Human Mars Exploration Research Objectives

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Abstract - *Mars has long been the ultimate goal for human space exploration. This paper will compile research objectives relevant to a Martian presence in an attempt to create a coherent justification for human expeditions to Mars. It will organize these objectives in a balanced human spaceflight architecture driven by a platform of research objectives inclusive of engineering research, pathfinding for commercial operations, and scientific research domains. It will then propose a Martian campaign that allocates sufficient manpower, surface stay time, and equipment to accomplish these objectives. Finally, it will demonstrate how such a campaign is not an Apollo-reminiscent "flag, footprints, and forget about it" venture but is instead a preparation for a relevant, long-term human endeavor on Mars, including linkage of initial Mars exploration to continued exploration of the planet and additional human exploration further into the solar system.*

Keywords: Mars, exploration, science, research, life, NSBE Visions for Human Space Flight Working Group.

1 Introduction

The Space Special Interest Group of the National Society of Black Engineers has commissioned a *Visions for Human Space Flight Working Group* to investigate technical challenges surrounding NASA human space flight and to identify an alternative path for the direction of United States human space flight. Research conducted by working group participants and documented in this paper represents volunteer labor executed on behalf of NSBE, a 501(c)3 nonprofit headquartered in Alexandria, VA. NSBE coordinates the inputs of aerospace industry experts to propose innovative solutions to complex technical challenges facing the United States. This paper, in coordination with six other Working Group papers, collectively encompasses the product of the Working Group's efforts. Recommendations, results, and conclusions in this paper do not reflect NASA policy or programmatic decisions.

1.1 Significance and Interest in Mars Exploration

One of the first credible proposals for human spaceflight to Mars was by German rocket scientist Wernher von Braun, whose original concept dates to the late 1940s and early 1950s. [13] There is general agreement throughout the spaceflight community that Mars is the most compelling destination for human exploration in the solar system.

The NASA Authorization Act of 2010 specifically calls out the human exploration of Mars as a long term goal. [1] The House and Senate versions of the NASA Authorization Act of 2013 (neither of which actually became law), while deeply divided on several issues and supported only along partisan lines, both specifically called out human exploration of the surface of Mars as an intended goal. [2], [3]

Some, perhaps romantically, view Mars exploration as a search for the meaning of life. [15] Whether life is found on Mars or not, some view either the discovery of any form of life on Mars, or the settlement of humans on Mars as a transformative event in human existence. However, none of this provides a defensible reason to go in the face of limited budgetary resources. Despite all of the wording in NASA Authorization acts, there is no matching appropriations funding from Congress. Further, while there are more than 200,000 people who have already submitted applications for a one-way trip to Mars [34], the commercial investors needed to back such a trip and technical expertise to conduct it remain in question.

1.2 Specific Rationale for Continued Mars Exploration beyond the First Human Expedition

The purpose of the Apollo program was to land a man on the Moon and return him safely to Earth. The tremendous scientific and technological results of that endeavor were a side benefit, not the actual purpose. However, this official purpose arguably is the direct cause of the program's cancellation. The purpose of the program was fulfilled in Apollo 11. There was no long term strategy, merely the intent to perform what was effectively a high tech stunt to impress the rest of the world.

It could be argued that it is irresponsible to conduct "technological stunts," given present-day economic conditions. Thus, a Mars architecture that is based primarily on "being the first nation on Mars" or any other short-term objective could be criticized as not the best possible use of the nation's resources.

A more sustainable interest in Mars exploration includes the desire to find or identify something that cannot be done on Earth, or that cannot be done as efficiently on Earth. The classic example is the long-sought-after promise of development of new crystals of pharmaceuticals aboard a space station, where it is thought that the microgravity environment will enable molecule formations that cannot be obtained on Earth. The general premise is that there is a legitimate benefit that may result in the growth of a particular industry or perhaps the creation of entirely new industries, with the promise of resulting economic growth. This did occur early in the space program with the development of telecommunications satellites and these satellites have completely reshaped life on Earth.

Mars provides a different scenario from the microgravity environment and there is interest in identifying processes or manufacturing or production activities that are enabled by the Martian environment. This may be a function of Mars' location in the solar system, or they may be things that do require some gravity, but are more efficient or effective with a lower level of gravity than that provided by Earth. Or they may be induced by some other factor related to Mars.

Short-term Mars exploration is intended to search for those areas of opportunity whereby the human experience can be enhanced by means of human activity on Mars. Once expeditions have identified opportunities for development, a long term human presence should begin to leverage and utilize these opportunities.

2 Targeted Areas for Mars Research

It is not sufficiently descriptive to list "Mars" as a destination. The NSBE Visions for Human Space Flight Working Group has identified a single location on the planetary surface, an aerostationary orbit, and both of its moons as key destinations, all of which are visited during every human expedition to Mars.

This represents a significant deviation is implied from many other Mars studies, which often take an "either/or" approach. Some have suggested a phased approach where an initial mission is merely a flyby. A subsequent mission may visit a moon, and eventually there are missions to the surface. Advocates of such architectures promote them as a way to reduce overhead. However, it is actually only a delay of overhead. If a surface mission exists in any part of the architecture then that overhead is by definition part of the architecture. And in actuality it must also by definition either increase total overhead (if all objectives are retained then the total number of surface days cannot be changed, thus adding additional transit flights to the architecture for those missions that do not land on the surface) or it must reduce mission objectives (if total number of launches are held constant then the number of missions including surface landings are accordingly reduced).

The common spacecraft architecture and modified program management, systems engineering, and risk management processes recommended by the NSBE Visions for Human Space Flight Working Group are intended to reduce the overhead of human Mars exploration to where planetary landings can be achieved on all Mars-bound flights. It is worth noting that the same Mars Transfer Vehicle and the same Mars Surface Outpost are reused by all four Mars expedition crews.

