National Research Council Dialogue to Assess Progress on

NASA's Human Planetary Landing Systems Capability Roadmap Development

General Background and Introduction

Rob Mueller
NASA APIO Coordinator
May 04, 2005

Agenda

Advanced Planning & Integration Office

- General Background and Introduction of Capability Roadmaps
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

Advanced Planning & Integration Office

National Goal	Advance U.S. scientific, security and economic interests through a robust space exploration program.	
National Objectives	Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

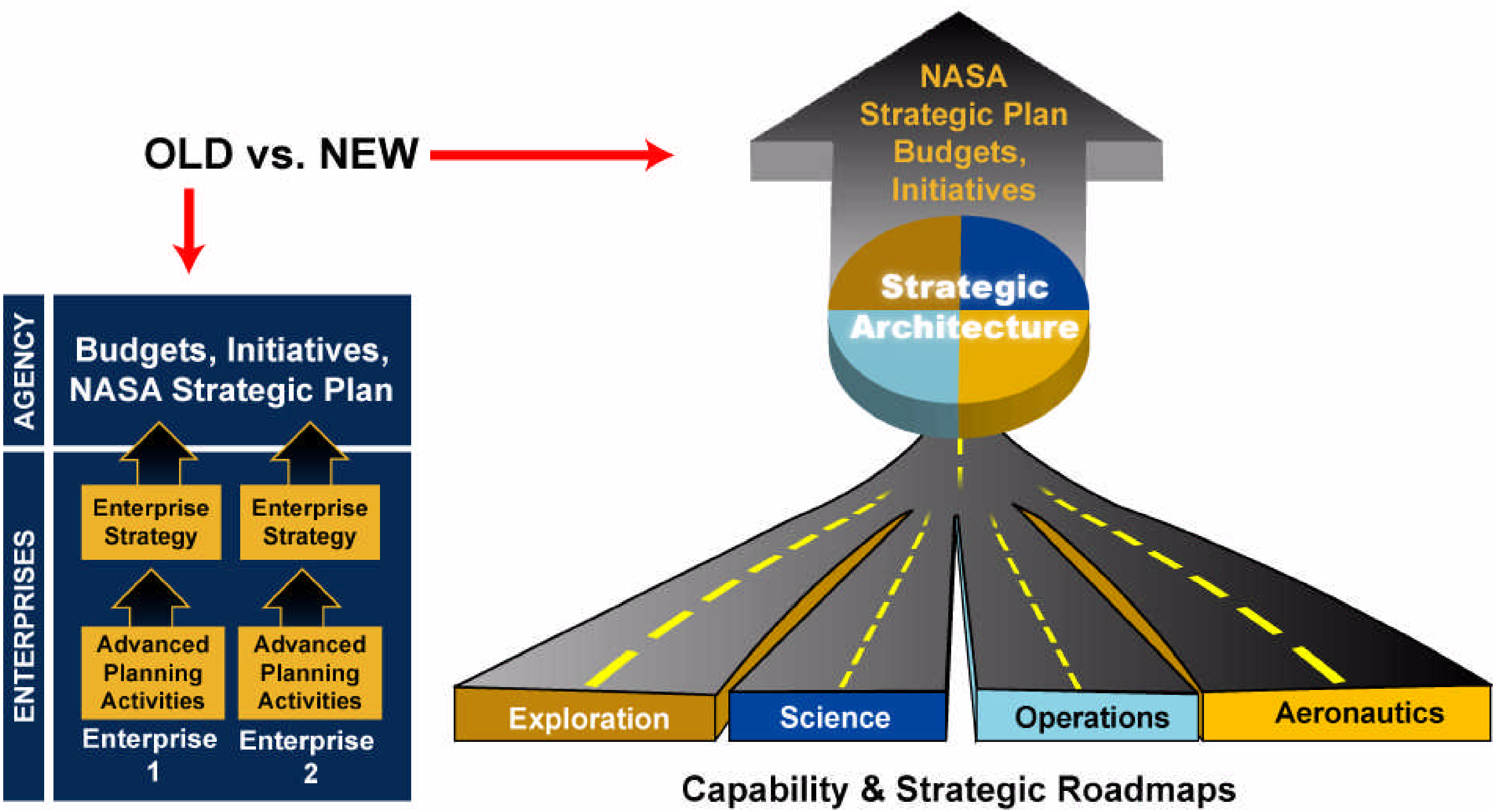
Agency Goals and Objectives

Advanced Planning & Integration Office

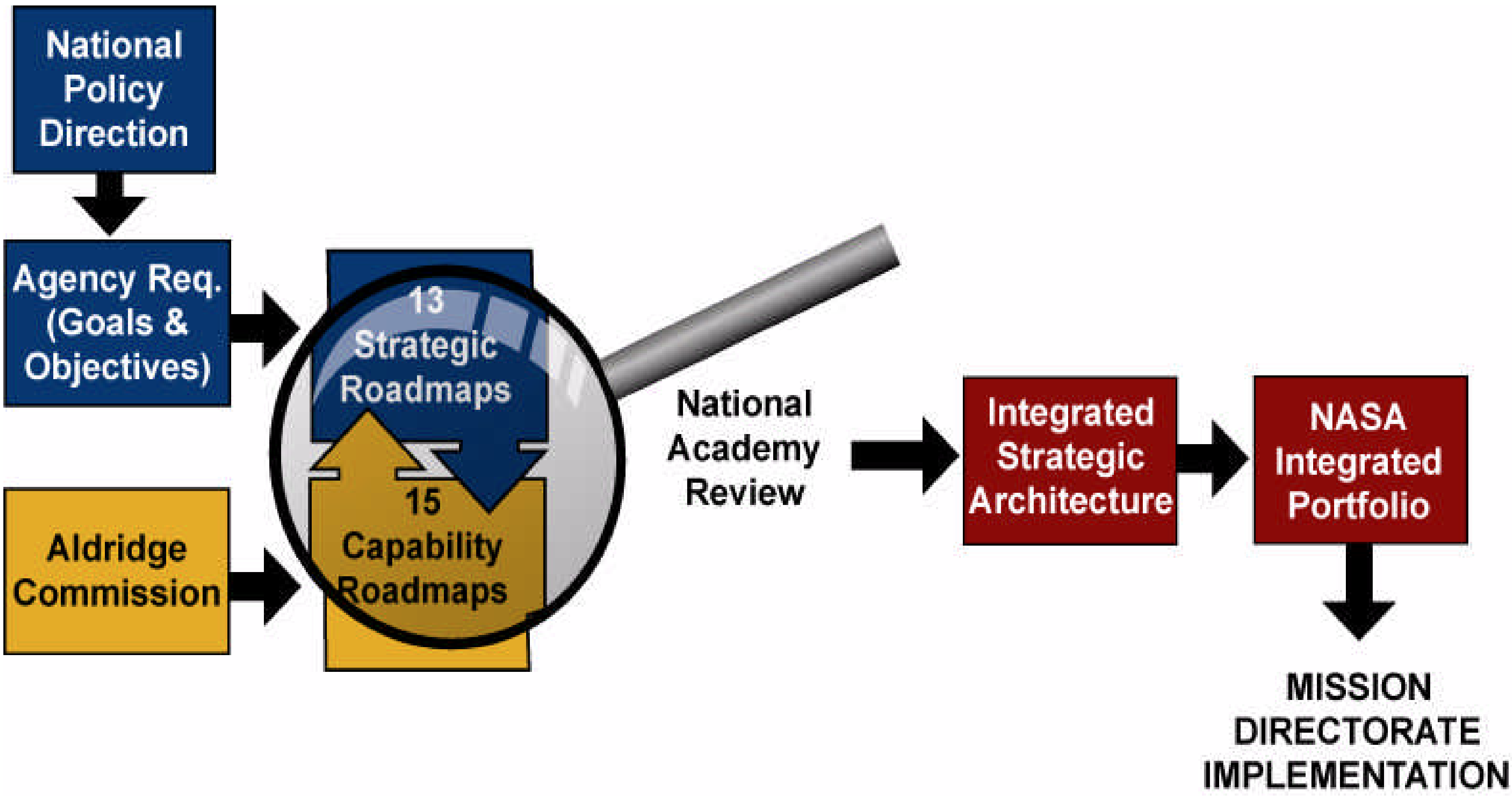
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	Develop innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.	Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems. (SRM 9)
	Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)	Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)
	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)	

