Capability Development Risks for Human Mars Exploration

NASA Advisory Council
Technology, Innovation, and Engineering Committee

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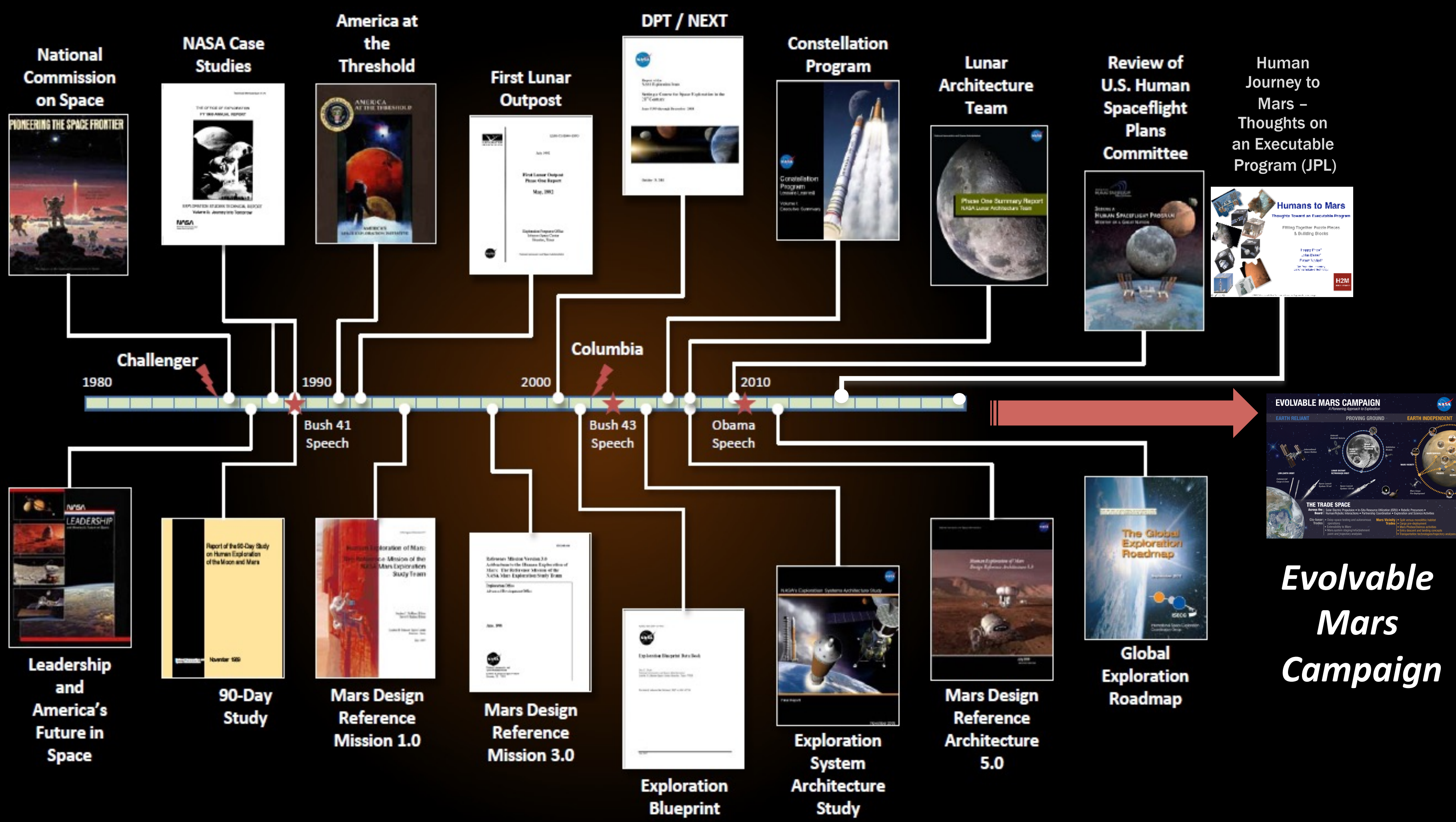
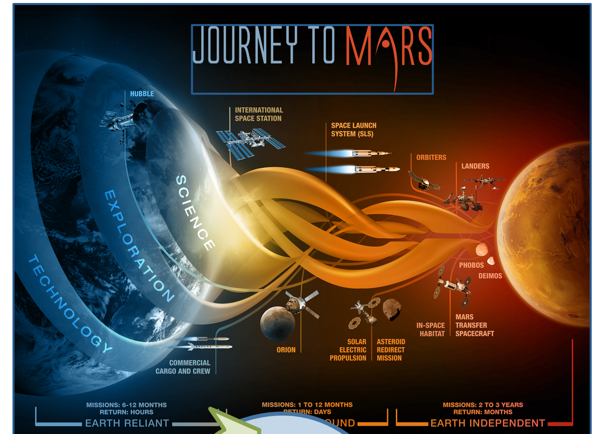
Topics

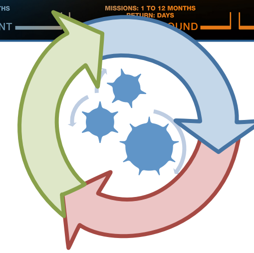
- Evolvable Mars Campaign
- HEOMD/STMD Technology Investment Strategy
- Capabilities Matrix for Human Mars Exploration
- Current Capability Development Activities
- Capability Development Risks

A Brief History of Beyond-LEO Spaceflight Architecture Development



Design Reference Missions vs Design Philosophy





Body of Previous Architectures, Design Reference Missions, Emerging Studies and New Discoveries

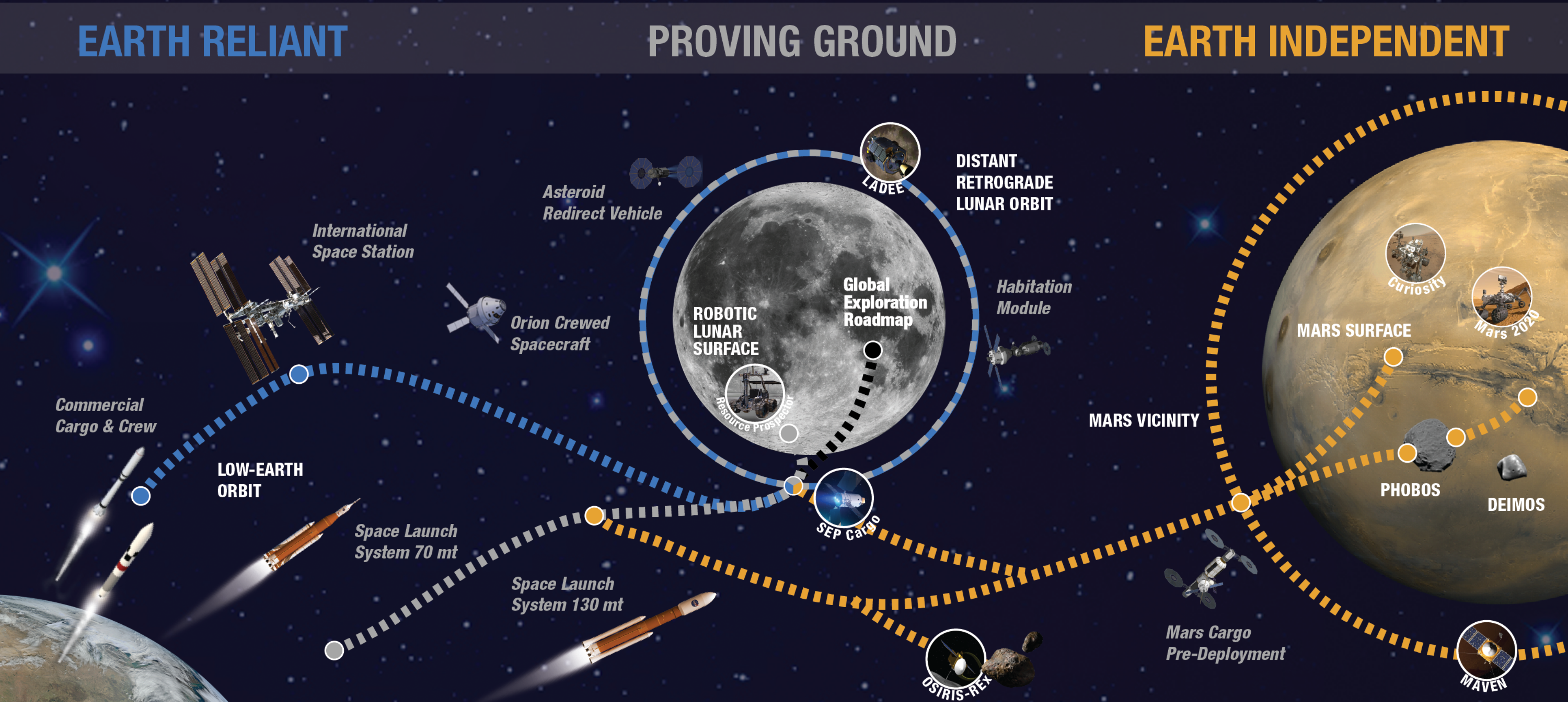
- Internal NASA and other Government
- International Partners
- Commercial and Industrial
- Academic
- Technology developments
- Science discoveries

