CHAPTER NUMBER

AN INTRODUCTION TO HUMAN MARS MISSION EQUIPMENT AND OPERATIONS

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Introduction

Human exploration of Mars has been an on-going subject of study at the National Aeronautics and Space Administration (NASA), beginning almost at its very inception (Portree, 2001). Although a human Mars flight program has yet to become official, NASA continues to view human Mars exploration as a “horizon” goal towards which it should direct its efforts, and continues to analyze contemporary descriptions of how this goal could be accomplished. As our knowledge of Mars expands and technologies relevant to human spaceflight advance, decisions regarding the timing and objectives for a human mission to Mars continue to evolve. Detailed studies incorporating these technological advances and expanding scientific knowledge continue to be made and results are in turn collected together into reference missions or architecture options. This cycle of studies and reference missions is used to provide meaningful characterizations for those making decisions regarding timing, objectives, and technologies for eventual human missions.

In the most recent series of Mars mission studies, beginning in the mid 1990’s, NASA adopted the strategic assumption of a sustained program of Martian exploration by human crews. Unlike the successful Apollo lunar missions, in which a series of one-time crewed expeditions were sent to different sites of interest, this assumption was driven by a recognition that the longer duration of Mars missions coupled with the goal of on-going human exploration missions argued for a different approach: multiple expeditions to a single location. This approach had a significant advantage for a sustained program of surface exploration in that it allowed for the buildup over time of reusable surface infrastructure (Hoffman and Kaplan, 1997; Drake, 1998).

As part of a major update, during the mid 2000’s, to the reference approach for Mars exploration, an effort was made to include a detailed science community assessment of the most useful approach for human Mars exploration. This interest was driven, in part, by the resurgence of robotic exploration of Mars from orbit and on the surface during the 1990’s and 2000’s. The Mars Exploration Program Analysis Group (MEPAG) was formally tasked with this assessment (MEPAG HEM-SAG, 2008), the results of which favored sending each human expedition to a separate surface site, albeit for 18 months at each location, in order to address the broad sweep of science questions emerging from this latest era of robotic exploration of Mars. The resulting update to the reference approach for Mars exploration (Drake, 2009a; Drake, 2009b; Drake and Watts, 2014) retained much of the previously studied hardware systems (including technological advances) and mission operations for human missions, but now duplicated the entire surface infrastructure at several widely separated sites, abandoning each after a single expedition.

While the MEPAG-inspired approach allowed exploration of several different regions of the planet, the cumulative cost of exploring and abandoning multiple sites was a concern. A recognition of the improving capabilities that could be employed by human explorers on the surface, coupled with an ever-improving understanding of the broad scope of exploration questions that could be addressed in a regional approach, led to the emergence of the Exploration Zone (EZ) concept (Bussey and Hoffman, 2016). Consciously selecting an EZ with both a diverse set of scientific questions that would not be exhausted during a single human expedition and with the potential for developing technologies and operations that would lead to extended and expanded human activities on Mars drove a return to the single surface site approach and adoption of the

Mars Surface Field Station concept (Toups and Hoffman, 2015). Multiple crews would use this multi-capability surface field station, with its gradually expanding infrastructure and its surrounding EZ, to achieve the strategic goal of an Earth-independent, extended human presence on Mars.

NASA's current architecture for the human exploration of the surface of Mars envisions at least three separate crews of four people exploring a single Exploration Zone over a period of approximately a dozen years. Three crews and a dozen years of exploration are seen as a reasonable amount of time and effort to realize a meaningful return on the resources invested to create this surface exploration capability. The stakeholders involved in this exploration program would then have an opportunity to consider what had been achieved and make a collective decision to continue on this path of Martian exploration, move on to a completely different exploration focus, or to carry on with some combination of both. The architecture needed to support this initial surface exploration capability will require (1) a transportation system that can launch heavy and volumetrically large payloads, move crew and cargo efficiently to and from Mars, and land payloads on the surface in increments of as much as 22 tons, and (2) surface systems that can support the crew and their exploration activities for up to 500 days in all types of Martian weather, make at least a portion of the propellant needed to depart the surface using local resources, and return the crew to their orbiting vehicle for return to Earth. The remainder of this introduction will focus on the surface exploration capability elements of this architecture and the role played by the surface environment, along with those transportation elements used to deliver crew and cargo to the surface as well as return them to their Earth return vehicle.

