National Aeronautics and Space Administration

Habitation and Destination Systems

Briefing to the National Research Council Technical Panel

March 27, 2013

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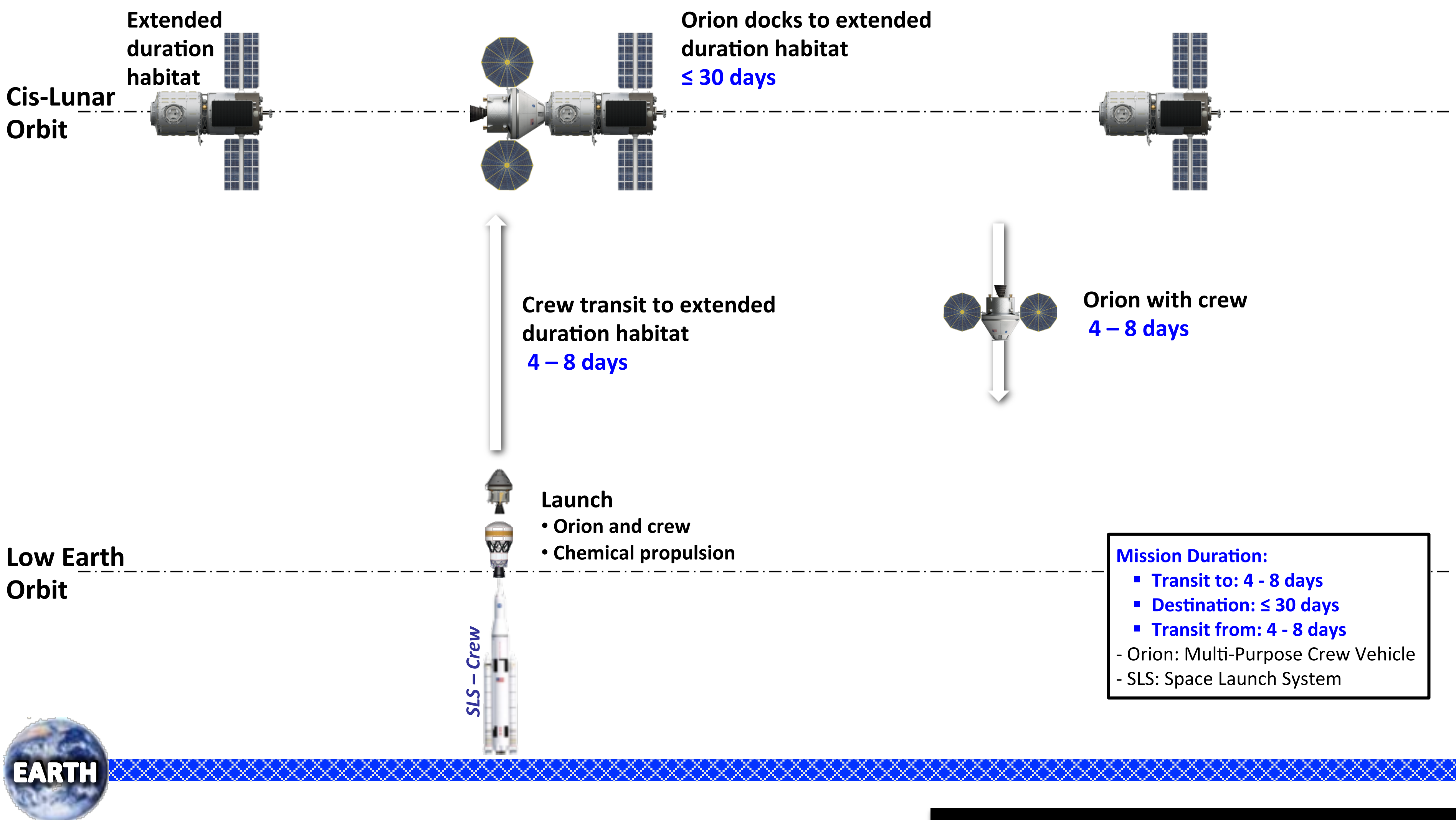
Habitation and Destination Systems

- **DRM Context**
- **Habitation**
  - Transit Habitation to potential destinations – Cis-Lunar, NEA, Mars
  - Destination Habitation – Mars
  - Technical Challenges
- **Potential Destination Systems**
  - NEA
  - Mars
  - Technical Challenges
- **Destination Strategic Knowledge Gaps**
  - SKG introduction
  - NEAs
  - Mars

Example Crewed Cis-Lunar 30 Day Mission

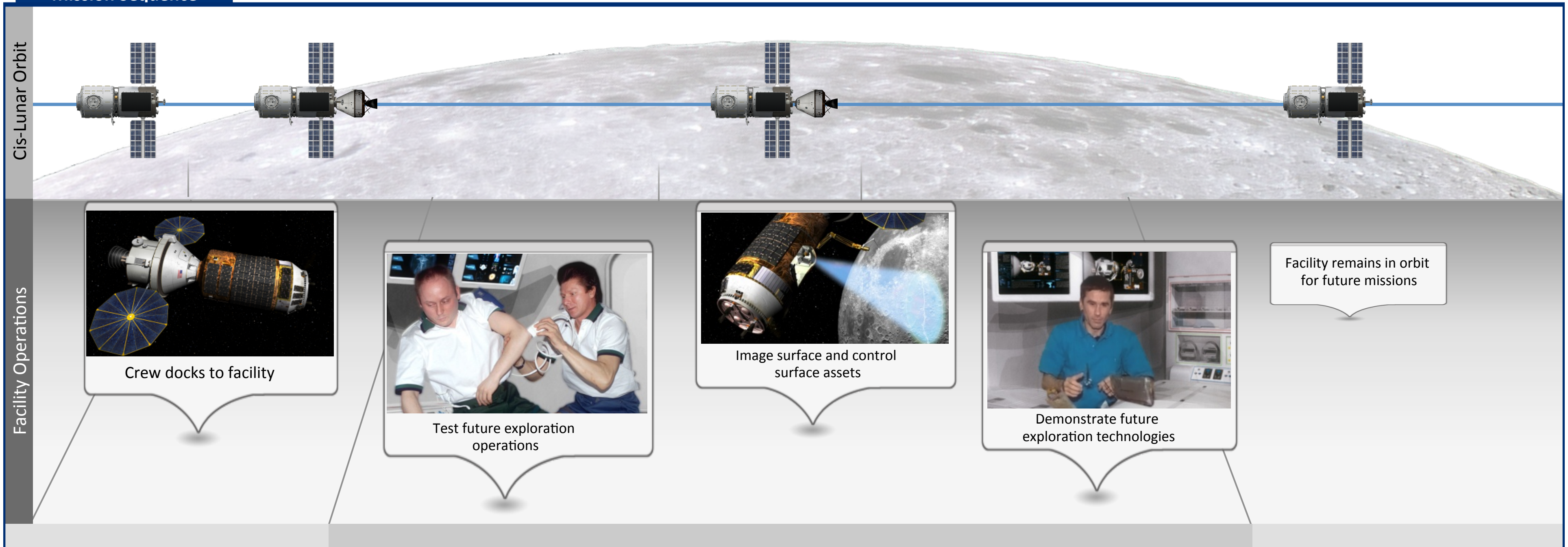


Mission Duration:
- Transit to: 4 - 8 days
- Destination: ≤ 30 days
- Transit from: 4 - 8 days

- Orion: Multi-Purpose Crew Vehicle
- SLS: Space Launch System

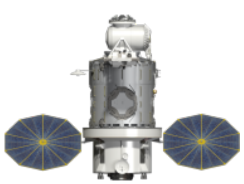
Example Crewed Cis-Lunar 30 Day Mission
- Potential Destination Operations

Mission Sequence



Destination Capabilities

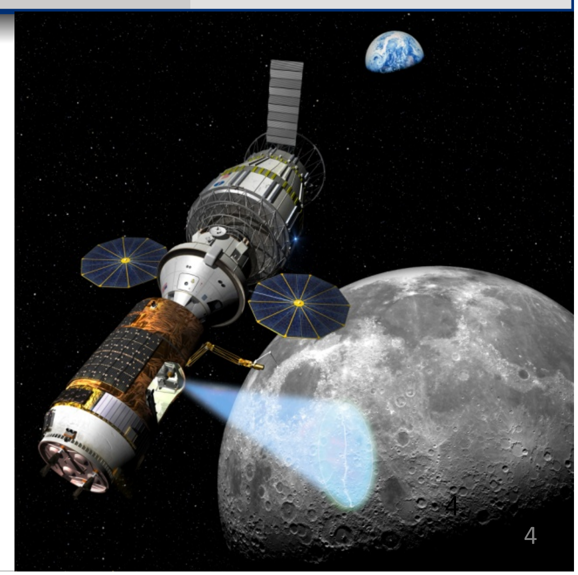
Orion



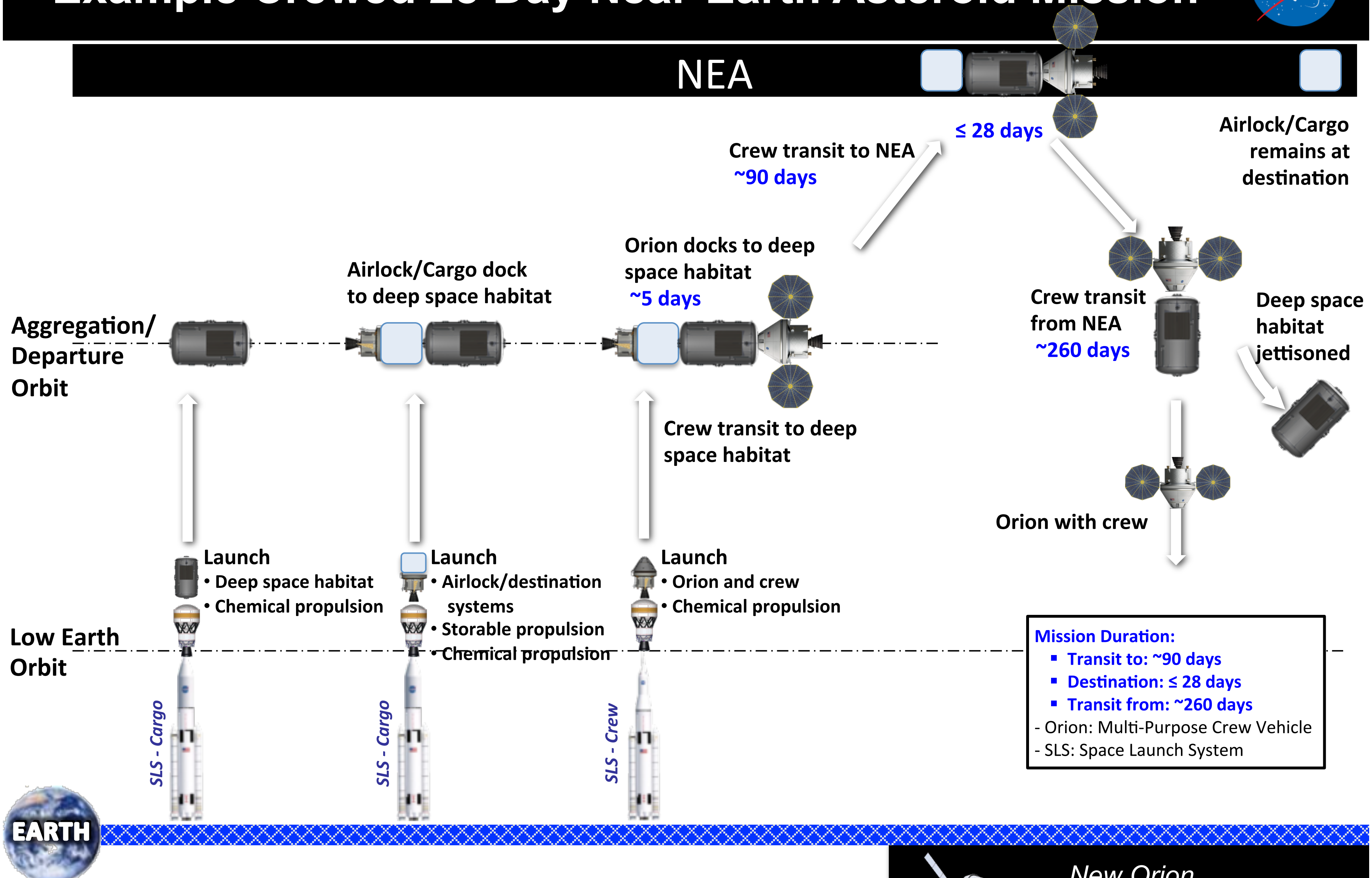
Extended Duration Habitat (notional)

