# NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES

## Restoring NASA's Technological Edge and Paving the Way for a New Era in Space

NATIONAL RESEARCH COUNCIL
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# Context: State of Space Technology

- Success in executing future NASA space missions will depend on advanced technology developments that should already be underway
- NASA's technology base is largely depleted
- Currently available technology is insufficient to accomplish many intended space missions in Earth orbit and to the Moon, Mars, and beyond
- Future U.S. leadership in space requires a foundation of sustained technology advances
- Importance of a foundational technology base cited in 2010 NASA Authorization Act
- Technologies prioritized in this study represent a foundation upon which to build the strategic goals outlined in the 2011 NASA Strategic Plan

**NASA Technology Roadmaps will help provide direction and stability**

# Technology Area Breakdown Structure (TABS)

**NASA generated 14 draft roadmaps based on a layered Technology Area Breakdown Structure:**

- **Level 1: Technology Areas**
  - Total of 14
- **Level 2: Technology Subareas**
  - Total of 64
- **Level 3: Technologies**
  - Total of 320
  - Modified / Reduced to 295 during initial assessment

**NASA Draft Roadmaps provided effective "point-of-departure" for study**

# Technology Area Breakdown Structure

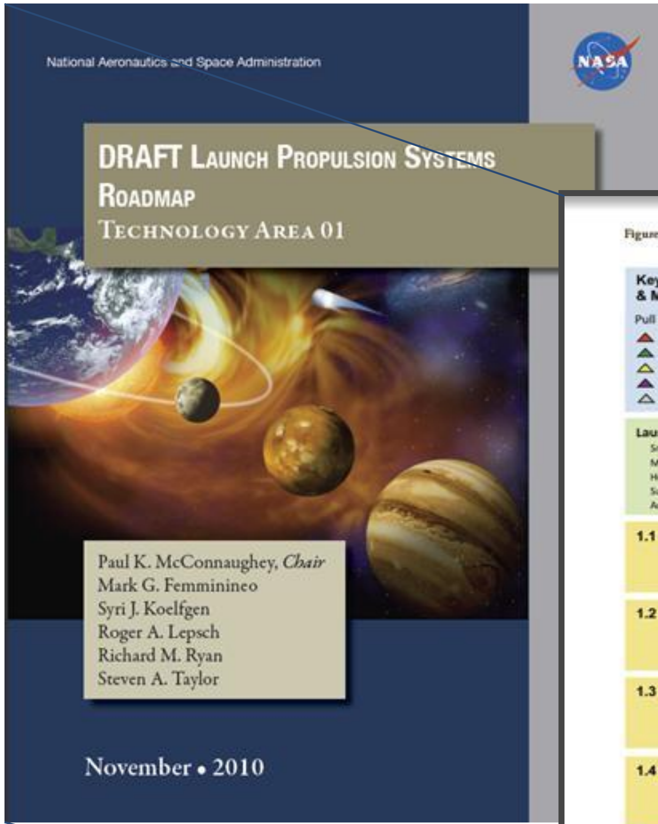
**Draft roadmap produced for each of 14 technology areas (TAs) with a total of 320 level 3 technologies**

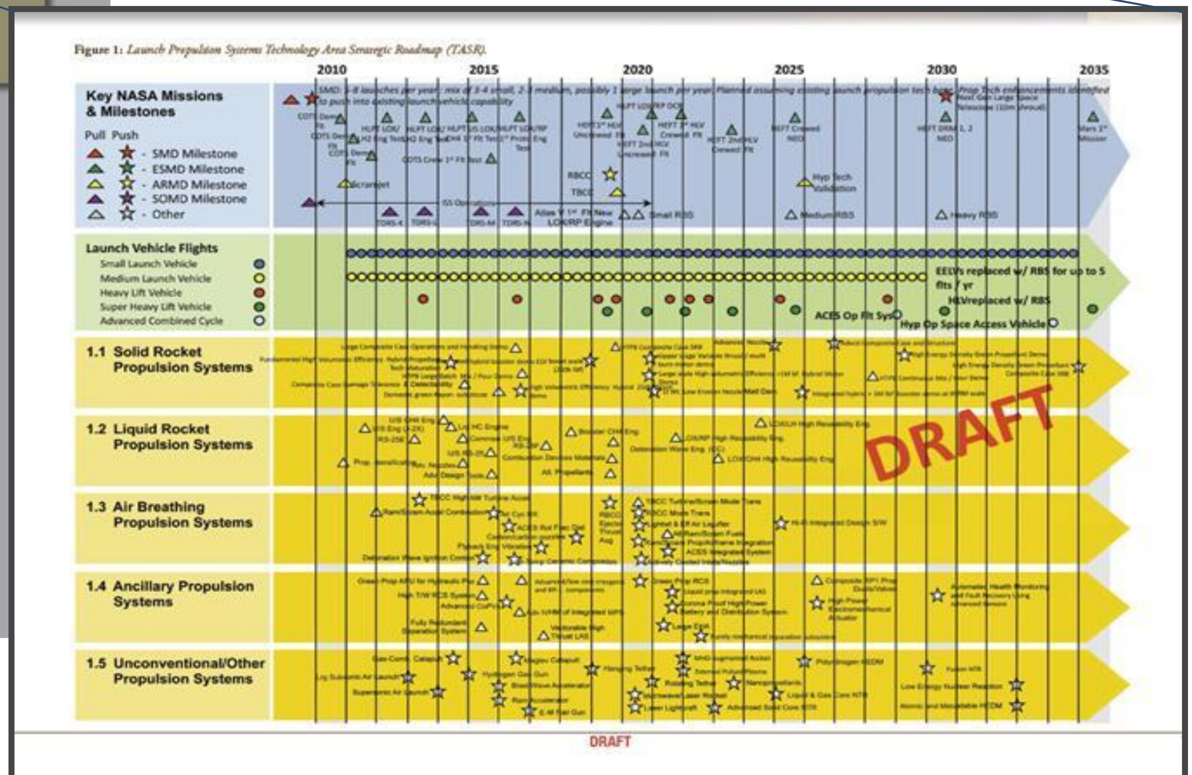
- TA01: Launch Propulsion Systems
- TA02: In-Space Propulsion Systems
- TA03: Space Power and Energy Storage Systems
- TA04: Robotics, Tele-Robotics, and Autonomous Systems
- TA05: Communication and Navigation Systems
- TA06: Human Health, Life Support and Habitation Systems
- TA07: Human Exploration Destination Systems
- TA08: Scientific Instruments, Observatories, and Sensor Systems
- TA09: Entry, Descent and Landing Systems
- TA10: Nanotechnology
- TA11: Modeling, Simulation, Information Technology, and Data Processing
- TA12: Materials, Structures, Mechanical Systems, and Manufacturing
- TA13: Ground and Launch Systems Processing
- TA14: Thermal Management Systems

**The study's interim report defined a modified TABS with 295 technologies**

# NASA Draft Roadmaps

## NASA Input—Study Point of Departure



# Technology vs. Engineering

- **Technology Development**
  - Process of understanding and evaluating concepts and capabilities that improve or enable performance advances over current state-of-the-art space systems
  - Intended focus of draft roadmaps
- **Engineering Development**
  - Implement and apply existing or available technology
  - High-priority technologies do not include items where engineering development is the next step