The Exploration Zone

An EZ is a collection of Regions of Interest (ROIs) that are located within approximately 100 kilometers of a centralized landing site. ROIs are areas that are relevant for scientific investigation and/or development/maturation of capabilities and resources necessary for a sustainable human presence (Bussey and Hoffman, 2016). Figure 1 shows a representative example of one of these EZs.

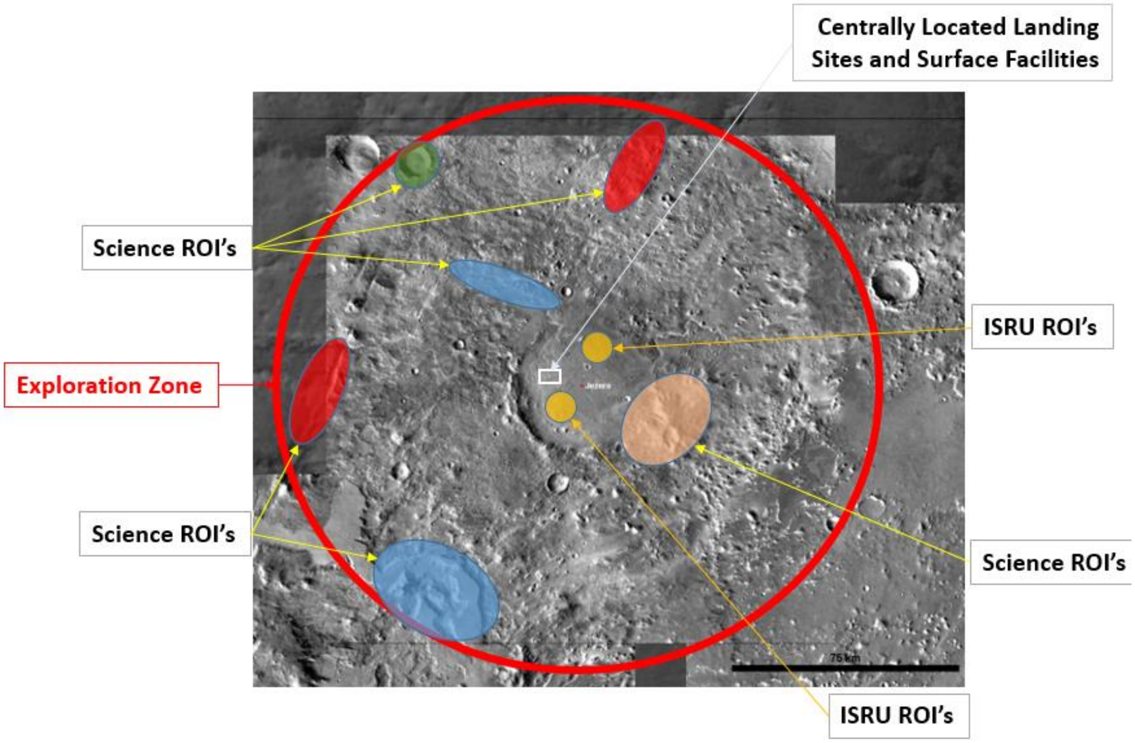

Fig. 1. A representative Exploration Zone, showing a centrally located area for Field Station facilities and infrastructure along with regions of interest associated with scientific investigations or ISRU production. (Bussey and Hoffman, 2016)

The centralized "landing site" actually serves a much broader function in this EZ concept than just landing. This centralized portion of the EZ serves as a research field station as would be seen here on Earth, providing much of the surface support infrastructure such as habitation, power, communication, laboratory facilities, logistical storage, and, eventually, commodity production through a variety of processes collectively referred to as in situ resource utilization (ISRU).

