Mars Base Camp

An Architecture for Sending Humans to Mars by 2028

A Technical Paper Presented by:

Timothy Cichan
Lockheed Martin Space
timothy.cichan@lmco.com

Stephen A. Bailey
Deep Space Systems, Inc.
stephen.a.bailey@lmco.com

Scott D. Norris
Lockheed Martin Space
scott.d.norris@lmco.com

Robert P. Chambers
Lockheed Martin Space
robert.p.chambers@lmco.com

Robert P. Chambers
Lockheed Martin Space
robert.p.chambers@lmco.com

Joshua W. Ehrlich
Lockheed Martin Space
joshua.w.ehrlich@lmco.com

October 2016

978-1-5090-1613-6/17/$31.00 ©2017 IEEE

Abstract—Orion, the Multi-Purpose Crew Vehicle, is a key piece of the NASA human exploration architecture for beyond earth orbit (BEO). Lockheed Martin was awarded the contracts for the design, development, test, and production for Orion up through the Exploration Mission 2 (EM-2). Additionally, Lockheed Martin is working on defining the cis-lunar Proving Ground mission architecture, in partnership with NASA, and exploring the definition of Mars missions as the horizon goal to provide input to the plans for human exploration of the solar system. This paper describes an architecture to determine the feasibility of a Mars Base Camp architecture within about a decade. This architecture would involve human exploration of both Martian moons, and provide an opportunity for the crew to interact with pre-staged robotic assets on Mars.

This study is a high-level assessment to identify architecture drivers and science opportunities. There are several key tenets for this architecture. For this first human interplanetary mission, system redundancy and a self-rescue capability is required. The number of system developments is minimized, and the use of the already developed systems like the Space Launch System and Orion is maximized. To minimize the number of events that could lead to the loss of the whole crew, the architecture does not require rendezvous and docking of pre-staged elements necessary for crew survival during the mission. This paper will describe the different enabling technologies required.

The trajectory assumptions will be described, including the results of studies performed for the transit to Mars and return to Earth, in addition to mission design trades for the exploration of the Martian system. The transfer vehicle module design concept will be detailed. Possible science activities will be described. Study results for propulsion technology, assembly methods, and the mission campaign will also be addressed, as well as a discussion of planned forward work. The results of this architecture study will show that a near term Mars mission is compelling and feasible, and will highlight the required key systems.

Table of Contents

1. Introduction

In 2010 to 2015, Lockheed Martin described a series of increasingly challenging Stepping Stone exploration missions to incrementally push farther into space and explore for longer durations [1-5]. Background content surrounding these initial studies can be found in earlier publications [6,7]. The Stepping Stones plan took full advantage of the Orion MPCV's capability beyond LEO and provided opportunities to perform and perfect telerobotic surface operations from orbit, space maneuvers near small bodies, and sample return. Lockheed Martin is currently working on Exploration Missions 1 and 2, on the production strategy for the EM-3 and up vehicles, and defining the cis-lunar Proving Ground mission architecture, in partnership with NASA. Independently, Lockheed Martin has developed the Mars Base Camp concept as a bold and achievable plan to get humans to Mars orbit. This plan is used to determine the feasibility of a Martian moons human exploration architecture within about a decade. The vision of Mars Base Camp is to transport scientist-astronauts from Earth to the moons of Mars to answer the fundamental science questions and prepare for a human Mars landing. The architecture involves human exploration of both Martian moons, and provides an opportunity to obtain samples from Mars by operating robotic assets pre-staged in orbit and on the surface of Mars. Mars Base Camp lays out a proposed technology road map to support NASA's Journey to Mars [6]. This is a mission designed to be led by NASA and its international and commercial partners. As exemplified by collaboration on the International Space Station, the contribution of additional resources, technology, expertise and investment will enhance the value and number of scientific investigations performed at Mars. A crewed orbital mission is a prudent and necessary precursor for a human Mars landing.

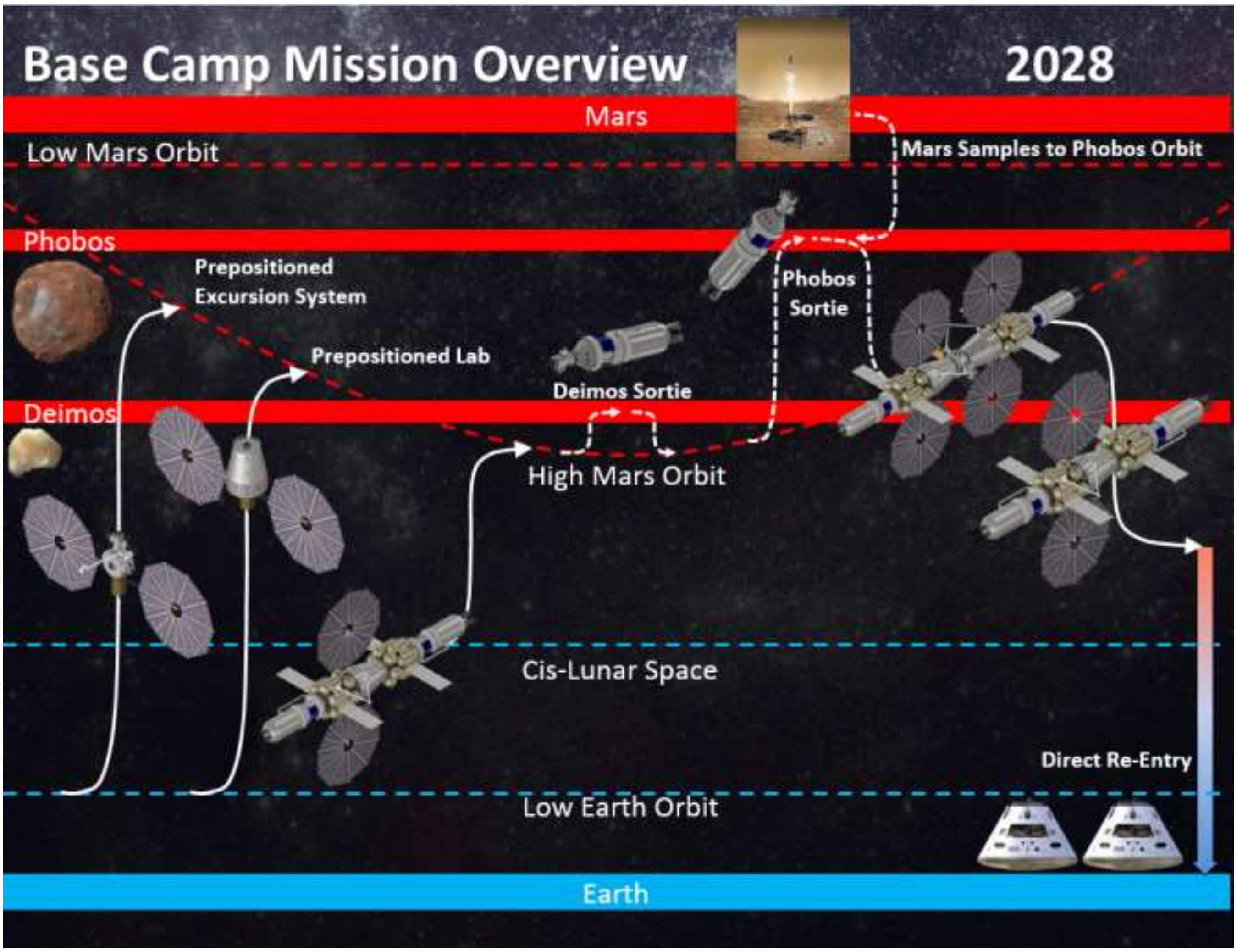


Figure 1. Mars Base Camp Mission Overview, Including SEP-Delivered Vehicle Components

2. Architecture Purpose and Tenets

The purpose of this architecture study was to determine the feasibility of a Martian moons human exploration architecture within about a decade to support the Mars Base Camp vision. The study was a high-level assessment of the mission concept, major elements and their technology, and scientific goals. The key science questions include: “Where did we come from?”, “Where are we going?”, and “Are we alone?” To address these questions, the MBC systems are designed to:

- Perform remote sensing and teleoperation of science ground assets on the surface of Mars
- Perform in-situ investigation and sample return from Phobos
- Perform in-situ investigation and sample return from Deimos
- Perform rendezvous and capture of Mars surface sample canisters in Mars orbit

The Mars Base Camp concept is built on a foundation of present-day technologies – making it safe, affordable and achievable – including currently mature and rapidly maturing programs and systems:

- Orion: The world’s only deep-space crew spacecraft, built for long duration deep space flight, with a multi-layered strategy for supplementing high reliability with deliberate levels of full fault tolerance, graceful degradation in the presence of multiple faults, and emergency systems focused on crew survival.
- Space Launch System: Super heavy lift system designed to send crew, critical labs, habitats and supplies to Mars.
- Habitats: Building on Lockheed Martin’s NextSTEP research for NASA [8], deep space habitats will give astronauts a safe place to live and work on the long voyage into Mars orbit and their subsequent return.
- Solar Electric Propulsion: Based on technology demonstrated in Earth orbit and in deep space, this advanced propulsion will pre-position modules in Mars orbit and haul items to HEO.

A few key tenets were selected to help drive the architectural solutions. This includes minimizing the number of system developments and maximizing the use of the already developed systems. There is no need to create new complex development programs if solutions already exist. For example, Orion is the core of the Mars Base Camp vehicle. Orion is architected with capabilities that include long duration, independent operation in deep space with layers of redundancy for mission robustness and crew safety. Orion can perform high-speed, precision Earth re-entry from any lunar return trajectory and all MBC-designed Mars return trajectories. Some of the roles Orion performs in the Mars Base Camp architecture are:

- Command and control flight deck
- Phobos and Deimos sortie vehicle
- Short duration contingency lifeboat
- Integral Earth reentry vehicle for simple and safe mission operations

For this first human interplanetary mission, system redundancy and self-rescue capability is required. Aborts from LEO take as little as 90 minutes to be safely back on Earth’s surface. Aborts from cis-lunar space take on the order of five to ten days depending on the orbit type. Aborts during a Mars mission are much less feasible, and would take months if executable. The crew of Mars Base Camp will need to be able to move to redundant elements if there are system failures in order to plan out and perform repair operations. They will also need to be able to perform rescue operations for any sortie missions. For the Mars Base Camp architecture there are no required rendezvous and docking operations of pre-staged elements at Mars or upon return to Earth that, if failed, would lead to loss of the crew. Examples of pre-staged elements include scientific modules, equipment, and consumable supplies not required to sustain the crew. For this reason, the Earth re-entry vehicle remains with the crew. This is to avoid single events that lead to loss of the crew.