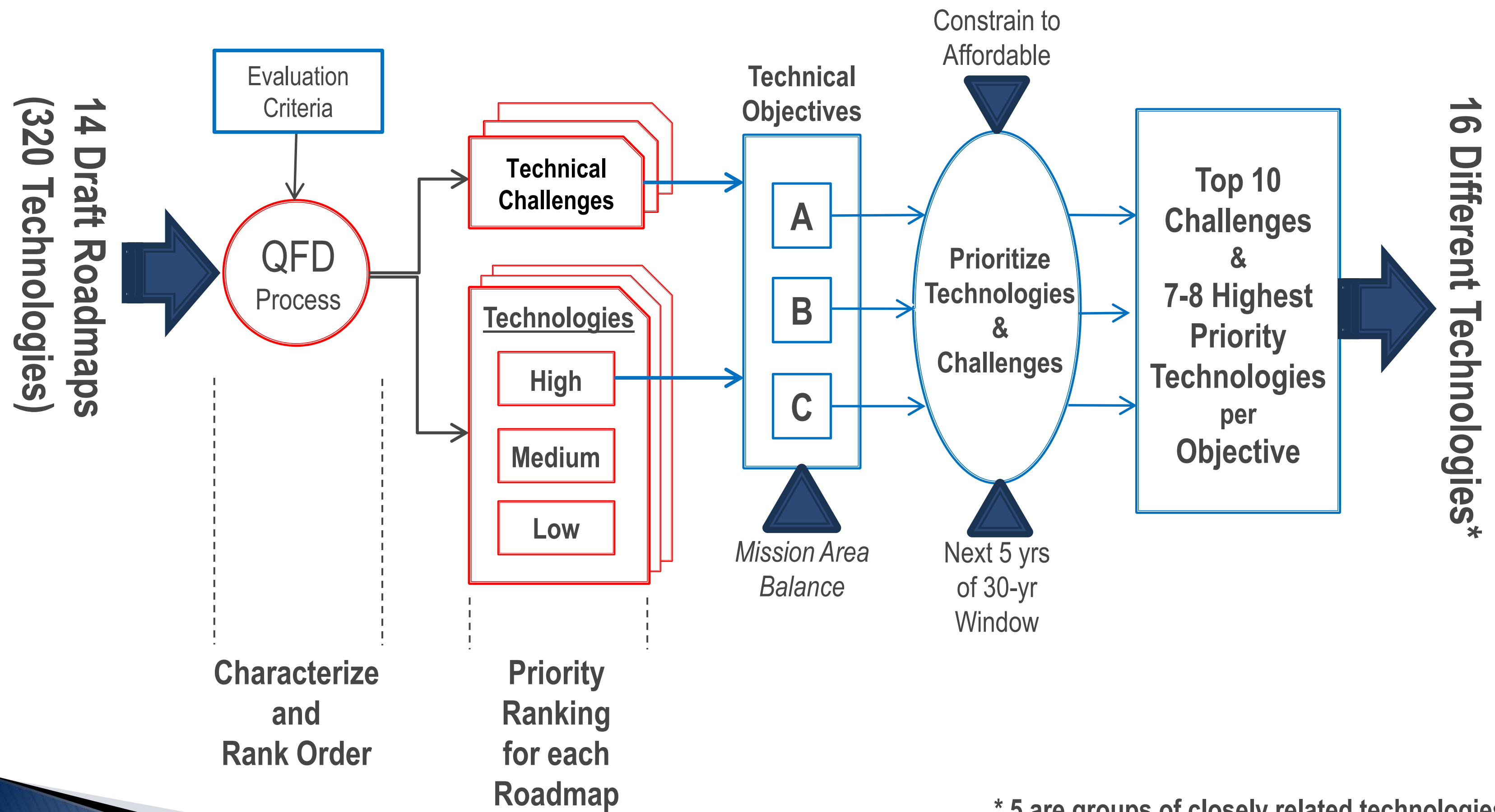
# Technology Push and Mission Pull

- **Roadmaps include "mission pull" technologies**
  - Contribute to specific future missions
  - Based on recognized need if not requirement
- **Roadmaps also include emerging "push" technologies**
  - Can shape future missions
    - Provide new opportunities
    - Open up options
  - Can influence future requirements
  - Fosters new and emerging centers of expertise/talent