Mission Benefits

- Reduces risk for future human and robotic exploration missions
- Enhances space science
- Develops capabilities required for future exploration missions
- Potential to facilitate sample return



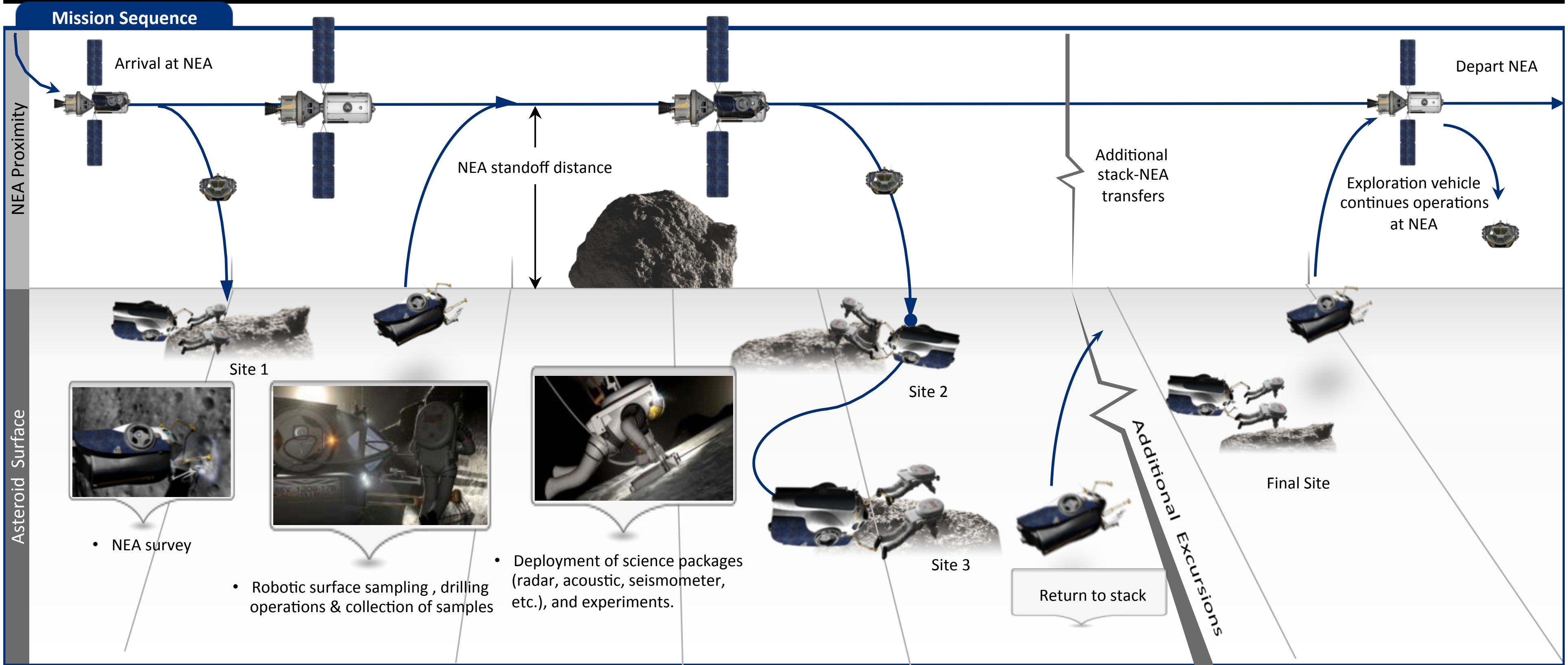
Example Crewed 28 Day Near-Earth Asteroid Mission



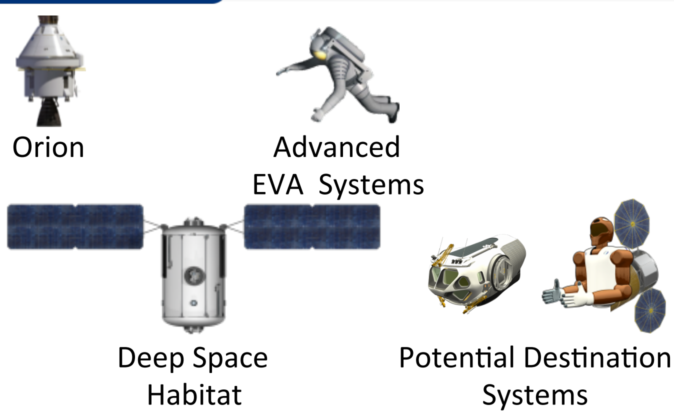
Mission Duration:
- **Transit to: ~90 days**
- **Destination: ≤ 28 days**
- **Transit from: ~260 days**

- Orion: Multi-Purpose Crew Vehicle
- SLS: Space Launch System

Example Crewed 28 Day Near-Earth Asteroid Mission - Destination Operations

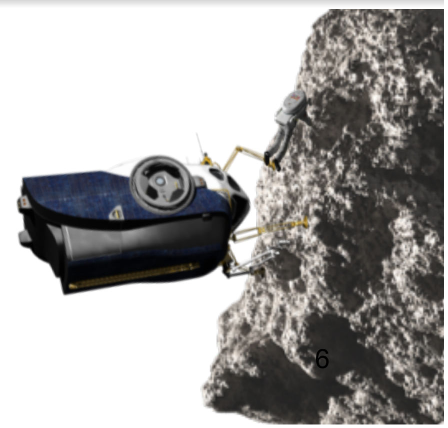


Destination Capabilities

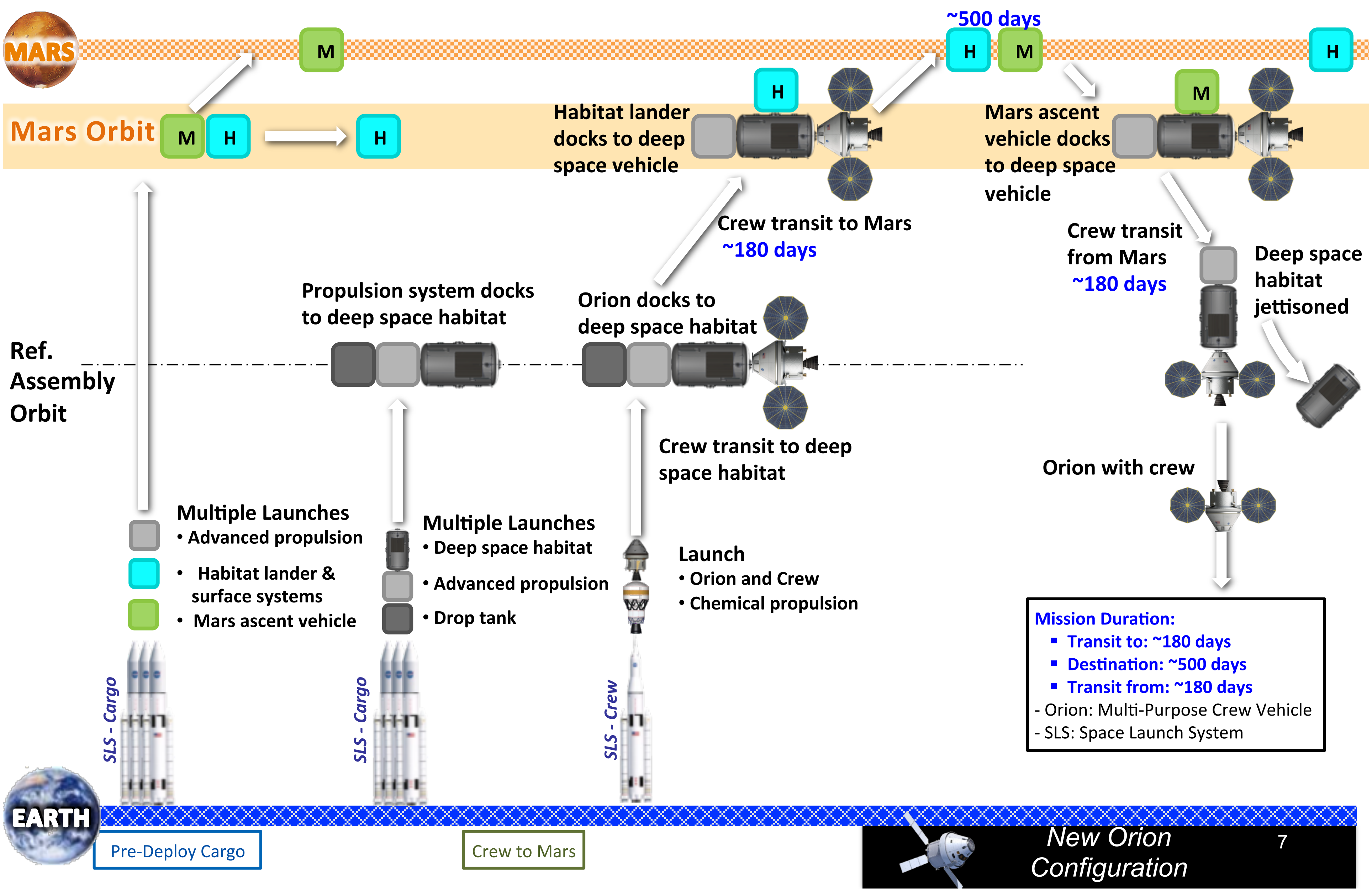


Mission Benefits

- Enhances space science
- Tests capabilities required for future exploration missions



Example Crewed Mars Surface Mission
(NASA Mars Design Reference Architecture 5.0 Derived)