The Mars Base Camp architecture is designed to include participation of commercial and international partnerships. From flight-proven hardware, such as robotic arms and laboratory modules on the ISS, to innovative concepts surrounding in-space propulsion and deep space habitats [9], utilization of technologies through government and industry partners is not just an ideal scenario to consider but one that is essential to turning MBC from concept to reality. Over the last several decades, commercial and international collaborations have become an essential building block in the design and maturation of space technologies and science missions, particularly in the context of larger and more complex missions. Access to space involves a group of private industry and global entities, many of which can provide a variety of options for supporting Mars Base Camp. Some possibilities for international collaboration include providing modules like the science laboratory or the center node, and providing major elements like a cupula, robotics arm, or solar arrays. Robotic science elements, such as rovers, that are pre-staged on Mars are another contribution possibility. Logistics flights will also be required both during the cis-lunar proving ground phase and during the build-up of the Mars-bound vehicle, which could be provided by international and commercial entities.

3. Mission Campaign, including Proving Ground Missions

A series of missions, starting with EM-1 in 2018, will be required to meet NASA's required objectives [10] for the Mars proving ground in cis-lunar space and to build up the Mars Base Camp system. Table 1 is a summary of a proposed mission campaign.

EM-1 includes a full system test of Orion and SLS transportation during a cis-lunar multiple week exploratory mission, certifying the system for human deep space exploration. The mission will demonstrate autonomous operations and on-board automation balanced with the ground mission operations. An ascent abort test to be performed in 2019 will certify Orion's Launch Abort System by performing an ascent abort off a test booster launched from Cape Canaveral. Mars Rover 2020 is critical for understanding the Mars surface and preparing for Mars Base Camp robotic science missions and the subsequent human landing. The mission includes Mars surface exploration and sample caching.

EM-2 will be the first crewed mission for SLS and Orion, and the first flight of SLS's EUS. It is also proposed to be the start of the outpost missions in cis-lunar space to begin addressing proving ground objectives. The initial outpost would be delivered by commercial launch and its SEP capabilities before the crew arrived. The initial outpost will also provide opportunities for scientific experiments, both during crew-tended periods and the untended periods between missions. The Next Mars Orbiter is planned to provide enhanced remote sensing capabilities, high-rate communications, and possible sample storage or transportation. EM-3 will continue the outpost's assembly in cis-lunar space.

Table 1. Proposed Proving Ground Mission Campaign

Date	Mission	Description
2018	EM-1	SLS and Orion are certified for human deep space exploration
2019	Ascent Abort Test	Orion's Launch Abort System, the crew escape method during a launch or ascent emergency, is certified
2020	Mars Rover 2020	Perform Mars surface exploration and sample cache
2021	EM-2	Begin the outpost's assembly in cis-lunar space
2022	Next Mars Orbiter Exploration Mission 3	The Next Mars Orbiter will provide an improved communications relay system essential for providing high bandwidth communications back to Earth and images of Mars sites at high resolution. EM-3 will continue the outpost's assembly in cis-lunar space.
2023	EM-4	Cis-lunar exploration enabled by solar electric propulsion—proving the ability to pre-deploy components to Mars
2024	EM-5	Conduct cis-lunar scientific exploration using propulsion and the deep space laboratory—demonstrating tele-operations and sample retrieval capabilities
2025	EM-6	Long-duration, low-gravity science operations with ARM — gives astronauts an opportunity to test-drive a Mars-class mission
2026	Mars 2026	Pre-deploy Mars Base Camp science assets with solar electric propulsion
2027	EM-7 & EM-8	Conduct full system tests of the assembled Mars Base Camp ahead of departure for Mars
2028	MBC-1	Depart for Mars

Before the crew arrives in Orion for EM-4, the prototype assembly platform will be delivered by solar electric propulsion. The ARM will also be demonstrating SEP's capability to transport large masses in deep space in this timeframe. A prototype crew quarters will be co-manifested with Orion. As the proving ground missions proceeds and mission durations increase, supplies and consumables will be delivered by commercial or international partnership launches. During EM-4, the crew will checkout systems, perform science experiments, and make progress against proving ground objectives. Before the crew arrives for EM-5, a prototype propulsion module will be launched. A prototype laboratory will be co-manifested with Orion, and EM-5 will be able to conduct cis-lunar scientific exploration using propulsion module and the deep space laboratory. They will demonstrate tele-operations and sample retrieval capabilities.

Co-manifested with EM-6 will be the first element of the Mars Base Camp vehicle, the large habitat. Along with the prototype modules already assembled, EM-6 will be a year-long duration shakedown cruise to test out systems. This mission will include low gravity EVA operations during the ARM portion of the mission. A visit to an asteroid in its native orbit is also being considered. The main assembly missions involving the use of crew, EM-4 to EM-6, is shown in Figure 2. In 2026, during the timeframe of the shakedown cruise, science assets like the excursion system/assembly platform, laboratory, and robotic assets will be pre-deployed to Mars with SEP stages. In 2027 and 2028, the MBC crew quarters/propellant tanks, propulsion stages, and consumables will be launched. EM-7 and EM-8 will be dedicated to assembly and full system tests. By the end of EM-8, all of the proving ground objectives will be completed. The objectives are:

- Transportation
    - Crew Transportation
    - Heavy Launch Capability
    - In-Space Propulsion
    - Deep Space Navigation and Communication
- Working In Space
    - Science
    - Deep Space Operations
    - In-situ Resource Utilization
- Staying Healthy
    - Deep Space Habitation

- ○ Crew Health

This progression of missions to a Mars Base Camp is not focused on minimalism [11], and could arguably be reduced in scope or bypass certain cis-lunar steps in order to reduce cost. However, the mission sequence is intended to be executed without any substantial increase in the current inflation-adjusted NASA human exploration budget, given a phased retirement of the International Space Station beginning in 2024. The key to a cost-effective near-term human exploration program for Mars, which begins with an orbital Mars Base Camp, is the choice of mature and nascent technologies throughout the architecture. The key emerging technologies upon which the MBC is dependent do not require any fundamental breakthroughs.

4. Mission Description and Concept of Operations

The initial steps to enable a Mars Base Camp mission have already begun. EFT-1 has been successfully accomplished [12]. EM-1 is in assembly and test at the Kennedy Space Center for launch scheduled in 2018, and EM-2 is on track for launch of the first deep space exploration crew, establishing a pathway that leads to Mars Base Camp and future human exploration of our solar system. That path leads through cis-lunar space, the proving ground for increasingly ambitious missions, in a logical progression that demonstrates capabilities in near Earth space before departure on missions of 1000 days and more.

The expedition begins with the prepositioning of mission elements that are important for mission success but are not essential for the survival of the crew. This includes the preplacement, via 350kW class SEP [13], of the Phobos/Deimos Excursion System, the Laboratory and science equipment, the Center Node, and certain consumables that are not required for survival.

While these pre-placed system elements are in transit to the 1-sol Mars Base Camp orbit, the final assembly of the Base Camp Transit Configuration demonstrates capabilities in near Earth space before departure on missions of 1000 days and more. The expedition begins with the prepositioning of mission elements that are important for mission success but are not essential for the survival of the crew. This includes the preplacement, via 350kW class SEP [13], of the Phobos/Deimos Excursion System, the Laboratory and science equipment, the Center Node, and certain consumables that are not required for survival.

While these pre-placed system elements are in transit to the 1-sol Mars Base Camp orbit, the final assembly of the Base Camp Transit Configuration is completed in HEO. Depending on the cis-lunar precursor mission architecture, this HEO may be a DRO, L2 Halo Orbit, NRO or simply a highly elliptical Earth orbit [14]. A HEO orbit is chosen based on its relatively low departure ΔV and the ability to support crew/ground training for increasingly remote operations, micro gravity operations, and telerobotics and telepresence operations on planetary surfaces from orbit.

