Proving Ground Potential Flight Test Objectives and Near-Term Architectures

R. Marshall Smith
NASA Headquarters
300 E ST SW
Washington, DC
202-358-0644
marshall.smith@nasa.gov

Douglas A. Craig
NASA Headquarters
300 E ST SW
Washington, DC
202-358-4491
douglas.a.craig-1@nasa.gov

Pedro Lopez Jr.
NASA Johnson Space Center
2101 NASA Pkwy
Houston, TX 77058
281-483-7124
pedro.lopez-1@nasa.gov

Abstract - **NASA is evolving a long-term strategy to pioneer space to expand human and robotic presence farther into the solar system, not just to explore and visit, but to stay. NASA's strategy is designed to meet technical and non-technical challenges, leverage current and near-term activities, and lead to a future where humans can work, learn, operate, and thrive safely in space for an extended, and eventually indefinite, period of time. An important aspect of this strategy is the implementation of proving ground activities needed to ensure confidence in both Mars systems and deep space operations prior to embarking on the journey to Mars.**

As part of the proving ground development, NASA is assessing potential mission concepts that could validate the required capabilities needed to expand human presence into the solar system. An initial step in the proving ground is to establish human presence in cislunar space to enable development and testing of systems and operations required to enable crewed Mars missions in the 2030s and safely explore other deep space destinations. These capabilities may also be leveraged to support potential commercial and international objectives for lunar surface missions.

This paper will identify a series of potential proving ground missions and flight test objectives that support NASA on the journey to Mars and can be leveraged for commercial and international goals. The paper will discuss how early missions will begin to satisfy these objectives, including extensibility and applicability to Mars exploration systems and operations. The initial capability provided by NASA's Space Launch System will be described as well as planned upgrades required to support longer and more complex missions. Potential architectures and mission concepts will be examined as options to satisfy proving ground objectives. In addition, commercial and international participation opportunities will be assessed on their ability to enable the development of exploration capabilities and operations applicable to Mars vicinity and surface missions.

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1. INTRODUCTION

NASA is developing the technology, systems and capabilities necessary to allow humans to live in deep space for extended durations. This is necessary to meet NASA's goal of sending humans to, and from, the Mars vicinity in the 2030s. These goals are outlined in the NASA Authorization Act of 2010 and in the 2010 U.S. National Space Policy. NASA's Human Exploration and Operations Mission Directorate (HEOMD) developed strategic principles for space exploration that were used in the development of the approach to developing necessary system capabilities or potential missions to enable Mars missions. [1] These principles are as follows:

- Implementable in the near term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth
- Exploration enables science and science enables exploration, leveraging scientific expertise for human exploration of the solar system
- 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 and integrated 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
- Resilient architecture featuring multi-use, evolvable space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions
- Substantial new international and commercial partnerships, leveraging current International Space Station partnerships and building new cooperative ventures for exploration

Just like the Mercury, Gemini and Apollo missions were all building blocks to enable humans to live and work in space and on the moon, a similar, well thought out approach will be needed to develop and test the capabilities required for living in deep space for extremely long periods of time. The goal of flight testing is to conduct tests in the environment you are likely to see during the mission. Testing on the ground or in Low-Earth Orbit (LEO) provides an opportunity to evaluate many systems and procedures prior to a deep space mission but still does not capture all the test objectives that should be demonstrated prior to committing humans to a multi-year long journey with no abort capability. The obvious next best location for such testing is in the region near the moon, called cislunar space. This region serves as a "Proving Ground", away from the protection of the Van Allen Belt and sufficiently far enough that operations and systems can be tested in a deep space environment similar to the one that astronauts would see in a typical Mars transit.

To enable these deep space missions, the NASA Human Exploration and Operations Mission Directorate (HEOMD) has defined the goals and multi-phase development plan for an Evolvable Mars Campaign (EMC), as shown in Figure 1.

