Autonomous Surface Site Establishment to Ensure Safe Crew Arrival and Operations

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Traditional human Mars missions have relied on crew to support the surface systems. However, for safety, the surface systems will likely need to be setup and capable of operating prior to the arrival of crew. To mitigate risks to the crew, a novel surface architecture has been developed that addresses risks associated with other Mars missions. This architecture relies on a reusable descent and ascent vehicle, extensive in-situ resource utilization, redundant habitation systems, and emerging autonomous capabilities. The resulting surface architecture increases safety for the crew while also providing potential to expand to support longer missions with larger populations in the future.

I. Introduction

Historically, human Mars mission studies have assumed that a human crew is available to setup the surface systems and perform assembly and repair. Although recent NASA architectures such as Design Reference Architecture 5.0 [1] and the Evolvable Mars Campaign [2] have assumed predeployment of cargo prior to the arrival of the first crew, they nonetheless expect the crew to be available to perform maintenance and handle unexpected situations. These missions have aimed to reduce the complexity on the surface by delivering fully integrated elements for which the crew performs any remaining setup and integration. Proposed lunar surface missions have also used either significant crew time or teleoperations from Earth to establish the surface infrastructure, similarly to the operations used to assemble the International Space Station.

Modern studies [3] have asserted that the site must be fully operational and safe prior to the arrival of the initial crew. A paradigm of safety before crew has been followed throughout human spaceflight programs that placed humans on the Moon and hundreds of astronauts in low Earth orbit [4]. Departing from this philosophy for human Mars missions is unlikely; thus, the surface site must be made safe through the use of autonomous systems. Advancements in in-situ manufacturing, assembly, robotics, machine learning, computer vision, and automation are increasing the feasibility of achieving this goal. The philosophy of autonomously creating a safe site prior to crew arrival will affect how other human exploration missions beyond low Earth orbit are designed and operated.

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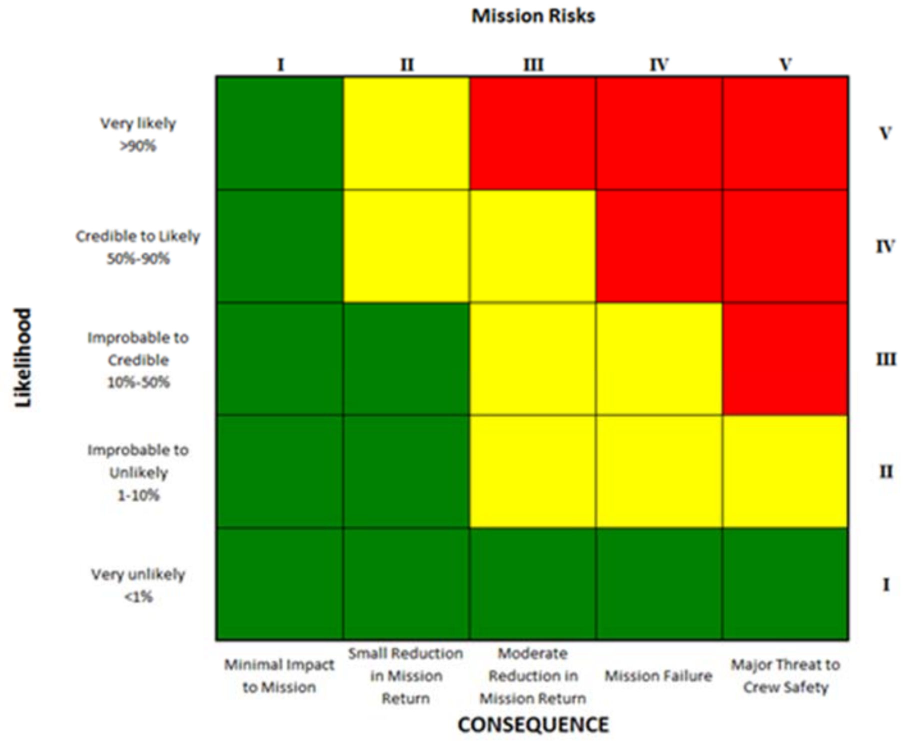
II. Previous Mars Mission Studies

