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MARS BASE CAMP UPDATES AND NEW CONCEPTS

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Abstract

Orion, the Multi-Purpose Crew Vehicle, is a key piece of the NASA human exploration architecture for beyond earth orbit. Lockheed Martin was awarded the contract for the design, development, test, and production for Orion up through Exploration Mission 2 (EM-2). Lockheed Martin is also working on defining the cislunar proving ground mission architecture, in partnership with NASA. In addition, Lockheed Martin is exploring the definition of Mars missions as the horizon goal to provide input to the plans for human exploration of the solar system. In 2016, Lockheed Martin presented a proposal for achieving crewed exploration of Martian space as early as the 2028 launch opportunity. Known as Mars Base Camp, this proposal involved establishing a crewed vehicle in Martian orbit from which astronauts could perform excursions to Deimos and Phobos, and could also perform telerobotic exploration of the Martian surface, including sample return. This concept presented a novel, practical, and affordable path to enable human exploration of the Martian system in the next decade. This paper will detail additional development for the Mars Base Camp concept, including the production of propellant from water, additional details for the cislunar proving ground missions, and a Mars lander concept. The orbiting base camp could generate oxygen and hydrogen from water via solar-powered electrolysis. Water may be provided directly from the Earth system or via in-situ resource production in the lunar, Martian, or other systems. The demonstration of Mars Base Camp capabilities at the Deep Space Gateway will be discussed, including systems, technology and scientific mission possibilities. The lander is envisioned as a fully reusable, lifting body that uses supersonic retro-propulsion to descend and land on the surface. Initial crewed missions using the lander, which would follow on later missions than the initial mission, are outlined as relatively short-duration, science-focused exploration missions. Multiple areas of the Martian surface would be explored with the objective to gather scientific data from a wide variety of sites of interest, and more fully characterize possible sites for future permanent settlements. Once a surface mission is completed, the lander returns to Mars Base Camp as a single stage to orbit launch vehicle to be refueled. With these additional developments, the Mars Base Camp concept can be seen as a core system that pivots humanity into a viable, sustainable long-term Mars exploration program.

Keywords: Mars Base Camp, Deep Space Gateway, Orion, Mars, NASA, Lockheed Martin

Acronyms/Abbreviations

ΔV = Velocity Change
CM = Crew Module
CPS = Cryogenic Propulsion Stage
DSG = Deep Space Gateway
DSN = Deep Space Network
ECLS = Environmental Control and Life Support
EDL = Entry, Descent, and Landing
EVA = Extra Vehicular Activity
Isp = Specific Impulse
ISRU = In-situ resource utilization
IVF = Integrated Vehicle Fluids
L/D = Lift to Drag Ratio
LOX = Liquid Oxygen
LH2 = Liquid Hydrogen
MBC = Mars Base Camp system
MBC-N = The Nth Mars Base Camp Mission
MBC-S = MBC Mission with Surface Sorties
MADV = Mars Ascent/Descent Vehicle
MT = Metric Ton (1000 kg)
OML = Outer Mold Line
RCS = Reaction Control System
SEP = Solar Electric Propulsion
SLS = Space Launch System
Sol = One Martian Day (24h, 37m, 23 s)
SRP = Supersonic Retro Propulsion
TPS = Thermal Protection System
TRL = Technology Readiness Level
WDV = Water Delivery Vehicle

1. Introduction

IN 2016, Lockheed Martin introduced Mars Base Camp: a Martian Moon Human Exploration Architecture[1]. This architecture is designed to enable human exploration of cis-Martian space on an accelerated timetable. The first mission utilizing this architecture, deemed Mars Base Camp 1 (MBC-1) enables a crew of 6 to spend a year in Martian orbit performing real-time telerobotic operation of rovers and unmanned aerial vehicles on the Martian surface, and also performing crewed sorties to the surface of Deimos and Phobos. This architecture also enables humans to become an interplanetary species, and would return a sizeable amount of science value due to the ability to do simultaneous, real-time crewed exploration of multiple areas in the Martian system. However, perhaps the greatest return on investment from the MBC-1 mission is the reusable infrastructure it puts in place to enable affordable, ongoing crewed missions to Mars of increasing scope and complexity.

This paper builds on the Mars Base Camp architecture proposed and also discusses the scientific operations and opportunities at the Deep Space Gateway and how these technologies and processes enable and directly translate to operations of Mars Base Camp. These mission capabilities include telerobotics, sample return, 3D printing for spare parts and tools, and solar electric propulsion.

This paper also establishes the concept of operations whereby the elements placed in orbit during MBC-1 can be used to enable crewed exploration of the Martian surface in follow-on MBC sortie missions (MBC-S). Core elements of the MBC transfer vehicle that remain in high Earth orbit after MBC-1 are refueled, and used as the transfer vehicle onto which two Orions are docked for transfer to Mars for the MBC-S mission. This time, however, the pre-placed Martian elements include at least one Mars Ascent/Descent Vehicle (MADV) and, optionally, one or more separate, Mars-orbiting, cryogenic fuel depots. These additional elements now enable MBC to be used as the basis of operations from which crewed sorties to the surface of Mars can be executed. Multiple, short-duration sorties to the Martian surface can be performed during the ensuing 11-month stay at Mars (if the separate orbiting fuel depots are assumed). This paradigm enables maximum flexibility in crewed exploration of the surface; landing sites can be adjusted in near real-time during the mission as targets of opportunity are remotely identified. In addition, the safety of these early surface missions is greatly enhanced as the crew can return to MBC at almost any time if equipment issues, medical concerns, etc. dictate. This includes the ability to abort to orbit at any point during Mars Entry, Descent and Landing.

Mars Base Camp is not a “flags and footprints” system. Rather, MBC-based missions not only enable human exploration of Mars on a near-term timescale, but also establish an infrastructure of reusable elements that enable sustainable, long-term crewed operations at Mars. This system is intended to embrace and leverage international and commercial partnerships, and several opportunities for purely commercial service as part of the overall concept of operations are identified.