Evolvable Mars Campaign

- An ongoing series of architectural trade analyses that we are currently executing to define the capabilities and elements needed for a sustainable human presence on Mars
- Builds off of previous studies and ongoing assessments
- Provides clear linkage of current investments (SLS, Orion, etc.) to future capability needs

EVOLVABLE MARS CAMPAIGN

A Pioneering Approach to Exploration



THE TRADE SPACE

Across the Board | Solar Electric Propulsion • In-Situ Resource Utilization (ISRU) • Robotic Precursors • Human/Robotic Interactions • Partnership Coordination • Exploration and Science Activities

Cis-lunar Trades

- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades

- Split versus monolithic habitat
- Cargo pre-deployment
- Mars Phobos/Deimos activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses

Evolvable Mars Campaign

EMC Goal: Define a pioneering strategy and operational capabilities that can extend and sustain human presence in the solar system including a human journey to explore the Mars system starting in the mid-2030s.

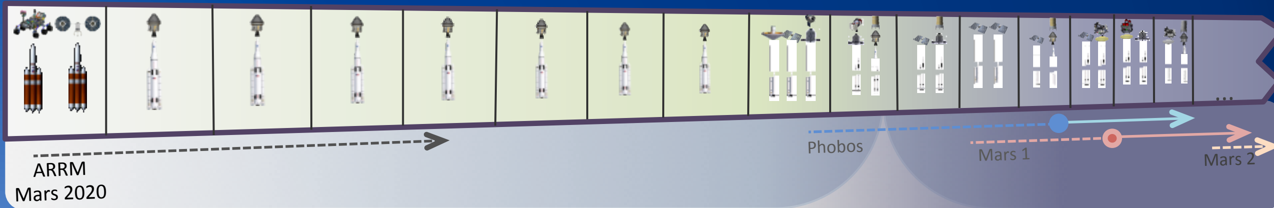
- **Identify a plan that:**
  - Expands human presence into the solar system to advance exploration, science, innovation, benefits to humanity, and international collaboration.
  - Provides different future scenario options for a range of capability needs to be used as guidelines for near term activities and investments
    - In accordance with key strategic principles
    - Takes advantage of capability advancements
    - Leverages new scientific findings
    - Flexible to policy changes
  - Identifies linkages to and leverage current investments in ISS, SLS, Orion, ARM, short-duration habitation, technology development investments, science activities
  - Emphasizes prepositioning and reuse/repurposing of systems when it makes sense
    - Use location(s) in cis-lunar space for aggregation and refurbishment of systems

<u>Internal analysis team members:</u>
- ARC, GRC, GSFC, HQ, JPL, JSC, KSC, LaRC and MSFC
- HEOMD, SMD, STMD, OCS and OCT

<u>External inputs from:</u>
International partners, industry, academia, SKG analysis groups

