Preparing for Mars: Evolvable Mars Campaign "Proving Ground" Approach

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***Abstract*—As the National Aeronautics and Space Administration (NASA) prepares to extend human presence beyond Low Earth Orbit, we are in the early stages of planning missions within the framework of an Evolvable Mars Campaign. Initial missions would be conducted in near-Earth cis-lunar space and would eventually culminate in extended duration crewed missions on the surface of Mars. To enable such exploration missions, critical technologies and capabilities must be identified, developed, and tested. NASA has followed a principled approach to identify critical capabilities and a "Proving Ground" approach is emerging to address testing needs. The Proving Ground is a period subsequent to current International Space Station activities wherein exploration-enabling capabilities and technologies are developed and the foundation is laid for sustained human presence in space. The Proving Ground domain essentially includes missions beyond Low Earth Orbit that will provide increasing mission capability while reducing technical risks. Proving Ground missions also provide valuable experience with deep space operations and support the transition from "Earth-dependence" to "Earth-independence" required for sustainable space exploration.**

A Technology Development Assessment Team identified a suite of critical technologies needed to support the cadence of exploration missions. Discussions among mission planners, vehicle developers, subject-matter-experts, and technologists were used to identify a minimum but sufficient set of required technologies and capabilities. Within System Maturation Teams, known challenges were identified and expressed as specific performance gaps in critical capabilities, which were then refined and activities required to close these critical gaps were identified. Analysis was performed to identify test and demonstration opportunities for critical technical capabilities across the Proving Ground spectrum of missions. This suite of critical capabilities is expected to provide the foundation required to enable a variety of possible destinations and missions consistent with the Evolvable Mars Campaign..

The International Space Station will be used to the greatest extent possible for exploration capability and technology development. Beyond this, NASA is evaluating a number of options for Proving Ground missions. An "Asteroid Redirect Mission" will demonstrate needed capabilities (e.g., Solar Electric Propulsion) and transportation systems for the crew (i.e., Space Launch System and Orion) and for cargo (i.e., Asteroid Redirect Vehicle). The Mars 2020 mission and follow-on robotic precursor missions will gather Mars surface environment information and will mature technologies. NASA is considering emplacing a small pressurized module in cis-lunar space to support crewed operations of increasing duration and to serve as a platform for critical exploration capabilities testing (e.g., radiation mitigation; extended duration deep space habitation). In addition, "opportunistic mission operations" could demonstrate capabilities not on the Mars critical path that may, nonetheless, enhance exploration operations (e.g., teleoperations, crew assisted Mars sample return). The Proving Ground may also include "pathfinder" missions to test and demonstrate specific capabilities at Mars (e.g., entry, descent, and landing).

This paper describes the (1) process used to conduct an architecture-driven technology development assessment, (2) exploration mission critical and supporting capabilities, and (3) approach for addressing test and demonstration opportunities encompassing the spectrum of flight elements and destinations consistent with the Evolvable Mars Campaign.

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1. INTRODUCTION

On April 15, 2010, in a speech at the National Aeronautics and Space Administration's (NASA) Kennedy Space Center (KSC) [1], President Obama stated, "*Fifty years after the creation of NASA, our goal is no longer just a destination to reach. Our goal is the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite. And in fulfilling this task, we will not only extend humanity's reach in space -- we will strengthen America's leadership here on Earth."*

Further executive guidance was provided via the National Space Policy of the United States [2], wherein NASA was directed to meet broad goals, such as expanding international cooperation and pursuing human and robotic activities. However, a set of specific civil space guidelines was also provided that would serve to guide human space exploration activities over several decades:

- *Set far-reaching exploration milestones. By 2025, begin crewed missions beyond the moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth…*
- *Continue the operation of the International Space Station (ISS)…*
- *Seek partnerships with the private sector…*
- *Implement a new space technology development and test program…*
- *Conduct [research and development] in support of next-generation launch systems…*
- *Maintain a sustained robotic presence in the solar system…*
- *Continue a strong program of space science…*

In response, NASA has established a set of strategic directives to guide our efforts in meeting these national goals over the next several decades. This includes specific goals and objectives within the NASA Strategic Plan [3], including the following:

- *Strategic Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space.*
- *Objective 1.1: Expand human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration.*
- *Objective 1.2: Conduct research on the International Space Station (ISS) to enable future space exploration…*
- *Objective 1.3: Facilitate and utilize U.S. commercial capabilities to deliver cargo and crew to space…*
- *Objective 1.7: Transform NASA missions and advance the Nation's capabilities by maturing crosscutting and innovative space technologies…*

Finally, this guidance is embodied in law in Congressional direction to the agency via Authorizations [4]; this Act specifically directs NASA to address the following to meet these broad directives and national goals:

> *"… [D]irect [NASA's Human Exploration & Operations Mission Directorate] to develop a Mars Human Exploration Roadmap to define the specific capabilities and technologies necessary to extend human presence to the surface of Mars and the mission sets required to demonstrate such capabilities and technologies…*
>
> *"In developing the Mars Human Exploration Roadmap, the Administrator shall… include the specific set of capabilities and technologies required to extend human presence to the surface of Mars and the mission sets necessary to demonstrate the proficiency of these capabilities and technologies with an emphasis on using the International Space Station, lunar landings, cis-lunar space, trans-lunar space, Lagrangian points, and the natural satellites of Mars, Phobos and Deimos, as testbeds, as necessary, and shall include the most appropriate process for developing such capabilities and technologies…*
>
> *"[P]rovide a specific process for the evolution of the capabilities of the…Orion crew capsule with the Space Launch System… [C]apabilities and technologies that could be demonstrated … on the International Space Station… [and]*
>
> *"[D]escribe a framework for international cooperation in the development of all technologies and capabilities…*
>
> *"…The International Space Station shall be utilized to the maximum extent practicable for the development of capabilities and technologies needed for the future of human exploration beyond low-Earth orbit… The Administrator shall utilize the International Space Station and commercial services for Space Technology Demonstration missions in low-Earth orbit wherever it is practical and cost effective to do so…"*

In response to these national goals and objectives, NASA is in the early stages of preparing to extend human presence beyond Low Earth Orbit (LEO). Initial missions

would be conducted in near-Earth cis-lunar space and would eventually culminate in extended duration crewed missions on Mars' surface (see [6] and [7] for overviews of NASA's exploration planning). To enable such exploration missions, critical technologies and capabilities must be identified, developed, and tested. NASA has followed a principled approach to identify critical capabilities and a Proving Ground approach is emerging to address demonstration and testing needs.

The Proving Ground is a period subsequent to current ISS activities wherein exploration-enabling capabilities and technologies are developed and the foundation is laid for sustained human presence in space. The Proving Ground domain essentially includes missions beyond LEO that will provide increasing mission capability while reducing technical risks. Proving Ground missions also provide valuable experience with deep space operations and support the transition from "Earth-dependence" to "Earth-independence" required for sustainable space exploration**.**

2. THE CAPABILITY DRIVEN FRAMEWORK AND EVOLVABLE MARS CAMPAIGN

NASA's Human Exploration and Operations Mission Directorate (HEOMD) established a framework for analysis and, in 2014, a leadership team to guide ongoing work performed by multiple groups across the agency.

The Capability Driven Framework: Progressive Expansion of Capabilities and Distance

Initial analyses to address strategic guidance and exploration goals led to a "Capability Driven Framework" (CDF). The CDF established a broad framework for all future analyses in support of defining the nation's path to Mars. The CDF, shown in Figure 1, describes an exploration path that follows incremental steps to build, test, refine, and qualify critical capabilities that will lead to affordable flight elements and deep space capability, eventually enabling crewed planetary exploration to destinations beyond the Earth-moon system, such as the surface of Mars. The path begins with initial exploration missions to establish the first steps, including use of the ISS (e.g., long-duration crewed missions in LEO, initial exploration technology and capability testing) and validation of transportation systems (i.e., the Space Launch System [SLS] and Orion crew vehicle). These initial steps are followed by missions in the Earth-moon system that extend our reach beyond LEO, to such destinations as cis-lunar space and High Earth Orbit (HEO). This phase is followed stepwise beyond these near-Earth destinations further into the solar system and, eventually, to the Mars system (including Mars' moons, Phobos and Deimos, and the surface of Mars for missions of increasing duration). All of the phases within the path are "capability-driven" in that each step focuses on incremental building, testing, and validating critical capabilities required to eventually field long-duration crewed missions to the Mars system.