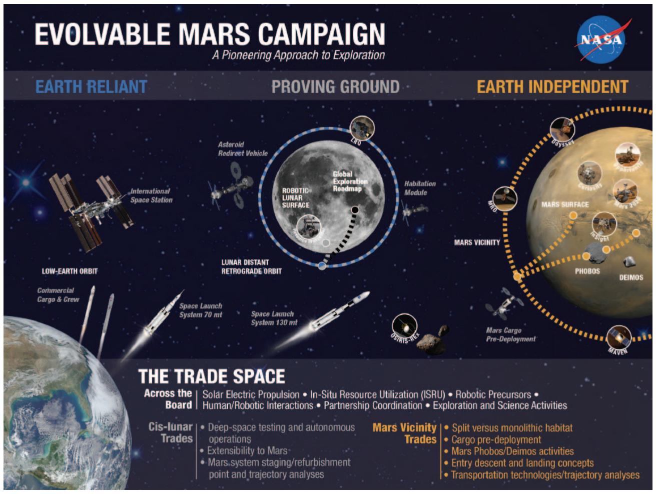

Figure 1: Multi-Phase Approach to Human Exploration of Mars

The EMC team has developed a plan that allows NASA and its partners to test systems in the most appropriate location and environment, as we get ready for the first deep space mission. EMC has divided up the approach into three phases. The Earth Reliant phase details work that can be accomplished in low-Earth orbit aboard the International Space Station (ISS). Astronauts on the orbiting laboratory will help develop and prove many of the technologies needed for human missions to deep space targets, including Mars. Key research and development required will address Human health and behavioral research, Advanced communications systems, material flammability tests, Extravehicular operations, Mars mission class environmental control and life support systems, 3-D printing and material handling tests for in-situ resource utilization (ISRU) demonstrations. The Proving Ground phase details work that must be accomplished in deep space, away from earth's protection. In parallel with the EMC team, the NASA Future Capabilities Team (FCT) has been working on concepts and scenarios for the Proving Ground to demonstrate and validate hardware and operational techniques that are more relevant to Mars than Low Earth Orbit (LEO) can demonstrate. Conceptually, each mission in the proving ground will build on the ones that came before it to enable longer duration missions while reducing reliance on Earth-based systems. Ultimately, these missions will develop the confidence and knowledge required to fly a multi-year human Mars mission. Once we have tested these systems, we will be ready to send humans into the Earth Independent phase allowing us to go further than ever before, enabling missions to planetary bodies in our solar system. We will be able to live and work in transit and surface habitats that can support human life for years, harvest resources from the solar system to generate fuel, water, oxygen, and building materials. NASA's goal is not to go to Mars and return, our goal is to enable a continuous human presence in the solar system.

This paper will discuss the overall objectives NASA has for the Proving Ground, called Proving Ground Objectives (PGOs) as well as flight test objectives supporting the PGOs. Based on these objectives it will discuss basic capabilities that will be needed and possible scenarios and missions that could meet these objectives as we strive toward Earth Independence.

2. PROVING GROUND CAPABILITIES

There are several basic elements required to meet NASA's main goal of sending humans to the Mars vicinity. Obviously, a launch vehicle capable of carrying crew and cargo to deep space destinations will be required. In addition, long duration deep-space habitats and propulsion systems required to move these habitats through deep space to their destinations also will be required. These systems will need to be tested in the Proving Ground to ensure they will perform properly when we are ready to move to the Earth Independent stage.

Transportation Systems

NASA is building a vehicle transportation system capable of meeting proving ground objectives and a number of possible missions scenarios as well as evolving to support Mars or other planetary missions. NASA will need to assemble, launch and service these vehicles and is doing that through the Ground Systems Development and Operations (GSDO) Program. GSDO will provide the support and services for the Space Launch System (SLS) launch vehicle and the Orion crew system. New commercial launch providers will augment the capability of the SLS and Orion, supporting LEO and cislunar missions. HEOMD is working with commercial partners to modernize Launch Complex 39B, develop a mobile launcher, upgrade control systems, and demonstrate ground processing capabilities to enable deep space missions, capable of launching the largest rocket ever built.

Orion is a deep space vehicle capable of supporting a crew of 4 for 21 days in space. Orion will transport the crew to cislunar destinations and return them safely to the Earth. Once NASA has begun assembling systems in cislunar space that are capable of transporting humans to Mars and other destinations the Orion will be used to ferry crew to and from those systems and provide safe-haven should it be necessary. Orion has successfully completed its first test flight, Exploration Flight Test 1 (EFT-1) in December 2014. Orion's next deep space flight test will be an uncrewed mission to cislunar space. As the reference mission is currently defined, Orion will be placed in a Distant Retrograde Orbit (DRO) around the Moon and will exercise most of the systems that don't require crew. The actual orbit destination in cislunar space is still being assessed. In 2021, Orion will conduct a final test flight, conducting its first crewed mission to deep space.

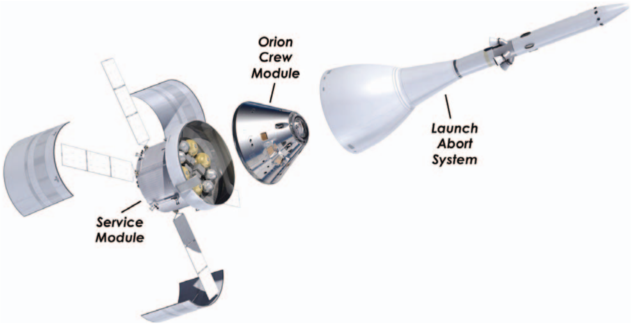

Figure 2: Orion

The Space Launch System is capable of transporting crew and cargo to deep space destinations. The SLS system will evolve to provide additional performance to support deployment of systems to cislunar space and Mars. SLS will be built in Blocks. SLS Block 1 (SLS B1) will be capable of carrying Orion and science experiments to cislunar space. The SLS system is composed of two, 5-segment solid rocket boosters (based on the Shuttle and Constellation Program), a Core Stage with four RS-25 engines (reused from the Shuttle) and an upper stage. The initial upper stage on SLS B1 will consist of an upper stage derived from the Delta Cryogenic Second Stage.