Strategic Planning Transformation

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

Advanced Planning & Integration Office

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Mary Kicza)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

- Broad human and robotic science and exploration goals, priorities, anticipated discoveries
- High-level milestones, options, and decision points
- Implementation approaches, suggested missions

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

= DoD Participation

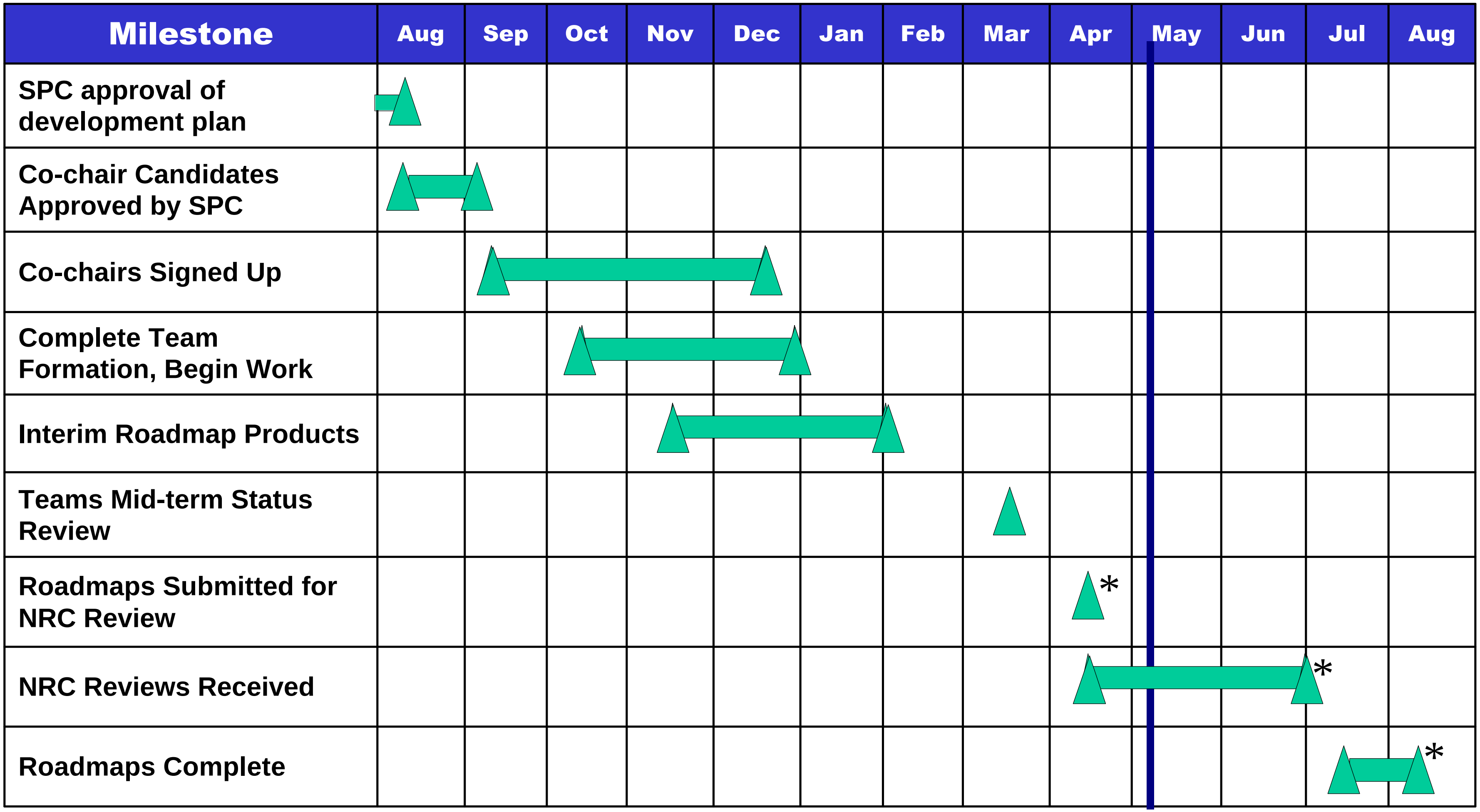
Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule