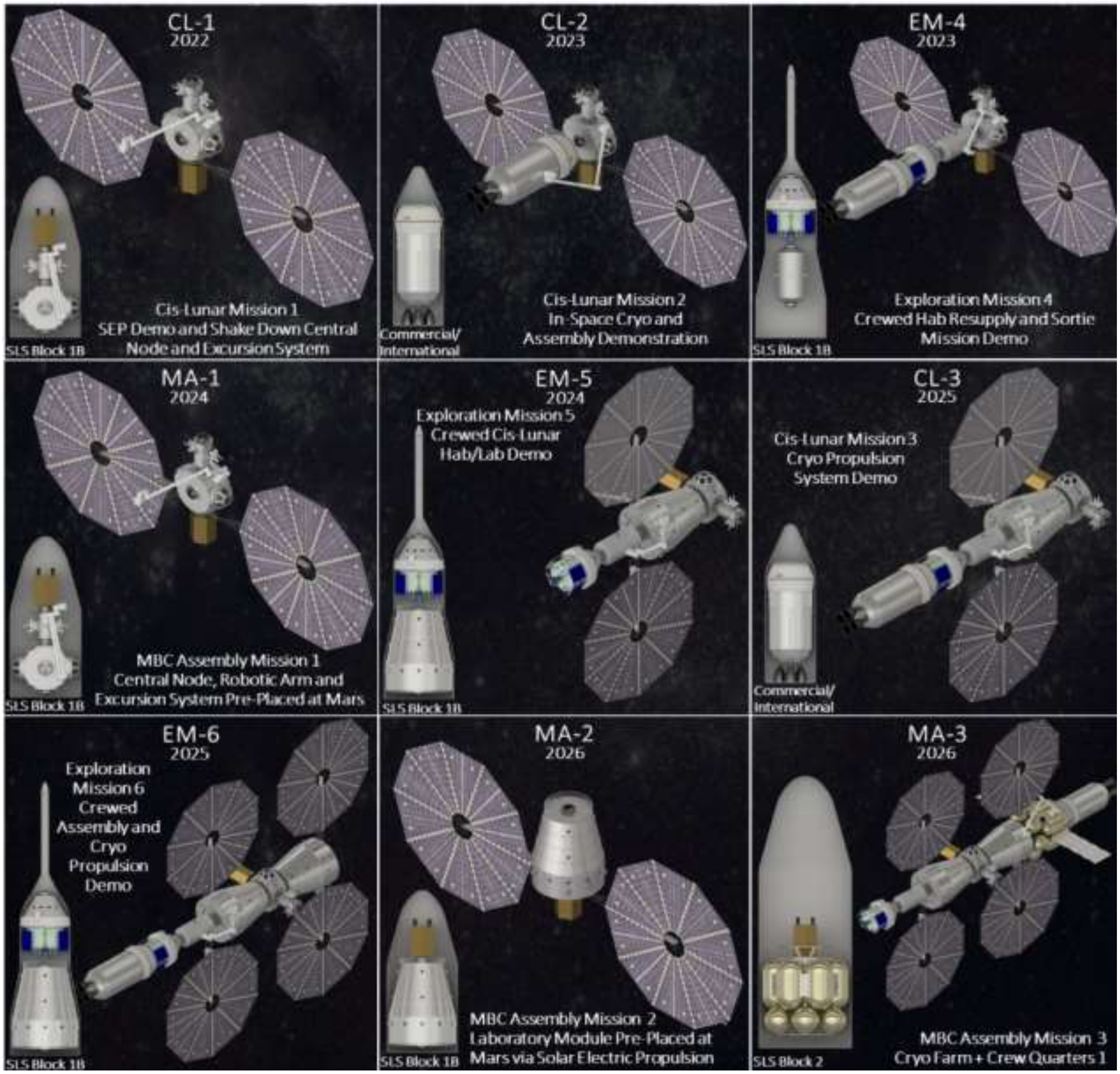


Figure 2. The MBC Launch Sequence through 2026 Includes Stepping Stone Mission in Cis-Lunar Space

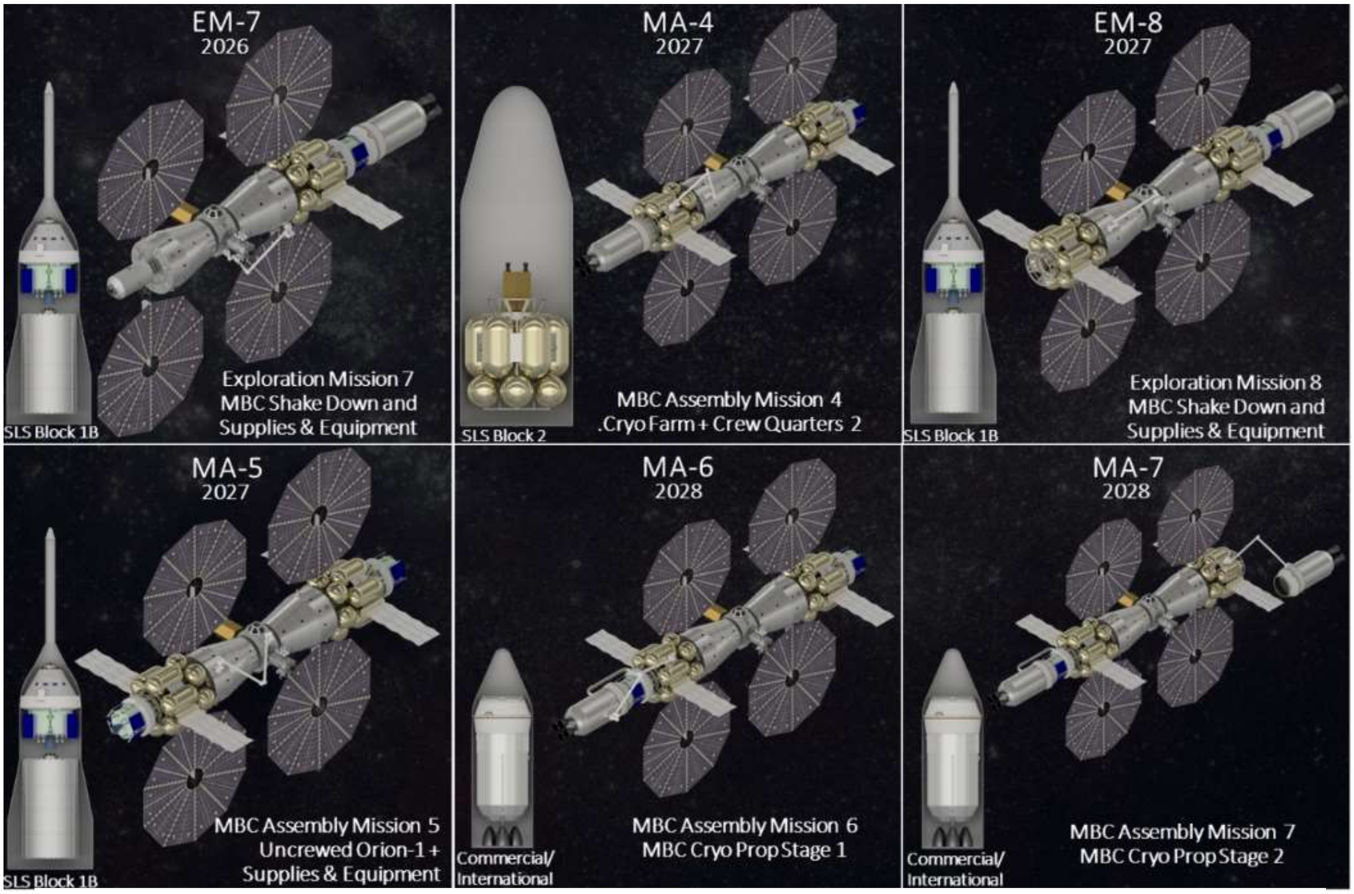


Figure 3. MBC Launches through 2028 to Complete the Mars Base Camp Earth Departure Configuration

The Transit Configuration is essentially identical for both trans-Mars and trans-Earth transportation of the crew and consists of two copies of all modules that are necessary for safe crew return in the event of a major element-level malfunction. The prototype Lab, Node, and Excursion System stay behind for further use in cis-lunar space. Once the Transit Configuration arrives in the 1-sol Science Orbit, it is mated with the elements pre-placed via SEP to form a unique expedition-class planetary science vehicle capable of supporting human exploration sorties to both Phobos and Deimos as well as robotic telepresence exploration and sample return from the surface of Mars.

Prior to the Mars Base Camp Assembly Mission sequence depicted in Figure 2, key elements of the Mars Base Camp are validated in shake down missions in cis-lunar space, including the Habitat, Excursion System, Cryogenic Propulsion, Power Generation, Solar Electric Propulsion (SEP), and Central Node elements. The nomenclature used to describe individual launches and missions is as follows:

- EM-N: Exploration Mission N, an Orion CM/SM + Co-Manifested Payload on an SLS Block 1B
- CL-N: Cis-Lunar Stepping Stone N, a cis-lunar flight test configuration that does not include Orion
- MA-N: Mars Base Camp Assembly mission N, MBC elements that will be assembled into the MBC system, destined for Mars Orbit, via either SEP pre-placement direct to Mars, or via SLS Block 1B, Block 2, or Commercial/International launch for assembly in High Earth Orbit
- MBC-1: The final launch of the Mars Base Camp Crew and supplies for departure to Mars

The 1-sol Science Orbit is chosen to allow surface synchronized telerobotic operations while optimizing the split between the large Transit

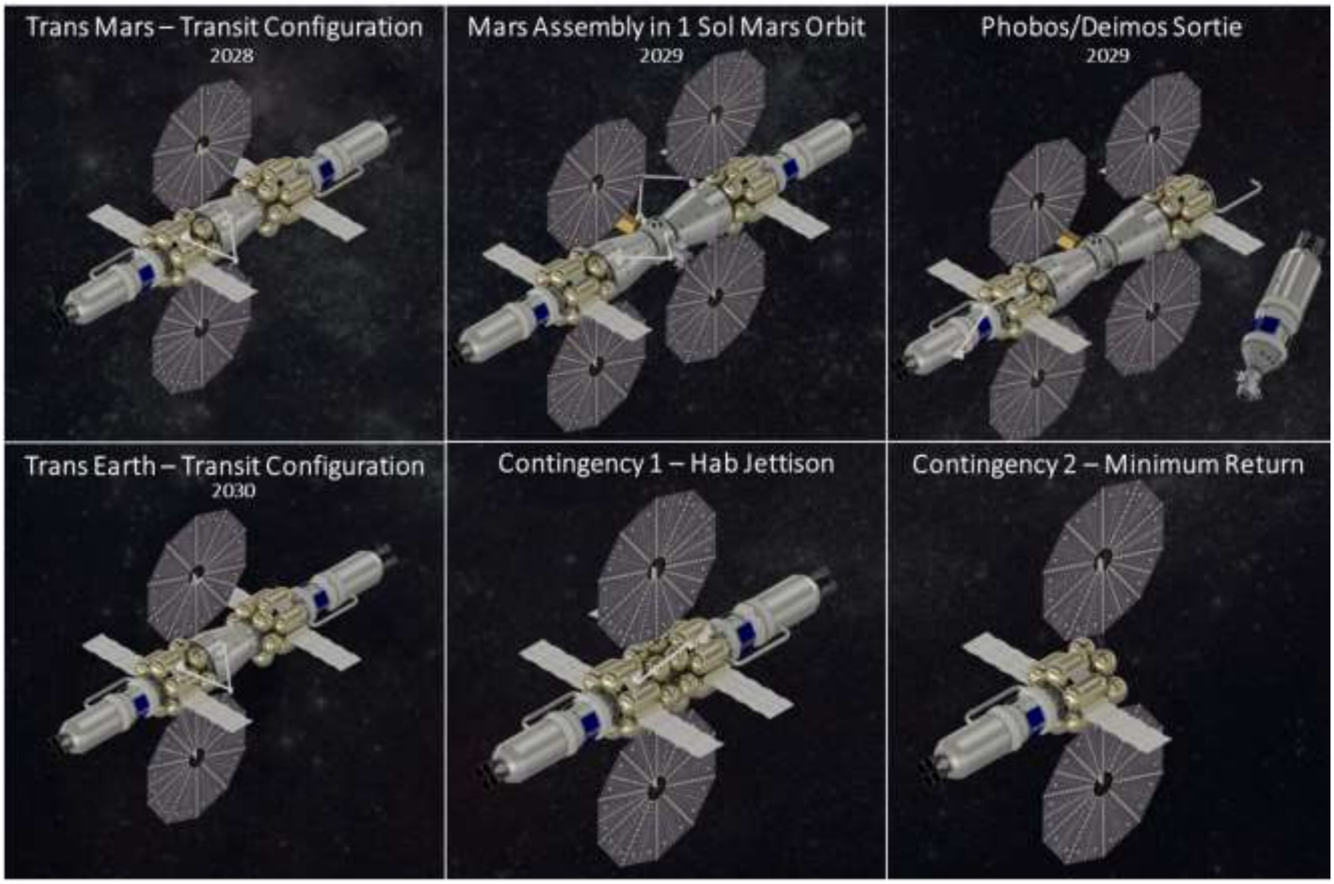
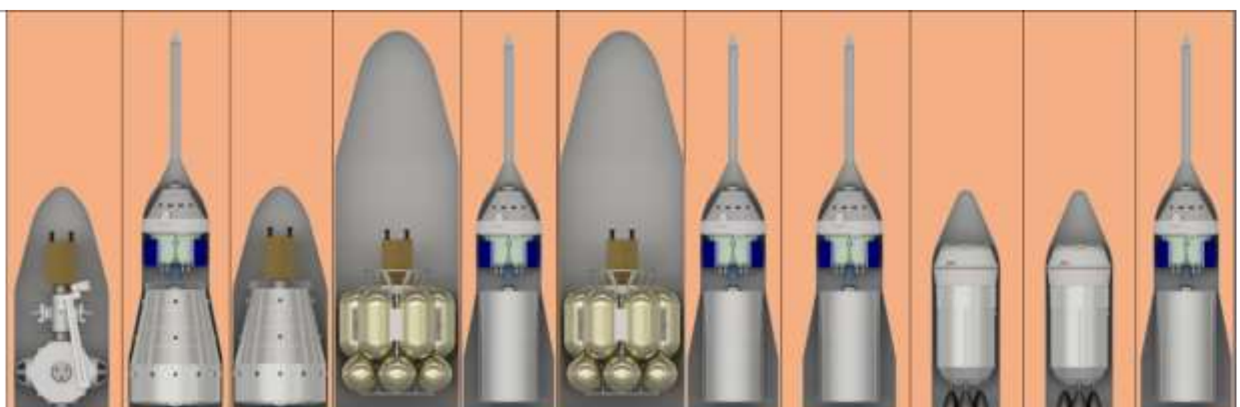