Traverses would be a key feature of the exploration strategy used at an EZ, but these traverses would be constrained by the capability of small pressurized rover. In the latest Mars surface exploration strategy, these rovers have been assumed to have a modest capability (compared with their terrestrial counterparts), notionally a crew of two, traversing at least 200 kilometers total distance before being re-supplied, within a 1- to 2-week duration. Thus, on-board habitation capabilities in these rovers would be minimal. However, these rovers are assumed to be sufficiently nimble to place the crew in close proximity to features of interest (i.e., close enough to view from inside the rover or within easy extravehicular activity (EVA) walking distance of the rover).

Surface Systems

In addition to this small pressurized rover, the surface systems that provide the balance of the capabilities needed by crews to support their exploration of an EZ are shown in Figure 2. Because of the difficulty in getting equipment and supplies to the surface of Mars, specific assessments have been conducted to identify those systems and processes that can perform in multiple, sometimes completely unrelated, situations and locations. Examples include: (a) habitation and logistics storage modules using a common pressure vessel and docking mechanism, (b) a centralized power plant capable of supplying power to a geographically distributed (but within the central field station zone) set of systems, (c) mobility systems that can be used to off-load and move payloads to specific locations at the field station that can also traverse long distances to reach some of the more remote ROIs and (d) robotic systems that can support various activities (such as system set up and maintenance) at the field station that can also be used to explore scientific ROIs and to support site-specific ISRU production activities.

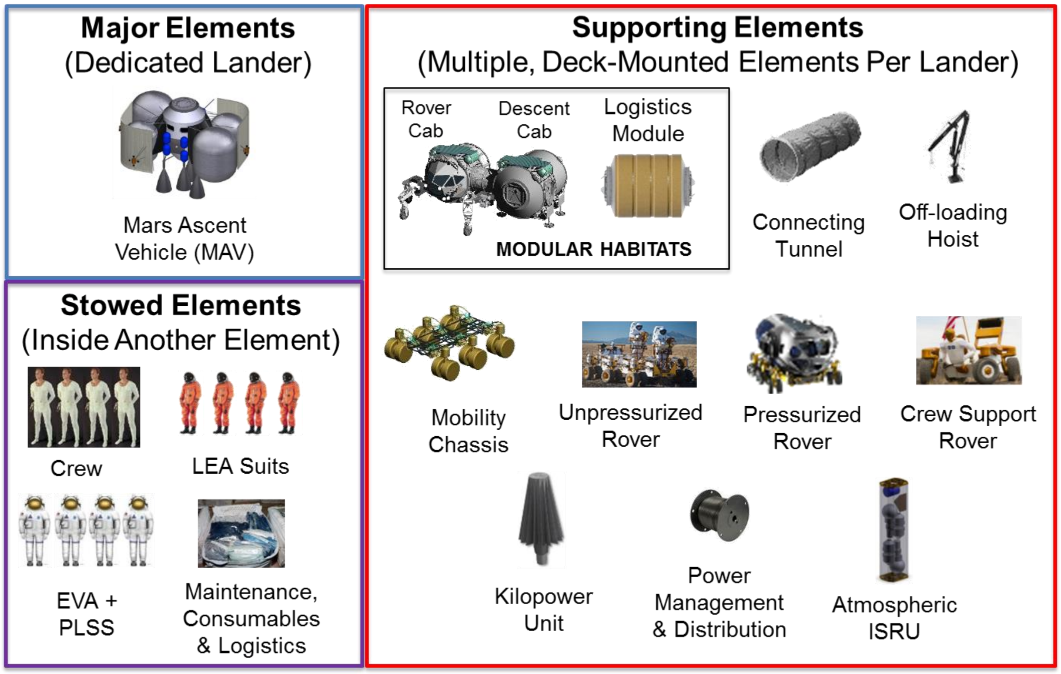

Fig. 2. Surface Systems Used at an Exploration Zone.

