 and 9.1.4, were in the 2010 draft roadmaps, and the steering committee did not include them in the list of highest-priority technologies, either as individual technologies or as elements of group X.4. Because this committee was not tasked with reprioritizing technologies that appeared in the 2012 report, technologies 9.1.3 and 9.1.4 have not been promoted to the list of highest-priority technologies as elements of group X.4. The other three technologies listed above are new in the 2015 roadmap (9.2.6, 9.2.7, and 9.2.8). As detailed in Chapter 2, this committee has ranked two of these as a high priority (9.2.7 and 9.2.8), and the committee added both of them to group X.4 to take the place of 9.4.7.

Technology 4.3.7

The committee then considered the interim list of highest-priority technologies produced by the 2012 steering committee (see Table 3.1). As shown in Table 3.2, two of the technologies related to Technology Objective B, In Situ Measurements, are related to robotics (4.3.6 and 4.6.3). The committee determined that both of these technologies are closely coupled to one of the five newly ranked high-priority technologies: 4.3.7, Grappling. Accordingly, the committee has created a new technology group, X.6, Grappling, Docking, and Handling. Given that two of these technologies appeared in the 2012 interim list of highest-priority technologies, and given the combined weight of these three technologies as a group, the committee also added group X.6 as a new item in the final list of highest-priority technologies, at the bottom of the column for Technology Objective B. In addition, because these technologies as a group are also relevant to the top technical challenges[4] for Technology Objective A, this group has also been added at the bottom of the list of highest-priority technologies for Technology Objective A.

Technologies 4.4.8 and 14.3.2

After examining technologies 4.4.8, Remote Interaction, and 14.3.2, TPS Modeling and Simulation, in accordance with the process outlined in Appendix C for identifying the highest-priority technologies, the committee determined that although both of these technologies are a high priority, neither warrants inclusion as a highest-priority technology.

[4] See Appendix C for a discussion of the top technical challenges and lists of challenges for each technology objective.

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Final 2016 List of Highest-Priority Technologies

The new list of grouped technologies appears below, and the new list of the highest-priority technologies appears in Table 3.2. In both the list and the table, new or modified items are shaded.

X.1, Radiation Mitigation for Human Spaceflight
- 6.5.1, Radiation Risk Assessment Modeling
- 6.5.2, Radiation Mitigation[5]
- 6.5.3, Radiation Protection Systems
- 6.5.4, Radiation Prediction
- 6.5.5, Radiation Monitoring Technology

X.2, Lightweight and Multifunctional Materials and Structures
- 10.1.1, (Nano) Lightweight Materials and Structures
- 12.1.1, Materials: Lightweight Structures
- 12.2.1, Structures: Lightweight Concepts
- 12.2.2, Structures: Design and Certification Methods
- 12.2.5, Structures: Innovative, Multifunctional Concepts

X.3, Environmental Control and Life Support System (ECLSS)
- 6.1.1, ECLSS: Air Revitalization
- 6.1.2, ECLSS: Water Recovery and Management
- 6.1.3, ECLSS: Waste Management
- 6.1.4, ECLSS: Habitation

X.4, Guidance, Navigation, and Control (GN&C)[6]
- 4.6.2, Relative Guidance Algorithms (for Automation Rendezvous and Docking)[7]
- 5.4.3, Onboard Autonomous Navigation and Maneuvering (for Position, Navigation, and Timing)
- 9.2.7, Terrain-Relative Sensing and Characterization (for Descent and Targeting)
- 9.2.8, Autonomous Targeting (for Descent and Targeting)

X.5, Entry, Descent, and Landing (EDL) Thermal Protection Systems (TPS)
- 9.1.1, Rigid Thermal Protection Systems
- 9.1.2, Flexible Thermal Protection Systems
- 14.3.1, Ascent/Entry TPS

X.6, Grappling, Docking, and Handling
- 4.3.6, Sample Acquisition and Handling (formerly Robotic Drilling and Sample Handling)
- 4.3.7, Grappling
- 4.6.3, Docking and Capture Mechanisms and Interfaces

Finding 2. Based on the review and analysis of the five new level 3 technologies that have been added to the list of high-priority technologies, three of the technologies (4.3.7, 9.2.7, and 9.2.8), along with two other technologies (4.3.6 and 4.6.3) that previously appeared in the interim list of highest-priority technologies in the 2012 NRC report, have been added to the list of the 16 highest-priority technologies, as follows:

- Technology group X.4, Guidance, Navigation, and Control, has been expanded to include 9.2.7, Terrain-Relative Sensing and Characterization (for Descent and Targeting), and 9.2.8, Autonomous Targeting (for Descent and Targeting). Technology 9.4.7, GN&C Sensors and Systems (for Entry, Descent, and Landing), which has no technical content in the 2015 roadmap for TA 9, has been deleted.

[5] Renamed Radiation Mitigation and Biological Countermeasures in the 2015 TABS.
[6] Technology 9.4.7, GN&C Sensors and Systems (for entry, descent, and landing), which was an element of group X.4 in the 2012 NRC report, has been deleted because it has no technical content in the 2015 roadmap for TA 9.
[7] Renamed GN&C Algorithms in the 2015 TABS.

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- A new technology group has been created: X.6, Grappling, Docking, and Handling. This group consists of 4.3.6, Sample Acquisition and Handling (formerly Robotic Drilling and Sample Handling); 4.3.7, Grappling; and 4.6.3, Docking and Capture Mechanisms and Interfaces. Group X.6 has been added to the list of highest-priority technologies for Technology Objective A, Human Space Exploration, and Technology Objective B, In Situ Measurements.

The revised list of highest-priority technologies has a total of 17 technologies/technology groups.

TABLE 3.2 The Committee's Final 2016 List of Highest-Priority Technologies, Ranked by Technology Objective, Comprising 17 Individual and Grouped Technologies, with Up to 9 per Technology Objective

Highest-Priority Technologies for Technology Objective A, Human Space Exploration	Highest-Priority Technologies for Technology Objective B, In Situ Measurements	Highest-Priority Technologies for Technology Objective C, Remote Measurements
Radiation Mitigation for Human Spaceflight (X.1)	GN&C (X.4)	Optical Systems (Instruments and Sensors) (8.1.3)
Long-Duration Crew Health (6.3.2)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)	High-Contrast Imaging and Spectroscopy Technologies (8.2.4)
ECLSS (X.3)	Electric Propulsion (2.2.1)	Detectors and Focal Planes (8.1.1)
GN&C (X.4)	Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)
(Nuclear) Thermal Propulsion (2.2.3)	EDL TPS (X.5)	Active Thermal Control of Cryogenic Systems (14.1.2)
Lightweight and Multifunctional Materials and Structures (X.2)	In Situ Instruments and Sensors (8.3.3)	Electric Propulsion (2.2.1)
Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)
EDL TPS (X.5)	Extreme Terrain Mobility (4.2.1)	
Grappling, Docking, and Handling (X.6)	Grappling, Docking, and Handling (X.6)	

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4

Future Independent Reviews

INTRODUCTION

This chapter recommends a methodology for conducting independent reviews of future updates to NASA's space technology roadmaps. This methodology takes into account the extent of changes expected to be implemented in the roadmap from one generation to the next and the amount of time since the most recent comprehensive independent review of the roadmaps.

The chapter reviews the path that led to the recommended methodology by discussing (1) the methodology used during the previous study as documented in the 2012 National Research Council (NRC) report *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*,[1] (2) the methodology used for this report, and (3) the NASA Office of the Inspector General report *NASA's Efforts to Manage Its Space Technology Portfolio*, published December 15, 2015. This review provides the foundation for understanding the value of an independent review and the suggested future methodology for such reviews.

2012 NATIONAL RESEARCH COUNCIL REVIEW AND PRIORITIZATION METHODOLOGY

In June 2010, Robert Braun, then NASA's chief technologist, requested that the NRC conduct a study of 14 space technology roadmaps that NASA had drafted. In response to this request, the NRC appointed an 18-member steering committee and six study panels with a total of 56 additional experts. The six panels covered various subsets of the 14 roadmaps. The steering committee and the panels met for the first time in January of 2011. The steering committee held three additional meetings between January and September of 2011. During the same time frame, each of the six panels held a 1-day public workshop and two additional meetings for each roadmap it was reviewing. Public input was also solicited from a website where 144 individuals provided 244 comments on the draft roadmaps. All of the gathered data allowed the prioritization all of the level 3 technologies in each roadmap, and those detailed analyses are provided as appendixes to the 2012 report. These data were then synthesized by the steering committee and documented in the main body of the report. An interim report was provided in late 2011,[2] and the final report

[1] NRC, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*, The National Academies Press, Washington, D.C.

[2] NRC, 2011, *An Interim Report on NASA's Draft Space Technology Roadmaps*, The National Academies Press, Washington, D.C.

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was published in early 2012. This significant effort was completed in roughly a year, which is rapid for a study by the National Academies of Sciences, Engineering, and Medicine (by contrast most NASA science decadal surveys take nearly 2 years to complete).

The methodology from the NRC's 2012 review is described in Appendix C of this report. Briefly, the individual panels were tasked with categorizing the level 3 technologies into high-, medium-, and low-priority groups. The panels generated a weighted decision matrix based on quality function deployment (QFD) techniques for each technology area. In this method, each criterion and subcriterion was given a numerical weight by the steering committee. The weighting was based on the importance of the criteria to meeting NASA's goals of technology advancement.

NASA's technology roadmaps and the review of the roadmaps by the Academies are just two steps in the overall effort to define and execute NASA's technology investment portfolio. The complete cycle is shown below.

- FY 2010—Space Technology Roadmaps—revised every 4 years
  —140 challenges, 320 level 3 technologies, 20-year horizon

- FY 2011—NRC Study—requested every 4 years
  —Prioritization: 100 top technical challenges; 83 high-priority technologies (roadmap specific), 16 highest of high-priority technologies (looking across all roadmaps)

- FY 2012—Development of the Strategic Space Technology Investment Plan (SSTIP)—revised every 2 years
  —Updated space technology roadmaps: incorporated NRC study results
  —Developing a Strategic Space Technology Investment Plan: current investments, current priorities of NASA's mission directorates and offices, opportunities for partnerships, gaps vs. current budget and capacities, 20-year horizon with a 4-year cadence

- FY 2013—Execution
  —Investment portfolio: NASA Technology Executive Council uses SSTIP to make decisions
  —Must accomplish: mission needs and commitments, push opportunities, affordability, technical progress, programmatic performance

As can be seen above, NASA intends to revise the roadmaps every 4 years, followed by an independent review, which then would be used to update the SSTIP, which would in turn guide the execution of the "investment portfolio." The 2010 roadmaps covered all NASA space technologies. The draft 2015 roadmaps also include a roadmap for aeronautics, as well as an additional volume: TA 0, Introduction, Crosscutting Technologies, and Index.

2015 ACADEMIES REVIEW AND PRIORITIZATION METHODOLOGY

The current review is more limited than the prior comprehensive review. This review is limited to technologies that appeared in the 2015 roadmaps but did not appear in the roadmaps in the 2012 NRC report (see Appendix B for the comparison between the Technology Area Breakdown Structure [TABS] in the 2010 roadmaps, the revised TABS from the 2012 NRC report, and the 2015 roadmap TABS). The review was designed to use the same methodology as the NRC's 2012 study (see Appendix C) to determine whether any of the new technologies should be added to the list of 83 high-priority technologies and the subset of 16 highest-priority technologies in the 2012 report. The QFD scores were compared with those in the 2012 report to verify that they were consistent.

When the 2012 report was prepared, the NASA design reference missions (DRMs) were not available, so as a substitute the panels identified a number of challenges for each technology area that served to drive the individual technology capabilities. These challenges were generated to provide a focus for the technology development and to assist in the prioritization of the level 3 technologies. For the current 2015 NASA technology roadmaps, instead

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of using the technical challenges, NASA used a newly produced set of DRMs, which are described in the first volume of the roadmaps.[3] The 2015 review did not include the following items:

- TA 0 Introduction, Crosscutting Technologies, and Index. This document includes the topics that cross multiple technology areas; the categorization of technologies as enabling or enhancing for each DRM; the technologies identified to support campaigns, such as the Evolvable Mars campaign; and the new crosscutting technology structure provided by NASA that built upon what was suggested in the 2012 NRC report.
- TA 15 Aeronautics roadmap. Because there was no TA 15 roadmap in the set of 2010 draft roadmaps that the earlier NRC study reviewed, there is no baseline against which to assess the aeronautics technologies.

SUMMARY OF OFFICE OF INSPECTOR GENERAL REPORT

The NASA Office of the Inspector General (OIG) performed an audit of NASA's technology portfolio, the results of which were published in December 2015.[4] The OIG profiled the top 15 space technology projects by fiscal year 2015 funding in the following programs: Technology Demonstration Missions Program, Game Changing Development Program, Advanced Exploration Systems Program, and the Science Mission Directorate's Research Divisions. The report found that deficiencies in NASA's management processes and controls may limit its efforts to effectively manage its portfolio of space technology investments. The issues cited included a delayed revision of the SSTIP (the one cited frequently in this report was prepared in 2012), an unclear process for initiating new space technology projects, and an inconsistent process for measuring technology projects' return on investment. One of the recommendations was a further prioritization of "core" and "adjacent" technologies in a revised SSTIP.

FUTURE INDEPENDENT REVIEWS

During the present study, NASA researchers presented information about the new technologies to the committee, including their evaluation of the technologies' value using the QFD methodology in the 2012 NRC report. It became clear that the researchers struggled to assign objective grades to their technologies—in almost every case, the QFD scores they assigned were the highest possible. These high scores often overstated the technology's value owing to the researchers' understandable bias in favor of their technology and or their limited understanding of broad technological needs. An independent review would provide an objective evaluation of individual scoring and also better captures the alignment to non-NASA aerospace needs, as well as with non-aerospace national goals.

The first volume of the 2015 NASA technology roadmaps includes lists of all level 4 research tasks that are designated as either enabling or enhancing for each DRM.[5] An informal review of the lists indicates that there may be a tendency to overstate the case for "enabling" versus "enhancing." Also, since the DRMs as a whole comprise all possible missions that NASA might carry out rather than a smaller, budget-constrained set that is more likely to be executed, it is difficult to assess the value of technologies based on their ability to support the DRMs. NASA has acknowledged that the existing set of DRMs might be too large, and it has been developing a smaller set. Since the DRMs are a significant new feature in the 2015 roadmaps, a more detailed review of the DRMs and their relationship to the development of the NASA technology portfolio is merited. An independent review of the relationships between the DRMs and the technologies that would enable or enhance them would strengthen the understanding of mission pull and technology push. DRMs tend to change with political cycles, especially for human missions, plans—as has occurred with the last two administrations—so an independent review of the DRMs when an administration changes might be merited.

The addition of TA 15 Aeronautics roadmap also merits an independent review. The Aeronautics thrusts that are used in place of the DRMs actually resemble the 2012 NRC report technical challenges more closely than do

[3] NASA, 2015, *NASA Technology Roadmaps: Introduction, Crosscutting Technologies, and Index*, May 2015 Draft, http://www.nasa.gov/offices/oct/home/roadmaps/index.html, accessed June 29, 2016, p. i-46.

[4] NASA Office of the Inspector General, 2015, *NASA's Efforts to Manage Its Space Technology Portfolio*, Report No. IG-16-008, Washington, D.C.

[5] NASA, 2015, *Technology Roadmaps, Introduction, Crosscutting Technologies, and Index*, Appendix E.

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NASA Space Technology Roadmaps and Priorities Revisited

the DRMs. Future reviews will need to address this inconsistency. Isolating aeronautics from the other 14 roadmaps eliminates the opportunity to assess possible synergies that exist between NASA's space and aeronautics technology portfolios in areas such as materials, electronics, and propulsion, to name just a few examples.

PROPOSED METHODOLOGY FOR FUTURE REVIEWS

Given the dynamic nature of technology development organization and management, the pace of technology advances, NASA missions, NASA organization, and so on, and because each iteration of the roadmaps and each independent review will result in new lessons learned, it is not useful to come up with a long-range plan for future reviews. In addition, future review plans will always be subject to change. Accordingly, there is little value in having one independent review make recommendations for more than one subsequent review.

Taking into account lessons learned from the current and prior review, as well as the recommendations from the NASA OIG report, the following methodology is proposed for the next review:

Recommendation 1. An independent review of a roadmap should be conducted whenever there is a significant change to the roadmap. NASA's technology roadmap revision cycle is expected to be performed every 4 years, but significant changes in NASA's direction might necessitate more frequent reviews. A review should be one of two types: either a comprehensive review of the complete set of roadmaps (including TA 15), such as the one performed in 2012, or a focused review, such as the one in this report. A focused review can be conducted using fewer resources because it addresses only a subset of the total technology portfolio. In making recommendations about the review methodology, each future independent review should focus on the methodology to be used for the next review rather than on a long-range plan covering multiple reviews.

NASA Roles in the Review

Initial Prioritization

A NASA internally generated prioritization of the technologies across all roadmaps would greatly improve the speed and efficiency of future independent reviews. This prioritzation could be done using either the same methodology as the NRC (see Appendix C) or some other process of NASA's devising. A key aspect of this effort is that it be a comprehensive prioritization to promote not only the top technologies in each roadmap, but also across all roadmaps.

The NASA Technology Executive Council (NTEC) and the Center Technology Council (CTC)[6] have the following responsibilities:

> Strategic Integration manages and coordinates the NASA Technology Executive Council (NTEC) meetings. These meetings are chaired by the NASA Chief Technologist. Council membership includes the Mission Directorate Associate Administrators, the NASA Chief Engineer, and the NASA Chief Health and Medical Officer. The function of NTEC is to perform Agency-level technology integration, coordination, and strategic planning. NTEC's responsibilities include:
>
> 1. Review, from an Agency perspective, the progress of each project level technology activity, against the baseline performance milestones.
> 2. Assess the program level budget and schedule adequacy of the Agency's technology development activities to meet Agency strategic goals.
> 3. Assess the Agency-level technology gaps, overlaps, and synergies between the Agency's technology programs.
> 4. Assess the technology maturation progress against the Mission Directorate's goals, objectives, missions, and timelines, as well as the Agency technology roadmaps and strategic goals.

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[6] NASA, "NASA Technology Executive Council (NTEC)," June 26, 2012, https://www.nasa.gov/offices/oct/home/ntec.html.

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5. Assess the balance and prioritization of the Agency's technology investment portfolio.
6. Develop and review decisional recommendations regarding the Agency's technology investment plans.

The Center Technology Council (CTC) is organized and chaired by the Office of the Chief Technologist (OCT). Council membership includes the center chief technologist from each NASA Center (including Jet Propulsion Laboratory) and a representative from the Office of the Chief Engineer and is observed by a representative from each Mission Directorate. The CTC focuses on institutionally funded activities and development of the programs of the OCT. The responsibilities of the CTC include:

1. Assess the Agency technology roadmapping and technology prioritization activities from a bottoms-up, institutional perspective and provide these assessments to NTEC.
2. Provide NTEC with recommended changes in technology program scope, prioritization, and roadmapping from the Centers' perspective.
3. Provide NTEC with "beyond-program" technology inputs for potential future development.
4. Develop Center reports on the performance of the innovation and technology development activities at each Center.
5. Identify inter-Center technology leveraging opportunities.
6. Develop technology reports (i.e., have the function to look outside the walls of NASA for technology opportunities).

