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National Aeronautics and Space Administration

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NASA's Efforts to Manage Its Space Technology Portfolio

December 15, 2015

Report No. IG-16-008

Office of Inspector General

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Results in Brief

NASA's Efforts to Manage Its Space Technology Portfolio

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December 15, 2015 IG-16-008 (A-14-017-00)

Why We Performed This Audit

For more than 50 years, NASA has been at the forefront of scientific and technological innovation in the United States. NASA-sponsored technology has enabled groundbreaking space science and exploration missions, contributed to the success of other Federal programs, cultivated commercial aerospace enterprises, and helped foster a technology-based U.S. economy. As NASA sets its sights on increasingly challenging human and robotic missions to deep space destinations, the Agency must continue to identify and mature technologies to make such missions feasible, affordable, and safe.

As of November 2015, the Agency is engaged in 1,400 diverse space technology projects with an annual cost of nearly $1 billion. However, Congress, the Office of Management and Budget, and the National Research Council have expressed concern that some NASA space technology projects do not align with Agency mission needs, may be of low priority, or may duplicate other work at NASA, other Federal agencies, or in industry and academia. Moreover, budgetary constraints have made it impossible for the Agency to carry out all of its proposed space technology projects. Nevertheless, NASA has continued to fund a large number of space technology projects, raising concerns about inefficient development as too many projects chase too few dollars.

NASA's portfolio of space technology projects is managed by numerous organizations and individuals at the Council, Mission Directorate, and Center levels. In addition, over the past 5 years NASA appointed a Chief Technologist, established the Space Technology Mission Directorate, and created technology "roadmaps," a Strategic Space Technology Investment Plan, and the TechPort database. The roadmaps outline a range of technology candidates and development pathways over a 20-year period, while the Technology Investment Plan prioritizes technology in light of NASA's planned missions. TechPort is an Agency-wide software system designed to track and manage NASA's portfolio of technology investments.

In this audit, we examined NASA's efforts to align and prioritize projects in its space technology portfolio to meet future mission needs. Specifically, we reviewed Federal and NASA policies, regulations, plans, and roadmaps; interviewed NASA officials; and assessed the methods and processes used to initiate, manage, and gauge projects' return on investment. We also profiled the top 15 space technology projects by fiscal year 2015 funding level in the following programs: Technology Demonstration Missions Program, Game Changing Development Program, Advanced Exploration Systems Program, and the Science Mission Directorate's Research Divisions.

What We Found

We found deficiencies in NASA's management processes and controls that may limit the usefulness of the Agency's efforts to better manage its space technology investments. First, although NASA has revised its technology roadmaps to provide additional information regarding how specific technologies will help meet Agency mission objectives, it needs to complete the ongoing revision of its Strategic Space Technology Investment Plan to provide the necessary detail to determine the projects that best support Agency priorities. Second, the information in TechPort remains incomplete and inaccurate, impairing the value of the database as a tool to manage and share information about NASA's space technology portfolio. For example, we selected a sample of 49 active projects and found the database contained no information for 16 (33 percent) of the projects. Third, the Agency's management structure, especially the role of its Technology Executive Council, needs to be clarified to ease efforts to align and prioritize investments. Fourth, while NASA's Mission Directorates and Centers have authority to initiate new space technology projects, the processes for initiating projects need to be better integrated and formalized to ensure cohesion and guard against duplication. Finally, the Agency needs to develop more consistent processes to measure and track return-on-investment for its space technology projects.

We acknowledge that managing space technology projects in a fluctuating budget environment is a significant undertaking. Consequently, adopting management processes that improve NASA's ability to make strategic decisions regarding its space technology portfolio will help the Agency better address this challenge.

WHAT WE RECOMMENDED

To clarify the role and authorities of NASA's Technology Executive Council, we recommended the NASA Administrator: (1) develop a charter outlining the Council's role, responsibilities, authority, and membership. To ensure management processes and controls better align and prioritize NASA's space technology projects with its mission goals, we recommended the Office of the Chief Technologist: (2) further prioritize "core" and "adjacent" technologies in the new Strategic Space Technology Investment Plan and (3) take steps to ensure project managers utilize TechPort as intended. In addition, we recommended the Office of the Chief Engineer update NASA Procedural Requirements 7120.8 to establish policy and procedures for: (4) initiating space technology projects that include Agency-wide awareness and coordination and (5) requiring all concluded technology projects complete closeout reports and technology infusion or transfer data for inclusion in TechPort.

In response to a draft of our report, NASA's Deputy Administrator concurred with recommendations 1, 2, and 3 and described corrective actions the Agency has or will take. We consider management's comments to these recommendations responsive and will close the recommendations upon completion and verification of the proposed corrective actions. The Deputy Administrator partially concurred with recommendations 4 and 5, which remain unresolved pending further discussion with the Agency.

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Acronyms

AES	Advanced Exploration Systems
ASRG	Advanced Stirling Radioisotope Generator
EDL	Entry, Descent, and Landing
FY	Fiscal Year
GCD	Game Changing Development
HEOMD	Human Exploration and Operations Mission Directorate
NRC	National Research Council
NTEC	NASA Technology Executive Council
OCT	Office of the Chief Technologist
SMD	Science Mission Directorate
SSTIP	Strategic Space Technology Investment Plan
STMD	Space Technology Mission Directorate
TDM	Technology Demonstration Missions
TRL	Technology Readiness Level

INTRODUCTION

For more than 50 years, NASA has been at the forefront of scientific and technological innovation in the United States. NASA-sponsored technology development programs have enabled groundbreaking space science and exploration missions, contributed to the success of other Federal programs, cultivated commercial aerospace enterprises, and helped foster a technology-based U.S. economy. As NASA sets its sights on increasingly challenging human and robotic missions to deep space destinations, the Agency must continue to identify and mature technologies to make such missions feasible, affordable, and safe.

In 2010, the President and Congress agreed on a new direction for NASA that included renewed investment in space technology development and called for the Agency to grow and maintain a space technology base that seeks to align investments, increase capabilities, lower mission costs, and support NASA's long-term needs. As of November 2015, NASA is engaged in 1,400 diverse space technology projects with an annual cost of nearly $1 billion. However, Congress, the Office of Management and Budget, and the National Research Council (NRC) have expressed concern that some of these projects do not align with Agency mission needs, may be of low priority, or may duplicate other work ongoing at NASA or being conducted by other Federal agencies, industry, or academia. Moreover, budgetary constraints over the past several years have made it impossible for the Agency to carry out all of its proposed space technology projects. Nevertheless, NASA has continued to fund a large number of space technology projects, raising concerns about inefficient development with too many projects chasing too few dollars.

NASA has initiated several efforts to improve management of its technology portfolio, including appointing a Chief Technologist; creating a directorate dedicated to technology development – the Space Technology Mission Directorate; developing "roadmaps," that outline a range of technology candidates and development pathways over a 20-year period and a strategic plan to guide investments; establishing a database to track and analyze space technology projects; and beginning the process of mapping and prioritizing its space technology investments.

In this audit, we examined NASA's efforts to align and prioritize projects in its technology portfolio to meet future mission needs. See Appendix A for details of the audit's scope and methodology.

Background

NASA defines space technology as applied research and development that furthers knowledge of a particular issue or field or produces materials, devices, systems, or methods applicable to space flight missions. To this end, the Agency is working to develop a portfolio of technologies that will enable it to sustain and extend human activities in space; explore the structure, origin, and evolution of the solar system; and search for evidence of past and present life.

NASA's Space Technology Portfolio

NASA's exploration goals include a crewed mission to the Mars vicinity by the 2030s. Along the path to Mars, the Agency is planning to test new systems and technologies in cis-lunar orbit, including visiting, capturing, and returning to cis-lunar space a portion of a near-Earth asteroid.[1] These missions will require technologies that enable humans to live and work in deep space, navigate and travel to distant locations, manufacture products in space, land on and depart from planetary surfaces, and communicate with Earth over significant distances. To address these and other Agency needs, NASA has established a portfolio of space technology development programs and projects in 11 specific areas that it considers indispensable for planned future missions:

1. Launch and in-space propulsion
2. High data rate communications
3. Lightweight space structures and materials
4. Robotics and autonomous systems
5. Environmental control and life support systems
6. Space radiation mitigation
7. Scientific instruments and sensors
8. Entry, descent, and landing
9. Power generation
10. Thermal control systems
11. Long-duration crew health

NASA classifies these space technology development programs and projects into nine Technology Readiness Levels (TRL). The lowest levels of this scale – TRL-1 and -2 – involve projects for which studies are underway, while TRL-3, -4, and -5 involve development of actual hardware and ground-based testing to determine feasibility. By the time a project reaches TRL-6 and -7, prototypes have been developed and demonstrated. Finally, TRL-8 and -9 are for projects that are flight-qualified or flight-proven, respectively. (For a more detailed explanation of how NASA measures TRLs, see Appendix B.)

Launch and In-Space Propulsion

All space missions require propulsion systems to launch and travel in space. As NASA plans crewed missions that travel deeper into space, the Agency is working to develop propulsion systems that will reduce transit times while increasing safety. For example, NASA is funding efforts to advance chemical, electric, and nuclear thermal propulsion systems; solar sails; and tethers.[2] The Agency is also developing cryogenic propellants with the potential to enable longer-range missions and enhance payload capability.[3]

Artist's Rendering of a Solar Electric Propulsion Vehicle

Source: NASA.

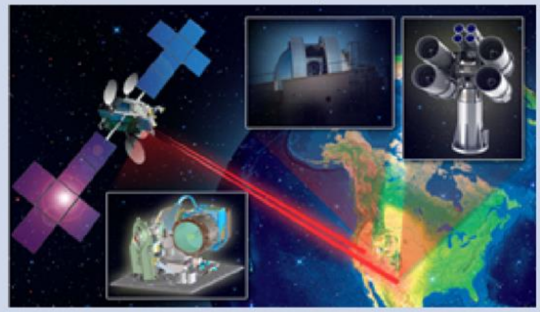
[1] Cis-lunar is the area between Earth and the Moon or the Moon's orbit.

[2] A solar sail is a large, ultra-thin sail that unfurls in space and uses the pressure of sunlight to provide propellant-free transport capabilities. Tether propulsion involves long, lightweight cables that produce thrust by carrying electrical current and interacting with a planetary body or by exchanging momentum between two tethered objects.

[3] Cryogenic propellants are gasses chilled to subfreezing temperatures and condensed to form highly combustible liquids.

High Data Rate Communications

Artist's Rendering of Laser Communication Relay Demonstration Project



Source: NASA.

NASA has used radiofrequency communications to send information between spacecraft and Earth for many years. However, with more complex missions and the desire to travel deeper in space, the Agency faces increasing demand to return more data at a quicker rate and from greater distances. To this end, NASA is working to improve traditional communication technologies while also developing new approaches. For example, the Agency is exploring optical communication technologies that would provide higher data transmission rates while using antennas with significantly smaller aperture sizes than current models. NASA demonstrated this technology in 2013 when it transferred data from the surface of the Moon as part of the Lunar Atmosphere and Dust Environment Explorer mission and will test it further during the 2-year Laser Communication Relay Demonstration mission scheduled to launch in 2018. Similarly, NASA is working to develop cognitive radio technology capable of sensing its environment, autonomously determining and attempting to fix problems, and learning as it operates. The Agency is also developing technology for ultra-wide-band radios that can communicate through rocket plumes and other harsh environments. Other projects within the portfolio seek to make advancements in the efficient use of power, available spectrum, and mass.

Lightweight Space Structures and Materials

Lightweight, compact, durable, and radiation-protective materials enable missions to spend more time in space, travel farther, and explore new destinations. NASA's space technology portfolio includes projects that focus on the weight, flexibility, multi-functionality, and electromechanical properties of such structures and materials. The portfolio also emphasizes weight reduction through use of special laminates and composites and includes research on optical and self-repairing materials and flexible materials for use on expandable habitats such as the Bigelow Expandable Activity Module.[4]

Robotics and Autonomous Systems

As missions travel farther from Earth for longer periods of time and use more complex technologies, they will need to operate with more independence and autonomy from ground control and the crew. To meet this need, NASA is developing technologies that will advance autonomous operations, vehicle systems management, rendezvous and docking, and robotics. Other projects within NASA's space technology project portfolio focus on the integration of flight path and attitude control.

Environmental Control and Life Support Systems

As human space missions extend beyond low Earth orbit, the logistics of resupply and waste disposal become more challenging, increasing the importance of systems that reuse waste to produce critical elements such as oxygen, water, and food. NASA is working on projects to advance air revitalization,

[4] The Bigelow Expandable Activity Module is a human-rated inflatable habitat module developed by Bigelow Aerospace under contract to NASA for use as a temporary module on the International Space Station.

water recovery, waste management, and habitation systems, including food preparation and laundry. In addition, the Agency is trying to mature technologies associated with trash stabilization, volume reduction, and water recovery from trash and human waste.

Space Radiation Mitigation

Space travelers are exposed to different and more dangerous types and levels of radiation than on Earth, and current technologies are not sufficient to shield astronauts on a mission to Mars from exposure to excessive amounts of radiation. Accordingly, developing ways to mitigate the dangers to human health and performance posed by space radiation is one of NASA's highest priority technology challenges. To address radiation issues, the Agency is working to advance technologies related to prediction of solar particle events, biological countermeasures, and vehicle and hardware protections such as advanced materials for vehicle shielding and suits.

Scientific Instruments and Sensors

Remote sensing instruments and sensors are components sensitive to electromagnetic radiation, electromagnetic fields, acoustic energy, seismic energy, and other physical phenomena. This technology is critical to many science missions and some exploration missions in order to improve sensitivity, resolution, speed, and operating temperatures. NASA's space technology project portfolio is investing in the development of remote sensing instruments and sensors with high efficiency, high resolution, improved durability, and reduced cost and weight. The Agency is also investing in projects to advance observatory technologies necessary to design, manufacture, test, and operate space telescopes and antennas.

Entry, Descent, and Landing

Artist's Rendering of a Hypersonic Inflatable Aerodynamic Decelerator

Source: NASA.

Entry, descent, and landing (EDL) technologies include thermal protection systems and other component technologies necessary for landing human and robotic missions on planetary bodies and returning humans to Earth. EDL technologies protect spacecraft from extreme high temperatures and overheating during entry, descent, and landing. Other EDL technologies encompass the components, systems, qualifications, and operations to safely bring a vehicle from approach conditions to contact with the surface of a planetary body. EDL technologies have to be designed for the specific atmosphere in which a mission will operate. For example, a mission to the surface of Mars has different EDL challenges than a mission that will land on the Moon or an asteroid. NASA's space technology portfolio includes projects to develop technologies for heat shields and rigid and flexible thermal protection systems, precision landing and hazard avoidance, and deployable hypersonic and supersonic decelerators.[5]

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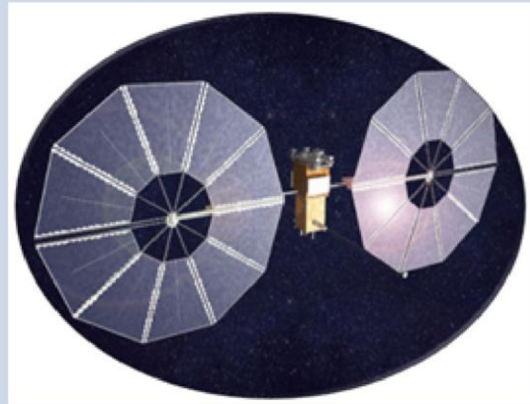
[5] Deployable decelerators are devices that slow spacecraft from their hypersonic (at least five times the speed of sound) or subsonic speeds (below the speed of sound) to enable them to safely enter a planetary atmosphere.

Power Generation

Every NASA mission requires power, and as missions become more complex and travel farther from Earth for longer periods of time, new developments in power generation are critical. NASA is investing in technologies for chemical, solar, radioisotope, fission, and fusion power, including the development of advanced fuel cells and solar arrays.

Artist's Rendering of Advanced Solar Power Arrays



Source: NASA.

Thermal Control Systems

Space missions require thermal control systems to maintain an appropriate temperature range in all vehicle surfaces and components through changing heat loads and thermal environments. NASA's space technology development portfolio includes projects focusing on technologies for heat acquisition, transport, and rejection, as well as active and passive thermal control.

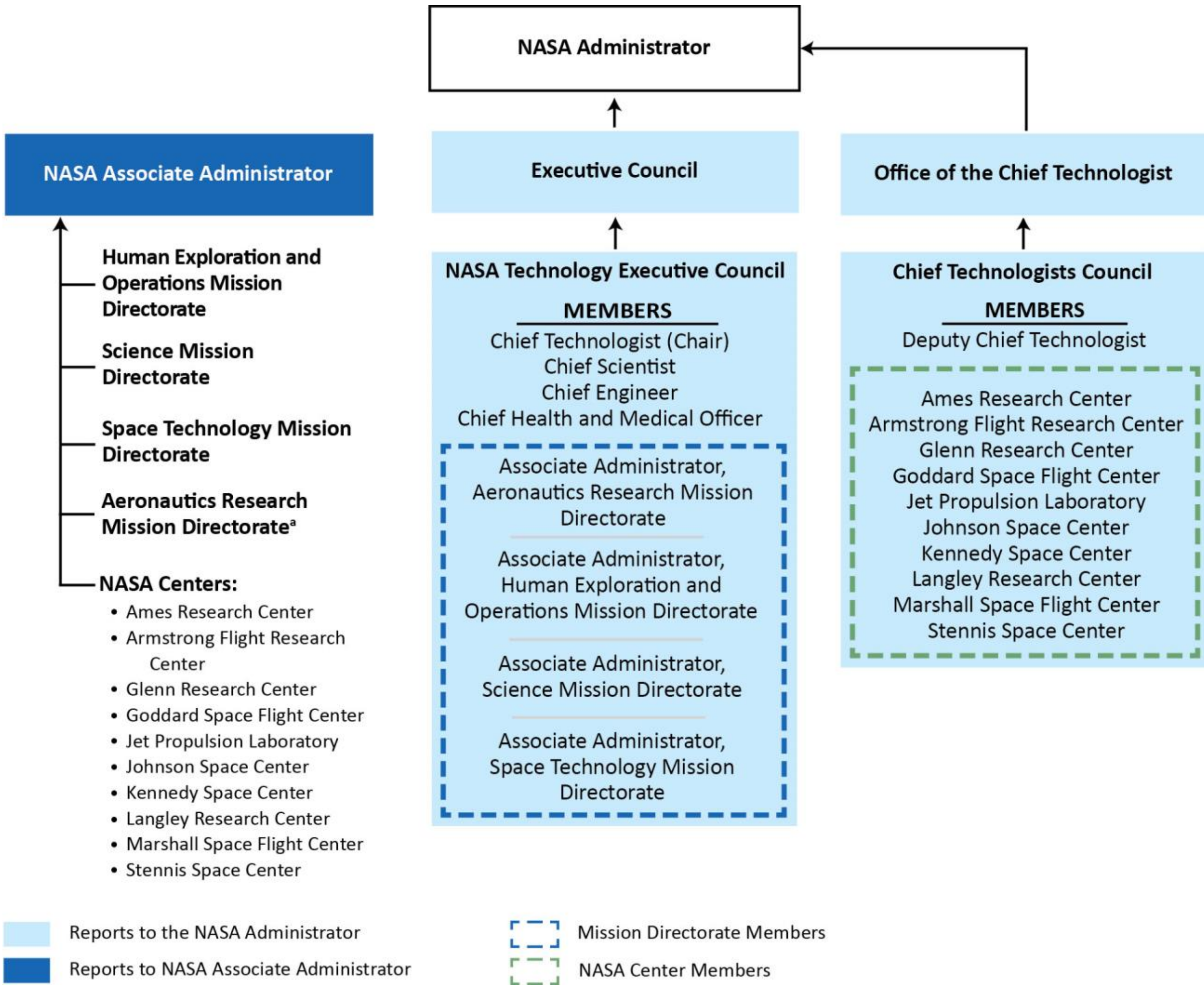
Long-Duration Crew Health

Humans traveling in deep space must be prepared to handle long stays in extreme environments with limited contact with familiar surroundings. Long-duration missions will require technologies to maintain the physical and behavioral health of the crew and sustain optimal performance of missions that could last as long as 3 years. In this regard, NASA is working on technologies to improve medical screening, long-duration space flight medical care and behavioral health, in-space diagnostic and treatment capabilities, and effective countermeasures for the challenges presented by the deep space environment.

Management of NASA's Space Technology Portfolio

NASA's portfolio of space technology projects is managed by numerous organizations and individuals at the Council, Mission Directorate, and Center levels (see Figure 1). In addition, over the past 5 years, the Agency appointed a Chief Technologist and created technology roadmaps, a Strategic Space Technology Investment Plan (SSTIP), and an integrated, Agency-wide software system to capture, track, and manage its portfolio of technology investments.

Figure 1: NASA's Organization Structure for Space Technology Projects



Source: NASA Office of Inspector General.

[a] At the time of our review, NASA's Aeronautics Research Mission Directorate was not included in strategic planning for space technology investments. The Agency plans to include the Directorate in future strategic plans.