Advanced Planning & Integration Office



* Schedule Under Review

Capability Roadmaps

Advanced Planning & Integration Office

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

Advanced Planning & Integration Office

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**
    - **1/3 Industry**
    - **1/3 NASA & other Government Agencies**
    - **1/3 Academia**
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Advanced Planning & Integration Office

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

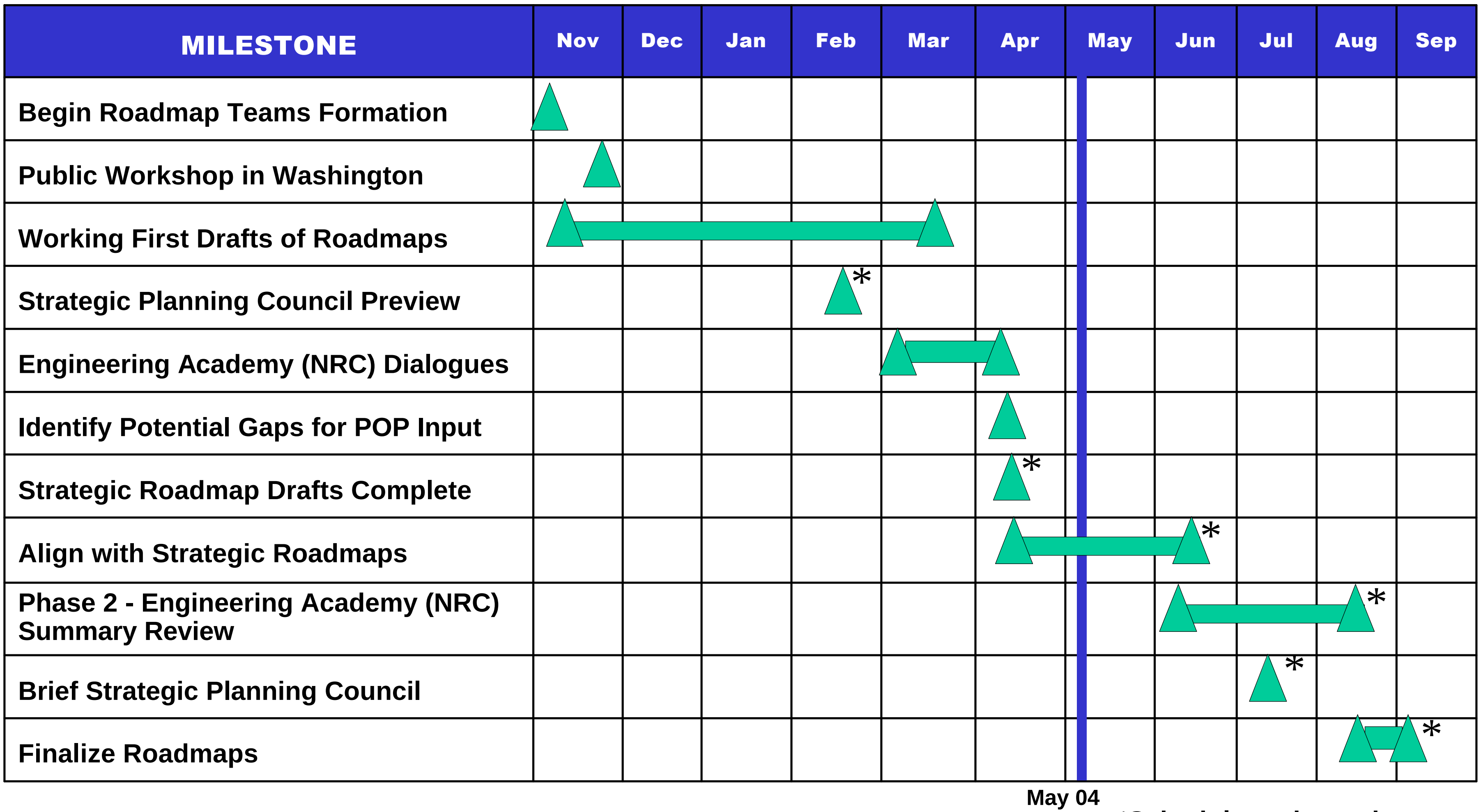
Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Capability Roadmaps - continued