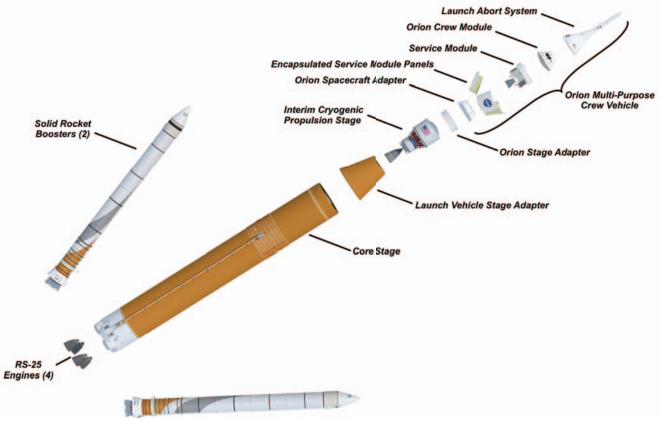

Figure 3: SLS Block 1

NASA will need more mass sent to cislunar space in the future and will require several evolutions to accommodate the systems and cargo required to meet the PGOs. The first evolution planned is the replacement of the SLS B1 upper stage with an Exploration Upper Stage (EUS). This will give NASA the capability of launching crew to cislunar space on Orion along with 10 metric tons of co-manifested cargo to be used at the destination. The volume available to carry co-manifested payloads is in excess of 285m^3, accommodating payloads nearing 10 m in length. This version is called SLS Block 1B (SLS B1B).

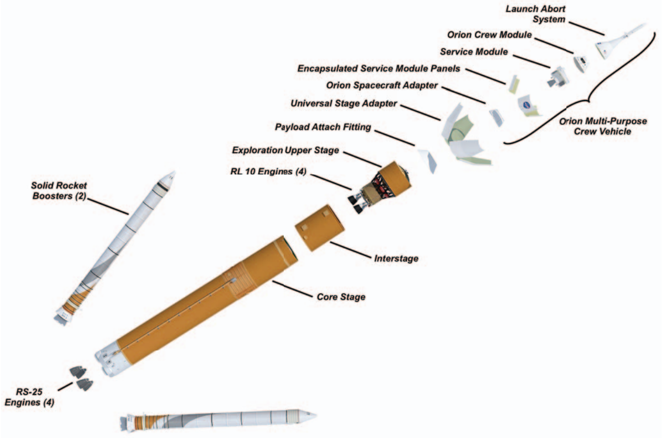

Figure 4: SLS Block 1B

The final major evolution of the SLS will upgrade the two 5-segment boosters to provide significantly more lift capability allowing more mass to be "thrown" to cislunar and planetary destinations. This version is called SLS Block 2 (SLS B2). SLS B2 will also substantially increase the co-manifested cargo capability as well.

Performance metrics for the SLS system commonly is expressed in mass to LEO; however, more important to NASA's campaign is the mass that can be delivered to cislunar and Mars destinations. In addition to delivering crew to deep space destinations, SLS will also be capable of delivering very large payloads using 8.4m or 10m fairings on top of the EUS. This capability will be required for deploying large habitation systems to deep space or the Mars surface. Table 2 below shows the performance requirements on the SLS system for each Block. A key metric is mass capable of being "thrown" to cislunar destinations, commonly expressed in Trans-Lunar Injection (TLI) mass.

Table 1: SLS LEO and TLI Performance

SLS Block	LEO Mass (metric tons)	TLI Mass w/Orion (metric tons)	TLI Cargo Mass (metric tons)
B1	70mt	26.5mt	26.5mt
B1B	105mt	37.5mt	41.5mt

B2	130mt	46.5mt	51.5mt

In-Space Propulsion

The development of new propulsion capabilities is necessary for journeys in excess of 50 million miles. The EMC team is currently considering two options for missions to the Mars vicinity that involve Solar Electric Propulsion (SEP) as well as chemical propulsion. For SEP, NASA is developing an advanced system that will be first demonstrated through an Asteroid Redirect Mission (ARM). The ARM will include an Asteroid Redirect Vehicle (ARV) that is composed of a system to capture a near earth asteroid and return it to the cislunar vicinity for astronauts to sample and interact with during the Asteroid Redirect Crewed Mission (ARCM) (see figure 5 below). [5]

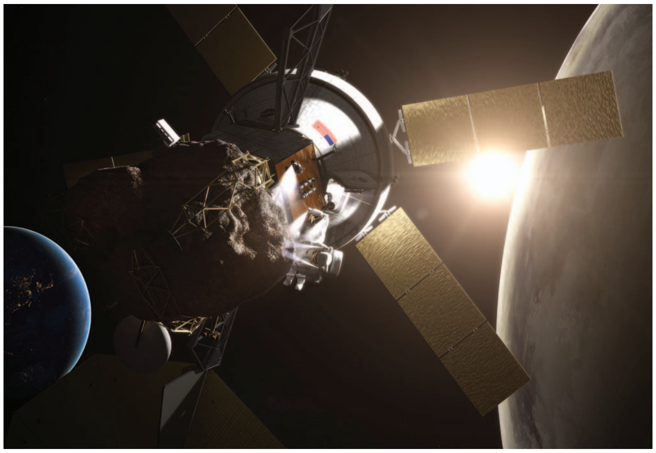

Figure 5: Concept image of an EVA exploring a returned asteroid during a Proving Ground mission in cislunar space. The Orion crew vehicle is pictured docked to the ARV.

One of the major benefits of this mission would be the test and demonstration of a 40-kW SEP system, representing some of the extensibility opportunities offered by ARCM. [6] SEP will be necessary to augment chemical propulsion on human flights as well as serve as the primary propulsion system for pre-placement of systems in Mars orbit or on the surface of Mars. This would represent the first step towards demonstrating higher-power SEP systems (150kW and higher) required to support Mars missions. The launch of the ARM and the initial demonstration of an advanced SEP system is planned for 2020.