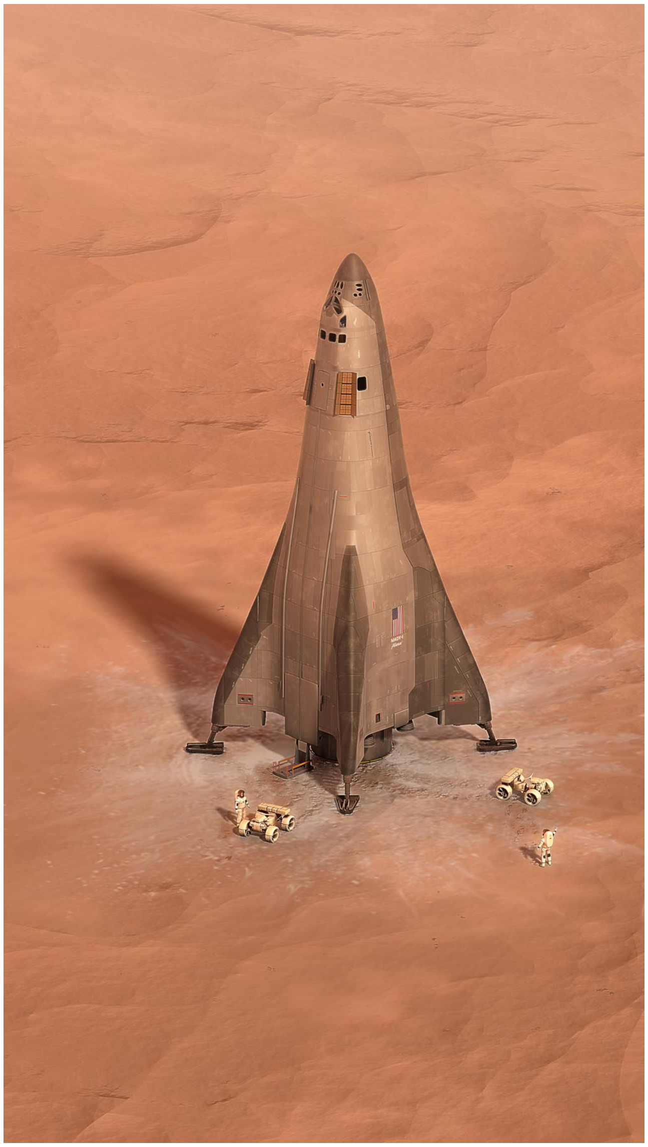

Figure 1: Mars Ascent/Descent Vehicle

2. Key Tenets for Long-Term Martian Exploration Architecture

The purpose of Mars Base Camp is to establish a vision for a realistic, achievable architecture whereby crewed exploration of the surface of Mars may be achieved within the timeframe (2030s) and budget currently outlined by US policymakers. Furthermore, the vision for Martian exploration presented here is driven by several main tenets:

- *Each mission should lay the groundwork for the next:* We here embrace the overall vision that the foremost goal of Martian human exploration should be to establish a sustainable long-term human presence at Mars. “Flags and footprints” missions – where a crewed landing has no viable follow-on without the development of an entirely new architecture – lead to large post-mission gaps and are to be avoided. Each mission should instead be designed fundamentally as a stepping stone on a path to longer surface missions rather than an end unto itself.
- *Reusability = Affordability:* The viability of a long-term Martian exploration policy depends upon the ability to get as much use out of the most expensive system elements as possible. Sacrificial, expendable modules are to be avoided in favor of reusable systems where each element deployed in a given mission is a key piece of a long term exploration infrastructure for future missions.
- *Leverage existing systems and technologies to the greatest extent possible:* This was one of the fundamental tenets of Mars Base Camp when first established. When such trade opportunities arise, the architecture should favor existing and/or higher TRL technologies that can be deployed on a shorter timeframe with lower development costs over potentially better performing, but more expensive and longer-lead technologies. The architecture should be evolvable such that newer technologies can be incorporated on future missions as they become practical. MBC was based around Orion and SLS, current NASA habitat development efforts, and current NASA solar electric propulsion development efforts for this reason.
- *Crew safety and reliability is paramount:* By its nature, interplanetary travel presents very limited opportunities for abort and early return. Thus, the architecture must seek to eliminate elements or operations where a single failure could lead to loss of crew, and should enable opportunities for self-rescue to the greatest extent possible. For this reason, most of the elements of Mars Base Camp are redundant – 2 Orions, 2 crew quarters, potentially 2 MADVs, etc.
- *Embrace and foster partnerships between NASA, international, and commercial contributors:* As with the first Mars Base Camp Study, this architecture is envisioned as NASA-led, but with extensive collaboration / partnering with international and commercial contributors. Where possible, opportunities for certain portions of the system operations to be realized via a purely commercially procured service are to be encouraged and highlighted.

3. Demonstrating Mars Base Camp Mission Capabilities at the Deep Space Gateway

At the NASA Advisory Council in May of 2017, NASA outlined the human space exploration phases starting from the ISS to the surface of Mars. This plan outlines the Deep Space Gateway buildup with the Habitation module being delivered on EM-3. The habitation module enables a crew of 4 to live and work in cislunar space for at least 30 days. Follow-on missions, EM-4-6, bring additional Gateway elements and are thought to be ideal candidates for science missions. The Deep Space Gateway is an ideal location to demonstrate many of the mission capabilities that will be needed for Mars Base Camp, including telerobotics, sample return, and solar electric propulsion. Just like at Mars, these capabilities enable significant science return. Lockheed Martin is developing an evolving architecture for human space exploration based on the capabilities of Orion and the Deep Space Gateway that will incrementally push human exploration towards Mars. Mars Base Camp extends and leverages the mission operations and technologies demonstrated at the Deep Space Gateway for telerobotic operations, sample return, and system maintenance.

A key piece of the Deep Space Gateway architecture is to perform robotic operations and use telerobotic systems to perform surface science from Orion and the Gateway. Design concepts are being developed that include an integrated science and robotic subsystem which provides flexible interfaces for control of surface robotics, display of any data and telemetry, and operational planning tools. This work includes developing an understanding of the limitations and constraints on robotic capabilities (power, communications, mobility, etc.). Telerobotics is extremely powerful in allowing humans to remotely operate rovers or UAVs on a planetary surface, particularly with tasks that are complex and require quick decisions such as drilling, driving, and sample collection[2]. As an example, the Curiosity and Opportunity rovers were operated by ground teams on Earth, but the tasks were limited based on power and the round trip communication time, which range between 380 and 2670 seconds, depending on the Earth-Mars orientation. With scientist-astronauts telerobotically operating rovers and UAVs from orbit, an increased volume of science can be collected due to the real-time control of the astronauts as well as the significantly smaller round-trip light time between the operators in orbit and the Martian surface[3]. To continuously operate rovers and UAVs from orbit over extended periods of time, the robotic systems need to be designed with better power storage, a communication system that supports teleoperation, and the mobility and manipulation to support scenarios with astronaut teleoperation. Additionally, the robots will need to have multiple control methods including telerobotic, automated, human supervised autonomy, and task level autonomy. Of course the habitat and laboratory modules need to support the astronauts performing telerobotics by scheduling in operations within their daily activities to align with opportunities for robotic surface operations, provide the astronaut situational awareness of the robot surroundings through a digital twin technology fusion, and provide the astronaut the ability to support any robotic system from a single robotic workstation. The process, planning, and methodologies of scientist-astronaut operating rovers from the Gateway is directly applicable to the same scenarios on the Martian surface. Figure 2 shows a scientist astronaut simulating lunar rover operations from a ground mockup.