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview



*Schedule under review

Purpose of NRC Review

Advanced Planning & Integration Office

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

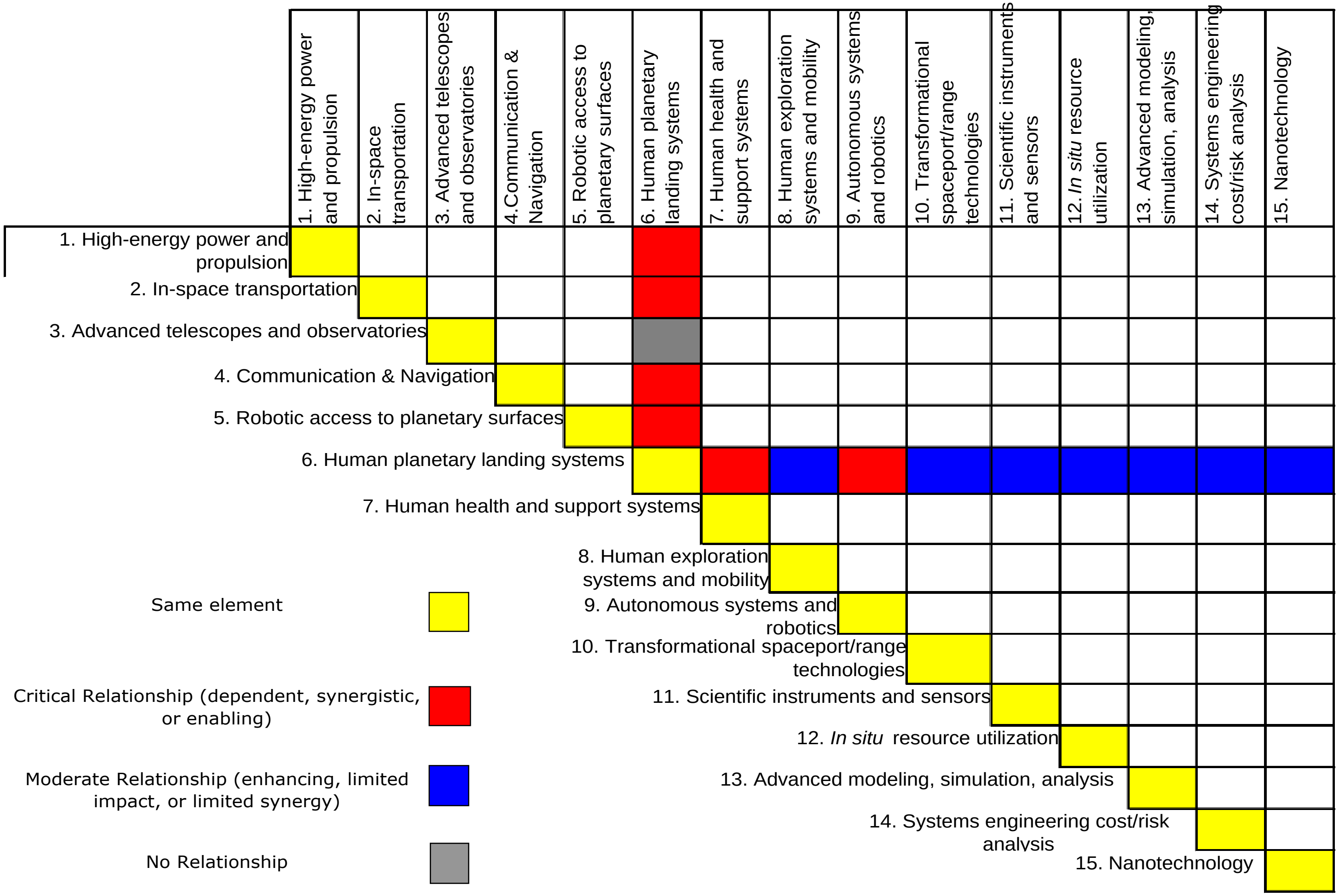
Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Backup Charts