The Evolvable Mars Campaign: Earth Reliance, Proving Ground, and Earth Independence/Mars Ready

In addition to the CDF, HEOMD established a team to guide and integrate all analyses performed by multiple groups across the agency in support of human space exploration definition efforts. During 2014, this team created the first instantiation of a representative "human space exploration path" to serve as a beginning point for all further work. This initial path was termed the "Evolvable Mars Campaign" (EMC). *The EMC is not a specific plan for conducting missions beyond LEO and eventually to Mars. The EMC is a framework for defining the pioneering strategy for extending human access and operational capabilities in the journey towards the Mars system in the mid-2030s, while laying the foundation for sustained human presence in the following decades.*

The EMC team began by establishing a set of key strategic principles for exploration implementation:

- *Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth*
- *Application of high Technology Readiness Level (TRL) technologies for near term missions, while focusing sustained investments on technologies and capabilities to address challenges of future missions*
- *Near-term mission opportunities with a defined cadence of compelling human and robotic missions providing for an incremental buildup of capabilities for more complex missions over time*
- *Opportunities for U.S. commercial business to further enhance the experience and business base learned from the ISS logistics and crew market*
- *Multi-use, evolvable space infrastructure*
- *Substantial international and commercial participation, leveraging current International Space Station partnerships*

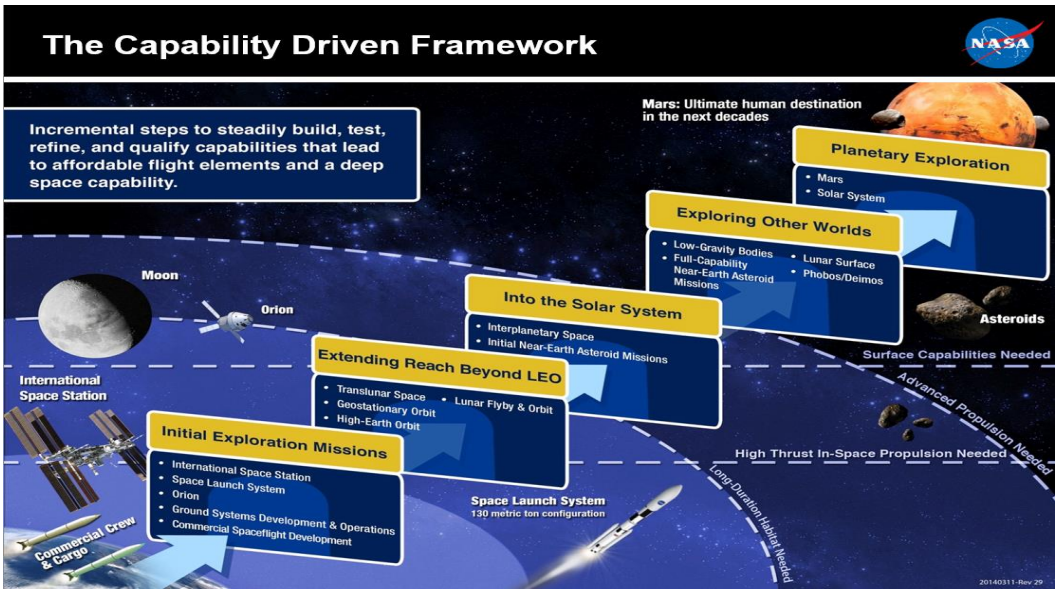

Figure 1: NASA's Capability Driven Framework (CDF) for human space exploration

In addition, key strategic principles were mapped to a set of statements to serve as a "guiding philosophy" to bound and shape the analyses performed during EMC definition; the primary principles of this guiding philosophy are briefly summarized below:

- *Leverages strong linkage to current investments across ISS, all systems in development, and science*
- *Develops Earth independence for long-term human presence through a series of steps, from LEO, through cis-lunar space, to the Mars surface*
- *Exploration enables science along the path*
- *Infrastructure is incrementally created on exploration missions*
- *Reflects the reality of annual budgets*
- *Emphasizes prepositioning and reuse of systems*
- *Incorporates flexibility to adjust to changing priorities across the decades*

To be clear, the primary purpose of this approach is to provide a basis for developing an architecture for eventual Mars surface missions, to identify appropriate trade studies, and to perform analyses with partners and stakeholders within a framework that is flexible enough to adjust to changing priorities and budgets over multiple decades and is, therefore, sustainable. The result is not a specific "plan" but a set of possible options that fit within a broad roadmap for moving crew explorers beyond LEO, through cis-lunar space, to the eventual destination of the surface of Mars.

An EMC "notional point-of-departure (POD)" was created that highlighted missions with increasing capability and distance from Earth. The POD began with a set of initial (robotic) exploration missions, followed by a phase embodying missions that extend our reach beyond LEO (e.g., lunar surface rovers, in-space transportation demonstrations), then missions that move "into the solar system" (e.g., Mars moon explorers), exploring other worlds via extended-duration, sustained planetary exploration. An overview of the EMC "notional POD" is given in Figure 2.

In addition, as part of EMC development, we identified three primary *phases* of missions that follow a path from Earth-to-Mars with increasing mission durations and capabilities. The initial phase was considered "Earth Reliant," wherein mission durations were six to 12 months and Earth return could be accomplished within hours (e.g., ISS). The second phase was termed the Proving Ground and encompassed mission durations of one to 12 months that require days for Earth return (e.g., cis-lunar space); it is expected that primary demonstration, testing, and validation of Mars-required capabilities would be accomplished within deep space during this second phase. The third and final phase was termed "Earth Independent/Mars Ready," with mission durations on the order of two to three years and Earth return requiring months. See Figure 3 for an overview of the three human exploration "Path to Mars" phases.

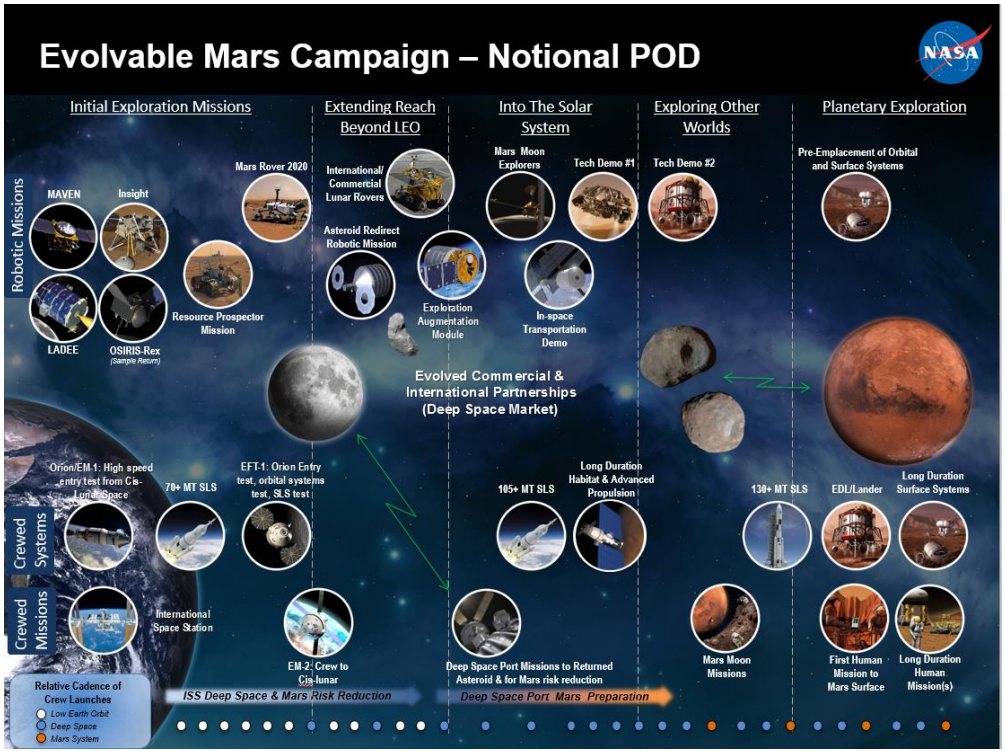

Figure 2: Evolvable Mars Campaign notional "Point-of-Departure"