2.1 Recommended Surface Outpost Site

The recommended surface outpost site for the Mars outpost is Ophir Chasma. A chasma is a deep, elongated, steep-sided depression. Ophir is located near the northern center of Valles Marineris. Named after the Mariner 9 Mars orbiter, Valles Marineris is the largest canyon system on Mars. Located on the Martian equator, it is nearly as wide as the United States, stretching a fifth of the circumference of Mars as shown in figure 1. [18] Ophir Chasma is indicated by the red box superimposed on the image of Mars in figure 1.

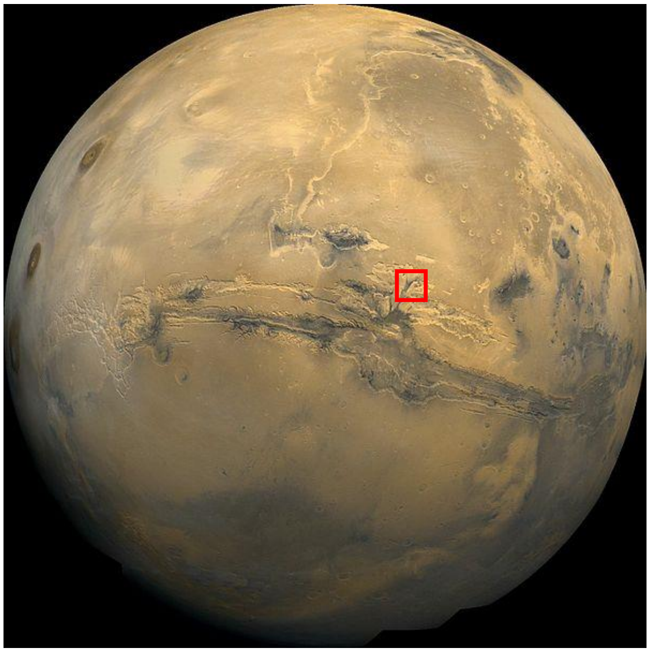

Figure 1. Valles Marineris

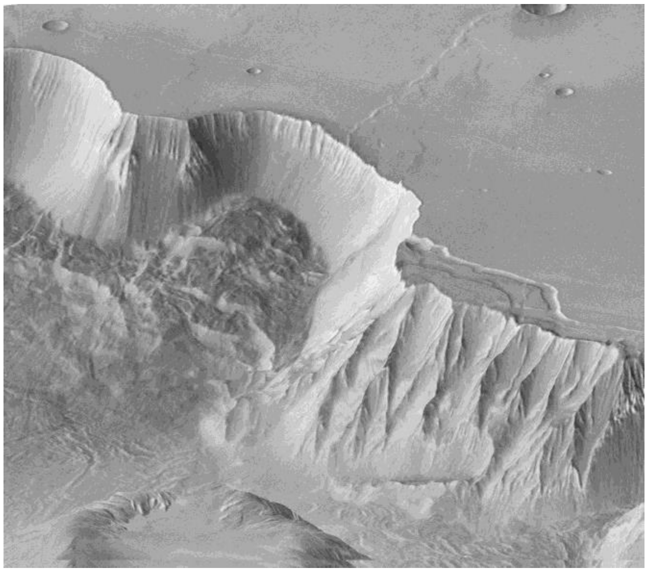

Figure 2. Ophir Chasma

The center of Ophir Chasma has latitude of -4° and longitude of 287.65° and it measures 314.71 km in diameter. [38] This near-equatorial location will minimize the propellant required for launch to orbit. It will also allow the outpost to remain in constant line of sight communication with spacecraft in aerostationary orbit as well as allow for anytime ascent or descent between such spacecraft and the outpost. As shown in figure 2, the walls of Ophir Chasma are relatively steep, and are roughly 4 km tall. [9] The chasm itself extends to a depth of approximately 6 km. [18] There are two advantages of these surface features. First, due to the depth there is a small increase in atmospheric pressure. Because the average atmospheric pressure on Mars is close to the triple point of water [32], suggesting a possibility of either finding liquid water in the vicinity or favorable environmental conditions for conducting liquid water experiments. Second, the walls of the canyon may provide crevices or caverns large enough to assemble the outpost surrounded or partially surrounded by canyon walls, thereby providing natural radiation shielding.

2.1.1 10 km Radius Immediate vicinity

The immediate vicinity of the Mars outpost is the region within EVA walk back distance – the range a crew member could theoretically walk back from a disabled rover if rescue is not possible. This region is roughly twice the size of the District of Columbia, leaving room for a significant amount of exploration. The walls and adjacent canyon floors provide a wealth of geologic features of interest, including slumping along the canyon walls, [11] with layered deposits that have remained unexplained despite decades of photogeologic exploration of Mars. [20]

2.1.2 480 km Surface Rover Range from Outpost

A dual-rover strategy will enable pressurized rover excursions up to 480 km away from the Mars outpost. [28], [30] This enables one rover to rescue the crew of the second rover in the event of a contingency and requires a rover capability to traverse a 480 km distance in approximately 20 hours. This exploration radius is a region measuring approximately 723,823 square kilometers, roughly equal to the land area of Texas, Maryland, Massachusetts, and the District of Columbia combined. The terrain of Ophir Chasma includes layered rock formations, wind etched rocks, and dune fields. [10] With respect to minerals, the Ophir Chasma contains iron oxides and sulfates including kieserite and jarosite. [22]

2.2 Martian Moons

2.2.1 Phobos

Phobos has a surface area of roughly 1548 square kilometers [26], making it roughly half the size of Rhode Island. [37] Due to the small size of Phobos it will not be necessary to restrict exploration to any particular location on the moon.

