NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES

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

January 2012

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

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

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.

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
This report lists and prioritizes the 295

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

Steering Committee and Panels

Steering Committee

Raymond S. Colladay, Chair

John D. Anderson, Jr.
James B. Armor, Jr.
Edward F. Crawley
Ravi B. Deo
Walt Faulconer
Phillip D. Hattis
Tamara E. Jernigan
John C. Karas
John M. Klineberg
Ivett A. Leyva
Lester L. Lyles
H. Jay Melosh
Daniel R. Mulville
Dava J. Newman
Richard R. Paul
Liselotte J. Schioler
Gerald Schubert

Panel One: TA01,02,03,13

John R. Rogacki, Chair
Douglas M. Allen
Henry W. Brandhorst, Jr.
David E. Crow
Alec D. Gallimore
Mark W. Henley
Anthony K. Hyder
Ivett A. Leyva **(L)**
Paulo Lozano
Joyce A. McDevitt
Rogers M. Myers
Lawrence J. Ross
Raymond J. Sedwick
George F. Sowers

Panel Two: TA04,05

Stephen P. Gorevan, Chair
Julie A. Adams
Edward J. Groth, III
Phillip D. Hattis **(L)**
Jonathan P. How
James W. Lowrie
David P. Miller
Jonathan Salton
Donna L. Shirley
George W. Swenson, Jr.

Panel Three: TA08,11

James L. Burch, Chair
Philip E. Ardanuy
Webster Cash
John A. Hackwell
Robert J. Hanisch
David Y. Kusnierkiewicz
Joel R. Primack
Gerald Schubert **(L)**
Daniel A. Schwartz
Alan M. Title
Daniel Winterhalter
Carl Wunsch

Panel Four: TA06,07

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David L. Akin
Dallas G. Bienhoff
Robert L. Curbeam, Jr.
Gregory J. Harbaugh
Tamara E. Jernigan **(L)**
Daniel R. Masys
Eric E. Rice
Ronald E. Turner

Panel Five: TA10,12,14

Mool C. Gupta, Chair
Gregory R. Bogart
Donald M. Curry
John R. Howell
George A. Lesieutre
Liselotte J. Schioler **(L)**
Robert E. Skelton
George W. Sutton

Panel Six: TA09

Todd J. Mosher, Chair
John D. Anderson, Jr. **(L)**
Tye M. Brady
Basil Hasaan
Stephen Ruffin
Robert J. Sinclair
Byron D. Tapley
Beth E. Wahl
Gerald D. Wahlberg

L: Liaison Member

Staff

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  - Michael Moloney
  - Alan Angleman, Staff Dir.
  - Joe Alexander
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  - Ian Pryke
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  - Terri Baker
  - Rod Howard
  - Linda Walker
- **Aerospace Corporation**
  - Torrey Radcliffe
  - Greg Richardson
  - Bob Kinsey
  - Dean Bucher
  - Marcus Lobbia
  - Kristina Kipp