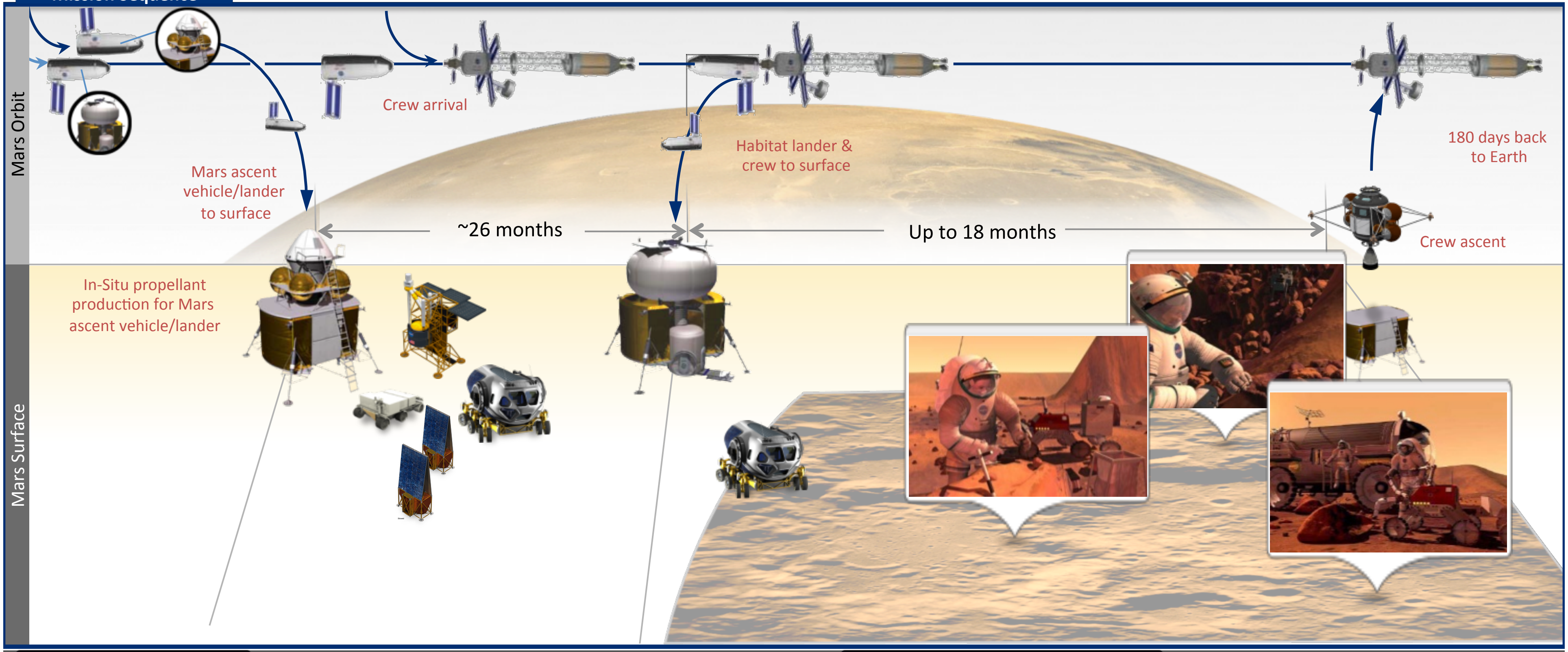


Mission Duration:
- **Transit to: ~180 days**
- **Destination: ~500 days**
- **Transit from: ~180 days**

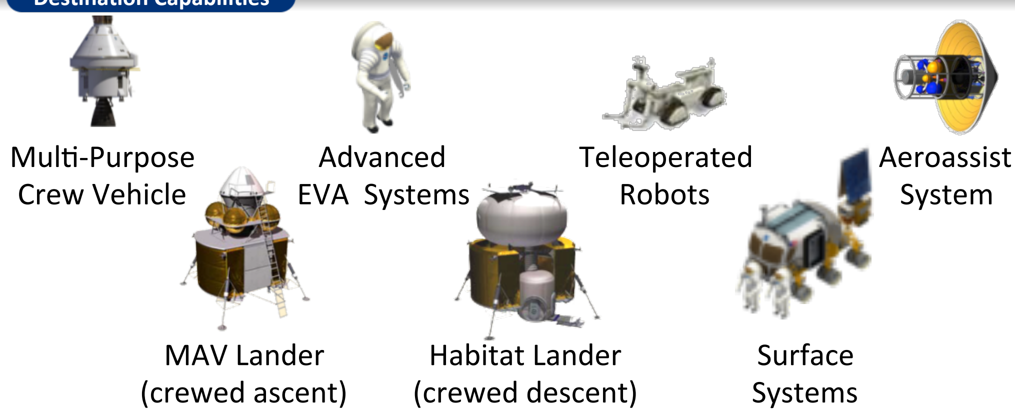
- Orion: Multi-Purpose Crew Vehicle
- SLS: Space Launch System

Example Crewed Mars Surface Mission (DRA 5.0 Derived) - Destination Operations

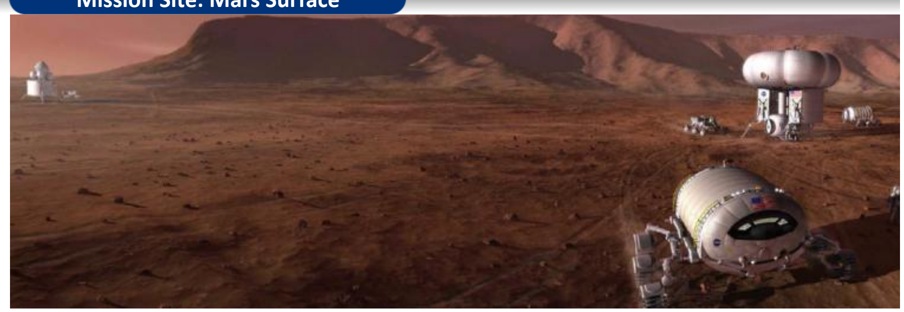
Mission Sequence



Destination Capabilities



Mission Site: Mars Surface



Benefits: Exploration of Mars

Mission Challenging Complexity: Potential Destination Comparisons

	Geostationary Orbit	Earth-Moon Libration	Near-Earth Asteroids	Mars Moons Short Stay	Mars Moons Long Stay	Mars Surface Long Stay
Typical Mission Duration						
In-Space Delta-v (km/s)	5.9	4.8	3.7-9.0+	8.3-14.1	6.6-8.0	6.0-7.1
Descent/Ascent or Vicinity Delta-v (km/s)	-	-	-	1.3-2.6 each	2.4	6.3
Total Mission Duration (days) [3]	10	16	178-365	600-800	900	900
Outbound Time (days) [3]	0.5	4	81-265	~250	180	180
Time at Destination (days) [3]	9	8	8 (tbd)	~60	540	540
Return Time (days) [3]	0.5	4	81-257	~350	180	180
Crew Mission Mode	Zero-g	Zero-g	Zero-g	Artificial-g (?)	Artificial-g (?)	0-3/8-g
Cargo Mode	Split	Split	All-up	Split	Split	Split
Typical Mission Opportunities	Daily	Weekly-Monthly	10-50+ Years	Every 26 Months	Every 26 Months	Every 26 Months
Quick Abort to Earth Availability	Anytime	Anytime	Long	Long	Long	Long
Typical Mission Parameters						
# SLS launches to send crew to destination	1	1	2-3+	3-7	3-7	3-7
# SLS launches for destination cargo	1	1	-	2-3	2-3	4-7+
Approximate total mass in LEO (t)	200	200	200-300	400-900	400-550	600-800
Typical Systems Required						
Orion Multi Purpose Crew Vehicle	✔	✔	✔ ✔	✔ ✔	✔ ✔	✔ ✔
Heavy Lift Launch (Space Launch System)	✔	✔	✔	✔ ✔	✔ ✔	✔ ✔
In-Space Propulsion	✔	✔	✔	✔	✔	✔
Destination Exploration Systems	✔	✔	✔	✔ ✔	✔ ✔	✔ ✔ ✔
Deep-Space Habitat		✔	✔	✔ ✔	✔ ✔	✔ ✔
Planetary Lander						✔
Key Technologies						
Cryogenic Propulsion	✔	✔	✔	✔	✔	✔
Radiation Protection			✔ ✔	✔ ✔	✔ ✔	✔ ✔
Advanced Propulsion (SEP, NEP, NTR)			✔	✔	✔	✔
Near-Zero Boil off Cryogenic Fluid Storage			✔	✔	✔	✔
High-speed Earth Entry			✔	✔ ✔	✔	✔
Life Support System Enhancements			✔	✔	✔	✔
Zero-g Countermeasures			✔	✔ ✔	✔ ✔	✔
In-Situ Resource Utilization						✔
Entry, Descent and Landing						✔
Nuclear Surface Power						✔

Habitation

- **Pressurized habitable element to support crew for the duration of the mission to potential destinations**
  - Cis-lunar missions: 30-180 days in deep space
  - NEA visit – 180-400 days in deep space
  - Mars – 150-210 day deep space transit, 30-500 days on the Martian surface, 150-360 day deep space transit
- **Includes all the functions necessary for extended duration crew support:**
  - Life Support
  - Fire Detection/Suppression
  - Crew Accommodations
  - EVA
  - Thermal Control
  - Avionics
  - Sleep, Galley, Waste Collection, Exercise
  - Workstations
  - Power Generation
  - Radiation Protection
  - Logistics Management
  - Science Support

HABITATION – Technical Challenges

Human Exploration technical challenges are captured in NASA's Human Exploration Architecture Technology Needs Database

	Destination DRMs		
	Cis-Lunar	NEA	Mars Landing
Closed-Loop, High Reliability, Life Support Systems		E	E
High Reliability Life Support Systems		E	E
Deep Space Mission Human Factors and Habitability	e	E	E
In-Flight Environmental Monitoring	e	E	E
Fire Prevention, Detection & Suppression (reduced pressure)		E	e
Space Radiation Protection – Galactic Cosmic Rays (GCR)	E	E	E
Space Radiation Protection – Solar Particle Events (SPE)	E	E	E
Space Radiation Shielding – SPE	E	E	
Inflatable: Structures & Materials for Inflatable Modules		e	E
Lightweight Structures and Materials (HLLV & In-Space Elements)		e	e
Mechanisms for Long Duration, Deep Space Missions		E	E
Low Temperature Mechanisms			e

E = Enabling = technology advancement is required to enable one or more DRMs at this destination

e = enhancing = technology advancement could provide benefits to one or more DRMs at this destination

Habitation Systems Technical Challenges

- **Life Support**
  - Atmosphere Management
  - Fire Safety
  - Environmental Monitoring
  - Water Management
  - Solid Waste Management
- **Life Sciences/HRP**
  - Radiation Exposure Prevention
  - Human SPE Radiation Protection
  - Human GCR Radiation Protection
  - Deep Space Mission Human Factors and Habitability
- **Mechanical Systems**
  - Low Temperature Mechanisms
  - Mechanisms for Long Duration, Deep Space Missions
- **Structures and Materials**
  - Inflatable: Structures & Materials for Inflatable Modules
  - Lightweight and Efficient Structures and Materials

Exploration Atmosphere – Pressure & Oxygen Concentration

NASA Working Group Recommendation:

- **Vehicle pressure and O_2 concentration of 8.2 psia / 34% O_2 for architecture elements involved in high frequency EVA (destination elements, not transit elements)**

Advantages:

- Reduce overhead associated with EVA – shorter prebreathe and less preparation time (currently up to 4 hours, reduced to 15-30 minutes)
- Flexibility to perform short EVAs
- Reduce contamination returned to the spacecraft (suitport/hybrid advantage)
- Reduce consumables

Challenges:

- Less reaction time for leak
- Vehicle materials flammability may limit lower mass material choices
- Less flexibility to use common equipment certified to current parameters
- New 8.2 psi Prebreathe Protocol must be developed
- Long-term physiological effects of exposure to 8.2 psi/34% O2

Pursuing necessary development efforts to enable this option for specific architecture elements:

- Materials flammability testing
- Prebreathe protocol development
- Human physiological research

ECLSS Roadmap & Gap Analysis

- **"Highly reliable ECLSS" was identified as one of the top priorities in the OCT roadmaps. "Closed Loop ECLSS" is also a high priority.**
  - TA06 – Human Health, Life Support, and Habitation Systems
- **In order to pinpoint areas within ECLSS requiring further work, the ECLSS community performed a gap analysis**
  - ECLSS broken into functional areas
  - State of the Art was measured against 3 representative missions which map to all candidate Exploration DRM's
    - 1- Short-duration microgravity or surface (< 1 month)
    - 2 - Long-duration microgravity (1 month – years)
    - 3 - Long-duration surface (1 month – years)
  - Gaps identified in 2 categories
    - "Enabling" – will not be able to perform mission without some improvement or additional capability
    - "Enhancing" – could perform mission with current SoA but improvement would be beneficial
  - Results recently reviewed and adopted by larger international partner ECLSS community. Now being used to guide PPBE planning.