One of the most recent missions developed by NASA for human Mars missions is the Design Reference Architecture 5.0, or DRA 5. The mission consists of two phases: a pre-deployment phase during which two nuclear thermal propulsion cargo vehicles deliver payload from low Earth orbit to Mars, and a crewed phase during which another nuclear thermal propulsion stage delivers the crew to Mars and returns them to Earth after the surface mission. Multiple surface concepts were explored in DRA 5, including a fixed surface habitat with mobility systems, and a mobile habitat used to explore more of the surface. The architecture also relied on surface nuclear power to run the habitation systems as well as an in-situ propellant production system to provide the oxygen for the Mars ascent vehicle that returned the crew to the in-space transportation system. The architecture supported a crew of six for approximately five hundred days on the surface, with subsequent missions duplicating capabilities at other sites on the surface of Mars. None of the systems at a given site were revisited or reused in subsequent missions, and to minimize the number of launches of the proposed Ares V launch vehicle, only the elements necessary for that single mission would be delivered to the surface [1].

Recent NASA studies have developed an Evolvable Mars Campaign that proposed an orbital mission to Mars followed by multiple surface missions to the same site. The surface missions were of a similar class to those in DRA 5, albeit with a crew of four and the surface stay reduced to accommodate the different in-space transportation architecture. A reusable in-space stage that used both chemical and electrical propulsion would transport the crew between cis-lunar space and high Mars orbit. Several cargo landers would be delivered by this same transportation system prior to the first crewed surface mission to build up habitation, power, mobility, and propellant production capabilities; for each crewed mission, a new ascent vehicle would be delivered to be used for that crew. As with DRA 5, minimization of the number of Space Launch System flights required to execute the architecture led to surface systems that meet the basic needs for the mission [2].

III. Risks of Conventional Mars Missions

An assessment of the risks associated with DRA 5 and the Evolvable Mars Campaign was performed to identify those systems that contributed the most to the overall risk profile of a human Mars mission. These high risk systems, and the associated risks, were then used to inform the development of a new mission architecture that reduces those risks while also being sustainable for future missions; this improvement in sustainability increases the long-term viability of human exploration relative to other Mars mission approaches.


Mission Risks

Likelihood	I	II	III	IV	V	
Very likely >90%	🟩	🟨	🟥	🟥	🟥	V
Credible to Likely 50%-90%	🟩	🟨	🟨	🟥	🟥	IV
Improbable to Credible 10%-50%	🟩	🟩	🟨	🟨	🟥	III
Improbable to Unlikely 1-10%	🟩	🟩	🟨	🟨	🟨	II
Very unlikely <1%	🟩	🟩	🟩	🟩	🟩	I
CONSEQUENCE	Minimal Impact to Mission	Small Reduction in Mission Return	Moderate Reduction in Mission Return	Mission Failure	Major Threat to Crew Safety	

Fig 1. Likelihood and consequence matrix for Mars mission risks.

Risks were generated for eight categories: launch vehicle, in-space propulsion, in-space habitation, descent (including entry, descent, and landing), surface habitation, surface power, surface mobility, and ascent. These risks were assessed using five element scales to classify the likelihood of the risk and the consequence. A score of one for a likelihood indicated a very unlikely event, with an estimated likelihood less than 1%, while a score of five indicated a very likely event, with an estimated likelihood greater than 90%. The consequence scale ranged from a value of one, indicating minimal impact to the mission, to a value of five, indicating a major threat to crew safety. The complete risk scale, in matrix form, is shown in Figure 1.

Table 1 Top risks for Mars missions systems.

Risk Name	Description	Average Likelihood	Average Consequence
Low/Microgravity	Low/Microgravity causes problems related to the heart, bones, muscles, digestive system, kidneys, eyes, organ & tissue, lungs, brain and balance.	3.92	4.25
Radiation exposure	Radiation causes problems with the heart, bones, muscles, digestive system, kidneys, eyes, organ & tissue, lungs, brain and balance.	3.92	4.25
Habitat malfunction/damage during dormant state	The habitat has to survive in dormant mode at Mars for 2+ years before the crew arrives.	2.75	4.25
Life support malfunction	Disruption to environmental control systems may threaten crew's survival.	2	4.75
Long-term storage of consumables	Consumables such as food and medicine must survive for years in potentially damaging radiation environments without resupply from Earth.	3.75	5
Systems do not land in planned location	The habitat may land far from other systems (e.g. power), removing the ability to support it on the surface.	2.5	4
No abort options during descent	Traditional entry, descent, and landing concepts lack the ability to support aborts during descent.	2.75	4.75
Turbomachinery of ascent engines	Ascent system must spend >1000 days in dormant state prior to use, with high performing components surviving landing and exposure to surface environment.	2.25	5
No abort options during ascent	No abort capabilities to either launch site or downrange, little margin on the system.	2.75	4.75

Space systems analysis experts assessed each risk using both scales, and the averaged values of likelihood and consequence were used to identify the greatest risks, and thus the greatest risk areas. The top risks, as identified by this assessment, are listed in Table 1. From this list, three categories of system and function were identified as high risk: descent, surface habitation, and ascent. Each of these categories has multiple high-consequence, medium-to-high likelihood risks associated with it, as well as other risks of lower consequence.