2.2.2 Deimos

Deimos is smaller than Phobos, with a surface area of approximately 483 square kilometers [25], approximately the size of Albuquerque, New Mexico. [36] Like Phobos, the entire surface of Deimos can be surveyed during an expedition if desired.

2.3 Mars Orbit

The recommended Mars orbit is an aerostationary orbit above the Ophir Charisma. This will focus most orbital sensing data on one hemisphere of the planet, but planet wide data can be obtained during inbound and outbound spirals

3 Engineering Research

A key objective of engineering research is to develop the operational techniques that will be needed to grow the human presence on Mars from small, prefabricated outposts to larger, indigenous complexes capable of accelerating the expansion of human exploration of the solar system.

3.1 Demonstrate Cost-Effective Systems Engineering Capabilities

It is not possible to send humans to Mars under the dual constraints of the current federal fiscal climate and modern acquisition strategies. [24] We are rapidly becoming a nation that cannot do anything because everything is too expensive. Even the military, which is often viewed as having a luxurious budget, is finding itself unable to meet its goals. The Navy and Marine Corps anticipate having to cut 25 aircraft from FY14 acquisitions, the Air Force plans to eliminate four to five F-35 acquisitions and cut up to 25,000 airmen and up to 550 aircraft, and the Army plans to reduce 45-50 Stryker vehicle acquisitions with additional impediments to other procurement plans. [4] The systems engineering challenge of executing a Mars exploration strategy in the context of parallel lunar and NEA exploration strategies [29] requires radical, innovative changes in NASA acquisition strategies on the order of the radical and transformative engineering development required for the Apollo program of the 1960s. Executing this architecture will force the development of new systems engineering models [29] and overall increased discipline with respect to both engineering and management processes that will permit the United States to explore complex undertakings in countless domains on Earth and beyond that are presently unaffordable.

3.2 Surface Infrastructure Development

3.2.1 Structural Shelters

There are four possible paths to building human shelters on Mars: deploy habitats fabricated off planet (Earth), build with component materials transferred off planet, use planetary materials to build shelters, or a combination of the above. Bringing material from earth has the advantage of Earth-based testing, but has the disadvantage of the mass and volume required to transport these materials. Using Martian materials reduces the transportation cost to that required for the fabrication and construction equipment, but does require the development of Mars-based testing capabilities to verify that such shelters are safe for human occupation.

Martian habitats will need to provide radiation protection, thermal control, and structural rigidity, and also maintain breathable atmospheres at appropriate pressure. This may be achieved through the sealing of existing Martian caverns or caves, or may involve fabrication of structures from regolith, iron, or other materials. Research will involve exploration of existing natural features on Phobos, Deimos, and the Martian surface for use as shelters, including the installation of pressure bladders into existing structures as well as methods of sealing natural structures to hold pressure. Additional research involves shelter fabrication on the Martian surface from in-situ resources.

3.2.2 Grading and Landscaping

In addition to building shelters, the surrounding terrain must be properly shaped to provide access to and between shelters, as well as to protect them from weather. Research will include development of techniques for cutting and filling, as well as methods for transport of excess waste, regolith, and rocks. This will enable the development of walkways, bridges, roads, blast deflectors, and dust barriers.

3.3 Renewable Energy

The initial power for a Mars outpost comes from the Power and Thermal Unit (PTU) [28] deployed with the outpost. (It is beyond the scope of this paper to define whether the PTU uses solar, nuclear or other sources of energy, and is only referenced here to state that it is sized to provide power for the outpost.) However, an expanded, long term human presence on Mars will require in-situ power generation capability.

This research will focus on pyroelectric energy. The Mars surface outpost is located in a region containing jarosite, which is a strongly pyroelectric material. [27] Research has suggested that pyroelectric energy harvesting may yield efficiencies up to 50% of Carnot efficiency. [16] Such systems could provide power for future expanded human settlements on Mars and could be exported to other spacecraft, space stations, and surface bases in the solar system.

There have also been suggestions of wind energy on Mars. However, such energy is generally only viable during dust storms due to the thin atmosphere. It is only during dust storms that enough wind energy is generated to operate a wind turbine. [19] Wind power may provide a useful complement to pyroelectric power sources in Mars surface settlements.

3.4 Mining and Manufacturing Industries

As previously noted, iron, oxygen, and sulfides are present in the Ophir Chasma region and volatiles are suspected to be present on Phobos and Deimos. Research will involve demonstration and refinement of ISRU equipment to mine and process these resources.

3.4.1 Iron

Iron ISRU research will initially focus on mere extraction of iron, including separation from the various iron oxides. Additional research will include forming this iron into various shapes, including structural members, aerodynamic surfaces, and pressure vessels.

3.4.2 Oxygen

Oxygen ISRU research will pursue oxygen extraction from both iron oxides and the Martian atmosphere. Research activity will also include developing the processes and hardware to incorporate this oxygen into spacecraft propellant and ECLSS oxygen and water supplies.

3.4.3 Sulfides

Sulfide ISRU research will primarily focus on techniques for the extraction of jarosite. Once extracted, the jarosite will be used in the previously mentioned renewable energy research. Consequently, research will also involve exploration of different ways to package the jarosite for use in pyroelectric energy systems.

3.4.4 Volatiles

While Phobos and Deimos have long been suspected of harboring volatiles (water, oxygen, hydrogen, etc.) there is no direct evidence to confirm or deny their presence. Thus, initial research on the Martina moons will focus on the search for volatiles. If volatiles are found on Phobos or Deimos, research in subsequent missions will refine techniques for their extraction and storage.