As noted above, the responsibilities of the NTEC include prioritization of NASA technology investments, and the CTC is charged with assisting the NTEC in this effort. The 2012 NRC report notes that prioritization of technologies would be facilitated by the use of systems analysis (see the recommendation on systems analysis in Appendix E).

Recommendation 2. Before the next independent review, the NASA Technology Executive Council and the Center Technology Council (NTEC/CTC), in accordance with their charters, should prioritize the technologies that will be examined in the review. The NTEC/CTC should present the results and rationale for the priorities to the next independent review committee. The prioritization process should take into account the factors included in the prioritization process described in Appendix C. It should also be supported by additional factors such as linkage of technologies to a concise list of design reference missions (DRMs), including an assessment of the technologies as enabling or enhancing; the use of systems analysis to establish the technology's benefit to the mission relative to the benefit of alternative technologies; and correlation of technology priorities with both expected funding and required development schedule.

Lead-Collaborate-Watch-Park

The 2012 NRC report included the following recommendation:

Cooperative Development of New Technologies. OCT should pursue cooperative development of high-priority technologies with other federal agencies, foreign governments, industry, and academic institutions to leverage resources available for technology development.

The resources available for development of NASA technologies are inadequate to support the development of the broad array of technologies in the roadmaps. One approach for improving the allocation of technology development resources would be to use a modified version of an approach applied by the Army Research Laboratory (ARL). ARL has classified each of the technologies in its 2015-2035 Science and Technology Campaign Plans[7] as falling into one of three categories: Lead, Collaborate, or Watch. The current study committee has modified the

[7] U.S. Army Research Laboratory, 2014, *S&T Campaign Plans 2015-2035*, Adelphi, Md., September, http://www.arl.army.mil/www/default.cfm?page=2401.

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definitions and added one category: Park. These four categories can help NASA determine the level of cooperative development with others and thus reduce their technology development expenditures.

- **LEAD:** NASA's needs and timing for a given technology are so unique that advancing the technology will require NASA investment without substantial shared investments by others. Maintaining in-house expertise and infrastructure for this technology is critical to unique NASA needs.
- **COLLABORATE:** NASA establishes an interdependent partnership with other organizations (government, industry, academia, or international partners) to pursue a technology using shared investments. This collaboration can take several forms. A common example is NASA and another government agency coordinating research and development and communicating the results to each other. Another form is a public-private partnership in which NASA provides part of the funding with cost sharing by the industry partner. NASA can also provide its research partners with access to unique infrastructure, technological advances, and in-house expertise that significantly influence the direction of the collaboration. Collaborating allows NASA's in-house technical experts to develop technologies that they may not have otherwise been afforded the opportunity to do so.
- **WATCH:** NASA maintains high vigilance monitoring emerging technologies and corresponding efforts within industry, academia, and international markets. Technologies in this category will most likely achieve advancement outside of NASA because of substantial interest and investment by outside organizations and the technology is not unique to NASA missions. It is important that NASA stay actively engaged in the national and international scientific dialog to remain poised to react to developments that make the technology a viable approach for NASA needs. One means of staying actively engaged in the national and international scientific dialog is the attendance at and the participation in scientific conferences by NASA researchers.
- **PARK:** Pursuing technology advancement requires better definition of mission or operational requirements before proceeding. The roadmap milestones need to be readjusted to achieve just-in-time rather than just-in-case delivery of value. NASA would minimize effort for technologies in this category until better definition is achieved.

Example of a Technology for Lead Status

Radiation protection and mitigation is well suited for a Lead designation (see technology group X.1, Radiation Protection and Mitigation for Spaceflight, in the group of highest-priority technologies). It was cited as the highest-priority technology for human spaceflight in the 2012 NRC report, it was one of the three highest priority technical capabilities identified in the 2014 NRC report on human spaceflight,[1] and it is well represented in NASA's SSTIP under several core technology investments such as Lightweight Space Structures and Materials, ECLSS, Space Radiation Mitigation, and Scientific Instruments and Sensors. Radiation hazards include both prompt and cumulative damage from ionizing radiation from the sun (the solar wind), from solar particle events (SPEs), and from galactic cosmic rays (GCRs). Shielding in the form of lightweight materials and structures can reduce the exposure of humans and sensitive components to ionizing radiation and SPEs during space travel and in surface habitats, but a satisfactory approach for mitigating GCRs has yet to be determined. GCRs have such high energies that they produce secondary radiation when they interact with shielding or other spacecraft and habitat materials. This secondary radiation can increase the radiation hazard to humans and equipment. Electrostatic deflecting shields have been proposed, but such systems would be heavy, require substantial electrical power, and could themselves pose a threat to human health.

In addition to investments in radiation protection technologies, investments in technologies that are unique to NASA's needs would also be required for long-term space missions. These needs include (1) smart dosimeters for tracking cumulative doses from all three forms of space radiation both within and external to spacecraft and protective habitats, (2) mitigating biomedical approaches such as dietary regimens and drugs, (3) sophisticated risk-assessment models that can model and simulate radiation risks due to changes in the space radiation environment during all phases of a mission, and (4) sensors and models to predict changes in the space radiation environment.

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Examples of Technology for Collaborate Status

NASA and General Motors have partnered to codevelop robots that can work side by side with people to assist in space missions and to enhance safety and productivity of automotive manufacturing. Further collaboration on this topic is encouraged, especially as it relates to technology 4.4.3, Proximate Interaction. Such collaboration is important and valuable, particularly during the current phase of fast-paced adoption of new proximate interaction technologies for industrial and assistive robotics. Investment in collaborative and co-development projects enable NASA to influence the directions of new development so that the technologies better align with NASA needs. As proximate interaction will be an important component of future human space exploration missions, collaborations are also necessary to build and strengthen in-house expertise, allowing NASA to take a lead role in this technology area when it becomes necessary.

Examples of Technologies for Watch Status

Examples of Watch technologies are 11.4.6, Cyber Infrastructure, and 11.4.8, Cyber Security. The use of these important technologies as they are developed by other government and nongovernment organizations is expected to increase within the NASA infrastructure. It is possible that in the future cyber-security needs within NASA flight segments could elevate this technology to the Collaborate category as specific cybersecurity elements are incorporated into flight systems. Another example of a Watch technology is 11.3.5, Exascale Simulation. Several different countries and companies are working toward exascale computing (1,000 petaflops), but that target is not expected to be achieved before 2022. In the United States, the recently announced National Strategic Computing Initiative is expected to provide an extra incentive to reach this goal. NASA will certainly make use of exascale computing, and by watching the development of these computers it will be ready to use them effectively without needing to engage in their development. As exascale computing moves closer to reality, this technology could move from the Watch status to Collaborate status.

Example of a Technology for Park Status

An example of a Park technology is 7.4.4, Artificial Gravity, which is produced by spinning a spacecraft. The requirements for and the efficacy of this technology are unclear at the moment, and the likelihood of its need is dependent on the effectiveness of other gravity countermeasures outlined in 6.3.2, Long-Duration (human) Health, including research task 6.3.2.1, Artificial Gravity, which is produced by spinning individual astronauts using apparatus installed within a spacecraft. It is possible that difficulties in achieving the goals of Long-Duration Health, combined with a near-term need for a deep-space-capable habitation system, would require the posture on 7.4.4, Artificial Gravity, to change from Park to Lead at some future date.

Recommendation 3. As part of its prioritization process, NTEC/CTC should classify each technology to be examined by the next independent review (at TABS level 3 or level 4) as Lead, Collaborate, Watch, or Park. In addition, the Office of the Chief Technologist (OCT) should update NASA's electronic technology database, TechPort, so that it, too, indicates for each technology whether NASA is pursuing it as Lead, Collaborate, Watch, or Park. For collaborative efforts, OCT should include in TechPort details on the nature of the collaboration, including facilities, flight testing, and the development of crosscutting technologies.

Design Reference Missions

Finding 3. A more concise list of design reference missions (DRMs) produced by NASA that more closely resembles a budget-enabled set of missions would result in better prioritization of "enhancing" and "enabling" technologies in the roadmaps. Whenever there is a substantial change to NASA mission

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plans and the DRMs are updated, technologies could be reprioritized by rescoring their benefit and relevance to NASA

The Next Independent Review

Recommendation 4. The next independent review should be comprehensive if there have been major changes to the roadmaps and/or the DRMs, or it should be a focused review and examine only the new technologies if they are few in number. The review should cover the following:

- **The prioritization of technologies previously completed by the NTEC/CTC and the process used to conduct the prioritization.**
- **Roadmap for TA 15 Aeronautics.**
- **The first volume of the technology roadmaps, TA 0 Introduction, Crosscutting Technologies, and Index.**
- **The relevance of technologies to the DRMs as either enabling or enhancing.**
- **Recommendation for the methodology to be used for the review that in turn follows it.**

In summary, the committee reviewing the 2015 NASA Technology Roadmaps has formulated a methodology for future independent reviews that will reduce their time and cost by (1) having the NASA NTEC/CTC do a preliminary prioritization of technologies based on the DRMs and (2) configuring the review based on the extent to which the technologies and/or the DRMs have changed. Sorting the level 3 technologies or level 4 research tasks into Lead-Collaborate-Watch-Park categories will help NASA identify technologies suitable for collaboration and will conserve technology development resources.

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Appendixes

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A

Statement of Task

The NRC will appoint an ad hoc committee to evaluate the most recent drafts of 14 technology roadmaps that NASA has revised and updated. The scope of the technologies to be considered includes those that enable NASA's human exploration and science missions.

With regard to assessing the revised roadmaps, the committee will in its report:

- Compare the list of technologies in the 2015 draft of NASA's space technology roadmaps to the list of technologies in the revised technology area breakdown structure that appears in the 2012 National Research Council report, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.
- Identify the technologies that appear in the 2015 roadmaps that do not appear in the 2012 report and assess these new technologies using the same prioritization criteria that were used to prioritize the technologies listed in the 2012 report.
- Determine which of the new technologies should be added to (1) the list of 83 high-priority technologies presented in the 2012 report and (2) the list of 16 highest-priority technologies that also appear in the 2012 report.

In addition the committee will recommend a methodology for conducting independent reviews of future updates to NASA's space technology roadmaps, which are expected to occur every four years. The recommended methodology should take into account the extent of the changes expected to be implemented in the roadmaps from one generation to the next and the amount of time since the initial comprehensive independent review of the roadmaps, which took place during the study that led to the 2012 NRC report.

The scope of this study does not include assessing or recommending changes to the content of the new aeronautics technology roadmap, nor does it include reassessing the prioritization of the technologies that appear in the NRC's 2012 roadmaps report.

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B

Comparison of the Technology Area Breakdown Structures for 2010, 2012, 2015

This study was not chartered to review the full breadth of NASA's 2015 technology roadmaps. Rather, its scope is limited to technologies appearing in the NASA 2015 roadmaps that were not evaluated in the 2012 NRC study. These technologies were identified by comparing (1) the Technology Area Breakdown Structure (TABS) in NASA's 2015 roadmap, (2) the TABS in the 2012 NRC report, and (3) the TABS in NASA's 2010 draft roadmaps, as detailed in the TABS comparison table (Table B.1).

The entries in the first column of Table B.1 denote the following:

- *New-Evaluate*: These are the 39 technologies that appear in the 2015 TABS but not in the TABS in the 2012 NRC report. They are prioritized in the present report.
- *Revised-Evaluate*: These three technologies appear in both the 2015 and the 2012 TABS but (1) the names of the technologies are different in the 2012 and 2015 TABS and (2) the description of related work for them in the 2015 roadmaps is substantially different from or has a much wider scope than any technology in the 2012 TABS. This report evaluates the priority of these technologies.
- *Revised-DNR*: Revised-Do Not Review. The technology appears in both the 2015 and 2012 TABS, and even though the name of the technology is different in the 2012 and 2015 TABS, (1) there seems to be only a modest change in the goals and/or scope of the technology effort or (2) the scope of the technology in the 2015 roadmap is not as broad as the scope of the technology in the 2012 roadmap, and so this report does not reevaluate the priority of this technology.
- *Revived*: The technology appears in the 2015 TABS but did not appear in the 2012 TABS. However, it is not evaluated as a new technology because it also appears in the 2010 TABS, meaning that the 2012 NRC study evaluated this technology and decided it should be deleted from the TABS. Given that the present study is intended to evaluate only the technologies that were not covered by the prior study, this report does not evaluate the priority for this technology.
- *Merged*: The technology appears in the 2015 TABS but does not appear in the 2012 TABS. However, it is not evaluated as a new technology because it appeared in the 2010 TABS, the prior NRC study merged it with another technology in the 2010 TABS, and the merged technology appears in the 2012 TABS under a different technology number. Thus, the prior NRC study already evaluated this technology, and given that this study is intended to evaluate only those technologies not covered by the prior study, this report does not evaluate the priority of this technology.

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- *Deleted*: The technology appears in the 2012 TABS but not in the 2015 TABS. Given that this study is only reviewing technologies that have been added to the 2012 TABS, this study does not evaluate the priority of this technology, nor does it review the decision to delete them.
- *Placeholder*: The technology appears in the 2015 TABS, but only as a placeholder, in that NASA does not propose conducting related research in the respective roadmap. For each of these technologies there is a note in the respective roadmap such as
  —NASA is not currently advancing any technologies in this area within the time frame of this roadmap.
  —Currently, no identified mission need exists to justify NASA's development in this technology.
  Thus, in essence, these technologies have been deleted from the TABS. Given that this study is only reviewing technologies that have been added to the 2012 TABS, this study does not evaluate the priority of these technologies, nor does it review NASA's decision not to propose related research.
- *Elsewhere*: The technology appears in the 2015 TABS, but the respective roadmap has no technical content. Rather, the roadmaps say that related research has been shifted to one or more other technologies. This study does not evaluate the priority of this technology, nor does it review NASA's decision to shift research elsewhere or the extent to which the content of the technology in the 2012 roadmap actually appears in the designated location.
- *No entry*: The technology appears in both the 2012 and 2015 TABS, so this study does not evaluate its priority.

The second column contains the TABS for July 2015 version of the TABS. This is the version of the TABS that was used to conduct this study.

The third column lists technologies from the TABS that was recommended to NASA in the 2012 NRC report. These technologies are listed out of sequence if they appear in the 2015 roadmap with a different number. (For example, see technology 7.6.2, which appears after 7.6.3.) There are some gaps in the numbering because if the committee that authored the 2012 report decided to drop a technology that was in the 2010 TABS (in the fourth column), it did not renumber subsequent technologies so that the numbering of identical technologies in the 2012 NRC TABS and the 2010 TABS would remain the same. (For example, the 2012 TABS has no technology 8.2.1.) However, in some cases the same technology has different numbers in the 2015 and 2012 roadmaps. For example, Onboard Autonomous Navigation and Maneuver is technology 5.4.2 in the 2015 roadmap and 5.4.3 in the 2012 roadmap.

The fourth column is NASA's 2010 TABS, which is evaluated in the 2012 NRC report. That report produced a modified TABS, which appears in the third column.

Based on the comparison of the 2010, 2012, and 2015 TABS, as detailed in Table B.1, and in accordance with the study statement of task, this report evaluates the priority of 42 level 3 technologies, which are listed below.

TA 1, Launch Propulsion Systems (11 new technologies)
- 1.1, Solid Rocket Propulsion Systems
  - 1.1.6, Integrated Solid Motor Systems
  - 1.1.7, Liner and Insulation
- 1.6, Balloon Launch Systems
  - 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

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TA 4, Robotics and Autonomous Systems (11 new technologies)
- 4.2, Mobility
  - 4.2.5, Surface Mobility
  - 4.2.6, Robot Navigation
  - 4.2.7, Collaborative Mobility
  - 4.2.8, Mobility Components
- 4.3, Manipulation
  - 4.3.7, Grappling
- 4.4, Human–System Interaction
  - 4.4.3, Proximate Interaction
  - 4.4.8, Remote Interaction
- 4.5, System-Level Autonomy
  - 4.5.8, Automated Data Analysis for Decision Making
- 4.7, Systems Engineering
  - 4.7.3, Robot Modeling and Simulation
  - 4.7.4, Robot Software
  - 4.7.5, Safety and Trust

TA 5, Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (4 new technologies)
- 5.1, Optical Communications and Navigation
  - 5.1.6, Optical Tracking
  - 5.1.7, Integrated Photonics
- 5.7, Orbital Debris Tracking and Characterization
  - 5.7.1, Tracking Technologies
  - 5.7.2, Characterization Technologies

TA 7, Human Exploration Destination Systems (1 new technology)
- 7.4, Habitat Systems
  - 7.4.4, Artificial Gravity

TA 9, Entry, Descent, and Landing Systems (3 new technologies)
- 9.2, Descent and Targeting
  - 9.2.6, Large Divert Guidance
  - 9.2.7, Terrain-Relative Sensing and Characterization
  - 9.2.8, Autonomous Targeting

TA 11, Modeling, Simulation, Information Technology, and Processing (8 new technologies)
- 11.2, Modeling
  - 11.2.6, Analysis Tools for Mission Design
- 11.3, Simulation
  - 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, Information Processing
  - 11.4.6, Cyber Infrastructure
  - 11.4.7, Human–System Integration
  - 11.4.8, Cyber Security

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TA 13, Ground and Launch Systems (3 new technologies)
- 13.1, Operational Life Cycle
  - 13.1.4, Logistics
- 13.2, Environmental Protection and Green Technologies
  - 13.2.5, Curatorial Facilities, Planetary Protection, and Clean Rooms
- 13.3, Reliability and Maintainability
  - 13.3.8, Decision-Making Tools

TA 14, Thermal Management Systems (1 new technology)
- 14.3, Thermal Protection Systems
  - 14.3.2, TPS Modeling and Simulation

There are no new technologies in the following technology areas:

- TA 2, In-Space Propulsion Technologies
- TA 3, Space Power and Energy Storage
- TA 6, Human Health, Life Support, and Habitation Systems
- TA 8, Science Instruments, Observatories, and Sensor Systems
- TA 10, Nanotechnology
- TA 12, Materials, Structures, Mechanical Systems, and Manufacturing

All of the technologies in the roadmap for TA 15 Aeronautics are new, because the 2010 and 2012 TABS did not include aeronautics. As noted in Chapter 1, however, TA 15 is outside the scope of this study.