Figure 4. Mars Base Camp Primary and Contingency Configurations



Mission	MA-1	EM-6	MA-2	MA-3	EM-7	MA-4	EM-8	MA-5	MA-6	MA-7	MBC-_1
Vehicle	SLS Block-1B	SLS Block-1B	SLS Block-1B	SLS Block-2	SLS Block-1B	SLS Block-2	SLS Block-1B	SLS Block-1B	Commercial/ International	Commercial/ International	SLS Block-1
Date	2024	2025	2026	2026	2026	2027	2027	2027	2028	2028	2028
Description	SEP + Central Node	Crew of 4 + Hab	SEP + Lab	Cryo Farm 1 & Crew Quarters	4 Crew Orion + Supplies & Equipment	Cryo Farm 2 & Crew Quarters	6 Crew Orion + Supplies & Equipment	Uncrewed Orion + Supplies & Equipment	Cryo Prop Module 1	Cryo Prop Module 1	MBC Crew of 6 + Supplies & Equipment
Assembly	Mars	Cis Lunar	Mars	Cis Lunar	Cis Lunar	Cis Lunar	Cis Lunar	Cis Lunar	Cis Lunar	Cis Lunar	Cis Lunar
Destination	Mars	Mars	Mars	Mars	Cis Lunar	Mars	Cis Lunar	Mars	Mars	Mars	Mars

Figure 5. Mars Base Camp Mission-Specific Launch Sequence

Configuration, the smaller Phobos and Deimos Sortie Systems, and the robotic Mars ascent vehicle that delivers samples to Mars orbit for recovery by the Phobos Sortie Crew in the vicinity of Phobos.

surrounding the Crew Quarters provide an excellent storm shelter for Solar Particle Events, and a partial but significant attenuation of the galactic cosmic ray environment during sleep and rest periods. Orion is also designed to function as a radiation shelter. The Hab includes work, recreation, dining, and exercise areas comparable in volume to the Skylab module. Without the Hab, crew well-being is compromised, and the return trip in particular takes on aspects of the rather spartan Mars Direct Mission [15], however even with the loss of a Propulsion Stage, a Crew Quarters, or an Orion vehicle the entire Crew can be still be returned safely to Earth and accommodate all 6 crew members. The Mars Base Camp architecture provides the crew with the resources necessary to support self-rescue throughout the mission if no other option exists. In this respect the MBC architecture is unique compared to most other Mars human exploration

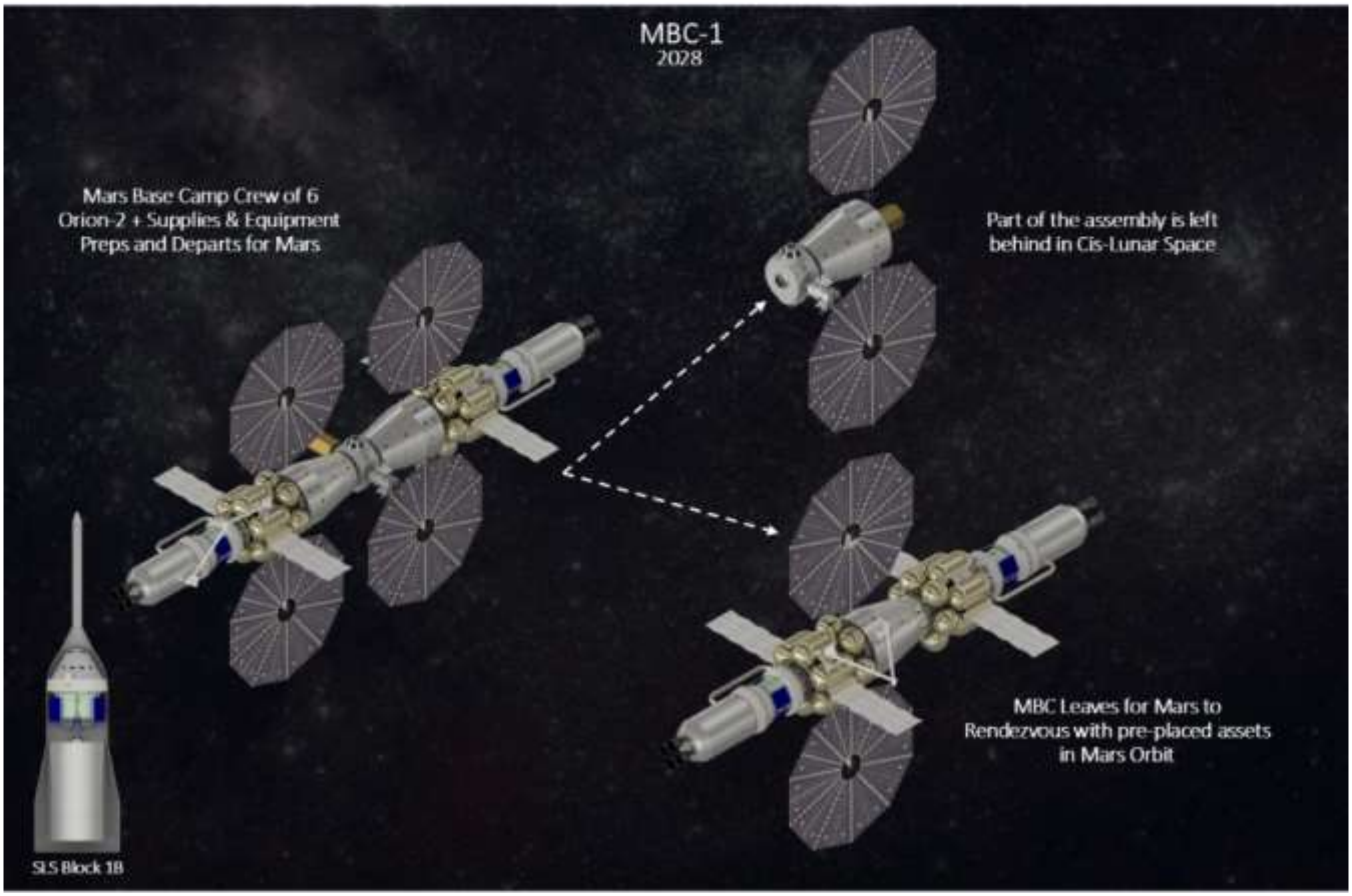


Figure 6. The Transit Configuration Departs, Leaving a Cis-Lunar Laboratory

The Laboratory Module and science equipment arrives in Mars orbit prior to the crew and remains in Mars orbit when the crew departs for Earth in the Transit Configuration. The only element of the Transit Configuration that is not mirrored for system level redundancy is the large Hab which is designed to provide habitable volume but could actually be jettisoned in the event of an emergency. The Hab could be discarded in a crisis situation because the closed loop environmental life support system hardware is contained in the smaller Crew Quarters modules that are surrounded by the cryogenic hydrogen and oxygen tanks (Tank Farms). The Tank Farms architectures. It could be argued that the Mars Base Camp mission could be done with a single Orion and a single Crew Quarters, and that the Propulsion Stages could be more efficiently combined into a single stage that still supported two sortie missions, but the added security of self-rescue provided by element-level redundancy is a reasonable mass trade-off.

The Mars Base Camp mission places humans on the two alien worlds Phobos and Deimos, whose origins, histories and compositions are largely unknown. One Orion, a propulsion stage, and the excursion module, together an excursion vehicle, separate from the main vehicle with a crew of three to travel to each moon in separate sorties. In the low gravity environment of Phobos and Deimos, care must be taken to avoid kicking or pluming the surface with thrusters as this will propel surface material into orbit or escape velocities. For free roaming exploration in this environment the Excursion System allows suited crew to perform EVAs with a Spider Flyer/Walker. This system is devised to allow scientist/astronaut crew to interact directly with the surface and robotic/science equipment on the surface, and to move freely about the surface using jumps to avoid pluming the surface. The system has a blended reaction control system that maintains contact with the surface, pushing towards the surface as necessary, to keep in contact while in walking mode. During the EVAs, one crew member would remain in Orion. Multiple EVAs would be possible during the roughly two week sortie mission. Figures 7 and 8 illustrates the intended interaction of the excursion system in route and on the surface of the Martian moons.