Several of these systems could be particularly susceptible to effects of the Martian surface environment.

Surface Power. The current NASA architecture assumes the use of a fission-based power system to support all of the systems located in the Field Station area. So-called "kilopower" fission systems are intended to provide reliable power for extended duration surface operations. The design is simplified from those assumed in previous NASA architectures by using an existing form of reactor fuel and advanced Stirling-type convertors. Multiple units are assumed to be "ganged" together to build up capability. These kilopower units are robotically relocated from the cargo lander that delivers them to a safe separation distance, spooling transmission cable along the way. After placement on the surface (or behind a natural feature or constructed berm to reduce separation distance), radiators are deployed if needed, and the unit(s) are activated. Following shutdown, these kilopower units are safe to approach within one day for robotic operations, or one week for crew, allowing for movement to a new location if desired.

Fission power systems continue to be traded with solar arrays and power storage. Because an Exploration Zone has not yet been chosen, locations for the Field Station are being considered in a band from 50° north latitude to 50° south latitude. The length of a Martian day will be a factor in determining the size and mass of a solar array-based system. However, of almost greater concern is the frequency and duration of local or regional dust storms. Protecting for the possibility of a dust storm that could last for weeks or months has tended to drive this trade off in favor of the fission-based system.

In Situ Resource Utilization (ISRU). Using local resources to make some or all of the propellant needed for the Mars Ascent Vehicle (MAV) has long been recognized as a means of saving a significant amount of mass that would otherwise be launched from Earth. The same can be said of other commodities likely to be needed by the crew, including breathing gases, water for life support, radiation protection, and, later on, food production and other local materials that can be used for a variety of construction purposes. The current NASA architecture assumes that the only local resource that will be relied upon for mission success is CO_2 that is captured from the Martian atmosphere and sent to a solid oxide electrolyzer to make oxygen for the MAV. The resulting oxygen is liquefied and stored in the Mars Ascent Vehicle's propellant tanks. While this approach does not make all of the propellant needed for ascent, oxygen does make up roughly 80 percent of the total propellant needed for the assumed methane-oxygen propulsion system. As experience in surface operations grows and as reliable sources of local materials are identified, expanded use of ISRU is assumed.

Dust in the Martian atmosphere will play a significant role in the design of this ISRU system and propellant storage system. Any dust in the atmosphere must be filtered out before the gas is sent on to the solid oxide electrolyzer. The atmosphere is known to have a certain amount of dust in it at all times and this must be accounted for in the ISRU design. However, the filtration system must also accommodate some unknown number of local dust storms of undermined magnitude. A temporary cessation of oxygen production may in fact be the only possible mitigation, but a much better understanding of the surface-level dust storm environment is needed before invoking this response. These same dust storms will add to the dust load that will coat the substantial radiator area needed for the electrolyzer and for the coolers that maintain the liquefied oxygen in the Mars Ascent Vehicle.

Habitable Volume. As noted above, the current NASA architecture assumes that several crews will return to the same set of surface assets over the course of several years, with each crew using these assets for as long as 500 days. This implies that a substantial amount of habitable volume will be needed to sustain the crew properly during these surface missions. This need has manifested in the form of several small habitable spaces, including a modular main habitat, logistics modules, and small pressurized rovers, that can all be interconnected to form a larger total volume or operated for a comparatively short time, depending on the activity.

Because of the anticipated number of EVA activities and extended duration traverses, dust is very likely to get inside of these habitable spaces. Mitigation, such as the incorporation of “mud rooms” between airlocks and rover docking interfaces, will help manage some of this infiltration. However, interior spaces and systems, such as door seals, air circulation fans, and the “wetted” components of ECLS systems, will still require additional mitigation in the form of additional filtration (a potential consumable item) and periodic cleaning by the crew.