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TABLE B.1 Technology Area Breakdown Structure Comparisons: NASA 2015/NRC 2012/NASA 2010

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	TA 1 Launch Propulsion Systems	**TA 1 Launch Propulsion Systems**	**TA 1 Launch Propulsion Systems**
	1.1 Solid Rocket Propulsion Systems	**1.1 Solid Rocket Propulsion Systems**	**1.1 Solid Rocket Propulsion Systems**
	1.1.1 Propellants	1.1.1 Propellants	1.1.1 Propellants
	1.1.2 Case Materials	1.1.2 Case Materials	1.1.2 Case Materials
	1.1.3 Nozzle Systems	1.1.3 Nozzle Systems	1.1.3 Nozzle Systems
	1.1.4 Hybrid Rocket Propulsion Systems	1.1.4 Hybrid Rocket Propulsion Systems	1.1.4 Hybrid Rocket Propulsion Systems
	1.1.5 Fundamental Solid Propulsion Technologies	1.1.5 Fundamental Solid Propulsion Technologies	1.1.5 Fundamental Solid Propulsion Technologies
New-Evaluate	1.1.6 Integrated Solid Motor Systems		
New-Evaluate	1.1.7 Liner and Insulation		
	1.2 Liquid Rocket Propulsion Systems	**1.2 Liquid Rocket Propulsion Systems**	**1.2 Liquid Rocket Propulsion Systems**
	1.2.1 LH2/LOX Based	1.2.1 LH2/LOX Based	1.2.1 LH2/LOX Based
	1.2.2 RP/LOX Based	1.2.2 RP/LOX Based	1.2.2 RP/LOX Based
	1.2.3 CH4/LOX Based	1.2.3 CH4/LOX Based	1.2.3 CH4/LOX Based
Placeholder	1.2.4 Detonation Wave Engines—Closed Cycle	1.2.4 Detonation Wave Engines (Closed Cycle)	1.2.4 Detonation Wave Engines (Closed Cycle)
Placeholder	1.2.5 Propellants	1.2.5 Propellants	1.2.5 Propellants
	1.2.6 Fundamental Liquid Propulsion Technologies	1.2.6 Fundamental Liquid Propulsion Technologies	1.2.6 Fundamental Liquid Propulsion Technologies
	1.3 Air Breathing Propulsion Systems	**1.3 Air Breathing Propulsion Systems**	**1.3 Air Breathing Propulsion Systems**
Placeholder	1.3.1 Turbine-Based Combined-Cycle	1.3.1 Turbine Based Combined Cycle (TBCC)	1.3.1 TBCC
Placeholder	1.3.2 Rocket-Based Combined Cycle	1.3.2 Rocket Based Combined Cycle (RBCC)	1.3.2 RBCC
Placeholder	1.3.3 Detonation Wave Engines—Open Cycle	1.3.3 Detonation Wave Engines (Open Cycle)	1.3.3 Detonation Wave Engines (Open Cycle)
Placeholder	1.3.4 Turbine-Based Jet Engines	1.3.4 Turbine Based Jet Engines (Flyback Boosters)	1.3.4 Turbine Based Jet Engines (Flyback Boosters)
Placeholder	1.3.5 Ramjet and Scramjet Engines	1.3.5 Ramjet/Scramjet Engines (Accelerators)	1.3.5 Ramjet/Scramjet Engines (Accelerators)
Placeholder	1.3.6 Deeply Cooled Air Cycles	1.3.6 Deeply Cooled Air Cycles	1.3.6 Deeply Cooled Air Cycles
Placeholder	1.3.7 Air Collection and Enrichment Systems	1.3.7 Air Collection and Enrichment System	1.3.7 Air Collection and Enrichment System
Placeholder	1.3.8 Fundamental Air Breathing Propulsion Technologies	1.3.8 Fundamental Air Breathing Propulsion Technologies	1.3.8 Fundamental Air Breathing Propulsion Technologies
	1.4 Ancillary Propulsion Systems	**1.4 Ancillary Propulsion Systems**	**1.4 Ancillary Propulsion Systems**
	1.4.1 Auxiliary Control Systems	1.4.1 Auxiliary Control Systems	1.4.1 Auxiliary Control Systems
	1.4.2 Main Propulsion Systems (Excluding Engines)	1.4.2 Main Propulsion Systems (Excluding Engines)	1.4.2 Main Propulsion Systems (Excluding Engines)
	1.4.3 Launch Abort Systems	1.4.3 Launch Abort Systems	1.4.3 Launch Abort Systems
	1.4.4 Thrust Vector Control Systems	1.4.4 Thrust Vector Control Systems	1.4.4 Thrust Vector Control Systems

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Placeholder	1.4.5 Health Management and Sensors	1.4.5 Health Management and Sensors	1.4.5 Health Management and Sensors
	1.4.6 Pyro and Separation Systems	1.4.6 Pyro and Separation Systems	1.4.6 Pyro and Separation Systems
	1.4.7 Fundamental Ancillary Propulsion Technologies	1.4.7 Fundamental Ancillary Propulsion Technologies	1.4.7 Fundamental Ancillary Propulsion Technologies
	1.5 Unconventional and Other Propulsion Systems	**1.5 Unconventional and Other Propulsion Systems**	**1.5 Unconventional and Other Propulsion Systems**
Placeholder	1.5.1 Ground Launch Assist	1.5.1 Ground Launch Assist	1.5.1 Ground Launch Assist
	1.5.2 Air Launch and Drop Systems	1.5.2 Air Launch/Drop Systems	1.5.2 Air Launch/Drop Systems
Elsewhere	1.5.3 Space Tether Assist	1.5.3 Space Tether Assist	1.5.3 Space Tether Assist
	1.5.4 Beamed Energy and Energy Addition	1.5.4 Beamed Energy/Energy Addition	1.5.4 Beamed Energy/Energy Addition
Placeholder	1.5.5 Nuclear	1.5.5 Nuclear	1.5.5 Nuclear
Placeholder	1.5.6 High Energy Density Materials and Propellant	1.5.6 High Energy Density Materials/ Propellants	1.5.6 High Energy Density Materials/ Propellants
	1.6 Balloon Launch Systems		
New-Evaluate	1.6.1 Super-Pressure Balloon		
New-Evaluate	1.6.2 Materials		
New-Evaluate	1.6.3 Pointing Systems		
New-Evaluate	1.6.4 Telemetry Systems		
New-Evaluate	1.6.5 Balloon Trajectory Control		
New-Evaluate	1.6.6 Power Systems		
New-Evaluate	1.6.7 Mechanical Systems: Launch Systems		
New-Evaluate	1.6.8 Mechanical Systems: Parachute		
New-Evaluate	1.6.9 Mechanical Systems: Floatation		
	TA 2 In-Space Propulsion Technologies	**TA 2 In-Space Propulsion Technologies**	**TA 2 In-Space Propulsion Technologies**
	2.1 Chemical Propulsion	**2.1 Chemical Propulsion**	**2.1 Chemical Propulsion**
	2.1.1 Liquid Storable	2.1.1 Liquid Storable	2.1.1 Liquid Storable
	2.1.2 Liquid Cryogenic	2.1.2 Liquid Cryogenic	2.1.2 Liquid Cryogenic
	2.1.3 Gels	2.1.3 Gels	2.1.3 Gels
	2.1.4 Solids	2.1.4 Solid	2.1.4 Solid
	2.1.5 Hybrid	2.1.5 Hybrid	2.1.5 Hybrid
	2.1.6 Cold Gas/Warm Gas	2.1.6 Cold Gas/Warm Gas	2.1.6 Cold Gas/Warm Gas
	2.1.7 Micropropulsion	2.1.7 Micropropulsion	2.1.7 Micropropulsion
	2.2 Nonchemical Propulsion	**2.2 Nonchemical Propulsion**	**2.2 Nonchemical Propulsion**
	2.2.1 Electric Propulsion	2.2.1 Electric Propulsion	2.2.1 Electric Propulsion
	2.2.2 Solar and Drag Sail Propulsion	2.2.2 Solar Sail Propulsion	2.2.2 Solar Sail Propulsion
	2.2.3 Thermal Propulsion	2.2.3 Thermal Propulsion	2.2.3 Thermal Propulsion
	2.2.4 Tether Propulsion	2.2.4 Tether Propulsion	2.2.4 Tether Propulsion

continued

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	2.3 Advanced (TRL<3) Propulsion Technologies	**2.3 Advanced (TRL <3) Propulsion Technologies**	**2.3 Advanced (TRL <3) Propulsion Technologies**
	2.3.1 Beamed Energy Propulsion	2.3.1 Beamed Energy Propulsion	2.3.1 Beamed Energy Propulsion
	2.3.2 Electric Sail Propulsion	2.3.2 Electric Sail Propulsion	2.3.2 Electric Sail Propulsion
	2.3.3 Fusion Propulsion	2.3.3 Fusion Propulsion	2.3.3 Fusion Propulsion
	2.3.4 High-Energy-Density Materials	2.3.4 High Energy Density Materials	2.3.4 High Energy Density Materials
	2.3.5 Antimatter Propulsion	2.3.5 Antimatter Propulsion	2.3.5 Antimatter Propulsion
	2.3.6 Advanced Fission	2.3.6 Advanced Fission	2.3.6 Advanced Fission
	2.3.7 Breakthrough Propulsion	2.3.7 Breakthrough Propulsion	2.3.7 Breakthrough Propulsion
	2.4 Supporting Technologies	**2.4 Supporting Technologies**	**2.4 Supporting Technologies**
Placeholder	2.4.1 Engine Health Monitoring and Safety		2.4.1 Engine Health Monitoring and Safety
	2.4.2 Propellant Storage and Transfer	2.4.2 Propellant Storage and Transfer	2.4.2 Propellant Storage and Transfer
Placeholder	2.4.3 Materials and Manufacturing Technologies		2.4.3 Materials and Manufacturing Technologies
Placeholder	2.4.4 Heat Rejection		2.4.4 Heat Rejection
Placeholder	2.4.5 Power		2.4.5 Power
	TA 3 Space Power and Energy Storage	**TA 3 Space Power and Energy Storage**	**TA 3 Space Power and Energy Storage**
	3.1 Power Generation	**3.1 Power Generation**	**3.1 Power Generation**
	3.1.1 Energy Harvesting	3.1.1 Energy Harvesting	3.1.1 Energy Harvesting
	3.1.2 Chemical	3.1.2 Chemical (Fuel Cells, Heat Engines)	3.1.2 Chemical (Fuel Cells, Heat Engines)
	3.1.3 Solar	3.1.3 Solar (Photovoltaic and Thermal)	3.1.3 Solar (Photovoltaic and Thermal)
	3.1.4 Radioisotope	3.1.4 Radioisotope	3.1.4 Radioisotope
	3.1.5 Fission	3.1.5 Fission	3.1.5 Fission
	3.1.6 Fusion	3.1.6 Fusion	3.1.6 Fusion
	3.2 Energy Storage	**3.2 Energy Storage**	**3.2 Energy Storage**
	3.2.1 Batteries	3.2.1 Batteries	3.2.1 Batteries
	3.2.2 Flywheels	3.2.2 Flywheels	3.2.2 Flywheels
	3.2.3 Regenerative Fuel Cells	3.2.3 Regenerative Fuel Cells	3.2.3 Regenerative Fuel Cells
Revised-DNR	3.2.4 Capacitors	3.2.4 Electric and Magnetic Field Storage	
Deleted		3.2.5 Thermal Storage	
	3.3 Power Management and Distribution	**3.3 Power Management and Distribution**	**3.3 Power Management and Distribution**
	3.3.1 Fault Detection, Isolation, and Recovery	3.3.1 Fault Detection, Isolation, and Recovery (FDIR)	3.3.1 FDIR
	3.3.2 Management and Control	3.3.2 Management and Control	3.3.2 Management and Control
	3.3.3 Distribution and Transmission	3.3.3 Distribution and Transmission	3.3.3 Distribution and Transmission
	3.3.4 Wireless Power Transmission	3.3.4 Wireless Power Transmission	3.3.4 Wireless Power Transmission
	3.3.5 Conversion and Regulation	3.3.5 [Power] Conversion and Regulation	3.3.5 Conversion and Regulation

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	3.4 Crosscutting Technology	**3.4 CrosscuttingTechnology**	**3.4 Crosscutting Technology**
Elsewhere	3.4.1 Analytical Tools	3.4.1 Analytical Tools	3.4.1 Analytical Tools
Elsewhere	3.4.2 Green Energy Impact	3.4.2 Green Energy Impact	3.4.2 Green Energy Impact
Elsewhere	3.4.3 Multifunctional Structures	3.4.3 Multifunctional Structures	3.4.3 Multifunctional Structures
Elsewhere	3.4.4 Alternative Fuels	3.4.4 Alternative Fuels	3.4.4 Alternative Fuels
	TA 4 Robotics and Autonomous Systems	**TA 4 Robotics, TeleRobotics, and Autonomous Systems**	**TA 4 Robotics, TeleRobotics and Autonomous Systems**
	4.1 Sensing and Perception	**4.1 Sensing and Perception**	**4.1 Sensing and Perception**
Revised-DNR	4.1.1 3D Sensing	4.1.1 Vision	4.1.1 Stereo Vision
Revised-DNR	4.1.2 State Estimation	4.1.5 Pose Estimation	4.1.2 LIDAR
Revised-DNR	4.1.3 Onboard Mapping	4.1.4 Localization and Mapping	4.1.3 Proximity Sensing
Revised-DNR	4.1.4 Object, Event, and Activity Recognition	4.1.3 Natural Feature Image Recognition	4.1.4 Sensing Non-Geometric Terrain Properties
Revised-DNR	4.1.5 Force and Tactile Sensing	4.1.2 Tactile Sensing	4.1.6 Tactile Sensing Arrays
Elsewhere	4.1.6 Onboard Science Data Analysis	4.1.6 Multi-Sensor Data Fusion	
Deleted		4.1.7 Mobile Feature Tracking and Discrimination	
Deleted		4.1.8 Terrain Classification and Characterization	4.1.5 Estimating Terrain Mechanical Properties
			4.1.7 Gravity Sensors and Celestial Nav.
			4.1.8 Terrain-Relative Navigation
			4.1.9 Real-Time Self-Calibrating of Hand-Eye Systems
	4.2 Mobility	**4.2 Mobility**	**4.2 Mobility**
	4.2.1 Extreme Terrain Mobility	4.2.1 Extreme Terrain Mobility	
	4.2.2 Below-Surface Mobility	4.2.2 Below-Surface Mobility	
	4.2.3 Above-Surface Mobility	4.2.3 Above-Surface Mobility	
	4.2.4 Small-Body and Microgravity Mobility	4.2.4 Small Body/Microgravity Mobility	
New-Evaluate	4.2.5 Surface Mobility		
New-Evaluate	4.2.6 Robot Navigation		
New-Evaluate	4.2.7 Collaborative Mobility		
New-Evaluate	4.2.8 Mobility Components		
			4.2.1 Simultaneous Localize and Mapping
			4.2.2 Hazard Detection Algorithms
			4.2.3 Active Illumination
			4.2.4 3-D Path Planning w/ Uncertainty
			4.2.5 Long-life Extreme Enviro. Mechanisms
			4.2.6 Robotic Jet Backpacks
			4.2.7 Smart Tethers
			4.2.8 Robot Swarms
			4.2.9 Walking in Microgravity

continued

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	4.3 Manipulation	**4.3 Manipulation**	**4.3 Manipulation**
Revised-DNR	4.3.1 Manipulator Components	4.3.1 Robot Arms	4.3.3 Robot Arms (light, high strength)
	4.3.2 Dexterous Manipulation	4.3.2 Dexterous Manipulators	
Elsewhere	4.3.3 Modeling of Contact Dynamics	4.3.3 Modeling of Contact Dynamics	
	4.3.4 Mobile Manipulation	4.3.4 Mobile Manipulation	
	4.3.5 Collaborative Manipulation	4.3.5 Collaborative Manipulation	
Revised-DNR	4.3.6 Sample Acquisition and Handling	4.3.6 Robotic Drilling and Sample Processing	
New-Evaluate	4.3.7 Grappling		4.3.1 Motion Planning Alg., High DOF
			4.3.2 Sensing and Control
			4.3.4 Dexterous Manipul., Robot Hands
			4.3.5 Sensor Fusion for Grasping
			4.3.6 Grasp Planning Algorithms Robotic Drilling Mechanisms
			4.3.7 Multiarm/Finger Manipulation
			4.3.8 Planning with Uncertainty
	4.4 Human–Systems Interaction	**4.4 Human–Systems Integration**	**4.4 Human–Systems Integration**
Revised-DNR	4.4.1 Multimodal Interaction	4.4.1 Multimodal Human–Systems Interaction	
Elsewhere	4.4.2 Supervisory Control	4.4.2 Supervisory Control	
Revised-Evaluate	4.4.3 Proximate Interaction	4.4.3 Robot-to-Suit Interfaces	
Elsewhere	4.4.4 Intent Recognition and Reaction	4.4.4 Intent Recognition and Reaction	
	4.4.5 Distributed Collaboration and Coordination	4.4.5 Distributed Collaboration	4.4.3 Distributed Collaboration
Elsewhere	4.4.6 Common and Standard Human System Interfaces	4.4.6 Common Human–Systems Interfaces	
Elsewhere	4.4.7 Safety, Trust, and Interfacing of Robotic and Human Proximity Operations	4.4.7 Safety, Trust, and Interfacing of Robotic/ Human Proximity Operations	
New-Evaluate	4.4.8 Remote Interaction		
			4.4.1 Crew Decision Support Systems
			4.4.2 Immersive Visualization
			4.4.4 Multiagent Coordination
			4.4.5 Haptic Displays
			4.4.6 Displaying Range Data to Humans
	4.5 System-Level Autonomy	**4.5 Autonomy**	**4.5 Autonomy**
Revised-DNR	4.5.1 System Health Management	4.5.1 Vehicle System Management and FDIR	4.5.2 Vehicle Health, Prognostic/Diagnostic Systems
			4.5.6 Integrated Systems Health Management
			4.5.7 FDIR and Diagnosis
			4.5.8 System Monitoring and Prognosis

