**Strategic Roadmap Focus Areas:
Full Titles**

1. Conduct robotic and human lunar expeditions to further science and to test new exploration approaches, technologies, and systems that will enable future human exploration of Mars.

2. Conduct sustained, long-term robotic and human exploration of Mars to understand its history and evolution, to search for evidence of life, and to expand the frontiers of human experience and knowledge.

3. Conduct robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.

4. Conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars.

5. Develop an exploration transportation system to deliver crew and cargo from the surface of Earth to exploration destinations and to return the crew safely to Earth.

6. Complete assembly of the International Space Station and focus its use on supporting space exploration goals.

7. Explore our Universe to understand its origin, structure, evolution, and destiny.

8. Explore the dynamic Earth system to understand how it is changing, to determine the consequences for life on Earth, and to inform our search for life beyond.

9. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.

10. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.

11. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation.

12. Develop a comprehensive national plan for utilization of nuclear systems for the advancement of space science and exploration.

Capabilities Roadmaps Focus Areas: Additional Detail

1.) High-Energy Power and Propulsion

The High Energy Power and Propulsion Capability Roadmap Team seeks information on current and potential future capabilities and technologies as they relate to enabling future NASA missions in support of the Vision for Space Exploration. The capabilities conveyed within this roadmap team shall be developed in the context of the three broad application areas listed below:

- Planetary Surface Power
  - Photovoltaics with energy storage for stationary and mobile applications
  - Nuclear fission power for stationary applications
  - Radioisotope power systems for stationary and mobile applications
- Deep Space Power
  - Radioisotope power systems for deep space probes
- High Energy Propulsion Systems
  - High power solar electric propulsion
  - Nuclear fission electric propulsion
  - Radioisotope electric propulsion
  - Nuclear thermal propulsion

Topics and technologies of special interest include:

- Solar cells and large photovoltaic arrays
- Energy Storage (advanced batteries and regenerative fuel cells)
- Nuclear fission reactors (both power and propulsion reactors)
- General Purpose Heat Source (radioisotope)
- Nuclear shielding
- Power conversion systems (Brayton, Stirling, Rankine, thermoelectrics, thermophotovoltaics)
- Thermal heat rejection
- Power management and distribution
- Electric propulsion systems (thrusters, power processing units, propellant feed systems)
- Fuel tanks
- Pumps
- Nozzles
- Materials and structures

2.) In-Space Transportation

The In-Space Transportation Capability Roadmap Team seeks information on current and potential future capabilities and technologies in the following areas as they relate to enabling future NASA missions in support of the Vision for Space Exploration:

- Advanced In-Space Main Propulsion Systems
- Cryogenic Fluid Management
- Autonomous Rendezvous and Docking (AR&D)

Topics of special interest include:

- LOX/LH2 Upper stage main engines
- LOX/Methane In-space main engines for service module and lunar or Mars descent / ascent propulsion

- LOX/LH2 and LOX/Methane auxiliary propulsion systems for in-space Mars support (OMS and RCS)
- Long Term zero boil-off propellant storage
- Zero-g fluid management
- On-orbit fluid transfer
- AR&D Sensors
- Automated Mission Planning
- Docking /Berthing Mechanisms
- AR&D Ground Test facilities
- Automated Electrical and Fluid Couplings
- Light Weight Cryogenic Propellant Tanks

Do not view this list as totally inclusive. There may be other critical technologies for in-space transportation that need to be identified and input is encouraged. Enhancing technologies should be considered only if they show a significant benefit either in cost or safety/reliability.

3.) Advanced Telescopes and Observatories

This team will assess the technical readiness of the nation in the area of Advanced Telescopes and Observatories to achieve NASA's priority long-range goals (over the period 2005 – 2030). It will consider technologies necessary to enable future telescopes and observatories collecting all electromagnetic bands, ranging from x-rays to millimeter waves, and including gravity-waves. Prioritize activities to be consistent with the current and developing Space Missions Directorate (SMD) science roadmaps. The Committee will consider all technologies associated with the collection and combination of observable signals.