The crew of the Phobos Excursion vehicle will also collect samples from Mars that have been placed in orbit near Phobos by robotic systems that are under the direction of the MBC crew. Teleoperations and telepresence are used to interact with rocket-propelled airplanes that target the source methane emissions on Mars, rovers on the surface, and the robotic Mars Ascent Vehicles that bring samples up to Phobos orbit altitude. The crew will stay in Mars orbit for about 11 months before undertaking the year long journey home to Earth.

The crew returns to Earth in the same Transit Configuration as was used to reach Mars. The Lab, Central Node, and Excursion System remain in Mars orbit for the next mission. The Habitat and multiple Crew Quarters and Orion Crew Modules provide sufficient partition-able habitable volume to support Crew well-being and safety for the long voyage home. In a nominal mission re-entry, the crew is divided into two groups of three along with containers of samples from Mars, Phobos and Deimos on both Orion vehicles. The mission is designed to limit the return velocity relative to Earth's atmosphere to be consistent with Orion's capabilities. Well prior to entry, the Cryo Propulsion Modules are removed from the Orion vehicle. The Astronauts suit up and transfer to their Orion return vehicles the day before Earth encounter. The two Orion vehicles can remain docked nose to nose until the time comes to maneuver to their respective entry coordinates. Each Orion CM/SM is a free flying vehicle that separates from the Mars Base Camp system and positions itself for entry, descent and landing. The CM and SM separate as in any Orion return, and the CM descends on parachutes for a mid ocean recovery. In the event of an anomaly or system level malfunction, the entire crew of 6 can return in a single Orion Crew Module.

Depending on the quantity of residual cryogenic propellant remaining, it may be possible to propulsively brake the remaining Mars Base Camp elements into a high elliptical Earth orbit. This could allow the two Cryo Tank Farms/Crew Quarters and the Habitat to be retrieved via an SEP tug and re-used in the future, either in Cis Lunar space or on a subsequent mission to Mars. Planning ahead for sufficient residual propellant provides some radiation shielding for the return journey, allows for recovery of MBC elements, and provides additional options for mission contingencies and emergency responses. The Cryo Tank Farms and Cryo Stage total propellant volumes are somewhat oversized to account for this possibility or potential mass growth elsewhere in the system.

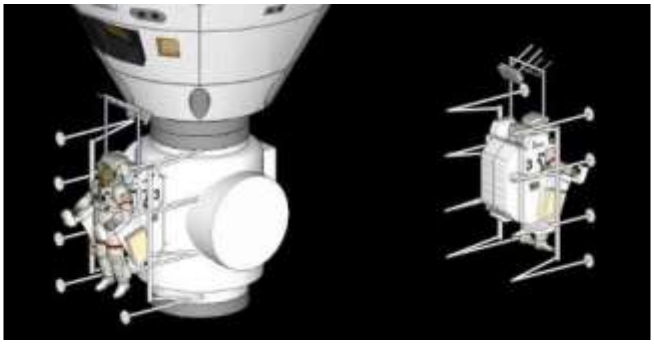


Figure 7. The Spider Flyer/Walker undocks from the MPCV excursion node

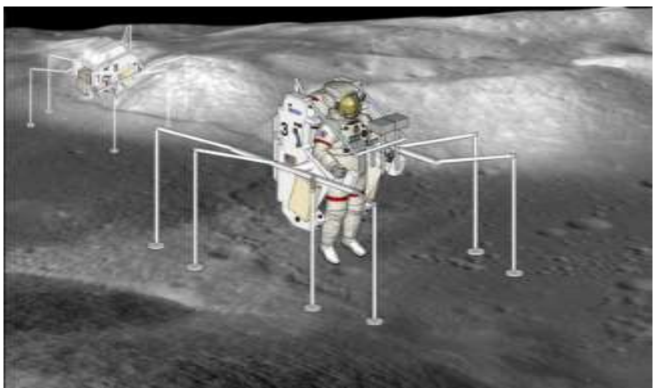


Figure 8. EVA's via Spider Flyer/Walker allow mobility and science activities on the Martian surface

5. Element Descriptions

The Orion Multi-Purpose Crew Vehicle (MPCV) Crew Module (CM) provides command and control capability throughout the mission. Orion is inherently a long duration deep space vehicle due to its high reliability, fault tolerant design, and proven long life systems and components. In a sortie configuration, endurance is only limited by consumables. In a mated configuration, where consumables are not used or are resupplied from Mars Base Camp, the spacecraft has an operational lifetime of at least 1000 days. Similar designs and processes are used for Lockheed Martin's deep space robotic exploration vehicles which often have a design life of 6 years and typically last over 10 years.

The Orion MPCV Service Module (SM) provides 6 degree of freedom attitude control, propulsion, power generation, thermal control, and consumables sufficient to support a crew of three for a month. EM-1 through EM-7 employ a full weight SM capable of a CM/SM total ΔV in excess of 1200 m/s. EM-8 through MBC-1 employ a lightweight Service Module with a 200 m/s CM/SM ΔV capability that is designed to be mated to a Cryogenic Propulsion Stage that enables high ΔV missions, giving the CM/SM/Cryo Stage Stack a ΔV capability of over 4.5 km/s. The lightweight SM still provides 6 degree of freedom attitude control, thermal control and consumables, but primary power generation is provided by the Mars Base Camp when docked and by the Cryo Stage when on a sortie mission.

The Crew Quarters is hidden inside the LOX/LH2 Tank Farm and is essentially a mini-habitat with over 40 m^3 of pressurized volume. It contains all essential MBC closed loop life support system hardware as well as individual sleeping quarters and storage space for consumables. Using the methodology [13] and consumption factors developed by Pedro Lopez et al, the MBC is sized to accommodate 21 metric tons of consumables, and includes an additional 1 metric ton of pressurized atmosphere in its fully assembled configuration. Consumables are distributed across the MBC elements, including the Crew Quarters avoiding single-fault tolerance. The Crew Quarters also includes bathing, hygiene and toilet facilities. The crew can sleep, relax and work in their quarters taking advantage of the solar particle event (SPE) safe haven and partial galactic cosmic ray (GCR) radiation shielding afforded by the cryogenic hydrogen tanks. The Hab module provides for additional habitable volume and equipment, but the Crew Quarters provides everything necessary for survival in the event of a Hab breach or jettison. For each element a short description and some specifications are also provided in Table 2.

The Cryo Tank Farm is an integral part of the Crew Quarters which are launched as a pre-integrated system. The tank system for cryogenic hydrogen and oxygen is designed for zero boiloff via active cooling in flight using power from the large solar arrays. By minimizing conductive penetrations into the multi walled vacuum shroud, these storage tanks minimize energy gain and are much better insulated compared to the Cryo Stage, which includes structural load paths, secondary structure, turbomachinery and equipment accommodations.

The large Habitat Module provides 300 m^3 of pressurized volume designed to enhance crew welfare and productivity. It contains exercise, work, observation, recreation, entertainment, medical, communication, and meeting facilities as well as a full galley. Like each of the modules on the MBC backbone, the Hab has redundant interfaces on each end for thermal control fluid, potable water, grey water, oxygen, nitrogen, 120V power, and fiber optic command and data lines. The Laboratory Module is an identical twin to the Hab of Module except that it contains an allocation of 7 metric tons of science equipment and is provided 40 kW of dedicated power while in Mars orbit. Although some preliminary items and operations concepts have been suggested, these allocations are intended to support a self-contained, multi-disciplined and well equipped remote field laboratory.

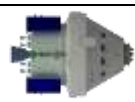
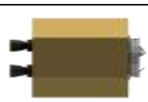
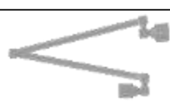
The shirt sleeve environment of the laboratory allows for the latest handheld scientific equipment to accompany the scientist astronauts on the MBC journey. Optical (laser) communications with Earth provides high bandwidth links to ensure that teams on Earth can augment and support the exploration crew in the most effective way practical given the speed of light delays. The 20 m diameter solar arrays and power storage, distribution and control modules are designed to be interchangeable between the solar electric propulsion modules which pre-emplace MBC mission elements at Mars and the MBC Cryo Tank Farms. A robotic arm is used to perform this repositioning operation, relocating the power system module without the need for an EVA. With a pair of solar arrays and lithium ion batteries the power module provides 150 kW of power at Mars and 30 kWhr of energy storage. Additional electrical energy storage exists on the Habitat, Laboratory, Orion and Cryo Tank Farm Modules. The Center Node, which is pre-placed by SEP along with the Phobos/Deimos Excursion Module, includes 2 opposed Cupolas which provide the Crew with 4-pi steradian observation capabilities while in Mars Orbit. This observatory can be equipped with telescopes, cameras and sensor systems designed to be operated manually and via automation from the Laboratory Module. The Center Node also has two docking ports and a Robotic Arm to facilitate reconfiguration of MBC elements and berthing. One of the docking ports is dedicated to the Phobos/Deimos Excursion Vehicle; the other is unallocated but can accommodate an Orion or similarly equipped spacecraft or future element.

The Phobos/Deimos Excursion Vehicle (EV) consists of an airlock with docking systems on each end. With the aid of the Center Node Robotic Arm, a CM/SM/Cryo Stage can be mated to the Excursion Vehicle in preparation for a Sortie mission to one of the moons of Mars. Two of the Crew will don and doff suits in the EV airlock while the 3rd Crew member remains in the Orion Control Center in a slow orbit or standoff position at Phobos or Deimos. Once suited, the Crew performs an EVA to strap into the Spider Flyers. The EV airlock provides service and mating interfaces for the Spider Flyers which use their robotic legs to facilitate embarking and disembarking. The Spider Flyers are designed as free flying six degree of freedom crew maneuvering vehicles equipped with tool and storage caddies designed to support field science. The Spider Flyer can autonomously fly a

Table 2. Mars Base Camp Element Descriptions

preplanned flight plan or can be manually flown or directed over the surface. In flying mode the system automatically avoids directing thrusters at the surface within prescribed altitude and plume angles.