NASA's Office of the Chief Technologist

In 2010, the NASA Administrator established the position of Chief Technologist to serve as a principal advisor on matters concerning Agency-wide technology policy and programs. NASA designated the position an Intergovernmental Personnel Act appointment, with the Administrator selecting an individual from outside the Agency to serve a 2-year term with the possibility of renewal for a second term. Since 2010, three individuals have served as Chief Technologist.

The Chief Technologist oversees the Office of the Chief Technologist (OCT), which has a staff of approximately 20, including contractors and staff detailed from other NASA offices. Among other functions, OCT works to infuse technologies into future missions; facilitate Agency technology governance such as risk acceptance and reporting; and document, demonstrate, and communicate the societal impact of NASA technology investments. In addition, OCT advocates for NASA research and technology programs through coordination with other Government agencies, academia, and the commercial aerospace industry. OCT also documents and tracks technology investments across the Agency and conducts technology assessments and Agency-level technology portfolio analysis. Finally, OCT leads technology transfer and commercialization activities across the Agency.

NASA's Technology Executive Council

OCT established the NASA Technology Executive Council (NTEC) in 2010 to bring together the Chief Technologist, Associate Administrators of NASA's four Mission Directorates, Chief Engineer, Chief Scientist, and Chief Health and Medical Officer to facilitate technology integration, coordination, and strategic planning. The Council is responsible for assessing the balance and prioritization of the Agency's technology investment portfolio and identifying technology gaps, overlaps, and synergies between programs. In addition, NTEC assesses the budget, schedule, and technology maturation progress of space technology projects to meet Agency goals, objectives, missions, and timelines. NTEC also reviews the progress of space technology projects against baseline performance milestones. Lastly, the Council develops and reviews decisional recommendations regarding the Agency's technology investment plans.

Space Technology Mission Directorate

In 2013, NASA established the Space Technology Mission Directorate (STMD) to develop crosscutting and pioneering technologies and capabilities the Agency needs to achieve current and future missions.[6] With a fiscal year (FY) 2015 budget of $600.3 million, STMD is responsible for developing, demonstrating, and infusing technologies through collaborative partnerships within NASA and between NASA and academia, industry, and other Federal agencies and international organizations. STMD oversees nine technology programs:

1. Technology Demonstration Missions (TDM)
2. Game Changing Development (GCD)
3. Small Business Innovation Research and Small Business Technology Transfer
4. Small Spacecraft Technology
5. Space Technology Research Grants
6. Flight Opportunities
7. NASA Innovative Advanced Concepts
8. Center Innovation Fund
9. Centennial Challenges

TDM and GCD account for $287.5 million, or 48 percent, of STMD's FY 2015 funding and include its largest projects.

[6] STMD became a Mission Directorate in 2013 after originating as the Space Technology Program in 2010 under OCT.

Technology Demonstration Missions Program. The TDM Program focuses on space technologies that have demonstrated viability through initial testing and provides funding to test technologies in mission like environments. Once tested and advanced past TRL-6, which includes prototype demonstrations in a relative environment, NASA is much more likely to infuse technologies into missions. Table 1 provides a summary of TDM's projects by FY 2015 funding. (See Appendix C for additional information on these projects.)

Table 1: FY 2015 Funding of TDM Projects

FY 2015 Projects (by funding)	FY 2015 Funding	Percentage of TDM Funding, FY 2015	Total TDM Funding, FYs 2012–2015	Percentage of Total TDM Funding, FYs 2012–2015
1. Low Density Supersonic Decelerator	$38,000,000	23%	$196,200,000	31%
2. Laser Communication Relay Demonstration	$37,000,000	23%	$121,400,000	19%
3. Solar Electric Propulsion	$35,900,000	22%	$43,900,000	7%
4. Green Propellant Infusion Mission	$16,100,000	10%	$54,100,000	9%
5. Evolvable Cryogenics	$12,900,000	8%	$12,900,000	2%
6. Composites for Exploration Upper Stage	$6,900,000	4%	$7,200,000	1%
7. Deep Space Atomic Clock	$5,100,000	3%	$29,900,000	5%
Inactive TDM projects and program support[a]	$10,100,000	6%	$162,100,000	26%
Total	**$161,900,000**		**$627,700,000**	

Source: NASA Office of Inspector General analysis of NASA data.

Note: Budget allocations are rounded to the nearest $100,000 and may not add up to total program funding. Percentages are rounded to the nearest whole number and may not add to 100 percent.

[a] In 2015, TDM had roughly $6 million budgeted for program and office support. In 2015, TDM cancelled the Solar Sail Demonstration and Terrestrial Hypersonic Inflatable Aerodynamic Decelerator Orbital Reentry projects, which had funding of $300,000 and $3.8 million, respectively. Historical funding from 2012 to 2015 also includes completed or cancelled projects.

Game Changing Development Program. The GCD Program focuses on the mid-TRL range to take technologies from proof of concept to component testing in a relevant environment. The Program seeks to fill a gap at TRL-4 which NASA identified as one of the barriers to successfully developing technology for infusion into missions. At any given period, roughly 30 projects are in the GCD Program. Table 2 provides a summary of GCD's top 15 projects by FY 2015 funding. (See Appendix C for additional information on these projects.)

Table 2: FY 2015 Funding of GCD Projects

Top 15 FY 2015 Projects (by funding)	FY 2015 Funding	Percentage of GCD Funding, FY 2015	Total GCD Funding, FYs 2012–2015	Percentage of Total GCD Funding, FYs 2012–2015
1. Human Robotic Systems	$15,300,000	12%	$64,700,000	12%
2. Human Exploration Telerobotics 2	$10,900,000	9%	$10,900,000	2%
3. In-Space Robotic Servicing	$10,000,000	8%	$61,000,000	11%
4. Thermal Protection System Materials	$7,800,000	6%	$11,000,000	2%
5. Entry Systems Modeling	$7,200,000	6%	$17,300,000	3%
6. Advanced Manufacturing Technology	$5,200,000	4%	$19,500,000	4%
7. Nuclear Systems	$4,900,000	4%	$16,500,000	3%
8. Next Generation Life Support	$4,500,000	4%	$24,000,000	4%
9. Deep Space Optical Communication	$4,100,000	3%	$10,800,000	2%
10. Lightweight Materials and Structures	$3,600,000	3%	$11,000,000	2%
11. Hypersonic Inflatable Aerodynamic Decelerator 2	$3,500,000	3%	$31,500,000	6%
12. In-Situ Resource Utilization	$3,500,000	3%	$17,100,000	3%
13. Nanotechnology	$3,200,000	3%	$12,100,000	2%
14. Station Explorer X-Ray Timing and Navigation	$3,000,000	2%	$13,700,000	2%
15. Coronagraph	$3,000,000	2%	$5,200,000	1%
Other GCD projects and program support[a]	$35,900,000	29%	$229,900,000	41%
Total	**$125,600,000**		**$556,200,000**	

Source: NASA Office of Inspector General analysis of NASA data.

Note: Budget allocations are rounded to the nearest $100,000 and may not add up to total program funding. Percentages are rounded to the nearest whole number and may not add to 100 percent.

[a] GCD has 16 other active projects with annual funding less than $3 million. Historical funding from 2012 to 2015 also includes completed or cancelled projects.

Advanced Exploration Systems

NASA's Advanced Exploration Systems (AES) Program operates out of the Human Exploration and Operations Mission Directorate (HEOMD). AES pioneers new approaches for developing prototype systems, demonstrating key capabilities, and validating operational concepts for future human missions beyond low Earth orbit. Program activities are focused on crew safety and mission operations in deep space and concentrate on vehicle development. AES consists of about 30 small projects that target high-priority capabilities necessary for human exploration, including advanced life support, deep space habitation, crew mobility, and extra-vehicular activity systems. The prototype systems AES develops are demonstrated in ground-based tests, field tests, underwater tests, and flight experiments on the International Space Station. AES focuses on four main areas: crew systems, vehicle systems, operations, and robotic precursor activities. Table 3 provides a summary of AES' top 15 projects by FY 2015 funding. (See Appendix C for additional information on these projects.)

Table 3: FY 2015 Funding of AES Projects

Top 15 FY 2015 Projects (by funding)	FY 2015 Funding	Percentage of AES Funding, FY 2015	Total AES Funding, FYs 2012–2015	Percentage of Total AES Funding, FYs 2012–2015
1. Life Support Systems	$16,400,000	10%	$43,100,000	7%
2. Advanced Spacesuit	$16,200,000	9%	$55,600,000	9%
3. Resource Prospector	$15,400,000	9%	$49,500,000	8%
4. Lander Technology	$11,300,000	7%	$11,300,000	2%
5. Radiation Sensors	$9,900,000	6%	$34,900,000	6%
6. Automated Propellant Loading	$8,300,000	5%	$32,200,000	5%
7. Spacecraft Fire Safety	$8,000,000	5%	$38,100,000	6%
8. Bigelow Expandable Activity Module	$7,600,000	4%	$27,600,000	5%
9. Nuclear Thermal Propulsion	$6,900,000	4%	$30,000,000	5%
10. Exploration Augmentation Module	$6,700,000	4%	$13,400,000	2%
11. Autonomous Mission Operations	$6,200,000	4%	$28,500,000	5%
12. Solar System Exploration Research Virtual Institute	$5,500,000	3%	$13,900,000	2%
13. Logistics Reduction and Repurposing	$4,700,000	3%	$19,100,000	3%
14. Modular Power Systems	$4,700,000	3%	$22,500,000	4%
15. Avionics and Software	$3,700,000	2%	$8,200,000	1%
Other AES projects[a]	$39,400,000	23%	$181,600,000	30%
Total	**$170,900,000**		**$609,500,000**	

Source: NASA Office of Inspector General analysis of NASA data.

Note: Budget allocations are rounded to the nearest $100,000 and may not add up to total program funding. Percentages are rounded to the nearest whole number and may not add to 100 percent.

[a] AES has 13 other active projects with annual funding less than $3.7 million. Historical funding from 2012 to 2015 also includes completed or cancelled projects.

Science Mission Directorate

The Science Mission Directorate (SMD) invests in technology development to enable current and future missions in four research divisions: Astrophysics, Earth Science, Heliophysics, and Planetary Science. SMD's development activities include both basic and applied research that primarily focus on TRLs 3–7 with 1- to 3-year project life cycles. SMD technology projects include development of sensors, instruments, space systems, and information technologies critical to improving observation and exploration of the Earth, solar system, and universe. Table 4 provides a summary of SMD's top 15 projects by FY 2015 funding. (See Appendix C for additional information on these projects.)

Table 4: FY 2015 Funding of SMD Projects

Top 15 FY 2015 Projects (by funding)	FY 2015 Funding	Percentage of SMD Funding, FY 2015	Total SMD Funding, FYs 2012–2015	Percentage of Total SMD Funding, FYs 2012–2015
1. Stirling Cycle Technology Development	$8,500,000	5%	$8,500,000	1%
2. Astrophysics Focused Telescope Assets Coronagraph	$8,000,000	4%	$14,000,000	2%
3. Large Array Infrared Detectors	$6,000,000	3%	$11,600,000	2%
4. Green Optical Autocovariance Wind Lidar Airborne Demonstrator	$3,800,000	2%	$3,800,000	1%
5. Thermoelectric Technology Development	$3,500,000	2%	$3,500,000	1%
6. Enhanced Multi-Mission Radioisotope Thermoelectric Generator	$3,400,000	2%	$11,400,000	2%
7. Auto-Gopher 2	$3,000,000	2%	$3,000,000	0%
8. Sub-glacial Polar Ice Navigation, Descent, and Lake Exploration	$2,000,000	1%	$2,000,000	0%
9. Affordable and Lightweight High-resolution Astronomical X-ray Optics	$1,900,000	1%	$5,700,000	1%
10. Ice Cube	$1,800,000	1%	$3,100,000	0%
11. Compact Solar Spectral Irradiance Monitor	$1,700,000	1%	$1,700,000	0%
12. Midwave Infrared Sounding Of Temperature And Humidity In A Constellation	$1,700,000	1%	$1,700,000	0%
13. High Velocity Research	$1,600,000	1%	$1,600,000	0%
14. Triple-Pulsed Lidar	$1,500,000	1%	$1,500,000	0%
15. Peregrine Rocket Development	$1,400,000	1%	$7,200,000	1%
Other SMD projects [a]	$129,300,000	72%	$554,400,000	87%
Total	**$179,100,000**		**$634,700,000**	

Source: NASA Office of Inspector General analysis of NASA data.

Note: Budget allocations are rounded to the nearest $100,000 and may not add up to total program funding. Percentages are rounded to the nearest whole number and may not add to 100 percent.

[a] SMD has 231 other active projects with annual funding less than $1.4 million. Historical funding from 2012 to 2015 also includes completed or cancelled projects.

NASA Centers

NASA Centers also conduct space technology development activities. While much of this work is directed through the Agency's Mission Directorates, Centers may initiate space technology projects using Institutional Research and Development funds or through competitive processes such as STMD's Center Innovation Fund, which distributes funding to each Center to support emerging technologies. Each NASA Center has a Chief Technologist who monitors technology activities and serves in an advisory capacity to Center management. Together the 10 Center Chief Technologists form the Center Chief Technologists Council, which is chaired by the Agency's Deputy Chief Technologist and serves as an advisory board to the Agency's Chief Technologist.

NASA's Technology Roadmaps

NASA has developed a set of technology roadmaps to guide the Agency's space technology development efforts. The roadmaps outline a range of technology candidates and development pathways over a 20-year period. The effort to develop the roadmaps began in 2010 with NASA identifying 14 technology areas, the top technical challenges in each area, and the spaceflight missions the technologies could impact or enable. NASA publicly released a draft of the original roadmaps in December 2010. At the same time, NASA contracted with NRC to perform an independent critique of the draft roadmaps. In its 2012 report, NRC identified 83 high-priority technologies and designated 16 of the 83 the top priorities for achieving NASA's exploration objectives.[7] NASA revised the draft roadmaps to include a section on NRC's recommendations and publicly released the final roadmaps in April 2012.

NASA began the process of updating the technology roadmaps in 2013 and issued a revised version in July 2015. The 2015 edition includes a crosscutting section, a 15th technology area for Aeronautics, and expanded content (see Table 5). For each technology area, NASA has included a "technology candidate snapshot" that contains standardized information tracing the technology to a needed capability and associated Agency missions. The revised roadmaps also identify technologies as either "enabling" or "enhancing." Enabling technologies solve an exploration challenge and satisfy a mission capability, while enhancing technologies will provide benefits over current capabilities but are not required to undertake a mission.

[7] NRC, "NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space," 2012.

Table 5: NASA's 2015 Technology Roadmaps

	Technology Roadmaps
TA01	Launch Propulsion Systems
TA02	In-Space Propulsion Technologies
TA03	Space Power and Energy Storage
TA04	Robotics and Autonomous Systems
TA05	Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
TA06	Human Health, Life Support, and Habitation Systems
TA07	Human Exploration Destination Systems
TA08	Science Instruments, Observatories, and Sensor Systems
TA09	Entry, Descent, and Landing Systems
TA10	Nanotechnology
TA11	Modeling, Simulation, Information Technology, and Processing
TA12	Materials, Structures, Mechanical Systems, and Manufacturing
TA13	Ground and Launch Systems
TA14	Thermal Management Systems
TA15	Aeronautics

Source: NASA Office of the Chief Technologist.

NASA's Strategic Space Technology Investment Plan

The technology roadmaps are comprehensive documents that outline technology candidates for development in each area. However, because NASA cannot afford to pursue all candidates, the Agency prioritizes those that would be the most beneficial. This prioritization is documented in the Agency's SSTIP. The SSTIP is intended to guide NASA's space technology investment over a 4-year period within the context of a 20-year horizon and incorporates the recommendations resulting from NRC's 2012 review of the roadmaps.

The SSTIP outlines three types of investment – core, adjacent, and complementary – to guide future space technology expenditures.

1. *Core* technology is the central focus of NASA technology investment, representing the majority of NRC's top priority recommendations. Core technology should comprise approximately 70 percent of the Agency's portfolio. According to the SSTIP, the core technologies are launch and in-space propulsion, high data rate communications, lightweight structures and materials, robotics and autonomous systems, environmental control and life support systems, space radiation mitigation, scientific instruments and sensors, and EDL systems.
2. *Adjacent* technology relates to but is not part of the core technologies. These technologies were among the 83 high priorities identified by NRC and should comprise approximately 20 percent of the Agency's portfolio. Examples of adjacent technologies include power generation, thermal control systems, and long-duration crew health.

3. *Complementary* technology investments are the remaining technologies identified in the roadmaps and should comprise approximately 10 percent of the Agency's space technology development portfolio. These investments are characterized by limited immediate relevance and include technologies with the potential to become important within the SSTIP's 20-year horizon but, if given the chance, could provide benefits sooner. Examples of complementary technologies include advanced in-space propulsion technologies like beamed energy, high-energy-density materials, antimatter, and advanced fission propulsion.

NASA's Technology Portfolio System

NASA's Technology Portfolio System (TechPort) is an integrated, Agency-wide software system designed to capture, track, and manage its portfolio of technology investments. TechPort provides information on individual space technology programs and projects throughout the Agency and is equipped with features that allow users to search and browse projects, identify technology gaps, and compile comprehensive reports about specific technology areas. OCT is responsible for managing TechPort, and Mission Directorates, Offices, and Centers enter information about their programs and projects into the system. NASA and other users can utilize the database for several activities, including:

- searching and sharing the Agency's technology information;
- analyzing the space technology development portfolio, such as mapping investments to future mission requirements;
- making decisions about future investments;
- generating reports;
- identifying prospective technology development partners; and
- providing Centers, programs, and projects the capability to dynamically capture information and manage technology.

As of November 2015, TechPort contained 1,400 project entries. Each project has its own webpage listing the name, type, program, and Mission Directorate affiliation; technology roadmap category; project funding; milestones; project status; and other criteria. Each entry also allows the project's manager to upload summaries of the project, photos, external documents, and project contacts. Users can compare projects by developing custom search criteria to isolate projects from a certain program, NASA Center, or technical area. TechPort can generate performance reports for individual projects or custom groupings that show the milestone status with red, yellow, or green signals and other selected criteria. TechPort is available to NASA civil servant and contractor employees, and in March 2015, NASA released a public version of TechPort with limited profiles for each project.

SPACE TECHNOLOGY DEVELOPMENT PORTFOLIO FACES FUNDING, PRIORITIZATION, AND DUPLICATION RISKS

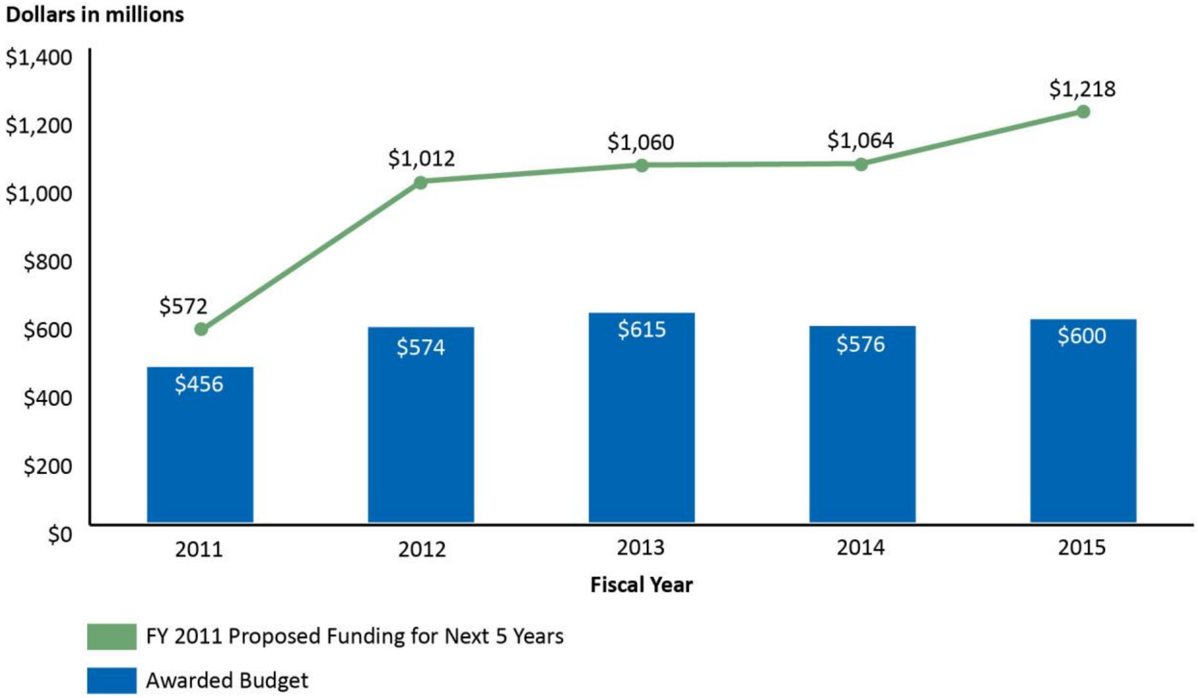
In recent years, NASA and NRC have identified multiple risks to the Agency's space technology development portfolio. For example, although NASA has 1,400 active space technology projects, Congress has not funded STMD, which funds the majority of these projects, at the level NASA requested for the past 5 years. Moreover, several of NASA's past space technology funding decisions do not appear consistent with the Agency's highest priority mission needs. At the same time, NASA can do more to avoid duplication of effort both within and outside the Agency on some space technology initiatives.