In support of this goal, a set of ground rules and constraints was identified to be applied to all EMC trade studies and analyses. For example, the following assumptions were made and applied to all analyses in support of EMC roadmap development:

- Use ISS to the greatest extent possible
- The first crewed mission to the Mars system would be conducted during the 2030's decade and would lay the foundation for further crewed missions to the Mars vicinity
- Assume Lunar Distant Retrograde Orbit (LDRO) as the location for aggregation of Mars mission elements
- Capabilities and technologies required for Mars missions will be demonstrated, tested, and validated within a Proving Ground environment
- An Exploration Augmentation Module (EAM) will be emplaced at LDRO to serve as a facility for deep-space testing in support of exploration capabilities and technologies, extending the initial work carried out on ISS. The EAM is a crew-tended habitat that comprises elements that will eventually be used during Mars missions.
- The SLS is used for delivery of cargo and crew to multiple exploration destinations and the Orion vehicle is used for crew transport.
- One SLS-based crew mission will be conducted per year within the Proving Ground.
- The Asteroid Redirect Crewed Mission (ARCM) will be conducted in approximately 2025, with the robotically- retrieved asteroid or boulder returned to the LDRO-vicinity in approximately 2024.
- A crew of four will be sent to the Mars system by the mid-2030's; the specific location is TBD and could be to Mars orbit, one or both of Mars' moons, or to the surface of Mars (multiple potential Mars missions are under consideration).
- A Solar Electric Propulsion (SEP) in-space transportation system is under consideration for use during all deep space missions (e.g., to pre-deliver cargo to Mars prior to crew arrival).
- Crewed habitation elements (e.g., a Mars transit habitat) will be "refurbishable" and reusable over multiple missions.

In summary, NASA developed an EMC that meets national strategic goals and provides a framework from which to define a set of robotic and crewed space exploration missions, progressively building upon each mission's accomplishments and capabilities. A major focus of the EMC analysis during 2014 has been (1) in identifying the critical capabilities and technologies required to eventually conduct a crewed mission to the Mars system, and (2) developing a strategy for the demonstration, test, and validation of these required capabilities and technologies in space within an evolving framework identified as the Proving Ground. The remainder of this paper will address these two primary issues.

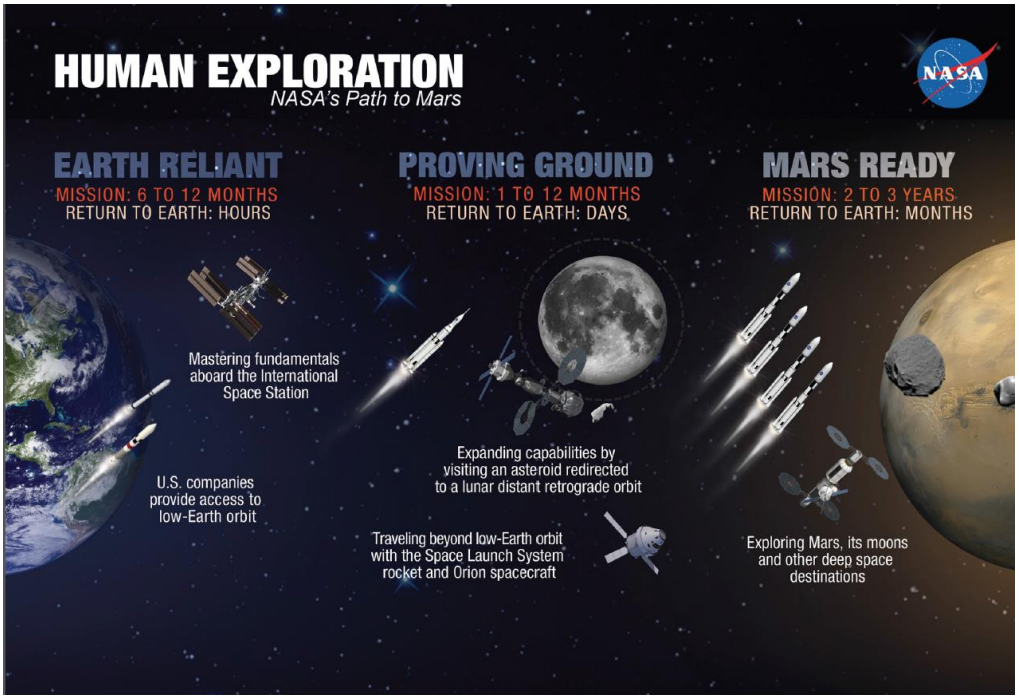

Figure 3: Evolvable Mars Campaign human exploration: NASA's path to Mars

3. EMC CRITICAL CAPABILITIES & TECHNOLOGIES

The EMC outlines a cadence of missions that fits within the bounds of the CDF philosophy. Prior CDF analysis has identified several critical technologies that are required for ultimately enabling sustained Mars surface missions. Each identified critical technology has performance characteristics metrics that identify the technology advancement required beyond the current state-of-the-art to enable the capability required for addressing the EMC Mars challenges.

Critical Technology Definition

These Mars challenges were grouped into three technology focus areas -- Transportation, Working in Space and Staying Healthy – which were decomposed into the primary objectives within each area (see Figure 4). Once developed, these technologies and, subsequently, the capabilities they provide, would enable future missions, including extended duration missions to the surface of Mars. The CDF facilitates affordable development and precludes the need to develop a large number of capabilities just prior to the Mars surface mission.

The identified EMC critical technologies were subsequently grouped into needed capabilities (e.g., merged solar array and thruster technologies to create a SEP capability) and the demonstration steps necessary to ready them for use on Mars was assessed. The EMC architecture studies provide a progression of flights that increase capability and mitigate technology risks for an extended Mars surface mission through test and demonstration opportunities across the Proving Ground.

One goal of our analysis was to focus our work on elements and missions within the EMC. Currently, these elements and missions include (1) the ISS and (2) Proving Ground assets of Exploration Missions (EM-1, -2), the ARM, EAM missions in cis-lunar space, and a precursor "pathfinder" mission to Phobos. We found that one additional "pathfinder" mission would be necessary to reduce the risks for the complete set of technologies; this would be an EDL/Mars Lander to demonstrate both EDL and LOx/CH4 (liquid oxygen/methane) Mars lander technologies to reach Mars' surface. (An added benefit of this capability pathfinder mission would be the inclusion of secondary payloads to demonstrate additional technologies on Mars' surface.) Further risk reduction could be substantially accomplished for several technologies by undergoing initial tests on the lunar surface prior to the Mars surface environment, most likely in collaboration with our International Partners.

We believe that many of the critical capabilities and "Strategic Knowledge Gaps" (i.e., gaps in our knowledge regarding the environments of exploration destinations) can be addressed through activities in the "Earth Reliant" and Proving Ground phases prior to committing to a specific path to Mars. It should be noted that the National Research Council recently reviewed NASA's human exploration program [8] and identified critical capabilities needed for Mars missions; these critical capabilities were compared to those in the current EMC portfolio and found to be common with NASA's.

Figure 4: Evolvable Mars Campaign enabling technologies

Mapping of Critical Capabilities and Technologies to Demonstration and Testing Platforms

We mapped the identified EMC critical capabilities and technologies to Proving Ground missions, by decomposing the EMC missions into logical mission "buckets" that could be viable test and demonstration opportunities for technical risk reduction while increasing mission capability. Although initially a wide spectrum of mission candidates was considered (for boundary condition analysis), a reduced set was baselined that more accurately reflects the current EMC architecture. The EMC mission "buckets" used in this analysis are summarized in Table 1.

Each critical capability and technology need was assessed from a test and demonstration perspective to find strategies that would take best advantage of the Proving Ground philosophy. For each identified EMC capability and technology, a preliminary level of detail was developed by the EMC team regarding a test and demonstration strategy (further definition is presently in development by System Maturation Teams, as described below).

The mapping results were captured in "Capability Test & Demonstration Templates" that provided preliminary details for each identified EMC capability. The information was also organized by Proving Ground "buckets" and summarized to enable evaluation of each proposed EMC platform's test and demonstration focus. The EMC Proving Ground test and demonstration analysis process is summarized in Figure 5.