Several findings emerged from this risk assessment that informed the subsequent campaign development. Due to the high performance demands for precision landing and dormancy of the descent and ascent systems, both will require significant testing and heritage prior to crew flight. In addition, abort capabilities would improve the safety profile of both maneuvers, as currently no abort options exist for either maneuver. Exposure to reduced gravity and radiation will have negative impacts on crew health, and the combinatorial effects of both health threats over long durations are currently unknown. The impact of radiation on other systems (e.g. electronics, food) are also a threat that likely requires mitigation.

IV. Safe Site Architecture

As a result of the risk assessment and findings, a new architecture for a human Mars mission was developed that addresses the findings above and is sustainable for longer-term human exploration. This new architecture addresses several of these risks, while also extending capability, at the expense of increased cost and delays to the start of crewed missions to the surface. It thus serves as a point in the architectural design space that is distinct from previous architectures: instead of emphasizing the minimal mass or cost required to quickly achieve an initial human capability on the surface, it uses greater initial investment to mitigate the identified risks. Table 2 summarizes how the resulting architecture addresses some of the top risks.

Table 2 Safe Site mitigations of top risks.

Risk	Mitigations
Low/microgravity	Not addressed in surface architecture; Hercules capability enables faster transits between Earth and Mars
Radiation exposure	Surface habitation buried under regolith to reduce radiation exposure
Habitat malfunction/damage during dormant state	Habitat must still survive long durations, but redundant habitat delivered
Life support malfunction	Systems operated prior to crew arrival to build time on system experience; redundant habitat
Long-term storage of consumables	Consumables stored in habitat beneath regolith to reduce radiation exposure
Systems do not land in planned location	Multiple flights of descent system to improve experience with precise landing; surface mobility to transport payloads from landing location to final location
No abort options during descent	Hercules vehicle can abort with crew to orbit and/or surface throughout entry trajectory
Turbomachinery of ascent engines	Hercules concept encapsulates engine systems; shorter dormancy periods due to reuse
No abort options during ascent	Hercules vehicle can abort with crew to orbit and/or surface throughout ascent trajectory

Key features of the Safe Site architecture include:

1) A reusable descent and ascent stage that develops heritage both prior to and while building up the Mars surface site, with crew abort abilities to the surface and to space.
2) Expansive in-situ resource utilization that leverages the increasing likelihood of high water concentration sites on Mars, especially for the production of propellant and crew consumables.
3) Redundant habitation and logistical capabilities to provide robustness to individual system failures as well as expandability to larger crews.
4) Surface site preparation to provide radiation protection and enable the reusable transportation architecture.

Each of these features is described in further detail below.

A. Reusable Ascent/Descent Stage

The Hercules concept [5] is a reusable system that can transfer between low Mars orbit and the surface using in-situ propellant. By operating from low Mars orbit, the propellant requirements are reduced, as are the heating loads experienced during entry; this removes the need for a non-reusable thermal protection system. The vehicle consists of three parts: a nose section, payload section, and ascent/descent section. The nose section possesses methane and oxygen propellant tanks and engines capable of supporting aborts and terminal descent, as well as a crew capsule used when crew is aboard the vehicle. The payload section is 4.5 m tall and 6.0 m in outer diameter, with doors that can open up to 5.25 m by 4.5 m to allow for payloads to be added or removed. The ascent/descent section consist of tanks and engines to support ascent to and descent from low Mars orbit, as well as landing legs and support structure. The integrated vehicle is 6 m in diameter and 18 m in length, capable of fitting within an 8.4 m SLS fairing. It has a dry mass of approximately 19 t and, fully loaded on the surface, can hold 142 t of methane and oxygen propellant (by comparison, both DRA 5 and EMC require approximately 30 t of oxygen produced from in-situ resources, in support of a total propellant load of less than 40 t).