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	4.5.2 Activity Planning, Scheduling, and Execution	4.5.2 Dynamic Planning and Sequencing Tools	4.5.4 Planning/Scheduling Resources
Elsewhere	4.5.3 Autonomous Guidance and Control	4.5.3 Autonomous Guidance and Control	
	4.5.4 Multiagent Coordination	4.5.4 Multiagent Coordination	
Elsewhere	4.5.5 Adjustable Autonomy	4.5.5 Adjustable Autonomy	
Elsewhere	4.5.6 Terrain-Relative Navigation	4.5.6 Terrain-Relative Navigation	
Elsewhere	4.5.7 Path and Motion Planning with Uncertainty	4.5.7 Path and Motion Planning with Uncertainty	
New-Evaluate	4.5.8 Automated Data Analysis for Decision Making		
			4.5.1 Spacecraft Control Systems
			4.5.3 Human Life Support Systems
			4.5.5 Operations
			4.5.9 V&V of Complex Adaptive Systems
			4.5.10 Automated Software Generation
			4.5.11 Software Reliability
			4.5.12 Semiautomatic Systems
	4.6 Autonomous Rendezvous and Docking	**4.6 Autonomous Rendezvous and Docking**	**4.6 Auton. Rendezvous and Docking**
	4.6.1 Relative Navigation Sensors	4.6.1 Relative Navigation Sensors (long, mid, and near range)	4.6.3 Relative Navigation Sensors
Revised-DNR	4.6.2 GN&C Algorithms	4.6.2 Relative Guidance Algorithms	
	4.6.3 Docking and Capture Mechanisms and Interfaces	4.6.3 Docking and Capture Mechanisms/ Interfaces	4.6.2 Low Impact and Androgynous Docking Systems and Interfaces
Elsewhere	4.6.4 Mission and System Managers for Autonomy and Automation		
			4.6.1 Rendezvous and Capture
			4.6.4 Robust AR&D GN&C Algorithms and FSW
			4.6.5 Onboard Mission Manager
			4.6.6 AR&D Integration and Standardization
	4.7 Systems Engineering	**4.7 RTA Systems Engineering**	**4.7 RTA Systems Engineering**
	4.7.1 Modularity, Commonality, and Interfaces	4.7.1 Modularity/Commonality	
	4.7.2 Verification and Validation of Complex Adaptive Systems	4.7.2 Verification and Validation of Complex Adaptive Systems	
Revised-Evaluate	4.7.3 Robot Modeling and Simulation	4.7.3 Onboard Computing	
New-Evaluate	4.7.4 Robot Software		
New-Evaluate	4.7.5 Safety and Trust		
			4.7.1 Human Safety
			4.7.2 Refueling Interfaces and Assoc. Tools
			4.7.3 Modular/Serviceable Interfaces
			4.7.4 High Perf., Low-Power Onboard Computers

continued

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
			4.7.5 Environment Tolerance
			4.7.6 Thermal Control
			4.7.7 Robot-to-Suit Interfaces
			4.7.8 Common Human-Robot Interfaces
			4.7.9 Crew Self-Sufficiency
	TA 5 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	**TA 5 Communications and Navigation**	**TA 5 Communications and Navigation**
	5.1 Optical Communications and Navigation	**5.1 Optical Communications and Navigation**	**5.1 Optical Communications and Navigation**
	5.1.1 Detector Development	5.1.1 Detector Development	5.1.1 Detector Development
	5.1.2 Large Apertures	5.1.2 Large Apertures	5.1.2 Large Apertures
	5.1.3 Lasers	5.1.3 Lasers	5.1.3 Lasers
	5.1.4 Acquisition and Tracking	5.1.4 Acquisition and Tracking	5.1.4 Acquisition and Tracking
	5.1.5 Atmospheric Mitigation	5.1.5 Atmospheric Mitigation	5.1.5 Atmospheric Mitigation
New-Evaluate	5.1.6 Optical Tracking		
New-Evaluate	5.1.7 Integrated Photonics		
	5.2 Radio Frequency Communications	**5.2 Radio Frequency Communications**	**5.2 Radio Frequency Communications**
	5.2.1 Spectrum-Efficient Technologies	5.2.1 Spectrum Efficient Technologies	5.2.1 Spectrum Efficient Technologies
	5.2.2 Power-Efficient Technologies	5.2.2 Power-Efficient Technologies	5.2.2 Power-Efficient Technologies
	5.2.3 Propagation	5.2.3 Propagation	5.2.3 Propagation
Elsewhere	5.2.4 Flight and Ground Systems	5.2.4 Flight and Ground Systems	5.2.4 Flight and Ground Systems
	5.2.5 Earth Launch and Reentry Communications	5.2.5 Earth Launch and Reentry Communication	5.2.5 Earth Launch and Reentry Comm.
	5.2.6 Antennas	5.2.6 Antennas	5.2.6 Antennas
	5.3 Internetworking	**5.3 Internetworking**	**5.3 Internetworking**
	5.3.1 Disruption-Tolerant Networking	5.3.1 Disruptive Tolerant Networking	5.3.1 Disruptive Tolerant Networking
	5.3.2 Adaptive Network Topology	5.3.2 Adaptive Network Topology	5.3.2 Adaptive Network Topology
Placeholder	5.3.3 Information Assurance	5.3.3 Information Assurance	5.3.3 Information Assurance
Placeholder	5.3.4 Integrated Network Management	5.3.4 Integrated Network Management	5.3.4 Integrated Network Management
	5.4 Position, Navigation, and Timing	**5.4 Position, Navigation, and Timing**	**5.4 Position, Navigation, and Timing**
	5.4.1 Timekeeping and Time Distribution	5.4.1 Timekeeping and Time Distribution	5.4.1 Timekeeping 5.4.2 Time Distribution
	5.4.3 Onboard Autonomous Navigation and Maneuver	5.4.3 Onboard Autonomous Navigation and Maneuver	5.4.3 Onboard Autonomous Navigation and Maneuver
	5.4.3 Sensors and Vision Processing Systems	5.4.4 Sensors and Vision Processing Systems	5.4.4 Sensors and Vision Processing Systems
	5.4.4 Relative and Proximity Navigation	5.4.5 Relative and Proximity Navigation	5.4.5 Relative and Proximity Navigation
	5.4.5 Auto Precision Formation Flying	5.4.6 Auto Precision Formation Flying	5.4.6 Auto Precision Formation Flying
	5.4.6 Autonomous Approach and Landing	5.4.7 Auto Approach and Landing	5.4.7 Auto Approach and Landing

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	5.5 Integrated Technologies	**5.5 Integrated Technologies**	**5.5 Integrated Technologies**
	5.5.1 Radio Systems	5.5.1 Radio Systems	5.5.1 Radio Systems
	5.5.2 Ultra Wideband	5.5.2 Ultra Wideband	5.5.2 Ultra Wideband
	5.5.3 Cognitive Networks	5.5.3 Cognitive Networks	5.5.3 Cognitive Networks
Elsewhere	5.5.4 Science from the Communications System	5.5.4 Science from the Communication System	5.5.4 Science from the Comm System
Elsewhere	5.5.5 Hybrid Optical Communications and Navigation Sensors	5.5.5 Hybrid Optical Communications and Navigation Sensors	5.5.5 Hybrid Optical Comm and Nav Sensors
	5.5.6 Radio Frequency and Optical Hybrid Technology	5.5.6 RF and Optical Hybrid Technology	5.5.6 RF and Optical Hybrid Technology
	5.6 Revolutionary Concepts	**5.6 Revolutionary Concepts**	**5.6 Revolutionary Concepts**
	5.6.1 X-Ray Navigation	5.6.1 X-Ray Navigation	5.6.1 X-Ray Navigation
	5.6.2 X-Ray Communications	5.6.2 X-Ray Communications	5.6.2 X-Ray Communications
	5.6.3 Neutrino-Based Navigation and Tracking	5.6.3 Neutrino-Based Navigation and Tracking	5.6.3 Neutrino-Based Navigation and Tracking
	5.6.4 Quantum Key Distribution	5.6.4 Quantum Key Distribution	5.6.4 Quantum Key Distribution
	5.6.5 Quantum Communications	5.6.5 Quantum Communications	5.6.5 Quantum Communications
	5.6.6 Superconducting Quantum Interference Filter Microwave Amplifier	5.6.6 SQIF Microwave Amplifier	5.6.6 SQIF Microwave Amplifier
	5.6.7 Reconfigurable Large Apertures	5.6.7 Reconfigurable Large Apertures Using Nanosat Constellations	5.6.7 Reconfigurable Large Apertures
	5.7 Orbital Debris Tracking and Characterization		
New-Evaluate	5.7.1 Tracking Technologies		
New-Evaluate	5.7.2 Characterization Technologies		
	TA 6 Human Health, Life Support, and Habitation Systems	**TA 6 Human Health, Life Support, and Habitation Systems**	**TA 6 Human Health, Life Support and Habitation Systems**
	6.1 Environmental Control and Life Support Systems and Habitation Systems	**6.1 Environmental Control, Life Support Systems, and Habitation Systems**	**6.1 Environmental Control, Life Support Systems, and Habitation Systems**
	6.1.1 Air Revitalization	6.1.1 Air Revitalization	6.1.1 Air Revitalization
	6.1.2 Water Recovery and Management	6.1.2 Water Recovery and Management	6.1.2 Water Recovery and Management
	6.1.3 Waste Management	6.1.3 Waste Management	6.1.3 Waste Management
	6.1.4 Habitation	6.1.4 Habitation	6.1.4 Habitation
	6.2 Extravehicular Activity Systems	**6.2 Extravehicular Activity Systems**	**6.2 Extravehicular Activity Systems**
	6.2.1 Pressure Garment	6.2.1 Pressure Garment	6.2.1 Pressure Garment
	6.2.2 Portable Life Support System	6.2.2 Portable Life Support System	6.2.2 Portable Life Support System
	6.2.3 Power, Avionics, and Software	6.2.3 Power, Avionics, and Software	6.2.3 Power, Avionics and Software
	6.3 Human Health and Performance	**6.3 Human Health and Performance**	**6.3 Human Health and Performance**
	6.3.1 Medical Diagnosis and Prognosis	6.3.1 Medical Diagnosis/Prognosis	6.3.1 Medical Diagnosis/Prognosis
	6.3.2 Long-Duration Health	6.3.2 Long-Duration Health	6.3.2 Long-Duration Health
	6.3.3 Behavioral Health	6.3.3 Behavioral Health and Performance	6.3.3 Behavioral Health and Performance
	6.3.4 Human Factors	6.3.4 Human Factors and Performance	6.3.4 Human Factors and Performance

continued

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	6.4 Environmental Monitoring, Safety, and Emergency Response	**6.4 Environmental Monitoring, Safety, and Emergency Response**	**6.4 Environmental Monitoring, Safety and Emergency Response**
	6.4.1 Sensors: Air, Water, Microbial, and Acoustic	6.4.1 Sensors: Air, Water, Microbial, etc.	6.4.1 Sensors: Air, Water, Microbial, etc.
Revised-DNR	6.4.2 Fire: Detection, Suppression, and Recovery	6.4.2 Fire: Detection, Suppression	6.4.2 Fire: Detection, Suppression
	6.4.3 Protective Clothing and Breathing	6.4.3 Protective Clothing/Breathing	6.4.3 Protective Clothing/Breathing
	6.4.4 Remediation	6.4.4 Remediation	6.4.4 Remediation
	6.5 Radiation	**6.5 Radiation**	**6.5 Radiation**
	6.5.1 Risk Assessment Modeling	6.5.1 Risk Assessment Modeling	6.5.1 Risk Assessment Modeling
	6.5.2 Radiation Mitigation and Biological Countermeasures	6.5.2 Radiation Mitigation	6.5.2 Radiation Mitigation
	6.5.3 Protection Systems	6.5.3 Protection Systems	6.5.3 Protection Systems
	6.5.4 Space Weather Prediction	6.5.4 Radiation Prediction	6.5.4 Space Weather Prediction
	6.5.5 Monitoring Technology	6.5.5 Monitoring Technology	6.5.5 Monitoring Technology
	TA 7 Human Exploration Destination Systems	**TA 7 Human Exploration Destination Systems**	**TA 7 Human Exploration Destination Systems**
	7.1 In Situ Resource Utilization	**7.1 In Situ Resource Utilization**	**7.1 In Situ Resource Utilization**
	7.1.1 Destination Reconnaissance, Prospecting, and Mapping	7.1.1 Destination Reconnaissance, Prospecting, and Mapping	7.1.1 Destination Reconnaissance, Prospecting, and Mapping
	7.1.2 Resource Acquisition	7.1.2 Resource Acquisition	7.1.1.1 Resource Acquisition
	7.1.3 Processing and Production	7.1.3 ISRU Products/Production	7.1.2 Consumables Production
	7.1.4 Manufacturing Products and Infrastructure Emplacement	7.1.4 Manufacturing and Infrastructure Emplacement	7.1.3 Manufacturing and Infrastructure Emplacement
	7.2 Sustainability and Supportability	**7.2 Sustainability and Supportability**	**7.2 Sustainability and Supportability**
	7.2.1 Autonomous Logistics Management	7.2.1 Autonomous Logistics Management	7.2.1 Logistics Systems
	7.2.2 Maintenance Systems	7.2.2 Maintenance Systems	7.2.2 Maintenance Systems
	7.2.3 Repair Systems	7.2.3 Repair Systems	7.2.3 Repair Systems
	7.2.4 Food Production, Processing, and Preservation	7.2.4 Food Production, Processing, and Preservation	
	7.3 Human Mobility Systems	**7.3 Advanced Human Mobility Systems**	**7.3 Advanced Human Mobility Systems**
	7.3.1 EVA Mobility	7.3.1 EVA Mobility	7.3.1 EVA Mobility
	7.3.2 Surface Mobility	7.3.2 Surface Mobility	7.3.2 Surface Mobility
	7.3.3 Off-Surface Mobility	7.3.3 Off-Surface Mobility	7.3.3 Off-Surface Mobility
	7.4 Habitat Systems	**7.4 Advanced Habitat Systems**	**7.4 Advanced Habitat Systems**
	7.4.1 Integrated Habitat Systems	7.4.1 Integrated Habitat Systems	7.4.1 Integrated Habitat Systems
	7.4.2 Habitat Evolution	7.4.2 Habitat Evolution	7.4.2 Habitat Evolution

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	7.4.3 Smart Habitats	7.4.3 Smart Habitats	
New-Evaluate	7.4.4 Artificial Gravity		
	7.5 Mission Operations and Safety	**7.5 Mission Operations and Safety**	**7.5 Mission Operations and Safety**
Elsewhere	7.5.1 Crew Training	7.5.1 Crew Training	7.5.1 Crew Training
			7.5.2 Environmental Protection
Revived	7.5.2 Planetary Protection		7.5.4 Planetary Safety
	7.5.3 Integrated Flight Operations Systems	7.5.5 Integrated Flight Operations Systems	
Elsewhere	7.5.4 Integrated Risk Assessment Tools	7.5.6 Integrated Risk Assessment Tools	
			7.5.3 Remote Mission Operations
	7.6 Crosscutting Systems	**7.6 Crosscutting Systems**	**7.6 Crosscutting Systems**
	7.6.1 Particulate Contamination Prevention and Mitigation	7.6.3 Dust Prevention and Mitigation	7.6.3 Dust Prevention and Mitigation
	7.6.2 Construction and Assembly	7.6.2 Construction and Assembly	7.6.2 Construction and Assembly
			7.6.1 Modeling, Simulations and Destination Characterization
	TA 8 Science Instruments, Observatories, and Sensor Systems	**TA 8 Science Instruments, Observatories, and Sensor Systems**	**TA 8 Science Instruments, Observatories and Sensor Systems**
	8.1 Remote Sensing Instruments and Sensors	**8.1 Remote Sensing Instruments/Sensors**	**8.1 Remote Sensing Instruments/Sensors**
	8.1.1 Detectors and Focal Planes	8.1.1 Detectors and Focal Planes	8.1.1 Detectors and Focal Planes
	8.1.2 Electronics	8.1.2 Electronics	8.1.2 Electronics
	8.1.3 Optical Components	8.1.3 Optical Systems	8.1.3 Optical Components
	8.1.4 Microwave, Millimeter-, and Submillimeter-Waves	8.1.4 Microwave/Radio	8.1.4 Microwave/Radio
	8.1.5 Lasers	8.1.5 Lasers	8.1.5 Lasers
	8.1.6 Cryogenic/Thermal	8.1.6 Cryogenic/Thermal	8.1.6 Cryogenic/Thermal
		8.1.7 Space Atomic Interferometry	
Deleted	**8.2 Observatories**	**8.2 Observatories**	**8.2 Observatories**
Merged	8.2.1 Mirror Systems		8.2.1 Mirror Systems
	8.2.2 Structures and Antennas	8.2.2 Structures and Antennas	8.2.2 Structures and Antennas
	8.2.3 Distributed Aperture	8.2.3 Distributed Aperture	8.2.3 Distributed Aperture
Deleted		8.2.4 High Contrast Imaging and Spectroscopy Technologies	
Deleted		8.2.5 Wireless Spacecraft Technologies	
	8.3 In Situ Instruments and Sensors	**8.3 In Situ Instruments and Sensors**	**8.3 In Situ Instruments and Sensors**
	8.3.1 Field and Particle Detectors	8.3.1 Particles, Fields, and Waves: Charged and Neutral Particles, Magnetic and Electric Fields	8.3.1 Particles: Charged and Neutral
Elsewhere	8.3.2 Fields and Waves		8.3.2 Fields and Waves
	8.3.3 In Situ (other)	8.3.3 In Situ (Instruments and Sensors)	8.3.3 In Situ
		8.3.4 Surface Biology and Chemistry Sensors: Sensors to Detect and Analyze Biotic and Prebiotic Substances	

continued

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	TA 9 Entry, Descent, and Landing Systems	**TA 9 Entry, Descent, and Landing Systems**	**TA 9 Entry, Descent and Landing Systems**
	9.1 Aeroassist and Atmospheric Entry	**9.1 Aeroassist and Atmospheric Entry**	**9.1 Aeroassist and Atmospheric Entry**
	9.1.1 Thermal Protection Systems for Rigid Decelerators	9.1.1 Rigid Thermal Protection Systems	9.1.1 Rigid Thermal Protection Systems
	9.1.2 Thermal Protection Systems for Deployable Decelerators	9.1.2 Flexible Thermal Protection Systems	9.1.2 Flexible Thermal Protection Systems
	9.1.3 Rigid Hypersonic Decelerators	9.1.3 Rigid Hypersonic Decelerators	9.1.3 Rigid Hypersonic Decelerators
	9.1.4 Deployable Hypersonic Decelerators	9.1.4 Deployable Hypersonic Decelerators	9.1.4 Deployable Hypersonic Decelerators
Elsewhere	9.1.5 Instrumentation and Health Monitoring		9.1.5 Instrumentation and Health Monitoring
Elsewhere	9.1.6 Entry Modeling and Simulation		9.1.6 Entry Modeling and Simulation
	9.2 Descent and Targeting	**9.2 Descent**	**9.2 Descent**
	9.2.1 Attached Deployable Decelerators	9.2.1 Attached Deployable Decelerators	9.2.1 Attached Deployable Decelerators
	9.2.2 Trailing Deployable Decelerators	9.2.2 Trailing Deployable Decelerators	9.2.2 Trailing Deployable Decelerators
	9.2.3 Supersonic Retropropulsion	9.2.3 Supersonic Retropropulsion	9.2.3 Supersonic Retropropulsion
Elsewhere	9.2.4 GN&C Sensors		9.2.4 GN&C Sensors
Elsewhere	9.2.5 Descent Modeling and Simulation		9.2.5 Descent Modeling and Simulation
New-Evaluate	9.2.6 Large Divert Guidance		
New-Evaluate	9.2.7 Terrain-Relative Sensing and Characterization		
New-Evaluate	9.2.8 Autonomous Targeting		
	9.3 Landing	**9.3 Landing**	**9.3 Landing**
Revised-DNR	9.3.1 Propulsion and Touchdown Systems	9.3.1 Touchdown Systems	9.3.1 Touchdown Systems
Elsewhere	9.3.2 Egress and Deployment Systems	9.3.2 Egress and Deployment Systems	9.3.2 Egress and Deployment Systems
Elsewhere	9.3.3 Propulsion Systems	9.3.3 Propulsion Systems	9.3.3 Propulsion Systems
Elsewhere	9.3.4 Large-Body GN&C		9.3.4 Large-Body GN&C
Elsewhere	9.3.5 Small-Body Systems	9.3.5 Small-Body Systems	9.3.5 Small-Body Systems
Elsewhere	9.3.6 Landing Modeling and Simulation		9.3.6 Landing Modeling and Simulation
	9.4 Vehicle Systems	**9.4 Vehicle Systems Technology**	**9.4 Vehicle Systems Technology**
Elsewhere	9.4.1 Architecture Analysis		9.4.1 Architecture Analyses
Elsewhere	9.4.2 Separation Systems	9.4.2 Separation Systems	9.4.2 Separation Systems
Elsewhere	9.4.3 System Integration and Analysis	9.4.3 System Integration and Analyses	9.4.3 System Integration and Analyses
Elsewhere	9.4.4 Atmosphere and Surface Characterization	9.4.4 Atmosphere and Surface Characterization	9.4.4 Atmosphere and Surface Characterization
	9.4.5 Modeling and Simulation	9.4.5 EDL Modeling and Simulation	
	9.4.6 Instrumentation and Health Monitoring	9.4.6 Instrumentation and Health Monitoring	
Elsewhere	9.4.7 GN&C Sensors and Systems	9.4.7 GN&C Sensors and Systems	