Functional Capability Needs – Atmosphere Management

Function	Need	Mission			
		ISS	1	2	3
CO2 Removal	Robust sorbent bed (improvement, solves SoA dusting)	X		X	X
O2 Supply	Oxygen Generation Assembly reliability improvements	X		X	X
O2 Supply	High pressure oxygen recharge for EVA	X		X	X
Trace Contaminant Control	Replace sorbents and catalysts which are becoming obsolete & performance improvement (enhancing)		X	X	X
Filtration	Surface dust pre-filter				X
Resource Recovery	CO2 reduction beyond Sabatier (possibly enabling depending on trades)	X		X	X
CO2 Removal	Lower power	X		X	X

Enabling **Enhancing**

Functional Capability Needs – Fire Safety

Function	Need	Mission			
		ISS	1	2	3
Fire Suppression	Replacement for Halon & CO_2 PFE (small volume, non-toxic)	X	X	X	X
Atmosphere Recovery	"Smoke Eater" for post-fire cleanup	X	X	X	X
Personal Protective Equip	PPE filtering mask (O_2 mask replacement for small volume O_2 safety)	X	X	X	X
Fire Suppression	Partial-g material flammability testing data				X
Monitoring	Fire combustion products monitor to replace obsolete SoA	X	X	X	X

Functional Capability Needs – Environmental Monitoring

Function	Need	Mission			
		ISS	1	2	3
Atm Monitoring	On-board trace contaminant monitor that doesn't rely on ground sample return	X		X	X
Atm Monitoring	Improved major constituent analyzer	X	X	X	X
Atm Monitoring	Targeted gas (formaldehyde, ammonia) monitor	X	X	X	X
Monitoring	On-board microbial monitor (quantify, speciate) – air, water, surfaces	X		X	X
Water Monitoring	Organic and inorganic species	X		X	X

Functional Capability Needs – Water Management

Function	Need	Mission			
		ISS	1	2	3
Urine processing	Increased water recovery from urine (minimum 85%), reliability improvements	X		X	X
Wastewater processing	Reduce Expendables, extend life	X		X	X
Wastewater processing	Ability to withstand long periods of dormancy			X	X
Laundry	Longer-wear clothing or simple laundry device			?	X
Microbial control	Replacement biocide (silver), method for redosing	X (RS)	X	X	X
Urine processing	Brine processor (recovers last 15% water from urine)			X	X
Urine pretreatment	Lower toxicity pretreat formula	X		X	X

Enabling   Enhancing

Functional Capability needs – Solid Waste Management

Function	Need	Mission			
		ISS	1	2	3
Metabolic waste	Common Compact Commode	X	X	X	X
Stabilization – trash and fecal	Long term stabilization/planetary protection			X	X
Wet trash disposition	Jettison capability (if dumped)			X	
Wet trash – storage & resource recovery	Compaction & dewatering			X	X
Metabolic waste - water recovery	If trades show needed			X	X

Enabling   Enhancing

ECLSS Forward Plan

- **Currently developing detailed plans with budget and schedule to fill gaps**
- **Plans utilize ISS as a testbed to demonstrate highly reliable ECLSS prior to future missions**
- **Involving international partners to see where they may contribute**
- **Timeline:**
  - "Mission 1" needs by Orion 1st crewed flight (2021)
  - All others by ISS end of life; however, some items will extend beyond 2020 for development/flight/2-year demonstration on ISS

Habitation Systems Technical Challenges

- **Life Support**
  - Atmosphere Management
  - Fire Safety
  - Environmental Monitoring
  - Water Management
  - Solid Waste Management
- **Life Sciences/HRP**
  - Radiation Exposure Prevention
  - Human SPE Radiation Protection
  - Human GCR Radiation Protection
  - Deep Space Mission Human Factors and Habitability
- **Mechanical Systems**
  - Low Temperature Mechanisms
  - Mechanisms for Long Duration, Deep Space Missions
- **Structures and Materials**
  - Inflatable: Structures & Materials for Inflatable Modules
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Habitation Systems Technical Challenges
Life Sciences / HRP

- **Description**
  - **Radiation Exposure Prevention**
    - Significant risk to crew, digital equipment, and vehicle systems associated with Solar Particle Events (SPEs).
    - Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR) pose a risk to the health and performance of crew, electronic equipment, and vehicle systems.
    - This technology development area focuses on preventing exposure to radiation. Separate technology development areas focus on mitigating the post-exposure effects on crew and vehicle systems.
    - The first stage of preventing radiation exposure is mission planning, ranging from decades in advance (“space climatology”) to hours or days in advance (“space weather”). The second stage of preventing exposure is shielding in response to the real time radiation environment.
  - **Human SPE Radiation Protection**
    - Exposure to solar particle events (SPEs) creates the risk of Acute Radiation Syndromes during the mission and exacerbates long term health risks (cancer, cardiovascular disease, dementia) after the mission.
    - This technology area focuses on mitigating the effects of SPE exposure on humans. A separate technology area addresses Radiation Exposure Prevention (e.g., SPE forecasting for long term mission planning, SPE warnings and alerts to change real time operations)
    - Radiation protection of the crew requires an overall risk model that calculates health outcomes based on the likelihood of different exposures, shielding options for the crew under different operational scenarios, in-mission dosimetry readings to guide operational planning, and biological countermeasures to mitigate exposures.
  - **Human GCR Radiation Protection**
    - Exposure to Galactic Cosmic Rays (GCR) raises the risk of long term health risks (cancer, cardiovascular disease, dementia) and contributes to the risk of Acute Radiation Syndromes during the mission. GCR is difficult to shield against due to its high energy. An insufficient amount of shielding can actually expose crew to a greater radiation dose than no shielding.
      - Therefore, the primary approaches to protect crew health are to match crew selection with the expected radiation exposure and to provide pharmaceutical and nutritional countermeasures that increase dose tolerance.
      - There are currently no demonstrated pharmaceutical or nutritional countermeasures that increase GCR dose tolerance.
    - The NASA Space Cancer Risk model (NSCR) is used by the agency to estimate the risk to crewmembers of different ages and gender. NSCR estimates of crew risk from GCR radiation exposure with long duration (~>1 year) missions beyond LEO exceed the NASA acceptable career standards for Risk of Exposure Induced Death (REID) for fatal cancers. There are large uncertainties (3-fold ratio between the upper limit of the 95% confidence interval and the median estimate) in the REID estimate.
  - **Deep Space Mission Human Factors and Habitability**
    - Technologies are required in the habitable volumes (e.g., suit, capsule, habitat, exploration vehicle, lander) to provide an adequate food system, and to meet human environmental standards for air, water, and surface contamination.

Life Sciences / HRP *(continued)*

- **Performance Targets**
  - **Radiation Exposure Prevention**
    - Climate models predict GCR levels with TBR accuracy.
    - Climate models predict the frequency and spectrum of SPEs with TBR accuracy.
    - Forecasting/probabilistic models predict 80% (TBR) of SPEs 72 hours (TBR) in advance, and 95% (TBR) of SPEs 1 (TBR) hour in advance.
    - Forecasting/probabilistic models incorrectly predict all-clear periods less than 5% (TBR) of the time.
    - Heliospheric environmental monitoring technology provides accurate alerts for SPEs at least TBR hours before the SPE propagates 1 AU
    - from the sun.
    - Multi-functional SPE shield systems, including shelters, that would limit absorbed doses from a (TBD) SPE to (TBD) mGy.
    - Active miniaturized dosimetry (mass < 100 g (TBR), volume < 50 cm3 (TBR), rechargeable battery with 40 hr (TBR) operating time)
  - **Human SPE Radiation Protection**
    - Satisfy NASA-STD-3001, Volume 1, 4.2.10 Space Permissible Exposure Limit for Space Flight Radiation Exposure Standard
    - SPE risk model includes skin damage, immune system response, microgravity effects, FishBowl Shield Tool
    - Pharmaceutical and nutritional countermeasures that increase SPE dose tolerance (TBD)-fold (TBR).
  - **Human GCR Radiation Protection**
    - Satisfy NASA-STD-3001, Volume 1, 4.2.10 Space Permissible Exposure Limit for Space Flight Radiation Exposure Standard
    - Reduce the uncertainty of NSCR to 50% for Mars surface missions.
    - Pharmaceutical and nutritional countermeasures that increase GCR dose tolerance (TBD)-fold (TBR).
  - **Deep Space Mission Human Factors and Habitability**
    - Reduce packaged food volume (30%) and mass (34%) so that supplies for one crew member for one year require 1.2 m^3 and 440 kg consistent with food shelf-life requirements, especially for long duration missions.
    - Microbial and chemical contamination are identified and measured in real-time with minimal resupply.

Life Sciences / HRP *(continued)*

- ## Applicable DRMs/Destinations, Testing/Development Locations

Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing)			Testing / Development Locations
	Cis-Lunar	NEA	Mars Surface	
Radiation Exposure Prevention	●	●	●	
Human SPE Radiation Protection	●	●	●	Ground-based and flight testing of multi-functional SPE shielding system and of advanced dosimetry/measurement systems.
Human GCR Radiation Protection	●	●	●	**ISS**: Candidate - ISS-NSRL high spatial and temporal resolution particle detectors to allow the NASA Space Radiation Laboratory to reproduce identical chronic exposures of human tissues that are first collected on ISS.
Deep Space Mission Human Factors and Habitability	○	●	●	

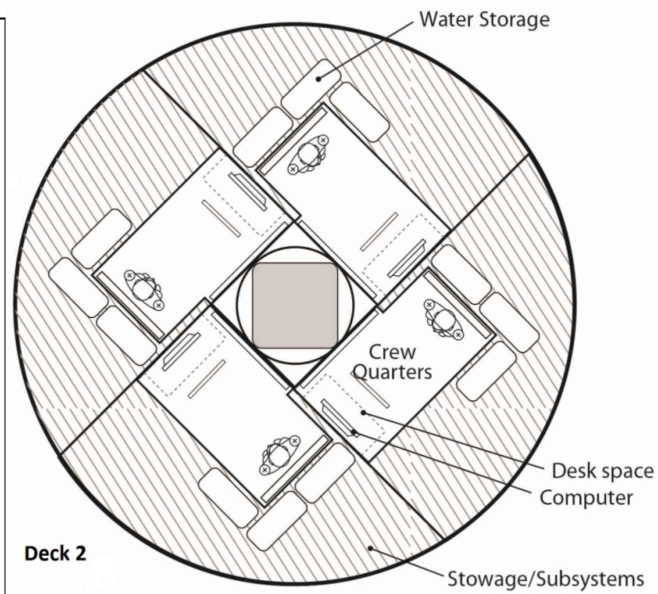
- ## Timeline

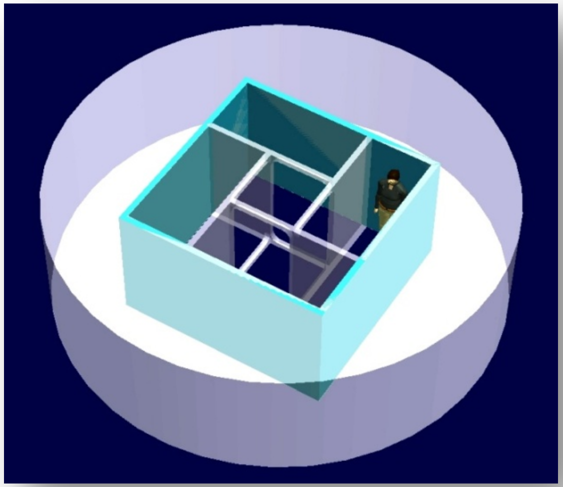
Technology Challenge	Current TRL	Years to TRL 6: 10	5	*TRL 6*
Radiation Exposure Prevention	TRL 3-4	▲		▲
Human SPE Radiation Protection	TRL 2/3 – 6/8	▲		▲
Human GCR Radiation Protection	TRL Various	▲		▲
Deep Space Mission Human Factors and Habitability	TRL 3-8	▲		▲