Table 1: EMC Test & Demonstration "Buckets"

Elements & Missions	Exploration Phase	Comments
ISS	Earth Reliant	ISS through 2020, (EAM at ISS TBD)
EM-1/2/X	Proving Ground	SLS & Orion; no additional pressurized elements
Asteroid Redirect Mission	Proving Ground	SEP delivered capture hardware (single mission) First Orion-deep space mission; capsule-based EVA's from Orion (no additional pressurized crew volume)
EAM / Habitat Prototype	Proving Ground	Pressurized elements; multiple cis-lunar missions
Capability Pathfinder	Earth Independent / Mars Ready	EDL/Lander Mission (currently the only EMC capability pathfinder mission identified as required)
Other	N/A	Additional test and demonstration high-value opportunities; e.g., Lunar, Free Flyers, Phobos

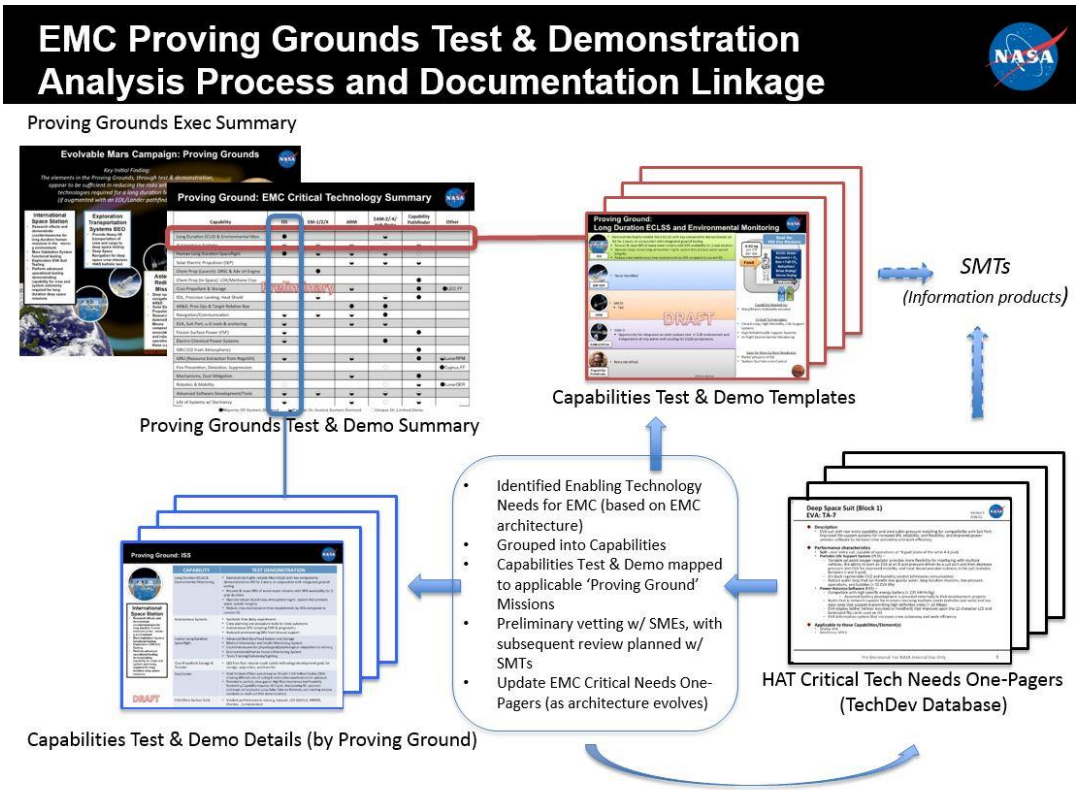

Figure 5: Evolvable Mars Campaign Proving Ground test and demonstration analysis process

NASA's System Maturation Teams

Further refinement of test and demonstration mapping, with increased fidelity of performance characteristics as the EMC architecture evolves, *is presently being performed* by HEOMD's System Maturation Teams (SMTs). These SMTs, grouped by the three technology focus areas (i.e., Transportation, Working in Space, and Staying Healthy") and "Other," are summarized in Table 2.

The purpose of each SMT is to develop a roadmap that defines the activities required to advance critical capabilities, the means of demonstrating system performance, and the implementation planning to achieve the steps of the roadmap. The SMTs also serve as Subject Matter Expert teams responsible for providing technical review of incoming proposals, recommendations for integrated ISS and ground tests, and input to the budget process for their respective areas.

The SMTs are a group of human exploration mission technology, capability and system experts that have been developing human and robotic exploration systems that will enable Mars exploration. These system development projects are traceable to various human spaceflight studies (such as the Human Spaceflight Architecture Team/HAT) and design reference missions (such as the Lunar Architecture Team/LAT and Mars Design Reference Architecture 5.0 studies). The SMTs have been actively developing systems on the ground, through terrestrial analogs and via ISS. SMTs encompass a variety of disciplines and provide the agency with the subject matter expertise to determine performance needs and requirements based on human spaceflight destinations and mission concepts of operations.

After initial analysis of EMC missions and using the Proving Ground technology test and demonstration analysis described above, *SMTs will determine the critical capabilities needed for Mars exploration specific to the EMC cadence of proposed missions*. In addition, the SMTs will compare element performance parameters identified by EMC element leads with the performance characteristics of each capability. When elements and capabilities performance needs have been mapped, SMTs will develop summary data products to determine development timelines, development activities and "rough-order-of-magnitude" cost for development. This analysis will provide NASA management the information needed to prioritize investments that will best enable near-term mission decisions. An overview of the initial "mapping" of EMC critical capabilities by SMT discipline to each Proving Ground platform is given in Table 3.

Table 2: NASA's System Maturation Teams by Technology Focus Area

TECHNOLOGY FOCUS AREAS	SYSTEM MATURATION TEAM
TRANSPORTATION	Power and Energy Storage
	Propulsion
	Entry, Descent, and Landing (EDL)
	Thermal (including Cryogenics)
	Avionics
	Logistics
	Habitation
	Ground Operations
WORKING IN SPACE	Extravehicular Activity (EVA)
	Human-Robotic Mission Operations
	Autonomous Mission Operations
	Communications and Navigation
	In-Situ Resource Utilization
STAYING HEALTHY	Environmental Control and Life Support and Environmental Monitoring
	Crew Health & Performance
	Radiation
	Fire Safety
OTHER	Structures and Materials

Each of the EMC test and demonstration "buckets" and associated preliminary data analysis is described in greater detail in the following sections. *This information describes tests and demonstrations of exploration capabilities and technologies under consideration at this time*.

- ISS is within the "Earth Reliant" phase of Human Exploration and potential use of this asset in preparing for deep space exploration is discussed first.
- In Section 4, the emerging Proving Ground strategy is summarized with a description of representative missions and test and demonstration objectives under consideration at this time. This phase encompasses multiple potential EMC missions within cis-lunar space and pathfinder missions (including precursor missions, for example, to gather environmental data to address Strategic Knowledge Gaps).

ISS Capability Development Activities within the "Earth-Reliant" Phase

The ISS is a unique resource available for testing and developing exploration capabilities, systems and operational techniques in space while at a relatively safe and accessible distance from the Earth (that is, with a crew return of hours). It is also a capable laboratory, equipped with valuable resources (e.g., power, communications, crew time) to enable exploration testing. High emphasis has been placed on best utilization of ISS for those test and demonstration activities that can be advanced in LEO. Although ISS is considered to fall within the "Earth-Reliant" phase and is outside of the Proving Ground phase, it provides an immediate test platform for many Mars-forward focused testing activities and it is assumed that ISS-based activities will continue in parallel with Proving Ground test and demonstration activities once these are initiated. Therefore, it's useful to provide a high-level overview of some of the exploration test and demonstration activities under consideration to be conducted on the ISS.

There are three primary categories of objectives associated with ISS exploration test and demonstration activities under consideration:

1. Develop and validate exploration capabilities in an in-space environment (i.e., LEO; ISS provides an environment for testing within a *microgravity* and *long-duration environment*, but not the *deep-space environment* beyond LEO).
2. Perform long-duration Human Research Program (HRP) testing and demonstrations, with a focus on crew health and performance, to serve as a foundation for extended-duration deep space crewed exploration missions.
3. Perform integrated testing of exploration hardware, especially under long duration conditions.