# Organizing Framework

Panels

Steering Committee




* 5 are groups of closely related technologies

# Sample Panel Evaluation

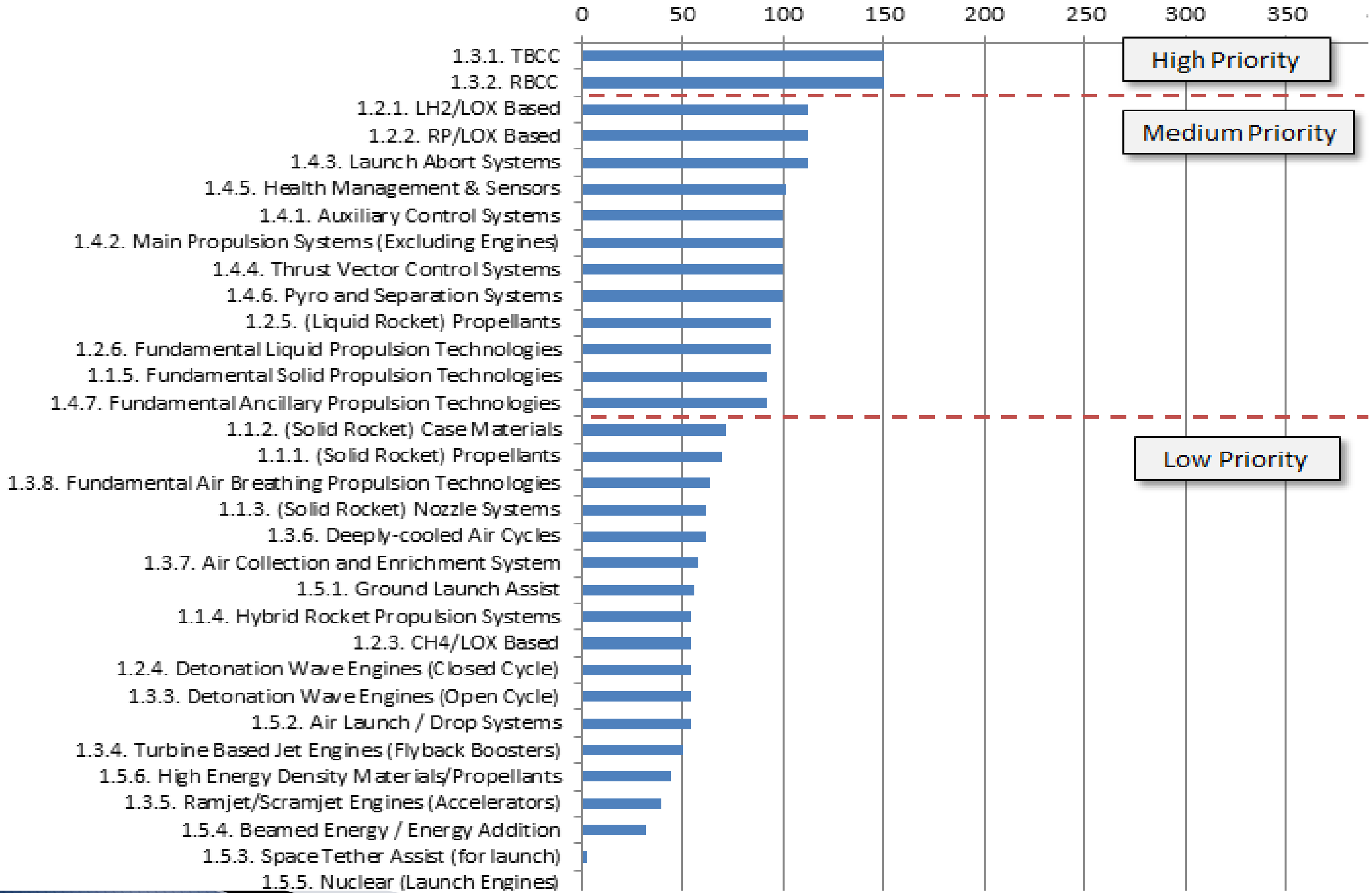
# TA01 Launch Propulsion Systems

# QFD Technology Panel Evaluation: TA01 Launch Propulsion Systems (p. 1 of 2)

| | Benefit | Alignment with NASA Needs | Alignment with Non-NASA Aero Tech Needs | Alignment with Non-Aerospace National Goals | Technical Risk and Reasonableness | Sequencing and Timing | Time and Effort | QFD Score (Weighted) | Panel Priority |
|---|---|---|---|---|---|---|---|---|---|
| Multiplier: | 27 | 5 | 2 | 2 | 10 | 4 | 4 | | |
| | 0/1/3/9 | 0/1/3/9 | 0/1/3/9 | 0/1/3/9 | 1/3/9 | -9/-3/-1/1 | -9/-3/-1/0 | | |
| Technology Name | Benefit | Alignment | | | Risk/Difficulty | | | | |
| 1.1.1. (Solid Rocket) Propellants | 1 | 3 | 3 | 0 | 3 | -1 | -1 | 70 | L |
| 1.1.2. (Solid Rocket) Case Materials | 1 | 3 | 3 | 1 | 3 | -1 | -1 | 72 | L |
| 1.1.3. (Solid Rocket) Nozzle Systems | 1 | 3 | 3 | 0 | 3 | -3 | -1 | 62 | L |
| 1.1.4. Hybrid Rocket Propulsion Systems | 1 | 3 | 3 | 0 | 3 | -3 | -3 | 54 | L |
| 1.1.5. Fundamental Solid Propulsion Technologies | 1 | 9 | 3 | 0 | 3 | -3 | -1 | 92 | M |
| 1.2.1. LH2/LOX Based | 1 | 9 | 9 | 0 | 3 | 1 | -3 | 112 | M |
| 1.2.2. RP/LOX Based | 1 | 9 | 9 | 0 | 3 | 1 | -3 | 112 | M |
| 1.2.3. CH4/LOX Based | 1 | 3 | 3 | 0 | 3 | -3 | -3 | 54 | L |
| 1.2.4. Detonation Wave Engines (Closed Cycle) | 1 | 3 | 3 | 0 | 3 | -3 | -3 | 54 | L |
| 1.2.5. (Liquid Rocket) Propellants | 1 | 9 | 3 | 1 | 3 | -3 | -1 | 94 | M |
| 1.2.6. Fundamental Liquid Propulsion Technologies | 1 | 9 | 3 | 1 | 3 | -3 | -1 | 94 | M |
| 1.3.1. TBCC | 3 | 9 | 9 | 0 | 3 | -3 | -3 | 150 | H |
| 1.3.2. RBCC | 3 | 9 | 9 | 0 | 3 | -3 | -3 | 150 | H |

H=High priority; M=Medium Priority; L=Low Priority

# QFD Technology Panel Evaluation: TA01 Launch Propulsion Systems (continued)



# Top Technical Challenges:
# TA01 Launch Propulsion Systems

1. **Reduced Cost:** *Develop propulsion technologies that have the potential to dramatically reduce the total cost and to increase reliability and safety of access to space*
2. **Upper Stage Engines:** *Develop technologies to enable lower cost, high specific impulse upper stage engines suitable for NASA, DOD, and commercial needs, applicable to both Earth-to-orbit and in-space applications*

# Technologies vs. Challenges: TA01 Launch Propulsion Systems

| | | Top Technology Challenges | |
|---|---|---|---|
| Priority | TA01 Technologies, Listed by priority | 1. Reduced Cost | 2. Upper Stage Engines |
| H | 1.3.1. TBCC | ● | |
| H | 1.3.2. RBCC | ● | |
| M | 1.2.1. LH2/LOX Based | ○ | ● |
| M | 1.2.2. RP/LOX Based | ○ | |
| M | 1.4.3. Launch Abort Systems | ○ | |
| M | 1.4.5. Health Management and Sensors | ○ | ○ |
| M | 1.4.1. Auxiliary Control Systems | | ○ |
| M | 1.4.2. Main Propulsion Systems (Excluding Engines) | | |
| M | 1.4.4. Thrust Vector Control Systems | | |
| M | 1.4.6. Pyro and Separation Systems | | |
| M | 1.2.5. (Liquid Rocket) Propellants | | |
| M | 1.2.6. Fundamental Liquid Propulsion Technologies | | |
| M | 1.1.5. Fundamental Solid Propulsion Technologies | | |
| M | 1.4.7. Fundamental Ancillary Propulsion Technologies | | |
| L | 1.1.2. (Solid Rocket) Case Materials | | |
| L | 1.1.1. (Solid Rocket) Propellants | | |
| L | 1.3.8. Fundamental Air Breathing Propulsion Technologies | | |
| L | 1.1.3 (Solid Rocket) Nozzle Systems | | |
| L | 1.3.6. Deeply-Cooled Air Cycles | | |
| L | 1.3.7. Air Collection and Enrichment System | | |
| L | 1.5.1. Ground Launch Assist | | |
| L | 1.1.4. Hybrid Rocket Propulsion Systems | | |
| L | 1.2.3. CH4/LOX Based | | |
| L | 1.2.4. Detonation Wave Engines (Closed Cycle) | | |
| L | 1.3.3. Detonation Wave Engines (Open Cycle) | | |
| L | 1.5.2. Air Launch / Drop Systems | | |
| L | 1.3.4. Turbine Based Jet Engines (Flyback Boosters) | | |
| L | 1.5.6. High Energy Density Materials/Propellants | | |
| L | 1.3.5. Ramjet/Scramjet Engines (Accelerators) | | |
| L | 1.5.4. Beamed Energy / Energy Addition | | |
| L | 1.5.3. Space Tether Assist (for launch) | | |
| L | 1.5.5. Nuclear (Launch Engines) | | |

Legend

| | |
|---|---|
| H | High Priority Technology |
| M | Medium Priority Technology |
| L | Low Priority Technology |
| ● | Strong Linkage: Investments by NASA in this technology would likely have a major impact in addressing this challenge. |
| ○ | Moderate Linkage: Investments by NASA in this technology would likely have a moderate impact in addressing this challenge. |
| [blank] | Weak/No Linkage: Investments by NASA in this technology would likely have little or no impact in addressing the challenge. |

# Panels' 83 High Priority Technologies

**TA01 Launch Propulsion Systems**

1.3.1 Turbine Based Combined Cycle (TBCC)
1.3.2 Rocket Based Combined Cycle (RBCC)

**TA02 In-Space Propulsion Technologies**

2.2.1 Electric Propulsion
2.4.2 Propellant Storage and Transfer
2.2.3 (Nuclear) Thermal Propulsion
2.1.7 Micro-Propulsion

**TA03 Space Power and Energy Storage**

3.1.3 Solar Power Generation (Photovoltaic and Thermal)
3.1.5 Fission Power Generation
3.3.3 Power Distribution and Transmission
3.3.5 Power Conversion and Regulation
3.2.1 Batteries
3.1.4 Radioisotope Power Generation

**TA04 Robotics, TeleRobotics, and Autonomous Systems**

4.6.2 Relative Guidance Algorithms
4.6.3 Docking and Capture Mechanisms/Interfaces
4.5.1 Vehicle System Management and FDIR
4.3.2 Dexterous Manipulation
4.4.2 Supervisory Control
4.2.1 Extreme Terrain Mobility
4.3.6 Robotic Drilling and Sample Processing
4.2.4 Small Body/Microgravity Mobility

**TA05 Communication and Navigation**

5.4.3 Onboard Autonomous Navigation and Maneuvering
5.4.1 Timekeeping and Time Distribution
5.3.2 Adaptive Network Topology
5.5.1 Radio Systems

# Panels' 83 High Priority Technologies (continued)

**TA06 Human Health, Life Support, and Habitation Systems**

6.5.5 Radiation Monitoring Technology
6.5.3 Radiation Protection Systems
6.5.1 Radiation Risk Assessment Modeling
6.1.4 Habitation
6.1.3 Environmental Control and Life Support System (ECLSS) Waste Management
6.3.2 Long-Duration Crew Health
6.1.2 ECLSS Water Recovery and Management
6.2.1 Extravehicular Activity (EVA) Pressure Garment
6.5.4 Radiation Prediction
6.5.2 Radiation Mitigation
6.4.2 Fire Detection and Suppression
6.1.1 Air Revitalization
6.2.2 EVA Portable Life Support System
6.4.4 Fire Remediation