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	TA 10 Nanotechnology	**TA 10 Nanotechnology**	**TA 10 Nanotechnology**
	10.1 Engineered Materials and Structures	**10.1 Engineered Materials and Structures**	**10.1 Engineered Materials and Structures**
Revised-DNR	10.1.1 Lightweight Structures	10.1.1 Lightweight Materials and Structures	10.1.1 Lightweight Structures
	10.1.2 Damage-Tolerant Systems	10.1.2 Damage Tolerant Systems	10.1.2 Damage Tolerant Systems
	10.1.3 Coatings	10.1.3 Coatings	10.1.3 Coatings
	10.1.4 Adhesives	10.1.4 Adhesives	10.1.4 Adhesives
	10.1.5 Thermal Protection and Control	10.1.5 Thermal Protection and Control	10.1.5 Thermal Protection and Control
	10.2 Energy Storage, Power Generation, and Power Distribution	**10.2 Energy Generation and Storage**	**10.2 Energy Generation and Storage**
	10.2.1 Energy Storage	10.2.2 Energy Storage	10.2.1 Energy Storage
	10.2.2 Power Generation	10.2.1 Energy Generation	10.2.2 Energy Generation
	10.2.3 Power Distribution	10.2.3 Energy Distribution	10.2.3 Energy Distribution
	10.3 Propulsion	**10.3 Propulsion**	**10.3 Propulsion**
	10.3.1 Propellants	10.3.1 Nanopropellants	10.3.1 Propellants
	10.3.2 Propulsion Components	10.3.2 Propulsion Systems	10.3.2 Propulsion Components
	10.3.3 In-Space Propulsion	10.3.3 In-Space Propulsion	10.3.3 In-Space Propulsion
	10.4 Sensors, Electronics, and Devices	**10.4 Sensors, Electronics, and Devices**	**10.4 Sensors, Electronics, and Devices**
	10.4.1 Sensors and Actuators	10.4.1 Sensors and Actuators	10.4.1 Sensors and Actuators
	10.4.2 Nanoelectronics	10.4.2 Electronics	10.4.2 Nanoelectronics
	10.4.3 Miniature Instruments and Instrument Components	10.4.3 Miniature Instrumentation	10.4.3 Miniature Instruments
	TA 11 Modeling, Simulation, Information Technology, and Processing	**TA 11 Modeling, Simulation, and Information Technology, and Processing**	**TA 11 Modeling, Simulation, Information Technology, and Processing**
	11.1 Computing	**11.1 Computing**	**11.1 Computing**
	11.1.1 Flight Computing	11.1.1 Flight Computing	11.1.1 Flight Computing
	11.1.2 Ground Computing	11.1.2 Ground Computing	11.1.2 Ground Computing
	11.2 Modeling	**11.2 Modeling**	**11.2 Modeling**
	11.2.1 Software Modeling and Model Checking	11.2.1 Software Modeling and Model-Checking	11.2.1 Software Modeling and Model-Checking
	11.2.2 Integrated Hardware and Software Modeling	11.2.2 Integrated Hardware and Software Modeling	11.2.2 Integrated Hardware and Software Modeling
	11.2.3 Human–System Performance Modeling	11.2.3 Human–System Performance Modeling	11.2.3 Human–System Performance Modeling
	11.2.4 Science Modeling	11.2.4a Science Modeling and Simulation	11.2.4 Science and Engineering Modeling
Deleted		11.2.4b Aerospace Engineering Modeling and Simulation	
	11.2.5 Frameworks, Languages, Tools, and Standards	11.2.5 Frameworks, Languages, Tools, and Standards	11.2.5 Frameworks, Languages, Tools and Standards
New-Evaluate	11.2.6 Analysis Tools for Mission Design		
	11.3 Simulation	**11.3 Simulation**	**11.3 Simulation**
	11.3.1 Distributed Simulation	11.3.1 Distributed Simulation	11.3.1 Distributed Simulation
	11.3.2 Integrated System Life-Cycle Simulation	11.3.2 Integrated System Life-Cycle Simulation	11.3.2 Integrated System Life-Cycle Simulation

continued

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	11.3.3 Simulation-Based Systems Engineering	11.3.3 Simulation-Based Systems Engineering	11.3.3 Simulation-Based Systems Engineering
	11.3.4 Simulation-Based Training and Decision Support Systems	11.3.4 Simulation-Based Training and Decision Support Systems	11.3.4 Simulation-Based Training and Decision Support Systems
New-Evaluate	11.3.5 Exascale Simulation		
New-Evaluate	11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods		
New-Evaluate	11.3.7 Multiscale, Multiphysics, and Multifidelity Simulation		
New-Evaluate	11.3.8 Verification and Validation		
	11.4 Information Processing	**11.4 Information Processing**	**11.4 Information Processing**
	11.4.1 Science, Engineering, and Mission Data Life Cycle	11.4.1 Science, Engineering, and Mission Data Life Cycle	11.4.1 Science, Engineering and Mission Data Life Cycle
	11.4.2 Intelligent Data Understanding	11.4.2 Intelligent Data Understanding	11.4.2 Intelligent Data Understanding
	11.4.3 Semantic Technologies	11.4.3 Semantic Technologies	11.4.3 Semantic Technologies
	11.4.4 Collaborative Science and Engineering	11.4.4 Collaborative Science and Engineering	11.4.4 Collaborative Science and Engineering
	11.4.5 Advanced Mission Systems	11.4.5 Advanced Mission Systems	11.4.5 Advanced Mission Systems
New-Evaluate	11.4.6 Cyber Infrastructure		
New-Evaluate	11.4.7 Human–System Integration		
New-Evaluate	11.4.8 Cyber Security		
	TA 12 Materials, Structures, Mechanical Systems, and Manufacturing	**TA 12 Materials, Structures, Mechanical Systems, and Manufacturing**	**TA 12 Materials, Structures, Mechanical Systems, and Manufacturing**
	12.1 Materials	**12.1 Materials**	**12.1 Materials**
	12.1.1 Lightweight Structural Materials	12.1.1 Lightweight Structure	12.1.1 Lightweight Structure
	12.1.2 Computationally Designed Materials	12.1.2 Computational Design	12.1.2 Computational Design
	12.1.3 Flexible Material Systems	12.1.3 Flexible Material Systems	12.1.3 Flexible Material Systems
	12.1.4 Materials for Extreme Environments	12.1.4 Environment	12.1.4 Environment
	12.1.5 Special Materials	12.1.5 Special Materials	12.1.5 Special Materials
	12.2 Structures	**12.2 Structures**	**12.2 Structures**
	12.2.1 Lightweight Concepts	12.2.1 Lightweight Concepts	12.2.1 Lightweight Concepts
	12.2.2 Design and Certification Methods	12.2.2 Design and Certification Methods	12.2.2 Design and Certification Methods
	12.2.3 Reliability and Sustainment	12.2.3 Reliability and Sustainment	12.2.3 Reliability and Sustainment
	12.2.4 Test Tools and Methods	12.2.4 Test Tools and Methods	12.2.4 Test Tools and Methods
	12.2.5 Innovative, Multifunctional Concepts	12.2.5 Innovative, Multifunctional Concepts	12.2.5 Innovative, Multifunctional Concepts
	12.2.6 Loads and Environments	See 12.5.3	See 12.5.3

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	12.3 Mechanical Systems	**12.3 Mechanical Systems**	**12.3 Mechanical Systems**
	12.3.1 Deployables, Docking, and Interfaces	12.3.1 Deployables, Docking, and Interfaces	12.3.1 Deployables, Docking and Interfaces
	12.3.2 Mechanism Life Extension Systems	12.3.2 Mechanism Life Extension Systems	12.3.2 Mechanism Life Extension Systems
	12.3.3 Electromechanical, Mechanical, and Micromechanisms	12.3.3 Electromechanical, Mechanical, and Micromechanisms	12.3.3 Electromechanical, Mechanical and Micromechanisms
	12.3.4 Design and Analysis Tools and Methods	12.3.4 Design and Analysis Tools and Methods	12.3.4 Design and Analysis Tools and Methods
	12.3.5 Reliability, Life Assessment, and Health Monitoring	12.3.5 Reliability/Life Assessment/Health Monitoring	12.3.5 Reliability/Life Assessment/Health Monitoring
	12.3.6 Certification Methods	12.3.6 Certification Methods	12.3.6 Certification Methods
	12.4 Manufacturing	**12.4 Manufacturing**	**12.4 Manufacturing**
	12.4.1 Manufacturing Processes	12.4.1 Manufacturing Processes	12.4.1 Manufacturing Processes
	12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems	12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems	12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems
	12.4.3 Electronics and Optics Manufacturing Process	12.4.3 Electronics and Optics Manufacturing Process	12.4.3 Electronics and Optics Manufacturing Process
	12.4.4 Sustainable Manufacturing	12.4.4 Sustainable Manufacturing	12.4.4 Sustainable Manufacturing
	12.4.5 Nondestructive Evaluation and Sensors	See 12.5.1	See 12.5.1
	12.5 Crosscutting	**12.5 Crosscutting**	**12.5 Crosscutting**
	12.5.1 Renumbered as 12.4.5	12.5.1 Nondestructive Evaluation and Sensors	12.5.1 Nondestructive Evaluation and Sensors
Deleted		12.5.2 Model-Based Certification and Sustainment Methods	12.5.2 Model-Based Certification and Sustainment Methods
	12.5.3 Renumbered as 12.2.6	12.5.3 Loads and Environments	12.5.3 Loads and Environments
	TA 13 Ground and Launch Systems	**TA 13 Ground and Launch Systems Processing**	**TA 13 Ground and Launch Systems Processing**
	13.1 Operational Life Cycle	**13.1 Technologies to Optimize the Operational Life Cycle**	**13.1 Technologies to Optimize the Operational Life Cycle**
	13.1.1 On-Site Production, Storage, Distribution, and Conservation of Fluids	13.1.1 Storage, Distribution, and Conservation of Fluids	13.1.1 Storage, Distribution and Conservation of Fluids
	13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems	13.1.2 Automated Alignment, Coupling, and Assembly Systems	13.1.2 Automated Alignment, Coupling, and Assembly Systems
	13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems	13.1.3 Autonomous Command and Control for Ground and Integrated Vehicle/Ground Systems	13.1.3 Autonomous Command and Control for Ground and Integrated Vehicle/Ground Systems
New-Evaluate	13.1.4 Logistics		
	13.2 Environmental Protection and Green Technologies	**13.2 Environmental and Green Technologies**	**13.2 Environmental and Green Technologies**
	13.2.1 Corrosion Prevention, Detection, and Mitigation	13.2.1 Corrosion Prevention, Detection, and Mitigation	13.2.1 Corrosion Prevention, Detection, and Mitigation
	13.2.2 Environmental Remediation and Site Restoration	13.2.2 Environmental Remediation and Site Restoration	13.2.2 Environmental Remediation and Site Restoration

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TABLE B.1 Continued

2015 vs 2012 Comparison	TABS: NASA July 2015 Draft	TABS: 2012 NRC Report	TABS: NASA 2010 Draft (rev 10)
	13.2.3 Preservation of Natural Ecosystems	13.2.3 Preservation of Natural Ecosystems	13.2.3 Preservation of Natural Ecosystems
	13.2.4 Alternate Energy Prototypes	13.2.4 Alternate Energy Prototypes	13.2.4 Alternate Energy Prototypes
New-Evaluate	13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms		
	13.3 Reliability and Maintainability	**13.3 Technologies to Increase F460**	**13.3 Technologies to Increase Reliability and Mission Availability**
Revised-DNR	13.3.1 Launch Infrastructure	13.3.1 Advanced Launch Technologies	13.3.1 Advanced Launch Technologies
	13.3.2 Environment-Hardened Materials and Structures	13.3.2 Environment-Hardened Materials and Structures	13.3.2 Environment-Hardened Materials and Structures
	13.3.3 On-Site Inspection and Anomaly Detection and Identification	13.3.3 Inspection, Anomaly Detection, and Identification	13.3.3 Inspection, Anomaly Detection, and Identification
	13.3.4 Fault Isolation and Diagnostics	13.3.4 Fault Isolation and Diagnostics	13.3.4 Fault Isolation and Diagnostics
	13.3.5 Prognostics	13.3.5 Prognostics Technologies	13.3.5 Prognostics Technologies
	13.3.6 Repair, Mitigation, and Recovery Technologies	13.3.6 Repair, Mitigation, and Recovery Technologies	13.3.6 Repair, Mitigation, and Recovery Technologies
	13.3.7 Communications, Networking, Timing, and Telemetry	13.3.7 Communications, Networking, Timing, and Telemetry	13.3.7 Communications, Networking, Timing and Telemetry
New-Evaluate	13.3.8 Decision-Making Tools		
	13.4 Mission Success	**13.4 Technologies to Improve Mission Safety/ Mission Risk**	**13.4 Technologies to Improve Mission Safety/ Mission Risk**
	13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies	13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies	13.4.1 Range Tracking, Surveillance and Flight Safety Technologies
	13.4.2 Landing and Recovery Systems and Components	13.4.2 Landing and Recovery Systems and Components	13.4.2 Landing and Recovery Systems and Components
	13.4.3 Weather Prediction and Mitigation	13.4.3 Weather Prediction and Mitigation	13.4.3 Weather Prediction and Mitigation
Elsewhere	13.4.4 Robotics and Telerobotics	13.4.4 Robotics/TeleRobotics	13.4.4 Robotics/Telerobotics
	13.4.5 Safety Systems	13.4.5 Safety Systems	13.4.5 Safety Systems
	TA 14 Thermal Management Systems	**TA 14 Thermal Management Systems**	**TA 14 Thermal Management Systems**
	14.1 Cryogenic Systems	**14.1 Cryogenic Systems**	**14.1 Cryogenic Systems**
	14.1.1 Passive Thermal Control	14.1.1 Passive Thermal Control	14.1.1 Passive Thermal Control
	14.1.2 Active Thermal Control	14.1.2 Active Thermal Control	14.1.2 Active Thermal Control
Elsewhere	14.1.3 Integration and Modeling	14.1.3 Systems Integration	14.1.3 Integration and Modeling
	14.2 Thermal Control Systems	**14.2 Thermal Control Systems**	**14.2 Thermal Control Systems**
	14.2.1 Heat Acquisition	14.2.1 Heat Acquisition	14.2.1 Heat Acquisition
	14.2.2 Heat Transport	14.2.2 Heat Transfer	14.2.2 Heat Transfer
	14.2.3 Heat Rejection and Energy Storage	14.2.3 Heat Rejection and Energy Storage	14.2.3 Heat Rejection and Energy Storage

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	14.3 Thermal Protection Systems	**14.3 Thermal Protection Systems**	**14.3 Thermal Protection Systems**
	14.3.1 Ascent/Entry TPS	14.3.1 Ascent/Entry TPS	14.3.1 Entry/Ascent TPS
Revised-Evaluate	14.3.2 TPS Modeling and Simulation	14.3.2 Plume Shielding (Convective and Radiative)	14.3.2 Plume Shielding (Convective and Radiative)
	14.3.3 TPS Sensors and Measurement Systems	14.3.3 Sensor Systems and Measurement Technologies	14.3.3 Sensor Systems and Measurement Technologies
n/a	**TA 15 Aeronautics**		

NOTE: NASA's 2015 TABS includes a new TA 15, Aeronautics. However, that technology area is outside the scope of this study and so the technologies for TA 15 do not appear in Table B.1.

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C

2012 Review and Prioritization Methodology

The steering committee and panels that authored the 2012 report by the National Research Council (NRC), *NASA Space Technology Roadmaps and Priorities,* used a two-step process to prioritize technologies in NASA's 2010 draft roadmaps. First, they identified 83 high-priority technologies. The steering committee then examined those 83 technologies in more detail to identify technologies that should be considered to be of the highest priority. This appendix describes the prioritization process using text taken from Chapters 2 and 3 of the 2012 report.

2012 NRC REPORT: PROCESS TO IDENTIFY THE HIGH-PRIORITY TECHNOLOGIES

A set of criteria was established by the steering committee to enable the prioritization of technologies within each and, ultimately, among all of the technology areas of the NASA technology roadmaps. These criteria were chosen to capture the potential benefits, breadth, and risk of the various technologies and were used as a guide by both the panels and the steering committee to determine the final prioritization of the technologies. In addition to the primary criteria used to prioritize the technologies, an additional set of secondary descriptive factors were also assessed for each technology. These descriptive factors were added to provide a complete picture of the panels' assessments of the technologies and assisted in the evaluations.

Broad community input was solicited through a public website, where more than 240 public comments were received on the draft roadmaps using the established steering committee criteria and other descriptive factors. The public and panels were given the same rubrics to evaluate the technologies so that the various inputs could be more fairly compared against each other. These views, along with those expressed during the public workshops, were taken into account by the panel members as they assessed the technologies. The panels then came to a consensus view for each criterion for each technology.

In evaluating and prioritizing the technologies identified, the steering committee made a distinction between technology development and engineering development. Technology development, which is the intended focus of the draft roadmaps, addresses the process of understanding and evaluating capabilities needed to improve or enable performance advantages over current state-of-the-art space systems. Technologies of interest include both hardware and software, as well as testing and evaluation of hardware (from the component level to the systems level) and software (including design tools) at various levels of technology readiness for application in future space systems. In contrast, engineering development, which generally attempts to implement and apply existing or available technology, is understood for the purposes of this study to be hardware, software, design, test, verification, and

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validation of systems in all phases of NASA's acquisition process. The high-priority technologies do not include items for which engineering development is the next step in advancing capabilities.

Top Technical Challenges

When the 2012 report was prepared, the NASA design reference missions were not available, so as a substitute the panels identified a number of challenges for each technology area that should be addressed for NASA to improve its capability to achieve its mission objectives.[1] These top technical challenges were generated to provide some focus for technology development and to assist in the prioritization of the level 3 technologies. The challenges were developed to identify the general needs NASA has within each technology area, whereas the technologies themselves address how those needs will be met. Once the top technical challenges were identified, the panels then determined the relative importance of the challenges within each technology area to put them in priority order.

Descriptive Factors

The steering committee identified three descriptive factors that helped characterize each technology. Although these factors were not primary in the determination of technology prioritization, they did assist in generating a better understanding of the current status or state of the art of the technology.

