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Access Mars: Assessing Cave Capabilities Establishing Specific Solutions: Final Report

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ACCESS Mars

Assessing Cave Capabilities Establishing Specific Solutions

Final Report

International Space University

Space Studies Program 2009

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ABSTRACT

The human race has evolved, grown and expanded through the exploration of Earth. After initial steps on the Moon, our next challenge is to explore the solar system. Mars shows potential for both scientific discovery and future human settlement, and so is a prime candidate for the next leap of human exploration. Such a bold endeavor will be a driver for an unprecedented worldwide cooperative effort and the catalyst for a new era of international, intercultural and interdisciplinary human relations. Scientific and technological progress will also accelerate as mankind is ushered into a new era of space exploration.

Currently proposed Mars missions have identified a number of challenges such as high levels of radiation, harsh climate and limited launch windows. Recently discovered lava tubes on Mars present potential solutions to some of these issues, but raise a variety of intriguing new challenges. These encompass not only technological and engineering considerations, but also legal, ethical and societal issues such as planetary protection and crew safety. This report assesses the feasibility of overcoming such challenges through the exploitation of Mars caves.

This report reviews existing reference missions and identifies areas of further research essential for adapting mission architectures to utilize caves. Cave suitability is considered with respect to size, type, location and their potential to mitigate hazards. They are also assessed with respect to their potential for scientific work adhering to astrobiology guidelines and the search for extra-terrestrial life. This report compares surface and subsurface habitat options. Engineering challenges arising from the use of caves are addressed along with proposals for alternate architecture solutions. Mission analysis is conducted to determine the transit trajectory and define two possible mission scenarios with surface crews of 6 and 12 crew members. Different types of habitat are described and evaluated. An architecture for precursor missions is provided utilizing surface rovers, cargo delivery rovers and pressurized human transport vehicles. The implications of sub-surface operations on thermal control, communications and power systems are investigated with recommendations given. Crew selection, training methods and life support system solutions are also addressed.

Literature suggests a low radiation environment within Martian caves, allowing for extended duration missions. The ACCESS Mars Team concludes that using lava tubes as human habitats is not merely a viable habitat solution for a Mars expedition, but also potentially more beneficial than proposed surface solutions.

FACULTY PREFACE

"…there is not a simple view of these other worlds."

- Epicureans View of the World (340 – 215 BC)

"Earth might not offer the best place for humans to live."

- Pythagoreans View of the World (500 BC)

Human beings have sought shelter, protection and security for thousands and thousands of generations since the dawn of humankind. Their emotions and feelings drove decisions to leave an open and often hostile environment and move into safety promising places like caves – long before constructing houses, places of worship or community buildings.

Now we plan to take the first uncertain steps into space, the new sea of humankind, leaving Earth towards one of our neighbors, planet Mars. Once again we seek for shelter, protection and security in a hostile environment – this time on another world far from home, planet Earth. Again caves seem to be promising locations for our explorers in space to stay and rest.

Fiftysix extraordinary and distinguished participants from 25 countries and five continents took the challenge and formed the ACCESS Mars team. A truly international, intercultural and interdisciplinary group which performed exceptionally well in many ways from the very beginning running smoothly but powerful like a large train – with a clear direction where to go and difficult to stop after accelerating. The team project (TP) was part of the 2009 International Space University (ISU) Space Studies Program (SSP) which took place during July and August at NASA Ames Research Center, Moffet Field, California, USA.

We, the TP faculty, are delighted and honored to support and work, to celebrate and suffer, but finally to succeed with such an outstanding, devoted and dedicated team. We highly recommend the findings and conclusions of the ACCESS Mars report as well as the members of the team. We wish all the best to the team members on their future personal journey to explore all the undiscovered places in their lives on Earth and maybe somewhere in space.

"We are still at the beginning of our journey, still standing on the quay of our only harbor, Earth, looking outwards and trying to witness the tiny simple ships, our space probes, leaving to far targets to uncover the unexplored."

-R. L. (TP Noumenia, 2008)

NASA Ames Research Center, Moffet Field, California, USA, Summer 2009

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TP Chair	TP Facilitator	TP Facilitator	TP Teaching Associate

AUTHOR PREFACE

We, the generation who lift ourselves
Through open skies
Move toward a world unknown
On the road we do not follow but build.
Our lonely plain of exploration
Stretches dimly 'cross a redscape
To this cavern of new beginnings
Of lessons we have learned.
We lucky few will march ahead
To walk this new terrain
And see a vision of futures freed
From past imaginations.
To those who hear this rally cry
From we, the pioneers
We say to you look deeper
Through this endless new frontier,
Look deeper to this new horizon
Look deeper too, within
For only with a common will
This new world can begin.
M. Kerrigan, SSP09

Forty years ago, humanity took on the challenge of placing a man on the Moon and returning him safely to Earth. The anniversary of this "first step" and the twenty-first Space Studies Program of the International Space University were hosted together at NASA Ames Research Center over the summer of 2009. Our generation is inspired to take the next step and commit to a new era of space exploration.