**TA07 Human Exploration Destination Systems**

7.1.3 In-Situ Resource Utilization (ISRU) Products/Production
7.2.1 Autonomous Logistics Management
7.6.2 Construction and Assembly
7.6.3 Dust Prevention and Mitigation
7.1.4 ISRU Manufacturing/ Infrastructure etc.
7.1.2 ISRU Resource Acquisition
7.3.2 Surface Mobility
7.2.4 Food Production, Processing, and Preservation
7.4.2 Habitation Evolution
7.4.3 Smart Habitats
7.2.2 Maintenance Systems

**TA08 Science Instruments, Observatories, and Sensor Systems**

8.2.4 High-Contrast Imaging and Spectroscopy Technologies
8.1.3 Optical Systems (Instruments and Sensors)
8.1.1 Detectors and Focal Planes
8.3.3 In Situ Instruments and Sensors
8.2.5 Wireless Spacecraft Technology
8.1.5 Lasers for Instruments and Sensors
8.1.2 Electronics for Instruments and Sensors

# Panels' 83 High Priority Technologies (continued)

**TA09 Entry, Descent, and Landing (EDL) Systems**

9.4.7 GN&C Sensors and Systems (EDL)
9.1.1 Rigid Thermal Protection Systems
9.1.2 Flexible Thermal Protection Systems
9.1.4 Deployment Hypersonic Decelerators
9.4.5 EDL Modeling and Simulation
9.4.6 EDL Instrumentation and Health Monitoring
9.4.4 Atmospheric and Surface Characterization
9.4.3 EDL System Integration and Analysis

**TA10 Nanotechnology**

10.1.1 (Nano) Lightweight Materials and Structures
10.2.1 (Nano) Energy Generation
10.3.1 Nanopropellants
10.4.1 (Nano) Sensors and Actuators

**TA11 Modeling, Simulation, Information Technology, and Processing**

11.1.1 Flight Computing
11.1.2 Ground Computing
11.2.4a Science Modeling and Simulation
11.3.1 Distributed Simulation

**TA12 Materials, Structures, Mechanical Systems, and Manufacturing**

12.2.5 Structures: Innovative, Multifunctional Concepts
12.2.1 Structures: Lightweight Concepts
12.1.1 Materials: Lightweight Structure
12.2.2 Structures: Design and Certification Methods
12.5.1 Nondestructive Evaluation and Sensors
12.3.4 Mechanisms: Design and Analysis Tools and Methods
12.3.1 Deployables, Docking, and Interfaces
12.3.5 Mechanisms: Reliability/Life Assessment/Health Monitoring
12.4.2 Intelligent Integrated Manufacturing and Cyber Physical Systems