Extravehicular Activity (EVA). An EVA suit is essentially a one-person spaceship with all of the interior concerns just described for habitable spaces plus concerns arising from interaction with the surface environment by all of the exterior components of the suit and portable life support system (PLSS). The garment and helmet portions of an EVA suit use a wide variety of materials: from fabrics to metals to composites to clear plastics (e.g., visors); from fixed components to rotating joints to connectors for power, data, and fluids or gases. Experience with EVA suits during the Apollo lunar missions found that dust coating or infiltrating some of these components caused significant problems after just three EVAs. The current NASA architecture envisions much longer surface missions compared with any of the Apollo missions as well as significantly more EVAs. This will drive a search for creative approaches to the design of the EVA garment and portable life support system as well as the materials used to implement these designs. It will also drive the need for a combined system that can be routinely maintained by the crew while on the surface.

Space Transportation Systems

Two elements of the space transportation system from the current Mars architecture are used to deliver both the surface systems and the crew to the surface and to return the crew to their orbiting Earth return vehicle. These two elements of the Mars space transportation architecture are the Mars Descent Module (MDM), shown using the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) reference configuration, and the two-stage Mars Ascent Vehicle (MAV), illustrated in Figure 3. Both of these transportation systems will interact with the Martian atmosphere, and, in particular, with the dust environment, during all phases of their operation, including entry and landing, surface operations, and ascent of the crew to Mars orbit. Several specific considerations, including descent/ascent trajectory, landing in close proximity with other previously deployed surface elements (for field station growth) and planetary protection for crewmember ingress into the MAV, result from these vehicles' interaction with the surface environment.

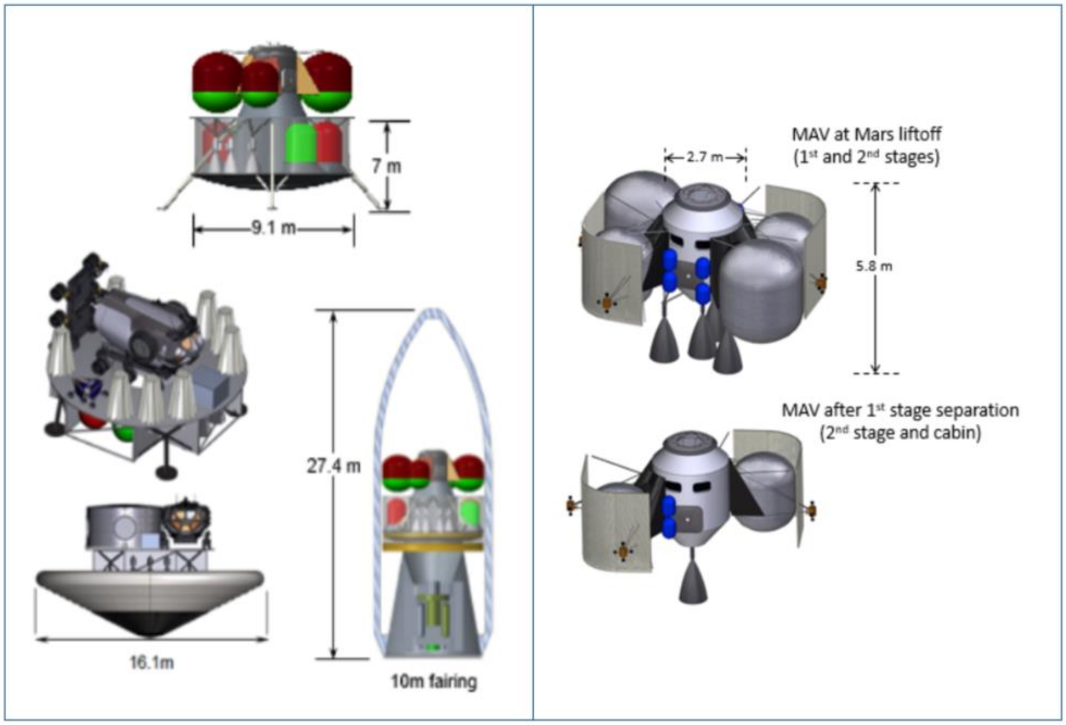

Fig. 3. This image depicts the Mars Descent Module (MDM) with the HIAD reference option in both payload and lander configurations (left) and the Mars Ascent Vehicle (MAV) with both the initial launch configuration and the final in-orbit configurations (right).