The spider legs provide stability on the surface in conjunction with the monopropellant

Module	*Function*	*Development Status*	*Specifications*
Orion 	Command and control through entire mission, re-entry vehicle	In production	*Mass*: 14000 kg *Quantity*: 2 *Crew*: 3 – 6 astronauts
Crew Quarters 	Crew living space, life support systems	New development, preliminary design	*Height*: 5 m *Width*: 3 m *Mass*: 5600kg
Tank Farm 	Propellant storage	New development, from heritage	Total for 2 Tank Farms *LH2 mass*: 35,000 kg *LOX mass*: 200,000 kg *Tank mass*: 8400kg *Quantity*: 12 tanks LOX, 12 tanks LH2
Habitat/ Laboratory 	Living and working spaces	New development, from high heritage	*Height*: 9 m *Width*: 7.5 m *Mass*: 7400kg
Solar Array 	Power generation	New development, from high heritage	*Diameter*: 20 m *Mass*: 3300 kg *Quantity*: 4 arrays Total Power Generated *Earth:* 350kw *Mars:* 150kw
Center Node 	Center module of MBC	New development, from high heritage	*Depth*: 3 m *Diameter*: 5 m *Mass*: 5700 kg
Excursion Module 	Human transportation on Phobos and Deimos; airlock and landing legs	New development, preliminary design	*Height*: 3 m *Width*: 5 m *Mass*: 4400 kg
Cryogenic Propulsion Stage 	Provides high thrust in-space propulsion	New development, from heritage	Per Stage *Dry Mass*: 4000 kg *Gross Mass*: 48000 kg *Isp*: 440 s
Solar Electric Propulsion Stage 	Delivers elements and cargo for cis-lunar staging and Mars	Proven technology, preliminary design	*Height*: 3.5 m *Width*: 2.5 m *Dry Mass*: 4000 kg *Gross Mass*: 16000 kg
Robotic Arm 	MBC assembly	New development, from high heritage	*Length*: 18 m *Mass*: 450 kg
Radiators 	Thermal control	New development, from high heritage	*Width*: 3 m *Length*: 10 m *Quantity*: 4

maneuvering system which helps provide downward force to prevent unintended hops. The legs allow the Spider Flyer to drop from initial altitudes of 100 m or more and arrest the relatively small (~1 m/s) touchdown velocity. Likewise, the use of the legs to impart a 1 m/s vertical leap will result in an apex of about 100 m in 180 seconds, at which time the propulsion system can transition to a traditional six degree of freedom control scheme. The Spider Flyer transitions to a spider walker on the surface with an articulating chassis that allows the Scientist/Astronaut to manipulate tools and interact with the surface from a stable platform. By modulating leg motion with thrusters directed away from or tangent to the surface, the spider walker can achieve slow but reasonable surface mobility. To make faster transitions the spider walker makes a hop to altitude and flies to a new drop down location.

6. Trajectory Design

To further validate requirements for ΔV and mission duration, as well as support more detailed mission design work, a reference trajectory for the MBC-1 has been developed. This reference trajectory begins in a reference HEO followed by a Trans-Mars-Injection (TMI) burn (Figure 9), the outbound transit to Mars (Figure 10), establishment of the 1-sol mission orbit around Mars via 4-burn Mars Orbit Injection (MOI) sequence (Figure 11), precession of this orbit during the mission (Figure 12), the departure from this orbit via a 4-burn Trans Earth Injection (TEI) burn sequence (Figure 13) , the return transit to Earth (Figure 14), and the final targeting of an Entry Interface target appropriate for the Orion crew vehicle (Figure 15). The timing and direction of the 9 major mission burns (1 TMI, 4 MOI & 4 TEI) as well as the initial HEO orbit alignments and final entry interface conditions were collectively optimized using Lockheed Martin in-house developed trajectory design optimization tool, TOSOCS (Trajectory Optimization with Sparse Optimal Control Software). This initial reference mission is a conjunction class mission which departs Earth in 2028.

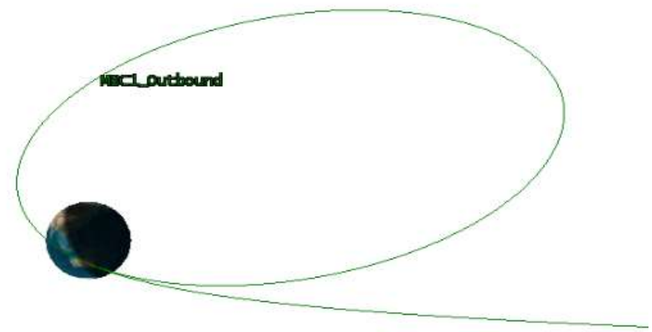
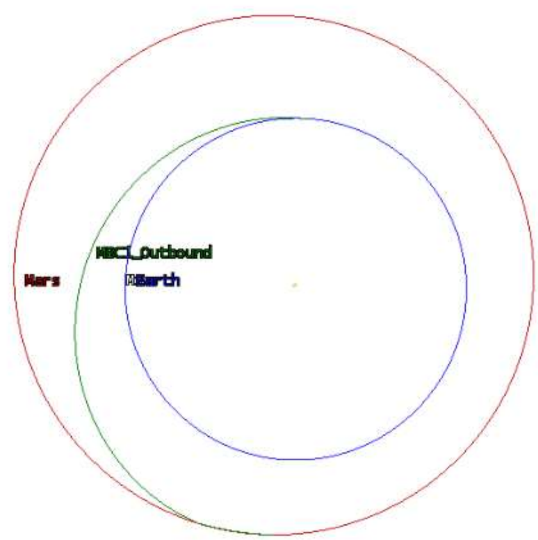


Figure 9. Earth Departure from HEO



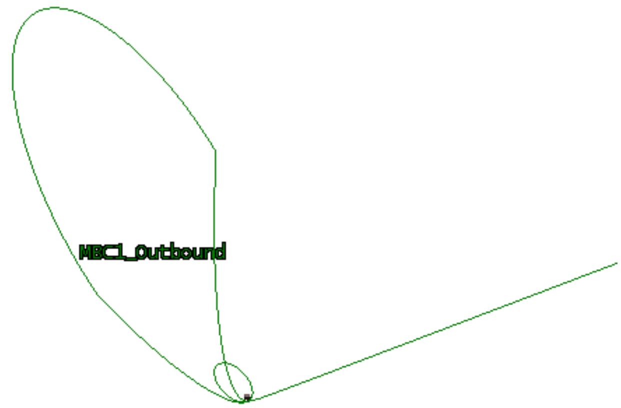


Figure 11. 4-Burn Mars Orbit Insertion

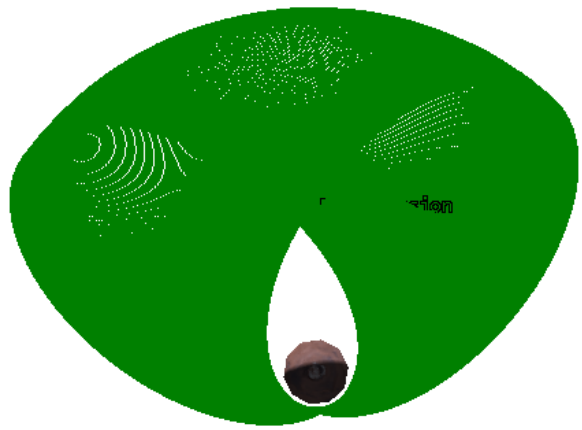


Figure 12. Precession of Mission Orbit

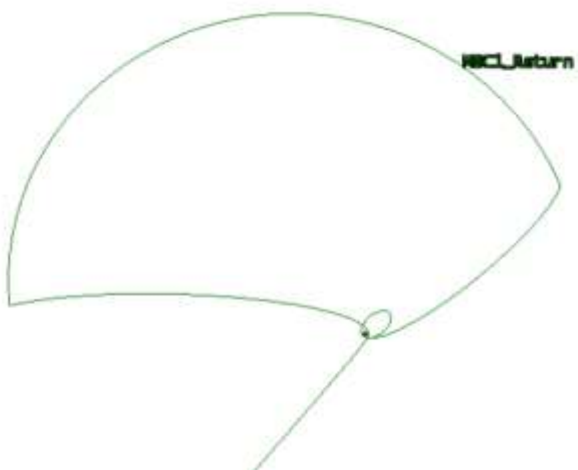


Figure 13. 4-Burn Trans-Earth Injection

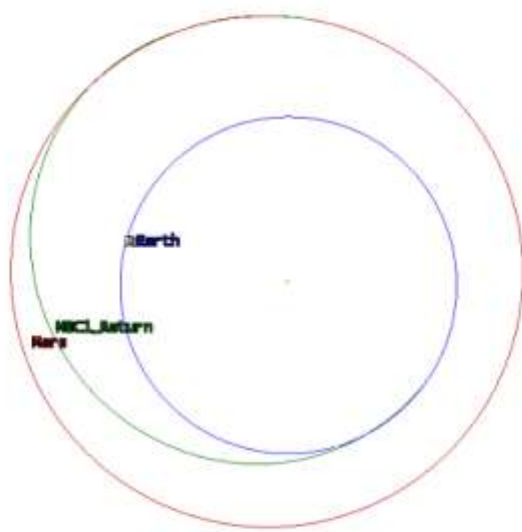


Figure 14. Return Transit to Earth

There are a number of key assumptions made and constraints considered as part of this mission design:

- Initial HEO of 400 x 19700 km @ 28.5 inclination
  - This is a generic placeholder for the HEO staging orbit.
  - It corresponds to what can be achieved with a 3 km/s delivery stage that uses an initial 400 km injection altitude.
  - Future work will use staging orbits that correspond to what can be established by leaving the cis-lunar assembly orbit at the right time of the month to establish proper

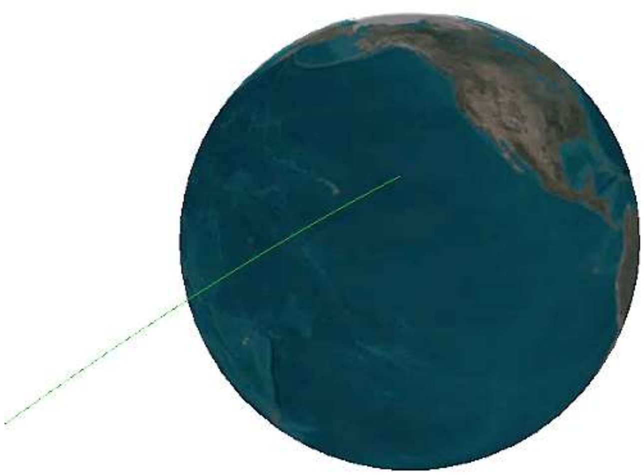


Figure 15. Final Entry Interface Targeting

alignment for Trans Mars Injection.