**TA13: Ground and Launch Systems Processing**

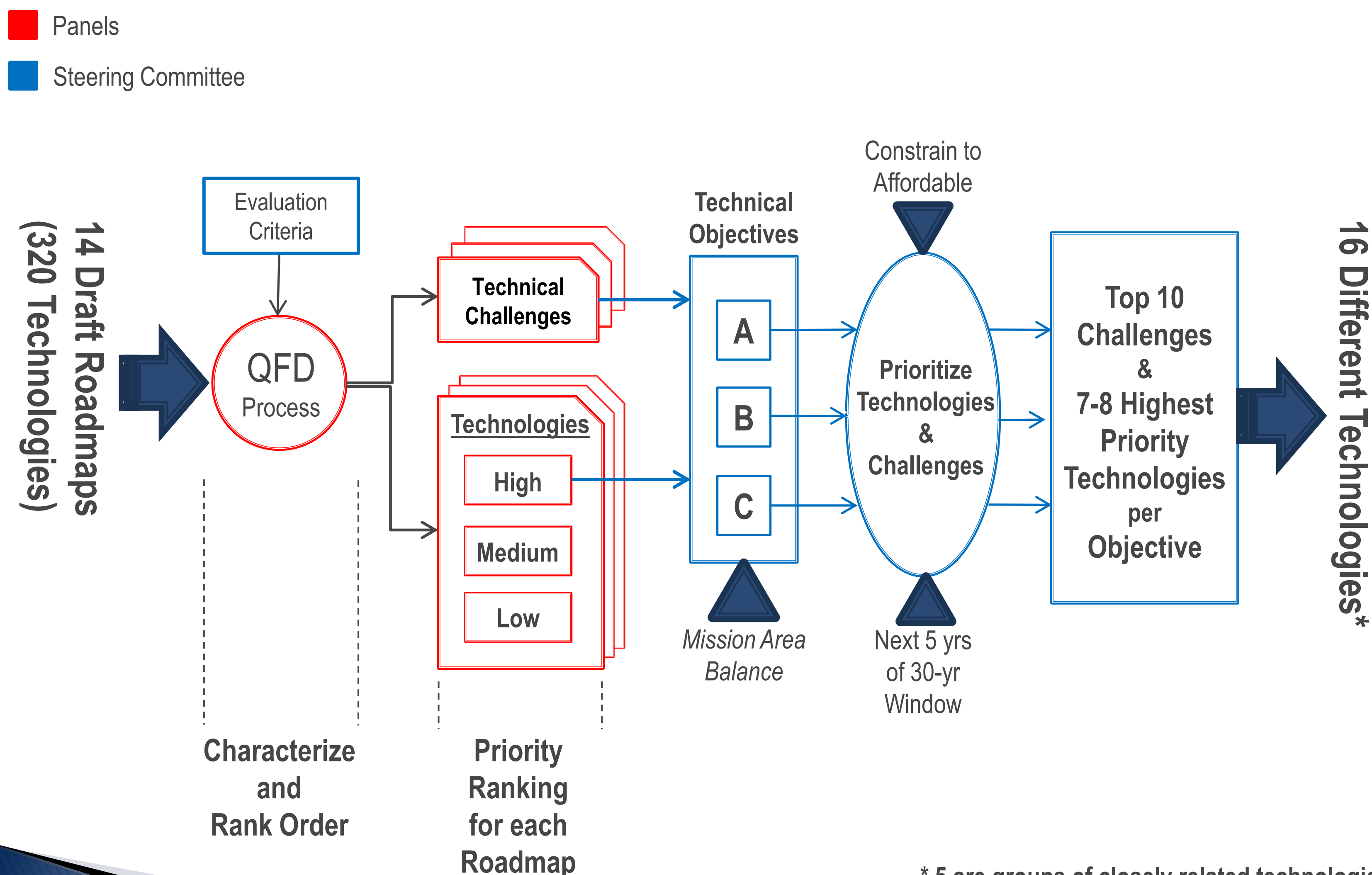
none

**TA14 Thermal Management Systems**

14.3.1 Ascent/Entry Thermal Protection Systems
14.1.2 Active Thermal Control of Cryogenic Systems

# Integrated Ranking

# Organizing Framework



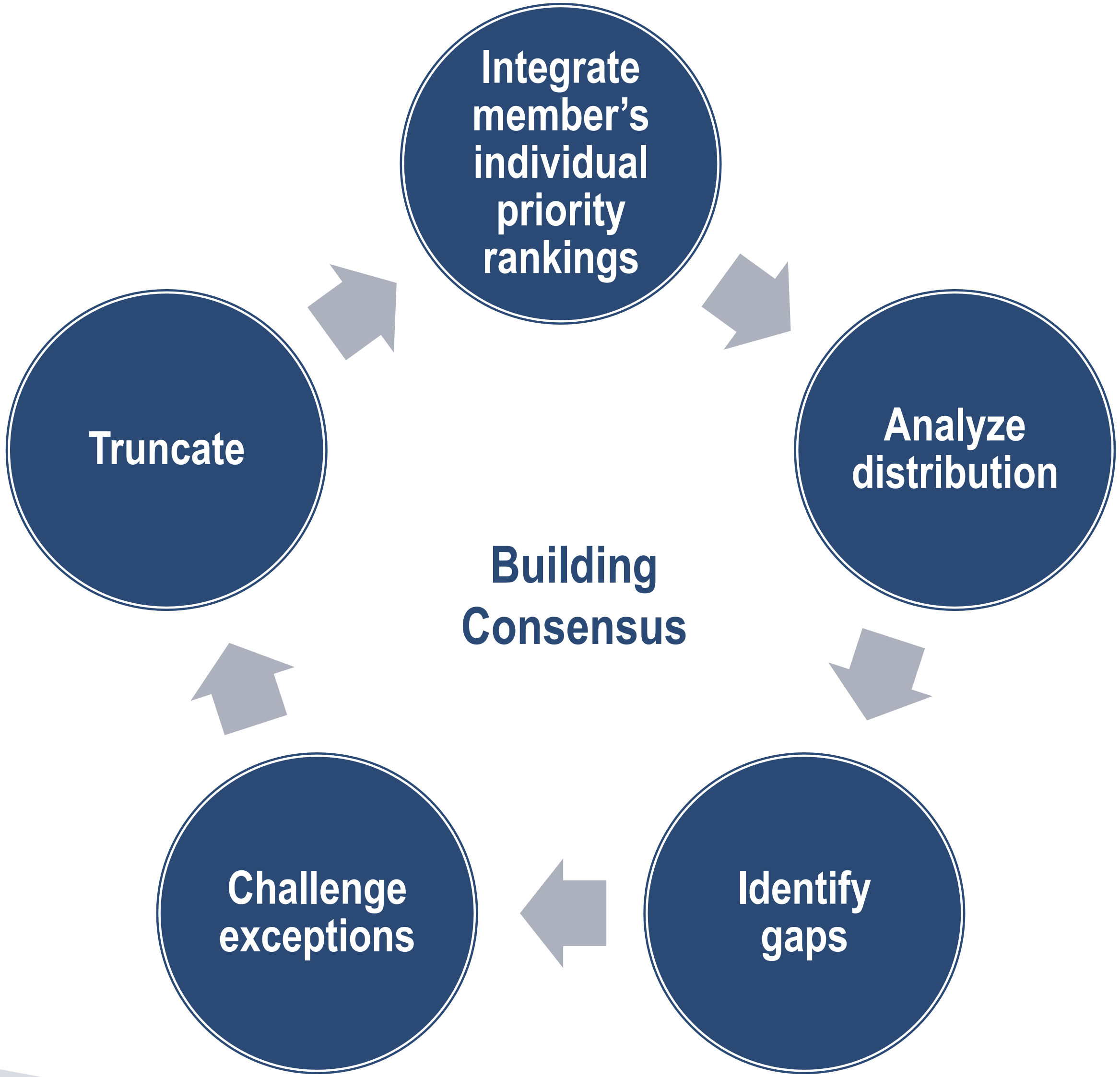

* 5 are groups of closely related technologies

# Technology Objectives

## Three technology objectives were defined by steering committee

- **Technology Objective A: Extend and sustain human activities beyond low Earth orbit.** *Technologies to enable humans to survive long voyages throughout the solar system, get to their chosen destination, work effectively, and return safely*
- **Technology Objective B: Explore the evolution of the solar system and the potential for life elsewhere.** *Technologies that enable humans and robots to perform* ***in-situ measurements*** *on Earth (astrobiology) and on other planetary bodies*
- **Technology Objective C: Expand our understanding of Earth and the universe in which we live.** *Technologies for* ***remote measurements*** *from platforms that orbit or fly by Earth and other planetary bodies, and from other in-space and ground-based observatories*

# Committee Deliberative Process



# Top Technical Challenges

| Technology Objective A<br>Extend and sustain human activities beyond LEO | Technology Objective B<br>Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements) | Technology Objective C<br>Expand understanding of the Earth and the universe (remote measurements) |
|---|---|---|
| A1. Improved Access to Space | B1. Improved Access to Space | C1. Improved Access to Space |
| A2. Space Radiation Health Effects | B2. Precision Landing | C2. New Astronomical Telescopes |
| A3. Long Duration Health Effects | B3. Robotic Maneuvering | C3. Lightweight Space Structures |
| A4. Long Duration ECLSS | B4. Life Detection | C4. Increase Available Power |
| A5. Rapid Crew Transit | B5. High Power Electric Propulsion | C5. Higher Data Rates |
| A6. Lightweight Space Structures | B6. Autonomous Rendezvous and Dock | C6. High Power Electric Propulsion |
| A7. Increase Available Power | B7. Increase Available Power | C7. Design Software |
| A8. Mass to Surface | B8. Mass to Surface | C8. Structural Monitoring |
| A9. Precision Landing | B9. Lightweight Space Structures | C9. Improved Flight Computers |
| A10. Autonomous Rendezvous and Dock | B10. Higher Data Rates | C10. Cryogenic Storage and Transfer |

# Highest Priority Technologies

| **Technology Objective A**<br>Extend and sustain human activities beyond LEO | **Technology Objective B**<br>Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements) | **Technology Objective C**<br>Expand understanding of the Earth and the universe (remote measurements) |
|---|---|---|
| 1. Radiation Mitigation for Human Spaceflight (X.1) | 1. GN&C (X.4) | 1. Optical Systems (Instruments and Sensors) (8.1.3) |
| 2. Long-Duration Crew Health (6.3.2) | 2. Solar Power Generation (Photovoltaic and Thermal) (3.1.3) | 2. High Contrast Imaging and Spectroscopy Technologies (8.2.4) |
| 3. ECLSS (X.3) | 3. Electric Propulsion (2.2.1) | 3. Detectors and Focal Planes (8.1.1) |
| 4. GN&C (X.4) | 4. Fission Power Generation (3.1.5) | 4. Lightweight and Multifunctional Materials and Structures (X.2) |
| 5. (Nuclear) Thermal Propulsion (2.2.3) | 5. EDL TPS (X.5) | 5. Active Thermal Control of Cryogenic Systems (14.1.2) |
| 6. Lightweight and Multifunctional Materials and Structures (X.2) | 6. In-Situ Instruments and Sensors (8.3.3) | 6. Electric Propulsion (2.2.1) |
| 7. Fission Power Generation (3.1.5) | 7. Lightweight and Multifunctional Materials and Structures (X.2) | 7. Solar Power Generation (Photovoltaic and Thermal) (3.1.3) |
| 8. EDL TPS (X.5) | 8. Extreme Terrain Mobility (4.2.1) | |

# 16 Technologies in the Final Prioritization

| Technologies included in the final prioritization, listed by TABS number | Technology Objective A | Technology Objective B | Technology Objective C |
|---|---|---|---|
| 2.2.1 Electric Propulsion | | #3 | #6 |
| 2.2.3 (Nuclear) Thermal Propulsion | #5 | | |
| 3.1.3 Solar Power Generation (Photovoltaic and Thermal) | #7 | #2 | #7 |
| 3.1.5 Fission (Power) | | #4 | |
| 4.2.1 Extreme Terrain Mobility | | #8 | |
| 6.3.2 Long-Duration (Crew) Health | #2 | | |
| 8.1.1 Detectors & Focal Planes | | | #3 |
| 8.1.3 (Instrument and Sensor) Optical Systems | | | #1 |
| 8.2.4 High-Contrast Imaging and Spectroscopy Technologies | | | #2 |
| 8.3.3 In Situ (Instruments and Sensor) | | #6 | |
| 14.1.2 Active Thermal Control of Cryogenic Systems | | | #5 |
| X.1 Radiation Mitigation for Human Spaceflight | #1 | | |
| X.2 Lightweight and Multifunctional Materials and Structures | #6 | #7 | #4 |
| X.3 Environmental Control and Life Support System | #3 | | |
| X.4 Guidance, Navigation, and Control | #4 | #1 | |
| X.5 Entry, Descent, and Landing Thermal Protection Systems | #8 | #5 | |