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

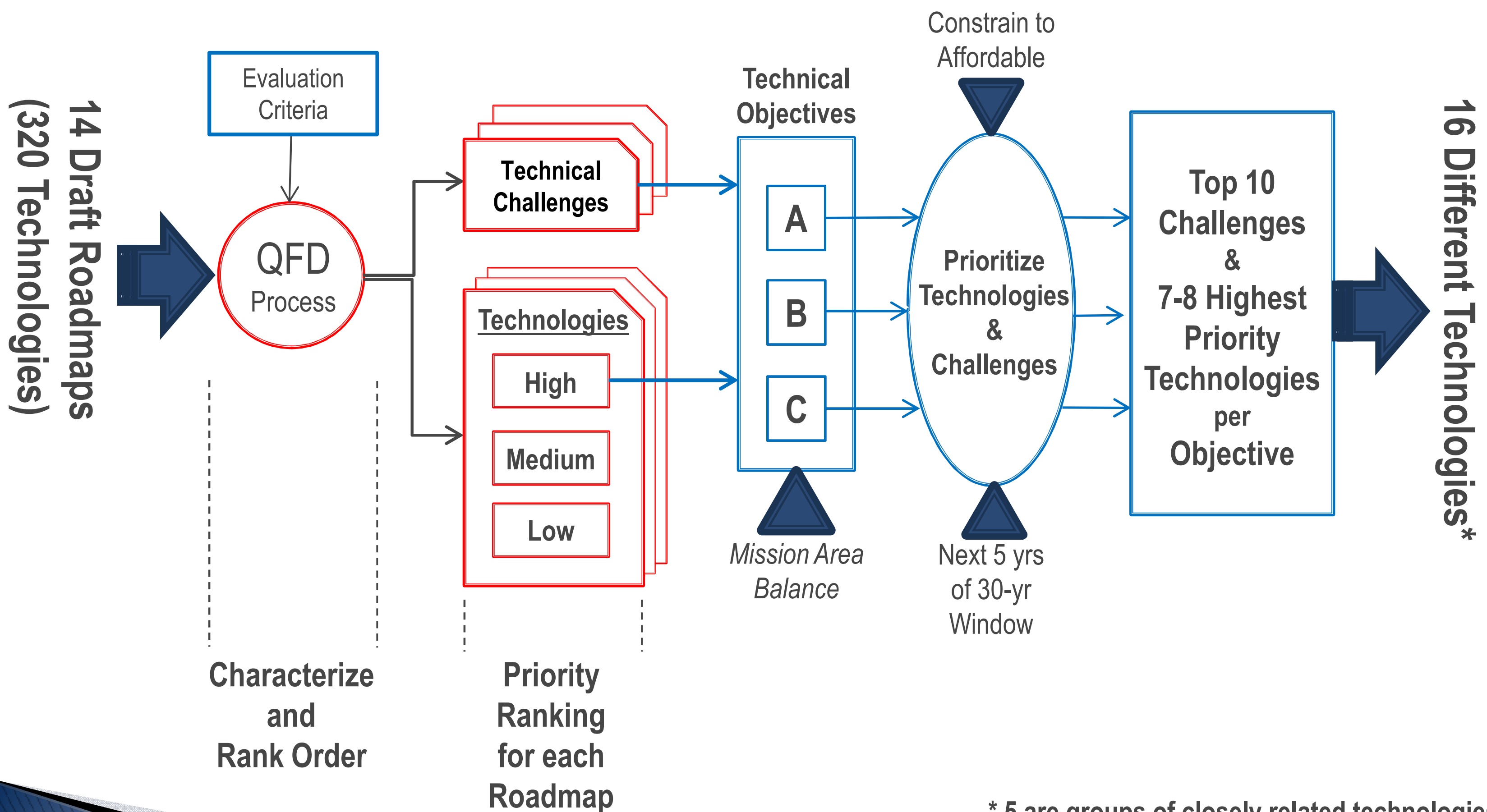
Public Input

- **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.

Organizing Framework

Panels

Steering Committee



* 5 are groups of closely related technologies

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?