Mars Descent Module (MDM). The current Mars architecture assumes pre-deployment of surface cargo prior to the arrival of the crew by means of a Mars Descent Module. These pre-deployed elements arrive in units of 22 mt payload per lander – a size determined by the delivery mass of the MAV, the largest indivisible element currently sent to the surface. The Martian dust presents several challenges to landing MDMs on the surface of Mars, especially for an architecture that emphasizes both an expanding field station, accomplished by landing multiple MDMs in close proximity, as well as cargo with mission life requirements in excess of 1000 days.

The intensity of Martian dust storms varies with season and with surface location, occurring typically when Mars reaches perihelion, near the start of summer season for Mars' southern hemisphere. Depending on the season, dust storms, which originate at the surface, could cause dust clouds that have been known to migrate across the surface and rise to varying altitudes. As a result, the large volume of dust within the atmosphere of Mars during a local, regional, or global dust storm has implications on MDMs attempting to land at a specific site on the Martian surface. For example, this could result in physical or chemical interactions with the HIAD heat shield. In addition, interaction between the MDM and atmospheric dust at high re-entry speeds could produce sand blasting on crucial cargo components, potentially coating or eroding windows and other surfaces due to the fine-grained dust. This could be avoided with covers for windows and with advanced materials to mitigate surface corrosion effects on landers and cargo. Furthermore, attempting to land during a severe dust storm could cause the MDM's automated navigation systems to veer off the intended course and complicate the aggregation of critical surface hardware prior to crew arrival. All of this implies testing to ensure these interactions are not detrimental to the MDM and its cargo or it could lead to other mitigations, such as waiting in orbit for an uncertain period of time while the dust storm dissipates, at the cost of mission time on the surface.

As the field station grows, newly arriving landers will need to land in relatively close proximity with pre-deployed surface elements. This leads to further dust environment challenges caused by human-created dust impacts related to the exhaust plume from braking engines on each MDM lander. The dust produced by newly arriving landers could cause problems ranging from something as minor as coating surfaces with dust to more severe issues, such as un-burned propellant mixing chemically with Mars dust, potentially damaging mission critical hardware.

Mars Ascent Vehicle (MAV). The Mars Ascent Vehicle is a critical component of the crewed mission architecture; it serves as both the vehicle that transports the crew from the surface to space and as the last line of defense for planetary protection. The crew must be able to successfully minimize the amount of dust contamination while transporting themselves, scientific samples, and other items to the MAV before leaving the surface of Mars on the way home to Earth. A solution to this might be to actually leave the EVA suits on the surface of Mars and return to the MAV via a pressurized tunnel to prevent or minimize Mars dust from contamination of the pressurized MAV.

Ascent from the Martian surface poses similar challenges to those faced by the MDM. During ascent, the MAV might be exposed to collisions with dust at high speeds produced either from the ascent engines during takeoff or from the Martian atmosphere if the launch occurs during a seasonal dust storm. Like the MDM, the MAV might experience sand blasting, limited visibility due to dust abrasion on windows used by the crew or by navigation sensors, and even possible malfunctions of mechanical and thermal systems as a result of interactions with the dust environment while transiting through the Martian atmosphere. Even with those challenges, advanced protective equipment for windows and more robust surface materials to prevent erosion are possible mitigation strategies.