EMC Assessment Capability Requires Breadth and Depth

Campaign Analysis, Timelines and Decision Needs



Congress

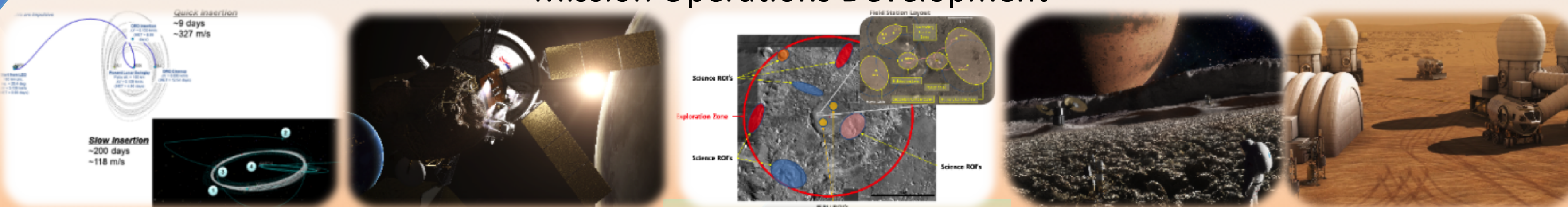
NAC

Int'l Partners

Industry

Public

Mission Operations Development



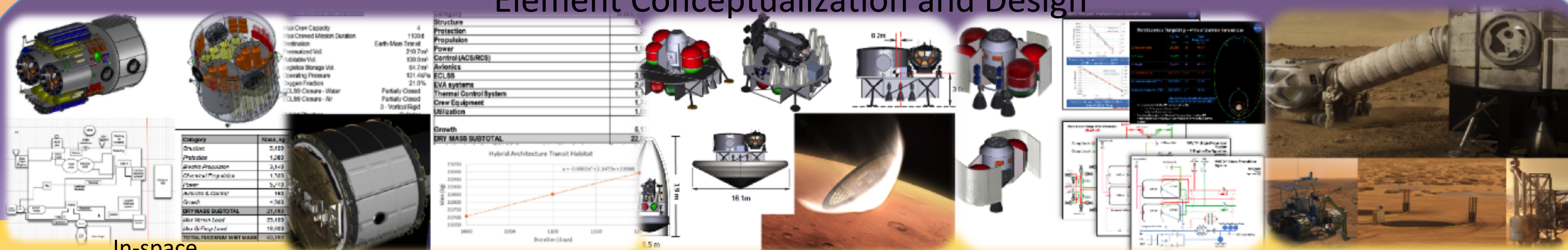
Trajectory and Orbit Analysis

Proving Ground Ops

Landing Site Selection and Layout

Destination Operations

Element Conceptualization and Design



In-space Transportation Systems

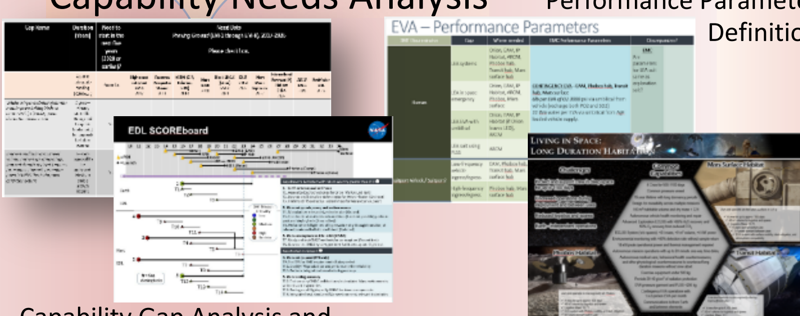
Habitat Sizing

Lander

Mars Ascent Vehicle Design

Destination Systems

Capability Needs Analysis

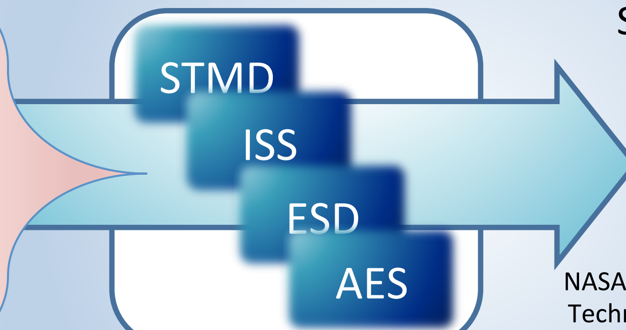


Performance Parameter Definition

Capability Gap Analysis and Roadmap Development

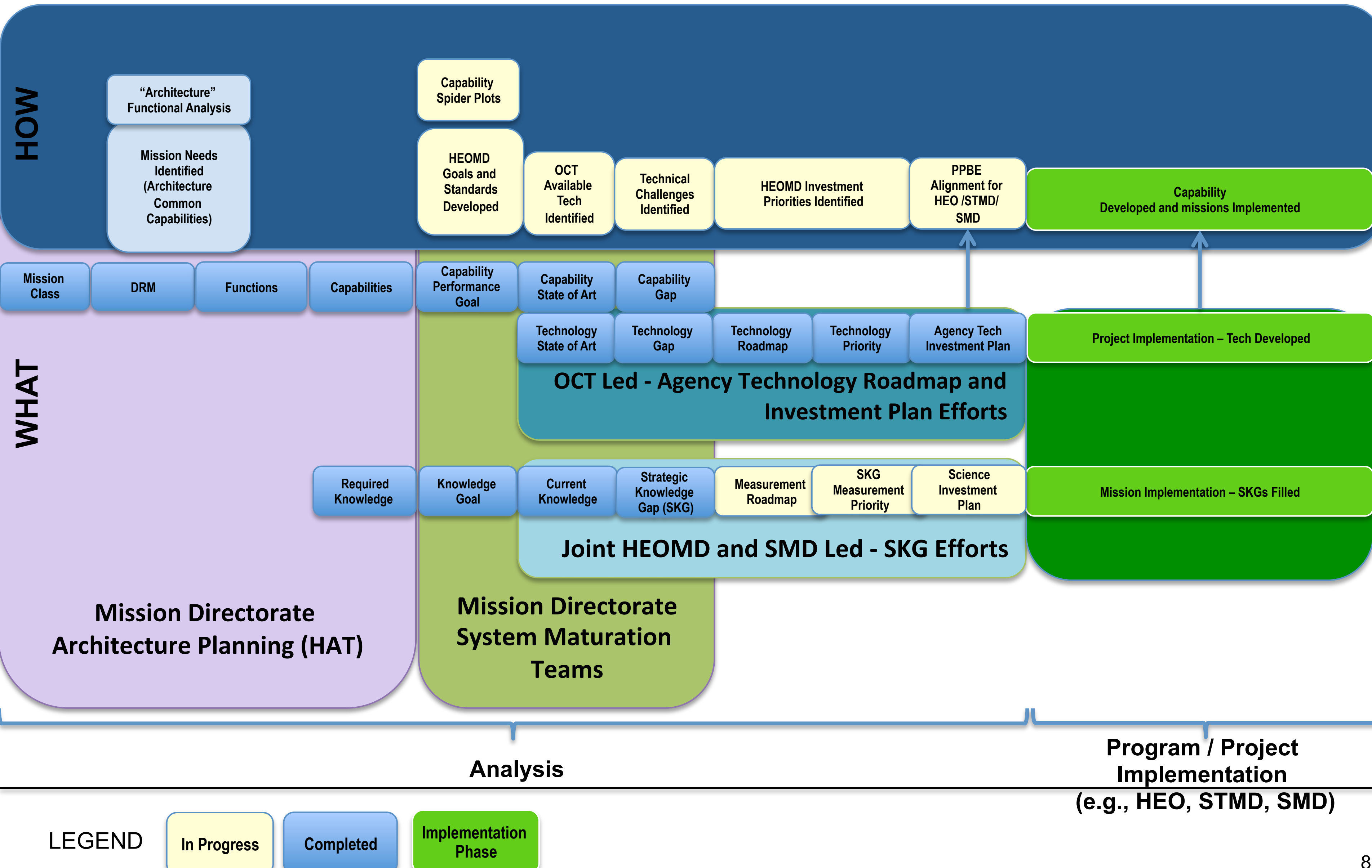
Pioneering Space Challenges

Strategic Planning



NASA Decision Processes, Technology Roadmaps & Strategic Investment Plan

NASA Technology Roadmaps & Investment Plan

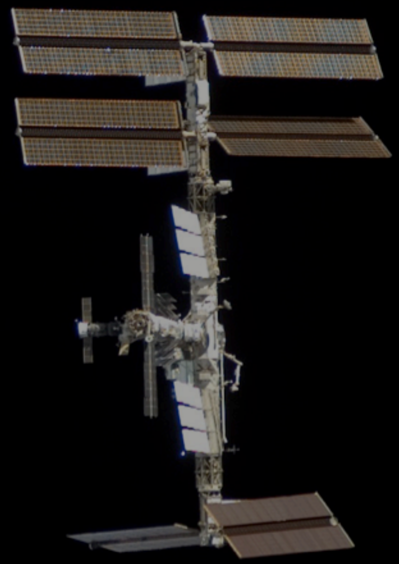


EARTH RELIANT

NEAR-TERM OBJECTIVES

DEVELOP AND VALIDATE EXPLORATION CAPABILITIES IN AN IN-SPACE ENVIRONMENT

- Long duration, deep space habitation systems
- Next generation space suit
- Autonomous operations
- Communications with increased delay
- Human and robotic mission operations
- Operations with reduced logistics capability
- Integrated exploration hardware testing



LONG-DURATION HUMAN HEALTH EVALUATION

- Evaluate mitigation techniques for crew health and performance in micro-g space environment
- Acclimation from zero-g to low-g

COMMERCIAL CREW TRANSPORTATION

- Acquire routine U.S. crew transportation to LEO

PROVING GROUND OBJECTIVES

Enabling Human Missions to Mars

TRANSPORTATION

- **Heavy Launch Capability**: beyond low-Earth orbit launch capabilities for crew, co-manifested payloads, large cargo
- **Crew**: transport at least four crew to cislunar space
- **In-Space Propulsion**: send crew and cargo on Mars-class mission durations and distances

WORKING IN SPACE

- **ISRU**: Understand the nature and distribution of volatiles and extraction techniques and decide on their potential use in human exploration architecture.
- **Deep-space operations capabilities**: EVA, Staging, Logistics, Human-robotic integration, Autonomous operations
- **Science**: enable science community objectives

STAYING HEALTHY

- **Deep-Space Habitation**: beyond low-Earth orbit habitation systems sufficient to support at least four crew on Mars-class mission durations and dormancy
- **Crew Health**: Validate crew health, performance and mitigation protocols for Mars-class missions

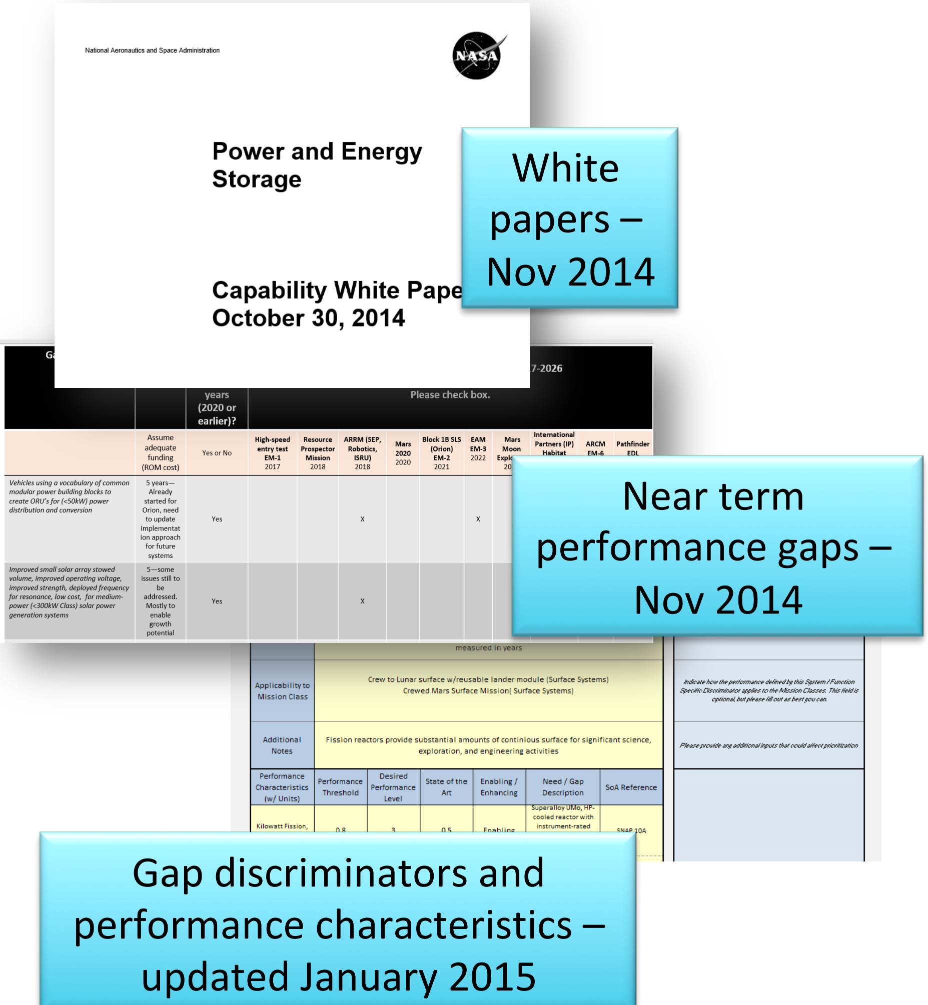
System Maturation Teams - Integrated capability investment decisions with traceability to human exploration needs