Systems and technologies of special interest are:

- Systems Engineering/Architectures
  - Imaging Systems
  - Interferometer Systems
  - Design, Modeling & Simulation Tools
  - Resistance to Space Environments

- Telescope
  - Optical Components
  - Structures and Materials
  - Wavefront sensors and control systems
  - Thermal control
  - Microwave

- Spatial Interferometry

- Observatory
  - Pointing & Tracking
  - Formation Flying
  - Sun Shades
  - Integration and Testing
  - Facilities

4.) Communication and Navigation

The Telecommunications and Navigation Capability Roadmap Team seeks information on current and potential future capabilities and technologies in the following areas as they relate to enabling future NASA missions in support of the Vision for Space Exploration. This vision will require a robust, extensible communications and navigation architecture. The architecture and capability roadmap will spring from the present legacy systems of the Deep Space Network, the Tracking Data Relay Satellite System, and Ground Systems, and will enable NASA's future human, robotic, and scientific endeavors.

General interest topics include:

- High Bandwidth Communications
- Spectrum efficient technologies
- Networking
- Interplanetary Navigation Techniques
- Integrated Comm/Nav
- Automated rendezvous and docking

Topics of special interest include:

- High power space-based transmitters
- Space-based optical communications
- In-space antenna arraying
- Commercial capabilities for lunar communications

5.) Robotic Access to Planetary Surfaces

Investments in technology, facilities, and human capital enable the delivery and access of scientific instruments to planetary surfaces and atmospheres. This includes landing, flying, roving, and digging, as well as sample acquisition for delivery to instruments. This roadmap will also address Earth entry vehicles for sample return missions, planetary protection, and contamination control for in situ missions. The planetary bodies of interest are the Moon, Mars, Venus, Titan, and the Icy Satellites of the outer planets.

Broad areas of application include:

- Surface Access
- Surface Material Access and Processing
- Entry, Descent, and Landing
- Aerial Systems

Topics and technologies of special interest include:

- Mobility
- Longevity and Survivability
- Sample access (surface, sub-surface, aerial)
- Contamination control and planetary protection
- Spacecraft Entry
- Spacecraft Descent
- Landing
- Surface Observations
- Aerial platform payload, range, mission duration
- Aerial system deployment
- Aerial Observations
- Subsurface Observations

6.) Human Planetary Landing Systems

The Human Planetary Landing Capability Roadmap Team seeks information on current and potential future capabilities and technologies in the following areas as they relate to enabling future NASA missions in support of the Vision for Space Exploration:

- Critical Activity Human Factors
- Hypersonic thermal protection Systems (fix and deployable)
- Hypersonic guidance and control systems algorithms actuators and sensors
- Supersonic decelerator systems
- Subsonic decelerator systems
- Parachute / other subsonic aero-guidance systems and sensors
- Terminal Descent hazard detection sensors
- Terminal Descent Guidance Systems and inertial and other navigation sensors
- Touchdown systems and sensors

Topics of special interest include:

- System configurations for Entry, Descent and Landing
- Deployable Hypersonic aerodynamic surfaces
- Pinpoint landing systems and simulations

7.) Human Health and Support Systems

The Human Health and Support Systems Capability Roadmap Team seeks information on current and potential future capabilities and technologies in the following areas as they relate to enabling future NASA missions in support of the Vision for Space Exploration.

Life Support and Habitation

- Air Revitalization
- Water Reclamation
- Thermal Control
- Solid Waste Management
- Food Management System
- Biomass Production

Environmental Monitoring and Control (Vehicle, lunar and Mars surfaces)

- Air, Water, Surface Monitoring
- External Environment Monitoring
- Life Support Integrated Controls
- Fire Prevention, Detection, Suppression

Exploration Habitats (lunar and Mars)

- Surface Construction
- Habitat Shell
- Internal Systems and Outfitting
- External Systems and Architecture

Extra-vehicular Activity (in space and lunar and Mars surface)

- EVA suits
- Portable Life Support Systems
- Airlock
- EVA Tools

Autonomous Medical Care

- Prevention
- Monitoring
- Diagnosis
- Treatment

Radiation

- Measurement Technologies
- Shielding Solutions
- Shielding Concepts/Recommendations

8.) Human Exploration Systems and Mobility

The Human Exploration Systems Capability Roadmap Team seeks information on current and potential capabilities and technologies that may relate to enabling future NASA missions in support of the Vision for Space Exploration in the following areas:

- Crew mobility systems, both in-space and on planetary surfaces.