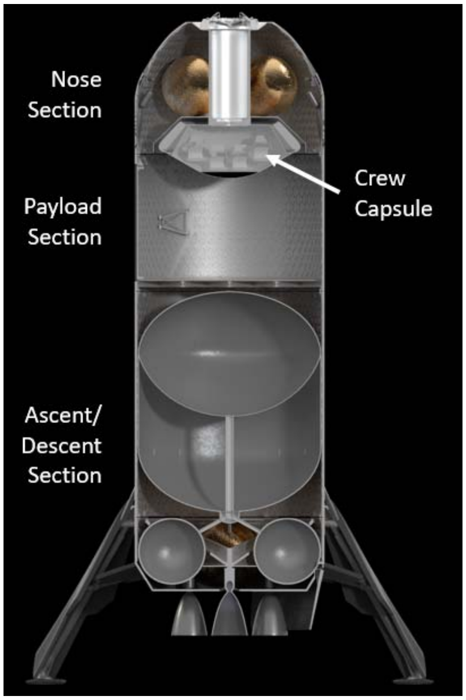


Fig. 2 Hercules reusable ascent/descent stage.

The system can operate in two modes: a repurposable mode where the nose section and payload section separate from the ascent/descent section; and a reusable mode where payload is removed from the payload section, the vehicle is refueled, and the vehicle ascends to low Mars orbit to acquire another payload. In the repurposable mode, the engines on the nose section are used to maneuver the payload bay to its final destination, then the nose section separates and leaves the payload section behind. In both modes, the system can deliver 20 t to the surface of Mars from low Mars orbit. Through a combination of repurposable and reusable flights, the Hercules delivers the elements that make up the Safe Site surface architecture. In addition, when carrying crew, the nose section can separate from the other two sections and carry crew either to orbit or to the surface [6].

B. Water-based In-Situ Resource Utilization

The use of a reusable descent and ascent system is predicated upon the existence of in-situ resource utilization to produce propellant at the surface of Mars. Although previous Mars mission studies have assessed the use of in-situ propellant production to reduce the landed mass of the Mars ascent vehicle, they have focused on only the use of atmospheric acquisition of carbon dioxide, which is used to produce liquid oxygen. While effective as a means of reducing landed mass, this approach does not enable reusability, as it does not produce the corresponding liquid methane used for ascent.

In recent years, there has been increasing evidence of water on Mars, in potentially abundant quantities at high latitudes [7]. Abundant supplies of water, in conjunction with atmospheric acquisition of carbon dioxide, allows for the production of both methane and oxygen. At appropriate scales (on the order of 142 t of propellant per roundtrip), this allows for a reusable system to be fully fueled with Mars-derived propellant, thus enabling the Hercules to be used as a means to deliver payload from low Mars orbit to the surface. A small increase in the propellant production rate would also yield acquisition of sufficient water and oxygen to supplement crew consumables and logistics, as well as eventual in-situ manufacturing of plastics [3]. Initial analysis has shown that a Mars in-situ propellant production capability that can support Hercules is well within the 20 t landed mass limit [3].

C. Surface Habitation

Protection from radiation and the dimensions of the Hercules payload bay influenced the design of the Safe Site habitation system. For long-duration missions, at least twenty-five cubic meters of habitable volume per crew member is recommended [8], which requires more than twenty-five cubic meters of pressurized volume per crew member to accommodate habitation systems. Several modular configurations were examined that would divide key habitat functions and space across multiple modules. However, such a configuration still requires duplication of many key functions in each module. Further, integrating the number of modules, tunnels for interconnectivity, and logistics required led to a high number of landings required with uncertain benefits relative to a monolithic approach. A monolithic softgoods habitat has the benefit of providing sufficient pressurized volume for all necessary logistics, while still providing sufficient habitable floor area.

The monolithic approach is inspired by the TransHab concept [9], using an inflatable torus surrounding a solid cylindrical core. The core is 3.6 m in diameter and 4.25 m in height, while the torus is 13 m in diameter when inflated, and increases the diameter by 0.7 m when stowed. When deployed, the habitat has two levels, with systems to support a crew of four for 500 days. The core design requirements included sufficient volume to store tanks for pressurant gases for the inflatable sections, as well as minimal function life support, thermal control, avionics, and idle power. Subsequent to landing and inflation, the habitat is outfitted with other system delivered on other landings (e.g. crew quarters). The habitat has two levels, with up to four tunnels capable of being connected to either other modules, airlocks, or rovers (see Figure 3).