4 Scientific Research

4.1 Life Science

4.1.1 Human Research

A primary concern with respect to human research and a key driver for Mars exploration is to provide information on whether or not the human is safe and healthy. The challenges faced with traversing to Mars include physiological effects from radiation and hypogravity environments, as well as unique challenges in medical support, human factors, and behavioral or psychological factors.

NASA has identified key human-related risks [33] that will be monitored as part of the Mars human research activity. Research will directly measure physiological markers such as Immunology, Cardiovascular, Renal, Vision, Bone Health, Nutrition, and Neurovestibular performance. Research will also assess overall human mission performance, including performance errors and control of spacecraft and systems. The crew will be monitored for health impacts related to environment or radiation, behavioral issues, and overall human factors acceptability and space system habitability.

Understanding these effects on the human generally involves bodily measurements where specimens are collected and subjected to an initial analysis, with data transmitted back to Earth for analysis. However, there is little interest in returning actual samples to Earth due to the length of the mission and the small return payload capacity of MPCV.

Human research is not limited to the Martian surface, but will occur in all phases of flight. Physiological research will be conducted at predetermined intervals, with a higher frequency of sampling during microgravity transit periods.

Medically trained crew will administer ultrasound scans of crew members during periodic health exams (PHEs). Urine collection can be administered during PHEs if necessary, but ideally will be built into the spacecraft waste collection systems, enabling autonomous sampling with no direct crew intervention.

Blood specimens can be tested in a micro array for the absence or presence of responses. Some are simple yes/no for a particular presence, while others are quantitative. Onboard medical instrumentation can sample this data from blood samples collected during PHEs by crew members trained in medical operations and securely transmit it to Earth.

These PHEs will likely be weekly, in order to provide enough data for Earth-based scientists and doctors. If test points are too far apart there is a risk of missing some transient activity that could provide insight about how the body is adapting. Most of what is used to define a person's health can be determined by the blood and urine samples. As directed by Earth investigators, other analyses can be incorporated into PHEs.

A particular area of interest is how the Martian gravity will affect the formation of proteins and how it will affect bone development. Microgravity has been shown to cause demineralization of bones and it is unclear if partial gravity on the Moon or Mars will have similar effects. This will involve research into both how cells develop that lead to the production of bone, and also how the bone is structured to interact with cofactors in the blood that are necessary for structurally strong bone – effectively development of the right bone set and the right bone growth. Both issues ultimately contribute to the strength of bone.

One area of human research that cannot be digitized as readily is behavior. Currently, behavior must still be assessed locally. There is also still significant research needed to identify the appropriate behavioral markers to indicate how the environment (whether the Martian environment or even the confines of the outpost and transfer vehicle) is affecting the crew.

Human research on Mars will largely require the same investigative equipment used on ISS. However, it is speculated that there may be substantive changes in equipment used to study vision and there is continuous research in developing lighter countermeasures (exercise) equipment, as the exercise devices used on ISS mass over two tons and it is desired to carry lighter equipment to distant destinations.

Current thinking is that the greatest risk is related to the least amount of gravity, so there will be a greater emphasis in PHE data collection during the outbound and inbound cruise phases, and during the Martian moon exploration. This emphasis will continue during the first part of the surface mission, perhaps the first three months or so, and depending on data analysis from Earth investigators may be reduced in frequency until near the end of the surface phase where frequency will possibly pick back up in preparation for the inbound cruise. Because of the duration of these missions, it is expected that significant data analysis will occur real-time, as opposed to shorter duration missions (e.g. shuttle missions) where data was analyzed post-landing. This will enable investigators to make changes to crew protocols during the course of a mission, allowing the data collected to inform what future data to collect. Some noninvasive physiological data will also be collected autonomously during hypergravity phases of flight (e.g. ascent and entry).

This research will still be necessary even after extensive research using ground-based analogs, decades of International Space Station operations, a continuous lunar presence, and several near earth asteroid missions because much of what we know today is based on what is healthy in Earth's environment and is based on statistical assessments of billions of people. Some of what defines health on Earth may not correlate to what defines health in microgravity or on Mars. For instance, some indicators such as breathing rate, respiration, and certain blood chemistries do vary from environment to environment on Earth, without correlating with a change in health status. Ultimately, research will seek to link changes in the body to how the crew member feels and what his or her performance is. Identification of changes in what defines healthy on Mars versus the Moon, microgravity, and Earth will help scientists and doctors to better understand how and why the human body works.

This need imposes a key requirement on the minimum number of Mars missions. Current thinking in the science community is that a sample size of fifteen or greater is needed to draw any conclusions from research data. Because Mars is a different environment from Earth, microgravity, or the Moon, research data from those missions cannot be used to reduce the sample size need. Given the four person crews planned by this architecture for exploration beyond LEO, this imposes a requirement of four Mars missions. Note that some other Mars architectures have used a crew size of six, which would provide the minimum sample size after three missions, but would require a second crew launch – whether MPCV or a commercial or international vehicle – and would also require increasing the quantity or performance of all human-carrying spacecraft (DSV, lunar outpost, Mars outpost, etc.) and the cost impact of a six-person architecture may be greater than the cost impact of adding a fourth Mars mission.

This will not constrain crew activity at Phobos and Deimos during the thirty-day Martian moon exploration segment. Because the duration is so short, it is not clear that there will be sufficient time for the body to adapt to any influences posed by those bodies. However, there is scientific interest in altering crew exposure to the moons across the four Mars missions in order to look for any variations in physiological monitoring that might indicate areas for future research. This can be implemented by varying the exploration protocol for the four missions. For instance, the first expedition might divide the thirty days to spend the first fifteen days at Deimos and the last fifteen at Phobos. The second expedition might spend all of their time at Phobos, the third at Deimos, and the fourth reverse the order of expedition one to spend the first fifteen days at Phobos and the last fifteen at Deimos.