In-space chemical propulsion systems, especially if pre-positioned to support the return trip from Mars, will require capabilities such zero boil-off. Various scenarios are being assessed through which such capabilities could be demonstrated in the Proving Ground.

Habitats

Astronauts will require habitats to live and work for long durations in space where they will test materials, systems and research the effect of the deep space environment on humans. In keeping with the guiding principles of staying within current budget profiles, NASA may elect to develop an initial, smaller habitat to enable initial proving ground objectives. This habitat could be built using co-manifested payloads with a crewed mission, extending cislunar operations significantly.

<u>Initial Habitat</u> - Initial cislunar transit habitats will focus on habitation needs for the initial proving ground objectives. Due to the launch constraints and development cost constraint, the initial habitat(s) could focus on developing the short duration habitation capabilities that are needed for elements such as excursion vehicles, Mars ascent vehicles, and Mars taxi. Short duration habitation capabilities are generally small and support crew for a time period of a few days to a few weeks. They may also share design elements and common capabilities with logistical modules. Another option could be to design the initial cislunar transit habitat to support crews of four for 30 to 90 days conducting increasingly Earth Independent operations. Common capabilities across these short duration habitats include partially closed, lightweight Environmental Control and Life Support Systems (ECLSS). These systems will need to operate autonomously and be tele-operated using high bandwidth communication systems. In addition they will have to be maintained over a 15-year lifetime with long periods of dormancy. The initial habitat could also be designed to support EVA systems required to independently maintain the habitat. The habitat would also be used to test the suitability of lightweight exercise systems and start pushing the requirements for maintainability during long dormancy periods between crew stays.

<u>Mars Transfer and Vicinity Long Duration Habitation</u> - Long duration habitation systems also leverage a common, but much larger (about 100m3 for habitable volume with a mass of less than 22mt), pressure vessel to support a crew of four for over 1,000 days. As with many of the short duration systems these habitats will be designed for a 15-year lifetime with reuse across multiple missions. These habitats will require advanced, highly reliable ECLSS systems with high efficiency water and oxygen recovery from CO2 that works with autonomous vehicle health monitoring and repair. Environmental monitoring systems will have to provide onboard detection of containments and microbiological growth. Additional common capabilities in the long duration habitats include exercise equipment for the full crew, radiation protection material, EVA systems common with the short duration habitats to support contingency EVAs, and high-bandwidth communications in local proximity and down link to Earth.

Other Capabilities

In addition to transportation systems, advanced SEP propulsion, initial and long duration habitats, other elements may be necessary to provide for capabilities required in the Mars vicinity. Some of the systems within these elements could be tested in the Proving Ground.

Excursion Vehicles - NASA may need to develop excursion vehicles to provide mobile habitation for a crew of two over two weeks, or a crew of four for one week in the event of a contingency. Many of the systems for the excursion vehicle could evolve from the initial cislunar habitat including similar EVA systems, lightweight Portable Life Support System (PLSS), and exercise equipment.

Landing, Ascent Vehicle and Mars Taxi – The Mars Landing and Ascent Vehicles as well as vehicles capable of moving between these vehicles and the Mars habitation systems will need to be developed prior to the first crewed Mars surface mission. Systems within these elements could also be evolved from those tested in the Proving Ground. Landing and Ascent Vehicles require short habitation duration (~3 days). A taxi may need to maintain an operational state for up to 560 days during Mars surface missions. In addition these systems will have to support long periods of dormancy between crew uses.

Logistics Modules – Logistics modules would be necessary to support long duration crewed missions on the initial as well as the Mars transfer habitation. A logistic module would provide several tons of supplies in a pressurized compartment and could be flown as part of an SLS or an ELV launch. Although not a traditional habitation system this pressurized space can provide additional habitation volume when attached to a vehicle or habitat.

3. OBJECTIVES

Proving Ground Objectives

In order for NASA to have the confidence of successfully completing a Mars vicinity mission, using the capabilities outlined above, Mars mission class spacecraft habitation and transportation systems must be fully tested in deep space. This testing phase, or proving ground phase, will be conducted in cislunar space. The PGOs are summarized in Table 2 and they must be addressed prior to the Mars vicinity missions. These PGOs fall within one of the following categories: Transportation, Working In Space, and Staying Healthy.

Table 2: HEOMD Proving Ground Objectives

PGO#	Category	Title	Objective
1	Transportation	Crew Transportation	Provide ability to transport at least four crew to cislunar space
2	Transportation	Heavy Launch Capability	Provide beyond low-Earth orbit launch capabilities to include crew, co-manifested payloads, and large cargo
3	Transportation	In-Space Propulsion	Provide in-space propulsion capabilities to send crew and cargo on Mars-class mission durations and distances
4	Transportation	Deep Space Navigation and Communication	Provide and validate cislunar and Mars system navigation and communication
5	Working In Space	Science	Enable science community objectives
6	Working In Space	Deep Space Operations	Provide deep-space operations capabilities • EVA • Staging • Logistics • Human-robotic integration Autonomous operations
7	Working In Space	*In-situ* Resource Utilization	Understand the nature and distribution of volatiles and extraction techniques and decide on their potential use in human exploration architecture.
8	Staying Healthy	Deep Space Habitation	Provide beyond low-Earth orbit habitation systems, sufficient to support at least four crew on Mars-class mission durations and dormancy
9	Staying Healthy	Crew Health	Validate crew health, performance and mitigation protocols for Mars-class missions

The strategic principles, coupled with the PGOs establish the baseline for the capabilities and potential scenarios outlined in this paper.