System Maturation Team
Autonomous Mission Operations (AMO)
Communication and Navigation (Comm/Nav)
Crew Health & Protection and Radiation (CHP)
Environmental Control and Life Support Systems and Environmental Monitoring (ECLSS-EM)
Entry, Descent and Landing (EDL)
Extra-vehicle Activity (EVA)
Fire Safety
Human-Robotic Mission Operations
In-Situ Resource Utilization (ISRU)
Power and Energy Storage
Propulsion
Thermal (including cryo)
Discipline Team - Crosscutting
Avionics
Structures, Mechanisms, Materials and Processes (SMMP)

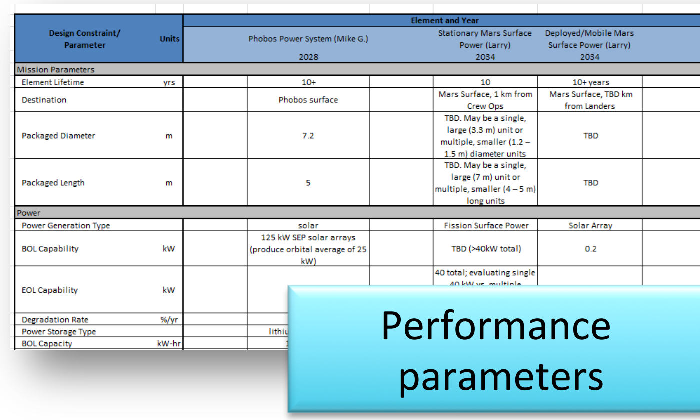
- A key piece to the Pioneering Space strategy is input from System Maturation Teams (SMTs). The SMTs comprise subject matter experts from across the agency who have been involved in maturing systems and advancing technology readiness for NASA.
- The SMTs are defining performance parameters and goals for each of the 14 capabilities, developing maturation plans and roadmaps for the identified performance gaps, specifying the interfaces between the various capabilities, and ensuring that the capabilities mature and integrate to enable future pioneering missions. The subject matter experts that compose each SMT are responsible for understanding their capabilities across all missions and elements within the Evolvable Mars Campaign.
- The SMTs work closely with the Evolvable Mars Campaign to coordinate capability needs & gaps.
- STMD's Principal Technologists are members of the SMTs and coordinate the STMD investment planning with capability needs and gaps.

Data collection and usage

SMT Data Sets



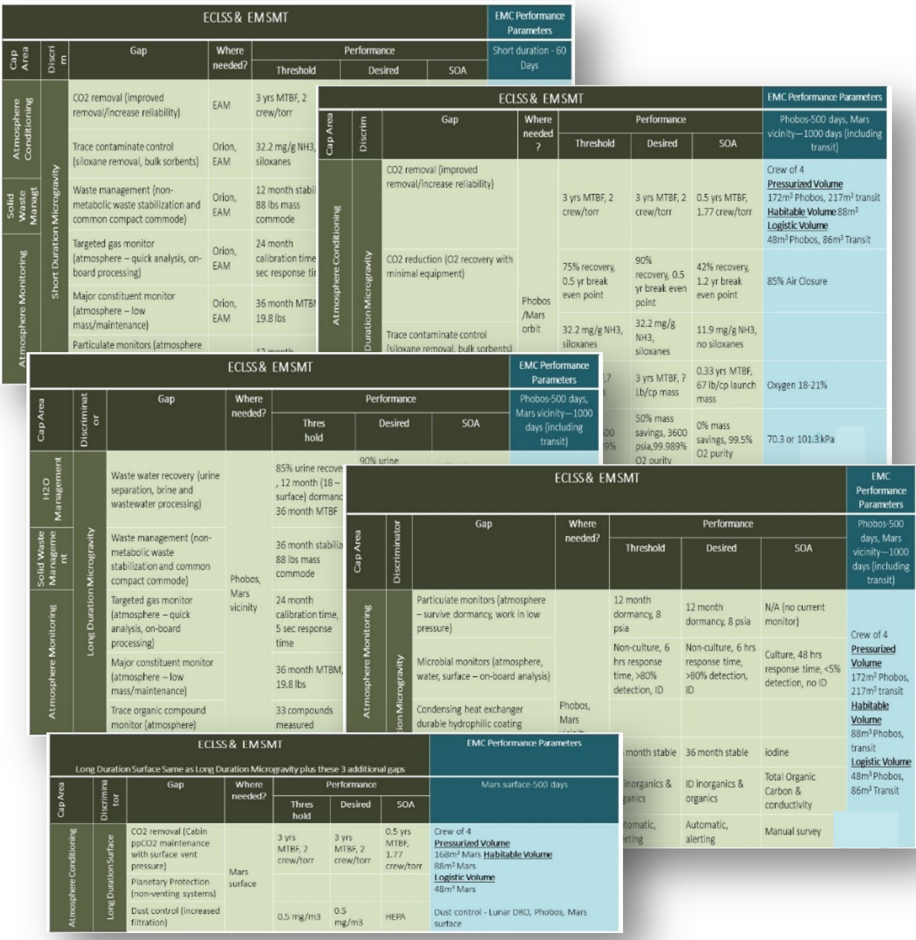
EMC Data Set



SMT and EMC Performance Metrics Validation

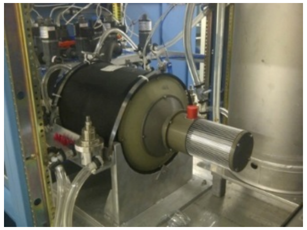
EVA SMT						EMC Performance Parameters
Gap Area	Discrim	Gap	Where needed?	Performance: Desired	Performance: SOA	
Exploration PLSS	Surface EVA	PLSS Compatibility with Exploration architecture – Mars atmosphere	Mars surface	Recharge services	EMU	**EAM, Phobos hab, Transit hab, Mars surface, and all mobility** EMC specified the same avionics as the SMT
Exploration EVA Avionics	Avionics	PLSS avionics system	With PLSS/PGS	*Vehicle-born HL comm *A dual-band radio (UHF for mission critical data and 802.11 variant protocol S-Band for high rate) *Separate HD camera connected via 802.11 Wi-Fi or dual-band radio	EMU	
		PGS avionics system				
		Avionics systems for EVA tasks	Any surface EVA		EMU	
Exploration EVA Architecture	Suit Maintenance and Planetary Protection	Long duration EVA Maintenance (>28 days)	Long duration surface	TBD hours MPT, Maintenance Area	EMU	**Phobos hab and Mars surface hab**
		Non-suit dust mitigation	Any geologic work (includes ARCM)	Partner with ECLSS & vehicle teams to mitigate dust, ingress/egress methods, operations (special regions)	Suits leak/vent	Need operational concepts, architecture (specifications of suitport or airlock)
		Planetary protection (forward and backward)	Phobos, Mars			No parameters specified
EVA Integration	Rescue	Integrated rescue operations	All EVA operations	Depends on ops and vehicle architecture		No 'acceptable' levels of dust identified

Environmental Control and Life Support System – Environment Monitoring (ECLSS-EM) SMT

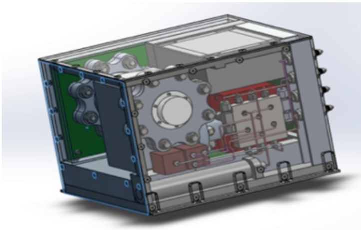


AES – FY16 Activities

- ✓ **Life Support Systems:** Developing improved sorbents for CO_2 removal, High Pressure Oxygen Generation system for replenishing space suits, Cascade Distillation System for waste water processing, and Spacecraft Atmosphere Monitor for detecting trace gas contaminants in ISS air.
- ✓ **Next Space Technology Exploration Partnerships (NextSTEP):** Developing advanced CO_2 removal technologies, modular ECLSS, and hybrid biological and chemical life support systems.
- ✓ Feeds forward to short and long duration habitats used for transit and surface destinations.