Due to the high importance of sample size, it is important that crew consent for all research involving human subjects be coordinated well before launch. No astronaut may be forced to take part as a subject in any research without his or her consent. However, if a key objective of the mission is to conduct such research, that mission is not “go” for launch unless the consent is present. It is not adequate to assume that a crew member will (or even should) simply agree in exchange for the “privilege” to be part of the crew to Mars or any other space destination. The human body is highly variable from individual to individual and it is inescapable that there will be some possibility, even if remote, of a crew member experiencing a negative reaction to a research study, possibly to the point of death or other life-altering condition.

Given that any mission beyond the surface of Earth may involve such risks, it seems a foregone conclusion that any reasonable government space flight architecture should include automatic insurance coverage to provide compensation to crew or families in the event of such adverse reactions. There may also need to be crew office representation on institutional review boards (IRBs) stood up to approve research for space flight missions beyond low Earth orbit and publication of research activities and potential risks as part of crew selection announcements, such that all potential crew applicants have already given informed consent prior to selection.

4.1.2 Animal Science

Long term storage of food packaged on Earth is not a viable path for human settlement on Mars. Even if transit times did not impinge on shelf life, the volume of food mass required becomes prohibitive as a Mars population grows. Thus, animal science research will expand on lunar-based research and include investigation of the most efficient livestock options for use as an indigenous food supply on Mars. Potential animal life for initial study includes forms of fish and small animals with rapid growth cycles.

4.1.3 Plant Science

Also building off of lunar research, plant science research on Mars will focus on both life support and nutrition. Selected plants will include fruits, vegetables, and grains.

4.1.4 Astrobiology

Astrobiology research is focused on the search for evidence of past or present life on Mars, as well as an understanding of the potential of a planetary environment to support microbial life of any kind. This research also includes a search for elements and molecules relevant to life.

Most scientists are largely of the opinion that the surface of Mars is barren and for the most part unable to support known life forms. However, data from robotic missions to Mars suggest that at some time in Mars past, in was a warmer planet with liquid water on its surface. [21] This leaves four possibilities about Mars life: (1) life as we know it exists on Mars in pockets either on the surface or underground; or (2) life as we know it once existed on Mars and may have left behind clues that will be difficult to detect; or (3) life exists on Mars today but does not conform to present Earth definitions of life; or (4) life never existed on Mars. In all of these cases, confirmation would be difficult with the present limitations of robotic missions and may call for a human presence on Mars.

4.2 Physical Science

4.2.1 Geology

Geology research will be conducted both on the surface of Mars and on Phobos and Deimos. Research on the moons will attempt to resolve questions surrounding their origin, particularly whether they are ejected material from Mars or asteroids that we captured into orbit. Surface geology will investigate the origins of Mars and support astrobiology investigations. In both cases, research will include soil chemistry, quantification of size and number of surface rocks, and the presence of volatiles.

Recent mineralogy experiments by the Mars Science Lab on board the Curiosity rover confirmed the presence of basaltic minerals similar to those found on Earth at Mauna Kea volcano in Hawaii. [23] These studies are yielding new information about the soil and the atmosphere of Mars. Curiosity has found both crystalline minerals and amorphous materials (plagioclase feldspar, forsteritic olivine, augite and pigeonite) [12], which is suggestive that Mars has been a dry planet for at least hundreds of millions of years. Curiosity landed at Gale Crater [8], which is on the opposite side of the planet as Ophir Chasma, location of the human Mars expeditions recommended by this paper. Geology research will also seek to identify similarities and differences between the two regions.

4.2.2 Meteorology

The Martian atmosphere has been studied by many past and present Mars probes. As an example, the Curiosity

Mars rover currently collects meteorological data on wind speed and direction, air and ground temperatures, UV levels, pressure, and humidity. [5] Human Mars expeditions will continue this research through a combination of surface and orbital assets.

Onboard sensors on the Mars Transfer Vehicle (MTV) will provide meteorological observation of the planet from its aerostationary orbit above Ophir Chasma during each expedition. Crews will also place an automated atmospheric monitoring station on Phobos.

Crew or robotically deployed sampling stations at various Mars surface locations may also obtain direct measurements of the Martian atmosphere to identify gas composition as well as to sample particulate matter, under both active and calm wind conditions. Proper selection of sampling station location can also enable measurements at varying altitudes. Figure 3 shows an eastward looking view of Ophir Chasma and central Candor Chasma. [7] North is to the left of the image and east to the top. The north to south distance in the image is approximately 200 kilometers [7], indicating the entire scene lies within dual-rover traverse distances. Several kilometers in altitude variation can be gained simply by conducting rover traverses between the floor of the canyon and the plateaus at the top.

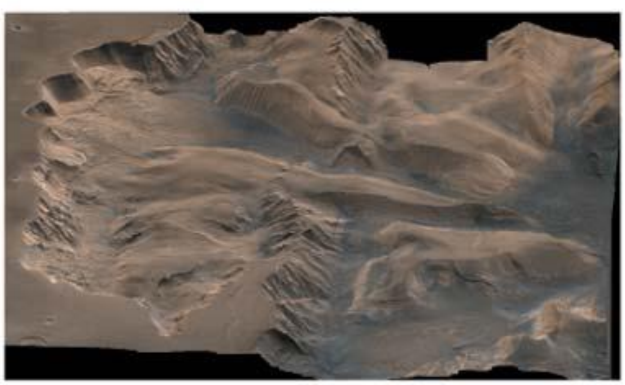

Figure 3. View of Ophir (left) and central Candor (right) Chasmata Viewed from West

Research on Martian sand dunes has provided insight about the interaction between the Martian atmosphere and its surface. [6] Since the morphology of sand dunes are representative of shifts in wind circulation and wind strengths, these data can provide clues to the sedimentary history of the surrounding terrain. [6] Continuing studies of Martian dunes will increase understanding of climatic and sedimentary processes.