The EMC study has identified the following high-value exploration capabilities that are under consideration for testing on the ISS:

- *ECLSS & Environmental Monitoring*: Improve reliability, maintainability, and packaging. Test on-orbit air, water, microbial, particulate, acoustic monitoring without sample return to Earth for analysis.
- *Extravehicular Activity (EVA*): Perform an exploration EVA suit demonstration and evaluate supporting systems.

Table 3: EMC Critical Capabilities by System Maturation Team Discipline Mapped to Proving Ground Phase

EMC Critical Capability by SMT Discipline	ISS	Proving Ground	Pathfinders / Precursors
EVA			
Deep Space Suit & Mars Surface Space Suit	•	•	
Suit Port / Airlock		•	
Human & Robotic Mission Operations			
Robotics (Telerobotics, Robots & Crew Working side-by-side)	•	•	
Mobility, microgravity tools & anchoring		•	Phobos Precursor
Crew Health & Performance			
Human Long Duration Spaceflight	•	•	
Autonomous Mission Operations			
Autonomous Systems	•	•	
Automated Rendezvous & Docking (AR&D), Proximity Operations, and Target Relative Navigation		•	EDL / Lander Pathfinder
Navigation / Communications	•	•	EDL / Lander Pathfinder
Environmental Control & Life Support System (ECLSS)			
Long Duration ECLSS & Environmental Monitoring	•	•	
Entry, Descent, & Landing (EDL) / Transportation		•	EDL / Lander Pathfinder
Power and Energy Storage (also supports Transportation)			
Fission Surface Power (FSP)			EDL / Lander Pathfinder
Electro-Chemical Power Systems	•	•	
Radiation			
Solar Particle Event (SPE) and Galactic Cosmic Radiation (GCR) Protection	•	•	
Thermal			
Cryogenic Propellant and Storage (supports Transportation)	•		EDL / Lander Pathfinder
Fire Safety			
Fire Prevention, Detection, and Suppression	•	•	Cygnus Free Flyer
Propulsion / Transportation			
Chemical propulsion (in-space) (LOx/Methane)			EDL / Lander Pathfinder
Solar Electric Propulsion (SEP)		•	
In-Situ Resource Utilization (ISRU)			
O2 from Mars Atmosphere (primary)			Mars 2020
Resources from Regolith (secondary)	•	•	Phobos Precursor
Avionics (includes support to Transportation)		•	EDL / Lander Pathfinder
Logistics			
Reduced Logistics Mass		•	
Habitation		•	Phobos Precursor
Structures & Mechanisms			
Mechanisms, Dust Mitigation		•	EDL / Lander Pathfinder
Inflatable Structures	•	•	

- *Fire Safety:* Demonstrate gas measurement and air cleaning systems, improved contingency breathing equipment, fire propagation protection, and cleanup testing.
- *Communications & Navigation:* Evaluate high-rate internetworked proximity networking.
- *Power and Energy Storage Systems*: Evaluate advanced solar arrays, advanced battery regeneration, and advanced fuel cell and electrolyzer operations in microgravity. Demonstrate delayed power management, high cycle life, and long duration energy storage.
- *Variable low mass thermal systems*
- *Habitation and Crew Systems*: Demonstrate exploration habitation systems (e.g., inflatable structures) and habitation support functionality (e.g., in-space manufacturing).
- *Logistics:* Demonstrate systems and technologies to reduce the mass of crew support logistics (e.g., laundry system; trash repurposing; lightweight carriers/packaging repurposing; reconfigurable structures; long shelf life pharmaceuticals).
- *Long Duration Crew Health and Performance:* Demonstrate microgravity biomedical countermeasures (e.g., a reduced mass and volume exercise suite) and evaluate crew health issues (e.g., G transitions, extended-duration microgravity exposure, behavioral health).
- *Radiation*: Demonstrate advanced active and passive radiation detection
- *Autonomous Rendezvous & Docking* (AR&D): Demonstrate advanced AR&D.
- *Autonomous Operations:* Demonstrate autonomous ground and flight operations with induced time delay. Evaluate in-situ crew training and mission planning.
- *Robotics / Telerobotics:* Evaluate improved robotic manipulation and human/robotic interaction.

4. NASA'S EMERGING PROVING GROUND STRATEGY

A Proving Ground strategy is in development to guide mission definition in support of Mars preparation activities. The focus is on near-term mission activities, exploration critical capabilities and technology demonstration, test, and validation. The approach is to use, to the greatest extent possible, existing or planned missions as platforms for such activities; that is, to "piggyback" on existing missions rather than define new missions for testing purposes. This philosophy includes demonstration and test during operations within planned elements, such that there is minimal requirement to build and operate a unique facility. Within the emerging Proving Ground strategy, we have identified a number of potential ways to achieve the testing and validation required; we have laid out a broad framework of testing missions and detailed planning is ongoing. The objectives of the Proving Ground strategy include:

- Develop and validate exploration capabilities and hardware in a deep space environment; and
- Perform long-duration HRP activities, examining the combined effects of deep space and microgravity potentially coupled with long-duration operations.

Multiple potential locations and mission types have been defined and are presently under analysis; these include:

1) Focused *Earth-to-orbit and in-space transportation missions* beyond LEO (e.g., EM-1 and EM-2)
2) *Robotic precursor missions* to exploration destinations prior to crew and *"Capability Pathfinder" / Strategic Knowledge Gap missions* (a limited set of unique missions to demonstrate critical capabilities, technologies, and operations in the Mars system)
3) Exploration demonstrations and tests during the *Asteroid Redirect Mission* (both the robotic and the crewed portion of the mission)
4) Multiple capability and technology demonstrations and tests at the *Exploration Augmentation Module* in cis-lunar space
5) Testing a "*Mars Habitat Prototype*" that could eventually be emplaced with the EAM at LDRO to test and validate long-duration habitat functionality prior to use during the crew transit portion of the actual Mars mission.

There is the potential for both International Partner and Industry partnership during exploration demonstration and test mission activities. And planning has begun to include explicit activities addressing science operations and technology demonstrations, as provided by NASA's Science Mission Directorate and Space Technology Mission Directorate, respectively. An overview of Proving Ground mission categories and representative types of mission activities is provided in Figure 6 below and each of the Proving Ground mission types is described in greater detail.

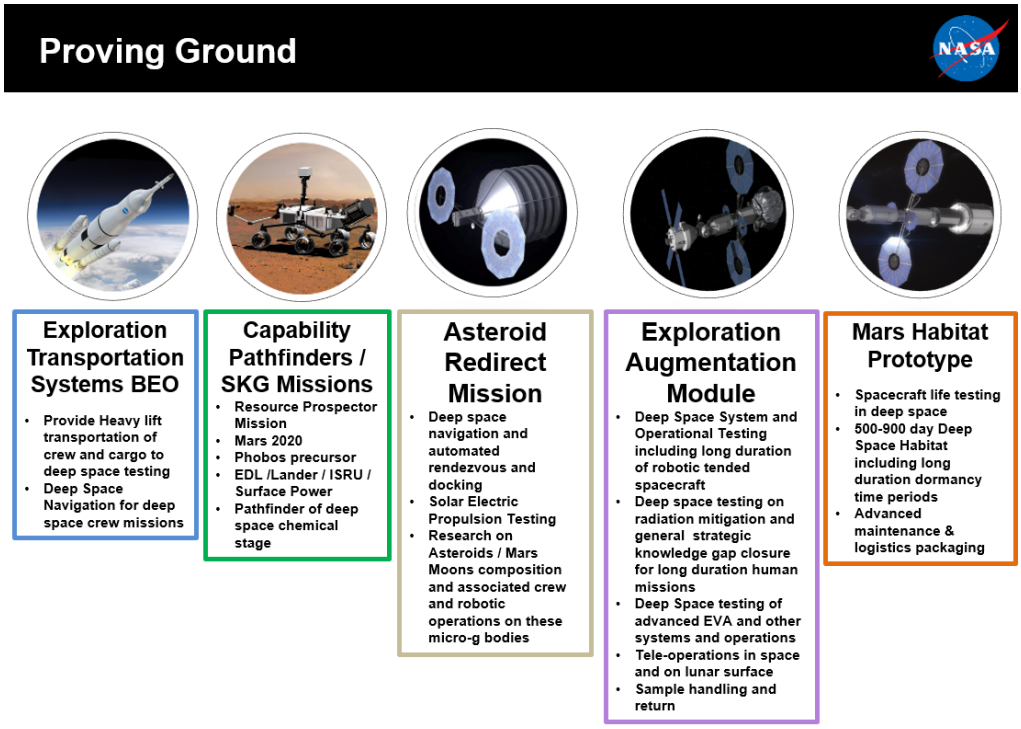

Figure 6: Overview of Proving Ground mission categories and potential test and demonstration objectives