In both the NRC-2007 and the most recent decadal survey report ranked sample returns from the lunar far side and the Martian surface as the highest priorities[4]. Burns, et al. have proposed sample returns from the South Pole-Aitken (SPA) basin and the Schrödinger basin[5]. The Deep Space Gateway can support both teleoperated rovers as well as receiving and partially analyzing sample returns. This process is applicable to MBC, as astronauts can perform the same planning and sample return collection and analysis. In a Martian orbit, the initial analysis by a scientist-astronaut is invaluable in assessing the sample and planning the next one as opposed to waiting for the sample to return to Earth for analysis and further planning. Sample collection capabilities are already being planned into the Mars2020 rover. The addition of a sample launcher element would allow collection of the sample in a Mars orbit, see Figure 3 for a visual representation.

The Deep Space Gateway allows for astronauts to live and work in space for 30-60 days with increasing durations. These long durations and the remote location of Gateway provides the astronauts the opportunity to maintain and operate the vehicle without the fallback of a quick Earth-return as available at ISS should an issue arise. The Deep Space Gateway platform allows for the development of 3D printers and the processes for printing and installing spare parts as opposed to bringing spares. On 1,000 day missions to Mars it is unrealistic to bring tools and spare parts for every contingency situation.

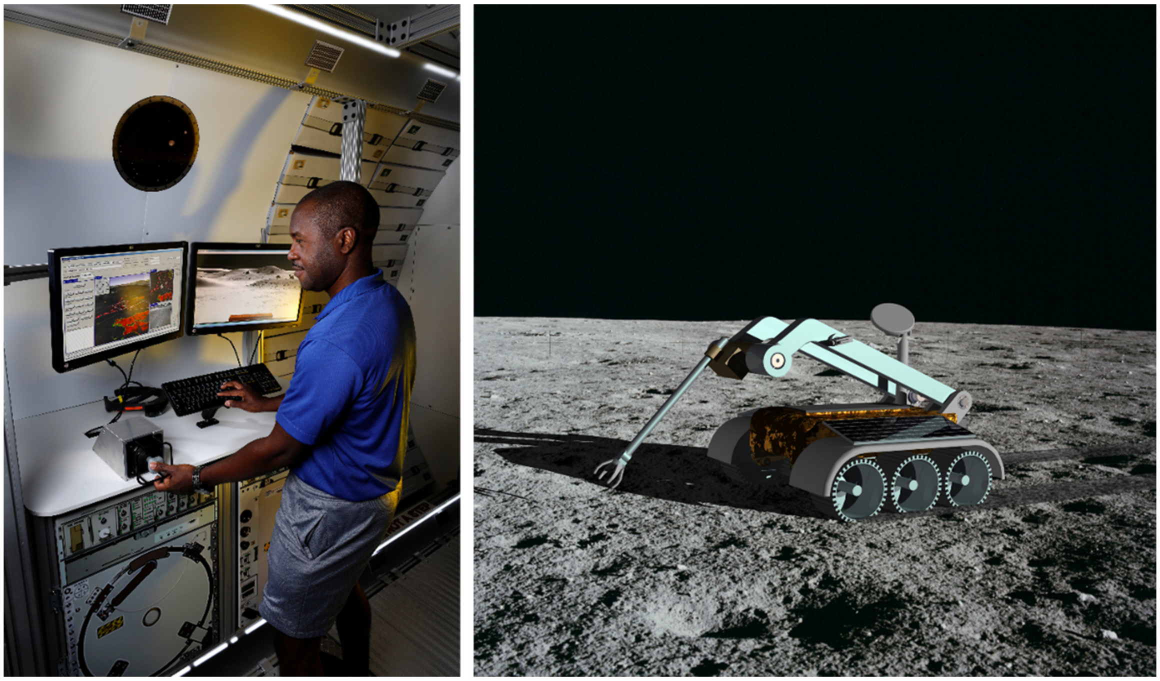

Figure 2: Scientist Astronaut Operating Rover on the Moon

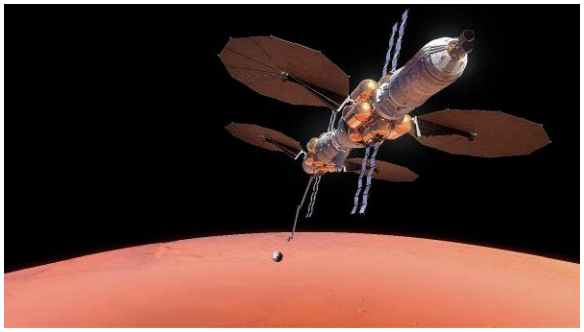

Figure 3: MBC Capture of Mars Sample Return

One of the key developments in deep space exploration, both in going to the Moon and Mars, is a more efficient means of propulsion. Solar Electric Propulsion (SEP) uses electricity generated from solar arrays to ionize atoms of the inert gas xenon. This system is low in thrust, but is extremely efficient with a high specific impulse, I_{sp}. Until recently, solar electric propulsion has been used primarily for low power applications such as station keeping. The Power Propulsion Element (PPE) of the Deep Space Gateway, will use SEP to reach its initial orbit in cislunar space. After mating with the habitat element, the PPE will be used to move the uncrewed habitat and additional Gateway elements to various orbits around the moon. To achieve these goals, the required power is at least 40kW, which is many times larger than thrusters currently flying, but is scalable to higher power systems with advancements in solar array technology and lab developments of thrusters and power processing units. Development and testing of higher class power systems at the Gateway enables the exploration of Mars. Power propulsion systems using SEP, similar to the PPE, would be used to preposition Mars exploration elements, like supplies, landers, and EVA modules, as seen in Figure 4.

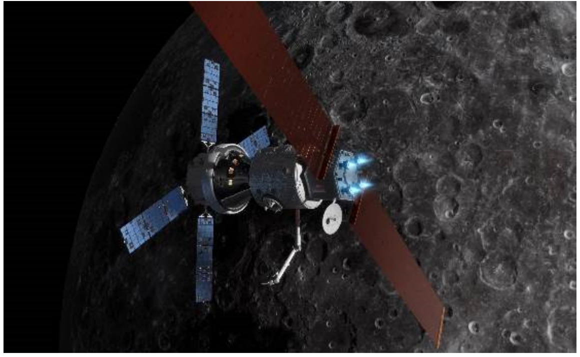

Figure 4: Deep Space Gateway Elements Enabled by Solar Electric Propulsion

4. MBC-S: Concept of Operations for Humanity's First Steps on Mars

Preparation for the MBC-S mission begins immediately upon the conclusion of the previous MBC mission. All system elements that were fielded in the MBC-1 mission (habitat and laboratory modules, LOX/LH2 tank farms, crew quarters modules, cryogenic propulsion stages, solar power generation stages) remain in space and are used again to provide Earth/Mars transit and the living environment in Martian orbit during MBC-S. This time, however, a Mars Ascent/Descent Vehicle (MADV) is also pre-deployed to Martian orbit and docked to the MBC station. This MADV is then used to enact relatively short, science-focused sorties from MBC to sites of interest on the Martian surface. Propellant consumed by the MADV for surface sorties is generated in Mars orbit via electrolysis performed on water that is supplied, ideally, by commercial providers. Initial missions assume water would likely be provided from Earth. However, commercial development of in-situ water sources (asteroids, Mars surface, and/or ideally on the moons of Mars) are encouraged as this represents an opportunity for significant savings in the recurring cost of a sustained exploration and development effort.