In addition to the primary habitat, a second habitat, with full life support but limited outfitting, is deployed and connected via a tunnel to provide a mostly redundant habitable volume for the crew, as well as expansion space for future missions with larger crews. The second habitat contains similar core packaging, but can be used to test new technologies to build heritage. Each habitat also has two tunnels leading to the environment, with airlocks for EVAs and the ability to connect to pressurized rovers. This provides each habitat a minimum of two means of egress. The airlocks and tunnels are sized to allow for additional outfitting to be installed (e.g. deployable floors, food subsystems, crew accommodations). The tunnels remain at the habitat pressurization levels and can be used for EVA suit repair and other maintenance tasks. The full habitation system (both habitats and the tunnels) are buried in a mound of regolith approximately thirty centimeters thick; this provides mitigation of radiation exposure without requiring several meters of overburden. Beyond this thickness, there are diminishing returns in radiation protection for additional thickness [10]. Future trades will evaluate locating the habitats underground or in the side of a cliff to further improve radiation protection.

D. Site Preparation and Other Systems

Several necessary features govern site selection and preparation. The site must be selected such that it is near a large supply of accessible water (e.g. a subsurface glacier), as the Hercules vehicle relies on production of large quantities of methane and oxygen propellant that are derived from water and atmospheric carbon dioxide. The site must then be modified to include locations to land and ascend from repeatedly with minimal risk of damage to the vehicle or surrounding systems. The in-situ resource utilization and habitation systems will require significant quantities of power; this leads to the need for a high power nuclear power system (on the order of 100 kW) located far enough from the site to mitigate radiation exposure to other crew systems (on the order of 1 km). Surface mobility systems will be needed that can not only transport the crew, but also offload payloads from the Hercules vehicle, transport those payloads to their final destinations, and perform civil engineering tasks at the site (e.g. preparing landing sites, moving regolith atop the habitats).

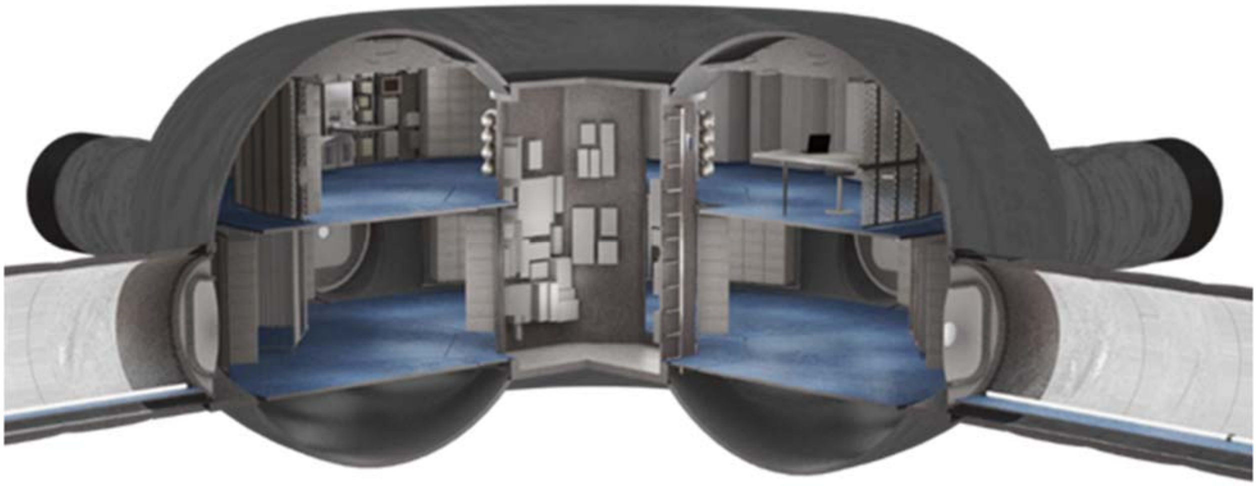


Fig. 3 Interior of habitat system.

E. Concept of Operations

Ten landings are required to deploy the systems of the initial Safe Site architecture. The first five are repurposable mode landings, with the nose section of the Hercules deploying payload sections to specific locations. The final five are reusable, with the offloading system that arrives in the fifth landing used to remove payloads from the Hercules prior to refueling and ascent. Table 3 lists the ten landings in sequence, while Figure 4 shows a notional view of the full Safe Site layout after the landings. Future trades include whether to collocate the Hercules landing and ascent locations, whether the offloading system can be deployed on a reusable landing, and whether to use centralized or distributed power systems.

Table 3 Safe Site architecture landing sequence.