HPLS CRM Crosswalk

Advanced Planning & Integration Office



Examples of Crosswalk Data

Advanced Planning & Integration Office

5. Robotic access to planetary surfaces		6. Human planetary landing systems	
Entry: Hypervelocity Transit	⟷	Hypersonic Entry/AeroCapture Aerothermal TPS Systems	Robotic Entry methods may be applied to Human Entry
Descent	⟷	Transonic decelerators	Robotic Descent methods may be applied to Human Descent
Landing	⟷	Terminal Descent Propulsion Touchdown Systems Terrain Relative Sensing	Robotic Landing methods may be applied to Human landing
Observations	⟷	Observations	Orbital reconnaissance requirements for surface site characterization and atmospheric characterization. Precursor surface-mission engineering observational requirements (meteorology, dust characterization, TPS/parachute performance).
Entry, Descent & Landing	⟷	Robotic-human interactions	Human interaction with Robotic systems during EDL
Navigation- Beacons & Orbital Assets	⟷	Communications and Navigation Infrastructure	Common assets can be shared for navigation
Extreme Environment Avionics	⟷	Hypersonic Entry/AeroCapture Aerothermal TPS Systems	Avionics must function in extreme environment of Mars Entry
Planetary Protection	⟷	EDL Systems Engineering, Guidance, Nav & Control Analysis & Rqmnts	Landed mass must adhere to Planetary Protection Rules Robotic methods may be employed in Human landings
Mobility	→	Touchdown Systems	Successful Landing includes deployment of surface asset - robotic methods may be used
Propulsion	⟷	Terminal Descent Propulsion	Robotic propulsion methods may be applicable to Human landing

CRM X SRM Crosswalk (Part 1)

SR-#	Short	Full Name	Chartered Objective	Flow	CRM #7 Human Planetary Landing Systems	Relationship	CRM Communications with SRM
1	Moon	Robotic and Human Lunar Exploration	Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.	⇔		Use common methods for landing on the Moon and on Mars where possible. These common technologies include Terminal descent systems, deep throttling propulsion engines, aerocapture Earth return systems, human systems & instrumentation for data during Earth return.	- Co-Chair (Harrison Schmitt) attended Meeting #2 - Potential invititation to present at Meeting #3 - Reviewing SRM presentations on Docushare
2	Mars	Robotic and Human Exploration of Mars	Exploration of Mars, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration; human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon.	⇔		Very Large (30-60 MT) landed masses on Mars will require new Aerocapture, Entry, Descent, Landing and Ascent (AEDLA) technologies/capabilites with long development/test times. Human factors, operations & training must be factored into AEDLA Mars mission planning and human rated design in order to safely land and return human crews from Mars. Aeroassist technologies will dramatically reduce the amount of propellant/mass that is required fo human travel to Mars and safe return to Earth.	-Chair (Rob Manning) presented at Meeting #2 -Chair presented at Meeting #3 -Team Member (Bobby Braun) is on SRM Committee - Reviewing SRM presentations on Docushare
3	Solar System	Solar System Exploration	Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.	NA		Not Applicable	-Reviewing SRM presentations on Docushare
4	Earth-like Planets	Search for Earth-Like Planets	Search for Earth-like planets and habitable environments around other stars using advanced telescopes.	NA		Not Applicable	NA
5	CEV / Constellation	Exploration Transportation System	Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.	⇔		Efficient and feasible CEV/Constellation designs and configurations will require close coordination, systems engineering and packaging o Aerocapture, Entry, Descent, Landing and Ascent (AEDLA) technologies, capabilities and systems. Very Large (30-60 MT) landed masses on Mars will require new AEDLA technologies/capabilites with long development times. Aeroassist technologies will dramatically reduce the amount of propellant/mass that is required for human travel to Mars and safe return to Earth. Large volume & area payload launch fairings will be required. Heavy Lift will be required for full scale earth based testing and actual missions	-Reviewing SRM presentations on Docushare - Chairs presented at Meeting #2
6	Space station	International Space Station	Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures.	⇒		ISS will provide human health and performance data, human factors and interfaces data, training opportunities & test bed, on orbit assembly experience.	-Reviewing SRM presentations on Docushare
7	Shuttle	Space Shuttle	Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration transportation system.	⇒		Space Shuttle will provide human health and performance data, human factors and interfaces data, training opportunities & test bed, Earth Entry Descent & Landing (EDL) data, Thermal Protection System (TPS) Data & Earth atmospheric conditions data.	-Reviewing SRM presentations on Docushare