The Assessing Cave Capabilities & Establishing Specific Solutions (ACCESS) Mars team has undertaken the challenge of developing a mission architecture for an initial settlement on Mars by assessing the feasibility of cave habitation as an alternative to proposed surface-based solutions.

This study encapsulates a new mission paradigm for Mars exploration to aid national space agencies and commercial organizations. This report offers a contribution towards the next steps in the quest for a sustainable future for humanity on Mars. In contrast to point designs, we deliver a set of guidelines intended for consultation in future Mars endeavors.
The ACCESS Mars project is the outcome of intense teamwork, supported by dedicated experts and driven by our vision and mission statement. Our internationally diverse team ranges from professionals seeking new inspiration to college graduates pursuing their passions. Lawyers, engineers, scientists, educators, business entrepreneurs, artists and architects have provided vision and context to this interdisciplinary endeavor. Together we unite as pioneers to explore an endless new frontier, looking deeper into possibilities for Martian exploration.

– Team ACCESS Mars, 2009
ISU SSP09

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ACCESS	Assessing Cave Capabilities & Establishing Specific Solutions
AM DRM	ACCESS Mars Design Reference Mission
AM EDRM	ACCESS Mars Extended Duration Reference Mission
AMO	Aerosynchronous Mars Orbit
APXS	Alpha Particle X-Ray Spectrometer
ARV	Autonomous Reconnaissance Vehicle

C

CERSSE	Committee on the Evaluation of Radiation Shielding for Space Exploration
CLLSS	Closed-Loop Life Support System
COSPAR	Committee on Space Research
CSTS	Cargo Surface Transportation System

D

DALI	Digital Addressable Lighting Interface
DAV	Descent/Ascent Vehicle
DRM	Design Reference Mission
DSN	Deep Space Network

E

EDL	Entry, Descent and Landing
EMCC	Earth Mission Control Center
ESA	European Space Agency
EVA	Extravehicular Activity

F

FMARS	Flashline Mars Arctic Research Station

G

GCR	Galactic Cosmic Rays
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GRS	Gamma Ray Spectrometer

I

IGA	Intergovernmental Agreement
IMLEO	Initial Mass in Low Earth Orbit
IPP	International Partnership Program
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ITAR	International Traffic in Arms Regulations

L

LAT	Lunar Architecture Team
LDCM	Landsat Data Continuity Mission
LED	Light-Emitting Diode
LEO	Low Earth Orbit
LSS	Life Support System

M

MARIE	Martian Radiation Environment Experiment
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MB	Mössbauer Spectrometer
MCC	Mars Control Center
MDRM	Mars Design Reference Mission
MDRS	Mars Desert Research Station
MER	Mars Exploration Rover
MEV	Mega Electron Volt
MLO	Manned Lunar Outpost
MOU	Memorandum of Understanding
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
N	
NASA	National Aeronautics and Space Administration
NGO	Non-Government Organization
NTR	Nuclear Thermal Rocket
O	
OCH	Outside Cave Habitat
OST	Outer Space Treaty
P	
PAR	Photosynthetically Active Radiation
PPP	Public Private Partnership
Q	
QWIP	Quantum Well Infrared Photodetector
R	
REID	Risk Exposure Induced Limit
RFC	Regenerative Fuel Cells
RS	Remote Sensing
RTG	Radioisotope Thermoelectric Generator
S	
SAD	Seasonal Affective Disorder
SAM	Sample Analysis at Mars
SHARAD	Shallow Radar
SPE	Solar Proton Event
SPHVSE	Space Radiation Hazards and the Vision for Space Exploration
STS	Space Transportation System
T	
TES	Thermal Emission Spectrometer
THEMIS	Thermal Emission Imaging System
TM	Telemetry
TPS	Thermal Protection System
TRL	Technology Readiness Levels
TT&C	Telemetry, Tracking, and Communications
U	
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UV	Ultraviolet
X	
XRD	X-Ray diffractometer

1 INTRODUCTION

"Two thousand years from now, their descendants might walk into this chamber, […], if it still existed – the first human dwelling built on Mars! And she had done it. Suddenly she felt the eyes of that future on her, and shivered. They were like Cro-Magnons in a cave, living a life that was certain to be pored over by the archaeologists of subsequent generations; […]" (Robinson, K. S., 1993).