Commercial and International Partnerships

The PGOs and guiding principles, as defined by HEOMD, provide opportunities for commercial and international participation. The goal is to build on the successful international cooperation model illustrated by the International Space Station (ISS). The potential scenarios would include international collaboration in cislunar activities. While current NASA space policy focuses on accomplishing PGOs that are directly relevant to deep space and Mars missions, these objectives also can support international partners desires to further investigate and provide access to the Moon. The architecture developed could be a platform to achieve both NASA's and our International Partners goals.

A set of “common agency goals” has been defined by the ISS Program and its international partners, mapping ISS exploration and cislunar goals to these common agency goals. The set of cislunar goals, mapped to the common agency goals, are shown in Figure 6.

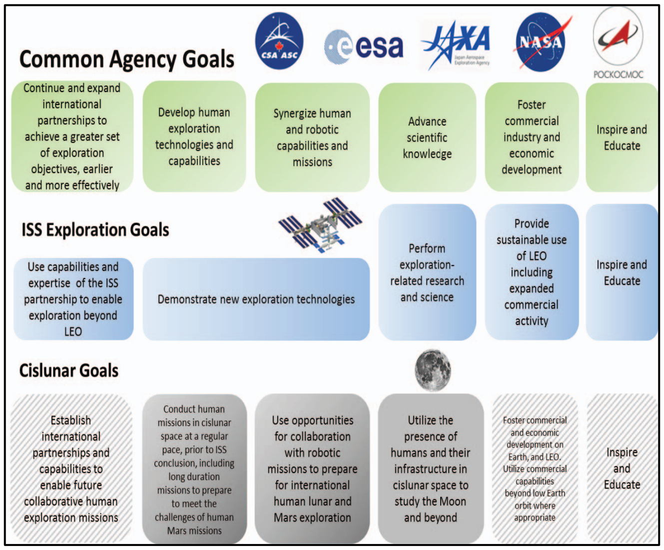

Figure 6: Common Agency Goals Mapped to ISS Exploration and Cislunar Goals.

By applying the principles and PGOs defined by HEOMD, as well as the International Cislunar Goals (see Figure 2), potential FTOs can be identified such that both NASA and International desires are met.

Potential Flight Test Objectives

In order to define a viable Proving Ground scenario that successfully validates the required capabilities needed to expand human presence into the solar system, a set of Flight Test Objectives (FTOs) that are derived from the PGOs should be developed that directly address these capabilities. These flight test objectives could then be used to assess how effective scenarios or campaigns would be in validating the required capabilities.

FTOs describe “how” to get the data that answers the respective PGO’s “what” and “why” questions. Each mission or flight test objective is eventually mapped to numerous requirements to show completion of the objective.

Most system designers are familiar with the verification methods used to validate or verify requirements - analysis, demonstration, inspection or test. The flight test objectives use a different phrasing or structure to satisfy completion and are based on the following:

- Demonstrate = an action or event
- Determine = describe system performance
- Evaluate = compare results against a physics model
- Obtain data = usually environmental and science-related

The Proving Ground flight test objectives document all or part of the rationale for undertaking specific elements of the mission. The flight test objectives for the Proving Ground are further categorized into Transportation, Working in Space, and Staying Healthy.

It should be noted that all candidate FTOs shown in this paper are potential objectives that could be included as part of the Proving Ground. Inclusion of a given Flight Test Objective in this paper does NOT represent any approval or advocacy of that FTO. The purpose is only to provide ideas on how the PGOs could be met through missions in the Proving Ground. Additional architecture, technical, risk, and cost trades must be performed before a final FTO list is derived.

Transportation FTOs define the rationale for undertaking a series of tests or data analyses allocated to a specific mission to characterize performance of the transportation systems, including launch vehicle, crew transport, and in-space propulsion systems. For the Proving Ground, the launch vehicle and crew transport objectives apply only to objectives not previously tested on earlier flights. Potential Transportation FTOs for the Proving Ground are listed on Table 3.

Table 3: Potential Transportation FTOs

Potential Transportation FTOs
Demonstrate Orion’s capability to extract co-manifested payload from SLS fairing.
Determine Orion’s ability to support missions with at least 4-Crew longer than 21 days in conjunction with additional elements.
Evaluate Orion’s mission-specific EVA operations.
Evaluate EUS TLI Performance with Orion plus Co-Manifested Payload.
Evaluate SLS Cargo EUS TLI Performance.
Evaluate high-power electric propulsion systems.
Evaluate high-efficiency, high-power solar arrays in deep space.
Demonstrate in-space SEP system refueling.
Demonstrate in-space chemical propulsion, including long-term fuel storage, zero-boiloff, and pressurization.
Demonstrate in-space chemical propulsion refueling.

Working In Space FTOs define rationale for undertaking a series of tests or data analyses allocated to working in space, including habitation systems, operations, and exploration. Potential Working In Space FTOs for the Proving Ground related to each sub-category are listed on Tables 4 through 6. The FTOs related to exploration (Table 6) include objectives that could be achieved if lunar and asteroid surface activities were included during the Proving Ground..