4.2.3 Hydrology

Liquid water is one of the most intriguing prospects surrounding Mars research. The average surface atmospheric pressure on Mars varies from 6-10 millibars depending on season. [16] By comparison, the triple point of water is 0.01C and 6.0795 millibar [35], suggesting that it may be possible for liquid water to exist under some conditions on the surface of Mars. Additionally, surface temperatures have been detected above freezing. [31]

Computer simulations [31] have demonstrated evaporation of Mars surface ice and water. However, multiple factors could not be modeled in this simulation which may have positive or negative impacts on the results. Mars research should test these simulations by administering liquid water and ice to the Mars local environment. Initial experiments should involve studies of water in sealed but non-insulated containers, allowing exposure of Mars temperature and pressure conditions but preventing water release. Subsequent experiments should involve actual release of liquid water into the Mars surface, enabling study of the transport of water into the atmosphere as well as into and beneath the surface.

Data from the Curiosity rover has suggested that Martian dust is about 2% water. [14] These experiments could help determine how water is absorbed into the Martian dust and may lead to optimized extraction techniques for the removal of water for future use.

4.2.4 Low Gravity Physics

Much of the microgravity physics research conducted aboard the International Space Station will be of interest in the Mars environment. Just as little is known about the effect of reduced gravity on biological processes, there are also significant uncertainties in areas such as fluid dynamics, flame propagation, surface tension, granular physics, and diffusion.

Also, laser rangefinding experiments between Mars, Phobos, and Deimos will also enable precise gravitational measurements of the three-body Mars system, which will provide data to compare against two-body Earth-Moon laser rangefinding data. Finally, crash investigations of discarded landing stages (heat shields, propulsion stages, etc.) will provide valuable insights that can be used in the design of future commercial Mars vehicles.

4.3 Astronomy

Similar to the advantages of the far side of the Moon, Phobos and Deimos provide ideal platforms for radio and visible light astronomy. Crew-deployed telescopes on these moons will add to the network of telescopes deployed on the Moon, asteroids, and Martian moons. The Mars location provides a vantage point similar to the Moon for celestial observation with limited interference from human-generated emissions. However, it also provides a unique location (when facing Earth) to specifically study the composite electromagnetic generation from Earth, essentially as a point source. Ultimately, interferometric techniques linking Earth, lunar, NEA, and Mars telescopes can be used to create virtual telescopes on the order of 2.5 astronomical units in diameter. MTV-based telescopes will supplement this network and may also be used in transit.

5 Proposed Martian Campaign

5.1 Expedition Format

All four Mars expeditions encompassed within this multi-destination human spaceflight program will have a similar format. Each expedition consists of an outbound cruise departing from an Earth distant retrograde orbit (DRO) in the MTV [28], separation of the lander with direct entry to the Martian atmosphere while the MTV captures to Mars orbit, surface mission, ascent, Martian moons exploration, and inbound cruise with separation of MPCV for direct entry to Earth while the MTV captures to DRO.

5.1.1 Outbound Cruise

The outbound cruise is anticipated to be an approximately 6-month journey, though the specific flight duration varies as a function of propulsion system and orbital mechanics. The crew will spend this time aboard the MTV.

The crew will be able to telerobotically operate assets on the Martian surface and can use onboard laboratory instruments for in-flight research. Periodically and towards the end of the cruise they will conduct remote checkouts of Mars surface systems and assess the health of the MTV and Mars lander.

As the crew reaches the end of the outbound cruise, they will transfer to the MAS/MEDLS [28] and separate from the MTV for direct entry to the Martian surface. Unmanned, the MTV will capture into an aerostationary parking orbit between the orbits of Phobos and Deimos. The aerostationary orbital altitude (17,000 km) lies between the orbits of Phobos and Deimos (9,400 km and 23,460 km respectively) which enables the MTV to serve as a communications relay between the surface outpost and deployed assets or Earth.

5.1.2 470-day Mars Surface Expedition

Once on the surface, the crew will use PSC/PSR [28] surface rovers to transfer from the lander to the surface Outpost. In addition to IVA research in the Outpost and local EVAs, they will conduct up to 14-day excursions away from the outpost in the two PSC/PSRs at ranges up to 480 km from the Outpost. Local EVA operations will be constrained to within a 10 km range of the Outpost.

5.1.3 30-day Mars Moons Exploration

Upon the conclusion of the surface mission, the crew will re-enter the MAS and lift off to rendezvous with the MTV. The crew will use the two PS/MS [28] spacecraft to conduct sorties from the MTV to explore either or both of the two moons for the next thirty days.

5.1.4 Inbound Cruise

The inbound cruise effectively mirrors the outbound cruise, with the flight time driven by orbital mechanics and propulsion and is expected to be similar in duration to the outbound cruise.

Several days from Earth, the crew will ingress the MPCV and separate from the MTV. The MPCV will splash down in the ocean, followed by Navy recovery of the capsule and crew.

The MTV will continue unmanned and will conduct a propulsive spiral capture to a DRO. It can there be serviced and used in future missions.

5.2 Accommodation of Research Objectives within Mars Expeditions

It should be noted that human missions to the Moon and deep space Near Earth Asteroids occur in parallel with each Mars expedition. There is a one-year period during each Mars expedition (with the exception of Expedition Four) where there are both lunar and NEA expeditions occurring in parallel. Expedition Four does share a one year overlap with the final lunar expedition, but depending on launch scheduling may only overlap days or weeks with the final NEA expedition. [28] It is likely that there will be significant space-to-space communication between crews of NEA, lunar, and Mars expeditions, giving rise to corresponding human interaction research throughout all phases of each expedition.