Space Technology Mission Directorate Not Funded at Planned Levels

As both NASA and NRC have noted, budgetary constraints have made it impossible for the Agency to carry out all the space technology projects outlined in the technology roadmaps and the SSTIP. According to NASA officials, when the roadmaps and STMD were created in 2010, NASA hoped to devote as much as $1 billion annually to STMD space technology projects beginning in FY 2012.[8] However, NASA's enacted budgets for FYs 2011 through 2015 ranged from $456 million to $615 million – more than $2 billion less than the amount proposed in the FY 2011 budget request for that time period (see Figure 2).

[8] STMD became a Mission Directorate in 2013 after originating as the Space Technology Program in 2010 under OCT. The effort to develop the roadmaps began in 2010 before their public release in April 2012.

Figure 2: NASA's 2011 Budget Proposal for STMD Versus Enacted Appropriations Amounts



Source: NASA Office of Inspector General analysis of NASA funding request and Agency appropriations.

The enacted funding levels have contributed to program changes and delays that have slowed project development. For example, STMD switched from demonstration testing in space to cheaper ground-based testing for its Cryogenic Propellant Storage and Transfer Project, which is examining methods for keeping liquid propellants stable over long periods of time in space. As a result, the Project's TRL has not advanced as quickly as NASA had planned. Similarly, STMD delayed the demonstration flight for the Solar Electric Propulsion Project by 2 years and reduced one of the test flights for the Low Density Supersonic Decelerator Project. Reduced funding also contributed to delays of 1.5 years for STMD's Laser Communication Relay Demonstration Project and 3 years for the Deep Space Optical Communication Demonstration Project. These schedule slips could delay the missions and applications for which the projects are needed, including the next generation Tracking and Data Relay Satellite System, the Asteroid Redirect mission, robotic and crewed Mars missions, Discovery missions, and the Space Launch System. As recently as April 2015, the NASA Advisory Council raised concerns about funding constraints, stating that because STMD's and HEOMD's current human exploration technology plans are inadequately funded they do not constitute a credible Mars Program.

Internal NASA and NRC Reports Have Noted Some Technology Funding Decisions Did Not Appear to Match NASA's Highest Priorities and that the Portfolio May Contain Duplicative Projects

Over the past several years, OCT has raised concerns that NASA's investments in certain high-priority areas, including radiation protection and nuclear propulsion systems, have been insufficient to make adequate progress toward finding the technological solutions necessary for long-duration exploration missions. At the same time, and despite significant investment in some cases from outside groups, the Agency has continued to fund projects in lower priority areas. For example, in a 2013 report, OCT pointed to atomic clock and additive manufacturing or "3-D printing" technology development efforts and noted that because many other Government agencies and industry groups are investing in these technologies, NASA could better leverage its limited funds by deemphasizing these issues and instead focusing on radiation or nuclear technologies.[9] In addition, in that same report, OCT pointed to projects in nuclear technology, 3-D printing, atomic clocks, carbon nanotubes and other nanotechnology, and medical technologies as potentially duplicative. For example, OCT expressed concern with the level of NASA's investment in 3-D printing technology in light of the approximately $1.3 billion investment the commercial sector is making in this technology. With regard to atomic clock technologies, OCT noted that the National Institute of Standards and Technology and the Department of Defense are supporting significant development efforts, dwarfing and making NASA's efforts duplicative and unlikely to lead to significant improvements in precision time-keeping technologies.

Similarly, in its 2012 review of NASA's roadmaps, NRC noted that several high-priority technologies necessary to support future human exploration missions urgently needed further development.[10] For example, projects focused on radiation protection, environmental control and life support systems, mobile pressure suits, lightweight rovers, improved human-machine interfaces, and in-situ resource utilization systems have not achieved the maturity levels necessary to enable NASA to execute its space exploration goals. Moreover, we found that NASA's technology spending in FY 2014 was nearly three times higher in the area of scientific instruments, observatories, and sensors than in the technical areas noted by NRC. In fact, spending in the human health, life support, and habitation systems and human exploration destination systems technology areas, as a percentage of all technology investments, decreased slightly between FYs 2012 and 2014.

In addition, NRC pointed to substantial private and public investment in nanotechnology efforts and noted that entities other than NASA will drive technology development in that area. NRC also noted the potential for substantial duplication of effort in this area, pointing to examples of nanosensor research at several NASA Centers. The report suggests NASA could partner with groups in industry, academia, and other Government agencies to leverage promising technologies already under development and target Agency funding to niche areas those entities are not funding and that relate to specific NASA missions.

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[9] NASA Planning, Programming, Budgeting, and Execution Issues Book, "OCT #2 – Technology Portfolio Optimization," July 2013.

[10] NRC, "NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space," 2012.

Improved Management Processes and Controls Would Help Ensure Space Technology Projects Better Address NASA's Future Mission Needs

NASA has instituted several initiatives to improve management of its space technology investments in recent years. However, we found deficiencies in the Agency's management processes and controls that may limit the usefulness of these efforts. Specifically, we found the Agency needs to (1) complete the ongoing update of its SSTIP to provide the necessary detail to determine the projects that best support Agency priorities, (2) ensure the information in TechPort is accurate and complete, (3) clarify the management structure and authorities for aligning and prioritizing projects, (4) formalize and integrate Mission Directorate and Center processes for initiating projects, and (5) develop processes to consistently measure and track projects' return on investment.

We acknowledge that managing space technology projects in a fluctuating budget environment is a significant undertaking. In our judgment, adopting management processes that improve NASA's ability to make strategic decisions regarding its space technology portfolio will help the Agency better manage this challenge.

Updated Strategic Planning Instruments Will Allow NASA to Better Identify the Projects that Best Support Agency Priorities

NASA uses its technology roadmaps and SSTIP to plan its technology investments. The roadmaps, first issued in 2012 and revised and reissued in 2015, identify a wide range of technologies and development pathways NASA missions are likely to require over the next 20 years in 15 technical areas. The SSTIP outlines the Agency's prioritization of these technology development areas over a 20-year period.

We found the 2012 versions of the roadmaps and SSTIP lacked sufficient detail to guide decision making, which limited their effectiveness as strategic tools. Specifically, as NRC pointed out in its review, some roadmaps did not explain why NASA needed a particular technology or indicate the capabilities and performance parameters necessary for missions to use the technologies. For example, NRC noted that an entire technology area within the Modeling, Simulation, Information Technology, and Processing Roadmap was focused on the development of multi-core processors yet the document contained no information regarding specific missions that would require these processors. Similarly, the original 2012 roadmaps did not distinguish between technologies that are absolutely critical to "enable" a future mission and those that would "enhance" existing capabilities. For example, large solar array structures to provide electrical power for solar electric propulsion are necessary to “enable” crewed missions to Mars, while radioisotope generators to power long-duration planetary missions will “enhance” existing capabilities.

We also found the 2012 SSTIP too general in some respects to enable the most effective prioritization of the Agency’s space technology investments. The SSTIP segregates the roadmaps’ broad technology areas – such as launch and in-space propulsion, scientific instruments and sensors, and power generation – into core, adjacent, and complementary categories. Based on these designations, project areas receive 70 percent, 20 percent, or 10 percent of the Agency’s technology dollars, respectively. While this strategy incorporates each of NRC’s highest priority technology recommendations, it also allows for numerous technologies not considered high priority to receive the same consideration for project funding because the definition of a core or adjacent technology is so broad it does not allow the Agency to further prioritize technologies within each category.[11] For example, the SSTIP’s core category of in-space propulsion includes technologies pertaining to multiple types of nonchemical propulsion such as solar electric, solar sail, thermal propulsion, and tether propulsion. Although solar electric and thermal propulsion are two of the roadmaps’ highest priority technologies, tether and solar sail propulsion are medium- and low-priority, respectively. Further, NASA included all 12 technologies in the Science Instruments, Observatories, and Sensor Systems Roadmap in the SSTIP’s core category even though NRC identified only about 6 of them as high-priority technologies. Moreover, NASA included 34 of the 37 technologies in the Robotics and Autonomous Systems Roadmap in the SSTIP’s core category even though NRC only identified 8 of the 37 as high priority. Overall, we traced back to the roadmaps each of the 222 technologies identified in the SSTIP as core or adjacent and found 139 that were not high priority.

We understand NASA’s prioritization strategy is influenced by factors other than NRC’s recommendations, including the priorities of other Government agencies and international partners. We also acknowledge the Agency needs to maintain a balanced space technology project portfolio that invests in a wide array of technologies, some of which many not have immediate relevance or relate to specific missions. However, by including so many technologies in its core and adjacent categories without further prioritization, NASA is potentially diluting funding from the Agency’s highest priority projects.

Finally, we found the lack of detail in the original roadmaps and SSTIP regarding the specific types of systems and capabilities NASA needs for its missions could lead to duplicative efforts. As such, nearly any type of project that related to the high-level technology descriptions could fall under one of the 15 technical areas. For example, many different types of systems can be developed within the nuclear thermal propulsion and power portfolios identified in the roadmaps and SSTIP as high-priority technology areas. However, the original 2012 roadmaps and SSTIP do not clearly identify the specific types of nuclear systems that would be most valuable for future missions. As a result, multiple NASA Mission Directorates have invested in various types of nuclear systems, including small, medium, and large fission, fusion, and nuclear thermal propulsion at an annual cost of nearly $24 million. As OCT pointed out in its 2013 paper, by spreading limited development funding across so many different types of systems, NASA risks duplicating efforts and having insufficient funds to enable any one system to develop to completion.[12]

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[11] NRC’s review of NASA’s technology roadmaps identified 83 high-priority technologies.

[12] NASA Planning, Programming, Budgeting, and Execution Issues Book, “OCT #2 – Technology Portfolio Optimization,” July 2013.

During the course of our audit NASA issued a revised set of roadmaps and was in the process of updating the SSTIP. To NASA's credit, the 2015 roadmaps provide additional information regarding how specific technologies will help meet Agency mission objectives and address the major deficiencies we identified in the 2012 roadmaps. In our judgment, the new roadmaps better link technologies with specific missions; identify need-by dates, required capabilities, and performance parameters; and distinguish between enabling and enhancing technologies. These improvements should help NASA focus funding on high-priority technologies.

TechPort Database Remains Incomplete and Contains Inaccurate Data

OCT developed TechPort in response to requests and concerns from the Office of Management and Budget and NRC regarding the importance of capturing, managing, and sharing NASA's space technology advancements with other Federal agencies, academic institutions, commercial enterprises, and the general public. Although TechPort has been operational since September 2012, it remains incomplete and there are concerns about the accuracy of information it contains.

As noted earlier, TechPort became available to NASA employees and contractors in 2012, and in March 2015, NASA made some of the information in the system available to the public. After the public release, we selected a sample of 49 active AES and STMD projects and examined related information in TechPort. We found that for 16 (33 percent) of the projects, the database contained no information. For example, at the time of our review, TechPort contained no information about the Solar Electric Propulsion Project, one of NASA's largest and most critical technologies to enable cost-effective trips to Mars. In addition, although TechPort contained information about the other 33 projects in our sample, for 30 of those projects the system lacked mission use agreements, 9 lacked FY 2014 budget data, and 5 did not report project milestones.[13]

According to a NASA official, the system remains incomplete and contains inaccurate data because project managers intentionally withhold or manipulate data, including information on budget, schedule, benefits received, and mapping to roadmap technical areas. For example, the official stated that after TechPort was released to the public as many as 35 active Center institutional research and development space technology projects were deleted from the system. The official indicated that although the Centers described the projects as a small percentage of the total space technology development portfolio and therefore not required to be entered into TechPort, Centers sometimes remove or withhold information from the system so that other Centers against whom they compete will not have full insight into their projects.

Consistent with our findings, a December 2014 NASA Independent Review Board study found TechPort data incomplete. In addition, a member of the TechPort Independent Review Board stated that information concerning financial data, benefits and expected results, and the link between the projects and NASA's roadmaps was missing for a large number of projects.[14] The study identified concerns Mission Directorate and Center personnel had with utilizing the system. Specifically, Mission Directorates and Centers had concerns that data could be misinterpreted, which in turn could lead to

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[13] Mission use agreements document the planned infusion path for a technology from developer to recipient interest in the technology to ensure NASA's expenditures are both desired and necessary.

[14] NASA Independent Review Board, "TechPort Independent Review Board Findings," December 2014.

incorrect judgments about projects and loss of funding or cancellation. In addition, Center personnel admitted they had not entered data into TechPort because they feared the visibility and insight into their projects the system provides could disadvantage them as they compete with other Centers for work. Further, Mission Directorate personnel questioned the relevance of an Agency-wide system since the Directorates already have tools to manage space technology projects. The Mission Directorates also felt OCT was overstepping the bounds of its authority by attempting to use TechPort as a management tool and indicated they did not want OCT interfering with their projects, fearing that the information entered in to the system would be used by internal and external sources to make misinformed decisions about investments.

To address some of these issues, NASA has begun to import financial data concerning space technology projects directly from the Agency's accounting system and has locked that data so that project managers and other users cannot edit or remove it. In addition, NASA's Associate Administrator issued a memorandum in March 2015 reiterating that Mission Directorates, Offices, and Centers that fund technology development are responsible for entering into TechPort accurate information about their programs and projects and verifying that the data is current, complete, and correct at least twice each fiscal year.

Despite these efforts, as of June 2015, TechPort remains incomplete and the accuracy of the project information in the system questionable. In our judgment, NASA must take further steps to overcome the reluctance of project personnel to enter required information in to TechPort.

Clarifying Management Structure and Authorities Will Assist Efforts to Align and Prioritize Space Technology Projects

Multiple NASA offices and entities coordinate and fund the Agency's technology development efforts. In addition, Mission Directorates and related program management councils assess individual projects for formulation, performance, and continuation decisions, while the Executive Council – NASA's senior decision-making body – decides issues of significant strategic direction and financial impact.

We found that current roles and authorities for monitoring, aligning, and prioritizing the Agency's space technology investments are unclear, and that Mission Directorates and Centers tend to invest in and manage projects at their discretion. In our judgment, absent a clearer process for overseeing its technology development portfolio, NASA increases the risk of duplicative efforts or of funding projects that do not meet the Agency's future needs and priorities.

We found the role of NTEC to be particularly unclear. While NTEC plays a key role in assessing and prioritizing the budget and schedule of NASA's space technology project portfolio, the Council currently does not have a formal charter. Moreover, NASA neither included NTEC in its recently updated Organizational Handbook nor listed the Council on the Agency's official organizational chart.[15] We found confusion about NTEC's overall purpose and its specific roles and responsibilities within the Agency. In addition, according to the Agency's 2010 Technology Integration Governance Policy, NTEC has the authority to issue decisional recommendations to coordinate, prioritize, or align space technology

[15] NASA Policy Directive 1000.3E, "The NASA Organization w/Change 2," April 15, 2015.

investments, which become final adjudications if all members concur.[16] These decisions can include reviews of individual projects against milestones, assessments of programs for budget and schedule adequacy, identification of technology gaps and overlaps, comparisons of technology maturation to NASA technology roadmaps and strategic goals, reviews and approval of the SSTIP, and prioritization of NASA's technology portfolio. In practice, however, we found that the authority the decisional recommendations have, where they go after approval, and how Mission Directorates are supposed to incorporate them into program and project planning are unclear.

The story of SMD's Advanced Stirling Radioisotope Generator (ASRG) Project illustrates several of the issues surrounding the NTEC process.[17] The ASRG Project could be used to enable or significantly enhance missions to destinations where inadequate sunlight, harsh environmental conditions, or operational requirements make other electrical power systems infeasible, such as the surface of Mars, Jupiter's moon Europa, or Saturn's moon Titan. NASA officials estimated the ASRG Project had the potential to generate a higher level of electricity using significantly less plutonium than the Multi-Mission Radioisotope Thermal Generator – roughly 1 kilogram compared to 5 kilograms, respectively – currently in use.[18]

In March 2013, all NTEC members, including the SMD representative, signed a decisional recommendation for SMD to complete the ASRG Project. At the time, NTEC's decision was considered a final adjudication because all NTEC members concurred. However, in July 2013, SMD started the process to cancel the ASRG Project. Although OCT, the Glenn Research Center, and the Project Manager submitted a recommendation to reestablish funding through the Executive Council's budget planning process, their proposal was not approved and the ASRG Project was officially cancelled in October 2013. Following this decision, NTEC members signed another recommendation stating ASRG technologies should be an Agency priority to enable science missions and human Mars surface missions. In January 2015, NASA's Technical Capability Assessment Team questioned SMD's decision to cancel the ASRG Project, stating the decision was unreasonable and SMD should have followed NTEC's guidance.[19] SMD officials stated that the decision-making authority over SMD space technology projects properly rests with them, not NTEC, and that in any event, the decision to cancel the ASRG Project was approved by the SMD Program Management Council.

After the ASRG Project was cancelled, SMD published a study to review future missions' nuclear power needs, including radioisotope power generation.[20] Issued in February 2015, the study found significant communication issues between HEOMD, SMD, and STMD, and external sources such as the Department of Energy as well as unclear lines of authority, responsibility, and management. The study recommended HEOMD and SMD improve coordination and that NASA nuclear investments be coordinated with the Department of Energy. STMD officials stated cancellation of the ASRG Project and

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[16] NASA, "NASA Technology Integration Governance Policy," May 2010.

[17] A radioisotope generator uses heat given from the decay of Plutonium 238 to expand a liquid and move a piston, similar to an alternator, to generate electricity.

[18] Over the past 50 years, NASA has used Multi-Mission Radioisotope Thermal Generators to generate power in the Apollo, Voyager, and Mars Rover Missions.

[19] The Technical Capability Assessment Team was tasked with establishing a more efficient Agency operating model that would maintain critical capabilities and meet current and future mission needs. As part of this process, the team reviewed NASA's nuclear power and propulsion capabilities, including cancellation of the ASRG Project.

[20] NASA, "Nuclear Power Assessment Study Final Report," February 2015.

the ensuing confusion delayed several STMD space technology projects, including development of components for the Stirling device for more than 1 year.

Another example is a 2013 NTEC recommendation on NASA's investments in highly mature and large-scale nuclear power research. The recommendation stated the Agency should reduce investments in highly mature and large-scale nuclear power research in favor of nuclear thermal propulsion and small-scale fission propulsion research. In August 2013, the Executive Council approved an OCT proposal for the FY 2015 budget to reallocate nuclear investments to increase funding for nuclear thermal propulsion and small fission activities. However, as of FY 2015, the Agency's only investment in nuclear thermal propulsion is AES's Nuclear Thermal Propulsion Project and its annual budget has remained relatively unchanged at approximately $7 million for the past 2 years. Moreover, the Agency does not have plans to initiate any small fission power projects until at least FY 2016, more than 2 years after NTEC and OCT recommended refocusing the projects. STMD officials explained the small fission power project was not started until HEOMD and SMD completed needs assessment studies, which were finalized roughly 2 years after the initial NTEC memorandum.

We do not question the reasonableness of the decisions made in the examples discussed and acknowledge there will always be a range of opinions on the proper prioritization and alignment of NASA's space technology projects. However, the examples demonstrate the management structure for space technology projects is unclear and the process lacks a formalized authority to identify issues across the Agency's entire portfolio and enforce strategic technology decisions. In our view, this increases the risk NASA will not be in a position to develop critical technologies needed to enable future missions.

More Formal and Integrated Processes for Initiating Space Technology Projects Would Help Ensure Cohesion and Guard against Duplication

NASA's Mission Directorates and Centers have the funding and authority to initiate new space technology projects. Despite this broad authority, we found the Agency's project management policies provide little guidance on the process these offices should follow to coordinate projects.[21] Rather, the policy delegates the authority to initiate a project to the Associate Administrator of each office who is responsible for ensuring that the start of a new project is aligned with the Agency's mission and critical technology needs. However, we found no formal requirements to coordinate decisions with other NASA entities that have similar planned or ongoing space technology projects or that could benefit from and perhaps participate in development. NASA officials identified varying degrees of integration and coordination among the Mission Directorates, such as attending each other's meetings when deciding what new projects to add to their technology portfolios and to prevent duplicative efforts, but procedures have not been formally documented to ensure consistent implementation.

Agency-wide policy for initiating new space technology projects requires project managers to conduct a literature review of related projects both within and outside NASA and document the results in project plans. The intent of this review is to leverage existing investments and avoid duplicating research and development activities. However, the policy allows the review to be conducted after authority to begin

[21] The requirements related to space technology project initiation are found in NASA Procedural Requirements 7120.8, "NASA Research and Technology Program and Project Management Requirements," February 2008.

a project has already been granted. Moreover, our analysis of a sample of space technology projects in AES and STMD revealed that only 3 of 34 projects actually conducted literature reviews.

In our judgment, a more formalized process to coordinate and initiate new space technology projects would better ensure the consistency and cohesion required to prioritize investments and guard against duplication. The initiation process would also benefit from including OCT's data mapping of NASA's space technology investments to mission requirements.[22] Utilizing this data in connection with a formal project initiation process would help ensure new investments are focused in the technology areas with the greatest unmet needs and NASA does not spend its limited resources funding space technology areas that are already receiving sufficient attention or for which no mission need exists.