Note: Current TRL levels comprised of component TRL levels

Habitat Radiation Shielding - Minimizing Crew Radiation Exposure

- **ISSUE:** Crew Radiation Exposure on Long Duration Missions
- **DESIGN CONSIDERATIONS:**
  - Potentially drives materials of construction
  - Ideally place as much equipment as possible between the crew and shell
    - But must be moveable, to access shell for repairs
  - "Water Wall" could increase protection
    - High mass penalty: for example, 10 cm thick water wall around 4 crew quarters requires 2,650 kg of water
  - Other potential solutions
    - Portable, reconfigurable water bags
    - Recycling plastic trash into radiation protection bricks





Habitation Systems Technical Challenges

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Habitation Systems Technical Challenges
Mechanical Systems

- **Description**
  - **Low Temperature Mechanisms**
    - Long life, cryogenic actuators have been identified as a key MSMM (TA-12) technology challenge, and enabling for outer planet and deep space probe missions. Long-life-by-design, modular (for ease of integration) actuators consisting of motors, gearboxes, position/speed sensors, and motor controller electronics will need to be capable of operating in dusty NEO environments at temperatures between 400K and 40K, for years, in order to meet those reliability demands.
  - **Mechanisms for Long Duration, Deep Space Missions**
    - Recent high impact, infant mortality and pre-mature hardware failures aboard the ISS (e.g. SARJ, Urine Processor bearings, Ammonia cooling pump, Canada Arm LEE, etc.) accentuate the need for tribological and mechanical component innovations to enable future HSF missions. Reliable, long-life, mission critical systems such as cooling pumps, circulators and components for Zero-Boil-Off systems, control moment gyros, robotic manipulation hardware, docking/hatch devices and pointing mechanisms must be more resilient and capable than current COTS technology allows. New lubricants, bearing and gear materials and designs are needed to ensure mission success.
    - Emerging lightweight superelastic materials (Nitinol alloys), advanced lubricants (ionic fluids), and novel mechanism designs (low sliding high contact ratio gears) are poised to help avoid mission ending/crippling mechanism failures but must be matured. Such innovations will enable silent, ultra-reliable spacecraft systems such as cabin blower motors and fans, thermal management pumps, etc. Innovative power transfer technologies (magnetic gears), can significantly reduce cabin noise levels enhancing astronaut health and operational efficiency over long duration missions.





- **Performance Targets**
  - **Low Temperature Mechanisms**
    - Current state-of-the-art (SOA) calls for heating to keep liquid lubricated actuators above -55 C to -70 C, with control electronics housed separately in a "warm electronics box" above -55 C. Cryogenic compatible actuator components (lubricants, bearings, gears, position sensor) and control electronics operational to -230 C allow integration of the motor controller with the actuator, greatly enhancing reliability, modularity and scalability. Cryo-compatible actuators / electronics would eliminate the hardware and wiring for heating (with ~30% power savings), and reduce by two orders of magnitude the interconnect cables, resulting in up to 50% reduction in mass of the electronics and electronic housings.
  - **Mechanisms for Long Duration, Deep Space Missions**
    - Mission critical systems (e.g. cooling pumps, circulators, control moment gyros):
      - Current SOA: < 10yr, sustain 6 g loads (designs must be 2X mission life and 2X Shuttle launch load)
      - Goal: >10 yr at + or -50°C from operating temperature sustaining 10 g loads (2X mission life, 2X launch load of 5g's)
      - Bearing and Gear Materials to handle higher loads:
        - » Current SOA: steel
        - » Goal: 15% weight reduction with comparable capability (superelastic materials)

Habitation Systems Technical Challenges

Mechanical Systems *(continued)*

- **Applicable DRMs/Potential Destinations, Testing/Development Locations**

Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing)			Testing / Development Locations
	Cis-Lunar	NEA	Mars Surface	
Low Temperature Mechanisms			○	**Ground Testing:** Extended testing in thermal vacuum. **Robotic Mission:** Demonstrate on surface mission.
Mechanisms for Long Duration, Deep Space Missions		●	●	**ISS**: Durability testing of key mechanism advancements by replacing space station mechanical component, or providing back-up system with new technology.

- **Timeline**

Technology Challenge	Years to TRL 6
	10 — 5 — TRL 6
Low Temperature Mechanisms	Low temperature actuator control electronics, position resolver-TRL 3-4 Low temperature actuators: small (100 W)-TRL 5 ; large (1.5 kW)-TRL 2 TRL 2-5 (year 5) → TRL 6
Mechanisms for Long Duration, Deep Space Missions	TRL 3-4 (year 5) → TRL 6

Habitation Systems Technical Challenges

- **Life Support**
  - Atmosphere Management
  - Fire Safety
  - Environmental Monitoring
  - Water Management
  - Solid Waste Management
- **Life Sciences/HRP**
  - Radiation Exposure Prevention
  - Human SPE Radiation Protection
  - Human GCR Radiation Protection
  - Deep Space Mission Human Factors and Habitability
- **Mechanical Systems**
  - Low Temperature Mechanisms
  - Mechanisms for Long Duration, Deep Space Missions
- **Structures and Materials**
  - Inflatable: Structures & Materials for Inflatable Modules
  - Lightweight and Efficient Structures and Materials

Habitation Systems Technical Challenges

Structures and Materials

- **Description**
  - **Inflatable: Structures & Materials for Inflatable Modules**
    - The primary advantage of inflatable/expandable structures are the readily collapsible walls that reduce stowage volume for the launch package, but provide extra volume for living space when expanded. The resulting mass-to-volume ratio for expandable structures can be lower than that for conventional hard shell structures.
    - The objective is to develop expandable structures technology for application as pressurized elements such as crew habitats, logistics add-ons, and airlocks. The goal is to develop expandable technology for increased deployed-habitable volume for minimal packing volume, with improved confidence in structural and thermal performance in the space environment.
  - **Lightweight and Efficient Structures and Materials**
    - Efficient Structures and Materials that demonstrate significant weight and cost savings for aerospace applications to provide a total systems-based efficiency. This includes multifunctional, lightweight and robust (i.e., inspectable, repairable, damage tolerant, etc.) structures and materials specifically tailored for mission applications.
    - Emerging innovations in manufacturing technology that offer significant improvement over SOA, critical to achieving the destination, performance, and affordability objectives for exploration
    - Design and certification methods to ensure timely introduction of advanced, multifunctional structures and materials into future reliable space systems
      - Damage models for reliability (certification and sustainment)
      - Optimized analysis and test for verification and validation
      - Streamlined design-analysis-certification processes
      - Rapid material properties development

Habitation Systems Technical Challenges

Structures and Materials *(continued)*

- **Performance Targets**
  - **Inflatable: Structures & Materials for Inflatable Modules**
    - Long-term creep performance characterization of the structural shell of the inflatable module (material testing).
      - Determine how these materials (Kevlar & Vectran) perform after being under constant load for many years. This will also influence what Structural Factor of Safety to use.
    - Inflatable Structure Restraint Layer damage tolerance (predictive modeling validated with testing).
      - Determine how to predict the type of damage the restraint layer can withstand and still be structurally sound & human-rated. This is analogous to "leak before burst" and "fracture analysis" for metallic pressure vessels. There is a potential here to significantly increase the state-of-the-art.
    - Multi-layer Insulation performance degradation prediction after folding/deployment (predictive modeling validated with testing).
      - Determine thermal performance of MLI after undergoing folding, launch vibration, and deployment. We must understand the MLI performance so that we can accurately predict the thermal environment of the inflatable through the various mission phases.
    - Bladder material selection.
      - There has never been a full-scale leak test of an inflatable module with the representative bladder material and representative seal interface. The bladder is critical and very sensitive to puncture, tear, folding, handling, flex cracking, brittleness at cold, etc.
    - Bladder-to-metal interface seal.
    - Predictive modeling of deployment dynamics.
  - **Lightweight and Efficient Structures and Materials**
    - Lightweight structures and materials optimization to realize structural system dry mass savings (minimum of 20-25%) and operational cost savings.
    - Multifunctional structures that offer improvements in radiation protection, MMOD shielding, thermal management, structural health management, and system damping benefits over conventional structures. Includes composite and metallic materials.

Materials, Structures, Mechanical Sys. & Mfg (OCT TA 12.1, 12.2)

Habitation Systems Technical Challenges
Structures and Materials *(continued)*

- **Applicable DRMs/Potential Destinations, Testing/Development Locations**

Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing)			Testing / Development Locations
	Cis-Lunar	NEA	Mars Surface	
Inflatable: Structures & Materials for Inflatable Modules		○	●	**ISS**: Candidate - Inflatable module demonstrator in low Earth orbit is feasible, and ultimately desired for proof of deployment. **Ground:** Materials characterization and ground-based testing will more significantly advance the state-of-the-art initially.
Lightweight and Efficient Structures and Materials		○	○	**Ground:** Out-of Autoclave large structures demo/test. **ISS**: In-space manufacturing experiment.

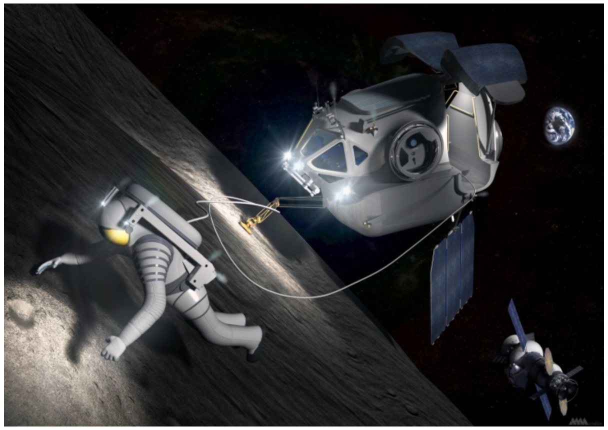
- **Timeline**

Technology Challenge	Years to TRL 6: 10	5	TRL 6
Inflatable: Structures & Materials for Inflatable Modules		TRL 3-5 ▲ (just under 6 years) →	▲
Lightweight and Efficient Structures and Materials		TRL 4-5 ▲ (5 years) →	▲

Materials, Structures, Mechanical Sys. & Mfg (OCT TA 12.1, 12.2)

Destination Systems

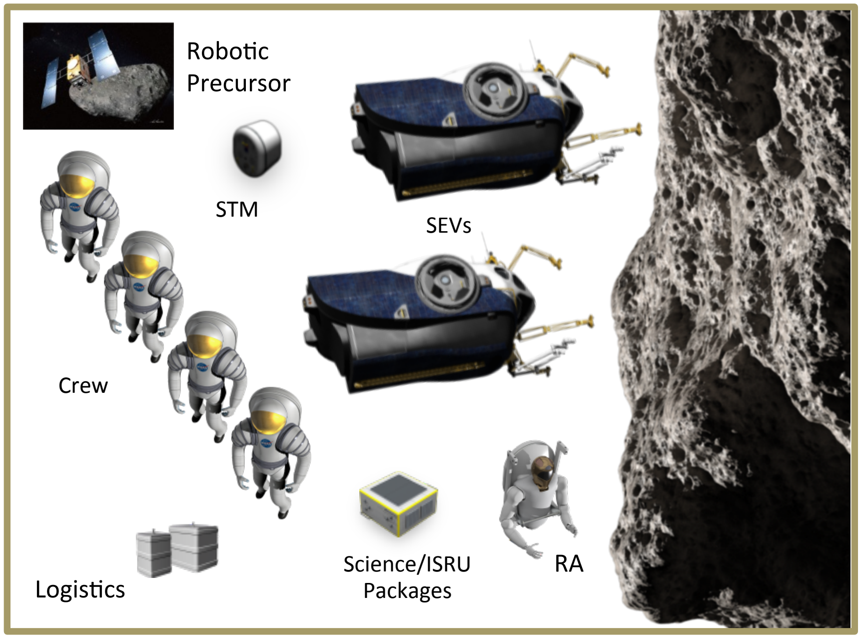
- **Elements and systems needed to support human crews and perform the science and exploration objectives at potential destinations**
  - NEA
  - Mars
- **Includes all the functions necessary for long duration crew support:**
  - Habitation (previous section)
  - Mobility
  - Surface Power
  - In-Situ Resource Utilization
  - (environment-specific systems – dust control, asteroid anchoring, Mars planetary protection)
- **Covered in other presentations:**
  - Landers, communication, navigation, EVA, robotics, thermal, medical and behavioral systems