Cascade Distillation System



Spacecraft Atmosphere Monitor

Life Support Systems: Completed Systems Requirements Review for Spacecraft Atmosphere Monitor. ISS demo planned in 2018.

STMD Strategic Planning

STMD Strategic Alignment Framework

- Core values, guiding principles, implementation goals flowdown

STMD Strategic Themes

- Get There, Land There, Live There, Observe There, Invest Here

Strategic Guidance

- Stakeholder input: Space Technology Roadmaps, NRC recommendations, STIP, MD roadmaps, Roundtables, etc.

STMD Thrust Areas

- Focused areas of STMD investments

Content Generation

- Principal Technologists: Technology investment plans

Technology Portfolio Integration

- Crosscutting Investent strategy and content selection

STMD Programs

- Impleentation instruments

National Science and Technology Priorities

STMD Strategic Themes

Get There
Improve the ability to efficiently access and travel through space

Land There
Enable the capability of landing more mass, more accurately, in more locations throughout the solar system

Live There
Make it possible to live and work in deep space and on planetary bodies

Observe There
Transform the ability to observe the universe and answer the profound questions in Earth and space sciences

Invest Here
Enhance the nation's aerospace capabilities and ensure its continued technological leadership

HEOMD/STMD Engagement on Technology Needs

- **Evolvable Mars Campaign (EMC) has a strategic set of needs for enabling long-range capabilities; Orion and SLS needs are primarily near-term and mission focused.**
- **Crosscutting needs identified by HEOMD:**
  - Radiation monitoring & protection (ISS, Orion, HRP, EMC)
  - EVA suit & PLSS (Orion, ISS, ARM, EMC)
  - Environmental monitoring (Orion, ISS, EMC)
  - Spacecraft fire safety (Orion, ISS, EMC)
  - Exercise equipment (Orion, HRP, EMC)
  - Advanced solar arrays (ARM, ISS, EMC)
  - Automated rendezvous & docking (Orion, ARM, EMC)
- **Areas with greatest number of gaps:**
  - Human Health, Life Support, & Habitation Systems (Orion, HRP)
  - Communications & Navigation (SCAN)
- **Categories of collaboration:**
  - **Deliveries:** STMD matures technology and delivers to AES for system-level evaluation (e.g., RCA, VOR, EVA Gloves, RPM instruments, etc.)
  - **Partnerships:** STMD and HEOMD/AES co-fund the development of technologies that are of mutual interest (e.g., MOXIE, MEDA, MEDLI-2, SCOR, etc.)
  - **Coordination:** STMD and HEOMD/AES define specific divisions of responsibility within a technical discipline (e.g., nuclear systems, synthetic biology, advanced manufacturing, etc.)

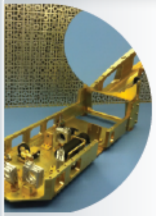
STMD Investment Thrust Areas

Space Technology focus investments in 8 thrust areas that are key to future NASA missions and enhance national space capabilities.

High Performance Space Propulsion

Create improvements in thrust levels, specific power, and alternatives to traditional chemical propulsion systems for destination-agnostic, deep space exploration spacecraft systems.

External Application: Enhanced propulsion capabilities for Commercial and OGA Satellites



High Bandwidth Space Optical Comm

Substantially increase available bandwidth and data rates for near earth and deep space, currently limited by power and frequency allocation limits. Assure robust and reliable interconnected space network.

External Application: High bandwidth for Commercial and OGA Satellites

Advanced Life Support & Resource Utilization

Human exploration missions beyond low earth orbit will require highly reliable technologies (e.g. reclaiming water reuse of trash, air revitalization) to minimize resupply requirements and increase independence from earth.

External Application: Mining Industry and other closed environments; OGA

Entry Descent and Landing Systems

Permits more capable science and future human missions to terrestrial bodies. Includes, hypersonic and supersonic aerodynamic decelerators, next-gen TPS materials, retro-propulsion, instrumentation and modeling.

External Application: Returning commercial assets from space and research from ISS

Autonomy and Space Robotic Systems

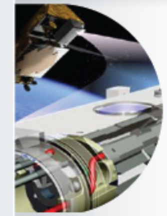
Extends our reach by helping us remotely explore planetary bodies, manage in-space assets and support in-space operations by enhancing the efficacy of our operations.

External Application: Human-safe Robotics for industrial use, disaster response, & overall autonomous operations

Lightweight Space Structures

Targets large decreases in structural mass for launch vehicles and spacecraft materials using nanotech, composites and in space manufacturing capabilities.

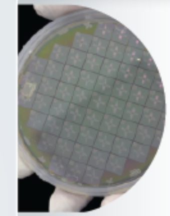
External Application: Industrial Materials and Composites for large structures (rockets, aircraft)



Deep Space Navigation

Allows for more capable science and human exploration missions; enables more precise entry trajectories for inserting into orbits around planets and bodies like Mars, Europa, and Titan.

External Application: Next Generation GPS and build new industrial base



Space Observatory Systems

Allows for significant gains in science capabilities including: coronagraph technology to characterize exo-planets, advances in surface materials and better control systems for large space optics.

External Application: Industrial Materials, Earth Observation

THRUST AREAS

Capabilities for Pioneering Space: Steps on the Journey to Mars

	Capability \ Mission	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Cis-Mars Robotic	Mars Orbit	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU Regolith	Exploratory ISRU	Exploratory ISRU & Atmosphere	Exploratory ISRU	Operational ISRU & High Power
	Habitation & Mobility	Long Duration with Resupply	Initial Short Duration	Initial Long Duration		Resource Site Survey	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Autonomous Rendezvous & Dock	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Full Duration	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Dust Toxicity	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration	Long Duration	Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Forecasting Shelter	Forecasting & Surface Enhanced
Transportation	Ascent from Planetary Surfaces				Sub-Scale MAV	Sub-Scale MAV	Human Scale MAV
	Entry, Descent & Landing				Sub-Scale/Aero Capture	Sub-Scale/Aero Capture	Human Scale EDL
	In-space Power & Prop		Low power	Low Power	Medium Power	Medium Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND				EARTH INDEPENDENT

Capabilities for Pioneering Space: Steps on the Journey to Mars
STMD Focus Areas

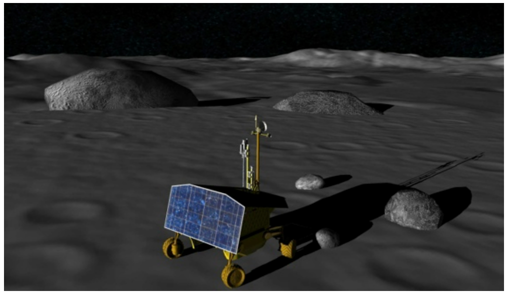
	Capability \ Mission	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Cis-Mars Robotic	Mars Orbit	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU Regolith	Exploratory ISRU	Exploratory ISRU & Atmosphere	Exploratory ISRU	Operational ISRU & High Power
	Habitation & Mobility	Long Duration with Resupply	Initial Short Duration	Initial Long Duration		Resource Site Survey	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Autonomous Rendezvous & Dock	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Full Duration	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Dust Toxicity	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration	Long Duration	Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Forecasting Shelter	Forecasting & Surface Enhanced
Transportation	Ascent from Planetary Surfaces				Sub-Scale MAV	Sub-Scale MAV	Human Scale MAV
	Entry, Descent & Landing				Sub-Scale/Aero Capture	Sub-Scale/Aero Capture	Human Scale EDL
	In-space Power & Prop		Low power	Low Power	Medium Power	Medium Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND				EARTH INDEPENDENT