The MBC-S mission is divided into five primary phases:

A. Preparation of existing MBC elements for Earth/Mars Transit during MBC-S. This includes:
    a. Capture of the MBC Earth/Mars transit elements into orbit with the Deep Space Gateway.
    b. Refueling of the two Cryogenic Propulsion Stages (CPS) and tank farms.
B. Preparation of pre-staged elements at Mars. This includes:
    a. As-needed adjustment of the orbit on the MBC elements that remain at Mars (Laboratory module, center node, Deimos/Phobos excursion vehicle) into the operational orbit for MBC-S.
    b. Launch of MADVs and rendezvous with existing MBC elements at Mars.
    c. Launch of fuel depot and rendezvous with existing MBC elements.
C. Launch of crew and transfer to Mars on the MBC transfer vehicle
    a. Same general concept as MBC-1.
    b. Final assembly of the full MBC at Mars.
D. Mars Surface Sorties
    a. Fueling of MADV.
    b. Descent and Landing.
    c. Surface operations.
    d. Launch and Return to MBC.
E. Return to Earth

a. Same general concept as MBC-1.

This overall mission concept is illustrated in Figure 5.

At the conclusion of the previous MBC mission, the crew returns to Earth in a subset of the MBC system called the Transfer Vehicle. The Transfer Vehicle approaches Earth on a hyperbolic trajectory and performs a braking burn to return it back to the cis-Lunar orbit with the Deep Space Gateway (DSG) where it originated its journey. It should be noted that, while return from the DSG is baselined, Orion has been sized for entry velocities up to 11.5 km/s and thus direct entry with Orion from a Mars/Earth transit orbit is possible in a contingency. Once the Transfer Vehicle has been returned to the Deep Space Gateway, it is ready to be refueled. Fueling the Tank Farms in preparation for the mission is a potential commercially procured service. Standard propellant transfer interfaces will be defined and implemented on the CPS and Tank Farms, providing an opportunity for delivery of these propellants to the Transfer Vehicle by multiple commercial and/or international partners. The Mars Base Camp Tank Farms are zero boil off designs that include active cryogenic cooling. The Cryo Stages are not. Therefore, transfer of propellants to the Cryo Stages happens just prior to the launch of the crew.

A portion of the MBC system remains in Mars orbit following MBC-1, as seen in Figure 6:

- Lab Module
- Center Node
- Deimos/Phobos Excursion Module
- 2 Solar Electric Propulsion Stages and related solar panels

Beginning on MBC-S, a new element is added to the system to enable sorties to the Martian Surface: The Mars Ascent/Descent Vehicle (MADV). The detailed concept of operations for the use of the lander is described in phase D below. In phase B, the lander is pre-staged at Mars in preparation for later arrival of the crew (see Figure 5 for an illustration of all mission phases).

One or two MADVs are launched – each on an SLS Block IB.

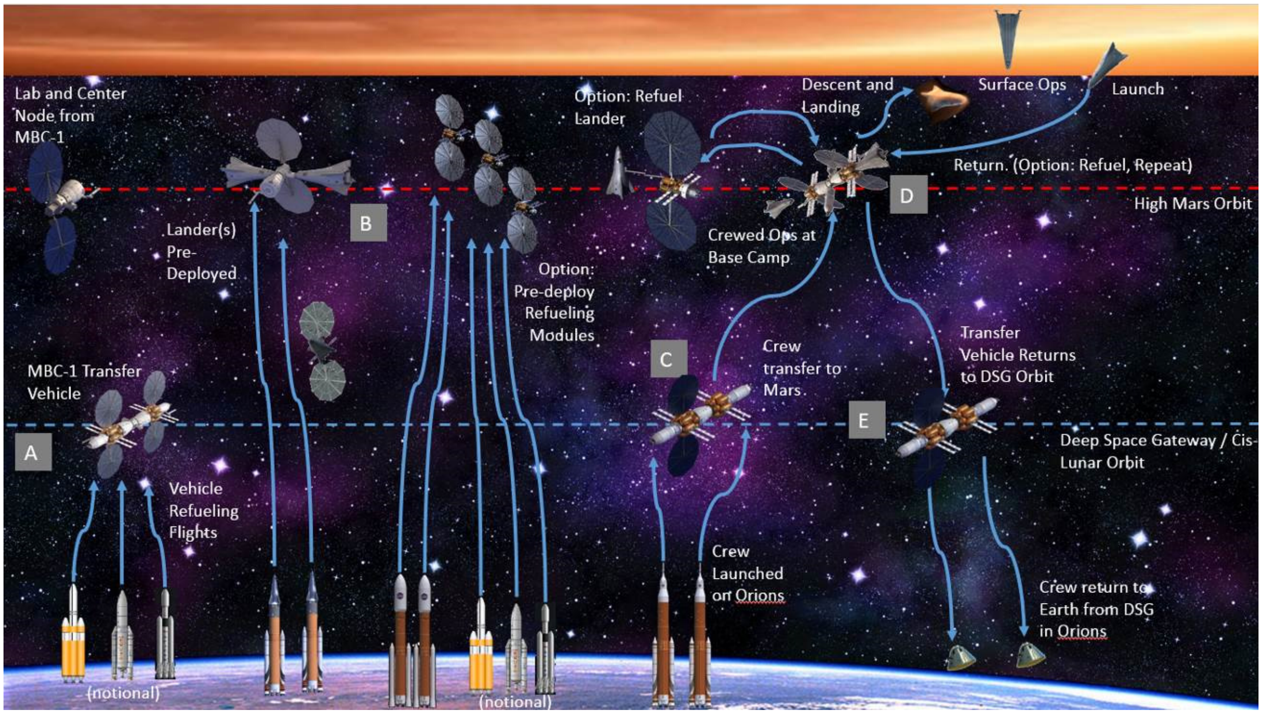

Figure 5. MBC-S Overall Mission Concept

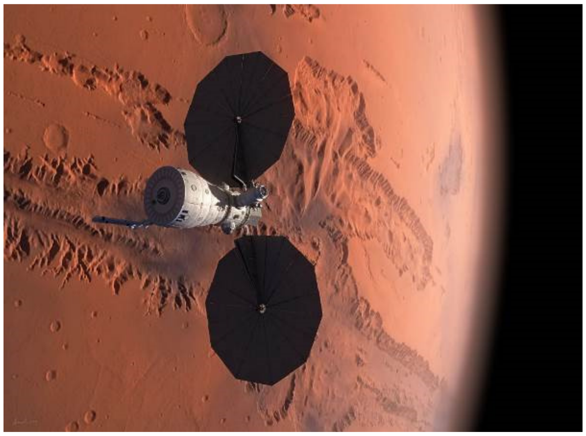

Figure 6 - Elements Remaining in Mars Orbit following MBC-1

While the entire MBC-S mission could be performed with only one lander, use of two MADVs is highlighted as an opportunity in this study to enable self-rescue in the event that the crew becomes stranded while on the surface.