- In-space assembly approaches, including robotics/humans, self-assembling systems, large, intermediate and fine scale assembly systems, metrology and positioning, intra vehicular assembly and construction and logistics and planning for assembly.

- In-Space System Deployment including the following:

  - Kinematically-Deployable Primary Systems
  - Inflatable Primary Systems
  - Deployable Intermediate Precision Systems
  - Deployable High Precision Systems
  - Structural and Pressurized Interconnections
  - Electrical and Data Interconnections
  - Thermal and Fluid Interconnections
  - Release and Latch-up Systems
  - Intelligent Rendezvous, Capture and Docking
  - Adaptive Terminal Guidance & Control
  - Docking Controls, Mechanisms & Actuators
  - Pressurized Module Docking Control and Mechanisms
  - Intelligent Modular/Miniaturized GN&C
  - Adaptive Self-Assembling System Architectures
  - Extra-Vehicular Inspection
  - Outgassing, Leak & Contamination Detection
  - Non-Destructive Evaluation and Test
  - Electronics Fault Detection, Isolation & Diagnosis
  - Software Fault Detection, Isolation and Diagnosis

- Servicing, Maintenance and Repair

  - Modular Subsystem and Component Replacement Units
  - Rescue and Intrusive Repairs
  - Propulsion System Refurbishment and RepairPropellant Lines
  - Refueling and Fluids Resupply Support Systems
  - Structural Materials-Level Repair Systems
  - Upgradeable and Reconfigurable Systems Concepts
  - Standards, Interfaces and Architectures

- Human-Robot Interaction

  - Multi-agent teaming strategies (both robot and humans)
  - Communications protocols
  - Shared work environment tools, adaptations, etc.

- Work definition tools (which tasks are better suited for robots, which are better suited for humans, etc.)

9.) Autonomous Systems and Robotics

The Autonomous Systems and Robotics roadmap focuses on two broad classes of capabilities: Autonomous Systems element focuses on capabilities to enable smarter more adaptive systems that can respond to environmental uncertainties both in close cooperation with humans and in remote locations. For human exploration, this capability will provide the underlying reasoning capabilities to augment, extend and at times replace the functionality traditionally performed by ground control thus enabling a crew-centered mode of operation. For robotic missions it enables increased productivity and the ability to explore environments that otherwise would not be accessible. The Robotics portion focuses on the development of integrated robotic systems that provide complex interaction with the physical environment often coupling mobility and manipulation mechanisms with embedded autonomy capabilities to navigate and perform tasks within the environment.

Broad applications include:

- Autonomous rendezvous and docking
- Crew-centered operations
- Autonomous operations in distant and harsh environments
- In-space construction and operations
- Ground-based automation and decision making
- Computing systems

Topics and technologies of specific interest include:

- Perception, Modeling. Localization, and Machine Vision
- Control of Robotic Mobility
- Control of Robotic Manipulation
- Planning, Execution, and Agent Architectures
- System Health and Status Management
- Robust Software Systems
- Human-Machine Interaction
- Information Management and Knowledge Representation
- Onboard Computing Systems

10.) Transformational Spaceport/Range

As defined in the Aldridge Commission Report, transformational spaceport/range technologies are "enabling technologies" that "will be critical to attainment of exploration objectives within reasonable schedules and affordable costs." The Spaceport and Range Capability Roadmap will focus on the launch site infrastructure and range capabilities needed to meet NASA's mission while considering impacts/synergies with non-NASA stakeholders of common assets. The Roadmap team will be using the Advanced Spaceport & Range Technologies Working Groups (ASTWG & ARTWG, http://artwg.ksc.nasa.gov/) products as a foundation for this effort. NASA seeks ideas and comments from industry regarding transformational spaceport and range technologies.