STMD focus areas (In Situ Resource Utilization & Surface Power; Human/Robotic & Autonomous Ops; Environmental Control & Life Support; Entry, Descent & Landing; In-space Power & Prop; Communication & Navigation)

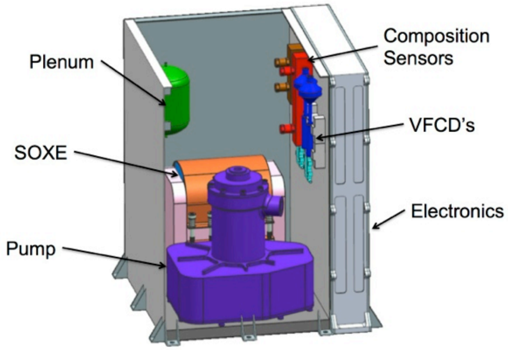
In Situ Resource Utilization & Surface Power

- **Objectives**
  - Reduce logistical support from Earth by utilizing local resources to produce water, oxygen, propellants, and other consumables.
  - Generate abundant power for surface systems.

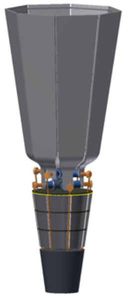
- **Current Activities**
  - **Resource Prospector**: Formulating robotic mission to prospect for ice and other volatiles in polar regions of the Moon. (AES)
  - **Mars Oxygen ISRU Experiment (MOXIE)**: Demonstration of oxygen production from the Mars atmosphere on the Mars 2020 mission. (AES/STMD)
  - **Fission Surface Power:** Ground demonstration of Stirling power conversion technology and small nuclear reactors for 1-10 kW modular surface power systems. (STMD)



Resource Prospector



MOXIE



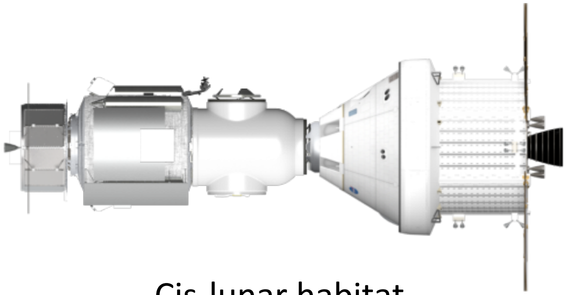
Kilopower fission surface power system

Habitation & Mobility

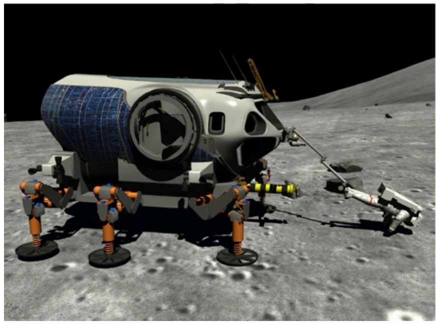
- **Objectives**
  - Develop a deep space habitat that will enable a crew to live in deep space on missions lasting 1,000 days.
  - Develop surface mobility systems that will allow the crew to explore regions beyond the immediate vicinity of the landing site.

- **Current Activities**
  - **Bigelow Expandable Activity Module (BEAM)**: Demonstration of inflatable habitat on ISS. (AES)
  - **Next Space Technology Exploration Partnerships (NextSTEP):** Commercial partnerships to develop concepts for cis-lunar habitats that are extensible to Mars transit habitats. (AES)
  - **Phobos Exploration Vehicle:** Developing concept for hopper to transport crew in a pressurized cabin. (EMC)

BEAM flight hardware



Cis-lunar habitat



Phobos Exploration Vehicle

Human/Robotic & Autonomous Ops

- **<u>Objectives</u>**
  - Develop robotic assistants to support human exploration.
  - Reduce the crew's dependence on ground-based mission control.
  - Automate ground operations to reduce cost.

- **<u>Current Activities</u>**
  - **Robonaut-2:** Anthropomorphic robotic assistant on ISS to support crew with IVA and EVA. (STMD)
  - **Astrobee free flyer**: Next generation IVA free flyer on ISS will demonstrate autonomous logistics management. (STMD)
  - **Autonomous Mission Ops**: Developing software tools for vehicle systems monitoring and fault diagnosis, automated scheduling of maintenance tasks, and automated procedure execution. Demonstrating capabilities on Orion and ISS. (AES)
  - **Automated Propellant Loading**: Demonstrating autonomous fueling of launch vehicles with cryogenic propellants. (AES)

Robonaut-2 on ISS

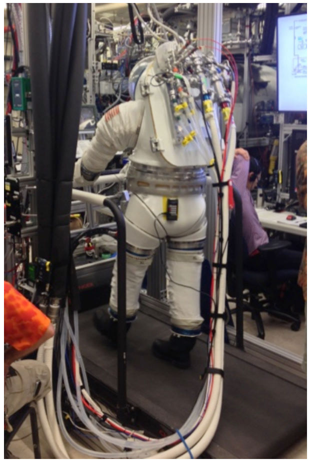
Astrobee free flyer

Crew-centric mission ops

Exploration EVA

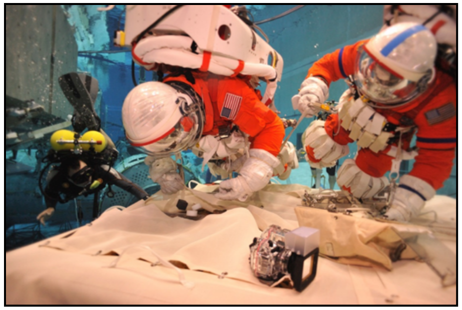
- **Objectives**
  - Enable the crew to conduct "hands-on" surface exploration and in-space operations.
  - Demonstrate advanced space suit on ISS.

- **Current Activities**
  - **Portable Life Support System (PLSS)**: Developing next generation PLSS with new technology components for carbon dioxide removal, pressure regulation, thermal control, and energy storage. (AES/STMD)
  - **Z-Suit:** Developing advanced space suit with improved mobility for surface exploration. (AES)
  - **Modified Advanced Crew Escape Suit (MACES):** Conducting neutral buoyancy tests of short duration space suit for Asteroid Redirect Mission. (AES)
  - **EVA Gloves:** Developing actuated and counter-pressure gloves with improved dexterity. (STMD)



Human-in-the-loop testing of PLSS 2.0

Z-2 suit



MACES testing in Neutral Buoyancy Lab

Crew Health

- **Objectives**
  - Keep the crew healthy on missions lasting up to 1,000 days.

- **Current Activities**
  - **1-year mission on ISS**: Studying the effects of long missions on crew health and performance. (ISS)
  - **Human Health Countermeasures**: Developing countermeasures such as exercise and pharmaceuticals for mitigating the detrimental effects of spaceflight on human physiology. (HRP)
  - **Exploration Medical Capability:** Developing medical technologies for in-flight diagnosis and treatment. (HRP)
  - **Synthetic Biology**: Developing genetically engineered bacteria to produce bionutrients to supplement the crew's diet. (AES)

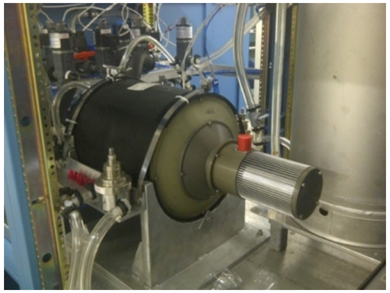
1-year mission on ISS

Exercising on ISS

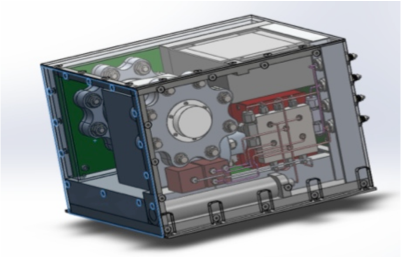
Environmental Control & Life Support

- **Objectives**
  - Develop highly-reliable life support systems that recycle air, water, and waste to reduce consumables.
  - Demonstrate next generation life support systems with integrated ground-based testing and ISS flight experiments.