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

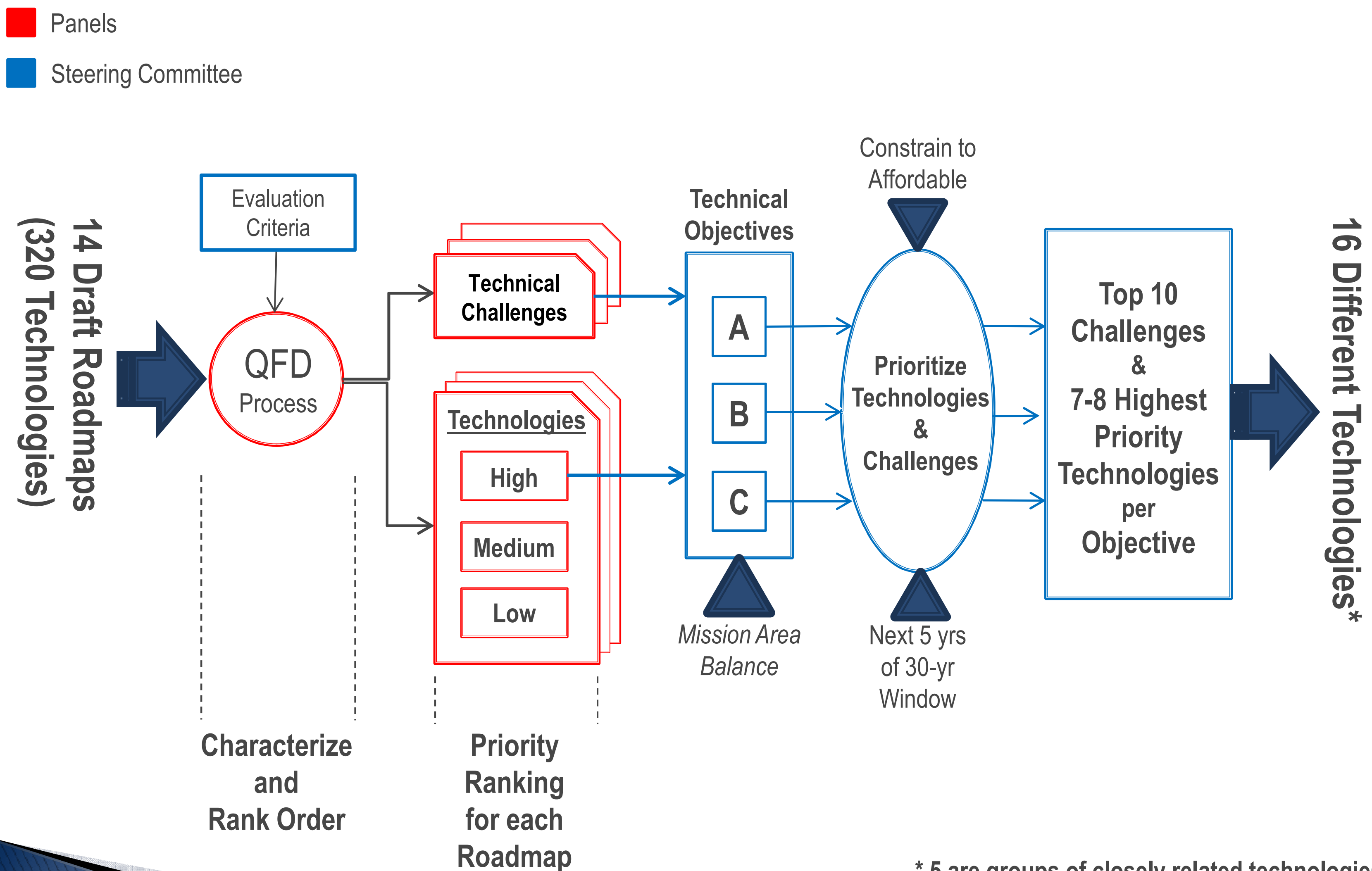
Technology Push and Mission Pull

- **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

Sample Panel Evaluation

TA01 Launch Propulsion Systems

Organizing Framework



* 5 are groups of closely related technologies

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

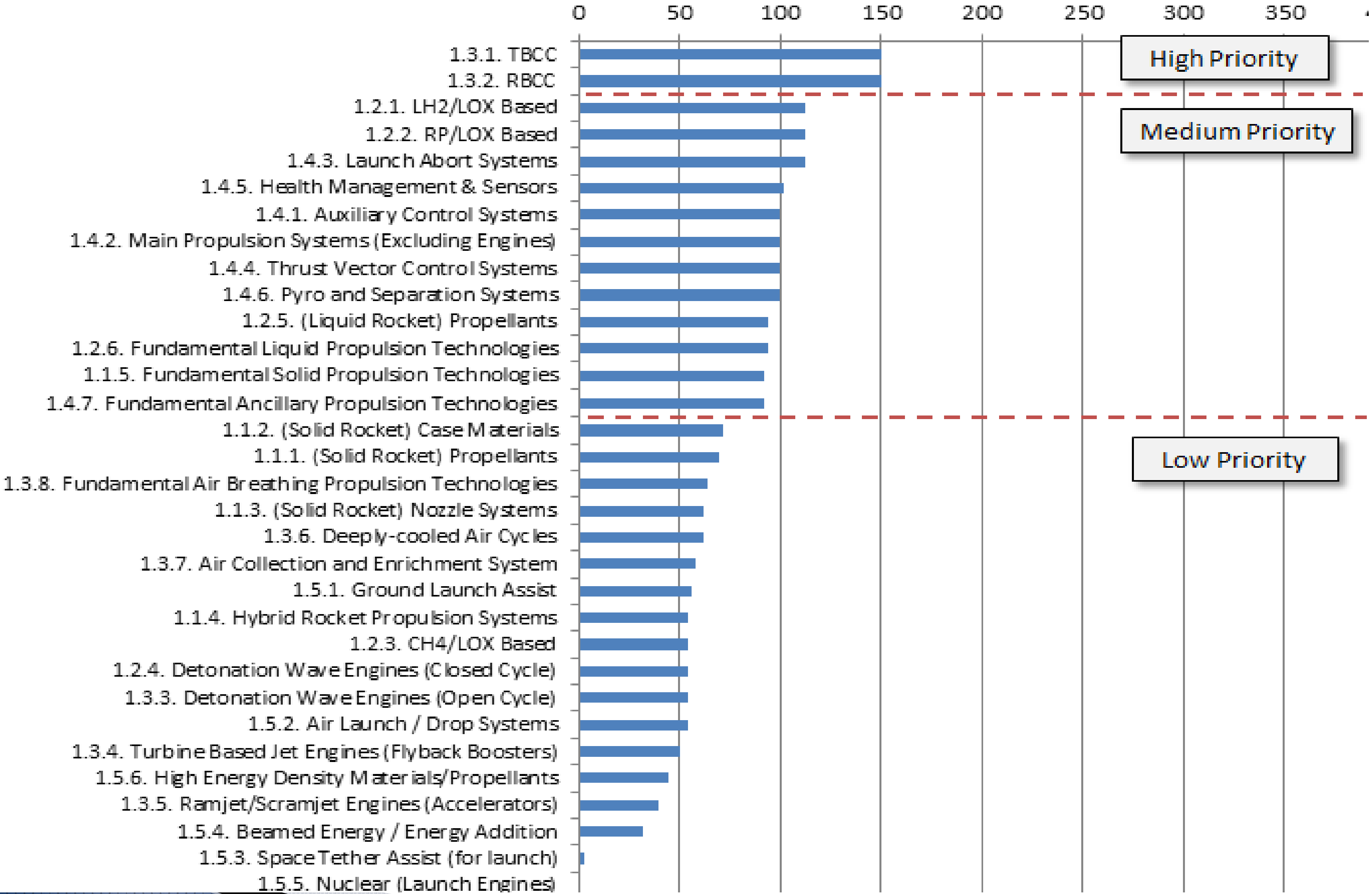
H=High priority; M=Medium Priority; L=Low Priority

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

Technology Name	Benefit	Alignment with NASA Needs	Alignment with Non-NASA Aero Tech Needs	Alignment with Non-Aerospace National Goals	Technical Risk and Reasonableness	Sequencing and Timing	Time and Effort	QFD Score (Weighted)	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

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

Priority	TA01 Technologies, Listed by priority	Top Technology Challenges: 1. Reduced Cost	Top Technology Challenges: 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