A MADV is launched empty, with the attached dual mode SEP Stage providing services including rendezvous and docking to MBC. (Dual-mode SEP stage provides both solar electric propulsion for long-period velocity change maneuvers and chemical thrust for attitude control and small translational maneuvers during rendezvous and docking). The SLS provides injection to Mars, and the SEP stage then controls attitude and trajectory as it captures at Mars and spirals into the chosen MBC-S orbit. With the MADV(s) pre-positioned at Mars, the system is ready for the crew to arrive.

Figure 7 – MADV Launch Configuration atop SLS IB

4.1 Mars Surface Sorties

The Mars Base Camp system presents a new and flexible approach to exploration of the Red Planet. The crew will have to be at Mars for around 11 months in any mission where Hohnmann transfers are used for the Earth/Mars transits (driven by the synodic period of the Earth/Mars system). In an MBC-based mission, however, the crew need not be on the surface, or even at one location on the surface, during this entire timeframe. In the MBC paradigm, initial landings on Mars are envisioned as relatively short-duration science expeditions. A crew of 4 descends to the surface to spend up to two weeks in a location collecting data and samples related to key science objectives. They then return to MBC to perform more thorough analysis on the collected samples in the MBC Lab Module and, ideally, refuel the lander for another sortie.

This approach offers several key advantages over a more traditional Mars exploration architecture where

Figure 8. Mars Base Camp – Complete MBC-S Configuration with MADVs

the crew spends the full duration of the mission in a base on the surface:

- Cost: A year-long stay on the surface of Mars requires additional system elements (habitat modules, power generation systems, rovers, provisions, tools, etc.) to be pre-positioned on the surface ahead of the crew. These systems (and the related cargo delivery systems to get them to the surface) represent development, procurement, and launch costs that are not needed for the first mission if the surface stay is of a duration where all provisions needed are contained within the lander itself.
- Safety: Short surface sorties from an orbiting base of operations fundamentally reduce or eliminate several failure modes that would result in loss-of-crew in a traditional architecture:
  1) *Reduced dependence on landing accuracy:* A year-long surface stay requires the crew to land in close proximity to the pre-positioned surface elements. In the MBC paradigm, this mode of failure is eliminated entirely.

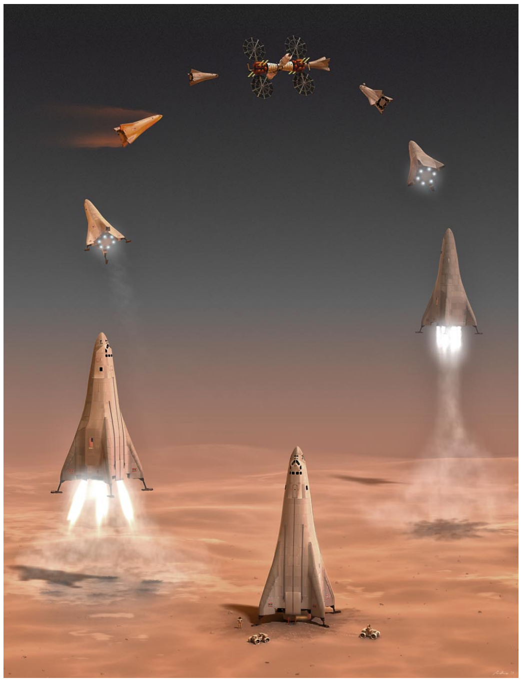

Figure 9 - Mars surface sortie sequence

  2) *Any time abort capability:* While MBC sorties are designed to last around a week, the lander can in fact return to the orbiting base camp early if warranted by equipment failure, medical emergencies, etc. Crew can also abort to orbit during a failed landing attempt.
  3) *Self-rescue capability:* If two landers are assumed, the crew that remains at MBC during the sortie has the ability to rescue the crew on the surface in the event that they become stranded.
- Flexibility: The landing site can be chosen and adjusted in near real-time. A sortie can target any area on the surface that is accessible from the operational orbit of MBC (which is the entire surface of Mars if a polar orbit is assumed). If capability to refuel the lander in-orbit between sorties is assumed, then the crew can actually visit multiple sites, separated by large distances, in a single mission. This not only has the potential to greatly increase the net science return for a single MBC mission, but also allows crews to explore a wide variety of candidate sites for a future surface outpost before committing to a single location.

All propulsion, attitude control and power generation systems on the MADV are designed to utilize LOX/LH2. Consumable water for the sortie is designed to be recovered from power generation fed by cryogenic boil-off. Thus, LOX and LH2 are the only resupply commodities that are required in order for the lander to execute additional sorties. The number of sorties that may be executed in a single MBC mission is therefore limited only by the quantity of LOX/LH2 that is available in Mars orbit.

The cryogenic tank farms on MBC were sized to provide propellant for the round trip to Mars as well as two sortie missions, first to Phobos and later to Deimos using the Orions, the Excursion Systems and the Cryogenic Propulsion Stages. If no Phobos/Deimos excursions are assumed for MBC-S, then the MBC system actually holds enough propellant at the time of Earth departure to fuel one MADV sortie without any resupply.

Performing more than one MADV sortie during a MBC mission requires additional LOX/LH2 beyond what can be carried onboard MBC. In the MBC-based exploration paradigm, resupply cryogenics are envisioned to be generated onsite by splitting water via electrolysis. The delivery of large quantities of water to MBC in orbit therefore presents a major enabler for long-term sustainment of an MBC-based exploration architecture, and a significant opportunity for development of a commercial industry to provide the water.

In all refueling scenarios, water is delivered to MBC via an autonomous Water Delivery Vehicle (WDV). WDVs could theoretically come in any size, but for the purpose of this study we assume a unit with 52 MT water capacity (2 WDVs required to refuel 1 MADV) and a 375kW-class solar powered electrolysis plant that doubles as a SEP stage. The WDV is a self-contained fuel station and consists of:

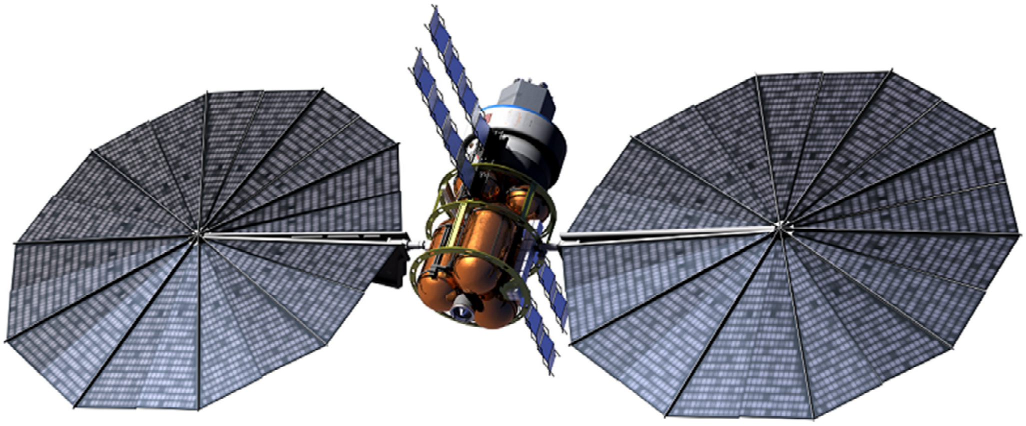

Figure 10 - WDV Concept

- Tankage for 52MT of water (full when launched)
- Tankage for 40MT of LOX/LH2 (6:1 ratio. Empty when launched)
- A 375kW-class SEP stage (375kW at Earth = 160kW at Mars)
- Electrolysis system (shares common power generation system with the SEP stage).
- Navigation and Communications systems

A WDV with this configuration will hereafter be referred to as a 50 MT Class WDV. Initially, WDVs would be launched from Earth. The 50 MT class WDV pictured above would require an SLS, but delivery of smaller variants is possible and could open the possibility for delivery of resupply consumables via a competitive commercial market. Over the long-term, water provider companies could ultimately develop in-space water production facilities to refill WDVs anywhere water ice and/or hydrated minerals are present (polar deposits on Earth's moon, asteroids, Martian surface, etc.).

Propellant remains in water form during the transit to eliminate boil-off loss (while MBC is designed to be zero boil-off, the MADV and WDVs are not) and to ensure that the full power output of the solar arrays is utilized to power SEP (full power output of the arrays is needed in both SEP and electrolysis modes). Once in Mars orbit, each WDV performs a rendezvous with MBC, is captured by one of MBC's robotic arms, and begins converting its water load into LOX/LH2. Two 50 MT class WDVs working in parallel would create the fuel for one MADV sortie in about 2.5 months.

The number of sorties that may be performed during a single MBC mission is primarily driven by the number of WDVs that are present. If more than 2 WDVs are planned, space limitations at MBC will likely mean that it is more practical to have the WDVs orbiting separately as a sort of fuel "depot." The separately-orbiting WDVs would be located in the same orbit as MBC, but phased slightly ahead or behind. Rather than filling up with cryogenics at MBC, a sortie would begin with the MADV performing an autonomous phasing maneuver using a small amount of propellant drawn from MBC to rendezvous with a WDV.

In any of the above options, once fueling is complete, the crew loads supplies for the sortie, then undocks and performs the descent/landing sequence. 4 crew go to the surface while 2 remain with MBC.

4.1.1 Descent and Landing

Once undocked from MBC, the MADV performs a deorbit burn and proceeds to perform direct Mars atmospheric entry. The analysis presented in this paper has sized the MADV for entry velocities up to 4.7 km/s to allow for operations out of the 1-sol orbit that was established on MBC-1.

Sorties will most likely target landing sites that had been selected ahead of time to ensure not only science value, but also maximize the odds of being able to land safely due to favorable grade of the terrain, absence of obstacles, etc. The MADV must therefore have a reasonable ability to do a controlled, lifting entry to adjust cross range trajectory on the fly. A mid-L/D profile is therefore preferred over a simpler blunt body for this study. Lifting entry proceeds with course corrections as needed until the vehicle reaches stall speed, which is assumed to be at or around local Mach 2[6], at which time the MADV initiates a pitch over to a supersonic retro propulsion (SRP) attitude and performs a powered gravity turn and to arrest the remaining velocity. The MADV deploys mechanical landing gear and touches down vertically.

The requirement for full reusability is important to note. Inflatable aerodynamic decelerators or other deployable deceleration devices would result in some savings in propellant or TPS mass, but have no viable way to be repacked after use or refurbished in-situ.

Parachutes could potentially be replaced on-orbit, but would need to be prohibitively large to arrest the descent of a 100+ MT vehicle such as the MADV. A fully reusable lander therefore must rely exclusively on retro propulsion to arrest the final velocity during descent.

4.1.2 Surface Operations

Once landed, the MADV is home for the crew of 4 for the next 10 days of nominal operations. For the purpose of this analysis, we assume 50% contingency margin, or 15 days of total operational capability. 2500 kg are allocated for equipment to support extravehicular activities, and science operations on the surface. MADV ingress/egress is provided via a 2-person airlock, with an accompanying mechanical lift on the exterior of the vehicle to transport 2 crew at a time to the surface. Consumables are sized to allow multiple EVAs per day. Two, 2-person EVAs per Sol are assumed for the purposes of this analysis.

Electrical power is generated throughout the sortie by utilizing the boil-off from the remaining LOX/LH2. Communications include a low data rate connection directly to Earth via the DSN, and high-data rate connections to MBC via Mars-orbiting relay satellites and/or directly to MBC when it passes overhead.

4.1.3 Launch and Return to MBC

Once the sortie is complete, the MADV becomes a single-stage-to-orbit launch vehicle. The same LOX / LH2 engines that were used for descent are used for ascent as well.

The resulting total ΔV budgets and related propellant mass fractions for the MADV are shown below. Here again we include the budget for the 1-sol (design reference) orbit as well as a 500 km circular orbit. Also note that the numbers presented here include budget for RCS maneuvers and phasing burns to take the MADV to/from the optional fuel resupply modules:

Table 1. Total ΔV Budgets for MADV Sorties

Return to MBC in:	***EDL ΔV: (m/s)***	***Ascent ΔV: (m/s)***	***Total ΔV: (m/s)***	***Propellant Mass Fraction***
500 km Circular	1270	4200	5470	71%
1-Sol	780	5220	6000	74%

Propellant mass fractions are calculated using the ideal rocket equation assuming a 450 second I_{sp} for LOX/LH2.

To put this mass fraction in perspective, the fully loaded Space Shuttle Orbiter plus External Tank at lift-off had a propellant mass fraction of ~ 85%. This is an encouraging result – even in the design-limiting case where MBC remains in the 1-sol orbit, the MADV need not achieve even the same level of dry mass efficiency as the Space Shuttle.

5. MADV Architecture

In order to execute the mission outlined in section IV, The MADV must be:

1) A 3-axis controlled spacecraft capable of both autonomous and piloted rendezvous and docking operations.
2) A mid-L/D entry vehicle with high landing accuracy
3) A vertical landing vehicle with supersonic retro propulsion capability.
4) A single-stage to orbit launch vehicle.

It must also be fully reusable. Any hardware that is required to be removed and replaced between sorties must be reasonably swapped by the MBC crew using hardware that can be carried on MBC. (For example – replacement of filters in the air revitalization system between sorties is reasonable. Replacement of an ablative heat shield between sorties is not). The architecture outlined is driven in large part by this mindset of maximum reusability and minimum refurbishment between sorties.