Critical Relationship

Moderate Relationship

Minimal or No Relationship

CRM = Capability Road Map

SRM = Strategic Road Map

CRM X SRM Crosswalk (Part 2)

8	Universe	Universe Exploration	Explore the universe to understand its origin, structure, evolution, and destiny.	NA		Not Applicable	NA
9	Earth	Earth Science and Applications from Space	Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.	NA		Not Applicable	NA
10	Sun-Solar System	Sun-Solar System Connection	Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.	NA		Forecasts of dangerous solar events and on board solar activity monitoring to preserve human health & performance in Aerocapture, Entry Descent & Landing (AEDL)	-Reviewing SRM presentations on Docushare
11	Aero	Aeronautical Technologies	Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.	↔		Direct Entry, Aerocapture, Aerobraking, Guided Hypersonic Flight, Supersonic deceleration, and Aerogravity Assist all require aeronautical technologies/capabilities & test facilities to successfully use the Mars atmosphere.	-Reviewing SRM presentations on Docushare
12	Education	Education	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the nation's scientific and technological capabilities.	↔		Use Aeronautics, Science & Engineering principles to educate, inspire and motivate, which provides a skilled labor force for Human Planetary Landing Systems implementation	-Reviewing SRM presentations on Docushare
13	Nuclear	Nuclear Systems	Utilize nuclear systems for the advancement of space science and exploration.	→		Use of advanced nuclear propulsion systems could reduce the transportation vehicle's arrival velocity at Mars alowing for reduced orbital capture delta velocity (Delta V) requirements	-Reviewing SRM presentations on Docushare
	Cross Cutting		HUMAN PLANETARY LANDING SYSTEMS ARCHITECTURAL ISSUES				

(red)	Critical Relationship
(blue)	Moderate Relationship
(gray)	Minimal or No Relationship