11.) Scientific Instruments/Sensors

The Science Instrument and Sensor Capability Roadmap Team will investigate enabling science technologies and capabilities required by future instruments aboard NASA's Exploration Vision missions. The instrument and sensor technical capabilities will be derived from scientific measurement priorities, system level requirements, and design reference mission needs. Our initial set of technical capabilities are currently grouped in the following broad application areas:

- Active and Passive Microwave Remote Sensing
- Multi Spectral Imaging & Spectrometry
- Laser / LIDAR Systems
- Direct Sensing of Fields, Waves and Particles
- Surface Sample Chemical and Physical Analysis

Topics and technologies of special interest include:

- Active electronics and antennae
- Passive electronics
- Onboard data processing systems, especially radiation-hardening
- Astronomical detector systems
- Optics, including coatings and filters
- Laser and LIDAR systems
- Thermal control systems
- Cryogenic systems
- Detectors and MEMS for particles and fields
- Surface instrument systems, including drills, sample preservation, and bio-assay

12.) In Situ Resource Utilization

The In-Situ Resource Utilization Team seeks information on current and potential future capabilities and technologies in the following areas as they relate to enabling future NASA missions in support of the Vision for Space Exploration:

- *Resource Extraction* - Efficient excavation and transport of resources in extremely cold (ex, permanent shadowed lunar crater), dusty/abrasive, and/or micro-g environments (e.g., asteroids, comets, Mars moons, etc.). Also, includes in-situ identification of resources and efficient physical and thermal extraction and separation of loosely bound volatiles and water. Techniques must be capable of extracting 100’s to 1000’s their own mass
- *Resource & Waste Transportation* - Efficient transportation (fixed or mobile assets) of excavated and/or extracted resource to location of use or location of further processing. Techniques must be capable of transporting 100’s to 1000’s their own mass.
- *Resource Processing* - Efficient (minimum power and Earth supplied reagents) and economical production of propellants and other critical mission consumables using in-situ resources. Efficient extraction and refining of surface manufacturing and construction feedstock (such as silicon, aluminum, iron, and plastic).
- *Surface Manufacturing with In-Situ Resources* - Processing and manufacturing techniques, capable of producing a broad range of products in their useful lifetimes, with reasonable quality. Reliable and accurate manufactured parts and equipment, with the minimum of required equipment and crew training necessary.
- *Surface Construction* - Construction and erection techniques capable of producing complex structures from a variety of available or in-situ manufactured materials and the minimum of Earth supplied consumables. Maintenance, repair, and replacement costs less than 20% of the cost of Earth delivered equipment and products. Also includes in-situ radiation shield fabrication and placement techniques.
- *Surface ISRU Product & Consumable Storage and Distribution* - Mass and power efficient storage and transfer of propellants, cryogenic fluids, gases, and Earth storable liquid in-situ products or consumables used in in-situ processing. EVA and robotic disconnects applicable to dusty/cold environments. Also, relevant is Mass and volume efficient delivery of hydrogen to Mars for resource processing.
- *Survivability & Autonomous Control* - Long meantime between failures while operating in harsh environments with minimal or no maintenance available. Autonomous control and failure recovery for non-continuous monitoring (for pre-deployed, robotic, and tele-operated missions) and to minimize crew involvement requirements in operation and maintenance.

Of particular interest for initial Spirals are development of technologies and systems for robotic precursor missions and eventual human missions to the Moon and Mars that include:

- Extraction and collection of regolith volatiles, potential water resources and atmospheric gases, along with production, storage, and transfer of mission critical consumables, such as oxygen, propellants, life support gases, and fuel cell reagents.
- Efficient and low maintenance excavation and material handling techniques for site and landing pad preparation, berms for surface reactors and plume debris, and radiation shielding for long-term stays.
- Manufacturing of spare parts, power and thermal utility, and high mass leverage items from in-situ resources to lower mission risk and provide mission flexibility.