5.1 Structure and Thermal Protection System

The SLS Block IB is the assumed lift vehicle for initial launch of the MADV. In order to maximize available volume, the MADV is not envisioned to be encapsulated within a payload fairing, but will instead sit exposed atop the SLS similar to other current rocket-launched lifting body concepts. It is therefore designed to have a maximum radius at the base of 10 m to be compatible with planned SLS upper stage interfaces[7]. Structures must therefore be sized to take aerodynamic loads and aero heating from SLS ascent in addition to those encountered during Mars operations as a result.

The Outer Mold Line (OML) of the MADV was chosen to strike a balance between several driving parameters:

- Must be able to perform repeated entry operations with the same TPS materials (no ablative coatings, etc.) So, sharp, wing-like edges can only be utilized if they do not create localized peak stagnation heat rates that require single-use TPS materials.
- Landing accuracy is considered here to be a tradeable parameter, but landing accuracy is desired to be as large as reasonably achievable.
- Volumetric efficiency.

This trade space resulted in a mid-range L/D lifting body. To ensure highest achievable L/D, the MADV enters at a fairly low angle of attack instead of as a blunt, capsule-like body.

Initial analyses of a vehicle of this configuration entering Mars atmosphere at velocities between 3 and 5 m/s show that a reusable thermal protection system is viable. The vehicle nose and other leading edges where peak stagnation heat rates are greatest will likely require a carbon-carbon composite lining, but the bulk acreage of the entry silhouette should be able to utilize metallic alloy skins. Optimization of entry corridor and vehicle OML to minimize required TPS mass is an ongoing area of current work.

5.2 Propulsion and Power Systems

The MADV propulsion system will run exclusively on LOX/LH2 for several reasons:

1) Highest specific impulse (~450s) of any currently available, high-thrust chemical rocket technology.
2) Propellants can be generated from water with no additional chemical reactants. This is critical to enable:
    a) Minimized cost of systems to deliver propellants from Earth (suppliers need only deliver large quantities of water to Mars orbit).
    b) Opens the door to in-situ production of propellants on any celestial body where water ice and/or hydrated minerals are present.

Both Main and RCS engines utilize Oxygen and Hydrogen. Gaseous oxygen and hydrogen RCS thrusters are chosen over more traditional hypergolic-fueled thrusters to allow RCS to be resupplied via the same water-based supply chain that is used for the main engines. This is critical to enable the long-term reusability and affordability of the MBC-based exploration effort: there exists no viable way to generate hypergolic fuels via ISRU, and the long-term viability of resupply chain for MBC is assumed to be greatest when the number and types of resupply consumables is minimized.

The main engines are used for large-scale in-space translational maneuvers, SRP during EDL, and launch from the Martian surface. For this study, 6 RL-10 equivalent throttle-able LOX/LH2 main engines are assumed:

The MADV systems run off of external power when mated to the SEP Stage, MBC or, eventually, a refuelling module. During sortie operations, the hydrogen and oxygen that will naturally boil off from the propellant tanks present a large supply of potential energy that would otherwise be wasted. Instead, this waste gas is used to generate electrical power for the vehicle.

Similar to the MBC Cryogenic Propulsion Stage, and "Integrated Vehicle Fluids" (IVF) LOX/LH2-based system combines power production, attitude control, and propellant thermal management[8]. The key tenets of this system are:

- Waste gasses from the LOX/LH2 tanks are burned in a hydrogen/oxygen internal combustion engine (ICE) which drives an electric generator to supply vehicle electrical power.
- LOX and LH2 are pulled from the main tanks via electric pumps and run through a set of vaporizers and accumulators that continuously replenish a set of high-pressure gaseous O2 and H2 tanks. Thermal energy for the vaporizers is provided from the ICE via an oil coolant loop. This high pressure gas is then utilized for tank pressurization, purges, pneumatic power, and in the H_2/O_2 RCS thrusters.

Orbital demonstrations of this integrated system are encouraged in the near term to ensure a system with a TRL that can support crewed flights in the MBC timeframe. A battery bank is also provided to ensure adequate energy to keep the vehicle systems running in the event of a temporary generator failure or during rendezvous and docking operations. However, fuel cells can also be run from MADV propellant waste gasses and remain under consideration as a fall-back technology for power generation. To reduce development costs and maximize interchangeability of parts between elements of the MBC/MADV system of systems, all batteries and power distribution/control components are assumed to reuse and/or be derived from designs currently in use on the Orion spacecraft, and MADV propulsion, RCS and power generation systems are derived from the MBC Cryo Propulsion Stage.

5.3 ECLS and Crew Systems

The MADV Environmental Control and Life Support system provides functions as follows.

- Resupply of Habitable Atmosphere (makeup gasses)

O_2 makeup gasses are presumed to come from the IVF system and makeup atmospheric N2 is supplied via replaceable canisters that are carried onboard MBC and replenished between sorties.

5.3.1 Air Revitalization System (ARS): Removal of CO_2 and Trace Contaminants

In order to maintain a breathable atmosphere, carbon dioxide and trace contaminants produced by the crew must be filtered and removed. MADV ARS systems are intended to re-use or be evolved from systems used on the Orion – again enabling minimized non-recurring engineering cost and maximum interchangeability between Orion and MADV systems in flight.

5.3.2 Consumable Water

The crew will need consumable water for drinking, washing, and food preparation during the sortie. Because of the relatively short duration of the sortie missions (nominally 10 days), clothes washing and full shower facilities are not assumed.