Potential Proving Ground Critical Capability Demonstration, Test, and Validation Missions

1) *Missions Demonstrating Exploration Transportation Systems* -- "Exploration Missions" utilizing the SLS and Orion will provide the first test and demonstration opportunities for beyond-LEO transportation operations. Initially, the EM flights will be uncrewed, followed eventually by crewed missions. Opportunities for this early Proving Ground testbed include:

- *Autonomous Systems*: On-board vehicle systems management at time-distant locations, deep space crew-ground coordinated operations of vehicle/habitat with time delays, advanced decision support tools for the Mission Control Center, off-nominal fault detection and vehicle safing
- *Human Long Duration Spaceflight:* Environmental monitoring during crewed missions
- *Cryogenic Propellant Storage and Transfer:* Unique or limited short-term passive thermal control and propellant gauging demonstration
- *AEDL, Precision Landing, and Heat Shield:* Aeroassist integrated flight test with high-energy ballistic test
- *Navigation & Communications:* Integrated network management demonstration
- *Software Development/Tools:* Software system infrastructure to leverage multi-core avionics

2) *Capability "Pathfinder" Missions and Robotic Precursor Strategic Knowledge Gap-filling Activities* -- EMC pathfinder missions were also identified during the analysis process. The team identified a set of significant high-risk items that would not be sufficiently tested within identified Proving Ground elements and missions, so these were grouped into one or more "pathfinder" missions. The concept of a "pathfinder" is a mission required to accomplish critical EMC test and demonstration objectives that could not be met within the existing EMC architecture cadence. A number of potential "pathfinder" missions have been identified; some of these include missions already under definition (which may demonstrate required capabilities) and some are new proposed missions. These include:

- *Mars Surface Access Pathfinder* (aka "EDL/Lander Pathfinder"): The primary objective is to demonstrate safe delivery of an exploration-class (multiple metric tonnes) of payload to the surface of Mars via an EDL/Mars Lander (LOx/Methane) system demonstrating precision landing and a Mars heat shield. Secondary payloads would utilize the available payload mass to the surface; secondary payloads under consideration include: fission surface power, autonomous system operations, Solar Electric Power in-space transportation, Mars In-Situ Resource Utilization (e.g., subscale O2 production, resource extraction from regolith), surface robot operations (e.g., surface mobility, dust mitigation), and deep space communications and navigation. In addition, there is opportunity to

address Mars science objectives and the potential for a small sample and return ascent vehicle.

- *Phobos Precursor mission* (aka "Mars Moons Prospector"): The primary objective of this mission is to demonstrate mobility, prospecting, and science capabilities through geological surveys of Phobos and Deimos to support infrastructure to characterize gravitational fields, scientific regions of interest, soils mechanics, and useful resource materials. Additionally, measurements could be taken to retire some Strategic Knowledge Gaps.
- *2020 Robotic Mission:* This mission is presently under study within NASA's Mars Program. Additional secondary demonstrations could include in-situ resource utilization, dust characterization, and "ground truth" for a human mission landing site, and instrumentation to gather Mars environmental data.
- *Lunar Resource Prospector:* This mission is presently in the concept development phase. This lunar surface asset could be included as part of the AEDL/Mars Lander pathfinder mission to demonstrate acquisition and processing on the lunar surface to produce oxygen.

3) Asteroid Redirect Mission (ARM) -- An Asteroid Redirect Mission (comprising both a robotic mission and a crew mission) is presently undergoing initial definition. The overall goals include identifying and retrieving/redirecting an asteroid or asteroid boulder to near-Earth space, exploring the asteroid or boulder, then returning a sample to Earth for detailed analysis. The ARM involves multiple individual missions and one, the Asteroid Redirect Crew Mission, includes a two- to four-person crew performing operations on a captured asteroid using the Exploration Augmentation Module as a base of operations. This mission would be the first human exploration conducted of an asteroid surface. It is planned that the crew would conduct multiple EVAs to the captured asteroid/boulder. In initial concepts, it is expected that the crewed mission duration would be ~22-25 days (but with use of the EAM as a base, the mission duration may be extended).

The ARM provides opportunities to demonstrate and test a number of exploration capabilities and technologies. For example:

- Solar Electric Propulsion operations during asteroid retrieval including autonomously deployable multi-kW in-space arrays, thrusters, power management and control, and propellant storage.
- Deep space mission asteroid retrieval robotic vehicle operations, including trajectory guidance, lunar gravity assists, heliocentric transfers, and systems pre-deployment.
- During the crew mission, a number of capabilities and technologies of importance to future exploration missions could be demonstrated, including the exploration EVA suit system; SLS, Orion, and EAM operations in deep space; automated rendezvous and docking and proximity operations; deep space timing and navigation; and sample handling, including sample retrieval, containment, transfer, and Earth return with the crew.

4) Exploration Augmentation Module Proving Ground Missions -- Orion can support a crew of four in deep space for up to 21 days; additional pressurized volume is required to support crew to enable missions beyond the 21-day duration. Therefore, a concept for augmenting Orion to enable crewed deep space operations for longer durations is in early development. It is assumed that this "Exploration Augmentation Module" (EAM) will be capable of supporting four crew in deep space for up to 60 days (with combined Orion and EAM functionality).

As noted earlier, the EAM may augment the crewed portion of the Asteroid Redirect Mission. However, a *primary purpose of the EAM is to provide a platform for Proving Ground demonstrations and tests of future exploration systems.* As such, it is a significant element within NASA's overall Proving Ground strategy. The EAM will operate in Lunar Distant Retrograde Orbit. Functionality under consideration includes support for proximity operations and AR&D, docking ports, an airlock/suitlock for EVAs, and pressurized habitable volume for the crew. As the primary long-term purpose of the EAM is to support long-duration exploration system demonstrations and tests, it must be emplaced in cis-lunar space early enough such that results can be integrated into mission elements for a crewed Mars mission by the 2030's.

The following is a brief summary of *capabilities categories under consideration for early demonstration and testing within the EAM*, beginning with emplacement at LDRO in the early 2020's and continuing through ~2027. *After discipline experts on System Maturation Teams have identified <u>required capabilities and technologies</u>, EAM test and demonstration activities will be refined.*

- *EVA:* Demonstrate and test microgravity EVA tools and aids for off-surface mobility, exploration EVA suit, and suitport operations within an exploration atmosphere (e.g., 8.2 psia/34% O2).
- *Human and Robotic Mission Operations:* Demonstrate crew-robot teaming and interaction in the IVA and EVA environment, especially regarding increasing crew autonomy and robotic tending of systems during dormancy periods. Demonstrate telerobotic control for near-real-time manipulation and examine operator-machine interface issues with varying time delays.
- *Crew Health and Performance:* Demonstrate and test medical imaging and treatment capabilities during deep space autonomous mission operations

and evaluate exploration habitat volume and layout concepts.