Consistent Processes to Measure and Track Space Technology Projects' Return on Investment Could Increase Infusion Rates and Prevent Duplication

We found the Mission Directorates do not consistently perform project closeout reviews on space technology projects. In order to assess return on investment, NASA policy requires all completed space technology development projects perform a closeout review describing accomplishments, independent assessments of final maturity levels and any other maturity measures, and lessons learned.[23] However, we found STMD performs closeout reviews only for large projects and HEOMD does not follow the process for AES projects.

The lack of closeout reviews has made it difficult for NASA to assess space technology projects' return on investment. NASA's 2014 Strategic Plan directs the Agency to facilitate technology infusion; however, because of insufficient data, a September 2014 Agency-wide analysis by OCT was unable to determine how many space technology projects were infused into missions or if the projects advanced their TRLs. In addition, we found that even when closeout reviews are completed, some Mission Directorates store related documentation in multiple locations, making it difficult for potential users to find. Only SMD made closeout documents accessible on an external e-books portal. Although NASA policy does not instruct Mission Directorates on how to track and store closeout documents, STMD officials indicated they are in the process of finalizing a storage location on their webpage to track this information.

NASA officials we spoke with are concerned that the lack of consistent closeout documentation and an accessible central repository for tracking results may lead to duplication, noting that if closeout procedures are not completed and the results readily available, users who do not have knowledge of the project or results may replicate the work. Moreover, without closeout reports NASA cannot determine how many of their space technology investments are being infused into missions or ensure future projects can utilize project results. In our judgment, including projects' results and infusion information as part of the closeout process for all space technology projects in one central location, such as TechPort, will assist the Agency in evaluating its return on investment in these projects.

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[22] OCT is in the process of mapping the Agency's technology investments to mission requirements to identify areas that have more investments than needed, as well as gaps where investments are needed but none exist. OCT hopes to use this data to make investment recommendations that better align the Agency's space technology development portfolio.

[23] The requirements related to technology closeout procedures are found in NASA Procedural Requirements 7120.8.

CONCLUSION

As NASA undertakes increasingly challenging missions to deep space destinations, it is essential the Agency identify and mature technologies that can increase the affordability, safety, and feasibility of such missions. Personnel from inside and outside the Agency have voiced concerns regarding the alignment and prioritization of NASA's technology development investment, and budgetary constraints have only intensified the need for a more focused and effective prioritization process. While NASA has made positive steps to better align and prioritize its space technology projects over the past 5 years, we found shortcomings in the Agency's management processes and controls that could limit the effectiveness of technology investments and delay future missions.

To address these deficiencies, NASA will need to complete the process of updating the Agency's SSTIP to provide the detail necessary to inform strategic decision making. In addition, developing policy regarding the mandatory use of the TechPort database will help ensure decision makers have the necessary data to make informed project investment and divestment decisions. Moreover, creating a formal charter for NTEC will assist in clarifying its roles and authorities. Finally, creating and formalizing both project initiation and closeout processes, including evaluating return on investment, will ensure a more integrated and cohesive process for new space technology projects and allow the Agency to measure the benefits and usefulness of the projects it undertakes.

RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To clarify the role and authorities of NTEC, we recommended the NASA Administrator

1. develop a charter outlining NTEC's role, responsibilities, authority, and membership.

To ensure management processes and controls better align and prioritize NASA's space technology projects with its mission goals, we recommended the Office of the Chief Technologist

2. further prioritize technologies identified as "core" and "adjacent" in the new SSTIP and
3. take steps to ensure that project managers utilize TechPort as intended. This could include additional training, policy clarification, or other measures to incentivize its use and increase accuracy.

In addition, we recommended NASA's Office of the Chief Engineer update NASA Procedural Requirements 7120.8 to establish policy and procedures for

4. initiating space technology projects that include Agency-wide awareness and coordination and
5. requiring all concluded technology projects complete closeout reports and technology infusion or transfer data for inclusion in TechPort.

We provided a draft of this report to NASA management. NASA's Deputy Administrator concurred with recommendations 1, 2, and 3 and described planned corrective actions. We will close these recommendations upon completion and verification of the proposed corrective actions.

The Deputy Administrator partially concurred with recommendations 4 and 5. With regard to recommendation 4, she disagreed with our suggestion to revise NASA Procedural Requirements 7120.8 but suggested alternative steps to improve awareness and coordination during technology project initiation. Although we find the Deputy Administrator's response encouraging, we continue to believe any remedial actions NASA takes should be properly documented in the appropriate Agency policy. Accordingly, this recommendation is unresolved pending further discussion with the Agency.

Regarding recommendation 5, the Deputy Administrator noted that policy related to closeout reports already exists in NASA Procedural Requirements 7120.8. We encourage the Agency to review that policy and take appropriate steps to ensure it clearly includes the requirement for a closeout review on all technology projects. As noted in the report, we found STMD performs closeout reviews only for large projects and HEOMD does not follow the process for AES projects. In addition, while we find the Deputy Administrator's suggestions for including additional data in TechPort encouraging, we continue to believe that the requirement should be properly documented in Agency policy. Therefore, this recommendation is unresolved pending further discussion with the Agency.

Management's full response to our report is reproduced in Appendix D. Technical comments provided by management have also been incorporated, as appropriate.

Major contributors to this report include, Ridge Bowman, Space Operations Director; Michael Brant, Project Manager; Megan Paxton; Andrew McGuire; and Robert Proudfoot.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from July 2014 through November 2015 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

We reviewed Federal and NASA policies, regulations, plans, and roadmaps to determine the requirements and criteria for the management of space technology projects. The documents we reviewed include the following:

- "National Aeronautics and Space Administration Authorization Act of 2010," Pub. L. No. 111-267, Title XI, October 11, 2010
- NASA Procedural Requirements 7120.8, "NASA Research and Technology Program and Project Management Requirements (w/change 3 dated 04/18/13)," February 5, 2008
- NASA Procedural Requirements 7120.5E, "NASA Space Flight Program and Project Management Requirements w/Changes 1-11," August 14, 2012
- "NASA Strategic Space Technology Investment Plan," December 5, 2012
- "Space Technology Roadmaps," 2012 and 2015

To gain a general understanding of the management of space technology projects we interviewed officials from NASA's Office of the Chief Technologist, Space Technology Mission Directorate, Advanced Exploration Systems, Office of the Chief Scientist, and Office of the Chief Engineer. We also interviewed two former NASA Chief Technologists.

We assessed the process used to initiate a space technology process and the methods used to gauge return on investments. We reviewed the organizational structure of NASA's Office of the Chief Technologist and the functionality of NASA's technology councils. We reviewed prior internal and external reports and other analyses that documented concerns with space technology projects.

We judgmentally selected a sample of 50 space technology projects active in August 2014. However, during our review, one of the 50 projects was cancelled, reducing our sample to 30 AES projects and 19 STMD projects. All 49 space technology projects are associated with future human exploration missions. We distributed questionnaires to AES and STMD project managers to obtain information and documentation on the space technology projects' cost, schedule, TRLs, and relationships to NASA's missions. We used the information and documentation provided to determine if the Agency's TechPort system was complete and accurate.

Use of Computer-Processed Data

We used computer-processed data for our assessment of the space technology projects contained in the NASA TechPort system to perform this audit. We obtained data from the system for the period of July 2014 through March 2015 to evaluate our judgmental sample of space technology projects. We performed audit steps to validate the accuracy of a limited amount of data contained in the system, however, the data is only as accurate as that entered by the project managers. The accuracy of the data did not affect our conclusions.

Review of Internal Controls

We evaluated the internal controls associated with the execution and management of space technology projects. The control weaknesses we identified are discussed previously in this report. Our recommendations, if implemented, will correct the identified control weaknesses.

Prior Coverage

During the last 5 years, the NASA Office of Inspector General (OIG), the Government Accountability Office (GAO), and the National Research Council have issued three reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/reports/FY16/index.html, http://www.gao.gov, and http://www.nap.edu, respectively.

NASA Office of Inspector General

NASA Efforts to Manage Health and Human Performance Risks for Space Exploration (IG-16-003, October 29, 2015)

Government Accountability Office

NASA Assessments of Selected Large-Scale Projects (GAO-15-320SP, March 2015)

National Research Council

NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space (2012)

APPENDIX B: NASA TECHNOLOGY READINESS LEVELS

Table 6 outlines criteria NASA utilizes for categorizing space technology projects into TRLs, ranging from TRLs 1 through 9. NASA managers use these standards to assess the status of the Agency's space technology projects.

Table 6: Technology Readiness Levels

Technology Readiness Level	Description	Hardware	Demonstration Environment
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.	None (paper studies and analysis)	None
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.	None (paper studies and analysis)	None
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Analytic studies and demonstration of nonscale individual components (pieces of subsystem).	Lab
4. Component and/or breadboard. Validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of ad-hoc hardware in a laboratory.	Low-fidelity breadboard.[a] Integration of nonscale components to show pieces will work together. Not fully functional or form or fit but representative of technically feasible approach suitable for flight articles.	Lab
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include high-fidelity laboratory integration of components.	High-fidelity breadboard. Functionally equivalent but not necessarily form and/or fit (size, weight, or materials). Should be approaching appropriate scale. May include integration of several components with reasonably realistic support elements/subsystems to demonstrate functionality.	High-fidelity Lab demonstrating functionality but not form and fit. May include flight demonstrating breadboard in surrogate aircraft.

6. System/ subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system that is well beyond the breadboard tested for TRL-5 tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated realistic environment.	Prototype. Should be very close to form, fit, and function. Probably includes the integration of many new components and realistic supporting elements/ subsystems if needed to demonstrate full functionality of the subsystem.	High-fidelity lab demonstration or limited/ restricted flight demonstration for a relevant environment. Integration of technology is well defined.
7. System prototype demonstration in a realistic environment	Prototype near or at planned operational system. Represents a major step up from TRL-6, requiring the demonstration of an actual system prototype in a realistic environment, such as in an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.	Prototype. Should be form, fit, and function integrated with other key supporting elements/subsystems to demonstrate full functionality of subsystem.	Flight demonstration in representative realistic environment such as flying test bed or demonstrator aircraft. Technology is well substantiated with test data.
8. Actual system completed and "flight qualified" through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended system to determine if it meets design specifications.	Flight qualified hardware	Developmental Test and Evaluation in the actual system application
9. Actual system "flight - proven" through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug-fixing" aspects of true system development. Examples include using the system under operational mission conditions.	Actual system in final form	Operational Test and Evaluation in operational mission conditions

Source: NASA Office of Inspector General presentation of GAO information.

[a] A breadboard is a low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software.

Appendix C: NASA's Space Technology Programs

NASA's Space Technology Mission Directorate (STMD), Human Exploration and Operations Mission Directorate (HEOMD), and Science Mission Directorate (SMD) all fund technology development programs. A summary of each Mission Directorate's programs and FY 2015 technology development funding is provided in Table 7.

Table 7: Overview of NASA's Space Technology Programs

Space Technology Programs	FY 2015 Funding
STMD Space Technology Programs	
Small Business Innovation Research and Small Business Technology Transfer	$190,700,000
Technology Demonstration Missions (TDM)	$161,900,000
Game Changing Development (GCD)	$125,600,000
Space Technology Research Grants	$23,700,000
Office of Chief Technologist	$31,300,000
Small Spacecraft Technology	$19,300,000
Center Innovation Fund	$12,900,000
Flight Opportunities	$10,000,000
NASA Innovative Advanced Concepts	$7,000,000
Centennial Challenges	$4,200,000
STMD Total[a]	**$600,300,000**
HEOMD Space Technology Programs	
Advanced Exploration Systems (AES)	**$170,900,000**
SMD Space Technology Programs	
Astrophysics	$65,700,000
Earth Science	$59,700,000
Planetary Science	$49,000,000
Heliophysics	$4,700,000
SMD Total	**$179,100,000**
Total FY 2015 Funding for NASA's Space Technology Programs	**$950,300,000**

Source: NASA Office of Inspector General analysis of program budget data.

[a] Roughly $14 million of STMD funding goes toward Space Technology Operations and the Strategic Integration Office.

Appendix Focus

For this appendix, we chose the top 15 space technology projects by FY 2015 funding level in the following programs: STMD's GCD and TDM programs, HEOMD's AES, and SMD projects in each of its four divisions. These programs represent the majority of large projects developing technologies for future science and human missions.

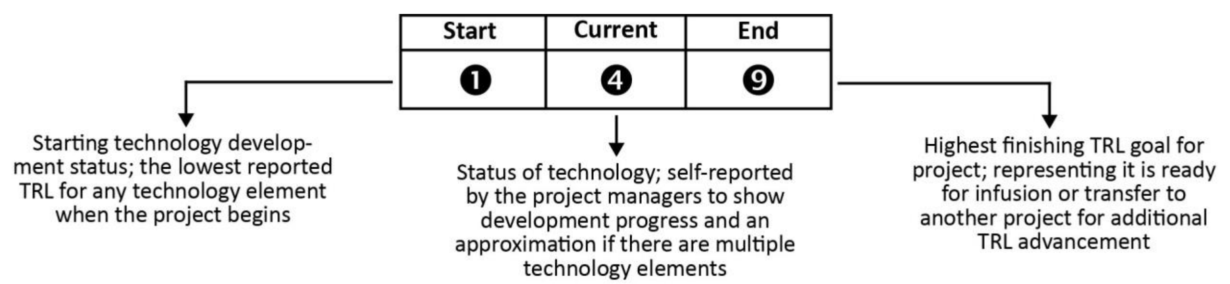
Other programs were not included because they either did not directly fund space technology projects for TRL advancement or the projects were of relatively low dollar value. In particular, STMD's Small Business Innovation Research/Small Business Technology Transfer program, with an annual budget of $190.7 million, was not included because its roughly 500 individual projects have individual budgets ranging from several hundred thousand dollars to no more than $2 million. The following five other STMD programs also have low budgets for individual projects: Space Technology Research Grants, Small Spacecraft Technology, Center Innovations Fund, Flight Opportunities, NASA Innovative Advanced Concepts, and Centennial Challenges.[24] In addition, the Office of the Chief Technologist funds prizes and challenges, but the majority of funding is for the Strategic Technology Integration and Technology Transfer offices. We did not review HEOMD's Human Research Program, which focuses on human health in space because the Program does not directly fund space technology projects; however, we examined NASA's efforts in this area in a report issued in October 2015.[25]

Space Technology Project Snapshots

For each program, the top 15 projects are subsequently profiled by FY 2015 funding levels. In addition to a program description, each profile includes the following elements:

- *Funding allocations.* Provided by NASA's Office of the Chief Financial Officer and adjusted based on program manager input for changes after yearly funding obligations.
- *Start and proposed end dates.* Provided by TechPort and program managers.
- *Link to Technology Roadmap.* Obtained from NASA's Technology Roadmaps, ranging from TA01 to TA14.
- *Link to future mission.* Provided by project managers and includes potential infusions for future missions.
- *TRL progression.* Provided by project managers who evaluate and assign a TRL rating from 1–9 based on the project's progress at the "start," "current," and "end" (see Figure 3).[26] A detailed explanation of the nine TRL levels can be found in Appendix B.

Figure 3: TRL Progression



Source: NASA Office of Inspector General.

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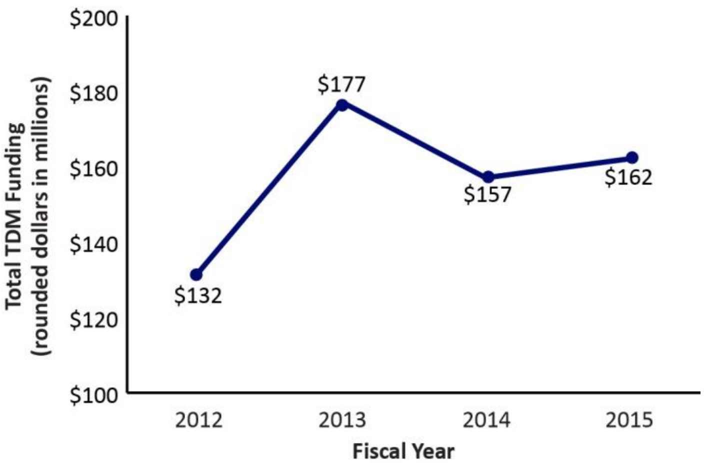
24 The Flight Opportunities Program does not develop space technology projects but provides microgravity flights to demonstrate and test other technologies.

25 NASA Office of Inspector General, "NASA Efforts to Manage Health and Human Performance Risks for Space Exploration" (IG-16-003, October 29, 2015).

26 We did not independently review information related to funding, proposed dates, links to roadmaps and missions, and TRLs.

TECHNOLOGY DEMONSTRATION MISSIONS



Source: NASA.

STMD's Technology Demonstration Missions (TDM) Program focuses on technologies that have already demonstrated proof of concept and completed component or subsystem testing (TRL-6 or greater). The TDM Program provides funding to test prototypes in realistic mission-like environments. Once tested and advanced past TRL-6, NASA is much more likely to infuse technologies into Agency missions. In addition, testing reduces mission risks while also potentially reducing costs. In FY 2015, TDM's budget was $161.9 million, trending lower than the previous 2 years. Over the past 4 years, the TDM Program received $627.7 million in funding.

TDM's Projects for FY 2015

1. LOW DENSITY SUPERSONIC DECELERATOR

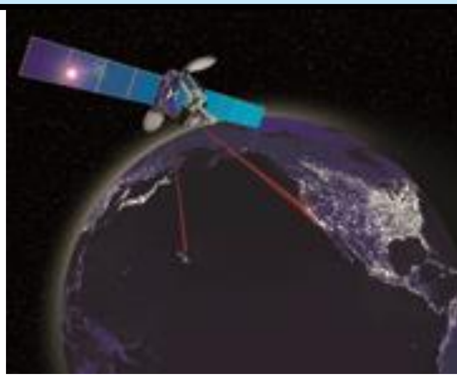
Artist's rendering Low Density Supersonic Decelerator above Earth. Source: NASA.

FY 2015 Funding	$38 million (23% of TDM)		
Total Funding, FYs 2012–2015	$196.2 million (31% of TDM)		
Lead Center	Jet Propulsion Laboratory		
Start Date	September 2010		
Proposed End Date	December 2016		
TRL Progression	Start	Current	End
	❹	❹	❻

Link to Technology Roadmap	Link to Future Missions
Entry, Descent, and Landing Systems (TA09)	Robotic/Manned Mars Missions

The Low Density Supersonic Decelerator Project inflates balloons around space vehicles and tests supersonic parachutes to decelerate large payloads in thin or low density atmospheres such as Mars, potentially doubling the payload weight for a Mars surface mission by effectively slowing the heavier landers. This Project hopes to validate deceleration of heavier vehicles by testing a 6-meter inflatable device, 8-meter inflatable device, and 33.5-meter supersonic parachute. The first demonstration mission in June 2014 tested the flight vehicle and inflatable balloon system but the parachute failed to deploy properly. The second demonstration in June 2015 was partially successful, although the parachute again failed to deploy. The third and final test flight had been scheduled for July 2015 but was rescheduled for the summer 2016. These tests will allow the Project to advance to prototype testing in a relevant environment (TRL-6).

2. LASER COMMUNICATIONS RELAY DEMONSTRATION



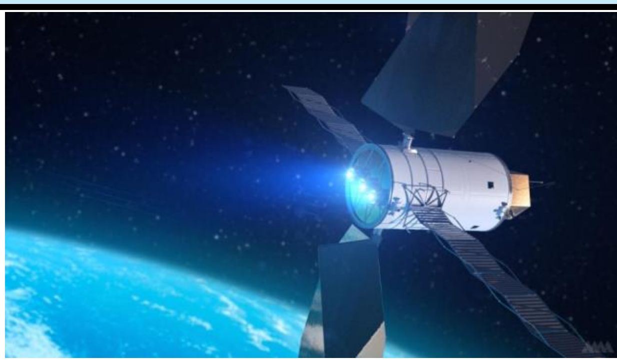
Artist's rendering of Laser Communications Relay Demonstration system testing data transmittal by laser. Source: NASA.

FY 2015 Funding	$37 million (23% of TDM)		
Total Funding, FYs 2012–2015	$121.4 million (19% of TDM)		
Lead Center	Goddard Space Flight Center		
Start Date	October 2011		
Proposed End Date	December 2019		
TRL Progression	Start	Current	End
	❻	❻	❾

Link to Technology Roadmap	**Link to Future Missions**
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (TA05)	Space Communication and Navigation Program

The Laser Communications Relay Demonstration Project (LCRD) will test lasers on a commercial satellite to transmit data to and from Earth or other satellites at a rate 10 to 100 times faster while using less power than current space radio wave communications. LCRD is NASA's first, long-term optical communication mission and, if successful, could enable delivery of high-resolution science data from spacecraft throughout the solar system. NASA's Space Communications and Navigation Program plans to contribute roughly $57 million between FYs 2012 and 2019 to infuse the technologies into its next-generation space communication relay systems. LCRD is scheduled to advance to TRL-9 through launch on a commercial satellite in 2018 for 2 years of operations and testing.