Landing	Payload	Mode
1	Power management and distribution, initial surface mobility	Repurposable
2	Surface power system	Repurposable
3	Water acquisition system	Repurposable
4	Propellant production system	Repurposable
5	Hercules offloading system	Repurposable
6	Habitat	Reusable
7	Habitat	Reusable
8	Tunnels, outfitting, and logistics	Reusable
9	Airlocks, outfitting, and logistics	Reusable
10	Pressurized rover	Reusable

F. Comparison to DRA 5 and EMC

Safe Site approaches human exploration of Mars in a fundamentally different way than recent NASA architectures. Both DRA 5 and EMC are designed to achieve the goal of landing humans on Mars quickly (i.e. with a minimum amount of predeployment prior to the first crewed mission), while only investing in those technologies deemed necessary to enable that goal. These approaches require fewer landings prior to the arrival of crew: DRA 5 required one 40 t landing, while EMC required three 20 t landings. By comparison, the Safe Site architecture has ten 20 t landings before the first crew arrives. These additional landings in Safe Site increase the cost and time required prior to the first crewed mission. Further, the Safe Site architecture requires additional capabilities not required by recent NASA architectures: large-scale water in-situ resource utilization, reusability of ascent and descent stages, and autonomous deployment and maintenance of systems for years prior to crew arrival. These capabilities will require additional capability investment and development time relative to the needs of DRA 5 and EMC.

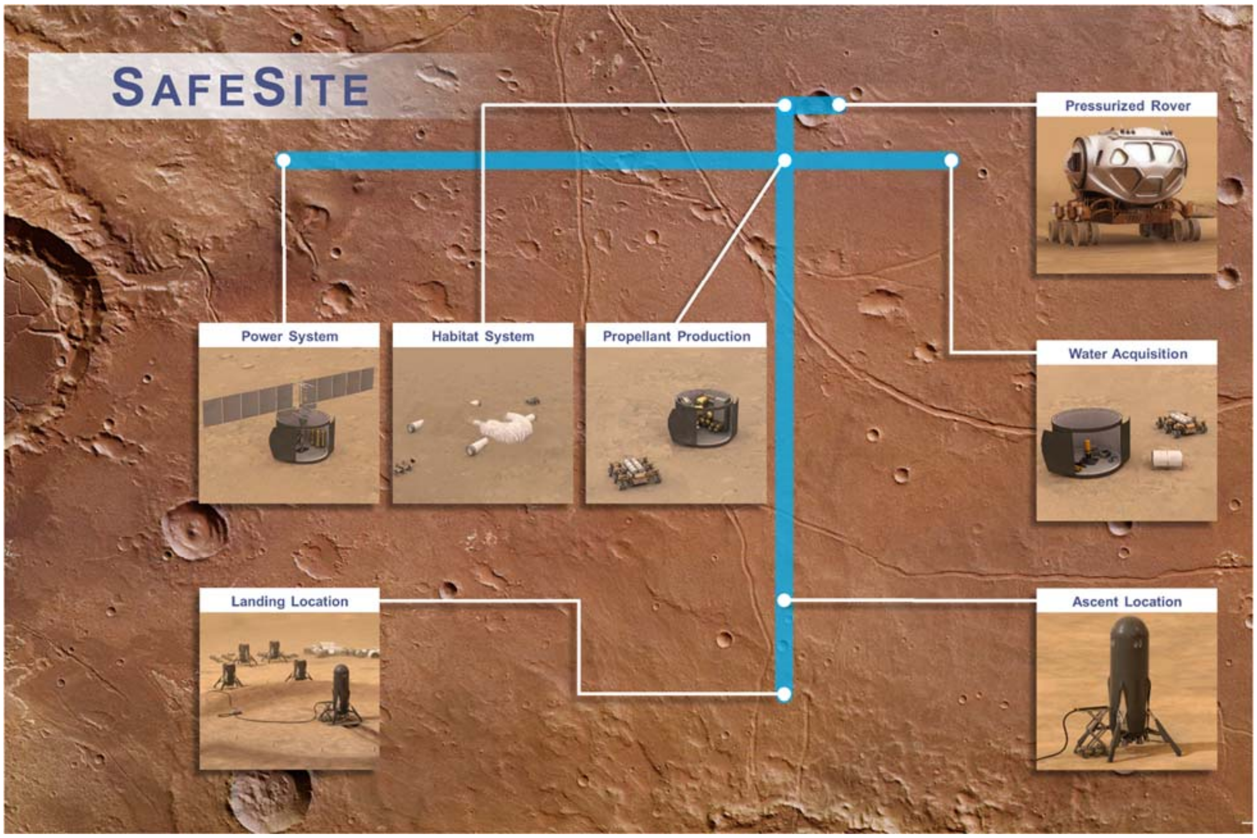


Fig. 4 Safe Site surface architecture.