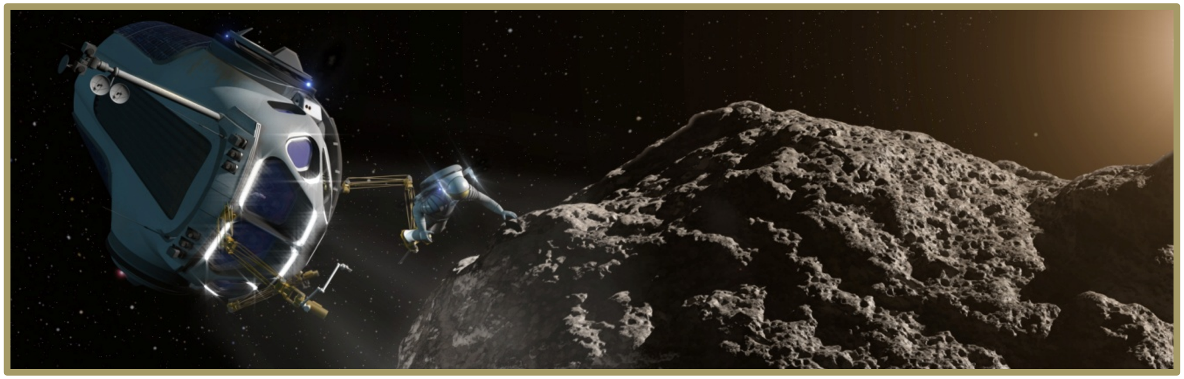


Example Crewed Near-Earth Asteroid Mission - Destination Systems

4-crew with stay time up to 28 days utilizing Space Exploration Vehicles (SEVs) and Robotic Assistant (RA)

Element	QTY	Notes
Robotic Precursor	1	Small robotic precursor sent to human target for proper characterization and engineering evaluation of target, including surface interaction and anchoring techniques. Potential to provide navigation aid and situational awareness during human mission.
Crew	4	International Astronaut Crew
SEV (Space Exploration Vehicle)	2 (TBR)	2 Suitports per SEV TBD kW-hr battery storage & TBD propellant
STM (Suitport Transfer Module)	1	Allows transfer of asteroid samples and equipment through a suitport
Logistics	TBD	Logistics required for up to 28 days (in addition to logistics for the outbound and inbound segments)
Robotic Assistant	1 (TBR)	Small NASA Robotic Assistant
Science/ISRU Packages	TBD	Science and In-Situ Resource Utilization (ISRU) packages deployed by crew during mission

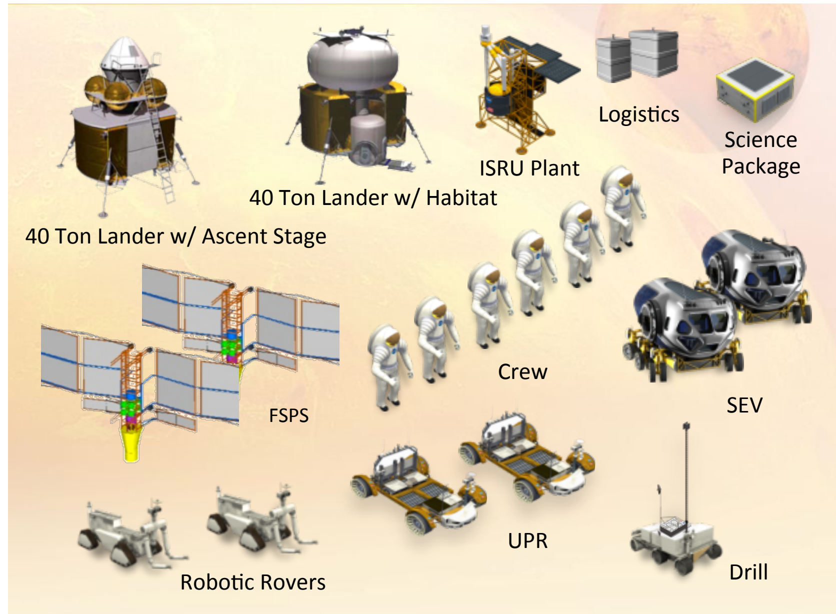




Example Crewed Mars Surface Mission (NASA DRA 5.0) -Destination Systems

DRA 5.0 describes three 18-month surface missions, each with a crew of six exploring a separate location on Mars

Element	QTY	Notes
Crew	6	International Astronaut Crew
40 Ton (payload) Lander	2	• Methane/Oxygen propellant • Carries mixed payloads to surface • Capable of precision landing
Mars Ascent Vehicle	1	• Methane/Oxygen propellant • Two stage vehicle
Mars Surface Habitat	1	• Inflatable structure
Space Exploration Vehicle (SEV)	2	• Average speed toward destination = 5 km/hr • Range of 100+ km • 2-crew for one week
Unpressurized Rover (UPR)	2	Provides short range excursion capability near lander
Fission Surface power System (FSPS)	2	• 40 Kw (electric) capability • Primary and backup systems
Robotic Rover	2	• One rover used to assist crew • One rover remains "sterile" for astrobiology tasks
Science Package	1	One ton of mass allocated for a mixture of science activities
Drill	1	Capable of reaching several 100 meters depth
PUP (Portable Utility Pallet)	2	Transported with SEVs Recharge SEV primary power storage



Element	QT(Y	Notes
ISRU Plant	1	Makes liquid oxygen from mars atmosphere to be used for ascent propellant
Logistics and Spares	1	Crew consumables for surface mission plus spare parts for major systems

DESTINATION SYSTEMS - Technical Challenges

HAT Technology Development Entry (Title)	Destination DRMs		
	Cis-Lunar	NEA	Mars Landing
High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays		e	
Fission Power for Surface Missions			E
Regenerative Fuel Cell		e	e
Long Life Battery		e	e
Autonomous Vehicle Systems Management	E	E	E
Crew Autonomy beyond LEO	E	E	E
In-Situ Resource Utilization (ISRU) - Mars: O2 from Atmosphere & Water from Soil		e	E
Surface Mobility		E	E
Mission Control Automation beyond LEO	E	E	E
Dust Mitigation		E	e

E = Enabling = technology advancement is required to enable one or more DRM at this destination

e = enhancing = technology advancement could provide benefits to one or more DRM at this destination

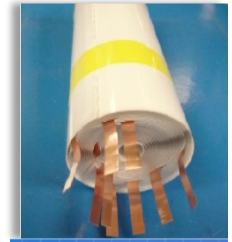
Destination Systems Technical Challenges

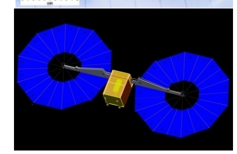
- **Power Systems**
  - High Strength / Stiffness Deployable 10-100 kW Class Solar Arrays
  - Fission Power for Surface Missions
  - Long Life Batteries
  - Regenerative Fuel Cells
- **ISRU**
  - In-Situ Resource Utilization (ISRU) - Mars: Oxygen from Atmosphere & Water Extraction from Soil
- **Robotics and Mobility**
  - Surface Mobility
- **Space Environment**
  - Dust Mitigation
- **Avionics and Software**
  - Autonomous Vehicle Management
  - Crew Autonomy Beyond LEO
  - Mission Control Automation Beyond LEO

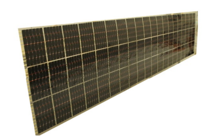
Destination Systems Technical Challenges

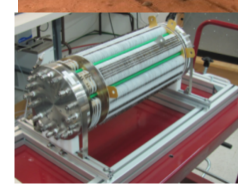
Power Systems

- **Description**
  - **High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays**
    - High power, high voltage, autonomously deployable surface solar arrays for partial gravity environments
    - In-space operations during low-g accelerations under propulsion (0.1g)
    - Enabling features include compact stowage, reliable deployment in partial gravity, on an irregular surface & dusty environment, Martian wind load strength, EVA compatibility, dust mitigation to limit photovoltaic power degradation and robust to surface arcing environment (Martian surface triboelectric charging).
    - Solar array panels would employ low mass, flexible panel substrates populated with advanced photovoltaic cells, like inverted metamorphic (IMM) triple junction solar cells, with bandgap tuning for the Martian surface solar spectrum substrates.
    - Would power both outpost surface elements (e.g. habs/labs, rovers, ISRU, lander/ascent stages, etc.) and in-flight space elements (e.g. CPS, DSH)
  - **Fission Power for Surface Missions**
    - Abundant power for surface missions is enabled by a surface-emplaced fission reactor
  - **Long Life Batteries**
    - Long life and low temperature survivable batteries will enable night survival & operations.
  - **Regenerative Fuel Cells**
    - RFC system includes a fuel cell and an electrolyzer, each of which can be used independently for power/water generation and H2/O2 generation, respectively. Electrical power can be used for any vehicle. Water and O2 can be used for life support for crewed vehicles. Also applicable to ISRU.
    - Technology development includes reducing the number of ancillary components to increase reliability and operational lifetime, and reduce parasitic power losses, mass, and volume.









Destination Systems Technical Challenges

Power Systems *(continued)*

- **Performance Targets**
  - **High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays**
    - High power (10-100 kW),
    - High voltage (< ~200 V)
    - Autonomously deployable surface solar arrays in partial gravity environments
    - Operational under low-g propulsion accelerations (0.1 g)
  - **Fission Power for Surface Missions**
    - 40 kWe Fission Power System (reactor, power conversion, heat rejection, PMAD)
    - 900 K reactor, 10 kWe Stirling convertors, 400 K radiators, 400 V PMAD
    - 150 kg/kWe for surface missions
  - **Long Life Batteries**
    - Battery-level specific energy > 220 Wh/kg and energy density> 410 Wh/liter at a C/10 discharge rate
  - **Regenerative Fuel Cells**
    - Power generation > 10 kWe for 8 hours or more
    - Operable with reactants at > 2000 psi to reduce tank volume
    - Round trip energy conversion efficiency > 50%
    - Minimize mass
    - Operational life > 10,000 hours

Destination Systems Technical Challenges

Power Systems *(continued)*

- **Applicable DRMs/Potential Destinations, Testing/Development Locations**

Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing)			Testing/Development Locations
	Cis-Lunar	NEA	Mars Surface	
High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays		○		**Ground:** Solar array wing deployment test **ISS:** Proposed demonstration for 300-kW class solar arrays would be scaled down and could be applicable to this size class.
Fission Power for Surface Missions			●	**Ground**: Non-nuclear system level demo in relevant environment
Long Life Batteries		○	○	**Ground Testing:** Including lifetime testing and low-temperature testing
Regenerative Fuel Cells		○	○	**Ground Testing:** Including lifetime testing **ISS:** Potential demonstration, highly beneficial to ensure systems operation in microgravity

- **Timeline**

Technology Challenge	Years to TRL 6: 10	5	*TRL 6*
High Strength/Stiffness Deployable 10-100 kW Class Solar Arrays			TRL 3
Fission Power for Surface Missions			TRL 4-5
Long Life Batteries			TRL 3-4
Regenerative Fuel Cells		TRL 2-3 Regenerative Fuel Cell 5 Primary Fuel Cell 3 Electrolyzer	TRL 2-5

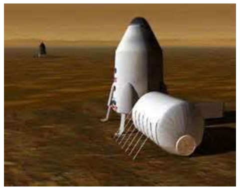
Destination Systems Technical Challenges

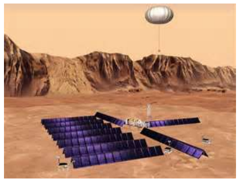
- **Power Systems**
  - Long Life Batteries
  - High Strength / Stiffness Deployable 10-100 kW Class Solar Arrays
  - Fission Power for Surface Missions
  - Regenerative Fuel Cells
- **ISRU**
  - In-Situ Resource Utilization (ISRU) - Mars: Oxygen from Atmosphere & Water Extraction from Soil
- **Robotics and Mobility**
  - Surface Mobility
- **Space Environment**
  - Dust Mitigation
- **Avionics and Software**
  - Autonomous Vehicle Management
  - Crew Autonomy Beyond LEO
  - Mission Control Automation Beyond LEO

In Situ Resource Utilization (ISRU)

- **Description**
  - **Mars: Oxygen from Atmosphere & Water Extraction from Soil**
    - Products and processes include:
      - Oxygen production from Mars atmosphere CO_2
      - Oxygen and fuel production from Mars soil water and atmosphere CO_2

- **Performance Targets**
  - **Mars: Oxygen from Atmosphere & Water Extraction from Soil**
    - Atmospheric CO_2 Processing; 3.5 kg O_2/hr & 1 kg CH_4/hr (option), 24 hr/day, 300 days. < 7 KWe/kg O_2 produced.
    - (Option) Water Extraction From Soil: 2 kg H_2O/hr, 24 hr/day, 300 days. ~40 kg soil/hr excavation and processing. < 15 Kwe/kg water extracted.