3. SOLAR ELECTRIC PROPULSION



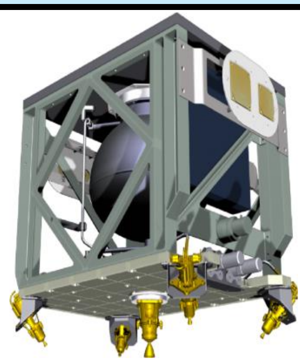
Artist's rendering of the Solar Electric Propulsion Project. Source: NASA.

FY 2015 Funding	$35.9 million (22% of TDM)		
Total Funding, FYs 2012–2015	$43.9 million (7% of TDM)		
Lead Center	Glenn Research Center		
Start Date	September 2013		
Proposed End Date	September 2021		
TRL Progression	Start	Current	End
	❹	❺	❾

Link to Technology Roadmap	**Link to Future Missions**
In-Space Propulsion Technologies (TA02)	Asteroid Redirect Mission; Deep Space Exploration Missions

The Solar Electric Propulsion Project (SEP) will demonstrate a large electric propulsion module with the potential to use 10 times less propellant than current chemical propulsion engines. SEP will combine efficient solar panels and a 30–50 kilowatt "Hall Thruster" electric propulsion drive. A Hall Thruster accelerates a propellant like xenon through an electrical field to create small thrust impulses to accelerate up to 65,000 miles per hour. The Project will be the largest test of the Hall Thruster technology to date and will establish the validity of the technology for cost-effective missions to asteroids or Mars. SEP is scheduled to advance to TRL-9 through a full-scale demonstration in 2019.

4. GREEN PROPELLANT INFUSION MISSION



Design for Green Propellant Infusion Mission payload with thrusters and green propellant. Source: NASA.

FY 2015 Funding	$16.1 million (10% of TDM)		
Total Funding, FYs 2012–2015	$54.1 million (9% of TDM)		
Lead Center	Marshall Space Flight Center		
Start Date	October 2012		
Proposed End Date	2017		
TRL Progression	Start	Current	End
	❺	❺	❼

Link to Technology Roadmap	**Link to Future Missions**
In-Space Propulsion Technologies (TA02)	Unknown; Potentially NASA and Commercial Missions

The Green Propellant Infusion Mission Project demonstrates the use of a nontoxic replacement to hydrazine for in-space maneuvering. This Project replaces hydrazine, an efficient but corrosive and toxic propellant used in rockets and satellites, with safer "green" propellant. The propellant system will expand current mission capabilities, reduce ground-handling costs, and increase handling safety. The Project is also developing new thrusters for the propulsion system and is scheduled to advance to TRL-7 through a prototype demonstration in space in 2016 using a Ball Aerospace spacecraft launched from a SpaceX Falcon Heavy rocket.

5. EVOLVABLE CRYOGENICS

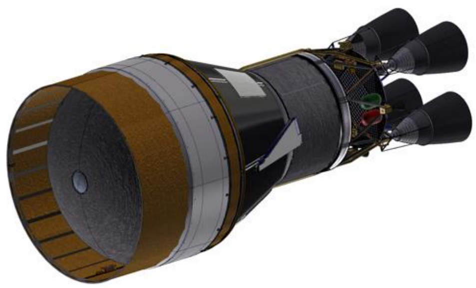
Workers at Glenn Research Center testing methods to reduce liquid hydrogen boil-off. Source: NASA.

FY 2015 Funding	$12.9 million (8% of TDM)		
Total Funding, FYs 2012–2015	$12.9 million (2% of TDM)		
Lead Center	Glenn Research Center		
Start Date	2014		
Proposed End Date	June 2019		
TRL Progression	Start	Current	End
	❹	❺	❻

Link to Technology Roadmap	**Link to Future Missions**
In-Space Propulsion Technologies (TA02)	Space Launch System

The Evolvable Cryogenics Project will demonstrate the capability to safely and efficiently store propellants in space for long missions or refueling. The goal of this Project is to develop new methods of managing cryogenic or low-temperature fluids for the space industry and NASA's Space Launch System. The Project will complete ground testing in a relevant environment for advancement (TRL-6) by 2019, which includes pressurized tank testing, validation of a fuel measuring system, and development of an integrated fluids system technologies.

6. COMPOSITES FOR EXPLORATION UPPER STAGE



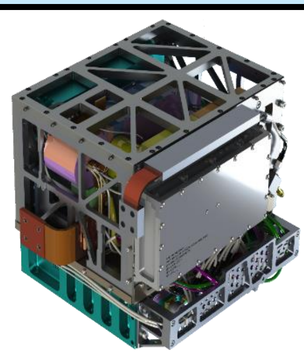
Design for composite components for the Space Launch System upper stage. Source: NASA.

FY 2015 Funding	$6.9 million (4% of TDM)		
Total Funding, FYs 2012–2015	$7.2 million (1% of TDM)		
Lead Center	Marshall Space Flight Center		
Start Date	June 2014		
Proposed End Date	August 2017		
TRL Progression	Start	Current	End
	5	5	6

Link to Technology Roadmap	Link to Future Missions
Materials, Structures, Mechanical Systems, and Manufacturing (TA12)	Space Launch System

The Composites For Exploration Upper Stage Project is developing composite components for the upper stage of the Space Launch System to decrease weight and potentially increase low Earth orbit payloads up to 25 metric tons. Using composite material technology, the Project will design and test a 8.4 meter-wide upper stage skirt, which is the outside cylindrical structure of the rocket. This Project uses an automated fiber placement system with robotic technology to develop the prototypes at Marshall Space Flight Center. The Project is scheduled to advance to TRL-6 through ground-based testing of the composite components and system demonstration in a relevant environment by 2017.

7. DEEP SPACE ATOMIC CLOCK



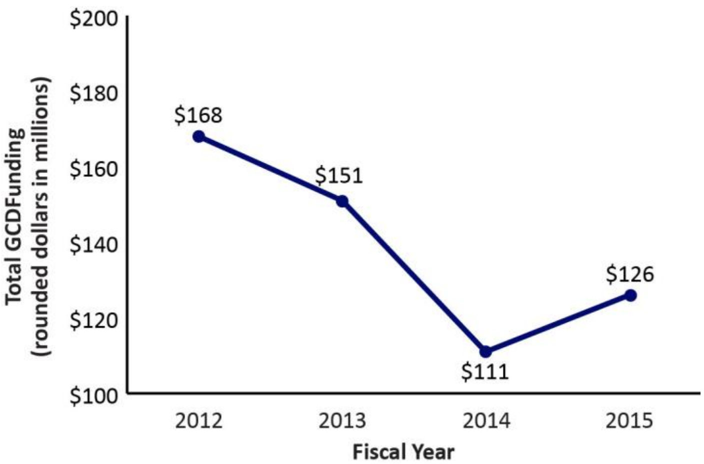
Design for Deep Space Atomic Clock, scheduled for launch in 2016. Source: NASA.

FY 2015 Funding	$5.1 million (3% of TDM)		
Total Funding, FYs 2012–2015	$29.9 million (5% of TDM)		
Lead Center	Jet Propulsion Laboratory		
Start Date	August 2011		
Proposed End Date	June 2017		
TRL Progression	Start	Current	End
	5	5	7

Link to Technology Roadmap	Link to Future Missions
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (TA05)	Space Communications and Network

The Deep Space Atomic Clock Project demonstrates mercury-based atomic clock technology that isolates ultra-precise vibrating mercury ions for timekeeping for potential use on space vehicles for communication, navigation, and scientific research. This Project may offer unique capabilities similar to Earth-based global positioning systems by using a one-way signal system for deep space navigation. The more accurate clock will also allow researchers to account for the effects of relativity, or the relative motion of an observer and observed objected, as impacted by gravity, space, and time. The Project is scheduled to launch on a Surrey Satellite Technologies spacecraft in 2016 to advance to TRL-7 through actual system prototype testing in a realistic environment.

GAME CHANGING DEVELOPMENT



Source: NASA.

STMD's Game Changing Development (GCD) Program generally focuses on the mid-TRL range to take technologies from proof of concept state (TRL-3) through component testing in a relevant environment (TRL-5). The GCD Program is meant to fill the gap at TRL-4 that NASA identified as one of the barriers to successfully developing technology for infusion into Agency missions. During FY 2015, GCD had 31 active projects and a budget of $125.6 million, which is slightly higher than the previous year but trending lower since 2012. Over the past 4 years, the GCD program received $556.2 million in funding.

GCD's Top 15 Projects for FY 2015

1. HUMAN ROBOTIC SYSTEMS


Artist's rendering of Rover for Resource Prospector Mission. Source: NASA.

FY 2015 Funding	$15.3 million (12% of GCD)		
Total Funding, FYs 2012–2015	$64.7 million (12% of GCD)		
Lead Center	Johnson Space Center		
Start Date	October 2014		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❹	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Robotics and Autonomous Systems (TA04)	Human Robotic Systems, AES's Resource Prospector Mission

The Human Robotics Systems Project develops advanced robotic technology, such as autonomous software and rover technologies, to increase human productivity and reduce mission risk. Human robotics are technologies that can assist before, during, or following human missions. This Project is currently developing technologies related to rovers for the Resource Prospector Mission to the Moon, assisting NASA's Space Robotics Challenge where competing student teams develop software to control the Agency's Robonaut 2 and Valkyrie robots, and designing an extended reach manipulator for asteroid retrieval or in-space assembly. The Project uses grants to support the Federal Government's multi-agency National Robotics Initiative to develop and use robots to work cooperatively with people. The Project is scheduled to advance to TRL-6 through the completion and testing of a lunar rover prototype in a relevant environment by 2017.

2. HUMAN EXPLORATION TELEROBOTICS 2

Robonaut 2 demonstrating reach and dexterity. Source: NASA.

FY 2015 Funding	$10.9 million (9% of GCD)		
Total Funding, FYs 2012–2015	$10.9 million (2% of GCD)		
Lead Center	Ames Research Center		
Start Date	October 2014		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❸	❸/❻[a]	❼

Link to Technology Roadmap	**Link to Future Missions**
Robotics and Autonomous Systems (TA04)	International Space Station

The Human Exploration Telerobotics 2 Project will advance development of the Robonaut 2 and Astrobee robots for testing on the International Space Station with a goal of reducing repetitive work for astronauts and enhancing crew capabilities. Robonaut 2 is a humanoid robot currently on the Station that demonstrates the use of semi-autonomous robots controlled from a distance, also known as telerobotics technology, to reduce crew demands for ISS maintenance. The robot, currently TRL-6 as a system prototype in a realistic environment, is mobile and can grasp and climb walls, conduct independent tasks, and navigate on its own. The Astrobee, which is scheduled to advance to TRL-7 through a system prototype demonstration on the ISS by 2017, will independently fly within the Station to allow visual and sensor monitoring for ground-based flight controllers.

[a] The current TRL status for Astrobee is TRL-3 and Robonaut is TRL-6.

3. IN-SPACE ROBOTIC SERVICING

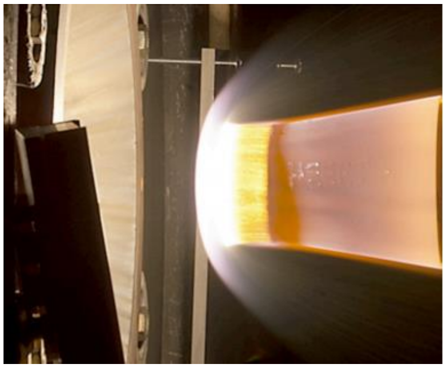
Artist's rendering of the Robotic Satellite Servicing Concepts. Source: NASA

FY 2015 Funding	$10 million (8% of GCD)		
Total Funding, FYs 2012–2015	$61 million (11% of GCD)		
Lead Center	Goddard Space Flight Center		
Start Date	June 2009		
Proposed End Date	September 2019		
TRL Progression	Start	Current	End
	❷	❺	❾

Link to Technology Roadmap	**Link to Future Missions**
Robotics and Autonomous Systems (TA04)	Asteroid Redirect Missions

The In-Space Robotic Servicing Project advances robotic technology to refuel, repair, and relocate existing Government and commercial satellites to extend or enhance their useful lives. Currently, the Project is conducting a multi-phased Robotic Refueling Mission on the International Space Station to demonstrate technologies and design concepts using easily replaceable parts, refueling techniques, or power sources. This Project also plans to utilize servicing technologies to develop reconfigurable SMD satellites with modular designs and advance its technologies to TRL-9 through prototype testing and flight demonstrations scheduled for 2019 and 2024.

4. THERMAL PROTECTION SYSTEM MATERIALS



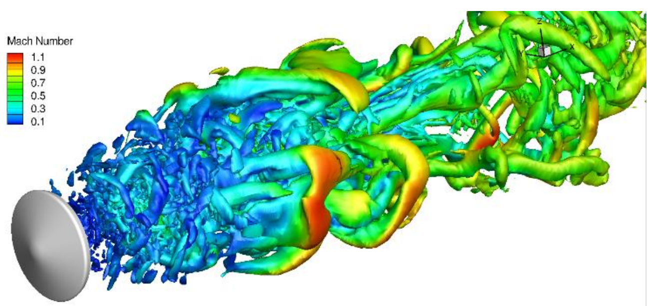
Thermal Testing of Material for Extreme Entry Heatshields. Source: NASA.

FY 2015 Funding	$7.8 million (6% of GCD)		
Total Funding, FYs 2012–2015	$11 million (2% of GCD)		
Lead Center	Ames Research Center		
Start Date	October 2011		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❷	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Thermal Management Systems (TA14)	Orion, SMD's Discovery Class Missions

The Thermal Protection System Materials Project utilizes technologies to develop thermal shielding for potential demonstrations on Orion or missions outside low Earth orbit in three areas: woven thermal protection material, heatshields for extreme entry conditions, and thermal protection felt material. The woven composite material provides heat shielding and structural support and is scheduled for component testing to advance to TRL-4 and may be used on the Orion capsule in 2019. The heatshield for extreme entries is designed to withstand missions through the atmospheres of Saturn, Venus, and other outer planets and is scheduled to be advanced to TRL-6 through prototype testing in a relevant environment by 2017. The flexible felt thermal protection material, scheduled to advance to TRL-5 or -6 through system model or prototype testing, is intended to cover gaps or awkward angles to simplify heatshield designs, reduce mass, and reduce costs.

5. ENTRY SYSTEMS MODELING



Model of atmospheric wake caused by entry created by NASA's Computational Fluid Dynamics software. Source: NASA.

FY 2015 Funding	$7.2 million (6% of GCD)		
Total Funding, FYs 2012–2015	$17.3 million (3% of GCD)		
Lead Center	Ames Research Center		
Start Date	April 2013		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❷	❺	❼

Link to Technology Roadmap	**Link to Future Missions**
Entry, Descent, and Landing Systems (TA09)	Unknown, Potentially Mars Missions

The Entry System Modeling Project develops modeling software and materials to improve manufacturing and resistance capabilities for thermal protection during entry, descent, and landing. This Project focuses on developing complex computational models for hypersonic or high-speed entry, descent, and landing to analyze the impact of entering different atmospheres such as Mars or Venus. The Project also develops entry, descent, and landing materials, which are currently in laboratory testing ranging from TRL-3 to TRL-4, for low cost, flexible, and effective thermal protection for potential use on a human vehicle to Mars. In 2015, the Project completed updates to hypersonic atmospheric modeling software to advance to TRL-7 through a full system demonstration. The Project also plans to advance various modeling software products to TRL-7 through full systems testing and advance the thermal protection materials to TRL-4 and -5 using laboratory testing.

6. ADVANCED MANUFACTURING TECHNOLOGY

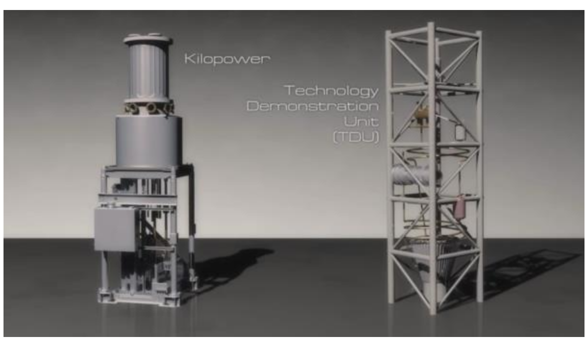
Testing of 3-D printed rocket with new copper alloys. Source: NASA.

FY 2015 Funding	$5.2 million (4% of GCD)		
Total Funding, FYs 2012–2015	$19.5 million (4% of GCD)		
Lead Center	Marshall Space Flight Center		
Start Date	October 2012		
Proposed End Date	September 2018		
TRL Progression	Start	Current	End
	❸	❸	❻

Link to Technology Roadmap	**Link to Future Missions**
Materials, Structures, Mechanical Systems, and Manufacturing (TA12)	Unknown, Potentially Future Spacecraft

The Advanced Manufacturing Technology Project develops and tests manufacturing techniques using specialized materials or advanced processes, including new copper alloys for upper stage propulsion, 3-D printing for use on the International Space Station, construction processes from materials on the Moon or asteroids, and single-piece launch vehicles. This Project intends to demonstrate a new upper stage propulsion engine using a 3-D printing process and new copper alloys. The engine is currently undergoing laboratory testing at TRL-3 with plans for advancement to TRL-6 through flight tests in 2017. The Project also fabricated a process scheduled for laboratory testing at TRL-3 in 2015 for creating single-piece cylinders for rocket stages or cold liquid tanks without long welds to reduce structural weakness and costs.

7. NUCLEAR SYSTEMS



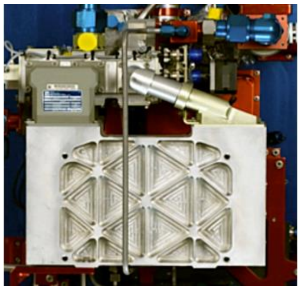
Design for the small fission power system (Kilopower) and ground-based nonnuclear test demonstration unit (TDU). Source: NASA.

FY 2015 Funding	$4.9 million (4% of GCD)		
Total Funding, FYs 2012–2015	$16.5 million (3% of GCD)		
Lead Center	Glenn Research Center		
Start Date	October 2011		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❸	❹	❺

Link to Technology Roadmap	**Link to Future Missions**
Space Power and Energy Storage (TA03)	SMD Outer Planet Robotic Missions; Mars Surface Missions

The Nuclear Systems Project will test and demonstrate low-cost, small (1 kilowatt) fission power systems and large (10–100 kilowatt) fission systems to increase power capabilities and reduce costs for surface exploration and deep space missions. The small fission power system, scheduled to begin in October 2015 and advance to TRL-5 through laboratory testing of system components, could expand the capabilities of robotic science missions and small exploration systems. Once advanced to TRL-5, the Project could potentially perform system-level testing of a fission power system in space. To test the viability of a large fission system, NASA created a nonnuclear, ground-based technology demonstration unit to simulate fission power systems in space. In 2015, the demonstration unit tested the following components in a laboratory environment for advancement to TRL-5: an electrically heated power unit that simulated fission power environments, a unit that converted thermal heat into electrical power, and a water cooling system that simulated space thermal radiators.

8. NEXT GENERATION LIFE SUPPORT



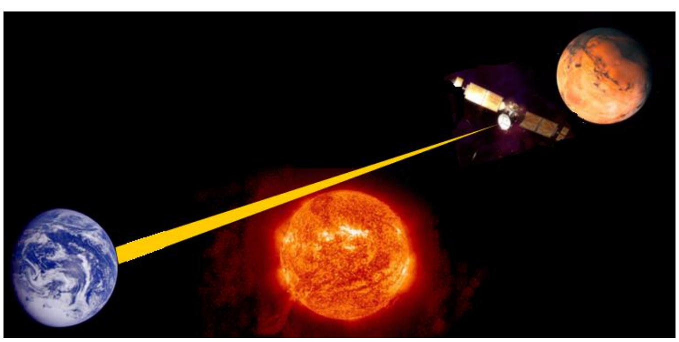
Prototype to remove carbon dioxide and control humidity during space walks. Source: NASA.

FY 2015 Funding	$4.5 million (4% of GCD)		
Total Funding, FYs 2012–2015	$24 million (4% of GCD)		
Lead Center	Johnson Space Center		
Start Date	October 2011		
Proposed End Date	September 2018		
TRL Progression	Start	Current	End
	❷	❸	❻

Link to Technology Roadmap	**Link to Future Missions**
Human Health, Life Support, and Habitation Systems (TA06)	AES's Life Support Systems and Advanced Spacesuit Projects

The Next Generation Life Support Project is developing air purification and oxygen recovery systems, spacesuit gloves, and improved oxygen pressure regulators for infusion into AES's Life Support Systems and Advanced Spacesuit projects. For missions that require astronauts to conduct extravehicular activities in spacesuits, the Project hopes to develop by 2018 a more efficient system for capturing carbon dioxide and humidity, a more precise oxygen pressure regulator, and new spacesuit gloves. Those projects will advance from prototypes at TRL-3 to system demonstrations at TLR-5 or -6. At the end of FY 2014, the Project transitioned a biologically-based water recycling system to the Life Support Systems Project within AES. This Project is also developing spacecraft oxygen recovery systems in at laboratory environment at TRL-3 for eventual component testing in a relevant environment to advance to TRL-5. After initially granting up to six awards, the Project plans to select two technologies for further development and potential testing on the International Space Station by 2018.