Table 4: Potential Habitation Working In Space FTOs

Potential Habitation Working In Space FTOs
Demonstrate crew accommodations for Beyond-LEO conditions.

Demonstrate cislunar transit habitat system performance and reliability during missions within Orion abort coverage.
Demonstrate cislunar transit habitat system performance and reliability to support missions beyond Orion abort coverage.
Evaluate the performance of electrical components in a deep-space radiation environment.
Demonstrate Life Support system capability and reliability to support a Humans-to-Mars mission, including dormancy periods.
Demonstrate high bandwidth and high data rate deep space communication capabilities.
Evaluate cislunar transit habitat airlock and EVA system servicing accommodation for ability to support contingency EVA operations.
Evaluate cislunar transit habitat airlock and EVA system servicing accommodation for ability to support nominal deep space mission EVA operations.
Evaluate exercise system capability and reliability.

Table 5: Potential Operations Working In Space FTOs

Potential Operations Working In Space FTOs
Demonstrate transition between crewed and uncrewed operations, including configuration for remote/dormant operations and reactivation for crewed support.
Demonstrate the ability to conduct extended missions of various duration in deep space leading to a Mars-transit type mission.
Demonstrate human spacecraft operations in the presence of communications latency.
Demonstrate autonomous rendezvous and docking (AR&D) methods and technologies to aggregate modules in cislunar space.
Demonstrate independent (On-board) mission and trajectory design/planning capability.
Demonstrate Earth-independent deep space navigation.
Demonstrate independent Maintenance and Repair Capabilities.
Evaluate stowage strategies to handle logistics and trash within available stowage volume for deep space missions.
Evaluate opportunities to reduce cislunar transit habitat system mass.
Demonstrate robotic operations and maintenance of orbiting habitat systems and/or lunar surface systems during quiescent operations or dormant operations.
Demonstrate side-by-side human and robotic operations.
Demonstrate use of the cislunar transit habitat capability to conduct remote robotic operation of systems on-orbit as well as on planetary bodies.

Table 6: Potential Exploration Working In Space FTOs

Potential Exploration Working In Space FTOs
Evaluate technologies and operations that enable future scientific and human exploration of planetary surfaces.
Demonstrate collection and return of geologic asteroid samples.
Demonstrate collection and return of geologic lunar samples.
Determine the distribution, quantity, and chemical/isotopic composition of the hydrogen-rich deposits on/near the Moon's surface in the lunar polar regions.
Demonstrate adaptable cislunar transit habitat accommodations for conducting high priority research objectives and testing Mars mission technologies.
Demonstrate research sample acquisition, handling, analysis, and curation requiring environmentally controlled conditions with no cross-contamination permitted.
Demonstrate mobility on planetary surface to maximize diversity of regions/terrains of study for science and engineering operations.
Demonstrate deployment of a global, long-lived network of geophysical instruments on the surface of the Moon.
Demonstrate cryogenic propellant long-term storage, zero-boil-off, and pressurization on planetary surface.

Staying Healthy FTOs define the rationale for undertaking a series of tests or data analyses allocated to crew health and crew performance in support of the Proving Ground. Potential Staying Healthy FTOs are shown in Table 7.

Table 7: Potential Staying Healthy FTOs

Potential Staying Healthy FTOs
Demonstrate/evaluate human flight operations crew physiological well-being on long-duration deep space human missions.
Demonstrate/evaluate human flight operations crew psychological well-being on long-duration deep space human missions.
Demonstrate/evaluate exploration medical capabilities.
Demonstrate/evaluate space radiation protection and monitoring.
Demonstrate/evaluate human health, performance, and environmental health in a hostile and closed environment.
Evaluate the effects of deep space on complex organisms, plants, food, medicines, and animal models.
Demonstrate/evaluate human health countermeasures.

4. PROVING GROUND SCENARIO OPTIONS

The capabilities and systems described above can be combined into a variety of ways to develop scenarios where PGOs and FTOs can be met. NASA is currently assessing various scenario options that could be pursued to prepare for Mars missions. Although many of these options are somewhat different, they all follow the same steps: develop and test the transportation and propulsion systems, work with an initial habitat system to develop necessary technologies to be placed in a long duration habitat, and then test out a Mars-class habitat and in-space propulsion. These steps are described below in more detail.

Developing the SLS and Orion transportation system will be the first PGOs addressed. SLS B1 will carry Orion on its first deep space mission on Exploration Mission 1 (EM-1), in 2018. This flight test will be the first integrated test of SLS and Orion, including characterizing SLS's launch ascent and TLI performance, Orion's heat shield, and deep-space propulsion communication and navigation capabilities. SLS B1 has limited capability to support the further development of the PGOs so NASA will move forward quickly to SLS B1B, adding the EUS, significantly improving the SLS's ability to throw more TLI mass, and the ability to carry co-manifested payloads. SLS B1B is targeted to be available for EM-2 in 2021 for the first crewed test flight and could carry pressurized logistics modules that would extend the deep-space capabilities of the Orion spacecraft and help develop a deep-space habitation capability on the initial crewed flight.