- **Technology Readiness Level (TRL):** This factor describes the current state of advancement of the technology using NASA's TRL scale.[2] It was determined that TRL should not be a basis for prioritizing technologies, because NASA should be investing across all levels of technology readiness. In assessing TRL levels, the panels were directed to evaluate the most promising developments that should receive attention. For example, electric propulsion systems are commonly used today, so as a whole, they would be assessed as TRL 9; however, the promising area of advancement of high power electric propulsion is less advanced, and thus 2.2.1 Electric Propulsion was assessed as TRL 3.
- **Tipping Point:** The tipping point factor was used to determine whether the technology was at a state such that a relatively small additional effort (compared to that which advanced the technology to its current state) could produce a significant advance in technology readiness that would justify increasing the priority associated with this technology.
- **NASA Capabilities:** This factor captured how NASA research in this technology aligns with the expertise, capabilities, and facilities of NASA and/or other organizations cooperating with NASA in this area. It also indicated how much value NASA research in this technology would add to ongoing research by other organizations. This was not a primary consideration in assessing which technologies should be prioritized. Instead it was a factor in considering whether the technology should be developed by NASA, or whether NASA should support other current efforts. The factor also addressed whether NASA should invest in improving its own capability for pursuing the high-priority technologies.

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[1] Design reference missions in the 2015 NASA roadmaps appear in the first volume of the roadmaps, NASA, 2015, *NASA Technology Roadmaps: Introduction, Crosscutting Technologies, and Index*, May 2015 Draft, http://www.nasa.gov/offices/oct/home/roadmaps/index.html, accessed June 29, 2016, pp. i-46.

[2] NASA's technology readiness levels are as follows:

TRL 1 Basic principles observed and reported.
TRL 2 Technology concept and/or application formulated.
TRL 3 Analytical and experimental critical function and/or characteristic proof of concept.
TRL 4 Component and/or breadboard validation in laboratory environment.
TRL 5 Component and/or breadboard validation in relevant environment.
TRL 6 System/subsystem model or prototype demonstration in a relevant environment.
TRL 7 System prototype demonstration in an operational environment.
TRL 8 Actual system competed and flight qualified through test and demonstration.
TRL 9 Actual system flight proven through successful mission operations

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Evaluation Criteria

The steering committee identified three main criteria on which the technologies were to be judged for evaluation. The three criteria were benefit, alignment with NASA's goals and objectives, and technical risk and challenge. Each of these is described in further detail below. For the latter two criteria, three further subcriteria were created to assist in evaluating the technologies.

For each evaluated criterion or subcriterion, a set of four (or in one case five) grades or bins were established, and the public and panel members were asked to determine what grade each technology should receive for that criterion. For consistency, a set of definitions were generated for each grade. The grading definitions were provided as guidelines to help the panel and steering committee members assign an appropriate range of grades necessary to prioritize the technologies in question. They were generated such that most technologies would be placed into one of the middle bins, while placement at the upper/lower bounds would need significant justification. The grades were assigned numeric scores on a nonlinear scale (e.g., 0-1-3-9) to accentuate the spread of the summed final scores. Higher numeric scores implied greater ability to meet NASA's goals. Negative numbers indicated characteristics that were not desirable.

Benefit: Would the technology provide game-changing, transformational capabilities in the timeframe of the study? What other enhancements to existing capabilities could result from development of this technology?

1. *The technology is unlikely to result in a significant improvement in performance or reduction in life cycle cost of missions during the next 20 years. Score: 0*
2. *The technology is likely to result in (a) a minor improvement in mission performance (e.g., less than a 10 percent reduction in system launch mass); (b) a minor improvement in mission life cycle cost; or (c) less than an order of magnitude increase in data or reliability of missions during the next 20 years. Score: 1*
3. *The technology is likely to result in (a) a major improvement in mission performance (e.g., a 10 percent to 30 percent reduction in mass) or (b) a minor improvement in mission life cycle cost or an order of magnitude increase in data or reliability of missions during the next 20 years. Score: 3*
4. *The technology is likely to provide game-changing, transformational capabilities that would enable important new projects or missions that are not currently feasible during the next 20 years. Score: 9*

Alignment: Three subcriteria were created to evaluate the alignment with NASA's goals and objectives criterion.

Alignment with NASA Needs: How does NASA research in this technology improve NASA's ability to meet its long-term needs? For example, which mission areas and which missions listed in the relevant roadmap would directly benefit from development of this technology, and what would be the nature of that impact? What other planned or potential missions would benefit?

1. *Technology is not directly applicable to NASA. Score: 0*
2. *Technology will impact one mission in one of NASA's mission areas. Score: 1*
3. *Technology will impact multiple missions in one of NASA's mission areas. Score: 3*
4. *Technology will impact multiple missions in multiple NASA mission areas. Score: 9*

Alignment with Non-NASA Aerospace Technology Needs: How does NASA research in this technology improve NASA's ability to address non-NASA aerospace technology needs?

1. *Little or no impact on aerospace activities outside of NASA's specific needs. Score: 0*
2. *Impact will be limited to niche roles. Score 1*
3. *Will impact a large subset of aerospace activities outside of NASA's specific needs (e.g., commercial spacecraft). Score: 3*
4. *Will have a broad impact across the entire aerospace community. Score: 9*

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Alignment with Non-Aerospace National Goals: How well does NASA research in this technology improve NASA's ability to address national goals from broader national perspective (e.g., energy, transportation, health, environmental stewardship, or infrastructure)?

1. *Little or no impact outside the aerospace industry. Score: 0*
2. *Impact will be limited to niche roles. Score: 1*
3. *Will be useful to a specific community outside aerospace (e.g., medicine). Score: 3*
4. *Will be widely used outside the aerospace community (e.g., energy generation or storage). Score: 9*

Technical Risk and Challenge*:* Three subcriteria were created to evaluate the technical risk and challenge criterion. In this criterion, the grades created were not as straightforward as those for benefit and alignment. They were developed to capture the steering committee's view on the appropriate risk posture for NASA technology developments.

Technical Risk and Reasonableness: What is the overall nature of the technical risk and/or the reasonableness that this technology development can succeed in the timeframe envisioned? Is the level of risk sufficiently low that industry could be expected to complete development of this technology without a dedicated NASA research effort, or is it already available for commercial or military applications? Regarding the expected level of effort and timeframe for technology development: (a) are they believable given the complexity of the technology and the technical challenges to be overcome; and (b) are they reasonable given the envisioned benefit vis-à-vis possible alternate technologies?

1. *The technical risk associated with development of this technology is very low, such that it is feasible for industry or a specific NASA mission office to complete development (without additional NASA technology funding if a mission need arises). Score: 1*
2. *The technical risk associated with development of this technology is low, and the likely cost to NASA and the timeframe to complete technology development are not expected to substantially exceed those of past efforts to develop comparable technologies. Score: 3*
3. *The technical risk associated with development of this technology is moderate to high, which is a good fit to NASA's level of risk tolerance for technology development, but the likely cost to NASA and the timeframe to complete technology development are expected to substantially exceed those of past efforts to develop comparable technologies. Score: 3*
4. *The technical risk associated with development of this technology is moderate to high, which is a good fit to NASA's level of risk tolerance for technology development, and the likely cost to NASA and the timeframe to complete technology development are not expected to substantially exceed those of past efforts to develop comparable technologies. Score: 9*
5. *The technical risk associated with development of this technology is extremely high, such that it is unreasonable to expect any operational benefits over the next 20 years without unforeseen revolutionary breakthroughs and/or an extraordinary level of effort. Score: 1*

Sequencing and Timing: Is the proposed timing of the development of this technology appropriate relative to when it will be needed? What other new technologies are needed to enable the development of this technology, have they been completed, and how complex are the interactions between this technology and other new technologies under development? What other new technologies does this technology enable? Is there a good plan for proceeding with technology development? Is the technology development effort well connected with prospective users?

1. *This is an extremely complex technology and/or is highly dependent on multiple other projects with interfaces that are not well thought out or understood. Score: –9*
2. *The development of this technology is just roughly sketched out and there are no clearly identified users (i.e., missions). Score: –3*

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3. *There is a clear plan for advancing this technology. While there is an obvious need, there are no specifically identified users. Score: –1*
4. *There is a clear plan for advancing this technology, there is an obvious need, and joint funding by a user seems likely. Score: +1*

Time and Effort to Achieve Goals: How much time and what overall effort are required to achieve the goals for this technology?

1. *National endeavor: Likely to require more than 5 years and substantial new facilities, organizations, and workforce capabilities to achieve; similar to or larger in scope than the Shuttle, Manhattan Project, or Apollo Program. Score: –9*
2. *Major project: Likely to require more than 5 years and substantial new facilities to achieve; similar in scope to development of the Apollo heat shield or the Orion environmental systems. Score: –3*
3. *Moderate effort: Can be achieved in less than 5 years with a moderately sized (less than 50 people) team (e.g., Mars Pathfinder's airbag system). Score: –1*
4. *Minimal effort: Can be achieved in a few years by a very small (less than 10 people) team (e.g., graduate student/faculty university project). Score: 0*

Evaluation Methodology

The individual panels were tasked with binning the individual technologies into high, medium, and low priority for level 3 technologies. This was done primarily by grading the technologies using the criteria described above. The panels generated a weighted decision matrix based on quality function deployment (QFD) techniques for each technology area. In this method, each criterion was given a numerical weight by the steering committee, described below. By multiplying the panel grades by the criteria weighting factor and summing the results, a single score was calculated for each technology.

The steering committee based the criteria weighting on the importance of the criteria to meeting NASA's goals of technology advancement. It determined that the potential benefit of the technology was the most important factor in prioritizing, with the risk and challenges being second, and alignment being third in importance of the three main criteria. To allow for weighting at the subcriteria level, the steering committee assigned a total weighting of 9 to alignment, 18 to risk and challenges, and 27 to benefits. It then divided those values among the subcriteria to generate the values shown in Table C.1.

This method provided an initial assessment of how technologies met NASA's goals via the criteria evaluation. After each panel came to a consensus on the grades for all criteria for each technology, a total QFD score was computed for each technology. Consider the example shown in Figure C.1. The QFD score for technology 1.1.1, Propellants, is computed using the score for each criterion and the corresponding multiplier as follows:

$$(1 \times 27) + (3 \times 5) + (3 \times 2) + (0 \times 2) + (3 \times 10) - (1 \times 4) - (1 \times 4) = 70$$

The technologies were then sorted by their total QFD scores. In Figure C.1, technology 1.3.1, TBCC, has the highest score, and thus it is the highest priority of the three technologies shown.

Once the panels had ordered the technologies by their total scores, they then divided the list into high-, medium-, and low-priority technology groups.[3] This division was subjectively performed by each panel for each technology area for which it was responsible, seeking where possible natural break points. For instance, in the case of the

[3] The panels were tasked with designating each technology as high, medium, or low priority only. Chapter 2 contains a figure for each technology area that lists technologies by QFD score, in descending order; this sequencing may be considered a rough approximation of the relative priority of the technologies within each technology area. Also, this ordering places the override technologies (which were designated as high priority despite their relatively low QFD scores) as least among the high-priority technologies, although that is not necessarily the case.

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TABLE C.1 Numerical Weighting Factors Given to Evaluation Criteria in Panel Assessments

Criterion	Numerical Weight
Benefit (27)	27
Alignment (9)	
Alignment with NASA needs	5
Alignment with non-NASA aerospace needs	2
Alignment with non-aerospace national goals	2
Technical Risk and Challenge (18)	
Technical risk and reasonableness	10
Sequencing and timing	4
Time and effort	4

	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	Priority
Multiplier	27	5	2	2	10	4	4		
	0/1/3/9	0/1/3/9	0/1/3/9	0/1/3/9	1/3/9	-9/-3/-1/1	-9/-3/-1/0		
Technology Name	**Benefit**	**Alignment**			**Risk/Difficulty**				
1.1.1. (Solid Rocket) Propellants	1	3	3	0	3	-1	-1	70	L
1.2.1. LH2/LOX Based	1	9	9	0	3	1	-3	112	M
1.3.1. Turbine Based Combined Cycle (TBCC)	3	9	9	0	3	-3	-3	150	H

FIGURE C.1 Sample QFD matrix, showing three technologies from TA 1 and their resulting QFD scores.

assessment of TA1, the panel decided that the split between high- and medium-priority technologies should occur at a score of 150, and that the split between medium- and low-priority technologies should occur at a score of 90.

To add flexibility to the assessment process, the panels were also given the option of identifying key technologies that they believed should be high priority but that did not have a numerical score that achieved a high priority rank. These override technologies were deemed by the panels to be high priority irrespective of the numerical scores. As such, by allowing the panels to use this override provision, the numerical scoring process could be used effectively without the evaluation becoming a slave to it. In the summary tables for each technology area, the override technologies are designated by "H*".

Based on the raw QFD scoring of the 295 level 3 technologies, 64 were initially classified as high priority, 128 as medium priority, and 103 as low priority. The panels subsequently decided to override the QFD scores to elevate 18 medium-priority technologies and 1 low-priority technology (6.4.4 Remediation) to the high-priority group. The final result was to have 83 high-priority technologies, 110 medium-priority technologies, and 102 low-priority technologies. The steering committee believes that the results of the panel scoring validate the design of the QFD scoring process and the decision to allow the panels to override those scores as appropriate.

The panels also assessed which of the technologies have the greatest chance of meeting the identified top technical challenges. While many of the technologies within a technology area could potentially address one or more of the challenges, the panels only labeled those where investment would have a major or moderate impact.

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This assessment was used to verify the proper identification of the high-priority technologies and occasionally as validation for using the override option.

2012 NRC REPORT: PROCESS TO IDENTIFY THE HIGHEST-PRIORITY TECHNOLOGIES

In prioritizing the 83 technologies evaluated as high-priority by the panels across all 14 draft roadmaps, the steering committee established an organizing framework that addressed balance across NASA mission areas; relevance in meeting the highest-priority technical challenges; and expectations that significant progress could be made in the next 5 years of the 30-year window of the roadmaps. Furthermore, the steering committee constrained the number of highest-priority technologies recommended in the final list in the belief that in the face of probable scarce resources, focusing initially on a small number of the highest-priority technologies offers the best chance to make the greatest impact, especially while agency mission areas, particularly in exploration, are being refined and can be shaped by technology options. Within this organizing framework, technology objectives were defined by the steering committee to address the breadth of NASA missions and group related technologies.

Technology Objectives

The 2011 NASA Strategic Plan[4] states:

> New in this 2011 Strategic Plan is a strategic goal that emphasizes the importance of supporting the underlying capabilities that enable NASA's missions.

The steering committee interpreted this formulation of NASA's strategic vision as the need to assess the technologies by the measure of how well they supported NASA's various missions.

The question became one of identifying the totality of NASA's missions that were all-inclusive of the agency's responsibilities and yet easily distinguished by the type of technologies needed to support them. The steering committee defined the following technology objectives to serve as an organizing framework for prioritization of technical challenges and roadmap technologies.

Technology Objective A, Human Space Exploration: Extend and sustain human activities beyond low Earth orbit.

Supporting technologies would enable humans to survive long voyages throughout the solar system, get to their chosen destination, work effectively, and return safely.

This objective includes a major part of NASA's mission to send humans beyond the protection of the Van Allen belts, mitigate the effects of space radiation and long exposure to the microgravity environment, enable the crew to accomplish the goals of the mission (contained in Technology Objective B), and then return to Earth safely. This objective includes using the International Space Station (ISS) for technology advancement to support future human space exploration, providing opportunities for commercial companies to offer services to low Earth orbit and beyond, and developing the launch capability required for safe access to locations beyond low Earth orbit.

Technology Objective B, In Situ Measurements: Explore the evolution of the solar system and the potential for life elsewhere.

Supporting technologies would enable humans and robots to perform in situ measurements on Earth (astrobiology) and on other planetary bodies.

This objective is concerned with the in situ analysis of planetary bodies in the solar system. It includes the detailed analysis of the physical and chemical properties and processes that shape planetary environments and

[4] *2011 NASA Strategic Plan*, NASA, 2011, p. 4.

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the study of the geologic and biological processes that explain how life evolved on Earth and whether it exists elsewhere. It involves development of instruments for in situ measurements and the associated data analysis. This objective includes all the in situ aspects of planetary science; measurement of interior properties, atmospheres, particles, and fields of planets, moons, and small bodies; and methods of planetary protection.

Technology Objective C, Remote Measurements:
Expand our understanding of Earth and the universe in which we live.

Supporting technologies would enable remote measurements from platforms that orbit or fly by Earth and other planetary bodies, and from other in-space and ground-based observatories.

This objective includes astrophysics research; stellar, planetary, galactic, and extra-galactic astronomy; particle astrophysics and fundamental physics related to astronomical objects; solar and heliospheric physics; and magnetospheric physics and solar-planetary interactions. This objective also includes space-based observational Earth-system science and applications aimed at improving our understanding of Earth and its responses to natural and human-induced changes. This objective includes all space science activities that rely on measurements obtained remotely from various observational platforms.

These objectives are not independent and are often shared by a single mission (e.g., humans to explore planetary bodies or to service observatories, as was the case with the Hubble Space Telescope), and there are technologies that support more than one of these objectives (e.g., multifunctional structures, electric propulsion, GN&C). Yet this taxonomy is a useful way to categorize NASA's responsibilities as described in its strategic plan and serves to prioritize the various technologies and technical challenges identified in this study.

Grouped Technologies

The steering committee determined that, in several instances, technologies on the original list of 83 high-priority technologies that were highly ranked in the final prioritization process were also highly coupled. During the prioritization process, these highly coupled technologies were grouped together and considered as one unit. There are a total of five grouped technologies (designated X.1 through X.5). Each one consists of 3 to 5 original technologies as follows:

- X.1, Radiation Mitigation for Human Spaceflight
  - 6.5.1, Radiation Risk Assessment Modeling
  - 6.5.2, Radiation Mitigation
  - 6.5.3, Radiation Protection Systems
  - 6.5.4, Radiation Prediction
  - 6.5.5, Radiation Monitoring Technology
- X.2, Lightweight and Multifunctional Materials and Structures
  - 10.1.1, (Nano) Lightweight Materials and Structures
  - 12.1.1, Materials: Lightweight Structures
  - 12.2.1, Structures: Lightweight Concepts
  - 12.2.2, Structures: Design and Certification Methods
  - 12.2.5, Structures: Innovative, Multifunctional Concepts
- X.3, Environmental Control and Life Support System (ECLSS)
  - 6.1.1, Air Revitalization
  - 6.1.2, ECLSS Water Recovery and Management
  - 6.1.3, ECLSS Waste Management
  - 6.1.4, Habitation
- X.4, Guidance, Navigation, and Control (GN&C)
  - 4.6.2, Relative Guidance Algorithms
  - 5.4.3, Onboard Autonomous Navigation and Maneuvering

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9.4.7, GN&C Sensors and Systems (for Entry, Descent, and Landing)
X.5, Entry, Descent, and Landing (EDL) Thermal Protection Systems (TPS)
9.1.1, Rigid Thermal Protection Systems
9.1.2, Flexible thermal Protection Systems
14.3.1, Ascent/Entry TPS

Prioritizing Technologies Across Roadmaps

Utilizing the panel results, which established a high degree of correlation between high-priority level 3 technologies and the respective technical challenges for each roadmap, the steering committee was able to relate high-priority technologies that aligned with each of the three technology objectives. This organizing principle in turn helped categorize similar technologies with similar drivers (i.e., technologies driven by keeping humans alive, able to be productive, and transported; in situ measurements; and remote measurements) and enabled prioritization among them on a meaningful basis.