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

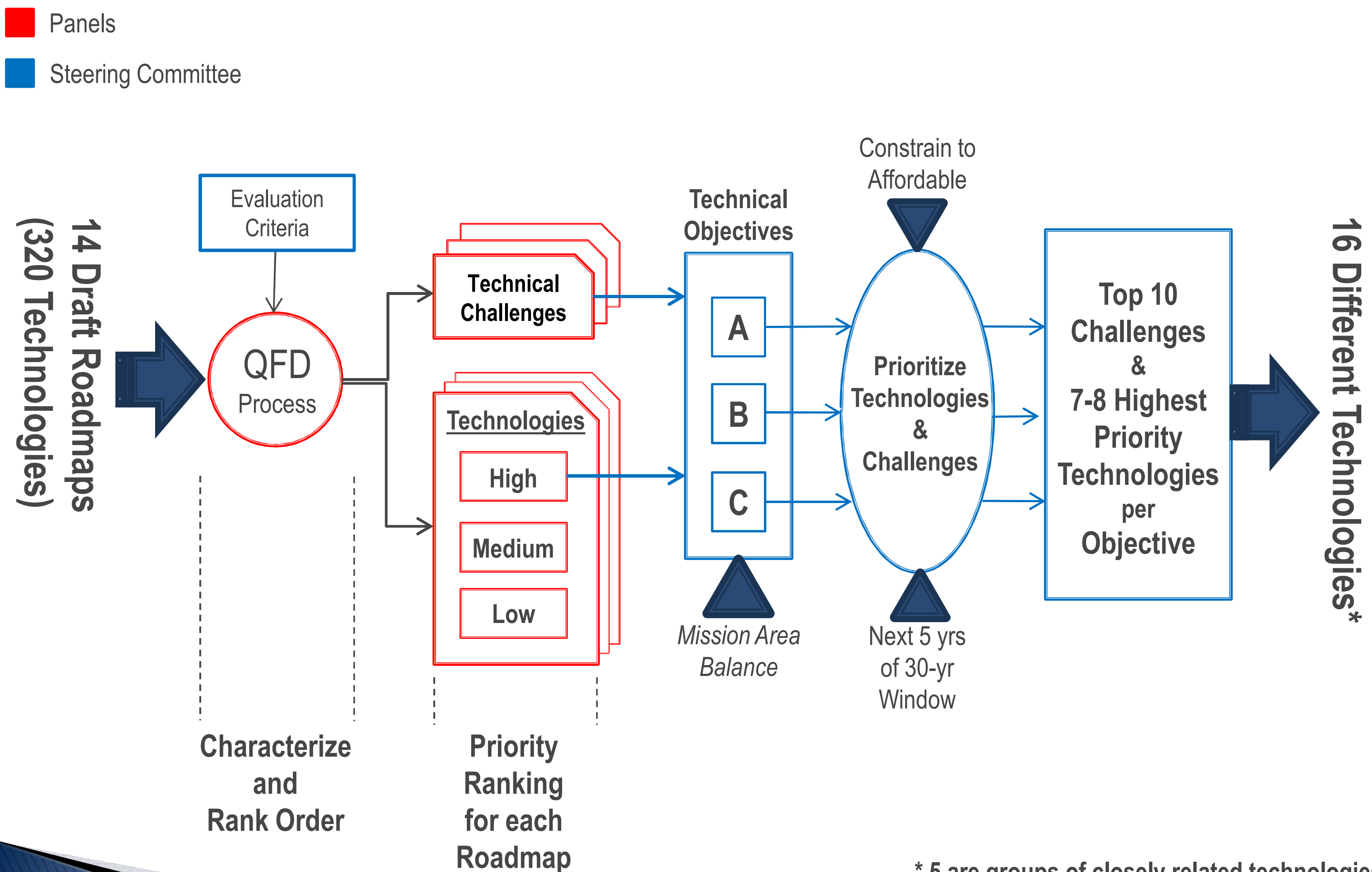
none

TA14 Thermal Management Systems

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

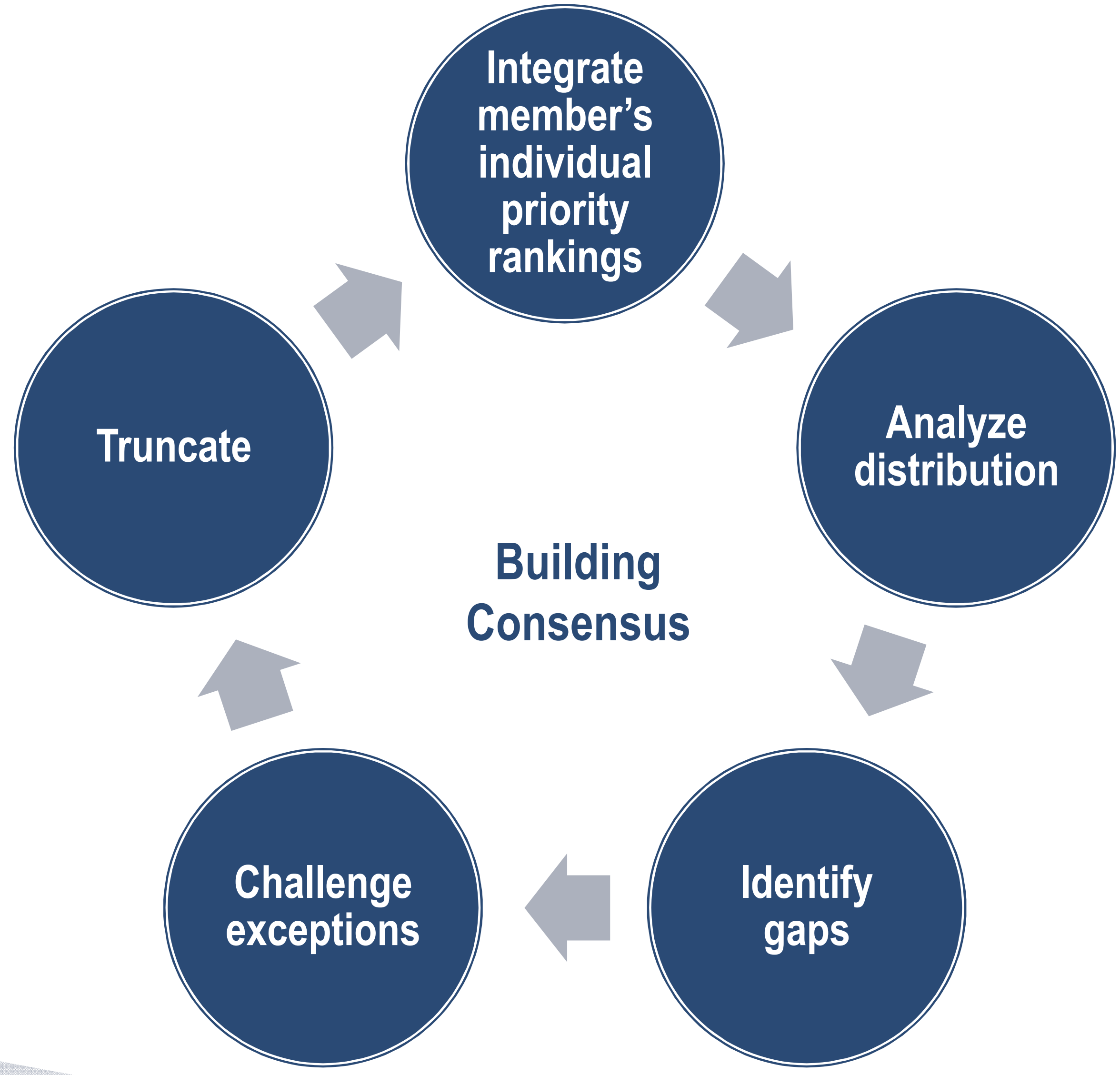
Integrated Ranking

Organizing Framework



* 5 are groups of closely related technologies

Committee Deliberative Process



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*

Technology Objectives (continued)

- One of the steering committee's basic assumptions was that NASA would continue to pursue a balanced space program across its mission areas of human exploration, space science, space operations, space technology, and aeronautics.
- Therefore, since OCT's technology program should broadly support the breadth of the agency's missions and serve to open up options for future missions, the steering committee established priorities in each of the three technology objective areas, A, B, and C, independently. No one technology objective area was given priority over another.

Technology Objectives (continued)

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

NASA Mission Areas	**Technology Objective A** Extend and sustain human activities beyond LEO	**Technology Objective B** Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements)	**Technology Objective C** 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

Top Technical Challenges

Technology Objective A Extend and sustain human activities beyond LEO	Technology Objective B Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements)	Technology Objective C 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

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*

Highest Priority Technologies

Technology Objective A Extend and sustain human activities beyond LEO	Technology Objective B Explore the evolution of the solar system and the potential for life elsewhere (in-situ measurements)	Technology Objective C 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)	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)	

A Few Interrelated Technologies Are Grouped