- All burns are modeled impulsively
- 8x8 gravity model assumptions for dominant body by mission phase with point mass modeling for non-dominant bodies (considering just Sun, Earth and Mars)
- The Mars Mission Orbit shall be equatorial, have a 1 sol period and be oriented in a manner to support telerobotic operations to wide variety of sites.
  - The equatorial constraint is driven by the desire to minimize ΔV costs for the transits to Phobos and Deimos which aren't included in this reference trajectory.
  - To minimize ΔV and provide long dwell times at apogee for science operations the orbit should be elliptical with a periapsis no lower than 250 km.
  - To support telerobotics the orbit should be aligned to provide line-of-site to a wide range of possible sites while they are sun lit. This requires the orbit to be in particular orientation with respect to the Sun.
- The final Earth entry interface shall have a relative velocity less than 11.5 km/s targeting a flight path angle appropriate for that velocity, consistent with the capabilities of the general Orion TPS design with minor upgrades over the current lunar-sized design
- Overall mission is optimized to minimize an equally weighted sum of all ΔV

Table 3. MBC-1 Reference Mission Performance Summary

Parameter	Units	Value
Total ΔV	km/sec	4.24
TMI ΔV	km/sec	0.71
MOI ΔV	km/sec	2.04
TEI ΔV	km/sec	1.49
Total Trip Time	days	970.5
TMI Date	TDB	12/24/2028 14:18:41.463
Outbound Duration	days	230.0
MOI1 Date	TDB	08/11/2029 14:21:26.088
MOI Duration	days	29.6
MOI4 Date	TDB	09/10/2029 05:46:35.762
Mission Duration	days	308.4
TEI1 Date	TDB	07/15/2030 14:46:20.888
TEI Duration	days	58.2
TEI4 Date	TDB	09/11/2030 18:52:05.646
Return Duration	days	344.4
Return Date	TDB	08/22/3031 03:23:13.119

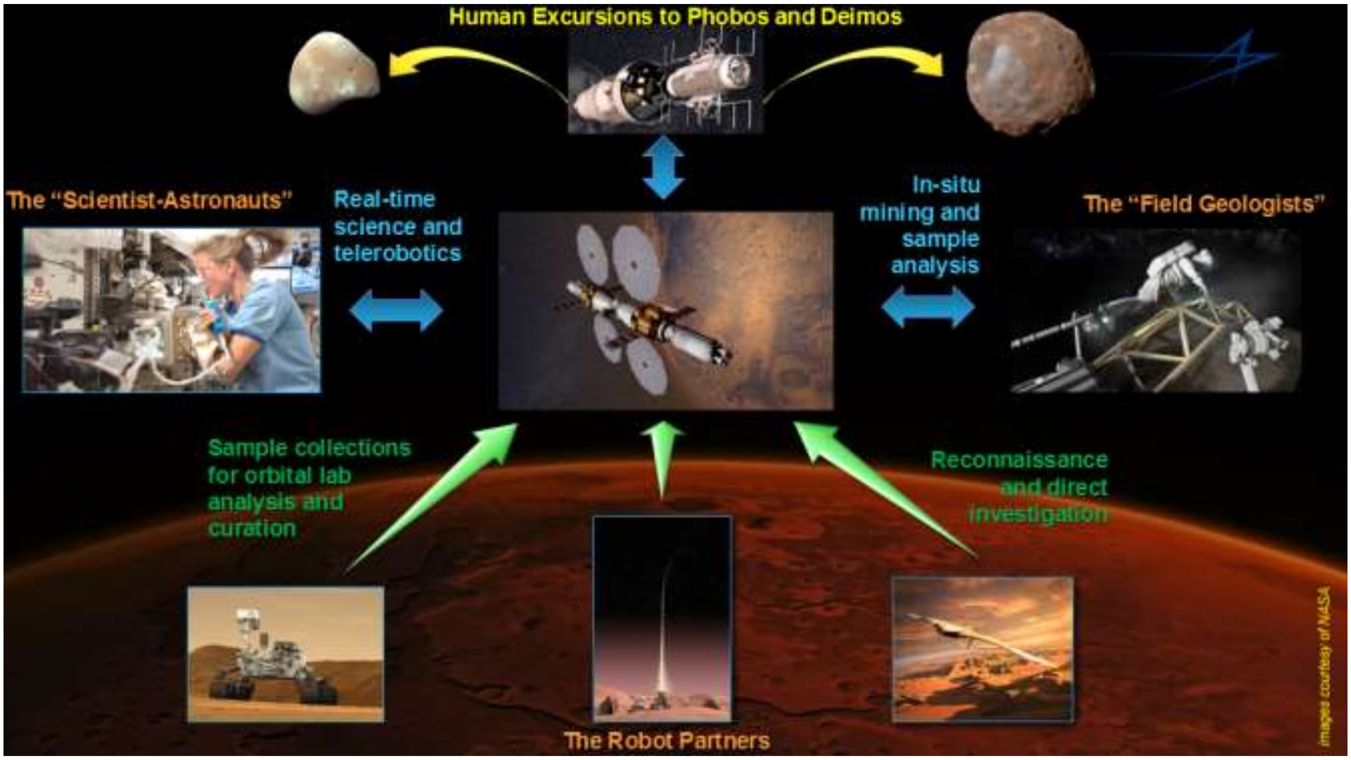


Figure 16. Mars Base Camp Mission Science Elements

7. Science

The mission accelerates scientific discovery of origins and the search for life using scientist-astronauts and advanced robotics to conduct unprecedented field science and in-situ sample analysis in the Martian system, pinpointing the right human landing zones and bringing back the right samples, as shown in Figure 16. On the Mars Base Camp itself a preliminary allocation of 7.0 metric tons of science equipment is allocated to the Laboratory Module, along with 40 kW of dedicated electrical power. These allocations, along with ability to access and download larger masses of raw data than compared to Mars-transmitted downlinks on Earth, are intended to be a starting point for the discussions of science objectives, measurement types, instruments and support equipment, sample curation, external robotic elements, interfaces, operational concepts, and the identification of driving functional and performance requirements. Further in-depth analysis will be conducted with the science community in examining the MBC mission concept, focusing on the most effective roles and use of robotic/automated and human/manual capabilities and systems for the advancement of key science objectives. Of particular interest are definition of the robotic systems, elements and missions, outside of the Mars Base Camp vehicle, that best complement the capabilities and limitations of the crew and science systems aboard the MBC vehicle. This will include factoring in the current and future plans of NASA, the objectives of international partners, and perhaps commercial interests in resource prospecting.

Mars Base Camp is intended to address the very fundamental questions of origins and evolution of our solar system as well as the fundamental question of life on Mars. The MBC architecture provides the ability to send robotic elements to locations on Mars, to return samples for analysis to a laboratory in Mars orbit, and to return those samples to Earth for in-depth analysis. The robotic elements may be launched to Mars as separate missions or may be deployed from Mars Base Camp. These robotic elements may be landers, rovers, or perhaps even aerial vehicles. The crew in Mars orbit will be able to operate these robotic assets with low latency, in addition to traditional operation by the ground. A key objective of the Mars surface robotic operation will be to place a sample into Martian orbit near the orbit of Phobos for the Phobos sortie mission to retrieve. This sample may be one of the samples selected and cached on the surface by the Mars 2020 rover, a sample selected by a later robotic mission, or a sample selected during the Mars Base Camp telerobotic operations. Even without specifically targeting the most probable locations for life, by the nature of Mars samples sent to MBC, the MBC mission and system designs must support the potential detection and handling of extraterrestrial life.

The crewed sorties to Phobos and Deimos will attempt to answer questions including the moons' origins. A 3-person crew will conduct missions at these locations for about two weeks in length, utilizing the excursion vehicle elements (propulsion stage, MPCV, airlock, Spider Flyer/Walker) to perform sortie rendezvous and MBC crew "landings". Before landing, the crew will map out the surface in more detail and select landing spots from the orbiting excursion vehicle. Astronauts will venture via Spider Flyer/Walkers to the surface, perhaps to multiple sites. While in the Spider Walker configuration, which provides the crew the ability to conduct scientific operations with minimal geologic disturbance in the milligravity of these 'alien' worlds, astronauts will collect various samples to be delivered back to the MBC Laboratory for study and analysis. The progression of Stepping Stones missions in cis-lunar space also provides opportunities to develop and validate sample return and low gravity body mission elements, systems and protocols prior to their use at Mars. In particular, the return of Lunar samples from the South Pole Aitken Basin meshes the accomplishment of a key Decadal Survey science objective with the complementary development of cis-lunar and Mars crewed and robotic system capabilities.

8. Mars Surface Access for Crew

Humans landing on Mars is the long-term goal of Mars Base Camp. To accomplish this, the study investigated a possible Mars Ascent/Descent Vehicle (MADV) designed to fit the following requirements:

1. Reusable vehicle supporting sortie missions from orbit to the surface and back to orbit
2. Lander departs from and returns to a 1 sol orbit with a 400 km periapsis
3. Lander accommodates 4 crew
4. Lander supports at least a 2 week surface stay
5. Lander has a maximum 100 metric ton gross (wet) mass
6. LOX and LH2 are the primary consumables, refueled in Mars orbit.
7. Lander provides near global access to Mars surface landing sites

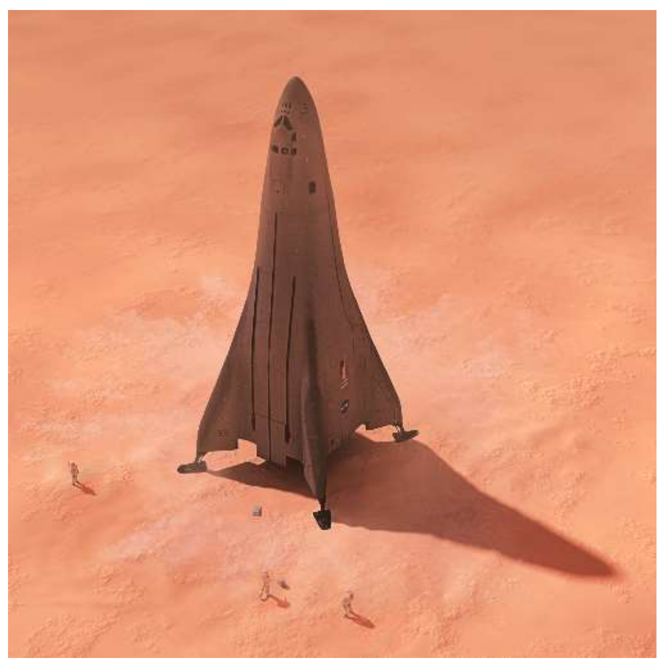


Figure 17. Mars Ascent/Descent Vehicle

To meet these requirements, this architecture utilizes a re-usable, single stage vehicle carrying

80,000 kg of propellant in the form of liquid oxygen and hydrogen. It has 6 RL-10 equivalent engines. The MADV shares much in common with the cryogenic propulsive stage which has been previously discussed for use in the MBC architecture. The pressure vessel at the top would contain much of the same internal components as Orion, including avionics, controls and displays, life support systems, and other crew systems. An alloy skin provides durable, zero maintenance protection for multiple re-entries and ascents through the Martian atmosphere. This vehicle has the potential to perform 6.5 km/s of ΔV, providing the capability to operate out of a high Mars orbit. The vehicle would also provide anytime abort capability.