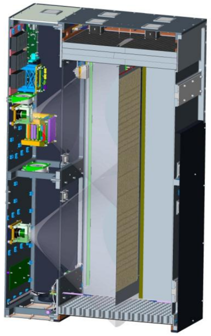
- **Current Activities**
  - **Spacecraft Oxygen Recovery**: Developing technologies to recover at least 75% of the oxygen from a spacecraft atmosphere revitalization system. (STMD)
  - **Sorbents for CO_2 Removal:** Developing new sorbents that do not generate dust. (AES)
  - **High Pressure Oxygen Generation:** Providing oxygen supply for replenishing space suits. (AES)
  - **Waste Water Processing**: Developing green pre-treatments, Cascade Distillation System, and Biological Water Processor. (AES/STMD)
  - **Spacecraft Atmosphere Monitor:** Instrument for detecting trace gas contaminants in ISS air. (AES)
  - **PCM Heat Exchanger**: Developing a large-scale Phase Change Material heat exchanger to maintain the crew cabin within safe/comfortable temperatures throughout exploration missions. (STMD)
  - **Spacecraft Fire Safety:** Saffire experiments will investigate the spread of fires in microgravity. Also developing technologies for fire suppression, combustion products monitoring, and post fire clean-up. (AES)
  - **Next Space Technology Exploration Partnerships (NextSTEP):** Developing advanced CO_2 removal technologies, modular ECLSS, and hybrid biological and chemical life support systems. (AES)



Cascade Distillation System



Spacecraft Atmosphere Monitor

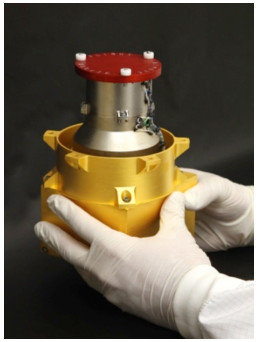


Saffire Fire Safety Experiment

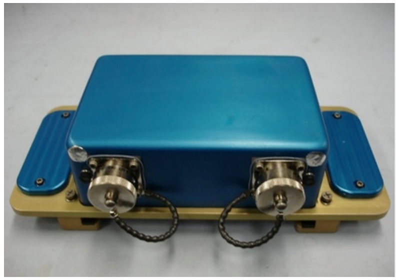
Radiation Safety

- **Objectives**
  - Characterize the radiation environments of potential destinations for human exploration.
  - Understand the biological effects of space radiation.
  - Develop shielding and countermeasures to protect crew from harmful space radiation.

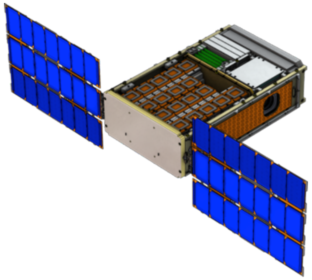
- **Current Activities**
  - **Radiation Assessment Detector (RAD)**: Characterizing Mars surface radiation environment on Mars Science Laboratory mission. (AES)
  - **Radiation Environment Monitors:** Measuring radiation environments on Orion and ISS. (AES)
  - **BioSentinel:** CubeSat that will investigate the effects of deep space radiation environment on yeast DNA. (AES)
  - **Radiation Forecasting:** Developing improved models to predict solar particle events. (AES)
  - **Advanced Radiation Protection:** Combined analytical and empirical effort to validate the radiation shielding efficiency of spacecraft materials to ultimately develop a minimal mass vehicle design. (STMD)
  - **NASA Space Radiation Laboratory**: Particle beam testing at Brookhaven National Laboratory to investigate the effects of galactic cosmic radiation on rodents and to validate radiation transport models for shielding design. (HRP)



Radiation Assessment Detector



Radiation Environment Monitor flown on EFT-1

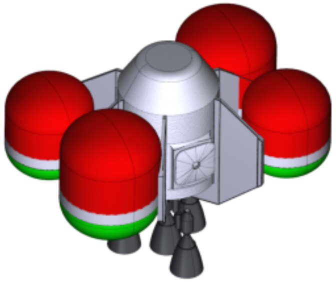


BioSentinel CubeSat

Ascent from Planetary Surfaces

- **Objectives**
  - Develop concepts and propulsion technologies for Mars Ascent Vehicle (MAV).

- **Current Activities**
  - **MAV Concepts**: Developing MAV concepts for Mars Sample Return and human missions. (EMC)
  - **LOX-Methane Propulsion:** Developing rocket engines that can use propellants produced from Mars resources. (AES)



MAV concept

LOX-methane engine test

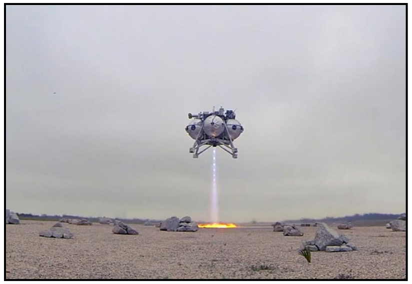
Entry, Descent, and Landing (EDL)

- **Objectives**
  - Develop the capability to land heavy payloads (> 18 mt) on Mars for human missions.

- **Current Activities**
  - **Low Density Supersonic Decelerator (LDSD):** Flight test of supersonic aerodynamic decelerator and supersonic ring sail parachute for future robotic missions to Mars. (STMD)
  - **Hypersonic Inflatable Aerodynamic Decelerator (HIAD):** Conducted sounding rocket flight tests of subscale HIAD. (STMD)
  - **Adaptable Deployable Entry & Placement Technology (ADEPT):** Deployable, semi-rigid aeroshell. (STMD)
  - **Supersonic Retro Propulsion**: Learning from SpaceX flyback booster tests. (STMD)
  - **Advanced Thermal Protection System (TPS) materials**: Developing woven and high heat flux TPS materials. (STMD)
  - **Entry Systems Modeling:** Updating and improving computational fluid dynamics codes to reduce design uncertainties for future missions. (STMD)
  - **Autonomous Landing & Hazard Avoidance Technology (ALHAT):** Flight test of ALHAT system on Morpheus lander. (AES)
  - **Mars Entry, Descent, & Landing Instrumentation (MEDLI-2):** Measuring temperatures and pressures on Mars 2020 heat shield to validate aerothermal models. (AES/STMD)
  - **EDL Pathfinder:** Studying EDL Pathfinder mission to Mars in 2026 to test subscale EDL system for human missions. (EMC)


LDSD flight hardware

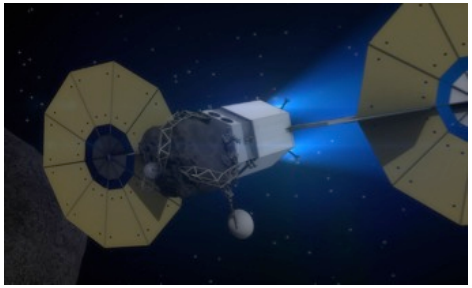

HIAD engineering model


ALHAT testing on Morpheus lander

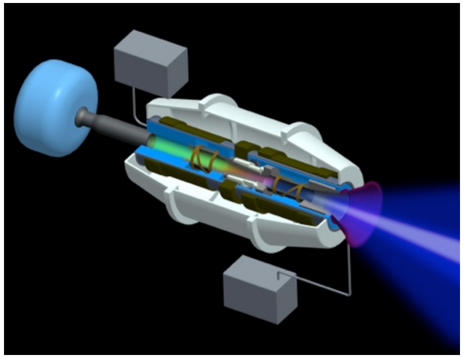
In-Space Power & Propulsion

- **Objectives**
  - Develop 100 kW-class solar electric propulsion systems for transporting cargo to Mars.
  - Develop technologies for nuclear thermal propulsion to enable rapid transport of crew to Mars.