9. DEEP SPACE OPTICAL COMMUNICATION



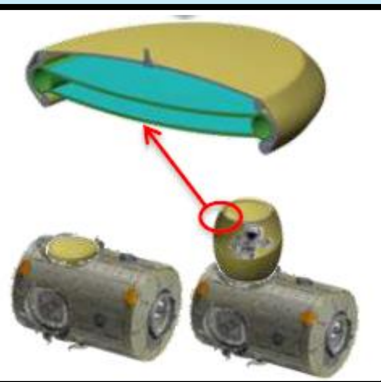
Artist's rendering for high bandwidth communication using lasers and optical receivers on spacecraft. Source: NASA.

FY 2015 Funding	$4.1 million (3% of GCD)		
Total Funding, FYs 2012–2015	$10.8 million (2% of GCD)		
Lead Center	Jet Propulsion Laboratory		
Start Date	October 2011		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❷	❸	❻

Link to Technology Roadmap	**Link to Future Missions**
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (TA05)	SMD's Discovery Class Missions

The Deep Space Optical Communication Project is developing technologies for sending and receiving laser communications in deep space, which will potentially be tested as part of a future technology demonstration mission. This technology will increase the sensitivity of spacecraft laser receivers to improve uploads from Earth by 1,000 times while also increasing download rates to Earth tenfold. In addition, the Project seeks to reduce the mass and power usage of the spacecraft receiver and transmitter. The Project is scheduled to advance to TRL-6 through model or prototype testing in a relevant environment and then further advance through a technology demonstration mission or infusion into SMD Discovery Class Mission.

10. LIGHTWEIGHT MATERIALS AND STRUCTURES



Artist's rendering demonstrating inflatable hatch for spacewalks. Source: NASA.

FY 2015 Funding	$3.6 million (3% of GCD)		
Total Funding, FYs 2012–2015	$11 million (2% of GCD)		
Lead Center	Langley Research Center		
Start Date	April 2014		
Proposed End Date	September 2016		
TRL Progression	Start	Current	End
	❷	❷	❹

Link to Technology Roadmap	**Link to Future Missions**
Human Exploration Destination Systems (TA07)	AES's Exploration Augmentation Module Project

The Lightweight Materials and Structures Project is developing an inflatable airlock that can be stowed on a spacecraft to deploy for extravehicular activities. Current airlocks are rigid hatches that are complicated to operate and require additional strengthening because of stresses during launch. A compact, inflatable airlock made of flexible fabric has the potential to reduce launch weight. In addition, inflatable airlocks would allow astronauts to prepare and depart for extravehicular activities or space walks from a separate compartment from the spacecraft. AES is currently reviewing whether to integrate this inflatable hatch design into the Exploration Augmentation Module Project, which is creating a future habitat module for deep space exploration. This Project is in the conceptual phase at TRL-2 and plans to advance to TRL-4 through basic component testing in a laboratory environment.

11. HYPERSONIC INFLATABLE AERODYNAMIC DECELERATOR 2

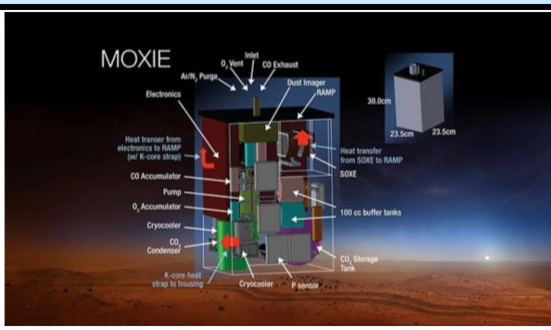
Engineers check the inflatable decelerator after testing in vacuum conditions at the Langley Research Center. Source: NASA.

FY 2015 Funding	$3.5 million (3% of GCD)		
Total Funding, FYs 2012–2015	$31.5 million (6% of GCD)		
Lead Center	Langley Research Center		
Start Date	October 2014		
Proposed End Date	September 2015		
TRL Progression	Start	Current	End
	❸	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Entry, Descent, and Landing Systems (TA09)	Evolvable Mars Campaign

The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) 2 project is developing and demonstrating hypersonic (five times the speed of sound) inflatable aeroshell (balloon) technologies to enable missions entering atmospheres such as Mars, Venus, or for reentry to Earth. As an extension of the original HIAD project, which ended in September 2014, the HIAD 2 Project will emphasize the maturation of flexible thermal protection materials, advanced structures, packing, and manufacturability at the appropriate scale. By 2016, the Project plans to conduct tests on a 3.7 meter inflatable aeroshell, test deployment of a 6 meter aeroshell, and perform analysis of thermal protection materials for inflatable devices to advance to TRL 6 through a prototype demonstration in a relevant environment.

12. IN-SITU RESOURCE UTILIZATION



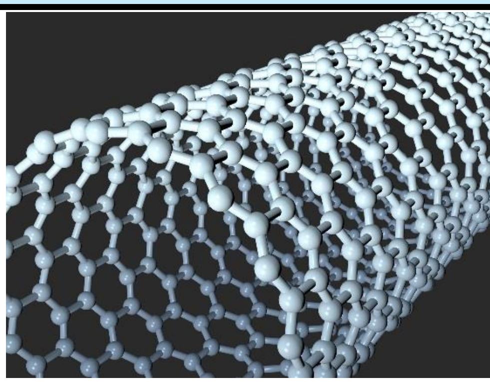
Design for In Situ Resource Utilization instrument to produce oxygen on the Mars 2020 Rover. Source: NASA.

FY 2015 Funding	$3.5 million (3% of GCD)			
Total Funding, FYs 2012–2015	$17.1 million (3% of GCD)			
Lead Center	Jet Propulsion Laboratory			
Start Date	July 2014			
Proposed End Date	September 2020			
TRL Progression	Start	Current	End	
	❹	❺	❾	

Link to Technology Roadmap	**Link to Future Missions**
Human Exploration Destination Systems (TA07)	Mars 2020 Rover

The In-Situ Resource Utilization Project is developing instruments for the first in-situ resource utilization demonstration on Mars. In-situ resource utilization is the practice of harnessing resources at the exploration site to reduce transportation costs and decrease mission reliance on resupply deliveries for long-term missions such as a mission to Mars. This Project plans to advance to TRL-9 by 2020 as an actual flight proven system by producing oxygen from the Mars atmosphere as an instrument on the Mars 2020 Rover.

13. NANOTECHNOLOGY



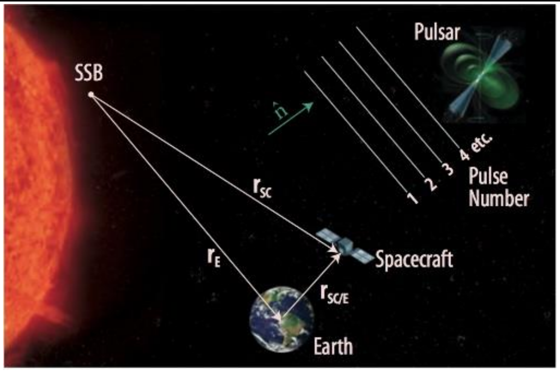
Model of carbon nanotubes used for new composite technology. Source: NASA.

FY 2015 Funding	$3.2 million (3% of GCD)			
Total Funding, FYs 2012–2015	$12.1 million (2% of GCD)			
Lead Center	Glenn Research Center			
Start Date	October 2012			
Proposed End Date	December 2018			
TRL Progression	Start	Current	End	
	❸	❹	❻	

Link to Technology Roadmap	**Link to Future Missions**
Nanotechnology (TA10)	Unknown, Potentially Future Spacecraft Designs

The Nanotechnology Project is developing stronger carbon-based materials to increase the strength and reduce the mass of existing composites. This Project intends to reduce the weight of spacecraft by 30 percent through matured technologies and advanced manufacturing techniques. The Project will also test the use of carbon nanotechnology for electrical and data wiring to reduce spacecraft mass. Spacecraft wiring can be roughly 25 percent of a vehicle's weight, and this Project could potentially reduce that weight by 90 percent compared to traditional copper wiring. To do this, the Project hopes to develop by 2018 nanotechnologies for advancement to TRL-6 through testing of system models or prototypes in relevant environments to improve existing carbon fiber reinforced plastics, develop new carbon nanotube structures for aerospace vehicles, and replace copper wiring with carbon nanotube wires for power and data cables on spacecraft.

14. STATION EXPLORER X-RAY TIMING AND NAVIGATION



Artist's rendering of Station Exploration X-Ray Timing and Navigation Project technology for space navigation. Source: NASA.

FY 2015 Funding	$3 million (2% of GCD)		
Total Funding, FYs 2012–2015	$13.7 million (2% of GCD)		
Lead Center	Goddard Space Flight Center		
Start Date	June 2011		
Proposed End Date	August 2018		
TRL Progression	Start	Current	End
	❸	❻	❽

Link to Technology Roadmap	**Link to Future Missions**
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems (TA05)	Space Communications and Navigation Program

The Station Explorer X-Ray Timing and Navigation Project could allow a spacecraft to autonomously determine its location and navigate through space using pulsars as beacons. The Project will use pulsars, which emit x-rays every millisecond, as navigational beacons to determine position and speed for deep space vehicles. This Project could also enable increased data communications over long distances. The Project is currently demonstrating its pulsar navigation technology as a prototype in a relevant environment at a TRL-6 through SMD's Neutron star Interior Composition Explorer Project on the International Space Station and plans to advance to TRL-8 through actual system tests and demonstrations.

15. CORONAGRAPH

Design for WFIRST-AFTA with the Coronagraph Instrument. Source: NASA.

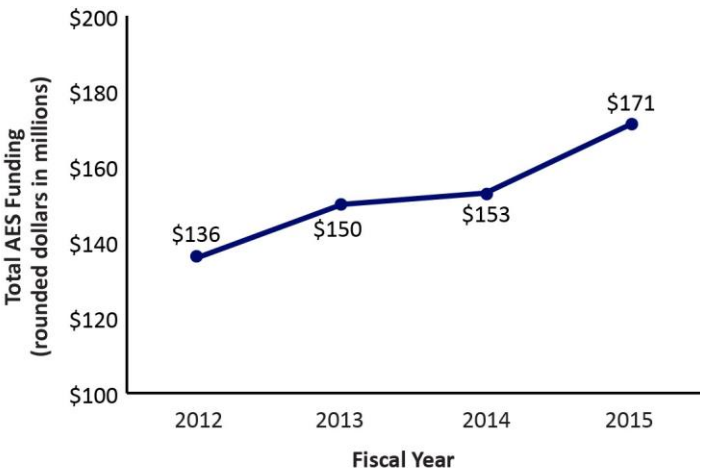
FY 2015 Funding	$3 million (2% of GCD)		
Total Funding, FYs 2012–2015	$5.2 million (1% of GCD)		
Lead Center	Jet Propulsion Laboratory		
Start Date	January 2014		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❸	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Science Instruments, Observatories, and Sensor Systems (TA08)	Wide-Field Infrared Survey Telescope Mission[a]

The Coronagraph Project is developing instruments that will identify planets orbiting stars. The Project is testing coronagraph technologies, which partially block a star's light to observe dimmer surrounding objects, to allow for direct imaging of planets and their atmospheric composition. The Project will be a secondary instrument on the 2.4 meter Wide-Field Infrared Survey Telescope, which is targeted for a launch in 2024.

[a] The Wide-Field Infrared Survey Telescope mission will use a 2.4 meter telescope for exoplanet exploration, dark energy research, and galactic and extragalactic surveys.

ADVANCED EXPLORATION SYSTEMS

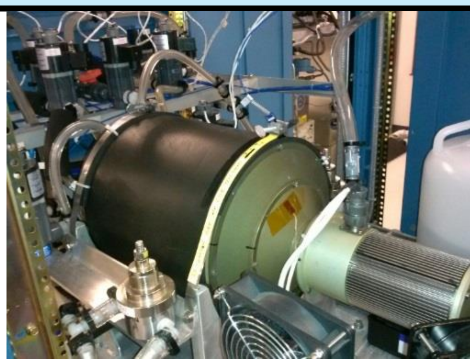


Source: NASA.

HEOMD's Advanced Exploration Systems (AES) is a technology program that builds prototypes, tests concepts, and conducts demonstrations for human spaceflight missions in deep space. AES seeks to develop prototype systems that integrate mid-TRL technologies and infuse them into human spaceflight missions. During FY 2015, AES had 28 active projects and a budget of $170.9 million. Some examples of current AES projects are the Advanced Spacesuit, Life Support Systems, and Exploration Augmentation Module. For FY 2015, AES's budget is trending higher than the previous 3 years. Over the past 4 years, the AES program received $609.5 million in funding.

AES's Top 15 Projects for FY 2015

1. LIFE SUPPORT SYSTEMS



Life support systems being tested in a laboratory environment. Source: NASA.

FY 2015 Funding	$16.4 million (10% of AES)			
Total Funding, FYs 2012–2015	$43.1 million (7% of AES)			
Lead Center	Marshall Space Flight Center			
Start Date	October 2011			
Proposed End Date	September 2017			
TRL Progression		Start	Current	End
		❸	❸	❺

Link to Technology Roadmap	**Link to Future Missions**
Human Health, Life Support, and Habitation Systems (TA06)	International Space Station, Orion, Deep Space Exploration Missions

The Life Support Systems Project develops life support systems and environmental monitoring instruments for extended missions beyond low Earth orbit. Specifically, the Project seeks to advance technologies intended for space and surface habitats, landers, and multi-mission space exploration vehicles, including technologies focused on carbon dioxide removal, oxygen generation, air-contaminate removal, and humidity removal. This Project is scheduled to advance to TRL-5 through ground testing of components in a relevant environment by 2017.

2. ADVANCED SPACESUIT

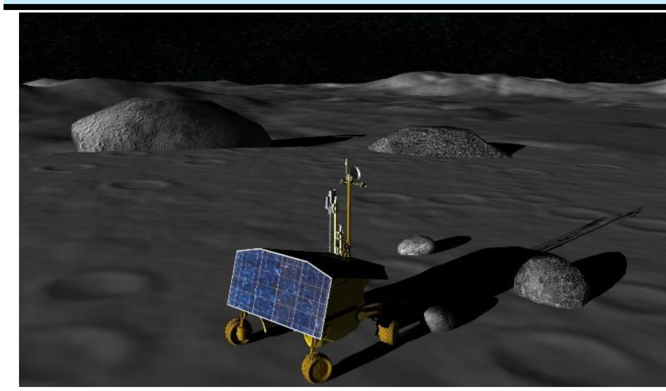

Human-in-the-loop testing of Portable Life Support System for an advanced space suit. Source: NASA.

FY 2015 Funding	$16.2 (9% of AES)		
Total Funding, FYs 2012–2015	$55.6 million (9% of AES)		
Lead Center	Johnson Space Center		
Start Date	October 2011		
Proposed End Date	2022		
TRL Progression	Start	Current	End
	❸	❹	❽

Link to Technology Roadmap	**Link to Future Missions**
Human Health, Life Support, and Habitation Systems (TA06)	International Space Station, Deep Space Exploration Missions

The Advanced Spacesuit Project is developing a portable life support system and pressure garment to enable surface extravehicular activity on an asteroid, the Moon, or Mars. This Project is intended to replace spacesuits previously used by crew on the Space Shuttle with a spacesuit that has increased technical capabilities, better reliability, and lower per-unit costs. To this end, AES is working to develop a new spacesuit with updated fabric, joints, and bearings; a portable life support subsystem for oxygen supply; and a subsystem for power, avionics, and software for updated battery systems, display controls, radio systems, and real-time navigation and tracking information. The Project is scheduled to demonstrate and test the new spacesuit on the International Space Station by 2022 as a prototype demonstration and advance to TRL-8 for potential use on asteroid or Mars exploration missions.

3. RESOURCE PROSPECTOR

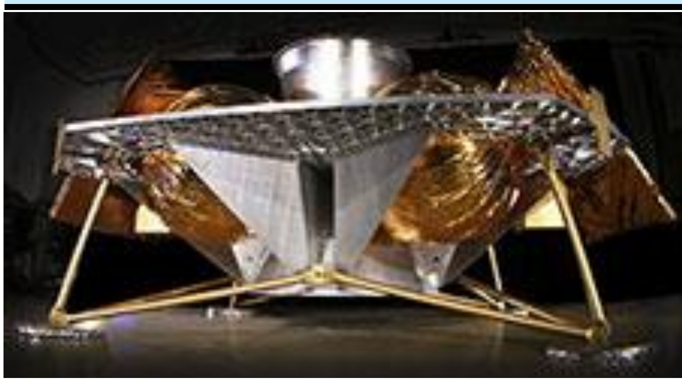

Artist's rendering of the Resource Prospector Rover. Source: NASA.

FY 2015 Funding	$15.4 million (9% of AES)		
Total Funding, FYs 2012–2015	$49.5 million (8% of AES)		
Lead Center	Ames Research Center		
Start Date	January 2013		
Proposed End Date	September 2021		
TRL Progression	Start	Current	End
	❸	❻	❻

Link to Technology Roadmap	**Link to Future Missions**
Human Exploration Destination Systems (TA07)	Robotic Precursor Missions

The Resource Prospector Project is developing technologies for a robotic vehicle to search for ice on the Moon and demonstrate local resource techniques for extracting oxygen from lunar dust to expand capabilities for future human missions to the Moon, asteroids, or Mars. In 2015, the Project completed an integrated test and mission simulation of the lunar rover to advance to TRL-6. The Resource Prospector mission is a collaboration of international and industry partners with a target launch date in 2020.

4. LANDER TECHNOLOGY



Astrobotic Technology's Griffin lander, Lunar CATALYST commercial partnership program. Source: NASA.

FY 2015 Funding	$11.3 million (7% of AES)		
Total Funding, FYs 2012–2015	$11.3 million (2% of AES)		
Lead Center	Marshall Space Flight Center		
Start Date	October 2014		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❺	❺	❾

Link to Technology Roadmap	Link to Future Missions
Entry, Descent, and Landing Systems (TA09)	Robotic Precursor Missions, Commercial Partners

The Lander Technology Project includes Lunar CATALYST (Lunar Cargo Transportation and Landing by Soft Touchdown) commercial partnerships to develop lunar payload delivery capabilities and NASA development of lander propulsion systems and autonomous precision landing technologies. For the Lunar CATALYST Program, AES has competitively selected three companies to advance robotic lunar capabilities through unfunded Space Act Agreements. In 2015, NASA provided technical expertise, test facilities, hardware, and software for model and prototype testing by the companies in relevant environments to reach the current status of TRL-5.

5. RADIATION SENSORS

Radiation Environment Sensor from AES's RadWorks. Source: NASA.

FY 2015 Funding	$9.9 million (6% of AES)		
Total Funding, FYs 2012–2015	$34.9 million (6% of AES)		
Lead Center	Johnson Space Center		
Start Date	October 2011		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❸	❹	❽

Link to Technology Roadmap	Link to Future Missions
Human Health, Life Support, and Habitation Systems (TA06)	Deep Space Exploration Missions

The Radiation Sensors Project (RadWorks) develops radiation sensors to measure the radiation environments on the International Space Station, Orion, and deep space missions beyond Earth orbit. RadWorks will develop and test technologies to accurately measure, predict, and model space radiation exposure to understand potential risks for future human space missions. The Project recently completed a test flight of the radiation sensor aboard the Orion Exploration Flight Test -1. Data collected has been used to further verify human exposure risk models and advance to TRL-4. In addition, the Project is conducting system tests and demonstrations to advance TRL-7 and TRL-8 by 2017.

6. AUTOMATED PROPELLANT LOADING

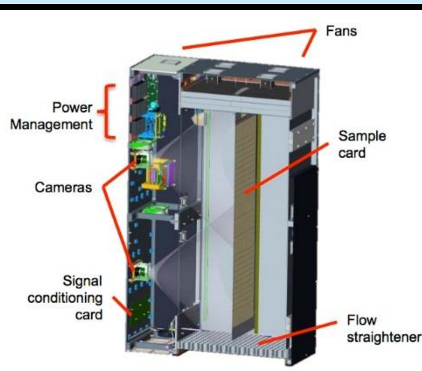
Automated Propellant Load Testing Facility at Kennedy Space Center. Source: NASA.

FY 2015 Funding	$8.3 million (5% of AES)		
Total Funding, FYs 2012–2015	$32.2 million (5% of AES)		
Lead Center	Kennedy Space Center		
Start Date	October 2011		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❹	❹	❼

Link to Technology Roadmap	Link to Future Missions
Ground and Launch Systems (TA13)	Space Launch System, Commercial Launch Vehicles

The Automated Propellant Loading Project tests systems for cryogenic propellant liquefaction, storage, and transfer to reduce the cost of ground operations. The goal of this Project is to convert a propellant into a liquid from a gas and store it in a tank with minimal boil-off (no conversion of liquid back into gas or leaking) and then increase the pressure of the tank. The Project plans to automate and mature methodologies to reduce the number of monitoring engineering staff required and to minimize propellant waste. In 2015, the Project advanced to TRL-4 through component testing of an automated loading of a 2,000-gallon liquid oxygen tank and plans to advance to TRL-7 through a system prototype demonstration.

7. SPACECRAFT FIRE SAFETY



Design for fire safety testing demonstration. Source: NASA.