5.2.1 2035 Expedition One

5.2.1.1 Outbound Transit

Research during the outbound phase will be primarily dominated by human research, which will establish crew responses to the microgravity environment and in addition to pre-existing medical records will form a baseline for assessment of the low gravity responses to be encountered on Mars.

Additionally, crew will perform remote checkouts of all Mars surface systems. Crews will also conduct microgravity counterpart experiments of all surface low gravity life science and physical science research to provide control data points. Finally, crews will use onboard telescopes to conduct astronomical observations.

This is the baseline outbound transit crew research profile for all four expeditions and will not be listed in subsequent sections.

5.2.1.2 Mars Surface

During Expedition One, surface rover traverses will be limited to the 10 kilometer walk-back distance. This expedition is expected to be the first time in human history that people will have traveled to Mars. So the unknown unknowns are sufficiently great to justify unusual caution throughout the first expedition. A key initial activity is to increase engineering confidence in the surface mobility assets (e.g. test dives under a variety of terrain and environmental conditions) and to focus initial scientific research in the area immediately surrounding the Outpost, with a goal of maximizing scientific return in this area prior to extensive human operations (with resulting contamination) in the immediate area. While a 10 kilometer radius does sound small, this is equivalent to 77,630.4 acres or roughly 3.6 times the size of Manhattan. It will actually be challenging to find sufficient crew time to thoroughly explore this region during the first expedition. Before venturing out in subsequent expeditions it is important to understand what is right around the Outpost.

The first EVA crew research priority is astrobiology and geology investigation within this 10 kilometer radius. In the course of this investigation, the crew will also deploy meteorology sampling stations and laser rangefinding equipment at pre-selected locations. Initial (contained) hydrology experiments will also be conducted at select locations, both above and below the triple point of water.

Based on results from the geology investigations and pre-existing orbital data, crews will begin focused searches for deposits of iron oxides and jarosite, and will begin to stockpile samples at the Outpost. Crews will research different techniques for both the mining and transport of these potential resources, but actual processing will be forward work for future expeditions. Crews will also attempt to locate any components of the cargo or manned Mars Entry, Descent, and Landing Stages (MEDLS) [28] that landed within the 10 kilometer traverse perimeter and perform crash investigations on these components, potentially returning some components to the Outpost for more detailed analysis and any salvageable components for possible future repurposing. (The MEDLS is based on the NASA JPL Sky Crane, which lowers the payload to the surface, then cuts cables and flies off to crash at a safe distance. There is no need for the lander itself to have a soft landing as it is not reused)

Crews will also begin searches for existing surface features for potential use as shelters, with preferences towards caves, lava tubes, or fissures in hills or canyon walls. As areas near the outpost, landing zone(s), and potential shelter locations are deemed complete with respect to astrobiology and geology, crews will also conduct grading and landscaping operations, forming walkways, bridges, roads, blast deflectors, and dust barriers where appropriate.

With respect to IVA activity, crews will conduct human research throughout the surface expedition. Additionally, crews will conduct small animal research and life support and nutrition plant research.

5.2.1.3 Phobos

The Phobos mission will begin with a complete survey of the surface of the moon using the two Microgravity Scout/Propulsion Sleds. [28] This survey will enable the crew to prioritize targets of interest. The crew will then re-visit priority sites to conduct geology investigations, search for volatiles, and deploy telescopes and laser rangefinding equipment

5.2.1.4 Inbound Transit

Human research will again form a large portion of inbound transit research, with an interest in assessing how the body adjusts to the transition from a low gravity environment to microgravity. Microgravity life science and physical research will also be continued. Additionally, the crew will remotely monitor autonomous equipment and robotic assets deployed on Mars and Phobos. Finally, the crew will devote significant amounts of time to report writing, including scientific and engineering experiment reports, lessons learned assessments, and other data compilations. This research profile will be followed for all inbound transits, with the exception that subsequent expeditions will also include remote monitoring of assets to be deployed on Deimos during Expedition Two. To avoid redundancy, inbound transits will not be described in subsequent sections.

5.2.2 2038 Expedition Two

5.2.2.1 Mars Surface

Expedition Two will expand astrobiology and geology research beyond the 10 kilometer initial exploration perimeter. Crews may operate up to the full 480 kilometer dual-rover exploration perimeter. Crews will deploy additional meteorology sampling stations during these traverses. Crews will also conduct initial (contained) hydrology experiments at pre-selected locations, including traverses to maximum depth extremes in nearby Candor

Chasma. Rover excursions will also expand the search for existing surface features to use as shelters. Additionally, crews will use the extended range to visit MEDLS crash sites located between 10 and 480 kilometers from the Outpost to perform crash investigations and return components to the Outpost for detailed analysis or salvage. Finally, rover crews will continue to search for iron oxide and jarosite deposits, returning stockpiles to the Outpost vicinity.

Expedition Two will also begin to conduct processing research in the Outpost vicinity. Crews will research techniques for extraction of iron, oxygen, and jarosite from the raw materials stockpiled near the outpost. Research will also investigate methods to package jarosite for future pyroelectric research. Oxygen storage may not be provided for this expedition, so processed oxygen may be lost to the environment.

IVA research begun during the previous expedition will continue. However, animal science research will shift from small land-based animals towards fish research. Additionally, investigations of recovered MEDLS hardware will be conducted at the Outpost's general maintenance workstation.

5.2.2.2 Deimos

Following the surface expedition, the crew will visit Deimos. There, the crews will follow the same research profile used by Expedition One for Phobos. However, because Deimos is significantly smaller, the surface survey should be completed faster, allowing a greater number of sites to be pursued for in-depth geology exploration and volatiles search.