The process followed by the steering committee was as follows: First, the steering committee considered only the 83 high-priority level 3 technologies as selected by the panels. These 83 technologies are listed in Table C.2. Next, following the correlation procedure used by the panels, the steering committee mapped those technologies against the top technical challenges (See Table C.3) that it had identified for each of the three objectives. The correlation matrix for the technologies that were ultimately determined to have the highest priority and the top technical challenges for Technology Objectives A, B, and C are shown in Tables C.4, C.5, and C.6, respectively.

In many cases there is little correlation between particular technologies and the top technical challenges for one or more technical objectives. For example, technologies from roadmaps relating to human exploration or life support would have little correlation with Technology Objective C, which is focused primarily on remote measurements from observational platforms, except if servicing is done by astronauts. The correlation information was then used by the steering committee as it voted on the priority of technologies against the three objectives. Each steering committee member voted on the importance of each technology to each objective using a weighted scale:

0 = Not relevant;
1 = Minor importance;
3 = Significant; and
9 = Essential.

The total of the members' scores assigned to each technology was then summed to create a rank-ordered list of technologies for each technology objective. There were several iterations of voting and discussion first to develop an interim list of 11 to 13 technologies per objective (see Table C.7), followed by another iteration of voting and discussion to obtain a consensus on the final list of 7 or 8 technologies per objective (see Table C.8).

The robustness of the final results was tested by the steering committee in numerous ways. The steering committee used other weighting schemes (such as voting on top five technologies rather than using a 0-1-3-9 weighting factor) and other voting schemes (such as voting to remove technologies rather than voting to include them). Initially the steering committee had removed from the voting any technologies that were uncorrelated to any technical challenge; to make certain all technologies were properly considered, that constraint was relaxed and all 83 technologies were voted upon. In all cases, however, the changes to the methods had little or no impact on the final outcome.

The final short list of the highest-priority individual and grouped technologies is shown in ranked order in Table C.8, showing three columns with 16 technologies. The steering committee that authored the 2012 report assumed that NASA would pursue enabling technology related to all three objectives in a balanced approach, and the steering committee did not recommend or advocate support for one objective over another.

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NASA Space Technology Roadmaps and Priorities Revisited

TABLE C.2 The 83 High-Priority Level 3 Technologies from the 2012 NRC Report

TA 1	Launch Propulsion Systems
1.3.1	Turbine Based Combined Cycle (TBCC)
1.3.2	Rocket Based Combined Cycle (RBCC)
TA 2	In-Space Propulsion Technologies
2.2.1	Electric Propulsion
2.4.2	Propellant Storage and Transfer
2.2.3	(Nuclear) Thermal Propulsion
2.1.7	Micro-Propulsion
TA 3	Space Power and Energy Storage
3.1.3	Solar Power Generation (Photovoltaic and Thermal)
3.1.5	Fission Power Generation
3.3.3	Power Distribution and Transmission
3.3.5	Power Conversion and Regulation
3.2.1	Batteries
3.1.4	Radioisotope Power Generation
TA 4	Robotics, TeleRobotics, and Autonomous Systems
4.6.2	Relative Guidance Algorithms
4.6.3	Docking and Capture Mechanisms/Interfaces
4.5.1	Vehicle System Management and FDIR[a]
4.3.2	Dexterous Manipulation
4.4.2	Supervisory Control
4.2.1	Extreme Terrain Mobility
4.3.6	Robotic Drilling and Sample Processing
4.2.4	Small Body/Microgravity
TA 5	Communication and Navigation
5.4.3	Onboard Autonomous Navigation and Maneuvering
5.4.1	Timekeeping and Time Distribution
5.3.2	Adaptive Network Topology
5.5.1	Radio Systems
TA 6	Human Health, Life Support, and Habitation Systems
6.5.5	Radiation Monitoring Technology
6.5.3	Radiation Protection Systems
6.5.1	Radiation Risk Assessment Modeling
6.1.4	Habitation
6.1.3	Environmental Control and Life Support System (ECLSS) Waste Management
6.3.2	Long-Duration Crew Health
6.1.2	ECLSS Water Recovery and Management
6.2.1	Extravehicular Activity (EVA) Pressure Garment
6.5.4	Radiation Prediction
6.5.2	Radiation Mitigation
6.4.2	Fire Detection and Suppression
6.1.1	Air Revitalization
6.2.2	EVA Portable Life Support System
6.4.4	Fire Remediation
TA 7	Human Exploration Destination Systems
7.1.3	In Situ Resource Utilization (ISRU) Products/Production
7.2.1	Autonomous Logistics Management
7.6.2	Construction and Assembly
7.6.3	Dust Prevention and Mitigation
7.1.4	ISRU Manufacturing/Infrastructure Emplacement
7.1.2	ISRU Resource Acquisition
7.3.2	Surface Mobility
7.2.4	Food Production, Processing, and Preservation
7.4.2	Habitation Evolution
7.4.3	Smart Habitats
7.2.2	Maintenance Systems
TA 8	Science Instruments, Observatories, and Sensor Systems
8.2.4	High-Contrast Imaging and Spectroscopy Technologies
8.1.3	Optical Systems (Instruments and Sensors)
8.1.1	Detectors and Focal Planes
8.3.3	In Situ Instruments and Sensors
8.2.5	Wireless Spacecraft Technology
8.1.5	Lasers for Instruments and Sensors
8.1.2	Electronics for Instruments and Sensors
TA 9	Entry, Descent, and Landing (EDL) Systems
9.4.7	GN&C Sensors and Systems (EDL)[b]
9.1.1	Rigid Thermal Protection Systems
9.1.2	Flexible Thermal Protection Systems
9.1.4	Deployment Hypersonic Decelerators
9.4.5	EDL Modeling and Simulation
9.4.6	EDL Instrumentation and Health Monitoring
9.4.4	Atmospheric and Surface Characterization
9.4.3	EDL System Integration and Analysis
TA 10	Nanotechnology
10.1.1	(Nano) Lightweight Materials and Structures
10.2.1	(Nano) Energy Generation
10.3.1	Nanopropellants
10.4.1	(Nano) Sensors and Actuators
TA 11	Modeling, Simulation, Information Technology, and Processing
11.1.1	Flight Computing
11.1.2	Ground Computing
11.2.4a	Science Modeling and Simulation
11.3.1	Distributed Simulation
TA 12	Materials, Structures, Mechanical Systems, and Manufacturing
12.2.5	Structures: Innovative, Multifunctional Concepts
12.2.1	Structures: Lightweight Concepts
12.1.1	Materials: Lightweight Structure
12.2.2	Structures: Design and Certification Methods
12.5.1	Nondestructive Evaluation and Sensors
12.3.4	Mechanisms: Design and Analysis Tools and Methods
12.3.1	Deployables, Docking, and Interfaces
12.3.5	Mechanisms: Reliability/Life Assessment/Health Monitoring
12.4.2	Intelligent Integrated Manufacturing and Cyber Physical Systems
TA 14	Thermal Management Systems
14.3.1	Ascent/Entry Thermal Protection Systems
14.1.2	Active Thermal Control of Cryogenic Systems

continiued

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TABLE C.2 Continued

[a] Fault detection, isolation, and recovery.
[b] Guidance, navigation, and control.

NOTES:
1. Technologies are listed by roadmap/technology area (TA 1 through TA 14; there are no high-priority technologies in TA 13). Within each technology area, technologies are listed in descending order by the quality function deployment (QFD) score assigned by the panels that helped to author the 2012 report. This sequencing may be considered a rough approximation of the relative priority of the technologies within a given technology area.
2. Except for the five new technologies, the name of each technology in this table is as it appears in the original list of 83 high-priority technologies in the 2012 NRC report. In some cases, the names have been slightly revised for the 2015 TABS (see Appendix B). Two technologies have been deleted and do not appear in the 2015 TABS: 8.2.4, High Contrast Imaging and Spectroscopy Technologies, and 8.2.5, Wireless Spacecraft Technologies. Three technologies have been renumbered: 5.4.3, 11.2.4a, 12.5.1, above, have become 5.4.2, 11.2.4, and 12.4.5, respectively, in the 2015 TABS.

TABLE C.3 Top Technical Challenges for Technology Objectives A, B, and C

A. Extend and Sustain Human Activities Beyond Low Earth Orbit	B. Explore the Evolution of the Solar System and the Potential for Life Elsewhere (In Situ Measurements)	C. Expand Understanding of Earth and the Universe in Which We Live (Remote Measurements)
A1, Improved Access to Space	B1, Improved Access to Space	C1, Improved Access to Space
A2, Space Radiation Health Effects	B2, Precision Landing	C2, New Astronomical Telescopes
A3, Long-Duration Health Effects	B3, Robotic Maneuvering	C3, Lightweight Space Structures
A4, Long-Duration ECLSS	B4, Life Detection	C4, Increase Available Power
A5, Rapid Crew Transit	B5, High-Power Electric Propulsion	C5, Higher Data Rates
A6, Lightweight Space Structures	B6, Autonomous Rendezvous and Dock	C6, High-Power Electric Propulsion
A7, Increase Available Power	B7, Increase Available Power	C7, Design Software
A8, Mass to Surface	B8, Mass to Surface	C8, Structural Monitoring
A9, Precision Landing	B9, Lightweight Space Structures	C9, Improved Flight Computers
A10, Autonomous Rendezvous and Dock	B10, Higher Data Rates	C10, Cryogenic Storage and Transfer

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NASA Space Technology Roadmaps and Priorities Revisited

TABLE C.4 Linkages Between Highest-Priority Technologies and Top Technical Challenges for Technology Objective A, Human Space Exploration

Highest-priority individual and grouped technologies for Technology Objective A / Top Technical Challenge		Radiation Mitigation for Human Spaceflight (X.1)	Long-Duration (Crew) Health (6.3.2)	ECLSS (X. 3)	GN&C (X.4)	Thermal Propulsion (2.2.3)	Lightweight and Multifunctional Materials and Structures (X.2)	Fission (Power) (3.1.5)	EDL TPS (X.5)
1	Improved Access to Space						●		
2	Space Radiation Health Effects	●							
3	Long-Duration Health Effects		●						
4	Long-Duration ECLSS			●					
5	Rapid Crew Transit					●			
6	Lightweight Space Structures	●					●		
7	Increase Available Power							●	
8	Mass to Surface						●		●
9	Precision Landing				●				●
10	Autonomous Rendezvous and Dock				●				

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TABLE C.5 Linkages Between Highest-Priority Technologies and Top Technical Challenges for Technology Objective B, In Situ Measurements

Highest-priority individual and grouped technologies for Technology Objective B / Top Technical Challenge		GN&C (X.4)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)	Electric Propulsion (2.2.1)	Fission (Power) (3.1.5)	EDL TPS (X.5)	In Situ (Instruments and Sensors) (8.3.3)	Lightweight and Multifunctional Materials and Structures (X.2)	Extreme Terrain Mobility (4.2.1)
1	Improved Access to Space							●	
2	Precision Landing	●				●			
3	Robotic Surface Maneuvering	●							●
4	Life Detection						●		
5	High-Power Electric Propulsion			●					
6	Autonomous Rendezvous and Dock	●							
7	Increase Available Power		●		●				
8	Mass to Surface					●			
9	Lightweight Space Structures							●	
10	Higher Data Rates							●	

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TABLE C.6 Linkages Between Highest-Priority Technologies and Top Technical Challenges for Technology Objective C, Remote Measurements

Highest-priority individual and grouped technologies for Technology Objective C / Top Technical Challenge		(Instrument and Sensor) Optical Systems (8.1.3)	High-Contrast Imaging and Spectroscopy (8.2.4)	Detectors and Focal Planes (8.1.1)	Lightweight and Multifunctional Materials and Structures (X.2)	Active Thermal Control of Cryogenic Systems (14.1.2)	Electric Propulsion (2.2.1)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)
1	Improved Access to Space				●			
2	New Astronomical Telescopes	●	●	●				
3	Lightweight Space Structures				●			
4	Increase Available Power							●
5	Higher Data Rates				●			
6	High-Power Electric Propulsion						●	
7	Design Software							
8	Structural Monitoring				●			
9	Improved Flight Computers							
10	Cryogenic Storage and Transfer				●	●		

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NASA Space Technology Roadmaps and Priorities Revisited

TABLE C.7 Interim List of Highest-Priority Technologies, Ranked by Technology Objective, Comprising a Total of 27 Individual and Grouped Technologies, with 11 or 12 per Technology Objective

Highest-Priority Technologies for Technology Objective A, Human Space Exploration	Highest-Priority Technologies for Technology Objective B, In Situ Measurements	Highest-Priority Technologies for Technology Objective C, Remote Measurements
Radiation Mitigation for Human Spaceflight (X.1)	GN&C (X.4)	Optical Systems (Instruments and Sensors) (8.1.3)
Long-Duration (Crew) Health (6.3.2)	Electric Propulsion (2.2.1)	High-Contrast Imaging and Spectroscopy Technologies (8.2.4)
ECLSS (X.3)	Solar Power Generation (Photo-voltaic and Thermal) (3.1.3)	Detectors and Focal Planes (8.1.1)
GN&C (X.4)	In Situ (Instruments and Sensor) (8.3.3)	Lightweight and Multifunctional Materials and Structures (X.2)
Thermal Propulsion (2.2.3)	Fission Power Generation (3.1.5)	Radioisotope (Power) (3.1.4)
Fission (Power) (3.1.5)	Extreme Terrain Mobility (4.2.1)	Electric Propulsion (2.2.1)
Lightweight and Multifunctional Materials and Structures (X.2)	Lightweight and Multifunctional Materials and Structures (X.2)	Solar Power Generation (Photo-voltaic and Thermal) (3.1.3)
EDL TPS (X.5)	Radioisotope (Power) (3.1.4)	Science Modeling and Simulation (11.2.4a)
Atmosphere and Surface Characterization (9.4.4)	Robotic Drilling and Sample Handling (4.3.6)	Batteries (3.2.1)
Propellant Storage and Transfer (2.4.2)	EDL TPS (X.5)	Electronics (Instruments and Sensors) (8.1.2)
Pressure Garment (6.2.1)	Docking and Capture Mechanisms/ Interfaces (4.6.3)	Active Thermal Control of Cryogenic Systems (14.1.2)
		(Mechanisms) Reliability / Life Assessment / Health Monitoring (12.3.5)
		Vehicle System Management and FDIR (4.5.1)

NOTE: Shaded items do not appear in the final list in Table C.8.

TABLE C.8 Final List of Highest-Priority Technologies, Ranked by Technology Objective, Comprising a Total of 16 Individual and Grouped Technologies, with 7 or 8 per Technology Objective

Highest-Priority Technologies for Technology Objective A, Human Space Exploration	Highest-Priority Technologies for Technology Objective B, In Situ Measurements	Highest-Priority Technologies for Technology Objective C, Remote Measurements
Radiation Mitigation for Human Spaceflight (X.1)	GN&C (X.4)	Optical Systems (Instruments and Sensors) (8.1.3)
Long-Duration Crew Health (6.3.2)	Solar Power Generation (Photovoltaic and Thermal) (3.1.3)	High Contrast Imaging and Spectroscopy Technologies (8.2.4)
ECLSS (X.3)	Electric Propulsion (2.2.1)	Detectors and Focal Planes (8.1.1)
GN&C (X.4)	Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)
(Nuclear) Thermal Propulsion (2.2.3)	EDL TPS (X.5)	Active Thermal Control of Cryogenic Systems (14.1.2)
Lightweight and Multifunctional Materials and Structures (X.2)	In Situ Instruments and Sensors (8.3.3)	Electric Propulsion (2.2.1)
Fission Power Generation (3.1.5)	Lightweight and Multifunctional Materials and Structures (X.2)	Solar Power Generation (Photo-voltaic and Thermal) (3.1.3)
EDL TPS (X.5)	Extreme Terrain Mobility (4.2.1)	

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D

Committee Member Biographies

TODD J. MOSHER, *Co-Chair*, is the vice president of engineering for Syncroness, where he leads the Syncroness product development engineering organization in developing medical, aviation, and other commercial products. Dr. Mosher has 25 years of experience as an engineering professional working in industry and serving as a professor at two universities. He has directed the design of both human spaceflight and robotic spacecraft projects. Previously, Dr. Mosher was the senior director of strategic opportunities for Sierra Nevada Corporation's (SNC's) Space Exploration Systems business area within the Space Systems Group. In that role he led the formation of strategic partnerships with Lockheed Martin, United Launch Alliance, Draper Laboratory, Aerojet Rocketdyne, the Walt Disney Corporation, and Lucasfilm. He directed the proposal efforts for the next phase of the NASA Commercial Crew Program and NASA's next Commercial Resupply Services contracts with possible values of over $5 billion. Dr. Mosher successfully led the three previous NASA crew proposals, valued at over $350 million. Prior to that role, Dr. Mosher was the director of design and development for the Dream Chaser program, managing the design team for all of the major subsystems and a staff of over 100 SNC engineers and contractors while keeping design and development milestones on schedule and within budget. He has been recognized as one of *The Denver Post*'s Colorado Top Thinkers (2012) and received the University of Colorado's Kalpana Chawla Outstanding Recent Alumni award (2012). At SNC, he was awarded the Explorer's Cup Management Team Award (2012), the SNC Director of the Year (2011), and the STAR Award for Technical Excellence (2010). Dr. Mosher holds a Ph.D. and M.S. in aerospace engineering from the University of Colorado, an M.S. in systems engineering from the University of Alabama in Huntsville, and a B.S. in aerospace engineering from San Diego State University. He has served on multiple studies of the National Academies of Sciences, Engineering, and Medicine, including the Entry, Descent, and Landing area lead for the last Academies' study of the NASA technology portfolio.

LISELOTTE J. SCHIOLER, *Co-Chair*, is the founder of Schioler Consulting. She retired in early 2016 from the National Institute of Aerospace (NIA), where she was responsible for the Federal Aviation Administration (FAA) and non-NASA Langley Research Center government agency programs. She has over 30 years of experience in fundamental research, as well as program and proposal development, proposal consulting, and program management. Prior to her employment at NIA, she worked for the federal government as a researcher in high-temperature structural ceramics (U.S. Army) and as a program manager for ceramics/high-temperature materials (USAF Office of Scientific Research and the National Science Foundation), as well as at a large aerospace company, a small high-tech business, and running her own consulting company. She has participated on several advisory commit-

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tees, including for the Department of Energy (DOE) and NASA, and was a member of the steering committee for the 2012 NRC review of NASA's Draft Space Technology Roadmaps. Dr. Schioler is a fellow of the American Ceramic Society. She holds a Sc.D. in ceramic science from the Massachusetts Institute of Technology (MIT).