# Linkages between Top Technologies and Technical Challenges for Technology Objective A

| Technology Objective A: Extend and Sustain Human Activities Beyond Low Earth Orbit — High Priority Technologies / Top Technical Challenges | | Radiation Mitigation for Human Spaceflight (X.1) | Long-Duration (Crew) Health (6.3.2) | ECLSS (X. 3) | GN&C (X.4) | Thermal Propulsion (2.2.3) | Lightweight Multifunctional Matls. and Structures (X.2) | Fission (Power) (3.1.5) | EDL TPS (X.5) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Improved Access to Space | | | | | | ● | | |
| 2 | Space Radiation Health Effects | ● | | | | | | | |
| 3 | Long Duration Health Effects | | ● | | | | | | |
| 4 | Long Duration ECLSS | | | ● | | | | | |
| 5 | Rapid Crew Transit | | | | | ● | | | |
| 6 | Lightweight Space Structures | ● | | | | | ● | | |
| 7 | Increase Available Power | | | | | | | ● | |
| 8 | Mass to Surface | | | | | | ● | | ● |
| 9 | Precision Landing | | | | ● | | | | ● |
| 10 | Autonomous Rendezvous and Dock | | | | ● | | | | |

# Findings and Recommendations

# Recommendation:
## *Technology Development Priorities*

- **16 identified high-priority technologies**
- **Associated top technical challenges**
- **Modest but significant investment in low-TRL technology (10%)**
- **Flight demonstrations (high TRL with cost share)**

**During the next 5 years, NASA technology development efforts should focus on (1) the 16 identified high-priority technologies and associated top technical challenges, (2) a modest but significant investment in low-TRL technology (on the order of 10 percent of NASA's technology development budget), and (3) flight demonstrations for technologies that are at a high-TRL when there is sufficient interest and shared cost by the intended user.**

**Recommendation sized to reasonable budget expectation for OCT**

# Remaining Recommendations

- Systems Analysis
- Managing the Progression of Technologies to Higher TRLs
- Supporting Foundational Tech Base
- Cooperative Development of New Technologies
- Flight Demonstrations and Technology Transition
  - *Cryogenic Storage and Handling*
  - *Advanced Stirling Radioisotope Generators*
- Industry Access to NASA Data
- NASA Investments in Commercial Space Technology
- Cross-Cutting Technologies

# Findings

- Plutonium-238
- Facilities
- Program Stability

# NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES

## Restoring NASA's Technological Edge and Paving the Way for a New Era in Space

http://www.nap.edu/catalog.php?record_id=13354

NATIONAL RESEARCH COUNCIL
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# Backup Slides

# Agenda

- Context
- Statement of Task
- Technology Area Breakdown Structure
- Steering Committee and Panel Structure and Membership
- Study Schedule
- Public Input
- Technology Evaluation Criteria
- Panel Evaluation Process
- Panel Results: Challenges and Technologies
- Steering Committee Evaluation Process
- Steering Committee Results:
  - Challenges and Technologies
  - Findings and Recommendations

# Statement of Task

- **Criteria:** Establish a set of criteria to enable prioritization of technologies within each and among all of the technology areas that the NASA technology roadmaps should satisfy;
- **Technologies:** Consider technologies that address the needs of NASA's exploration systems, Earth and space science, and space operations mission areas, as well as those that contribute to critical national and commercial needs in space technology;
- **Integration:** Integrate the outputs to identify key common threads and issues and to summarize findings and recommendations; and
- **Prioritization:** Prioritize the highest-priority technologies from all 14 roadmaps.

# Six Panels Cover 14 TAs/Roadmaps

### Panel 1: Propulsion and Power

**TA01:** Launch Propulsion Systems
**TA02:** In-Space Propulsion Systems
**TA03:** Space Power and Energy Storage Systems
**TA13:** Ground and Launch Systems Processing

### Panel 2: Robotics, Communications, and Navigation

**TA04:** Robotics, Tele-Robotics, and Autonomous Systems
**TA05:** Communication and Navigation Systems

### Panel 3: Instruments and Computing

**TA08:** Scientific Instruments, Observatories, and Sensor Systems
**TA11:** Modeling, Simulation, Information Technology, and Data Processing

### Panel 4: Human Health and Surface Exploration

**TA06:** Human Health, Life Support and Habitation Systems
**TA07:** Human Exploration Destination Systems

### Panel 5: Materials

**TA10:** Nanotechnology
**TA12:** TA12 Materials, Structures, Mechanical Systems, and Manufacturing
**TA14:** Thermal Management Systems

### Panel 6: Entry, Descent, and Landing

**TA09:** Entry, Descent, and Landing Systems

# Study Schedule

| | |
|---|---|
| • Committees Approved | January 2011 |
| • First Meetings – Panels | January 2011 |
| • First Meeting – S.C. | January 25-27, 2011 |
| • Second Meetings – Panels | March/April 2011 |
| • Second Meeting – S.C. | May 18-20, 2011 |
| • Third Meetings – Panels | May/June 2011 |
| • Fourth Meetings – Panels | June/July 2011 |
| • Interim Report to Review | June 15, 2011 |
| • Third Meeting – S.C. | August 9-11, 2011 |
| • Interim Report to NASA | August 25, 2011 |
| • Fourth Meeting – S.C. | September 20-22, 2011 |
| • Final Report to Review | November 18, 2011 |
| • Final Report to NASA | January 26, 2012 |

# Public Input

- **Public workshop held for each roadmap:** Technology panels engaged with invited speakers, guests, and members of the public in a dialogue on the technology areas and their value.
- **Community input solicited from a public website:** 144 individuals completed 244 public input forms on the technologies in draft roadmaps. Included 91 personnel from NASA, 6 from other government organizations, 26 from industry, 16 from academia, and 5 from other organizations or no organization identified.

# Technology Evaluation Criteria

- **BENEFIT**
- **ALIGNMENT**
  - — Alignment with NASA needs
  - — Alignment with non-NASA aerospace needs
  - — Alignment with non-aerospace national goals
- **TECHNICAL RISK AND CHALLENGE**
  - — Technical risk and reasonableness
  - — Sequencing and timing
  - — Time and effort

# Technology Evaluation Criteria (continued)

- **BENEFIT**
  — Game-changing, transformational capabilities in the timeframe of the study?
  — Other enhancements?
- **ALIGNMENT WITH NASA NEEDS**
  — Meet long-term NASA needs?
  — Impact on missions and mission areas?
- **ALIGNMENT WITH NON-NASA AEROSPACE TECHNOLOGY NEEDS**
  — Address non-NASA aerospace technology needs?

# Technology Evaluation Criteria (continued)

- **ALIGNMENT WITH NON-AEROSPACE NATIONAL GOALS**
  - National goals addressed?
- **TECHNICAL RISK AND REASONABLENESS**
  - Development succeed in timeframe envisioned?
  - Risk so low industry could complete development on its own?
  - Already available for commercial or military applications?

# Technology Evaluation Criteria (continued)

- **SEQUENCING AND TIMING**
  - Technology needed when?
  - Status of other requisite technologies?
  - Other technologies enabled by this one?
  - Good plan for proceeding?
  - Effort connected with prospective users?
- **TIME AND EFFORT TO ACHIEVE GOALS**
  - Time and effort required for to achieve goals?