A human mission to Mars is a bold endeavour and will launch humankind into a new era of space exploration. The success of such a mission depends on several critical factors including technological and engineering challenges, planetary protection concerns, and crew safety. Given the complex technical and ethical dimensions involved in the exploration of another planet, it will be necessary to manage and optimize the associated benefits while reducing the risks and hazards to crewmembers on Mars. Optimizing the benefits requires consideration and analysis of diverse habitation options so that crewmembers can perform key science and exploration tasks while maintaining safety as a first priority. In the following sections, we assess the use of caves as a possible habitation scenario. The advantages of caves include but are not limited to shielding against solar radiation, protection from surface environmental hazards, the possible discovery of an unexplored scientific goldmine, and mission cost optimization with respect to launch mass. This report addresses each of these factors to satisfy the ACCESS Mars mission statement.

1.1 Project Mission Statement and Scope

Assessing Cave Capabilities and Evaluating Specific Solutions (ACCESS) Mars explores the future of robotic and human exploration missions to Mars via subsurface habitation. Our mission statement is:

> ***To develop a mission architecture for an initial settlement on Mars by assessing the feasibility of cave habitation as an alternative to proposed surface-based solutions.***

As we are at the cusp of becoming a space-faring civilization, capable of establishing a sustainable human presence beyond our home planet, our vision for humanity's role in space exploration is this:

Our generation must commit itself to enable the first human expedition to Mars. Through the Exploration of Earth, humanity has evolved, grown, and expanded. Space is the final frontier. Our next challenge is to leave the cradle of Earth and push the limits of knowledge beyond our own planet.

This bold endeavour will be the driver for an unprecedented worldwide cooperative effort and the catalyst for a new era of international and intercultural human relations. This global commitment is paramount to advance scientific and technological progress, foster economic growth, as well as enhance social and ethical values.

Establishing a human presence on another planet will inspire further space exploration. A glimpse of Earth from Mars will enlighten the way we think and act on our own planet, as well as encourage us to understand, protect and expand life in the universe...this must be our generation`s legacy – as we boldly go where no human has gone before.

ACCESS Mars will assess habitation scenarios that maintain crew health and safety in the

Martian environment. Aside from the engineering and technological challenges of such a mission, the assessment of cave-based solutions will also deal with issues related to social impacts, international cooperation, policy, law, planetary protection, and cost. Several key tasks are outlined by the Mars cave program requirements and focus on the above factors in relation to caves as an initial human settlement. These are presented in Table 1-1 along with the locations of where they are addressed in the report.

Table 1-1: Mars Cave Task Index

1. Examination of current Mars reference mission roadmaps	Chapter 1
2. Cave location and site selection	Chapter 2
3. Establishing requirements to make caves a feasible habitation option	Chapter 3
4. Comparison between cave-based and surface-based habitation solutions	Chapter 3
5. Consideration of ethical, political, philosophical, and social issues	Chapter 4
6. Establishment of a business case for private sector involvement	Chapter 4
7. Evaluation of a combined Moon/Mars strategy	Chapter 2, 3, 5
8. Application of terrestrial and lunar analogues for a Mars cave mission	Chapter 2,3,5

1.2 Historical Perspective and Rationale for Caves

Never before in the history of humankind have people left their home planet to settle permanently on `another celestial body. The Apollo Moon missions in the 1960's were both inspiring and fascinating, but did not lead to an enduring off-Earth human presence. Instead, the achievements of the Apollo efforts led to the establishment of space stations in low Earth orbit. Present generations must extend the work accomplished during the Apollo era and commit to a new vision of exploration to include an initial settlement on Mars.

Our understanding of the Mars environment has changed over the years from a barren, hostile, and dry planet environment into a planet with ice, methane, and formaldehyde as well as other minerals that are witnesses of a warmer, wetter, and more active past. The potential of finding signs of life on Mars due to the presence of these compounds is inspiring (Peplow, Mark. 2005). The presence of lava tubes, the detection of the "seven sisters" (seven dark spots near the Mars equator that could be entrances to caves) by the 2001 Mars Odyssey Orbiter, and recent pit detections by the Mars Reconnaissance Orbiter (MRO) provides some evidence of possible locations for future human habitats. These discoveries could also be a useful base for conducting science and searching for life.