By providing global access, and multiple landings, scientist/astronauts would be able to better further our understanding of the origins of Mars. With the addition of the MADV to the architecture, Mars Base Camp provides a method to explore both low gravity objects like Phobos and Deimos, as well as the entire planet Mars. The orbit-only mission in 2028 will provide invaluable data for future human landings on the surface during following missions. NASA and other international partners will use this data to select the most promising landing sites to search for life, and direct astronaut/scientists in the best ways to advance science and exploration objectives.

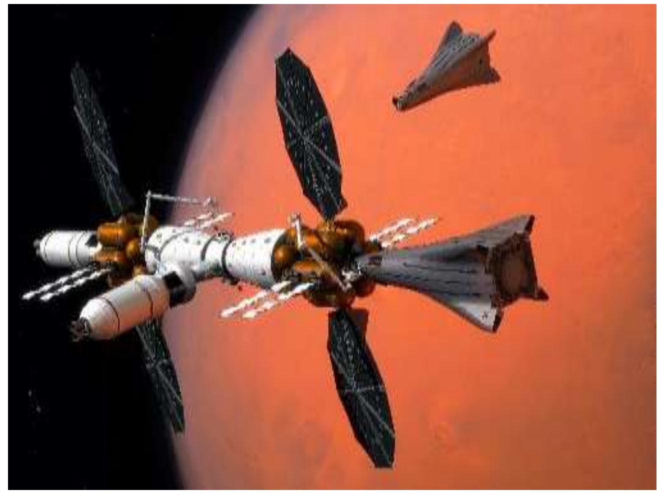


Figure 18. Operations from Mars Base Camp

9. Conclusion

Since well before the first Viking lander touched down on Mars 40 years ago, humanity has been fascinated with the Red Planet. Lockheed Martin built NASA’s first Mars lander and has been a part of every NASA Mars mission since. The Mars Base Camp concept builds upon existing deep space technologies in development today and provides a blueprint for NASA’s Journey to Mars. This plan provides the opportunity for significant scientific discovery, can be evolved to accommodate specific mission objectives, and ensures the safety of our astronauts. The results of this architecture study show that a near term Mars mission is compelling and feasible.

References

[1] J. Kwong, et al, Stepping Stones: Exploring a Series of Increasingly Challenging Destinations on the Way to Mars, AIAA 2011-7216, AIAA Space 2011 Conference, Long Beach, California, 2011 September.

[2] J.B. Hopkins, W.D. Pratt, Comparison of Deimos and Phobos as Destinations for Human Exploration and Identification of Preferred Landing Sites, AIAA 2011-7140, AIAA Space 2011 Conference, Long Beach, California, 2011 September.

[3] J.B. Hopkins, et al, Proposed Orbits and

Trajectories for Human Missions to the Earth-Moon L2 Region, IAC-13-A5.1.4, 64th International Astronautical Congress, Beijing, China, 2013 September.
[4] W.D. Pratt, et al, Human-Assisted Sample Return From The Moon And Mars Using The Orion Spacecraft, IAC-14-A5.1.7, 65th International Astronautical Congress, Toronto, Canada, 2014 September.
[5] T. Fong, et al, Testing Astronaut-Controlled Telerobotic Operation Of Rovers From The International Space Station As A Precursor To Lunar Missions, IAC-14-A3-2A-7, 65th International Astronautical Congress, Toronto, Canada, 2014 September.
[6] T. Cichan, et al, Mars Base Camp: A Martian Moon Human Exploration Architecture, AIAA-2016-5457, AIAA Space 2016 Conference, Long Beach, California, 2016 September.
[7] T. Cichan, et al, Martian Moon Human Exploration Architecture, IAC-16.A5.2.10x35709, 67th International Astronautical Congress, Guadalajara, Mexico, 2016 September.
[8] National Aeronautics and Space Administration (NASA), NASA's Journey to Mars: Pioneering Next Steps in Space Exploration, NASA Headquarters, NP-2015-08-2018-HQ, Washington D.C., 2015 October.
[9] Pratt, W.D., et al, Concept Study of a Cislunar Outpost Architecture and Associated Elements that Enable a Path to Mars, IAC-16-A5.1.8, 67th International Astronautical Congress, Guadalajara, Mexico, 2016 September.
[10] Chapman, T., et al, Concept of Crew-Tended Platform in Cislunar Space: Initial Configuration, IAC-16-A5.1.6, 67th International Astronautical Congress, Guadalajara, Mexico, 2016 September.
[11] R.M. Smith, D.A. Craig, P. Lopez Jr., Proving Ground Potential Flight Test Objectives and Near-Term Architectures, IEEE Aerospace Conference , Big Sky, Montana, 2016 March.
[12] H. Price, J. Baker, N. Firouz, A Minimal Architecture for Human Journeys to Mars, New Space, Vol. 3 Issue 2 (2015) 73-81.
[13] T. Cichan, S.D. Norris, P.F. Marshall, Orion: EFT-1 Flight Test Results and EM-1/2 Status, AIAA 2015-4414, AIAA Space 2015 Conference , Pasadena, California, 2015 August.
[14] H.W. Price, et al, Human Missions to Mars Orbit, Phobos, and Mars Surface Using 100-kWe-Class Solar Electric Propulsion, AIAA 2014-4436, AIAA Space 2014 Conference , San Diego, California, 2014 August.
[15] R. Whitney, R. Martinez, Options for Staging Orbits in Cislunar Space, IEEE Aerospace Conference , Big Sky, Montana, 2016 March.
[16] R.M. Zubrin, D.A. Baker, O. Gwynne, Mars Direct: A Simple, Robust, and Cost Effective Architecture for the Space Exploration Initiative, AIAA-91-0328, 29th Aerospace Sciences Meeting, Reno, Nevada 1991 January.

BIOGRAPHY

Timothy Cichan is the Space Exploration Architect at Lockheed Martin, where he leads a multi-disciplinary team of engineers who figure out how to help astronauts and robots visit the Moon, asteroids, and Mars. He previously was the Orion System Architect. Timothy joined Lockheed Martin in 2002, and has worked for both human spaceflight and commercial communication satellite teams, in optimal trajectory design, mission analysis, subsystem development, and systems engineering. He has a Master's and Bachelor's degree in Aerospace Engineering from Penn State.

Stephen A. Bailey is the President and founder of Deep Space Systems, Inc. (DSSI). Steve has systems engineering experience at NASA's Johnson Space Center on the Space Shuttle program and the Space Exploration Initiative, and at the Jet Propulsion Laboratory for the Mars Pathfinder, Polar Lander, and Mars Climate Orbiter. At DSSI, he has had technical leadership roles on the Mars Reconnaissance Orbiter (MRO) and Orion programs and the Mars Phoenix and OSISRIS-REx proposals. He has a B.S. in Aerospace Engineering from the University of Texas.

Scott D. Norris is the Senior Manager of Business Development for Human Space Flight at Lockheed Martin Space Systems Company, Mr. Norris is responsible for supporting business development and strategic planning for human space flight systems with a focus on the Orion program. Norris has over 32 years of aerospace experience, which has included work on the manned maneuvering unit, Titan, Atlas, Athena, Space Shuttle, Ares 1-X, and Orion programs. In addition to his Lockheed Martin experience, Norris served as Director of Business Development at MicroSat Systems, a small satellite manufacturing company. Mr. Norris is a member of the FAA Center of Excellence for Commercial Space Transportation Industry Advisory Council (CESTAC) and also serves as a steering committee member for the Lunar University Network for Astrophysics Research. Norris holds a Bachelor of Science degree in Mechanical Engineering from Ohio State University.

Rob Chambers has been with Lockheed Martin since 1993 and has worked on a variety of Space Systems Company programs including Earth remote sensing satellites, the Space Shuttle, and Orion. Rob has Bachelor's and Master's degrees in Aeronautical and Astronautical Engineering from Purdue University, and over the years has led the development of guidance and controls subsystems, avionics, and flight software. Rob has been with Orion since 2006 and is currently the program strategy lead for Orion production, focused on defining the capabilities and timelines for Orion's future exploration missions.

Dr. Steve Jolly is the Lockheed Martin Chief Engineer for the Civil Space line of business. He was the Chief Engineer and Principal Scientist for the GOES-R program and Chief Engineer and Deputy PM for the Mars Reconnaissance Orbiter. He was Program Manager for the Mars Science Lab (MSL) Aeroshell. He has served as a member of EDL systems engineering team and critical events risk process for Phoenix, Stardust and Genesis and served on the National Research Council's EDL panel. He was chief systems engineer for Mars Sample Return (MSR) and co-inventor of the original concept for the MSL Sky Crane. He has served HEOMD and Orion off and on as an independent advisor and tiger team lead for entry, descent and landing, and most recently for the Mars Base Camp architecture and science mission. He is a 2007 recipient of the NASA Public Service Medal for distinguished service. He is a member of the board of directors for the Space Science Institute (SSI). He has a B.S. in aerospace engineering from CU-Boulder, an M.S. from Florida Tech, and a Ph.D. in aerospace engineering sciences from CU-Boulder.

Joshua Ehrlich is a Systems Engineer for Lockheed Martin Space Systems Company. He is currently working Test & Verification for the Orion European Service Module. His previous job experience includes testing and integration on the SpaceX Falcon 9 Payload Fairing and systems engineering design on science payload experiments for the International Space Station at NASA's Kennedy Space Center. He has a B.S. in Aerospace Engineering from the University of Florida and an M.S. in Mechanical Engineering from Embry-Riddle Aeronautical University.