Safe Site trades these additional costs and longer schedules for increased capability and risk mitigation. Many of the top risks identified in the assessment of DRA 5 and EMC are addressed in the Safe Site architecture. The increased capability allows for expansion to longer-term settlement with greater numbers of crew [3], while also providing redundancy for the initial crewed missions. In addition, the time on system, heritage, and redundant capabilities all contribute to mitigating some of the key risks, as does the design of the Hercules vehicle.

Thus, the value of Safe Site relative to other approaches for Mars exploration depends upon the goals of human space exploration. If reaching the destination as soon as possible, with as little expense as possible, is the objective, then Safe Site performs poorly; it takes on greater costs, more challenging capabilities, and longer schedules than approaches that quickly deliver humans to the surface. However, if the objective is instead to increase the likelihood of the crew surviving the mission, while enabling longer-term pioneering of Mars, then Safe Site offers a way to establish a presence on Mars that supports that broader vision. Safe Site should be viewed as a different point in the architectural design space than DRA 5 and EMC; it is a concept better suited for emphasizing safety and expandability at the expense of cost and time.

V. Autonomous Capabilities

The need to minimize risks to the crew is a driver for autonomous robotic deployment and assembly of surface systems. The use of robotics to prepare the landing site prior to crew arrival allows for systems to be established and functioning before landing humans on Mars, while implementing autonomy enables those robotic systems to prepare surface assets at a faster pace than a human-in-the-loop system characterized by high-latency communication between Earth and Mars. Before the crew arrive, the surface architecture must be capable of providing safe habitation, surface mobility, and ascent capability; these requirements also necessitate other systems such as surface power and propellant production. Deployment of these systems involves a number of similar “non-routine cognitive” activities that the autonomous systems must perform. These activities, associated requirements, and example capabilities are described in Table 4. Many of the capabilities required for these activities are common across multiple activities, which motivates the use of common robotic systems capable of performing multiple tasks. Several potential technologies that could support the necessary capabilities have been identified in the areas of communications, entry/descent/landing, object detection and pose estimation, and motion planning. Future trades and conceptual design will focus on further definition of the autonomous system requirements, concepts for systems that can be used to perform the necessary activities, as well as the development paths from current state-of-the-art to the levels needed for the Safe Site architecture.

Table 4 Autonomous robotic activities, requirements, and example capabilities.

Activity	Requirements	Example Capabilities
Communication	Send information between surface systems, orbital assets, and Earth with minimal latency and high bandwidth	Short range communication Long range communication
Land payload	Safely and precisely perform entry, descent, and landing of payloads with mass of up to 20 t at landing site	Short range communication Hazard detection and avoidance Hazard relative navigation Terrain relative navigation
Unload payload	Unload payload with mass of up to 20 t from lander	Short range communication Object detection 3D pose estimation Object manipulation
Move payload	Move payloads with mass of up to 20 t from unload location up to 2 km to final destination	Short range communication Hazard detection and avoidance Motion planning
Position payload	Coarse and fine positioning of payloads of up to 20 t	Short range communication Relative positioning 3D pose estimation Fine positioning Motion planning
Surface assembly	Perform locating, fixturing (e.g. clamping), fastening (e.g. bolting), joining (e.g. welding), and other assembly of surface elements	Short range communication Object detection Fine positioning Hazard detection and avoidance Motion planning
Extract resources	Excavate regolith, acquire water, acquire atmospheric carbon dioxide	Short range communication Relative positioning Object detection Motion planning
Protect surface elements	Cover surface elements up to 5 m in height with 30 cm of regolith	Short range communication Relative positioning Object detection Motion planning

Autonomous systems will require the ability to communicate with each other to facilitate site deployment prior to crew arrival. The system will contain a set of heterogeneous robots, each capable of performing the autonomous activities described in Table 3. This system represents an explicit-dynamic coordination system where a multiple, mobile robot system (MMRS) has members explicitly communicating to each other in a dynamically changing environment [11, 12]. The Mars On-site Shared Analysis, Information, and Communication (MOSAIC) architecture is being developed by JPL to provide a platform for robotic systems to communicate to each other in a centralized way and enable this coordination [13]. Additionally, high-fidelity, high-bandwidth, low-latency, short-range communications systems can ensure proper coordination between systems and accelerate surface site development relative to a human-in-the-loop communication system that transmits data back to Earth for decisions. Hardware systems using Ultra-High Frequency (UHF) radio antenna have historically been used for short-range communication between surface and orbital assets [14]; Ka-band offers an alternative with faster data rates [15]. Integrating Ka-band into the Safe Site mission architecture would increase data exchange between surface assets, orbital systems, and descent/ascent vehicles.