X.1 Radiation Mitigation for Human Spaceflight

6.5.1 Radiation Risk Assessment Modeling

6.5.2 Radiation Mitigation

6.5.3 Radiation Protection Systems

6.5.4 Radiation Prediction

6.5.5 Radiation Monitoring Technology

X.2 Lightweight and Multifunctional Materials and Structures

10.1.1 (Nano) Lightweight Materials and Structures

12.1.1 Materials: Lightweight Structures

12.2.1 Structures: Lightweight Concepts

12.2.2 Structures: Design and Certification Methods

12.2.5 Structures: Innovative, Multifunctional Concepts

A Few Interrelated Technologies Are Grouped (continued)

X.3 ECLSS

- 6.1.1 Air Revitalization
- 6.1.2 ECLSS Water Recovery and Management
- 6.1.3 ECLSS Waste Management
- 6.1.4 Habitation

X.4 GN&C

- 4.6.2 Relative Guidance Algorithms
- 5.4.3 Onboard Autonomous Navigation and Maneuvering
- 9.4.7 GN&C Sensors and Systems (EDL)

X. 5 EDL TPS

- 9.1.1 Rigid Thermal Protection Systems
- 9.1.2 Flexible thermal Protection Systems
- 14.3.1 Ascent/Entry TPS

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. 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. 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				●				

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	○

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

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

Backup Slides

Statement of Task

- **STRUCTURE**
  - The NRC will appoint a steering committee and up to seven panels to solicit external inputs to and evaluate the 14 draft technology roadmaps that NASA has developed as a point of departure. The study committee will also provide recommendations that identify and prioritize key technologies.
- **SCOPE**
  - The scope of the technologies to be considered includes those 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. (This study will not consider aeronautics technologies except to the extent that they are needed to achieve NASA and national needs in space; guidance on the development of core aeronautics technologies is already available in the National Aeronautics Research and Development Plan.)