# QFD Technology Panel Evaluation: TA01 Launch Propulsion Systems (Partial)

| | Benefit | Alignment with NASA Needs | Alignment with Non-NASA Aero Tech Needs | Alignment with Non-Aerospace National Goals | Technical Risk and Reasonableness | Sequencing and Timing | Time and Effort | QFD Score (Weighted) | Panel Priority |
|---|---|---|---|---|---|---|---|---|---|
| Multiplier: | 27 | 5 | 2 | 2 | 10 | 4 | 4 | | |
| | 0/1/3/9 | 0/1/3/9 | 0/1/3/9 | 0/1/3/9 | 1/3/9 | -9/-3/-1/1 | -9/-3/-1/0 | | |
| **Technology Name** | **Benefit** | **Alignment** | | | **Risk/Difficulty** | | | | |
| 1.3.3. Detonation Wave Engines (Open Cycle) | 1 | 3 | 3 | 0 | 3 | -3 | -3 | 54 | L |
| 1.3.4. Turbine Based Jet Engines (Flyback Boosters) | 1 | 3 | 1 | 0 | 3 | -3 | -3 | 50 | L |
| 1.3.5. Ramjet/Scramjet Engines (Accelerators) | 1 | 0 | 3 | 0 | 3 | -3 | -3 | 39 | L |
| 1.3.6. Deeply-cooled Air Cycles | 1 | 3 | 3 | 0 | 3 | -3 | -1 | 62 | L |
| 1.3.7. Air Collection and Enrichment System | 1 | 3 | 1 | 0 | 3 | -3 | -1 | 58 | L |
| 1.3.8. Fundamental Air Breathing Propulsion Technologies | 1 | 3 | 3 | 1 | 3 | -1 | -3 | 64 | L |
| 1.4.1. Auxiliary Control Systems | 1 | 9 | 3 | 0 | 3 | -1 | -1 | 100 | M |
| 1.4.2. Main Propulsion Systems (Excluding Engines) | 1 | 9 | 3 | 0 | 3 | -1 | -1 | 100 | M |
| 1.4.3. Launch Abort Systems | 3 | 3 | 1 | 0 | 3 | -1 | -3 | 112 | M |
| 1.4.4. Thrust Vector Control Systems | 1 | 9 | 3 | 0 | 3 | -1 | -1 | 100 | M |
| 1.4.5. Health Management & Sensors | 1 | 9 | 3 | 1 | 3 | -1 | -1 | 102 | M |
| 1.4.6. Pyro and Separation Systems | 1 | 9 | 3 | 0 | 3 | -1 | -1 | 100 | M |
| 1.4.7. Fundamental Ancillary Propulsion Technologies | 1 | 9 | 3 | 0 | 3 | -3 | -1 | 92 | M |
| 1.5.1. Ground Launch Assist | 1 | 3 | 3 | 1 | 3 | -3 | -3 | 56 | L |
| 1.5.2. Air Launch / Drop Systems | 1 | 3 | 3 | 0 | 3 | -3 | -3 | 54 | L |
| 1.5.3. Space Tether Assist (for launch) | 0 | 3 | 1 | 0 | 1 | -3 | -3 | 3 | L |
| 1.5.4. Beamed Energy / Energy Addition | 1 | 3 | 1 | 1 | 1 | -3 | -3 | 32 | L |
| 1.5.5. Nuclear (Launch Engines) | 0 | 0 | 0 | 0 | 1 | -3 | -9 | -38 | L |
| 1.5.6. High Energy Density Materials/Propellants | 1 | 3 | 3 | 1 | 1 | -3 | -1 | 44 | L |

H=High priority; M=Medium Priority; L=Low Priority

# Technology Objectives

- **Relationships Between NASA's Mission Areas and the Three Technology Objectives**

| NASA Mission Areas | Technology Objective A<br>Extend and sustain human activities beyond LEO | Technology Objective B<br>Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements) | Technology Objective C<br>Expand understanding of the Earth and the universe (remote measurements) |
|---|---|---|---|
| Planetary Science | X | X | X |
| Astrophysics | | | X |
| Earth Science | | X | X |
| Heliophysics | | | X |
| Human Exploration | X | X | X |
| Operations | X | X | X |

# Challenges for Objective A: Extend and sustain human activities beyond LEO

**A1 Improved Access to Space:** *Dramatically reduce the total cost and increase reliability and safety of access to space*

**A2 Space Radiation Health Effects:** *Improve understanding of space radiation effects on humans and develop radiation protection technologies to enable long-duration space missions*

**A3 Long-Duration Health Effects:** *Minimize the crew health effects of long duration space missions (other than space radiation)*

# Challenges for Objective A (continued): Extend and sustain human activities beyond LEO

**A4 Long-Duration ECLSS:** *Achieve reliable, closed-loop Environmental Control and Life Support Systems (ECLSS) to enable long-duration human missions beyond low Earth orbit*

**A5 Rapid Crew Transit:** *Establish propulsion capability for rapid crew transit to and from Mars or other distant targets*

**A6 Lightweight Space Structures:** *Develop innovative lightweight materials and structures to reduce the mass and improve the performance of space systems*

# Challenges for Objective A (continued): Extend and sustain human activities beyond LEO

**A7 Increase Available Power:** *Eliminate the constraint of power availability for space missions by improving energy generation and storage with reliable power systems that can survive the wide range of environments unique to NASA missions*

**A8 Mass to Surface:** *Deliver more payload to destinations in the solar system*

**A9 Precision Landing:** *Increase the ability to land more safely and precisely at a variety of planetary locales and at a variety of times*

**A10 Autonomous Rendezvous and Dock:** *Achieve highly reliable, autonomous rendezvous, proximity operations and capture of free-flying space objects*

# Challenges for Objective B:
# Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements)

- **B1 Improved Access to Space:** *Dramatically reduce the total cost and increase reliability and safety of access to space*
- **B2 Precision Landing:** *Increase the ability to land more safely and precisely at a variety of planetary locales and at a variety of times*
- **B3 Robotic Maneuvering:** *Enable mobile robotic systems to autonomously and verifiably navigate and avoid hazards and increase the robustness of landing systems to surface hazards*
- **B4 Life Detection:** *Improve sensors for in-situ analysis to determine if synthesis of organic matter may exist today, whether there is evidence that life ever emerged, and whether there are habitats with the necessary conditions to sustain life on other planetary bodies*
- **B5 High-Power Electric Propulsion:** *Develop high-power electric propulsion systems along with the enabling power system technology*

# Challenges for Objective B (continued): Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements)

**B6 Autonomous Rendezvous and Dock:** *Achieve highly reliable, autonomous rendezvous, proximity operations and capture of free-flying space objects*

**B7 Increase Available Power:** *Eliminate the constraint of power availability for space missions by improving energy generation and storage with reliable power systems that can survive the wide range of environments unique to NASA missions*

**B8 Mass to Surface:** *Deliver more payload to destinations in the solar system*

**B9 Lightweight Space Structures:** *Develop innovative lightweight materials and structures to reduce the mass and improve the performance of space systems*

**B10 Higher Data Rates:** *Minimize constraints imposed by communication data rate and range*

# Challenges for Objective C: Expand understanding of Earth and the universe (remote measurements)

**C1 Improved Access to Space:** *Dramatically reduce the total cost and increase reliability and safety of access to space*

**C2 New Astronomical Telescopes:** *Develop a new generation of astronomical telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects by developing high-contrast imaging and spectroscopic technologies to provide unprecedented sensitivity, field of view, and spectroscopy of faint objects*

**C3 Lightweight Space Structures:** *Develop innovative lightweight materials and structures to reduce the mass and improve the performance of space systems*

**C4 Increase Available Power:** *Eliminate the constraint of power availability for space missions by improving energy generation and storage with reliable power systems that can survive the wide range of environments unique to NASA missions*

**C5 Higher Data Rates:** *Minimize constraints imposed by communication data rate and range*

# Challenges for Objective C (continued): Expand understanding of Earth and the universe

**C6 High-Power Electric Propulsion:** *Develop high-power electric propulsion systems along with the enabling power system technology*

**C7 Design Software:** *Advance new validated computational design, analysis and simulation methods for design, certification, and reliability of materials, structures, thermal, EDL and other systems*

**C8 Structural Monitoring:** *Develop means for monitoring structural health and sustainability for long duration missions, including integration of unobtrusive sensors and responsive on-board systems*

**C9 Improved Flight Computers:** *Develop advanced flight-capable devices and system software for real-time flight computing with low-power, radiation-hard and fault-tolerant hardware*