ARDEN L. BEMENT, JR. (NAE) is the David Ross Distinguished Professor of Nuclear Engineering Emeritus at Purdue University. He has held academic appointments in materials science and engineering and nuclear engineering at the Massachusetts Institute of Technology (MIT) and in materials engineering, electrical and computer engineering, and nuclear engineering, at Krannert School of Management (courtesy), industrial engineering (courtesy) and technology leadership and innovation (courtesy) at Purdue University. His government experience includes director, Office of Materials Science, Defense Advanced Research Projects Agency (DARPA); deputy undersecretary for research and advanced technology, Department of Defense; director of the National Institute of Standards and Technology, Department of Commerce; director of the National Science Foundation and member of its National Science Board. His previous space science and technology experience includes vice president for science and technology, TRW (1980-1992), and member of the Technology Advisory Committee and Space Station Subcommittee for NASA (under Administrator Daniel Goldin). He is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. He recently (2011-2015) participated in the following NRC studies: Performance Metrics for the Global Nuclear Detection Architecture (chair), Globalization of S&T: Opportunities and Challenges for the Department of Defense (co-chair), and Aligning the Governance Structure of the NNSA Laboratories to Meet 21st Century National Security Challenges (member).

JOHN C. BROCK is an independent aerospace technology consultant. He is retired from Northrop Grumman Aerospace Systems, where he was director of technology strategy and planning. Before TRW's acquisition by Northrop Grumman, Dr. Brock was chief technologist of its space and technology sector and a senior scientist with expertise in optoelectronics, high-energy lasers, space systems and technologies, and technology planning and roadmapping. Before joining TRW in 1980, Dr. Brock was a NASA-Jet Propulsion Laboratory (JPL) NRC fellow studying atmospheric photochemistry. He served as member of the Air Force Scientific Advisory Board and chaired that board's study on the operational utility of small satellites. He also served on the Defense Science Board's Advisory Group on Electron Devices, the Air Force Tactical Applications Center's Space Advisory Group, and the advisory boards of numerous university optoelectronic centers of excellence. He is an associate fellow of the American Institute of Aeronautics and Astronautics (AIAA), received the Air Force Exemplary Civilian Service Medal in 2008, and was a TRW/Northrop Grumman senior technical fellow from 1995 until his retirement. Dr. Brock earned a B.S. in chemistry from the University of Washington and a Ph.D. in chemical physics from the University of California, Berkeley. He has participated in one NRC study as a member of the Committee on NASA's Strategic Direction.

JAMES L. BURCH is vice president of the division of space science and engineering at the Southwest Research Institute in San Antonio, Texas. He is an expert in the design and use of space plasma physics instruments. He has served as principal investigator on the IMAGE, Rosetta, Dynamics Explorer 1, and ATLAS-1 space science missions, and he is principal investigator of the instrument suite science team for the NASA Magnetospheric Multiscale mission. He received a B.S. in physics from St. Mary's University, a Ph.D. in space science from Rice University, and an M.S.A. in R&D management from George Washington University. He has an extensive history with the NRC, having served as a chair for the Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop, the Committee on Exploration of the Outer Heliosphere: A Workshop, and the Committee on Solar and Space Physics, and as a member on the Committee on the Scientific Context for the Exploration of the Moon, the Committee for the Review of NASA Science Mission Directorate Science Plan, the Committee on the Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, and the Space Studies Board's Committee on Solar and Space Physics: A Community Assessment and Strategy for the Future, its Panel on Solar-Wind-Magnetosphere Interactions, and its Committee on Solar and Space Physics, and the Air Force Office of Scientific Research's (AFOSR's) Atmospheric Sciences Review Panel.

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STEPHEN GOREVAN is the chairman and cofounder of Honeybee Robotics Spacecraft Mechanisms Corporation of New York. Honeybee Robotics is a NASA and DOD supplier of advanced robotics research and development engineering as well as a supplier of spacecraft subsystems. Honeybee has produced devices such as the Phoenix Lander Soil Acquisition Device, the Mars Exploration Rover Rock Abrasion Tool, and the Dust Removal Tool and Sample Manipulation System aboard the Curiosity Rover. Mr. Gorevan has guided Honeybee to act as a close industry R&D companion to the planetary science community as well focusing on the development of sampling acquisition and containment systems for future missions to comets, asteroids, the Moon, Mars, Venus, and the outer planets. Mr. Gorevan has also guided Honeybee to support DARPA in the use of robotics for on-orbit servicing operations. Mr. Gorevan has a B.A. in music from New York University and a B.S. in mechanical engineering from the City College of New York. He previously served as a member of the NRC Steering Committee for Workshops on Issues of Technology Development for Human and Robotic Exploration and Development of Space.

CHARLES L. ISBELL, JR., is the senior associate dean of computing at Georgia Institute of Technology. He conducts research on artificial intelligence. In particular, he focuses on applying statistical machine learning to building autonomous agents that must live and interact with large numbers of other intelligent agents, some of whom may be human. Lately, Dr. Isbell has turned his energies toward adaptive modeling, especially activity discovery (as distinct from activity recognition); scalable coordination; and development environments that support the rapid prototyping of adaptive agents. As a result, he has begun developing adaptive programming languages, worrying about issues of software engineering, and trying to understand what it means to bring machine learning tools to nonexpert authors, designers, and developers. Dr. Isbell was a National Academy of Sciences Kavli Fellow for 3 years and earned both the NSF CAREER and the DARPA CSSG awards for young investigators. He has had best papers at international conferences on autonomous agents and machine learning. He has served on the organizing committees for ICML, NIPS, RoboCup, Tapia, and the NAS Frontiers of Science Symposia, among others, and organized meetings at a number of conferences. Dr. Isbell holds a Ph.D. in computer science from MIT. He has not previously served as a member of an NRC study committee.

H. JAY MELOSH (NAS) is a distinguished professor of Earth and atmospheric sciences, physics, and aerospace engineering at Purdue University. Dr. Melosh's previous positions include professor of planetary sciences at the Lunar and Planetary Laboratory, University of Arizona; associate professor of planetary science at Caltech; and associate professor of geophysics at the State University of New York. He has made many important contributions to Earth and planetary sciences, including definitive studies of the collisional origin of the Moon and the process of impact cratering. His other major contributions include acoustic fluidization, dynamic topography, and planetary tectonics. He is active in astrobiological studies relating chiefly to microorganism exchange between the terrestrial planets. Dr. Melosh is a member of the National Academy of Sciences. He received an A.B. in physics from Princeton University and a Ph.D. in physics and geology from Caltech. Dr. Melosh has served on the Committee on Planetary and Lunar Exploration and on both the Steering Committee and the Mitigation Panel for the Review of Near-Earth Object Surveys and Hazard Mitigation Strategies. He also served on the steering committee of the NRC study on NASA space technology roadmaps and priorities.

DAVID P. MILLER is a professor of space science and robotics in the School of Aerospace and Mechanical Engineering at the University of Oklahoma with additional appointments in the School of Computer Science and the bioengineering programs at the University of Oklahoma and the College of Teachers at the International Space University. While at JPL, Dr. Miller led the design and prototyping of the lab's small rover program, which eventually led to the Sojourner rover on the Mars Pathfinder Mission. He was one of the founders of ISRobotics, which became iRobot, and was a cofounder of KIPR, a robotics outreach nonprofit. Dr. Miller's research interests include planetary robot mobility, the interplay between mechanics and intelligence, and the development of assistive technologies related to human mobility and technology education. His space robotics work has been recognized with numerous NASA certificates of recognition, NASA group achievement awards, a NASA space act board award, the JPL Lew Allen Award, and the NASA Exceptional Service Medal. His outreach work resulted in receiving

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the Ames Research Center Dave Lavery Technology Award. He earned his Ph.D. in computer science from Yale University. He served as a member of the 2011-2012 NRC study on NASA technology roadmaps.

DANIEL O'SHAUGHNESSY is a member of the principal professional staff at the Johns Hopkins University, Applied Physics Laboratory. At JHU/APL, Mr. O'Shaughnessy most recently served as the mission systems engineer for the MESSENGER mission to Mercury. In this role, he was responsible for all technical matters related to the project, including the health, safety, and operability of the spacecraft, ground systems, operations, and science planning. He successfully oversaw two mission extensions culminating in a novel mission termination phase that allowed observation of Mercury at unprecedented altitudes using unconventional propellants, enabling entirely new and unique science investigations of the planet. His interests include practical use of autonomy in space vehicles as well as using modeling and simulation to reduce the operational cost and complexity of space missions. Previously, Mr. O'Shaughnessy served as MESSENGER's guidance and control team lead, where he pioneered the flight use of solar sailing for planetary flyby risk reduction. He has also led APL efforts to develop an autonomous aerobraking capability, helping to demonstrate through simulation that aerobraking mission costs can be reduced substantially. For his work on solar sailing he was the inaugural recipient of the Heinlein Award for Space Technology. He earned his M.S. in mechanical and aerospace engineering from the University of Missouri in 2000. He has served on the Naval Research Advisory Committee, assessing the state of autonomous technologies and their potential benefits for the Navy, and is currently a member of the OSIRIS-REx project's standing review board.

TORREY RADCLIFFE is the associate director of the Space Architecture Department at the Aerospace Corporation. Dr. Radcliffe leads conceptual design studies and independent analysis of space systems at the architecture and vehicle level for national security and civil space agencies. While supporting all types of space systems, his main areas of interest are launch vehicles and human spaceflight. While Dr. Radcliffe has worked at Aerospace for his whole career, he also served as a lecturer at UCLA for a number of years. He also currently serves at the co-chair for the Management, Systems Engineering, and Cost track for the IEEE Aerospace Conference. He earned his Ph.D. in aeronautics and astronautics from MIT. He has no previous NRC committee experience.

JOHN R. ROGACKI is associate director of the Florida Institute for Human and Machine Cognition (IHMC). Since March 2015, he has been detailed to the Doolittle Institute in Ft. Walton Beach, Florida, as deputy director. He has an extensive background in space transportation technology, air and space propulsion and power, air vehicles, and materials. He also has experience with robotics, assistive technologies, natural language processing, and technology transfer. Prior to joining IHMC, Dr. Rogacki served as director of the University of Florida's Research and Engineering Education Facility (REEF), a unique educational facility in northwest Florida supporting U.S. Air Force research and education needs through graduate degree programs in mechanical, aerospace, electrical, computer, industrial, and systems engineering. Dr. Rogacki's has also served as the NASA's deputy associate administrator for space transportation technology (in charge of the Space Launch Initiative); program director for the Orbital Space Plane and Next Generation Launch Technology Programs; co-chair of the NASA/DOD Integrated High-Payoff Rocket Propulsion Technology (IHPRPT) program; director of the NASA Marshall Space Flight Center's Space Transportation Directorate; director of the propulsion directorate for the Air Force Research Laboratory; director of the USAF Phillips Laboratory Propulsion Directorate; and deputy director of the Flight Dynamics Directorate of the USAF Wright Laboratory. An accomplished pilot, Dr. Rogacki has logged more than 3,300 flying hours as pilot, instructor pilot, and flight examiner in aircraft ranging from motorized gliders to heavy bombers. He has served as primary NASA liaison for the National Aerospace Initiative; co-chair of the DOD Future Propulsion Technology Advisory Group; co-chair of the DOD Ground and Sea Vehicles Technology Area Readiness Assessment Panel; member of the National High Cycle Fatigue Coordinating Committee; and senior NASA representative to the Joint Aeronautical Commanders Group. Dr. Rogacki also served as associate professor of engineering mechanics and chief of the materials division at the USAF Academy. In 2005 he graduated from the Senior Executives Program in National and International Security at Harvard's John F. Kennedy School of Government. In addition, he is a recent graduate of Leadership Florida. Dr. Rogacki earned a Ph.D. and

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an M.S. in mechanical engineering from the University of Washington and a B.S. in engineering mechanics from the USAF Academy. He previously chaired the NRC NASA Technology Roadmap: Propulsion and Power Panel.

JULIE A. SHAH is an associate professor in the Department of Aeronautics and Astronautics at MIT and leads the Interactive Robotics Group of the Computer Science and Artificial Intelligence Laboratory. Dr. Shah received her S.B. (2004) and S.M. (2006) from the Department of Aeronautics and Astronautics at MIT and her Ph.D. (2010) in autonomous systems from MIT. Before joining the faculty she worked at Boeing Research and Technology on robotics applications for aerospace manufacturing. She has developed innovative methods for enabling fluid human–robot teamwork in time-critical, safety-critical domains, ranging from manufacturing to surgery to space exploration. Her group draws on expertise in artificial intelligence, human factors, and systems engineering to develop interactive robots that emulate the qualities of effective human team members to improve the efficiency of human–robot teamwork. In 2014 Dr. Shah was recognized with an NSF CAREER award for her work on "human-aware autonomy for team-oriented environments," and by the MIT Technology Review TR35 list as one of the world's top innovators under the age of 35. Her work on industrial human–robot collaboration was also recognized by Technology Review as one of the 10 Breakthrough Technologies of 2013, and she has received international recognition in the form of best paper awards and nominations from the International Conference on Automated Planning and Scheduling, the American Institute of Aeronautics and Astronautics, the IEEE/ACM International Conference on Human-Robot Interaction, the International Symposium on Robotics, and the Human Factors and Ergonomics Society. Dr. Shah served on the NAE 2013 Panel on Information Sciences at the Army Research Laboratory.

ALAN M. TITLE is a senior fellow at the Lockheed Martin Advanced Technology Center in Palo Alto, California. He is a leading expert in the development of advanced solar astronomy instruments and sensors. He has played a major role in making all heliophysics data available to the community without restriction in as close to real time as possible. He has been either the principal investigator or responsible scientist for the development of seven space science missions—the Solar H-alpha telescopes on Skylab (NASA), SOUP on Spacelab 2 (NASA), MDI on SOHO (ESA), TRACE (NASA), the Focal Plane Package on Hinode (JAXA), HMI on SDO (NASA), AIA on SDO (NASA), and IRIS (NASA). He is a member of the National Academy of Sciences, the National Academy of Engineering, the International Academy of Astronautics, and a fellow of the American Geophysical Union. He has received the Hale Prize of the American Astronomical Society (AAS), the NASA Public Service and Exceptional Scientific Achievement Medals, and the George Goddard Award of the SPIE, and he was selected to be a member of the Silicon Valley Hall of Fame. He is a former member of the NRC's Space Studies Board (SSB) and has served on the steering committee of two decadal surveys and on advisory committees for NASA, NSF, national laboratories, and universities. He is a current member of the Aeronautics and Space Engineering Board and the Committee on Achieving Science Goals with CubeSats.

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E

2012 Findings and Recommendations on Observations and General Themes

The 2012 National Research Council report on technology roadmaps included 11 findings and recommendations related to observations and general themes. The present study was not tasked with reviewing those findings and recommendations, which are repeated in this appendix, although some of the topics they address are mentioned in some of its recommendations.[1]

Recommendation. ***Systems Analysis.*** NASA's Office of the Chief Technologist (OCT) should use disciplined systems analysis for the ongoing management and decision support of the space technology portfolio, particularly with regard to understanding technology alternatives, relationships, priorities, timing, availability, down-selection, maturation, investment needs, system engineering considerations, and cost-to-benefit ratios; to examine "what-if" scenarios; and to facilitate multidisciplinary assessment, coordination, and integration of the roadmaps as a whole. OCT should give early attention to improving systems analysis and modeling tools, if necessary to accomplish this recommendation.

Recommendation. ***Managing the Progression of Technologies to Higher Technology Readiness Levels (TRLs).*** OCT should establish a rigorous process to down-select among competing technologies at appropriate milestones and TRLs to ensure that only the most promising technologies proceed to the next TRL.

Recommendation. ***Foundational Technology Base.*** OCT should reestablish a discipline-oriented technology base program that pursues both evolutionary and revolutionary advances in technological capabilities and that draws upon the expertise of NASA centers and laboratories, other federal laboratories, industry, and academia.

Recommendation. ***Cooperative Development of New Technologies.*** OCT should pursue cooperative development of high-priority technologies with other federal agencies, foreign governments, industry, and academic institutions to leverage resources available for technology development.

[1] National Research Council, 2012, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* The National Academies Press, Washington, D.C., pp. 78-85.

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Recommendation. ***Flight Demonstrations and Technology Transition.*** OCT should collaborate with other NASA mission offices and outside partners in defining, advocating, and where necessary co-funding flight demonstrations of technologies. OCT should document this collaborative arrangement using a technology transition plan or similar agreement that specifies success criteria for flight demonstrations as well as budget commitments by all involved parties.

Finding. ***Facilities.*** Adequate research and testing facilities are essential to the timely development of many space technologies. In some cases, critical facilities do not exist or no longer exist, but defining facility requirements and then meeting those requirements fall outside the scope of NASA's Office of the Chief Technologist (and this study).

Finding. ***Program Stability.*** Repeated, unexpected changes in the direction, content, and/or level of effort of technology development programs have diminished their productivity and effectiveness. In the absence of a sustained commitment to address this issue, the pursuit of OCT's mission to advance key technologies at a steady pace will be threatened.

Recommendation. ***Industry Access to NASA Data.*** OCT should make the engineering, scientific, and technical data that NASA has acquired from past and present space missions and technology development more readily available to U.S. industry, including companies that do not have an ongoing working relationship with NASA and which are pursuing their own commercial goals apart from NASA's science and exploration missions. To facilitate this process in the future, OCT should propose changes to NASA procedures so that programs are required to archive data in a readily accessible format.

Recommendation. ***NASA Investments in Commercial Space Technology.*** While OCT should focus primarily on developing advanced technologies of high value to NASA's own mission needs, OCT should also collaborate with the U.S. commercial space industry in the development of precompetitive technologies of interest to and sought by the commercial space industry.

Finding. ***Crosscutting Technologies.*** Many technologies, such as those related to avionics and space weather beyond radiation effects, cut across many of the existing draft roadmaps, but the level 3 technologies in the draft roadmaps provide an uneven and incomplete list of the technologies needed to address these topics comprehensively.

Recommendation. ***Crosscutting Technologies.*** OCT should review and, as necessary, expand the sections of each roadmap that address crosscutting level 3 technologies, especially with regard to avionics and space weather beyond radiation effects. OCT should assure effective ownership responsibility for crosscutting technologies in each of the roadmaps where they appear and establish a comprehensive, systematic approach for synergistic, coordinated development of high-priority crosscutting technologies.

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Acronyms

ARL	Army Research Laboratory
CTC	Center Technology Council
DOD	Department of Defense
DRM	design reference mission
ECLSS	environmental control and life support system
EDL	entry, descent, and landing
EVA	extravehicular activity
FDIR	fault detection, isolation, and recovery
GCR	galactic cosmic rays
GN&C	guidance, navigation, and control
ISRU	in situ resource utilization
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NTEC	NASA Technology Executive Council
OCT	Office of the Chief Technologist
OIG	Office of the Inspector General
QFD	quality function deployment
RBCC	rocket-based combined cycle

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SLS	Space Launch System
SPE	solar particle event
SSTIP	Strategic Space Technology Investment Plan
TA	technology area
TABS	Technology Area Breakdown Structure
TBCC	turbine-based combined cycle
TPS	thermal protection systems
TRL	technology readiness level

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