5.2.3 2041 Expedition Three

5.2.3.1 Mars Surface

Expedition Three will continue to perform medium range (10-480 kilometer) astrobiology and geology research throughout Ophir and surrounding chasmatas. Excursions may also climb select grades to the top of the canyon to conduct higher altitude investigations. At lower altitudes, particularly in locations where the ambient environment is below the triple point of water, hydrology experiments will involve release of liquid water into the ambient environment.

Excursions will conduct follow-up visits to potential shelter sites and after interior robotic and human exploration crews will deploy inflatable test modules inside these naturally-occurring surface features. Crews will also visit any MEDLS sites not previously visited to perform crash investigations and will salvage any MEDLS hardware from any previous site not already recovered. Finally, rover excursion crews will continue to collect and stockpile jarosite and iron ore.

IVA activity will incorporate both Expedition One and Two activities. Additionally, crews will begin to incorporate oxygen produced by plant research into Outpost and rover ECLSS subsystems. Crews will also begin to incorporate edible plants, fish, and small animals into their food supply, with a dietary goal of 5% of their food from locally grown sources.

Expedition Three will see an increase in local EVA activity. Crews will continue to harvest iron, oxygen, and jarosite from the raw material stockpile. Beginning in this expedition, the oxygen will be incorporated into Outpost subsystems, including gaseous oxygen for Outpost, rover, and EVA air, and water produced by reaction with stored hydrogen. Additionally, liquid oxygen will be produced but not stored. Pyroelectric energy experiments will begin in this expedition, using locally produced jarosite to produce electricity through exposure to repeated heating and cooling cycles. Research will also focus on forming the extracted iron into structural members and aerodynamic surfaces.

5.2.3.2 Phobos

During the second human expedition to Phobos, crews will harvest any volatiles discovered during Expedition One and demonstrate storage capabilities. Regardless of whether or not volatiles have been found, the crews will continue geology exploration of the moon. As has been done on the surface of Mars, they will also assess existing Phobos surface features, particularly caves, deep craters, fissures, lava tubes, etc. for use as shelters. If any promising features are located, initial exploration will be conducted. Depending on the size of the feature this may involve free flying robots, EVA crew, or even an entire Microgravity Spacecraft/Propulsion Sled. If a located feature appears viable after interior inspection, an inflatable test object will be anchored to the interior and inflated. A communications relay will be deployed on the surface of Phobos in order to transmit telemetry from the test object.

5.2.4 2044 Expedition Four

5.2.4.1 Mars Surface

Expedition Four will perform any prioritized astrobiology and geology exploration, including return to previously visited sites if warranted. Crews will conduct additional water release hydrology experiments and deploy more meteorology sampling stations. Crews will return to previously deployed inflatable test modules inside candidate shelter locations and inspect their condition.

Crews will also visit any MEDLS sites not previously visited or return to any sites warranted by analyses conducted to date. And crews will continue collection of iron oxide and jarosite.

IVA research will continue work begun during prior Expeditions. However, crews will increase the percentage of plant-generated oxygen supplied to Outpost, rover, and EVA subsystems. Crews will also attempt to increase the percentage of their food produced from local sources to 25% and will demonstrate techniques for producing non-refrigerated foods that can be packaged for use by rover crews during two-week excursions from the Outpost.

Local EVA research will continue the extraction and utilization of iron, oxygen, and jarosite. Energy production experiments will attempt to demonstrate pyroelectric energy production in the kilowatt range. Additionally, wind energy research will attempt to use aerodynamic iron structures to operate a wind turbine. Iron research will move to the fabrication of pressure vessels. These pressure vessels will in turn be used with oxygen extraction research to store liquid and gaseous oxygen. Gaseous oxygen will continue to be incorporated into spacecraft subsystems, with a goal of increasing the percentage of extracted oxygen used by the spacecraft.

Finally, through a combination of IVA general maintenance workstation activity and EVA work, crews will fabricate an engine test stand from recovered and repurposed MEDLS hardware. The test stand will be used to conduct multiple test firings of locally produced oxygen, demonstrating use of ISRU propellant. Initial firings will be oxygen only, with no fuel in the system. If successful, subsequent firings will introduce quantities of fuel delivered in logistics modules.

5.2.4.2 Deimos

The Deimos expedition will mirror the Expedition Three mission to Phobos. In the case of the Deimos mission, the inflatable test object will be equipped with ECLSS and thermal control subsystems and an airlock and docking port. If the shelter is sufficiently stable, crew will ingress into the shelter and conduct an overnight stay.

6 Recommended Transition to Long-Term Mars Operations

It is likely that the first commercial opportunities on Mars will center on tourism, mining, energy, and construction industries. Meanwhile, there is likely to be continued scientific interest from multiple nations and even some research corporations.

Governance models explored on the Moon [30] will be leveraged to transition from the initial four Mars expeditions to a continuous human presence on the planet. New commercial or government entities will leverage the spacecraft systems designed under the initial exploration program, with deployments local to the Ophir Chasma, elsewhere on the planet, or even in the orbital Mars-Phobos-Deimos system. Based on the lunar research, international regulations will allocate roles and responsibilities between government and commercial entities.

7 Conclusions

Research proposed in this paper can be achieved in a four-expedition exploration sequence to Mars and its moons, with the end result a comprehensive understanding of how humans can live and work on Mars, as well as of some of the potentially valuable Martian resources that can be utilized in the context of a permanent human presence. This research also leads to dramatic improvements in systems engineering processes that can enable nations and commercial enterprises to participate that would otherwise be unable to afford the financial investments. This improvement in systems engineering also has direct application to challenges faced by the US Department of Defense and many other US industries and technology-based agencies. Further, these lessons learned can give future Mars operators, whether commercial or government, a high degree of confidence that their missions can be survivable and produce desired returns on investment.

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