In Situ Resource Utilization (ISRU) *(continued)*

- **Applicable DRMs/Destinations, Testing/Development Locations**

Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing)			Testing / Development Locations
	Cis-Lunar	NEA	Mars Surface	
Mars: Oxygen from Atmosphere & Water Extraction from Soil		○	●	**Robotic**: Candidate - 2012 Integrated System Demo– atmosphere, soil processing and system components Candidate - 2018 Mars ISRU demo on NASA or SpaceX ("Red Dragon") Mars lander mission **Analog**: Candidate - 2014 Analog field demo– Mars Sample Return scale autonomous demo

- **Timeline**

Technology Challenge	Years to TRL 6 (10 … 5 … *TRL 6*)
Mars: Oxygen from Atmosphere & Water Extraction from Soil	TRL 3-6 → TRL 6 Mars DRM 5.0: ISRU plant produced all necessary oxygen for an ascent vehicle and consumables for ECLS system, consisting of water, oxygen and inert gases (nitrogen and argon, byproducts of the Mars atmosphere).

Destination Systems Technical Challenges

- **Power Systems**
  - Long Life Batteries
  - High Strength / Stiffness Deployable 10-100 kW Class Solar Arrays
  - Fission Power for Surface Missions
  - Regenerative Fuel Cells
- **ISRU**
  - In-Situ Resource Utilization (ISRU) - Mars: Oxygen from Atmosphere & Water Extraction from Soil
- **Robotics and Mobility**
  - Surface Mobility
- **Space Environment**
  - Dust Mitigation
- **Avionics and Software**
  - Autonomous Vehicle Management
  - Crew Autonomy Beyond LEO
  - Mission Control Automation Beyond LEO

Destination Systems Technical Challenges

Robotics and Mobility

- **Description**
  - **Surface Mobility**
    - Examples include roving, climbing, crawling, hopping or burrowing into the surface.
    - Systems for moving cargo include prepositioning cargo for future human use, or repositioning payloads for re-use.
    - Instruments can be pointed by mobility systems, or pushed into contact for data collection, approaching simple manipulation by using the mobility system's transport mechanisms.
    - Crew mobility aids expand crew range, speed and payload capacity while also providing power, habitation and environmental shelter.
- **Performance Targets**
  - **Surface Mobility**
    - Mars Surface
      - Pressurized cabin supporting crew of 2(nominal) and 4(contingency) for sortie durations of up to 10 days between resupply.
      - Range of approximately 200 km radial distance from landing site.

Destination Systems Technical Challenges

Robotics and Mobility *(continued)*

- **Applicable DRMs/Potential Destinations, Testing/Development Locations**

Technology Challenge	Applicable DRMs / Destinations ● Enabling ○ Enhancing			Testing/Development Locations
	Cis-Lunar	NEA	Mars Surface	
Surface Mobility		●	●	

- **Timeline**

Technology Challenge	Years to TRL 6: 10	5	TRL 6
Surface Mobility		TRL 3-5 ▲	▲

Destination Systems Technical Challenges

- **Power Systems**
  - Long Life Batteries
  - High Strength / Stiffness Deployable 10-100 kW Class Solar Arrays
  - Fission Power for Surface Missions
  - Regenerative Fuel Cells
- **ISRU**
  - In-Situ Resource Utilization (ISRU) - Mars: Oxygen from Atmosphere & Water Extraction from Soil
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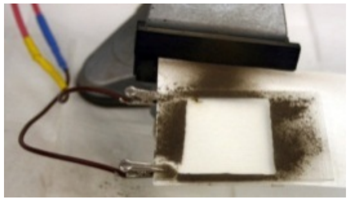
- **Space Environment**
  - Dust Mitigation
- **Avionics and Software**
  - Autonomous Vehicle Management
  - Crew Autonomy Beyond LEO
  - Mission Control Automation Beyond LEO

Space Environment

- **Description**
  - **Dust Mitigation**
    - There is a risk of regolith induced system degradation. The NEO environment may include suspended "clouds" of particulates, and is in any case an unknown. Particulate mitigation will be accomplished by:
      - Identification of NEO soil contamination issues for mechanisms and thermal systems.
      - Investigate specific risk mitigation technologies (e.g. seals) applicable to NEO missions. Develop technologies to limit regolith contamination, or mitigate its effects.
      - In a relevant environment, integrate and test mechanical component-level technologies to TRL 6.
    - Required for both robotic and human missions, NEO, Phobos/Deimos, and Mars destinations. NEO simulants are required to develop tools for anchoring, sample acquisition, etc., and Mars simulants are needed to develop ISRU technology.
    - Regolith dust self cleaning radiators needed for surface operations.
    - Active dust removal technology (SPARCLED) can also be used to acquire small-sized samples from NEOs or dust-sized samples from reduced-gravity bodies.
- **Performance Targets**
  - **Dust Mitigation**
    - Mitigation technologies must:
    - - maintain the solar absorptivity of a dust contaminated radiator surface within +20% of the pristine surface value, and
    - - provide negligible dynamic seal wear to 2 million cycles (approx. 6 month life) or 20 million cycles for a 5 year life.



Destination Systems Technical Challenges

Space Environment *(continued)*

- **Applicable DRMs/Potential Destinations, Testing/Development Locations**

Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing)			Testing/Development Locations
	Cis-Lunar	NEA	Mars Surface	
Dust Mitigation		●	○	**ISS**: Potential- Electrodynamic dust shield (EDS) submitted as a funded MISSE-X experiment; on core experiments list. **Robotic Mission:** Dust/Regolith surface system-degradation characterization on robotic mission.

- **Timeline**

Technology Challenge	Years to TRL 6			
		10	5	TRL 6
Dust Mitigation			TRL 1-2 & 3-4	TRL level dependent on specific mitigation technology

Destination Systems Technical Challenges

- **Power Systems**
  - Long Life Batteries
  - High Strength / Stiffness Deployable 10-100 kW Class Solar Arrays
  - Fission Power for Surface Missions
  - Regenerative Fuel Cells
- **ISRU**
  - In-Situ Resource Utilization (ISRU) - Mars: Oxygen from Atmosphere & Water Extraction from Soil
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  - Dust Mitigation
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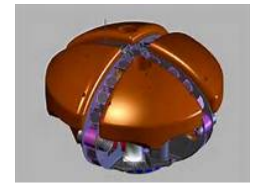
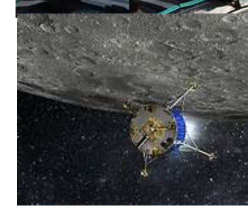
  - Autonomous Vehicle Management
  - Crew Autonomy Beyond LEO
  - Mission Control Automation Beyond LEO

Avionics and Software





- **Description**
  - **Autonomous Vehicle Systems Management**
    - Enables autonomous vehicle management with limited crew effort and little to no ground oversight.
    - Required to ensure safe vehicle operations and monitoring of complex systems, especially at increased distances from Earth where communications time delays are present.
  - **Crew Autonomy beyond LEO**
    - Systems and Tools to provide the crew with independence from earth-based ground operations support (planning, commanding, fault recovery, maintenance) in Beyond LEO missions
  - **Mission Control Automation beyond LEO**
    - Support problem solving activities during remote or long-duration exploration missions, where reliance on mission control is critical and dependent upon minimum reaction time; needed to reduce operations costs and to maximize mission safety with Earth-based operators.

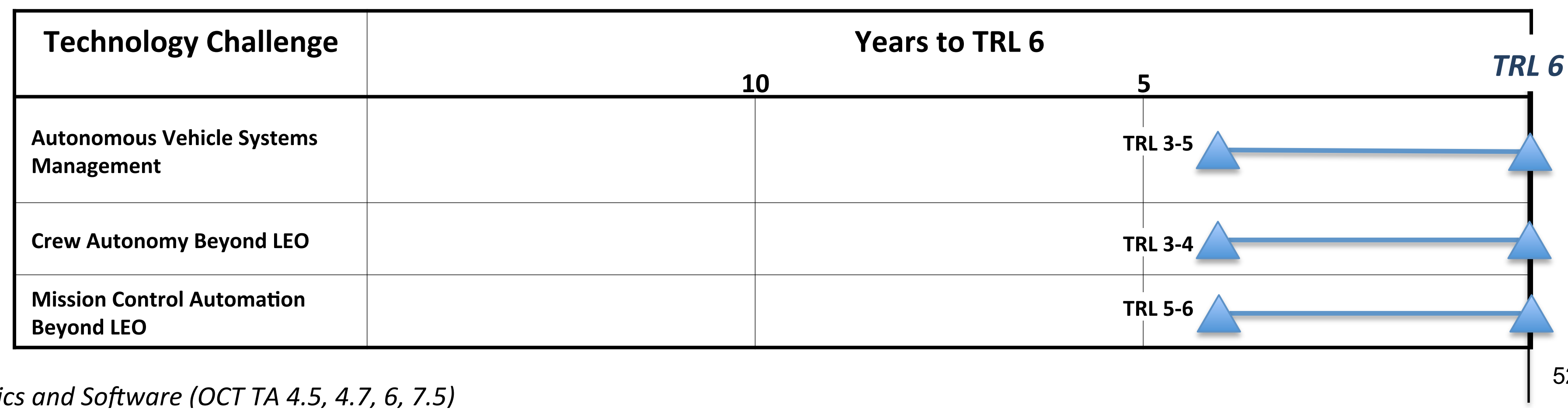
- **Performance Targets**
  - **Autonomous Vehicle Systems Management**
    - Enable autonomous nominal operation and Fault Detection, Isolation, and Recovery (FDIR).
    - Reduce on-board crew time to sustain and manage vehicle by a factor of 2x at destinations with > 6 second time delay.
  - **Crew Autonomy beyond LEO**
    - Enable crew nominal operation of vehicle or habitat at destinations with > 6 second time delay to Earth.
  - **Mission Control Automation beyond LEO**
    - Enable Earth-based nominal operation of vehicle or habitat at destinations with > 6 second round-trip time delay to Earth.
    - Enable hand-offs in Mission Ops between ground and crew for operations in transit and at destinations with > 6 second round-trip time delay.