**C10 Cryogenic Storage and Transfer:** *Develop long-term storage and transfer of cryogens in space using systems that approach near-zero boiloff*

# Linkages between Top Technologies and Technical Challenges for Technology Objective B

| Technology Objective B: Explore the Evolution of the Solar System and the Potential for Life Elsewhere (in-situ measurements) — High Priority Technologies / Top Technical Challenges | | GN&C (X.4) | Solar Power Generation (3.1.3) | Electric Propulsion (2.2.1) | Fission (Power) (3.1.5) | EDL TPS (X.5) | In Situ (Instruments & Sensor) (8.3.3) | Lightweight Multifunctional Matls. and Structures (X.2) | Extreme Terrain Mobility (4.2.1) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Improved Access to Space | | | | | | | ● | |
| 2 | Precision Landing | ● | | | | ● | | | |
| 3 | Robotic Surface Maneuvering | ● | | | | | | | ● |
| 4 | Life Detection | | | | | | ● | | |
| 5 | High-Power Electric Propulsion | | | ● | | | | | |
| 6 | Autonomous Rendezvous and Dock | ● | | | | | | | |
| 7 | Increase Available Power | | ● | | ● | | | | |
| 8 | Mass to Surface | | | | | ● | | | |
| 9 | Lightweight Space Structures | | | | | | | ● | |
| 10 | Higher Data Rates | | | | | | | ● | |

# Linkages between Top Technologies and Technical Challenges for Technology Objective C

| Technology Objective C: Expand our Understanding of Earth and the Universe in Which We Live (remote measurements) — Top Technical Challenges | High Priority Technologies | (Instrument and Sensor) Optical Systems (8.1.3) | High-Contrast Imaging and Spectroscopy (8.2.4) | Detectors and Focal Planes (8.1.1) | Lightweight Multifunctional Matls. and Structures (X.2) | Active Thermal Control of Cryogenic Systems (14.1.2) | Electric Propulsion (2.2.1) | Solar Power Generation (3.1.3) |
|---|---|---|---|---|---|---|---|---|
| 1 | Improved Access to Space | | | | ● | | | |
| 2 | New Astronomical Telescopes | ● | ● | ● | | | | |
| 3 | Lightweight Space Structures | | | | ● | | | |
| 4 | Increase Available Power | | | | | | | ● |
| 5 | Higher Data Rates | | | | ● | | | |
| 6 | High-Power Electric Propulsion | | | | | | ● | |
| 7 | Design Software | | | | | | | |
| 8 | Structural Monitoring | | | | ● | | | |
| 9 | Improved Flight Computers | | | | | | | |
| 10 | Cryogenic Storage and Transfer | | | | ● | ● | | |

# Relevance of High-Priority Technologies to National and Commercial Space Needs

| Technologies included in the final prioritization, listed by TABS number | | National Needs | Commercial Needs |
|---|---|---|---|
| 2.2.1 | Electric Propulsion | ◉ | ◉ |
| 2.2.3 | Thermal Propulsion | ◉ | ○ |
| 3.1.3 | Solar Power Generation (Photovoltaic and Thermal) | ● | ● |
| 3.1.5 | Fission (Power) | ○ | ○ |
| 4.2.1 | Extreme Terrain Mobility | ○ | ○ |
| 6.3.2 | Long-Duration (Crew) Health | ◉ | ○ |
| 8.1.1 | Detectors & Focal Planes | ◉ | ◉ |
| 8.1.3 | (Instrument and Sensor) Optical Systems | ◉ | ◉ |
| 8.2.4 | High-Contrast Imaging and Spectroscopy Technologies | ◉ | ◉ |
| 8.3.3 | In Situ (Instruments and Sensor) | ○ | ○ |
| 14.1.2 | Active Thermal Control of Cryogenic Systems | ◉ | ◉ |
| X.1 | Radiation Mitigation for Human Spaceflight | ○ | ○ |
| X.2 | Lightweight and Multifunctional Materials and Structures | ◉ | ◉ |
| X.3 | ECLSS | ○ | ◉ |
| X.4 | GN&C | ◉ | ◉ |
| X.5 | EDL TPS | ◉ | ◉ |
| | Key | Substantial | ● |
| | | Significant | ◉ |
| | | Minor | ○ |

# Recommendation: *Systems Analysis*

- **Disciplined system analysis for management of the space technology portfolio**
- **Improve systems analysis and modeling tools, if necessary**

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

# Recommendation: *Managing the Progression of Technologies to Higher TRLs*

- **Rigorous process to down select**
- **Only most promising technologies proceed**

**OCT should establish a rigorous process to down select among competing technologies at appropriate milestones and TRLs to assure that only the most promising technologies proceed to the next TRL.**

# Recommendation:
# *Foundational Technology Base*

- Discipline-oriented technology base program
- Evolutionary and revolutionary advances
- Expertise of NASA, other departments, industry, and academia

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

# Recommendation:
## *Cooperative Development of New Technologies*

- **Cooperative development with other organizations to leverage resources**

**OCT should pursue cooperative development of high-priority technologies with other organizations to leverage resources available for technology development.**

# Recommendation: *Flight Demonstrations and Technology Transition*

- **OCT collaboration with mission offices and outside partners for flight demonstrations**
- **Document collaborative arrangements**
- **Two recommended flight demonstrations:**
  - Cryogenic Storage and Handling
  - Advanced Stirling Radioisotope Generator Technology

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

# Recommendation:
# *Cryogenic Storage and Handling*

- **At a “tipping point”**
- **On-orbit flight testing and flight demonstrations**

**Reduced gravity cryogenic storage and handling technology is close to a “tipping point,” and NASA should perform on-orbit flight testing and flight demonstrations to establish technology readiness.**

# Recommendation:
# *Advanced Stirling Radioisotope Generators*

- **At a "tipping point"**
- **Flight demonstration of Advanced Stirling Radioisotope Generator technology**

**The NASA Office of the Chief Technologist should work with the Science Mission Directorate and the Department of Energy to help bring Advanced Stirling Radioisotope Generator-technology hardware to flight demonstration on a suitable space mission beyond low Earth orbit.**

# Finding: *Plutonium-238*

- **Restarting production of Pu-238 essential for deep-space missions**

**Consistent with findings of previous National Research Council reports on the subject of plutonium-238 (NRC 2010, NRC 2011), restarting the fuel supply is urgently needed. Even with the successful development of Advanced Stirling Radioisotope Generators, if the funds to restart the fuel supply are not authorized and appropriated, it will be impossible for the United States to conduct certain planned, critical deep-space missions after this decade.**

# Finding: *Facilities*

- **Adequate facilities essential**
- **Some critical facilities lacking**
- **Outside scope of OCT acknowledged**

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

# Finding: *Program Stability*

- **Repeated, unexpected program changes diminish productivity and effectiveness**

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

# Recommendation:
# *Industry Access to NASA Data*

- **Make NASA technical data more readily available to U.S. industry**
- **Particularly for companies not working with NASA**
- **Archive data in a readily accessible format**

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

# Recommendation: *NASA Investments in Commercial Space Technology*

- **Focus on technologies supporting NASA mission needs,**
- **Collaborate with the U.S. commercial space industry for industries needs (precompetitive technologies), similar to aeronautics**

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

# Finding and Recommendation:
## *Crosscutting Technologies*

- **Many technologies cut across multiple roadmaps**
- **Review / expand roadmap sections on crosscutting technologies**
  - Avionics
  - Space weather beyond radiation effects
  - Others
- **Assure effective ownership for crosscutting technologies**
- **Coordinated development of high-priority crosscutting technologies**

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

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

# Looking Ahead

- Breadth of country’s space mission has expanded
- Necessary technological developments less clear
- Recommendations would enhance effectiveness of OCT technology development in the face of scarce resources
- Focus on the highest-priority challenges and technologies in the first 5 years of the 30 year assessment window

# NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES

## *Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*

2012