Concept of Operations

As mentioned above, NASA’s current architecture for the human exploration of the surface of Mars envisions at least three separate crews, each consisting of four people, exploring a single Exploration Zone over a period of approximately a dozen years. The concept of an Exploration Zone and the establishment of a Mars Surface Field Station to support this exploration defined certain surface system capabilities needed to accomplish this objective. Certain other assumptions driven in part by an attempt to improve the overall efficiency and sustainability of the campaign, such as making part of the propellant for the MAV, led to the addition of other capabilities to these surface systems.

The transportation systems needed to deliver all of these surface systems from Earth to Mars are being defined in parallel with the cargo it must deliver, and thus are based in part on assumptions that must be consistent across the entire architecture. The Space Launch System (SLS) and its payload mass and volume capabilities are assumed for the Earth launch portion of the transportation architecture. As mentioned above, the payload capability of the MDM is defined by the mass of the MAV plus the ISRU system, which are best integrated on Earth rather than attempting to do so on Mars. Adding more payload with the MAV on a single MDM would significantly stress the other elements of the transportation system, so an assumption was made to limit the MDM to payloads no larger (in mass and volume) to the MAV. As a result, multiple MDMs will be required to deliver all of the systems to establish the Field Station and consumables needed by each crew for their individual mission.

With multiple MDMs now required for each crew, an additional consideration was the point in the campaign at which the full capabilities of the Field Station would be in place. If the full capability were to be in place by the time that the first crew arrives, then there would be a “bow wave” of cargo-only MDMs needed before the first crew could be sent to Mars. This “bow wave” was not terribly significant – one or two MDMs above what later crews would require after the Field Station was fully operational – but it would introduce additional time delays in the campaign before surface exploration could begin. An assumption was made to stretch out the delivery of all Field Station infrastructure across the first two crews rather than delivering it all for the first crew, because the first crew was likely to spend much of its time simply learning how to operate on the surface of Mars and may not have been able to take full advantage of all of the Field Station capabilities. In addition, this approach had the added benefit of establishing a regular cadence of three MDMs for each of the three crews in the initial campaign: one MDM for the MAV, a second MDM for cargo (infrastructure plus surface mission consumables), and a third MDM to deliver the crew and the balance of any cargo needed for their surface mission.

It should be noted that the crew is not planned to arrive in the MAV for several reasons. First, an assumption was made to make some of the propellant needed by the MAV using local resources. Thus, the crew would be unable to leave the surface until this propellant was made even if there was an emergency. Therefore, each MAV is delivered and propellant production is started well before the crew arrives in Mars orbit. The crew would land only after it is confirmed that the MAV is fully fueled and ready for a launch if necessary. Second, the MAV cabin will be made as small and light as possible – this element has, by far, the greatest leverage in terms of mass saved at launch for every kilogram saved in system weight. This also means that the time spent on board the MAV would be as short as possible, likely just a few hours or perhaps as much as a few days. However, when the crew arrives from Earth they will be deconditioned and will require several days – perhaps as much as two weeks – to recover the strength and coordination to carry out EVAs or drive rovers. Therefore, they would need space for re-adaptation activities and associated equipment and consumables – more space and mass than would be realistic for the MAV cabin.

The first crew will be responsible for "commissioning" the Field Station in its "minimal" configuration. The first MDM must deliver the power systems needed by the MAV to make propellant. These power systems will not require the full payload mass or volume capability of the MDM, so one small pressurized rover, a modular habitation element, and some of the other smaller elements depicted in Figure 2 are delivered on this MDM. The MAV follows on the second MDM and is connected, using the small support robotic rovers, to the power systems delivered earlier. The third MDM will be loitering in Mars orbit, having been delivered earlier by the in-space elements of the transportation system, waiting for crew arrival. The crew will be transported from Earth to Mars in a dedicated transit habitat that will wait in Mars orbit until the completion of the surface mission, after which it will return the crew to Earth. This transit habitat will rendezvous with the third MDM and, after the MAV has been confirmed as fully fueled, the crew will descend to the nascent Field Station. The payload on the third MDM will include a "descent" module of sufficient size and capability to support the crew while they re-adapt to a gravity environment. The payload will also include a dedicated airlock module.