FY 2015 Funding	$8 million (5% of AES)		
Total Funding, FYs 2012-2015	$38.1 million (6% of AES)		
Lead Center	Glenn Research Center		
Start Date	October 2011		
Proposed End Date	December 2016		
TRL Progression	Start	Current	End
	❺	❺	❾

Link to Technology Roadmap	Link to Future Missions
Human Health, Life Support, and Habitation Systems (TA06)	International Space Station, Deep Space Exploration Missions

The Spacecraft Fire Safety Project is launching a series of experiments on Orbital ATK's Cygnus capsule to study the behavior of large-scale fires in microgravity in order to develop a fire safety strategy for future exploration vehicles. After delivering cargo to the International Space Station and undocking, the Project will ignite small and contained fires within the Cygnus to study the rate of fire growth and the flammability of different materials in microgravity to advance the technology to TRL-9 as a flight-proven system. The fire experiment was scheduled to launch in 2015 but the target launch date is now uncertain because of the October 2014 failure of Orbital ATK's third resupply mission to the International Space Station.

8. BIGELOW EXPANDABLE ACTIVITY MODULE

Fully expanded Bigelow habitat (16 cubic meters). Source: NASA.

FY 2015 Funding	$7.6 million (4% of AES)		
Total Funding, FYs 2012–2015	$27.6 million (5% of AES)		
Lead Center	Johnson Space Center		
Start Date	January 2013		
Proposed End Date	September 2018		
TRL Progression	Start	Current	End
	7	7	9

Link to Technology Roadmap	**Link to Future Missions**
Human Health, Life Support, and Habitation Systems (TA06)	International Space Station, Deep Space Exploration Missions

The Bigelow Expandable Activity Module Project will fly a human-rated inflatable habitat module to the International Space Station to demonstrate the technology. The purpose of the Project is to bring the Bigelow habitat to TRL-9 as a flight-proven system for use in future commercial and NASA missions. In addition, an inflatable habitat concept is currently being considered in the architectural roadmap for deep space missions. The Project was scheduled to launch on SpaceX-8 in September 2015 for docking with the Station and be fully inflated for 2 years, but the launch date will now occur no earlier than January 3, 2016, because of the SpaceX's Falcon 9 failure in June 2015.

9. NUCLEAR THERMAL PROPULSION

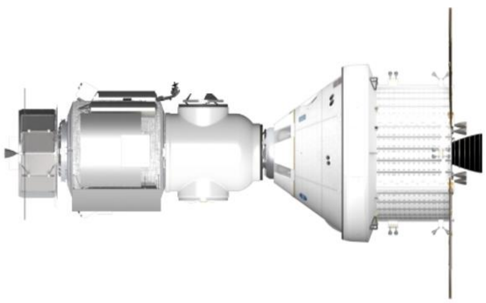
Nuclear Thermal Rocket Element Environment Simulator at Marshall Space Flight Center. Source: NASA.

FY 2015 Funding	$6.9 million (4% of AES)		
Total Funding, FYs 2012–2015	$30 million (5% of AES)		
Lead Center	Marshall Space Flight Center		
Start Date	October 2011		
Proposed End Date	September 2015		
TRL Progression	Start	Current	End
	4	4	4

Link to Technology Roadmap	**Link to Future Missions**
In-Space Propulsion Technologies (TA02)	Mars Missions, Deep Space Exploration Missions

The Nuclear Thermal Propulsion Project will develop critical components for nuclear thermal propulsion technology for future HEOMD missions. The Project, which uses heat given off nuclear reactions to heat a propellant such as hydrogen, is expected to be capable of thrust twice as powerful as the current chemical engines and has been identified as a critical technology for human exploration missions. This Project intends to develop all facets of a nuclear thermal engine ranging from high-level architecture designs to methods for fabricating the nuclear fuel. In 2015, the Project completed component testing of reactor fuel elements in a non-radioactive nuclear power simulator at a TRL-4 for future ground testing

10. EXPLORATION AUGMENTATION MODULE



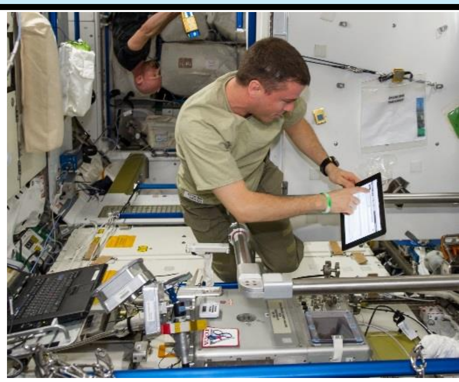
Design for Exploration Augmentation Module (on left). Source: NASA.

FY 2015 Funding	$6.7 million (4% of AES)		
Total Funding, FYs 2012–2015	$13.4 million (2% of AES)		
Lead Center	Johnson Space Center		
Start Date	April 2014		
Proposed End Date	September 2015		
TRL Progression	Start	Current	End
	❺	❺	❽

Link to Technology Roadmap	**Link to Future Missions**
Human Health, Life Support, and Habitation Systems (TA06)	Deep Space Exploration Missions, Commercial Partners

The Exploration Augmentation Module Project is developing concepts and subsystems for a habitation module to enable extended human missions near the Moon's orbit. The flight module is designed to perform deep space research, potentially dock with an Asteroid Redirect Vehicle, enable 30-to-60-day crewed missions, and serve as a deep space port for future deep space missions. The Project plans to integrate technological advances from other AES projects such as Avionics and Software, AES Modular Power Systems, and Life Support Systems. AES issued a broad agency announcement in 2014 for commercial partnerships to develop concepts and the Project is scheduled to advance to TRL-8 through system testing and demonstration on a space launch in 2020 or later.

11. AUTONOMOUS MISSION OPERATIONS



Automated experiment system (bottom) monitored on the International Space Station. Source: NASA.

FY 2015 Funding	$6.2 million (4% of AES)		
Total Funding, FYs 2012–2015	$28.5 million (5% of AES)		
Lead Center	Ames Research Center		
Start Date	October 2011		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❺	❺	❼

Link to Technology Roadmap	**Link to Future Missions**
Robotics and Autonomous Systems (TA04)	International Space Station, Deep Space Exploration Missions

The Autonomous Mission Operations Project is developing technologies to reduce crew dependence on ground-based mission control. Future human space flight missions will occur with long communication delays to Earth and this Project develops automation technologies to adjust to these delays and to potentially reduce ground support costs for missions. The Project is developing automated tasks related to mission phases such as launch checkout, cruise, or robotics operations; unexpected events such as unplanned maneuvers or solar flares; and failures such as leaks, power failures, or medical emergencies. AES plans to utilize the International Space Station, Orion, Space Launch System, and Resource Prospector to the Moon to advance the new automation technologies to TRL-7 through prototype testing in a relevant environment. In 2014, the Project demonstrated component systems to automatically power up and conduct scientific testing on the International Space Station from ground control with minimal instructions.

12. SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE

Source: NASA.

FY 2015 Funding	$5.5 million (3% of AES)			
Total Funding, FYs 2012–2015	$13.9 million (2% of AES)			
Lead Center	Ames Research Center			
Start Date	October 2013			
Proposed End Date	September 2016			
TRL Progression	Start	Current	End	
	N/A[a]	N/A[a]	N/A[a]	

Link to Technology Roadmap	Link to Future Missions
Human Exploration Destination Systems (TA07)	Robotic Precursor Missions

The Solar System Exploration Research Virtual Institute is jointly funded by SMD and AES to provide broad based basic and applied research to conduct studies regarding human exploration of the Moon, near-Earth asteroids, and the moons of Mars. In 2013, NASA selected nine academic research teams with focus areas ranging from the study of the formation of terrestrial planets and the asteroid belt to studies of lunar and asteroid dust.

[a] This is a collaborative institute for scientific research and does not have TRL assessments.

13. LOGISTICS REDUCTION AND REPURPOSING

Heat Melt Compactor prototype to consume waste on the International Space Station. Source: NASA.

FY 2015 Funding	$4.7 million (3% of AES)		
Total Funding, FYs 2012-2015	$19.1 million (3% of AES)		
Lead Center	Johnson Space Center		
Start Date	October 2011		
Proposed End Date	September 2016		
TRL Progression	Start	Current	End
	❸	❹	❼

Link to Technology Roadmap	Link to Future Missions
Human Health, Life Support, and Habitation Systems (TA06)	International Space Station, Deep Space Exploration Missions

The Logistics Reduction and Repurposing Project develops technologies to reduce launch mass through development of a trash compactor, extended wear clothing, and a universal waste management system for Orion, the International Space Station, and exploration missions. The Project's purpose is to reduce initial mass requirements for human exploration missions by reducing or reusing logistics materials, such as packaging or cargo bags, and improve tracking of packing containers to save on-orbit crew time. In 2015, the Project tested proof of concepts at a TRL-3 for extended wear clothing with the International Space Station crew to reduce laundry needs and a trash compactor to create cubes for radiation shielding and water recovery.

14. MODULAR POWER SYSTEMS

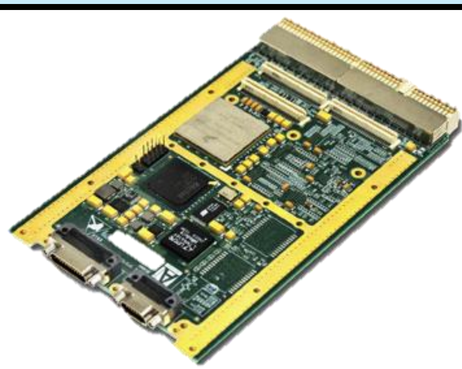
Battery fuel cells tested at Glenn Research Center. Source: NASA.

FY 2015 Funding	$4.7 million (3% of AES)		
Total Funding, FYs 2012–2015	$22.5 million (4% of AES)		
Lead Center	Glenn Research Center		
Start Date	October 2011		
Proposed End Date	September 2018		
TRL Progression	Start	Current	End
	❹	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Space Power and Energy Storage (TA03)	Deep Space Exploration Missions

The Modular Power Systems Project will integrate and test battery, fuel cell, and other power systems to develop improved power systems for future missions. This Project will also improve power systems within other AES ground or flight demonstrations. The Project seeks to infuse designs from STMD's Advanced Space Power Systems Project, Small Business Innovation Research activities, and other Government agencies as practicable. By 2018, the Project intends to demonstrate modular power systems for advancement to TRL-6 through ground testing prototypes or models for infusion into future flight hardware such as AES's Exploration Augmentation Module.

15. AVIONICS AND SOFTWARE



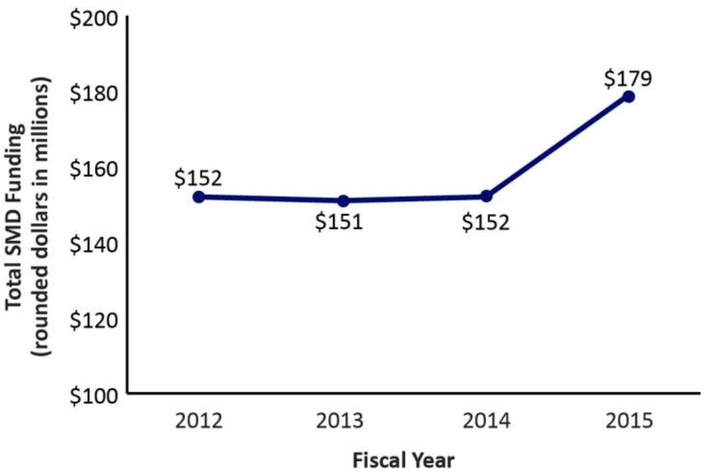
Design for common avionics enabler for multiple types of vehicles. Source: NASA.

FY 2015 Funding	$3.7 million (2% of AES)		
Total Funding, FYs 2012–2015	$8.2 million (1% of AES)		
Lead Center	Johnson Space Center		
Start Date	October 2012		
Proposed End Date	September 2017		
TRL Progression	Start	Current	End
	❹	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Modeling, Simulation, Information Technology, and Processing (TA11)	Orion, Deep Space Exploration Missions

The Avionics and Software Project develops modular or scalable avionic architectures, common avionic components, and core flight software for exploration systems. This Project will be utilized by other AES projects such as the Exploration Augmentation Module to implement and evaluate the core avionics architecture and serve as an avionics test bed for AES. The Project will focus on developing a common architecture for advancement to TRL-6 through system demonstrations in a relevant environment by 2017 with a focus on using low power sensors, wireless communications, and wire weight minimization to reduce costs and weight while also increasing capabilities.

SCIENCE MISSION DIRECTORATE



Source: NASA.

All four divisions of the SMD – Earth Science, Heliophysics, Planetary Science, and Astrophysics – conduct technology research for potential infusion into scientific missions and each division manages its own projects and technology investment decisions. The bulk of SMD space technology projects range from laboratory testing (TRL-3) to prototype demonstrations (TRL-7) and have 1–3 year project cycles. During FY 2015, SMD had 246 space technology projects with a budget of $179.1 million, trending higher than the previous 3 years. Over the past 4 years, SMD space technology projects received $634.7 million.

SMD's Top 15 Projects for FY 2015

1. STIRLING CYCLE TECHNOLOGY DEVELOPMENT

Advanced stirling convertor, white box on right, being tested at Glenn Research Center. Source: NASA.

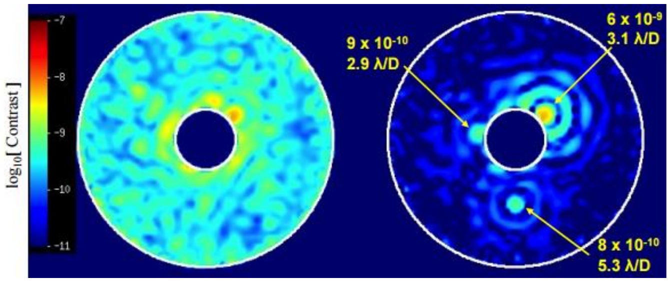
FY 2015 Funding	$8.5 million (5% of SMD)		
Total Funding, FYs 2012–2015	$8.5 million (1% of SMD)		
Lead Center	Glenn Research Center		
Start Date	January 2015		
Proposed End Date	Ongoing		
TRL Progression	Start	Current	End
	❶	❸	❻

Link to Technology Roadmap	**Link to Future Missions**
Space Power and Energy Storage (TA03)	New Frontiers Mission Class[a]

The Planetary Science Division's Stirling Cycle Technology Development Project develops, manufactures, and tests devices to convert nuclear heat into electrical power. Stirling cycle convertors use the thermal energy given off during nuclear radioisotope decay to move a piston to generate electricity. The Project intends to continue refining stirling cycle manufacturing techniques, assess the current TRL status of the technologies, and develop requirements for future flight testing of the devices. This Project is scheduled to complete a prototype for flight testing for advancement to TRL-6 by 2021.

[a] Missions competitively selected by SMD to launch medium-sized scientific and unmanned missions roughly every 3 years.

2. ASTROPHYSICS FOCUSED TELESCOPE ASSETS CORONAGRAPH



Demonstration of coronagraph technology taking all photos of a star on the left and comparing for changes to find exoplanets on the right. Source: NASA.

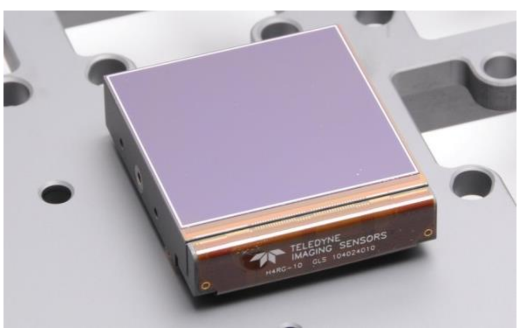
FY 2015 Funding	$8 million (4% of SMD)		
Total Funding, FYs 2012–2015	$14 million (2% of SMD)		
Lead Center	Jet Propulsion Laboratory		
Start Date	January 2014		
Proposed End Date	January 2017		
TRL Progression	Start	Current	End
	❸	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Science Instruments, Observatories, and Sensor Systems (TA08)	Wide-Field Infrared Survey Telescope Mission[a]

The Astrophysics Division's Astrophysics Focused Telescope Assets Coronagraph Project, which is the same project as GCD's Coronagraph Project, will be an imaging instrument used to identify and image ice and gas giant exoplanets and debris clouds surrounding stars. The Project is co-funded by STMD's GCD and will partially block light from a star (as shown in the dark inner circle in the photo) to more easily identify and view surrounding planets and debris. The Project is testing various coronagraph technologies to select and incorporate into the Wide-Field Infrared Survey Telescope as a second imaging instrument. The coronagraph technology will be tested in environments similar to the future mission conditions for technology advancement to TRL-6 in 2016.

[a] The Wide-Field Infrared Survey Telescope mission will use a 2.4 meter telescope for exoplanet exploration, dark energy research, and galactic and extragalactic surveys.

3. LARGE ARRAY INFRARED DETECTORS



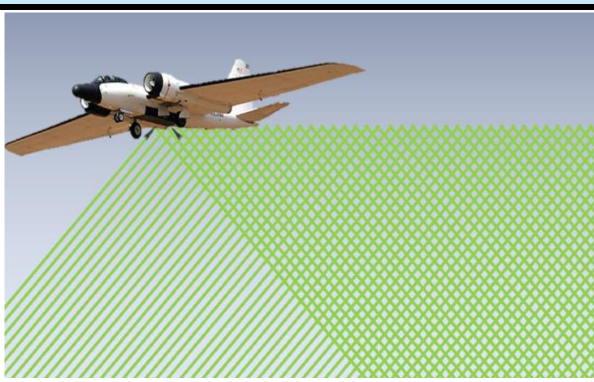
Large array infrared detector to be tested for infusion with the Wide-Field Survey Telescope. Source: NASA.

FY 2015 Funding	$6 million (3% of SMD)		
Total Funding, FYs 2012–2015	$11.6 million (2% of SMD)		
Lead Center	Goddard Space Flight Center		
Start Date	January 2012		
Proposed End Date	January 2017		
TRL Progression	Start	Current	End
	❹	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Science Instruments, Observatories, and Sensor Systems (TA08)	Wide-Field Infrared Survey Telescope Mission

The Astrophysics Division's Large Array Infrared Detectors Project will develop a 16 gigapixel near-infrared detector array for use in the Wide-Field Infrared Survey Telescope. The Project objectives are to achieve chip and pixel design improvements to meet Wide-Field Infrared Survey Telescope pixel operability requirements and to reduce the impact of strong light sources on subsequent images. The detector array was identified as a critical enabling technology needed to achieve the goals of future SMD missions. The Project is scheduled to advance to TRL-6 by developing a model to test the performance of the detector in a relevant environment by 2017.

4. GREEN OPTICAL AUTOCOVARIANCE WIND LIDAR AIRBORNE DEMONSTRATOR



Demonstration of the "two look" lidar system to be flight tested. Source: NASA.

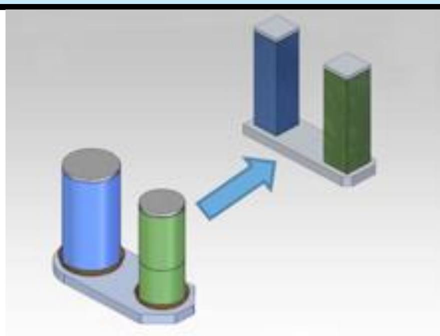
FY 2015 Funding	$3.8 million (2% of SMD)		
Total Funding, FYs 2012–2015	$3.8 million (1% of SMD)		
Lead Center	Goddard Space Flight Center		
Start Date	April 2015		
Proposed End Date	February 2017		
TRL Progression	Start	Current	End
	❸	❸	N/A[a]

Link to Technology Roadmap	Link to Future Missions
Science Instruments, Observatories, and Sensor Systems (TA08)	3-D Winds Mission

The Earth Science Division's Green Optical Autocovariance Wind Lidar Airborne Demonstrator Project will build on existing laser technology by creating two simultaneous scans with the same device to better measure the Earth's wind patterns. This Project, currently conducting laboratory testing at TRL-3, will build on existing laser transmitter and receiver technologies by performing high-altitude aircraft test flights to measure and validate line-of-sight wind profiles from two looks over a series of atmospheric conditions. The airborne flight tests are scheduled for 2016.

[a] SMD's Earth Science Division does not assign an exit TRL until project completion.

5. THERMOELECTRIC TECHNOLOGY DEVELOPMENT



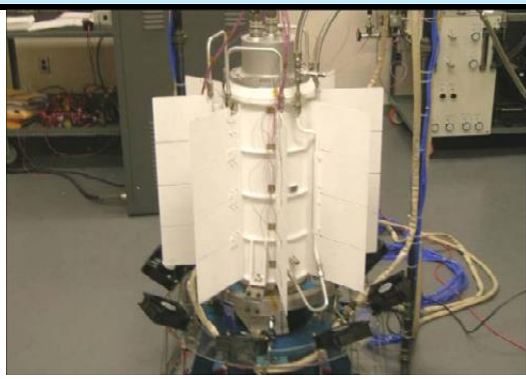
Design changes to thermoelectric coupling using new materials and techniques to provide improved power performance. Source: NASA.