CRM = Capability Road Map

SRM = Strategic Road Map

SRM X CRM Example Data

Advanced Planning & Integration Office

Mars Go Back

Capability	Requirement	Date Required	Investment Start	Rationale for Capability	SRM Concurrence
Aerocapture, Entry, Descent & Landing (AEDL) Architecture Asessment	Decide what AEDL methods/technologies could work	2008	2006	Trade studies and research to define an ensemble of Evaluation architectures and AEDLA methods/technologies	
At Earth Sub Scale AEDL Component Development & Architecture Evaluation Testing	Technology development and testing to define & answer questions about AEDL architectures	2015	2009	Technology options & capabilities must be explored in order to get data for rationale of down selection	
Scaled Mars AEDL Validation Flights	4 MT Landing Capability at Mars: Validate AEDL Models	2022	2015	Use Robotic Mars program to validate scaleable Mars Human AEDL methods	
Earth Based Full Scale Development Program	Develop & Qualify the Full Scale Hardware	2028	2020	Use mostly Earth based Sub-Orbital qualification tests to develop the full scale of the hardware	
Prepare & Fly Cargo & Piloted Human Missions to Mars	Fly first Human Missions to Mars > 40 MT AEDL Systems Qualified & Flown	2032	2025	Deliver Cargo & Humans to Mars.	
Validate Mars Surface Models	Mars Odessy and MRO Surface Assessment	2010	2006	DTM's and Site Hazard Maps for Human Scale Site Selection	
Utilize Mars Robotic Overlap Technology	MSL, MSR, MTO, MSR Data Analysis	2015-2034	2006	Develop Pin Point Landing Radar, Terrain Relative Navigation, Guidance, Hazard Avoidance Sensors	
Validate Mars Atmosphere Models	Entry, Descent & Landing (EDL) In Situ Measurements & 3 Mars Years Atmosphere Monitiring Mission	2022	2010	Mars Atmospheric variations and dust characteristics must be understood in order to successfully design high reliability EDL systems.	
Interaction with Lunar & Earth Return Development	Component Development & Architecture Evaluation Testing	2008-2015	2008	Use Lunar program and CEV to gain data and test common hardware	
Shuttle & ISS Return Human Physiological Performance Data	Human Performance Data	2006-2015	2006	Use empirical human performance data to drive designs and enable Human landings on Mars	
Special Test facilities and knowledge	Specialized supersonic and large scale wind tunnels for aerodynamic testing & Other Test Facilities for Terminal Descent Landing	2015	2009	Test Facilities are required to efficiently develop Aerocapture, Rntry, Descent & Landing Hardware on Earth	

Technology Readiness Levels (TRL)

Advanced Planning & Integration Office

- Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA.

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 9 Actual system “flight proven” through successful mission operations

Capability Readiness Levels

- **7** Capability Operational Readiness
- **6** Integrated Capability Demonstrated in an Operational Environment
- **5** Integrated Capability Demonstrated in a Relevant Environment
- **4** Integrated Capability Demonstrated in a Laboratory Environment
- **3** Sub-Capabilities* Demonstrated in a Relevant Environment
- **2** Sub-Capabilities* Demonstrated in a Laboratory Environment
- **1** Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Guidelines for Using CRLs

- A Capability is defined as a set of systems with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.
- The scope of a Capability includes the knowledge or infrastructure (process, procedures, training, facilities) required to provide the Capability.
- A Capability needs to be demonstrated and qualified, just as a technology does, in both laboratory and relevant environments.
  - The infrastructure and knowledge (process, procedures, training, facilities) of the Capability needs to be:
    - Demonstrated and qualified in both laboratory and relevant environments
    - Available in order for the Capability to be considered mission-ready.
- A minimum level of TRL 6 is required to integrate technologies into a Sub-capability.
- Sub-capabilities are required to reach CRL 3 before integration into a full Capability.

CRL vs. TRL

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Advanced Planning & Integration Office

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

3 Sub-Capabilities* Demonstrated in a Relevant Environment

Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- -of appropriate scale
- -functionally equivalent flight articles
- -major system interactions and interfaces identified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

4 Integrated Capability Demonstrated in a Laboratory Environment

A representative model or prototype of the integrated Capability is tested in an ambient laboratory environment. Performance of the constituent Sub-capabilities is observed in addition to the Capability as an integrated system. Analytical modeling of the integrated Capability is performed.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

5 Integrated Capability Demonstrated in a Relevant Environment

An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- -of appropriate scale
- -functionally equivalent flight articles
- -all system interactions and interfaces identified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

6 Integrated Capability Demonstrated in an Operational Environment

The Capability is near or at the completed system stage. The integrated Capability is demonstrated in an operational environment with the intended user organization(s).

- -full scale flight articles
- -demonstrated in the intended operational 'envelope'

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

7 Capability Operational Readiness

The Capability has been proven to work in its final form under expected operational condition. This level represents the application of the Capability in its operational configuration and under “mission” conditions.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)