Once the transportation system is tested SLS and Orion will be expected to launch crew and co-manifested cargo once per year to support key missions and capability demonstration concepts through the 2020s to ensure progress toward Earth Independence. These missions could include the launch of the asteroid robotic redirect mission and SEP demonstration in 2020 and the first crewed mission to the redirected asteroid in 2025.

Using SLS Block 1B and Orion the crew would be expected to deploy, build and incrementally increase the capabilities of a habitats in cislunar space. The missions would be of increasing duration and complexity as systems are tested for Mars-class capability. These conceptual missions would not only demonstrate the ability to live and work beyond LEO, but they could accomplish the PGOs and FTOs required to validate key operational capabilities to becoming Earth Independent by the 2030s.

In keeping with the guiding principles of staying within current budget profiles, and using the capability offered by the SLS Block 1B vehicle, the initial cislunar habitat would be built based on 10t elements launched as co-manifested payloads with Orion. The initial habitat elements will serve to augment the capabilities of Orion in cislunar space, providing additional capabilities for crew habitation, utilization, and stowage and enabling longer-duration missions. These habitat elements could be provided by international and/or commercial partners or built by NASA. The initial habitat could also provide docking capabilities to allow other elements to be co-located in cislunar space, including Orion, logistics modules, and additional habitation elements. SLS could continue to deliver modules on subsequent missions increasing the capability for the initial habitat to support longer duration missions and deliver for testing new systems. Logistics and additional utilization payloads could be delivered to the initial habitat via Logistics Resupply Modules, co-manifested on crewed missions or delivered commercially. Concepts for the initial habitat are shown in Figures 7 and 8. Figure 7 shows the Orion with the first habitat module and an airlock, while Figure 8 depicts a habitat module with a dedicated docking element and an electric propulsion bus. Additional modules could be added should it be advantageous to meet PGOs and FTOs.

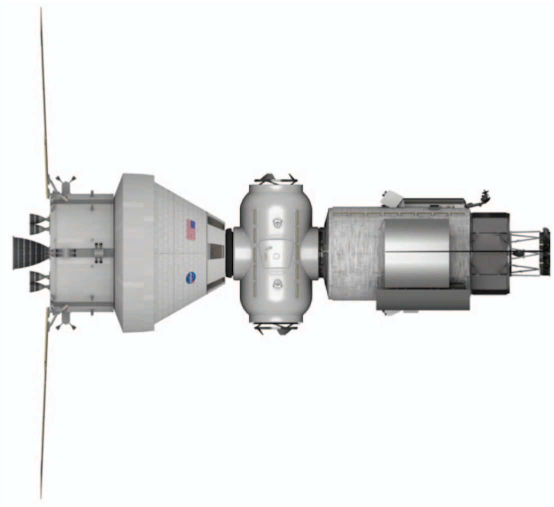

Figure 7: Concept for Initial Habitat with Airlock.

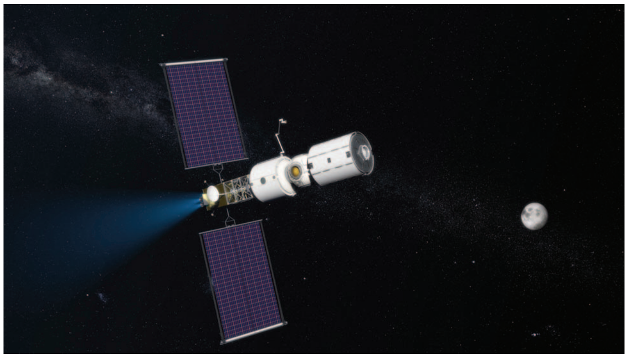

Figure 8: Concept for Initial Habitat with Dedicated Node and Electric Propulsion Bus

NASA will take the lessons learned from the SEP system tests and experience gained from the testing and operations on the ISS and the initial habitat to develop the Mars Transfer Habitat (MTH). The MTH will require a much larger habitat with much higher reliability. SLS B2 will be required to put a system of this size in cislunar space, along with its chemical/SEP propulsion system. It is anticipated that this class of mission will be needed in the late 2020's to meet Mars mission timelines in the early 2030's. Missions in the late 2020's would deliver the Mars-class habitat and a large solar-electric power and propulsion bus to cislunar space. This habitat would be used to test capabilities required for Mars missions that are not addressed by the ISS or the initial small crew-tended habitat. That same habitat could then be used for an initial crewed mission to deep space or even to the Mars vicinity (e.g. visit Phobos). The habitat includes an advanced life support system, developed from knowledge gained from ISS and the initial habitat, to be able to recycle water and oxygen with very little loss. The power and propulsion bus could drive the combined Cislunar Transit Habitat stack on excursions lasting up to a year, visiting destinations within and beyond the Earth-Moon system, further demonstrating the capabilities needed for Mars missions. [7] Between such potential excursions, the stack would operate in lunar orbit. There it can serve as a transportation hub and refueling depot for human landings on the Moon, led by NASA's international collaborators. Figure 9 shows a conceptual view of the Mars-class habitat and SEP bus.

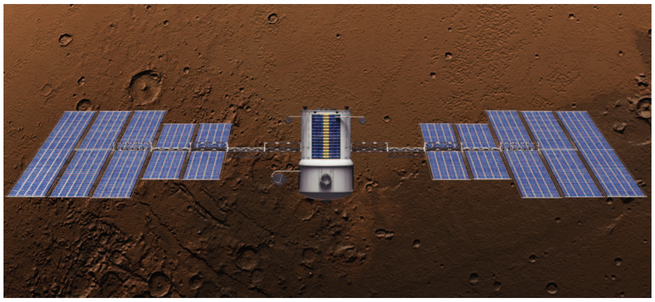

Figure 9: Conceptual View of a Mars-Class Habitat and SEP Bus.