- *Autonomous Mission Operations:* Demonstrate and test onboard vehicle systems management at time-distant locations; advanced decision support tools; crew autonomy at time delays; off-nominal fault detection and vehicle safing; and deep space proximity operations, target relative navigation, and AR&D.
- *Communications & Navigation:* Demonstrate high rate forward uplink to spacecraft and 100 Mbps integrated network management, integrated service execution and space internetworking. Demonstrate complex proximity/navigation maneuvers among multiple in-space elements.
- *ECLSS:* Demonstrate deep space vehicle in-situ environment monitoring with no return of samples to Earth for analysis, including identifying and quantifying "unknowns" (i.e., unanticipated chemicals and microorganisms).
- *Radiation:* Demonstrate Solar Particle Environment (SPE) and GCR monitoring and radiation mitigation approaches.
- *Thermal:* Demonstrate short-term passive thermal control and propellant gauging technologies and low boil-off liquid oxygen storage.
- *Propulsion:* Demonstrate 13-kW-class thruster systems scalable to higher powers with a ~10t xenon propellant load.
- *Power and Energy Storage:* Demonstrate 25 kW-class solar arrays and a Power Management and Distribution system scalable to higher powers (strong enough for nominally 0.1 g loads and suitable for high voltage operation) in a representative deep-space environment.
- *Fire Safety:* Demonstrate long duration operation of fire detection sensors in an exploration vehicle atmosphere.
- *ISRU:* ISS platforms enable early proof-of-concept experiments for regolith capturing, transfer, handling and processing for resource extraction and on-board resource processing in microgravity. ISS lessons then enable definition of engineering requirements for selected technologies to mature aboard the EAM and progressively achieve target values for production of commodities (e.g., water, oxygen), power efficiency, operational longevity, maintenance frequencies, automation and teleoperation. The following are examples of demonstrations under consideration for maturing ISRU systems on the EAM:
    - Demonstrate subsystem operation in micro-gravity and validate technologies for material transfer, mixed phases (solid/liquid/gas) processing, and product separation and conditioning/storage
    - Demonstrate pilot-scale water extraction and oxygen generation systems using asteroidal materials as resources
    - Demonstrate a crew-ISRU systems interface for production and maintenance operations with teleoperations and EVA
    - Demonstrate resource (O2, propellant) extraction from onboard trash and packaging for deep space transit missions
    - Validate ISRU systems for operations in the Mars system to support Phobos/Deimos and Mars surface missions
- *Avionics:* Demonstrate high reliability and recovery with extended periods of dormancy in the deep space environment.
- *Logistics:* Demonstrate reduced logistics mass, advanced logistics packaging, and long-duration storage of consumables.
- *Habitation:* Perform an integrated long duration, deep space systems test of all Mars habitation systems, including advanced maintenance operations support.
- *Structures & Mechanisms:* Demonstrate low temperature structures and mechanisms for long duration, deep space missions, including inflatable structures.

In addition to demonstrating and testing critical exploration capabilities and technologies, it is possible that there will be crew time to perform mission activities that are not in the critical path to Mars, but that, if carried out, could enhance Mars mission operations. There are a number of these "*opportunistic mission activities and payloads"* that could be conducted at EAM under consideration.

For example, the crew may perform Low-Latency Teleoperations from the EAM [9] [10]. One mission concept involves the crew operating a lunar surface rover to perform reconnaissance and sample acquisition (including from the lunar farside), then transporting the sample to Earth on their return. This mission concept, sometimes referred to as human-assisted sample return or crew-assisted sample return, could be valuable for practicing a range of important operations that may be needed during Mars orbital and surface missions (see [11] and [12]); these include, for example, teleoperations; human factors; telerobotic sample collection, handling, analysis, and curation; capturing a sample in space; and planetary protection protocols. (It is possible that in-space telerobotic assets could be used to ensure the sample containment unit is safely and thoroughly inspected and, perhaps, cleaned to the specifications required.) Demonstrations could examine the interplay between (longer distance) ground-based and space-based (via crew) teleoperations tasks; some of the basic operations have been tested from the ISS (see [13] and [14]).

Finally, crew teleoperations could be used to perform ISRU operations (e.g., surface prospecting) and resource production (e.g., with returned asteroid materials; see [15] and [16]); maintenance tasks on surface and in-space assets; site reconnaissance, site assessment, and site preparation as practice for eventual human landings; and science operations (e.g., constructing large assets).

5) *Mars Habitat Prototype* -- After serving as a base for performing demonstration, test, and validation of critical exploration capabilities and technologies, the EAM could transition to serve as a platform for directly supporting Mars missions. Initially, the EAM could support a "Mars Habitat Prototype" over a 500-900-day deep space habitation test with long periods of dormancy – essentially, a "shakedown cruise" of the Mars mission crew's transit habitat.

In addition, the EAM could support aggregation of elements of the Mars mission stack at LDRO. An EAM crew could perform a Phobos mission surface habitat checkout and supply prior to deployment to Phobos in preparation for crew arrival. Eventually, uncrewed Mars mission elements could be launched to LDRO and the EAM crew could oversee integration and eventual deployment of the integrated element stack to the Mars system prior to deployment to Mars in preparation for eventual crew arrival.

And finally, after a crewed mission to Mars, the crew returns to Earth's vicinity, vacates the transit habitat, and returns to Earth via Orion. At this time, the uncrewed Mars transit habitat could be deployed to the EAM for refurbishing and resupply prior to reuse by a follow-on Mars crew.

5. SUMMARY

NASA's Evolvable Mars Campaign team is addressing strategic guidance from multiple sources above and within the agency. We have begun the process of identifying the critical capabilities needed for a crewed Mars mission in the late 2030's. After initial analysis by a number of groups across the agency, we are further defining and refining future exploration mission concepts.

Preliminary EMC critical capabilities and associated technologies have been assessed from a test and demonstration perspective to develop strategies that would best take advantage of a Proving Ground philosophy for Mars surface readiness. In preparation for future deep space exploration missions, the EMC team is moving forward with critical research and technology demonstrations on the ISS to the greatest extent possible and we have identified a number of candidate capabilities for demonstration and test at this facility. We have an emerging Proving Ground strategy that involves multiple approaches to test and validate exploration capabilities in space, including using existing missions, fielding "pathfinder" missions to exploration destinations, and performing extended duration in-space testing at a small facility emplaced at LDRO, the EAM

We have begun making detailed plans for missions and activities within the Proving Ground to prepare for eventual crewed missions to the Mars system in the 2030's. We have identified a number of possible candidate demonstrations and tests for in-space testing and we are performing a deeper analysis of those candidates at present. And we have built a representative set of missions and a manifest that we will be refining over the next several years.

To meet engineering needs to design, develop, and test elements and vehicles required for a crewed Mars mission in the late 2030s, we need to begin demonstrations and tests of critical capabilities and technologies as soon as possible. In fact, given that we have already started such demonstrations and testing on ISS, we plan to continue these efforts in parallel with deep space testing carried out on the EAM, when it is eventually emplaced at LDRO.

While we have focused on human space exploration requirements in our early analyses, we have recently begun directly interacting with other NASA mission directorates, in particular, NASA's Science Mission Directorate and Space Technology Mission Directorate, to coordinate our efforts over the long term, pool our resources, and craft an integrated approach to enabling a solar system exploration vision with robotic systems and, eventually, humans.

Finally, we have begun to inform stakeholders of our emerging solar system exploration vision, including elements of our government, our International Partners, Industry, and the public (of which this conference is one). We plan to move humans beyond LEO into the solar system and NASA has begun initial planning and testing in space to enable this future. An overview of our exploration vision is given in Figure 7 below.

Figure 7: Overview of NASA's Evolvable Mars Campaign capability and mission extensibility to enable solar system exploration

ACRONYMS

AEDL	**Aerocapture, Entry, Descent, & Landing**
ARC	**Ames Research Center**
AR&D	**Autonomous Rendezvous & Docking**
ARM	**Asteroid Redirect Mission**
ARCM	**Asteroid Redirect Crewed Mission**
ARRM	**Asteroid Retrieval Robotic Mission**
ARV	**Asteroid Redirect Vehicle**
CDF	**Capability Driven Framework**
CH4	**Methane**
EAM	**Exploration Augmentation Module**
ECLSS	**Environmental Control & Life Support System**
EDL	**Entry, Descent, & Landing**
EM	**Exploration Missions**
EMC	**Evolvable Mars Campaign**
EVA	**Extravehicular Activity**
FSP	**Fission Surface Power**
G	**Gravity**
GCR	**Galactic Cosmic Radiation**
GRC	**Glenn Research Center**
GSFC	**Goddard Space Flight Center**
HAT	**Human Spaceflight Architecture Team**
HEO	**High Earth Orbit**
HEOMD	**Human Exploration & Operations Directorate**
HRP	**Human Research Program**
ISRU	**In-Situ Resource Utilization**
ISS	**International Space Station**
JSC	**Johnson Space Center**
KSC	**Kennedy Space Center**
LaRC	**Langley Research Center**
LAT	**Lunar Architecture Team**
LDRO	**Lunar Distant Retrograde Orbit**
LEO	**Low Earth Orbit**
LOX	**Liquid Oxygen**
NASA	**National Aeronautics & Space Administration**
O2	**Oxygen (molecular)**
PGS	**Pressure Garment Subsystem**
PLSS	**Portable Life Support System**
PMAD	**Power Management & Distribution**
POD	**Point-of-Departure**
SEP	**Solar Electric Propulsion**
SETI	**Search for Extraterrestrial Intelligence Institute**
SLS	**Space Launch System**
SMT	**System Maturation Team**
SPE	**Solar Particle Event**
STEM	**Science, Technology, Engineering, and Math**
TRL	**Technology Readiness Level**