13.) Advanced Modeling, Simulation, and Analysis

Modeling and simulation are being used more pervasively and more effectively throughout the space program, for both engineering and science pursuits, than ever before. These are tools that allow high fidelity simulations of systems in environments that are difficult or impossible to create on earth, allow removal of humans from experiments in dangerous situations, and provide visualizations of datasets that are extremely large and complicated. Examples of past simulation successes include hypersonic flowfield simulations around the Space Shuttle Columbia that allowed a detailed understanding of the shuttle tile impact, simulations of entry conditions for man-rated space flight vehicles, visualizations of distant planet topography via simulated fly-over and three-dimensional visualizations of coupled ocean and weather systems. In many of these situations, assimilation of real data into a highly sophisticated physics model is needed.

Topics and technologies of special interest include:

- identifying new potential areas in which simulations may be effective,
- predicting the future development of both existing and new areas of simulation and assessing investments needed by NASA to foster further development
- determining the tools and software systems that would be needed to exploit all simulations in the future, as the modeling sophistication increases
- determining the future hardware and networking needs to enable the exploitation of simulation for NASA.

14.) Systems Engineering Cost/Risk Analysis

The Systems Engineering capability roadmap team seeks information on current and potential future capabilities and technologies in the following areas as they relate to enabling future NASA missions in support of the Vision for Space Exploration:

- Systems Engineering
- Risk Management
- Life Cycle Cost Analysis
- Safety and Mission Assurance

Topics of special interest include:

- Process Management
  - Organizational Process Focus
  - Organizational Process Definition
  - Organizational Training
  - Organizational Process Performance
  - Organizational Innovation and Deployment

- Project Management
    - Project Planning
    - Project Monitoring & Control
    - Supplier Agreement Management
    - Integrated Project Management
    - Risk Management
    - Integrated Training
    - Integrated Supplier Management
    - Quantitative Project Management
- Engineering
    - Requirements Management
    - Requirements Development
    - Technology Solution
    - Cost Estimation
    - Cost Estimation
    - Reliability and Safety
    - Product Integration
    - Verification
    - Validation
- Support
    - Configuration Management
    - Process and Product Quality Assurance
    - Measurement and Analysis
    - Decision Analysis and Resolution
    - Organizational Environment for Integration
    - Causal Analysis and Resolution

Systems engineering is decision making for the development of complex systems through leadership, engineering processes and methods. The team will analyze NASA's current systems engineering processes for and application to large, complex systems comprising the Space Exploration Vision. The team will use the Systems Engineering Capability Maturity Model (SE-CMMI)* as the basis for comparison to NASA practices, the identification of capability gaps, and the visioneering for future needs required to support the projects within the Exploration Vision.

The roadmap team will use the SE-CMMI model for assessment of the system engineering process (including risk) and will update the model to include cost and safety which are key Level 0 system requirements for the Exploration Vision. The SE-CMMI model includes the work breakdown structure, descriptions, goals, and methods for capability assessment.

Information on best practices of SE-CMMI, cost estimation, and reliability and safety are sought to identify capability gaps to establish requirements for future development.

[*] Capability Maturity Model® Integration (CMMI[SM]) for Systems Engineering, Software Engineering, Integrated Product and Process Development, and Supplier Sourcing, Version 1.1, CMMI Product Team, (http://www.sei.cmu.edu/publications/documents/02.reports/02tr011.html)

15.) Nanotechnology

Nano-scale technology represents a revolution in capability that spans all NASA mission areas and its effects are pervasive throughout many areas of technology critical to NASA's future. Nanotechnology is not a unique technology unto itself, but encompasses technological advances that enable precise control over the composition and placement of matter on the scale of nanometers. The significance is that at the nano-scale extraordinary electrical, mechanical, optical and thermal properties emerge that are not present at larger scales. With this comes the opportunity to develop new materials, devices and systems with levels of performance not achievable by current technological approaches. Five years ago NASA recognized the opportunities arising from discoveries at the nano-scale as critical areas for long term and initiated focused strategic investments to exploit the rapid rate of discovery.

The principle focus of this capability area will be on developing core underlying nano-scale technology and demonstrations that can be incorporated in to higher level applications such as:

- High performance, multi-functional materials for aeronautics and space vehicles,
- High density, low power space durable electronics and computing,
- High sensitivity measurement and detection for scientific instruments, human health monitoring, vehicle health monitoring and detection of past or current extraterrestrial life
- Lightweight, high efficiency power and communications