Statement of Task (continued)

- **The steering committee and panels will prepare two reports, as follows:**
  - — **PROCESS:** The steering committee will 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.
  - — **PUBLIC INPUT:** Each panel will conduct a workshop focused on one or more roadmaps, as assigned, to solicit feedback and commentary from industry and academia on the 14 draft roadmaps provided by NASA at the initiation of the study. Other means of community engagement may be employed including submission of community white papers.
  - — **INTERIM REPORT:** Based on the results of the community input and its own deliberations, the steering committee will prepare a brief interim report that addresses high-level issues associated with the roadmaps, such as the advisability of modifying the number or technical focus of the draft NASA roadmaps.

Statement of Task (continued)

PANELS: Each panel will meet individually to:

Suggest improvements to the roadmaps in areas such as:

- —the identification of technology gaps,
- —the identification of technologies not covered in the draft roadmaps,
- —development and schedule changes of the technologies covered,
- —a sense of the value (such as potential to reduce mass and/or volume, number of missions it could support, new science enabled, facility to operate, terrestrial benefit) for key technologies,
- —the risk, or reasonableness, of the technology line items in the NASA technology roadmaps, and
- —the prioritization of the technologies within each roadmap by groups such as high, medium, or low priority; this prioritization should be accomplished, in part, via application of relevant criteria described above and in a uniform manner across panels.

Prepare a written summary of the above for the steering committee

Statement of Task (continued)

STEERING COMMITTEE: The steering committee will subsequently develop a comprehensive final report that

- Summarizes findings and recommendations for each of the 14 roadmaps
- Integrates the outputs from the workshops and panels to identify key common threads and issues
- Prioritizes, by group, the highest priority technologies from all 14 roadmaps

Technology Evaluation Criteria

- **BENEFIT**
  — Would the technology provide game-changing, transformational capabilities in the timeframe of the study? What other enhancements to existing capabilities could result from development of this technology?
- **ALIGNMENT WITH NASA NEEDS**
  — How does NASA research in this technology improve NASA's ability to meet its long-term needs? For example, which mission areas and which missions listed in the relevant roadmap would directly benefit from development of this technology, and what would be the nature of that impact? What other planned or potential missions would benefit?

Technology Evaluation Criteria (continued)

- **ALIGNMENT WITH NON-NASA AEROSPACE TECHNOLOGY NEEDS**
  - How does NASA research in this technology improve NASA's ability to address non-NASA aerospace technology needs?
- **ALIGNMENT WITH NON-AEROSPACE NATIONAL GOALS**
  - How well does NASA research in this technology improve NASA's ability to address national goals from broader national perspective (e.g. energy, transportation, health, environmental stewardship, or infrastructure).

Technology Evaluation Criteria (continued)

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

Technology Evaluation Criteria (continued)

- **SEQUENCING AND TIMING**
  - Is the proposed timing of the development of this technology appropriate relative to when it will be needed? What other new technologies are needed to enable the development of this technology, have they been completed, and how complex are the interactions between this technology and other new technologies under development? What other new technologies does this technology enable? Is there a good plan for proceeding with technology development? Is the technology development effort well connected with prospective users?
- **TIME AND EFFORT TO ACHIEVE GOALS**
  - How much time and what overall effort is required to achieve the goals for this technology?

Looking Ahead

As the breadth of the country's space mission has expanded, the necessary technological developments have become less clear, and more effort is required to evaluate the best path for a forward-looking technology development program. NASA has now entered a transitional stage, moving from the past era in which desirable technological goals were evident to all to one in which careful choices among many conflicting alternatives must be made. This report provides specific guidance and recommendations on how the effectiveness of the technology development program managed by NASA's Office of the Chief Technologist can be enhanced in the face of scarce resources by focusing on the highest-priority challenges and technologies.