Activities in the Proving Ground pave the way for human exploration of Mars by building up spacecraft capable of sustaining crews for years, and potentially taking that spacecraft on excursions through, and later away from, the Earth-Moon system. Such development scenarios can be designed so that the spacecraft is built in a logical sequence, tolerate delays and changes in the launch order of its components, provide adequate logistics traffic, respect projected budgets and SLS/Orion flight rates, provide engaging flight activities each year, accommodate participation from commercial and international partners, and execute exploration missions of increasing range and difficulty that could include a human exploration mission of an asteroid in its native orbit.

When our experience with long duration flights in deep space with reliable systems, healthy crews, and relative independence from Earth reaches a high enough level, the Proving Ground will draw to a close and we would be able to commit to human exploration of Mars and other deep space points of interest.

6. CONCLUSIONS

This paper has shown that a long-term strategy to pioneer space that extends humans and robotic presence into the solar system requires the development and validation of new capabilities in areas such as launching crew and heavy cargo beyond low Earth orbit, deep space navigation, habitation systems, environmental control and life support systems, autonomous deep space operations, and high reliability in-space transportation systems. Developing, testing and validating these capabilities in a deep space environment is essential to gain the confidence that the systems are ready for missions to the Mars vicinity. The deep space testing area, or cislunar proving ground, is a key aspect to NASA's strategy in the capability validation for future human exploration missions throughout the solar system. These capability validation activities form the foundation of the Proving Ground Flight Test Objectives which will be satisfied through a steady cadence of missions and test demonstrations in cislunar space. This cadence of missions can be satisfied by several different mission manifest options in the early phase of the proving ground with the final set of missions being selected by taking both technical and non-technical factors into consideration. The final mission manifest selected will implement the proving ground activities that are crucial to ensure confidence in both Mars systems and deep space operations prior to embarking on the journey to Mars.

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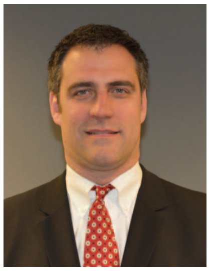
BIOGRAPHY

Douglas A. Craig *received his Bachelor of Science in Aeronautical & Ocean Engineering from the Virginia Polytechnic institute and State University and a Masters of Business Administration from the Florida Institute of Technology. Mr. Craig began his* *career working for the Air Force at Wright-Patterson AFB as a systems engineer for the Advanced Tactical Fighter (ATF) program. He then joined NASA and has worked in various NASA program offices at NASA's Kennedy Space Center, Langley Research Center and Headquarters. Mr. Craig is currently the Manager of Strategic Analyses for the Human Exploration and Operations Mission Directorate's (HEOMD) Advanced Exploration Systems (AES) Division at NASA Headquarters. His responsibilities include leading the human exploration architecture studies, co-leading the System Maturation Teams capability and technology roadmap development; modeling and simulation for architecture analysis; leading the AES crew mobility domain, overseeing the habitation contracts in the NextSTEP broad agency announcement activity as the contract officer representative; and leading the creation of associated partnerships.*

Pedro Lopez Jr. *received his B.S. and M.S. in Mechanical Engineering from the University of Texas – Pan American in 2000 and 2003, respectively, and his Ph.D. in Mechanical Engineering from Rice University in 2014. He joined NASA JSC in 2007. He currently works as the a Systems Engineering & Integration (SE&I) Lead for the Exploration Mission Planning Office (EMPO), and is currently the chair for the Future Capabilities Mission Design Team, which has been tasked with producing mission design documents for the Proving Ground. Prior to this, he worked as an SE&I Lead for the Advanced Mission Development Group (AMDG), designing concepts for various potential mission scenarios including the Asteroid Redirect Crewed Mission (ARCM). He started his JSC career working as the Aerothermodynamics and Aerodynamics Technical Manager for the Space Shuttle Program SE&I Office, while also serving as the Debris Integration Group (DIG) Deputy Manager.*



R. Marshall Smith *received his Bachelor of Science in Electrical and Computer Engineering Bachelor of Science in Electrical Engineering in from the University of Tennessee in 1987 and a Master of Science in Electrical Engineering from Virginia Polytechnic Institute and State University in 1991. Mr. Smith is currently the Deputy Director of Cross-Program Systems Integration (CSI) in the Exploration Systems Division (ESD) at NASA HQ. ESD is the arm of HEOMD responsible for the development, integration and operation of the systems required for the deep space missions. ESD is currently developing the SLS, Orion and GSDO systems and CSI is responsible for integrating them into a working system. Prior to this, Mr. Smith worked at Langley Research Center, serving as SE&I Chief for the Ares I-X mission that flew the first large-scale vehicle that NASA has designed and launched in 30 years. Before the Ares I-X assignment, he supported human spaceflight vehicle development and oversaw projects in science and robotic mission areas. In the early stages of his career, Mr. Smith was a leader in the development of flight simulation and aircraft systems to meet engineering, development and research goals.*