After the crew has re-adapted and has been cleared for surface activities, one of their first duties will be to assemble all of the various habitable elements delivered thus far – including the descent module, the airlock, various logistics modules, and other habitable elements delivered on the first MDM – into an integrated surface habitat. With just one pressurized rover available to the crew, exploration of the surface will be limited to a distance no farther than a crew member could walk back to the habitat using EVA equipment should the rover fail while on a traverse. However, this should be sufficient for the crew to deploy the scientific and experimental equipment delivered with them – currently allocating up to one ton of equipment distributed among the MDMs. With all of these Field Station infrastructure elements and other allocated payloads, the mass remaining for crew consumables and maintenance items will limit the surface mission to approximately 160 sols. This amount of time is considered reasonable given that this is the first surface mission by a human crew. At the completion of this period of time, the crew will place many of the surface systems in a dormant state while waiting for the arrival of the second crew. Some systems, such as the science and experiments set up by this crew, will be able to continue operation after the crew departs. The crew assemble all of the scientific samples and other material that they will return to Earth and use the pressurized rover to drive to the waiting MAV. A pressurized tunnel will connect the rover with the MAV and allow the crew to enter with a minimum amount of uncontained Mars material. The rover is then moved a safe distance away and the MAV returns the crew to their waiting transit module for the journey back to Earth.

The second crew will continue to expand Field Station capabilities sufficient to allow an exploration of the EZ. The first MDM for this crew will deliver their MAV, which will be connected to the surface power systems delivered for the first crew. The second MDM will deliver a second small pressurized rover and logistics module(s) with consumables, spare parts, and other equipment needed by the crew. The crew will arrive on the third MDM, in another descent module, along with the rest of the equipment and logistics for their surface mission. As with the first crew, this second crew will spend time re-adapting to the gravity environment in their descent module. After being cleared for surface mission activities, this crew will also assemble the habitable modules and logistics containers with the surface habitat, expanding the total habitable volume and increasing its capabilities. Because of the Field Station infrastructure previously delivered, there is enough payload mass available on the second and third MDMs to allow this crew to remain on the surface for up to 300 sols, a limit set by the in-space transportation systems and the trajectory used. Moreover, with the delivery of a second pressurized rover, the crew will have the ability to traverse out to the limits of the EZ because one rover can return the entire crew to the habitat should the second rover suffer a failure while on a traverse. This crew is also allocated up to one ton of payload mass for scientific and experimental equipment. At the completion of their 300 sol mission, this crew follows the same procedure for placing the Field Station in a dormant condition and returning to their waiting transit habitat using the MAV.

All of the envisioned surface capabilities will have been delivered and made operational at the Field Station before the third crew arrives. This allows the MDMs to deliver not only enough consumables and maintenance items for a another 300 sol surface mission, but also has unallocated mass that can be used to provide additional redundancy among existing surface systems or expand capabilities based on knowledge gained or lessons learned during the earlier missions. The third crew follows the same general sequence of activities as the second crew, from arrival of the MAV to placing the field station in a dormant state before returning to the orbiting transit habitat.

By the completion of this third surface mission, a total of 12 crew members will have spent up to 760 sols exploring a region of over 30,000 square kilometers (roughly the size of the state of Maryland).

Mars Dust and Human Exploration

The exploration of Mars by human crews will be a complex endeavor as illustrated by this description of NASA’s current architecture for the human exploration of the surface of Mars. The surface environment, in particular the ubiquitous dust, will be an important factor in designing the systems and operations needed for a safe and effective campaign of missions to achieve this objective. This introduction has described the exploration architecture with some indication of where and how dust could affect it. The remainder of this volume will describe details of these dust effects on the crews, the systems, and the operations that make up this exciting and challenging enterprise.

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