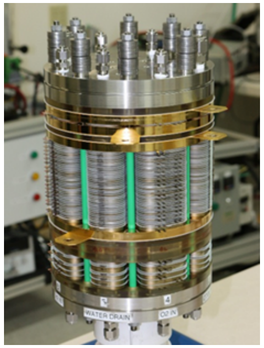
- **Current Activities**
  - **Solar Electric Propulsion (SEP):** Developing 40 kW SEP system for Asteroid Redirect Mission (ARM). (STMD)
  - **Next Space Technologies Exploration Partnerships (NextSTEP):** Developing 100 kW electric propulsion systems and testing for 100 continuous hours. (AES)
  - **Nuclear Thermal Propulsion**: Developing fuel elements, reactor concepts, and affordable ground testing methods. (STMD)
  - **Advanced Solar Arrays:** Developing 50 kW solar arrays for SEP and in-space power generation. (STMD)
  - **Extreme Environment Solar Power**: Competitively developing advanced solar power technologies capable of operating in deep space environments (low temperature, low intensity, and high radiation). (STMD)
  - **High Temperature Boost PPU:** Maturing silicon carbide devices and a non-isolated boost topology to potentially provide a low mass, high efficiency PPU. (STMD)
  - **Energy Storage**: Developing high energy density batteries for space suits and fuel cells for SLS. (AES/STMD)



SEP for ARM



Variable Specific Impulse Magnetoplasma Rocket (VASIMR)



1 kW fuel cell

Beyond LEO: SLS & Orion

- **Objectives**
  - Develop the integrated transportation system for enabling human missions beyond Earth orbit.

- **Current Activities**
  - **Orion**: Developing crew vehicle for human exploration beyond Earth orbit. First crewed mission in 2021. (HEOMD)
  - **Space Launch System (SLS)**: Developing heavy lift launch vehicle for human exploration beyond Earth orbit. First launch in 2018. (HEOMD)
  - **Ground Systems:** Developing spaceport infrastructure to support launches of SLS and Orion. (HEOMD)

Orion

SLS

Commercial Cargo & Crew

- **Objectives**
  - Develop commercial services to reduce the cost of launching cargo and crew to LEO.
  - Support ISS with multiple vehicles to ensure continuity of operations.

- **Current Activities**
  - **Commercial Cargo**: Contracts with Orbital ATK and SpaceX for cargo resupply of ISS. (HEOMD)
  - **Commercial Crew:** Contracts with Boeing and SpaceX to develop commercial crew transportation services to LEO. (HEOMD)
  - **Lunar CATALYST:** Space Act Agreements with Astrobotic Technologies, Moon Express, and Masten Space Systems to stimulate commercial payload delivery services to lunar surface. (AES)

Orbital ATK Cygnus

SpaceX Dragon

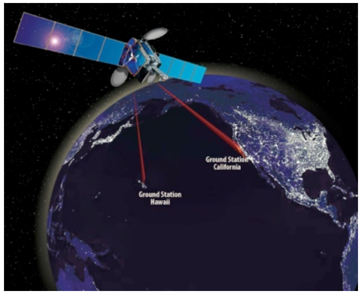
Boeing CST-100

SpaceX Dragon 2

Communication & Navigation

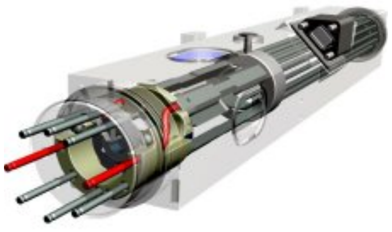
- **Objectives**
  - Develop high-data rate communications infrastructure to support deep space missions.
  - Develop new technologies for precise deep space navigation.

- **Current Activities**
  - **Laser Communications Relay Demonstration (LCRD)**: Flight test of optical communications between ground and GEO. (SCAN/STMD)
  - **Deep Space Optical Communications (DSOC)**: Developing photon counting detectors and vibration isolation systems for laser communications across interplanetary distances. (SCAN/STMD)
  - **Ka-Band Objects Observation & Monitoring (KaBOOM):** Demonstrating antenna arrays with atmospheric disturbance compensation for future space communications and radar applications. (AES)
  - **Disruption Tolerant Networking (DTN):** Infusion of store and forward communications protocols into NASA and international missions. (AES)
  - **Deep Space Atomic Clock:** Flight test of ultra-precise atomic clock for deep space navigation**.** (STMD)
  - **NICER/SEXTANT**: Demonstration of deep space navigation using X-ray pulsars. (STMD)



LCRD

KaBOOM at KSC



Deep Space Atomic Clock

Capability Development Risk Reduction

= Sufficiently Funded
= Partially Funded
= Not Funded

	Capability \ Mission	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Cis-Mars Robotic	Mars Orbit	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU Regolith	Exploratory ISRU	Exploratory ISRU & Atmosphere	Exploratory ISRU	Operational ISRU & High Power
	Habitation & Mobility	Long Duration with Resupply	Initial Short Duration	Initial Long Duration		Resource Site Survey	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Autonomous Rendezvous & Dock	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Full Duration	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Dust Toxicity	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration		Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Forecasting Shelter	Forecasting & Surface Enhanced
Transportation	Ascent from Planetary Surfaces				Sub-Scale MAV	Sub-Scale MAV	Human Scale MAV
	Entry, Descent & Landing				Sub-Scale/Aero Capture	Sub-Scale/Aero Capture	Human Scale EDL
	In-space Power & Prop		Low power	Low Power	Medium Power	Medium Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND				EARTH INDEPENDENT

Current Capability Risks

Capabilities	L X C	Rationale
In Situ Resource Utilization & Surface Power	Risk Assessment in Work	Resource Prospector and MOXIE are small-scale demonstrations of ISRU on planetary bodies. These would need to be significantly scaled up to support human exploration needs.
Habitation & Mobility		ISS is demonstrating long-duration habitation in LEO, but duration depends on resupply. Conceptual studies are underway for short duration cis-lunar habitats.
Human/Robotic & Autonomous Ops		Human/Robotic & Autonomous Ops are being demonstrated on ISS. Substantial additional work is needed to enable maintenance of human exploration systems.
Exploration EVA		Uncertain if next generation spacesuit will be ready before 2024 for demonstration on ISS.
Crew Health		Human Research Program is investigating crew health risks on ISS, and developing medical diagnostics and countermeasures. Some health risks may not be controlled by 2024.
Environmental Control & Life Support		ISS life support systems require frequent maintenance. New ECLSS technologies are being demonstrated on ISS. Long-duration, closed-loop, system-level ECLSS demonstration is being planned.
Radiation Safety		Characterizing LEO, cis-lunar, and Mars surface radiation environments. Improving forecast models for solar particle events. Reducing uncertainty in radiation effects on humans. Effective shielding has not been developed.
Ascent from Planetary Surfaces		Little work is being done in this area except for MAV concept studies and small LOX-methane propulsion efforts.
Entry, Descent & Landing		There are multiple EDL technology development activities for Mars robotic missions but analogous projects for human missions are in early stages of progress.
In-space Power & Propulsion		Developing 40 kW SEP system for ARM. Initiating ground testing of 100 kW electric thrusters. Developing small fission reactors for surface power (low funding level).
Beyond LEO: SLS & Orion		Working towards first flight of SLS and Orion in 2018.
Commercial Cargo & Crew		Working towards Commercial Crew IOC in 2018. Opportunites for resupply of cis-lunar habitats.
Communication & Navigation		Demonstrating high bandwidth optical communications for cis-lunar and Mars Deep space optical comm is a candidate for demonstration on SMD missions.

Next Steps

- Continue Capability Risk Assessments.
- Engage international partners in contributing to capability risk reduction.
- Create future opportunities for commercial services beyond LEO such as cargo resupply for a cis-lunar habitat.
- Ensure that critical technology demonstrations and crew health research on ISS are accomplished before the program ends in 2024.
- Update Technology Investment Plans consistent with Exploration and Science priorities.
- Continue to coordinate Science, Exploration, and Technology objectives for all future Mars robotic missions to demonstrate needed capabilities for human missions (EDL, ISRU, MAV).

Summary

- The Journey to Mars requires a resilient architecture that can embrace new technologies, new international / commercial partners, and identify agency investment choices to be made in the near, mid and long term.
- The Evolvable Mars Campaign:
  - Informs the agency choices by providing technical information from a cross agency, end-to-end integrated analysis
  - Needs to continue to develop linkages to the agency decision making and capability investment processes
- Regardless of which path is ultimately selected, there are a set of common capabilities required to be developed by NASA and its partners over the next 10 years