Long-range communication enables robots and humans to interact with each other and perform a check on the progress of autonomous systems; it allows humans to solve any issues that the systems cannot resolve on their own. A software system like the Robot Application Programming Interface Delegate (RAPID) system would facilitate communication between robotics and human operators [16]. As for hardware, traditional systems have used X-band low-gain antenna to omni-directionally receive information and communicate at low rates back to Earth and X-band high-gain antenna to point to Earth and send data directly back [17, 18]. Laser communication between ground and satellites is currently being investigated as a way to increase data transfer rates over the current radio communication rate [19]. These systems could be used to transfer data between systems at Mars, and back to Earth, at must higher bandwidths.

The Cooperative Blending of Autonomous Landing Technology (COBALT) [20, 21] is a system that enables safe and precise landing by combining the Lander Vision System (LVS) [22] led by NASA Jet Propulsion Laboratory with the Autonomous Landing Hazard Avoidance Technology (ALHAT) [23-25] developed by NASA Langley. The system uses lidar or a lander vision system along with Terrain Relative Navigation (TRN) algorithms to compare *in situ* images to *a priori* maps of the landing area to determine position relative to the landing site. Using this information and position and velocity information from Navigational Doppler Lidar [26, 27], COBALT is able to autonomously make decisions to correct course and bring it closer to the landing site [28, 29]. Additionally, the COBALT system is able to detect hazards and take evasive maneuvers to avoid them. The goal of COBALT is to land a spacecraft within one hundred meters of its *a priori* designated landing site, a key step towards achieving a precision landing system.

Autonomous systems require the ability to extract objects from an image and determine where in the image those objects are located. In the case of Safe Site, the autonomous systems may need to recognize each other, large systems (the Hercules lander, habitats, airlocks, payloads, etc.), hazards, and structural reference elements (datums, pins, holes, slots, etc.). Autonomous systems can use optical systems and/or lidar, which has become smaller and less massive due to advances in solid-state lidar [30, 31], to construct images and/or 3D maps of their environment [32-34]. A convolutional neural network (CNN) can be trained to detect the aforementioned objects and their location within these images or 3D maps [35, 36]. The autonomous robot's position and velocity then can be determined relative to the objects of interest. These technologies and capabilities are essential to unloading and unpacking payloads from cargo landers prior to crewed landings and to surface assembly of objects.

Autonomous systems will need to perform both path planning from one place to another and robotic positioning of an object, which are both considered motion planning [37]. From grid-based methods to tree-based methods, a number of methods exist for non-holonomic motion planning - each method has its benefits and shortcomings and they can be applied as the situation requires [38, 39]. When combined with a sensor suite (lidar, radar, etc.), obstacle detection algorithms, and inertial navigation systems, these methods can allow surface vehicles to perform path planning and determine routes to objects of interest while avoiding hazards [40, 41]. They can also ensure robotic appendages sweep through a set of motions that avoids collisions and is beneficial during object manipulation or assembly [42].

VI. Beyond Safe Site

The initial Safe Site architecture is designed to support a crew of four for 500 days. However, it also can serve as the starting point for a longer-term Mars outpost, eventually capable of supporting more crew for more days. The initial pair of habitats have the necessary systems to support a crew of eight, and would require only minor additional outfitting as well as logistics resupply to enable that crew size. With the landing of additional habitats and tunnels, the crew capacity could be further expanded. Alternatively, to better address the radiation challenges, future habitats could be located either in underground lava tubes or in the sides of cliff faces. This would necessitate delivering additional mobility and excavation capability, which would also allow for more complex civil engineering of the surface site.

Further expansion would also require increases in the available power, surface mobility systems, and in-situ resource utilization capabilities. In keeping with the philosophy of the Safe Site architecture, the systems that expand capability should be delivered well before the additional crew arrives; this would provide more time on system prior to the system being in the critical path as well as increased margin for the existing level of crew. New systems should be delivered further in advance than additional copies of existing system to allow for more time to verify successful operations. The existing systems of the Safe Site architecture would also provide heritage to upgraded versions of those systems that would be subsequently delivered to expand humanity's ability to live on Mars.

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