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- *In-Situ Resource Utilization Team:* Rob Mueller/KSC (Lead), Dr. Laurent Sibille / Enterprise Advisory Services, Inc. (EASI) KSC, Chris Jones/LaRC, Jerry Sanders/JSC

- *Low-Latency Teleoperations & Human-Assisted Sample Return Team:* Dr. Mark Lupisella/GSFC (Lead), Alida Andrews/JSC, Dr. Dale Arney/LaRC, Jake Bleacher/GSFC, Dr. Robert Gershman/JPL, James Johnson/JSC, Scott Mest/GSFC, Dr. Margaret Race/SETI, Hilary Shyface/LaRC, Fred Stillwagen/LaRC, Mike Wright/GSFC

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- *Technology Development Integration Team:* Scott Vangen/KSC (Lead), Leslie Alexander/MSFC, David Alfano/ARC, Alida Andrews/JSC, Johanna Goforth/JSC, David Hornyak/JSC, Kevin Larman/JSC, Carolyn Mercer/GRC, Donald Palac/GRC, Shamim Rahman/JSC, Jonette Stecklein/JSC, Lisa Stephenson/JSC, Julie Williams-Byrd/LaRC

- *Proving Ground Integration Team:* Dr. Marianne Bobskill/LaRC (Lead), Dr. Ruthan Lewis/GSFC

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BIOGRAPHY

Marianne Bobskill *received a Ph.D. in Experimental Psychology (Cognitive Science) from Temple University and has 25+ years of experience in space crew systems analysis and human exploration mission concept development. She began her career with NASA in 1985 in the Man-Systems Division at Johnson Space Center, where she established and directed the Human-Computer Interaction Laboratory In this role, she led the definition of requirements, guidelines, and standards for the Space Station Freedom flight data management system and led the HCIL to a nationally-recognized human-computer interface applied research, rapid prototyping, and system development support facility. In 1994, she moved to NASA's Langley Research Center in Hampton, VA, where for the last several years she has served in lead positions on NASA-wide teams performing human space exploration architecture studies. She co-led the Human Spaceflight Architecture Team (HAT) Cis-Lunar Destination Team. She has authored or co-authored 50+ papers and books on human-space system integration, crew-flight data system interface design, space habitation, and crew operations.*

Mark Lupisella *received a B.S. in Physics, an M.A. in Philosophy of Science, and a Ph.D. in Evolutionary Biology from the University of Maryland, where he did his dissertation on modeling microbial contamination of Mars from human missions. He manages Goddard Space Flight Center's Advanced Exploration Systems and Architecture support for Human Exploration and recently led analysis for crew-assisted sample return and low-latency telerobotics. He co-led the Cis-Lunar Destination Team, was a participant in the Keck Asteroid Retrieval Mission Study, and recently worked on a 500-day Mars surface ops con. He has worked on Hubble Space Telescope, wearable computing, cooperative robotics, and astrobiology.*

Rob Mueller *is a Senior Technologist for Advanced Projects Development at NASA's Kennedy Space Center (KSC) in the Engineering & Technology Directorate and is co-founder of the NASA Swamp Works and the KSC Granular Mechanics & Regolith Operations Lab. Mr. Mueller is chair of the American Society of Civil Engineers Committee for Regolith Operations, Mobility and Robotics; he is a member of the American Institute for Aeronautics and Astronautics Space Resources Technical Committee; and he is Head Judge of the annual NASA Lunabotics/Robotic Mining Competition for Universities. Mr. Mueller has been leading the development of technologies required for Lunar Surface Systems, including developing Lunar Regolith Excavation and other Surface Support Equipment. He has also worked for NASA at the Johnson Space Center and the Jet Propusion Laboratory. Mr. Muller was awarded a BSc. degree in Mechanical Engineering from the University of Miami (1988) and a Master of International Space Systems Engineering from the Technical University of Delft (2006) in the Netherlands, as well as a Master of Business Administration from the Florida Institute of Technology (FIT, 1994). Mr. Mueller has 25 years of engineering and management experience in the space industry and has been the recipient of numerous NASA awards, including the Astronaut's Personal Achievement "Silver Snoopy" award.*

Laurent Sibille *is a lead technology development scientist and a project lead for Enterprise Advisory Services Inc. (EASI), a partner of Team Vencore-ESC in the Surface Systems Group and the SwampWorks lean development group at NASA's Kennedy Space Center, FL, with specific expertise in space resources utilization. His twenty years of science investigation experience and new technology development for NASA programs have covered many disciplines with particular expertise in materials, materials processing, energy conversion, electrochemical and biochemical systems and their space applications. He was the PI for two Space Shuttle experiments on the formation of low-density materials in low gravity and Assistant Mission Scientist for the United States Microgravity Payload-4 (USMP-4) Spacelab mission aboard STS-87 (1997). He is a graduate of the National Institute for Applied*

Sciences in Toulouse, France as an Engineer of Materials and received a Ph.D. in solid-state physics from the University Paul Sabatier of Toulouse. After his tenure in the microgravity science program at NASA's Marshall Space Flight Center, he co-founded the current Lunar Simulant Materials program in 2005 and the workshop on Lunar Regolith Simulant Materials that has produced simulant materials standards and evaluation tools since. He currently leads technology development in mission concepts for the utilization of space resources, including lunar oxygen production systems, and is a technical lead project manager on the RESOLVE ("Regolith & Environment Science and Oxygen & Lunar Volatile Extraction") prototype payload team, whose mission is to obtain and analyze core samples of lunar icy regolith. Dr. Sibille is an Associate Fellow of the American Institute for Aeronautics and Astronautics (AIAA) and he co-chairs the Educational Outreach sub-committee of the AIAA Space Resources Technical Committee.

Scott Vangen *is currently lead of the Technology Development Assessment Team for HEOMD's Human Spaceflight Architecture Team, in addition to the NASA lead for the International Space Exploration Coordination Group Technology Working Group. Mr. Vangen joined NASA at Kennedy Space Center in 1982, starting his career as an Experiment & Payloads Engineer for numerous space shuttle scientific payload missions. Mr. Vangen served as an Alternate Payload Specialist astronaut for STS-67/Astro-2, an ultraviolet astronomy mission flown on Space Shuttle Endeavour in March 1995. After completing assignments supporting International Space Station ground assembly & checkout operations, Mr. Vangen was named the Chief Operating Officer for the KSC Space Life Sciences Lab in 2003, until he transitioned into the Constellation Program as the Deputy Project Manager for the Lunar Surface Systems Office in 2008. He holds a B.S. in Electrical Engineering from South Dakota School of Mines & Technology, and M.S. in Space Technology from Florida Institute of Technology.*

Julie Williams-Byrd *received a B.S and M.S. in Physics from Hampton University and has10+ years of experience in systems analysis with an emphasis on technology and capability assessment and integration for human spaceflight exploration and 15+ years of experience in development of advanced electro-optics systems with emphasis on laser systems developed specifically for remote sensing of the atmosphere. She began her career at NASA Langley Research Center, developing solid-state laser used in instruments that perform remote sensing of the atmosphere. After several years of laser research and development, she transitioned to the System Analysis and Concepts Directorate, where she provides NASA Human Spaceflight decision-makers with capability and technology assessments and decision analysis products that assist in determining capability investments that enable human spaceflight exploration. She leads a capability development and system maturation integration team. She has authored and co-authored over 30 papers on laser research and systems analysis.*