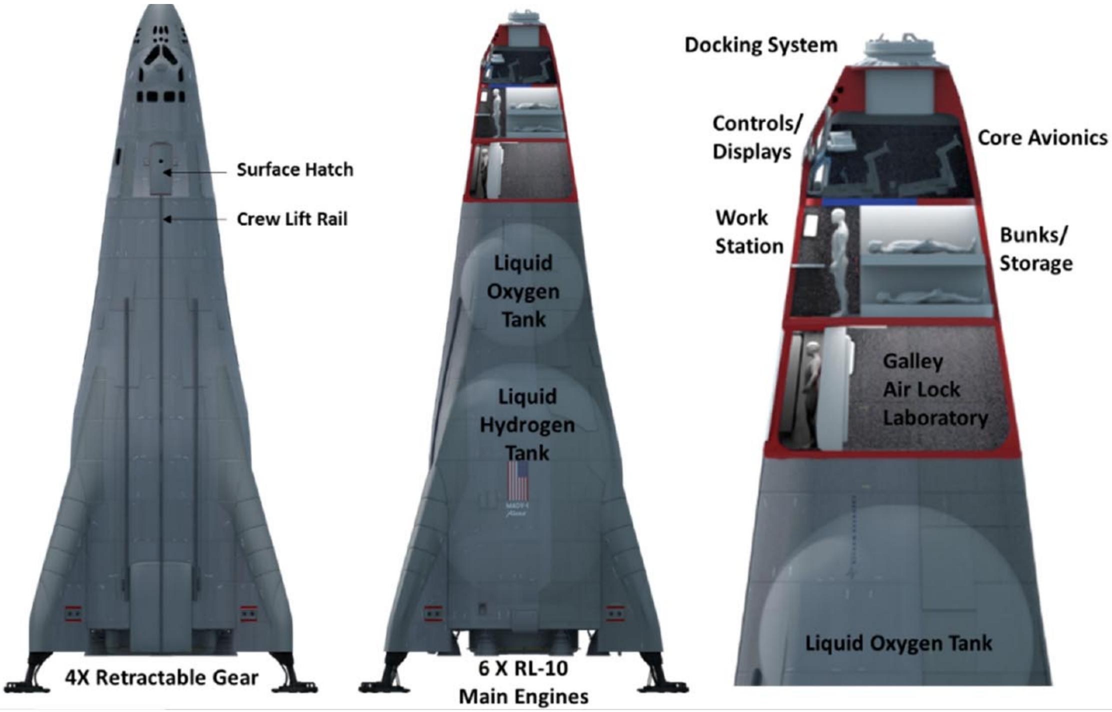

Figure 11 - MADV Layout

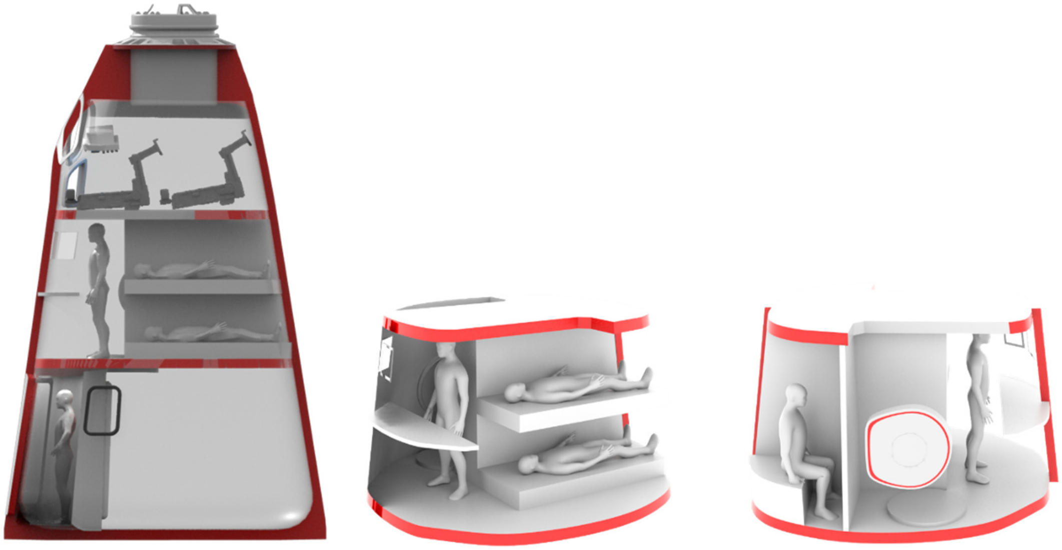

Figure 12 - MADV Pressurized volume with Mid-Deck details

The power generation system generates over 2 MT of byproduct water during the sortie. This byproduct is captured and supplies all needed consumable water for the crew throughout the sortie. This not only creates significant mass savings since additional consumable water is not carried through the various propulsive maneuvers, but also reduces the complexity, mass, and cost of the ECLS.

5.3.3 Crew Accommodations

Mass estimates include a little over 1MT for the equipment needed to support the day-to-day health of the crew throughout the sortie including

5.4 Physical Configuration

Overall physical layout of the MADV is shown in Figure 11 and Figure 12.

The habitable volume consists of three decks: a flight deck, a mid-deck with crew quarters, and an aft deck that contains the galley and lab facilities as well the airlock for surface access. Seats, displays and controls, avionics, and physical layout on the flight deck leverage common designs with the Orion capsule to the greatest extent possible.

The forward end of the MADV must be covered in carbon-carbon composite for re-entry operations, but is also the docking interface during orbital operations. The docking interface is therefore covered by an articulated, TPS-covered cone. The leeward side of the TPS below the crew cabin is also articulated to expose radiators that are used to help regulate avionics and crew cabin temperatures during orbital operations.

Crew gain access to the surface through the airlock on the aft deck and a lift that runs along the leeward side of the vehicle from the airlock to the ground. Retractable landing gear are deployed from the four aft corners of the vehicle. The center section of the aft end, located between the six main engines, is a retractable equipment lift that lowers to give the crew access to the rovers and other equipment for surface science operations.

6. Conclusion

While the first Mars Base Camp mission would only see crew operate in Mars orbit, MBC can naturally evolve into a true “base camp” from which crewed missions to the surface of Mars are launched. Via the addition of a reusable lander / single-stage-to-orbit launch vehicle and a fuel supply module to support it, MBC can form the core of an architecture that enables a vision of humanity’s first steps on Mars. Instead of having to commit crew to a long-duration stay at a single location on Mars, surface sorties from MBC are flexible, with the ability to visit multiple surface sites in a single, year-long mission, and provide multiple opportunities for the crew to return early to the orbiting base camp in the event of a problem on the ground. The short-duration, scientific research sorties in MBC-S can gradually evolve into longer duration sorties for the construction of more permanent settlements. MBC can therefore be seen as the core system that pivots humanity into a viable, sustainable long-term Mars exploration program. Testing and proving the technologies and processes for telerobotic operations, including sample return and analysis, at the Moon using the Deep Space Gateway is critical to the success of the MBC scientific missions. The knowledge in how to incorporate telepresence and multiple modes of operations into a rover as well as the astronaut’s workstation will carry forward into the Mars robotic missions. The Gateway will also demonstrate critical technologies, such as solar electric propulsion. Key focus areas for further development and research to enable the architecture include demonstration of on-orbit LOX/ LH2 propellant generation, storage, and transfer, and the characterization of potential ISRU sources.

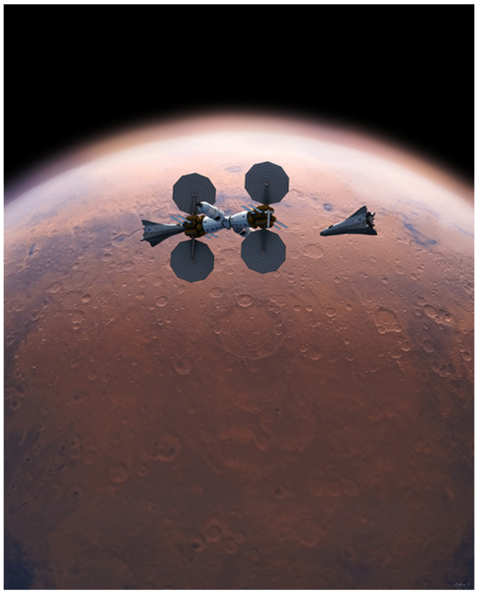

Figure 13: Mars Base Camp

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