FY 2015 Funding	$3.5 million (2% of SMD)		
Total Funding, FYs 2012–2015	$3.5 million (1% of SMD)		
Lead Center	Jet Propulsion Laboratory		
Start Date	January 2014		
Proposed End Date	Ongoing		
TRL Progression	Start	Current	End
	❶	❸	❻

Link to Technology Roadmap	Link to Future Missions
Space Power and Energy Storage (TA03)	New Frontiers Mission Class

The Planetary Science Division's Thermoelectric Technology Development Project continues development of technologies for radioisotope power generation, which uses heat from the isotope decay of Plutonium 238 to generate electricity. NASA has used this technology for more than 50 years to provide electricity and heating when solar power options are limited. In 2015, the Project developed advanced thermoelectric materials and new coupling techniques to improve power performance for an Enhanced Multi-Mission Radioisotope Thermoelectric Generator. The enhanced coupling technique system will be tested in a relevant environment for advancement to TRL-6 for potential infusion with future SMD missions such as the proposed Europa mission.

6. ENHANCED MULTI-MISSION RADIOISOTOPE THERMOELECTRIC GENERATOR



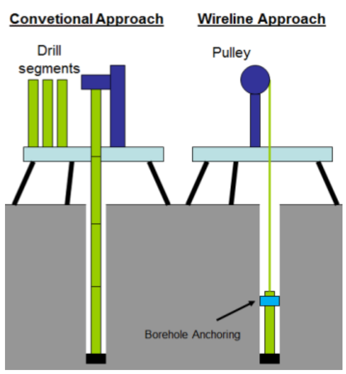
Multi-Mission Radioisotope Thermoelectric Generator engineering unit. Source: NASA.

FY 2015 Funding	$3.4 million (2% of SMD)		
Total Funding, FYs 2012-2015	$11.4 million (2% of SMD)		
Lead Center	Jet Propulsion Laboratory		
Start Date	June 2014		
Proposed End Date	June 2018		
TRL Progression	Start	Current	End
	❸	❸	❼

Link to Technology Roadmap	**Link to Future Missions**
Space Power and Energy Storage (TA03)	New Frontiers Mission Class

The Planetary Science Division's Enhanced Multi-Mission Radioisotope Thermoelectric Generator Project is developing a device to more efficiently convert the heat released by radioisotope decay of plutonium into electricity for use on a spacecraft or surface robot. The Project plans to incorporate the improvements to coupling techniques from the Thermoelectric Technology Development Project to improve efficiencies. The enhancement will allow additional capabilities for radioisotope power generation for use in future missions such as SMD's New Frontiers Program.

7. AUTO-GOPHER 2



Comparison of conventional approach with the Auto-Gopher 2 pulley and by-wire boring system. Source: NASA.

FY 2015 Funding	$3 million (2% of SMD)		
Total Funding, FYs 2012–2015	$3 million (0% of SMD)		
Lead Center	NASA Headquarters		
Start Date	September 2015		
Proposed End Date	September 2018		
TRL Progression	Start	Current	End
	❹	❹	❻

Link to Technology Roadmap	**Link to Future Missions**
Robotics and Autonomous Systems (TA04)	Europa Mission

The Planetary Science Division's Autonomous Wireline Core and Cutting Acquisition Probe for Deep Penetration and Sampling of Bodies in the Solar System Project (Auto-Gopher 2) will be used to determine the structure of icy surfaces by robotically sampling icy cores at depths greater than one kilometer. The purpose of the instrument is to search for habitable regions in areas where thick icy layers provide radiation protection for biomarkers and extant life. The Project will develop a drill to bore into icy bodies and take core samples, incorporating core breakoff, core capture, and core ejection. The Auto-Gopher 2 will integrate all the components and conduct laboratory and field-testing of the device in a relevant environment for advancement to TRL-6 by 2018.

8. SUB-GLACIAL POLAR ICE NAVIGATION, DESCENT, AND LAKE EXPLORATION

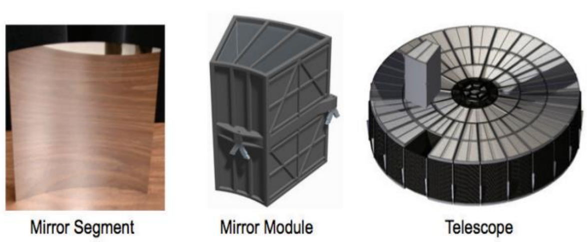
Artist's rendering of an autonomous underwater vehicle to conduct research at Lake Vostok, Antarctica. Source: NASA.

FY 2015 Funding	$2 million (1% of SMD)		
Total Funding, FYs 2012–2015	$2 million (0% of SMD)		
Lead Center	NASA Headquarters		
Start Date	August 2015		
Proposed End Date	January 2017		
TRL Progression	Start	Current	End
	❹	❺	❺

Link to Technology Roadmap	**Link to Future Missions**
Robotics and Autonomous Systems (TA04)	Europa

The Planetary Science Division's Sub-glacial Polar Ice Navigation, Descent, and Lake Exploration Project is developing a robot to penetrate through a thick layer of ice to release an underwater vehicle to conduct reconnaissance, search for life, and collect samples. This robotic drilling concept could potentially be used to bore through a terrestrial ice sheet, such as Europa, to release a submersible robot to study the saltwater ocean beneath. The Project plans to test the ice-penetrating robot technology for advancement to TRL-5 by 2017 in Antarctica's Lake Vostok.

9. AFFORDABLE AND LIGHTWEIGHT HIGH-RESOLUTION ASTRONOMICAL X-RAY OPTICS



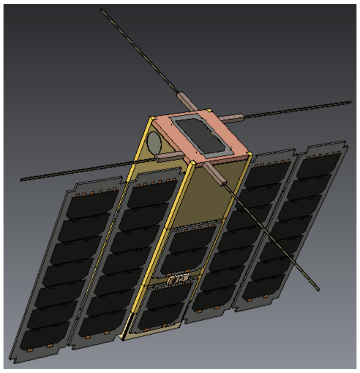
X-ray mirror segments are combined with mirror modules to form an x-ray telescope. Source: NASA.

FY 2015 Funding	$1.9 million (1% of SMD)		
Total Funding, FYs 2012-2015	$5.7 million (1% of SMD)		
Lead Center	Goddard Space Flight Center		
Start Date	January 2015		
Proposed End Date	January 2016		
TRL Progression	Start	Current	End
	❸	❹	❺

Link to Technology Roadmap	**Link to Future Missions**
Science Instruments, Observatories, and Sensor Systems (TA08)	X-Ray Surveyor Mission

The Astrophysics Division's Affordable and Lightweight High-Resolution Astronomical X-Ray Optics Project is developing lightweight x-ray mirrors to create better resolution telescopes for future SMD missions. The Project intends to develop and test hundreds of mirror segments to form a significantly better x-ray telescope while keeping mass and cost at levels similar to current technologies. The Project will test various x-ray mirror component manufacturing and assembly techniques for advancement to TRL-5 by 2016.

10. ICE CUBE



Design for ICE Cube Project, using a CubeSat, with the radiometer on the top. Source: NASA.

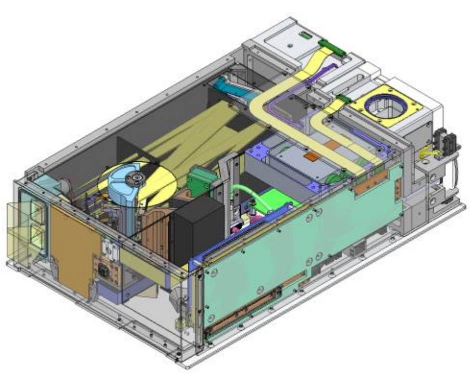
FY 2015 Funding	$1.8 million (1% of SMD)		
Total Funding, FYs 2012–2015	$3.1 million (0% of SMD)		
Lead Center	Goddard Space Flight Center		
Start Date	July 2014		
Proposed End Date	August 2016		
TRL Progression	Start	Current	End
	❺	❺	N/A[a]

Link to Technology Roadmap	**Link to Future Missions**
Science Instruments, Observatories, and Sensor Systems (TA08)	Aerosol-Cloud-Ecosystem

The Earth Sciences Division's ICE CUBE Project will conduct spaceflight validation of a radiometer – a device for measuring electromagnetic radiation – for ice cloud remote sensing. The radiometer will be able to measure paths and particle sizes of ice water during weather conditions. The Project, currently validated and tested in a relevant environment to TRL-5, plans to test the radiometer receiver on a miniature satellite scheduled to launch in 2016 to low Earth orbit to validate the system for use in future NASA missions.

[a] SMD's Earth Science Division does not assign an exit TRL until project completion.

11. COMPACT SOLAR SPECTRAL IRRADIANCE MONITOR



Design for the Compact Solar Spectral Irradiance Monitor. Source: NASA.

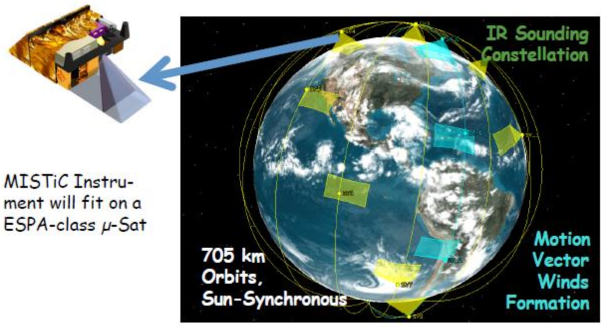
FY 2015 Funding	$1.7 million (1% of SMD)		
Total Funding, FYs 2012–2015	$1.7 million (0% of SMD)		
Lead Center	Langley Research Center		
Start Date	September 2014		
Proposed End Date	April 2017		
TRL Progression	Start	Current	End
	❸	❸	N/A[a]

Link to Technology Roadmap	**Link to Future Missions**
Science Instruments, Observatories, and Sensor Systems (TA08)	Climate Absolute Radiance and Refractivity Observatory Mission

The Earth Science Division's Compact Solar Spectral Irradiance Monitor Project will develop a compact instrument to monitor the power of the Sun's rays using simplified optical components and commercially available subsystems in order to reduce costs. The Project will compare the assembled device to current technologies for spectral wavelength stability, thermal stability and control, and optical material selection quantification. The completed compact monitor, which has been tested in a laboratory at TRL-3 to demonstrate proof of concept, is expected to be tested using a miniature satellite with assembly, environmental testing, and calibration of instrument completed by 2017.

[a] SMD's Earth Science Division does not assign an exit TRL until project completion.

12. MIDWAVE INFRARED SOUNDING OF TEMPERATURE AND HUMIDITY IN A CONSTELLATION



MISTiC Instrument, deployed in a constellation pattern, to measure wind across the Earth. Source: NASA.

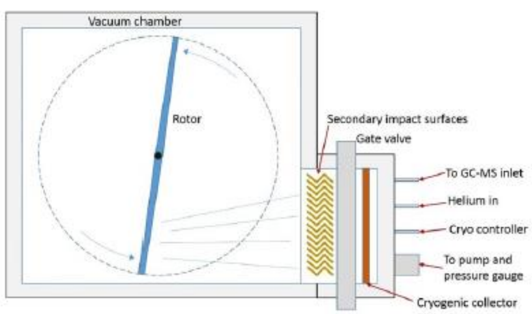
FY 2015 Funding	$1.7 million (1% of SMD)		
Total Funding, FYs 2012-2015	$1.7 million (0% of SMD)		
Lead Center	Goddard Space Flight Center		
Start Date	October 2014		
Proposed End Date	December 2016		
TRL Progression	Start	Current	End
	❹	❹	N/A[a]

Link to Technology Roadmap	Link to Future Missions
Science Instruments, Observatories, and Sensor Systems (TA08)	3-D Winds Mission

The Earth Science Division's Midwave Infrared Sounding of Temperature and Humidity in a Constellation Project (MISTiC Winds) will improve existing hardware to better measure the temperature and humidity of the Earth's atmosphere to create 3-D wind measurements. The Project, currently tested and validated in a laboratory at TRL-4, seeks to deploy a constellation of low-cost satellites roughly the size of a shoe box and weighing 15 kilograms. By the end of 2016, the Project will demonstrate the scanner technology using flight and ground tests while also testing for space radiation tolerance.

[a] SMD's Earth Science Division does not assign an exit TRL until project completion.

13. HIGH VELOCITY RESEARCH



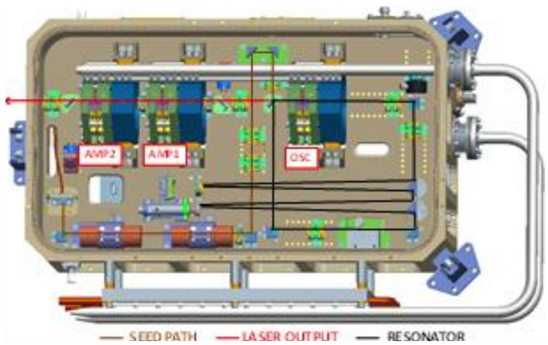
Design for molecules impacting high velocity rotor for observation. Source: NASA.

FY 2015 Funding	$1.6 million (1% of SMD)		
Total Funding, FYs 2012–2015	$1.6 million (0% of SMD)		
Lead Center	NASA Headquarters		
Start Date	August 2015		
Proposed End Date	July 2017		
TRL Progression	Start	Current	End
	❸	❹	❹

Link to Technology Roadmap	Link to Future Missions
Science Instruments, Observatories, and Sensor Systems (TA08)	Europa Mission

The Planetary Science Division's High Velocity Research Project will introduce molecules into a vacuum chamber to be impacted by a rotor at high velocities (several kilometers per second) to study the reactions and thermodynamics of the molecules. This analysis is intended to be used in future flyby or orbiter missions. The Project intends to utilize its analysis of chemical reactions induced by high velocity impacts for potential use in a Europa mission and to review previous missions' data to verify the types and amounts of compounds identified. By 2017, the Project plans to advance to TRL-4 by validating its laboratory testing and analysis of high velocity impacts.

14. TRIPLE-PULSED LIDAR



Design for Triple-Pulsed Lidar to measure carbon dioxide and water vin Earth's atmosphere. Source: NASA.

FY 2015 Funding	$1.5 million (1% of SMD)		
Total Funding, FYs 2012–2015	$1.5 million (0% of SMD)		
Lead Center	Langley Research Center		
Start Date	December 2014		
Proposed End Date	June 2017		
TRL Progression	Start	Current	End
	3	3	N/A[a]

Link to Technology Roadmap	Link to Future Missions
Science Instruments, Observatories, and Sensor Systems (TA08)	SMD's Active Sensing of CO2 Emissions over Nights, Days, and Seasons Mission

The Earth Science Division's Triple-Pulsed Lidar Project will detect and measure carbon dioxide and water vapor in the Earth's atmosphere using laser scanning technology. The Project, currently tested in laboratory at TRL-3 to demonstrate proof of concept, will design and fabricate a laser radar that uses three separate sensing lines to accurately measure carbon dioxide and water vapor for future SMD missions. The laser system is scheduled for integration and ground testing in 2016 and airborne testing in 2017.

[a] SMD's Earth Science Division does not assign an exit TRL until project completion.

15. PEREGRINE ROCKET DEVELOPMENT

NASA engineers demonstrate the scale of the new Peregrine Rocket for NASA's Sounding Rocket Program. Source: NASA.

FY 2015 Funding	$1.4 million (1% of SMD)		
Total Funding, FYs 2012–2015	$7.2 million (1% of SMD)		
Lead Center	Goddard Space Flight Center		
Start Date	January 2012		
Proposed End Date	Ongoing		
TRL Progression	Start	Current	End
	3	4	8

Link to Technology Roadmap	Link to Future Missions
Launch Propulsion Systems (TA01)	Sounding Rocket Program

The Heliophysics Division's Peregrine Rocket Development Project will develop a new rocket engine for the Sounding Rocket Program to enable scientific experimentation and engineering tests in space for very low costs compared to Earth-orbiting platforms. The goal of the Sounding Rocket Program is to develop a larger motor than the current design to improve performance and capability while also simplifying fabrication. The Project conducted open air testing and water proofing in 2014 and plans to advance the rocket with the new engine design to TRL-8 through full system test flights and demonstrations by 2016.

Appendix D: Management's Comments

National Aeronautics and Space Administration
Office of the Administrator
Washington, DC 20546-0001

December 8, 2015

TO: Assistant Inspector General for Audits

FROM: Deputy Administrator

SUBJECT: Response to OIG Draft Report: "NASA's Efforts to Manage Its Space Technology Portfolio" (A-14-017-00)

NASA appreciates the opportunity to review the Office of Inspector General (OIG) draft report entitled "NASA's Efforts to Manage Its Space Technology Portfolio" (A-14-017-00) dated November 13, 2015.

In the draft report, the OIG makes five recommendations addressed to the Administrator, Office of the Chief Technologist (OCT), and the Office of the Chief Engineer (OCE), intended to: 1) clarify the role and authorities of the NASA Technology Executive Council (NTEC); 2) ensure management processes and controls better align and prioritize NASA's space technology projects with its mission goals; and 3) update NASA Procedural Requirement (NPR) 7120.8.

NASA's response to the OIG's recommendations, including planned corrective action dates follows:

To clarify the role and authorities of NTEC, the OIG recommends the NASA Administrator:

Recommendation 1: Develop a charter outlining NTEC's role, responsibilities, authority, and membership.

Management's Response: Concur. NTEC was established by the Agency as documented in the NASA Technology Integration Governance Plan developed in 2010, which states the NTEC's roles, responsibilities, authority, and membership. During the five years the council has been in operation, the Agency has established the Space Technology Mission Directorate, and three Chief Technologists have chaired the council. Consequently, the council's membership and operations have evolved since its establishment. The Agency will review and update, as needed, NTEC's existing charter to clarify its role in the overall NASA governance structure.

Estimated Completion Date: May 31, 2016.

To ensure management processes and controls better align and prioritize NASA's space technology projects with its mission goals, the OIG recommends the Office of Chief Technologist:

Recommendation 2: Further prioritize technologies identified as "core" and "adjacent" in the new SSTIP.

Management's Response: Concur. The next version of the NASA Strategic Space Technology Investment Plan (SSTIP) will be renamed the NASA Strategic Technology Investment Plan (STIP), acknowledging the expanded content of the updated technology roadmaps. As a strategic document, the STIP provides additional guidance for technology investments from the broad 15 Technology Areas of the Roadmaps for the Agency. The STIP will assess the technologies in the updated roadmaps and will include prioritization of the technology candidates and determination of the portion of the Agency portfolio that is core, adjacent, and complementary. The Mission Directorates, who have the program authority, will continue to utilize the STIP guidance, balancing it with their respective programmatic and budgetary constraints in determining specific technology investments associated with their mission needs.

Estimated Completion Date: September 30, 2016.

Recommendation 3: Take steps to ensure that project managers utilize TechPort as intended. This could include additional training, policy clarification, or other measures to incentivize its use and increase accuracy.

Management's Response: Concur. In FY2015, the Associate Administrator issued a policy memo directing the Agency in the use of TechPort. OCT will continue to execute regular quality checks of the data in TechPort and is exploring reorganizing the TechPort Center Representatives team to improve training and conduct Agency-wide advocacy and outreach. Additionally, the Deputy Associate Administrator will further assess the requirements, implementation, and uses of TechPort.

Estimated Completion Date: June 30, 2016.

The OIG recommends NASA's Office of the Chief Engineer update NASA Procedural Requirement (NPR) 7120.8, NASA Research and Technology Program and Project Management, to establish policy and procedures for:

Recommendation 4: Initiating space technology projects that include Agency-wide awareness and coordination.

Management's Response: Partially concur. OCE disagrees with adding policy language in NPR 7120.8. As policy, Agency-wide awareness and coordination for technology portfolio determination is achieved as part of the Agency's strategic planning and acquisition process, which is outside the purview of NPR 7120.8. In practice, this interaction currently exists between the Mission Directorates which actively collaborate in the initiation of projects to ensure Agency-wide awareness and coordination through each Mission Directorates' Program Management Councils processes. The Agency will assess a more structured interaction between Mission Directorates to further improve awareness and coordination during technology project initiation.

Estimated Completion Date: June 30, 2016.

Recommendation 5: Requiring all concluded technology projects complete closeout reports and technology infusion or transfer data for inclusion in TechPort.

Management's Response: Partially concur. OCE agrees with requiring all concluding technology project to complete closeout reports. The requirement for a project close-out report currently exists in NPR 7120.8, section 4.6.2, "Close Out Review" and 4.6.3. "Data Archiving and Publication." The option for inclusion of data in TechPort, specifically, would best be accomplished through additional training, handbook guidance, and incentives as outlined in the Associate Administrator's policy memo regarding the use of TechPort.

Estimated Completion Date: Action is completed; consequently, we request this recommendation be closed upon issuance of the report.

We have reviewed the draft report for information that we believe should not be publicly released and have communicated our concerns regarding the release of information.

Thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact G. Michael Green on (202) 358-4710.

Dr. Dava J. Newman.

cc:
Office of the Chief Technologist/Dr. Miller
Office of the Chief Engineer/Mr. Roe
Space Technology Mission Directorate/Mr. Jurczyk
Science Mission Directorate/Dr. Grunsfeld
Human Exploration and Operations Mission Directorate/Mr. Gerstenmaier

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(Assignment No. A-14-017-00)