Avionics and Software *(continued)*

- **Applicable DRMs/Destinations, Testing/Development Locations**

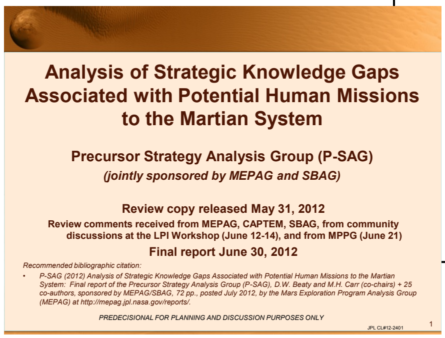
Technology Challenge	Applicable DRMs / Destinations (● Enabling ○ Enhancing) Cis-Lunar	NEA	Mars Surface	Testing/Development Locations
Autonomous Vehicle Systems Management	●	●	●	**Ground:** Mission Control Center - Analog simulations of FDIR for off-nominal operations. **ISS**: ECLSS system management demonstration, including off-nominal operations and fault detection, isolation, and recovery/re-planning of critical functions and activities.
Crew Autonomy Beyond LEO	●	●	●	**ISS**: Potential - ISTAR ISS DTO Procedure execution Increment 31-32 Potential - ISTAR ISS DTO Crew Countermeasures Increment 31-32(?) Candidate - ISTAR ISS DTO Crew Self Scheduling; Increment 33-34 Candidate - ISTAR ISS DTO Autonomous Mission Operations TBD
Mission Control Automation Beyond LEO	●	●	●	**Ground:** Mission Control Center simulation of time-delayed nominal ops. Analog simulations of off-nominal operations. **ISS**: Potential - ISS DTO Procedure execution Increment 31-32, 32-34 Candidate - ISS DTO Procedure execution TBD (2014)

- **Timeline**



Destination Strategic Knowledge Gaps

- To inform mission/system planning and design *and* near-term Agency investments, NASA teams have captured gaps in both technical capabilities and destination data sets in a “Strategic Knowledge Gap” (SKG) master spreadsheet
- Significant advances in filling the knowledge gaps has been made (examples: MRO and MSL)
- NASA’s initial cut at Strategic Knowledge Gaps have been further refined by external assessment groups representing human space exploration destinations
- Additional refinement has been performed in conjunction with NASA’s international partners


Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System

Precursor Strategy Analysis Group (P-SAG)

(jointly sponsored by MEPAG and SBAG)

Review copy released May 31, 2012

Review comments received from MEPAG, CAPTEM, SBAG, from community discussions at the LPI Workshop (June 12-14), and from MPPG (June 21)

Final report June 30, 2012

Recommended bibliographic citation:

- *P-SAG (2012) Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System: Final report of the Precursor Strategy Analysis Group (P-SAG), D.W. Beaty and M.H. Carr (co-chairs) + 25 co-authors, sponsored by MEPAG/SBAG, 72 pp., posted July 2012, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/.*

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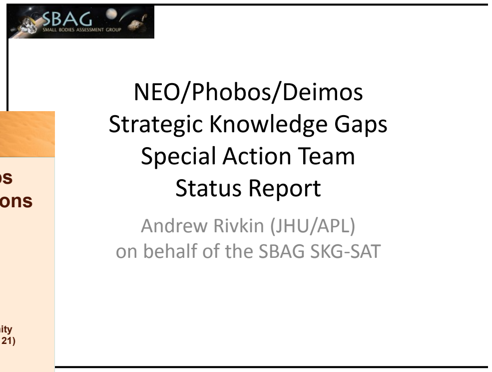
JPL CL#12-2401 1



NEO/Phobos/Deimos Strategic Knowledge Gaps Special Action Team Status Report

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Strategic Knowledge Gaps Common Themes

- **Strategic Knowledge Gaps often combine gaps in knowledge of destinations (environments, surface characteristics) and gaps in technology**
  - Technology “gaps” were covered in Technical Challenges section of this presentation

- **There are common themes across destinations (not in priority order)**
  - The three R’s for enabling human missions
    - Radiation
    - Regolith
    - Reliability
  - Geotechnical properties
  - Volatiles (i.e., for science, resources, and safety)
  - Propulsion-induced ejecta
  - In-Situ Resource Utilization (ISRU)/Prospecting
  - Operations/Operability
  - Plasma Environment
  - Human health and performance

NEA Strategic Knowledge Gaps - 1

Strategic Knowledge Gap	Description	Relevant Location/Context	Crew Safety Risk if GAP not Filled	Mission Risk if GAP not Filled
Human Health/Mission Constraints	Determine acceptable radiation exposure, microgravity effects, and mission duration constraints for crews exploring Small Bodies	Earth-based research ISS testing Robotic Missions	High	High
NEO Orbit Distribution	Identify long-synodic period NEOs having multiple mission opportunities to improve the number of exploration targets available at any given opportunity	Earth-based observation Space-based observation	High	High
NEO Composition/Physical Characteristics	Determine NEO size frequency and distribution, albedo and rotation state in order to assess targets for exploration missions	Earth-based observation Space-based observation Robotic Missions	High	High
NEO Water Resources	Remotely identify water-rich NEOs; develop techniques to excavate/collect NEO material to be processed; develop methods to refine and store resources in zero-g	Research & Analysis Earth-based Testing Iss Testing Robotic Missions	Low	Low
Phobos/Deimos Water Resources	For Phobos/Deimos missions, measure the subsurface resource potential, develop techniques to access resource material at depth, test storage and transfer of extracted water and resources.	Research & Analysis Earth-based testing ISS testing Robotic Missions	Low	Low

NEA Strategic Knowledge Gaps - 2

Strategic Knowledge Gap	Description	Relevant Location/Context	Crew Safety Risk if GAP not Filled	Mission Risk if GAP not Filled
Particulate Environment in the Proximity of Small Bodies	Measure size-frequency and velocity distributions of IDPs as a function of NEO orbit and time of year; model expected dust environment due to ejecta from micrometeoroid impacts and the population of a dust torus around the Phobos/Deimos orbits from micrometeoroid impacts and material ejected from Mars; model and measure the dust environment in the asteroid exosphere due to charged particle levitation following surface disturbances.	Research & Analysis Robotic Missions	Medium	Medium
Small Body radiation environment	Understand the ionizing radiation environment at Small Body surfaces, including contributions from secondary charged particles and neutrons produced in the regolith.	Robotic Missions Research & Analysis	High	High
Mitigation Strategies to Preserve Human Health	Utilize Small Bodies as shields against solar proton events	Research & Analysis Robotic Missions	Low	Low
Local and global stability of small bodies	Global and local Small Body structural stability based on remote measurements	Robotic Missions	High	High
Biohazards & Mitigation	Biological effects of SB surface dust.	Research & Analysis Robotic Missions	High	Medium
Hazards to equipment and mitigation	Mechanical/electrical effects of SB surface dust.	Research & Analysis Robotic Missions	High	High

NEA Strategic Knowledge Gaps - 3

Strategic Knowledge Gap	Description	Relevant Location/Context	Crew Safety Risk if GAP not Filled	Mission Risk if GAP not Filled
Small Body Surface Mechanical Properties	Macro-porosity of Small Body interior, mechanical strength of Small Body interior materials.	Robotic Missions	High	High
Mobility around and interaction with Small Body surface in Microgravity conditions	Anchoring for tethered activities, non-contact close proximity operations for detailed surface exploration and surveys	Research and Analysis Earth-based technology development ISS testing	High	High
Habitat Expansion Options	Expanding habitat volume to SB interior for shielding and human factors	Earth-based technology development ISS testing	Low	Low

Mars Strategic Knowledge Gaps - 1

Strategic Knowledge Gap	Description	Relevant Location/Context	Crew Safety Risk if GAP not Filled	Mission Risk if GAP not Filled
Upper Atmosphere.	The current Martian atmospheric observations (density, pressure, temperature, aerosols and dynamics) have significant limitations for supporting aerocapture and aerobraking design, especially for human-scale missions.	Mars orbit	Low	Medium
Atmospheric Modeling.	The atmospheric models for Mars have not been well validated due to a lack of sufficient observational data, and thus our confidence in them (for use in mission engineering) is significantly limited.	Research and Analysis	High	High
Orbital Particulates.	We have insufficient information about the orbital particulate environment in high-Mars orbit that may impact the delivery of cargo and crew to the Martian system.	Mars Orbit	Low	Low
Lower Atmosphere	We do not have sufficient martian atmospheric observations to confidently model winds, which significantly affect EDL design, or atmospheric electricity, in the forms of electric fields and conductivity, to understand the risks to ascent vehicles, ground systems, and human explorers.	Mars Orbit Mars EDL Mars Surface	High	High
Back Contamination to Earth	We do not know whether the Martian environments to be contacted by humans are free, to within acceptable risk standards, of biohazards that might have adverse effects on some aspect of the Earth's biosphere if uncontained Martian material were returned to Earth.	Research and Analysis Mars Surface Sample Return	High	High

Mars Strategic Knowledge Gaps - 2

Strategic Knowledge Gap	Description	Relevant Location/Context	Crew Safety Risk if GAP not Filled	Mission Risk if GAP not Filled
Crew Health & Performance: GCRs, Neutrons and energetic particles, radiation shielding, dust toxicity	We do not understand in sufficient detail the factors affecting crew health and performance, specifically including the biological effects of the radiation environment at the martian surface and the potential toxic properties of the martian dust.	Deep Space/Mars Orbit Mars Surface Sample Return	High	High
Dust Effects on Engineered Systems	Physical, chemical, mineralogical and electrical properties of the Martian dust	Mars Surface Sample Return	Low	Medium
Forward Contamination to Mars	Predict with sufficient confidence the potential consequences of the delivery and subsequent dispersal of a large bioload associated with a future human mission to the martian surface.	Earth-based Testing Mars Surface Sample Return	Low	Low
Atmospheric ISRU	Understand in sufficient detail the properties of atmospheric constituents near the surface to determine the adverse effects on ISRU atmospheric processing system life and performance within acceptable risk for human missions.	Mars Surface Mars Sample Return	Low	High
Landing Site and Hazards	Certified to be safe for human landing, and for which we understand the type and location of hazards that could affect the ability to safely carry out mobile surface operations	Mars Orbit Mars Surface Mars Sample Return	High	High

Mars Strategic Knowledge Gaps - 3

Strategic Knowledge Gap	Description	Relevant Location/Context	Crew Safety Risk if GAP not Filled	Mission Risk if GAP not Filled
Phobos/Deimos surface science	For missions targeted to Mars' moons, understand the geological, compositional, and geophysical properties of Phobos and Deimos in order to design focused human-based scientific investigations and engineering activities with precise objectives.	Phobos and/or Deimos rendezvous and lander	Low	Medium
Phobos/Deimos surface Operations	For missions targeted to Mars' moons, understand how to perform close proximity and surface interactions (docking/anchoring/mobility) in the conditions present near/at the surface of the martian satellites (low gravity/loose regolith/significant temperature variations/etc.) in order to implement human-based scientific investigations and engineering activities	Phobos and/or Deimos rendezvous and lander	Low	Medium
Technology: Phobos/Deimos.	We do not have the technologies required to perform close proximity and surface interactions in the conditions present near/at the surface of the martian satellites in order to safely and efficiently implement human-based scientific investigations and engineering activities.		Low	Medium
Mars Resources	Understand if resources (most importantly water, but also other useful material) on Mars or its moons occurs in a location/form that could influence the high-level architecture of the missions/infrastructure associated with a sustained human presence in the martian system	Mars Surface Mars Sample Return	Low	Low

Integrated Schedule Development

- **As technical challenges are resolved, new technology solutions can be incorporated into spacecraft design at PDR if TRL 6 or greater**
- **Many new technologies require substantial testing (Earth-based and space based) to achieve the confidence needed to incorporate them into a mission-critical human flight system**
- **Some data gaps may need to be filled in order to begin flight system design (e.g., choice of an asteroid target, planetary surface characteristics)**
- **Other data gaps can be incorporated later in the design process (e.g., narrowing a landing site)**