Caves have been and still are natural protection against hostile environments. They also represent the cradle of human culture and society and are still in use today. In Northern China for example, caves still serve as home for about 40 million people. These caves require minimal technology to make them habitable and serve as a natural shelter (Ebrey, Patricia B., 2009). Similarly, the largest cave dwelling community in Europe is located in Granada, Spain. The constant temperature in these caves are a logical rationale for habitation and has led to the refurbishment of these caves specifically for habitation. The functionality of caves extends into housing, restaurants, hotels, theatres, and spas (Leary, Charles, Perret, Vaughn, 2009). A modern example of cave dwellers is in Coober Pedy, South Australia. A feature of these caves is the constant relief provided from the hot climate during opal mining. Both the Granada caves and the Coober Pedy caves support community buildings such as churches, restaurants and hotels (District Council of Coober Pedy, 2009).

Humans search for a habitat for protection and security. The above case studies demonstrate that caves are a suitable living environment. It is therefore likely that caves on Mars may also provide the protection and security necessary for crewmembers to establish an initial settlement. The first humans on Mars can use the knowledge of terrestrial cave dwellings to adapt more easily to a hostile environment, paving the way for a permanent human settlement on the planet.

1.3 Mars Caves

The ACCESS Mars report focuses on caves because of their known presence and potential benefits, including hazard protection against the extreme Martian environment, and engineering advantages. ACCESS Mars will comparatively discuss the work necessary to prepare for the robotic and human exploration of Mars caves. Furthermore, ACCESS Mars will address the business, social and political arguments for the use of caves for an initial settlement on Mars. Space agencies have developed a conservative approach to habitation design and selection by avoiding exploration strategies with many uncertainties. These uncertainties arise because of the large cost of planetary missions and the negative implications in the case of failures.

The current knowledge of the cave environment will be explored by ACCESS Mars to reach the level of political and engineering confidence required to satisfy a risk avoidance philosophy that is acceptable to national space agencies. In preparation for Martian cave exploration, the ACCESS Mars team surveyed Mars Design Reference Missions (DRM) developed by national space agencies as a starting point for a cave exploration strategy. A brief summary of each mission is included in the following section and will be used to further recommendations for a Mars cave reference mission with the consideration of an additional cave mission scenario.

1.4 Design Reference Mission Overview

1.4.1 Human Mission Overview

NASA and ESA design reference missions are a baseline for the ACCESS Mars mission analysis. Parameters that change as a direct result of cave habitation will be adjusted for the Mars cave mission design. The two most significant parameters are the number of cargo launches and the mass budget. ACCESS Mars chose to stay within the NASA DRM as a guideline for the mission analysis parameters that do not change due to cave habitation.

Table 1-2 summarizes the key parameters that ESA and NASA addressed for the Mars Design Reference Missions.

Table 1-2: Comparison of key elements from ESA and NASA Mars Reference Design Missions

Parameters	NASA DRM	ESA DRM
Mission Type	Conjunction Interplanetary transit	Conjunction Interplanetary transit
Timeline	Late 2020 to 2030s	2020 to mid-to-late 2030s
Human Mission Duration	860 days	923 days
Number of crew	6	4
Mars Capture Method	Aerocapture	Aerocapture
ISRU	O_2, Methane	O_2, H_2O, Buffer gas
Propulsion	Nuclear Thermal	Nuclear Thermal
Cargo Deployment *Number of Launches*	Pre-Deploy 4 Ares V	Pre-Deploy 4 Ares V
Use of Launch Windows	1 window	1st window: 2 to Mars surface 2nd window: 1 to surface, 1 to Manned Lunar Outpost (MLO)
Crew Deployment Launches	3 Ares V + 1 Ares I	2 Ares V + 1 Ares I
Surface transportation	Pressurized rover Crew: 2, 15 day sortie	Pressurized rover Crew: 2, 15 - 20 day sortie
Power generation	Nuclear (fission)	Nuclear (fission)
Mass budget	41.3 t Transit Habitat 70.1 t Surface Habitat 62.4 t Descent/Ascent Vehicle (DAV) DAV payload: 106.1 t Hab. payload: 113.8 t	50 t[1]/ 38 t[2] Transfer Habitat 32 t[1]/ 31.9 t[2] Surface Habitat 29.3 t[1]/ 31.5 t[2] Ascent Vehicle Total payload: 90 t

A conjunction class mission is the baseline for each reference program because it requires less propellant and energy than an opposition class mission, reduces zero-g effects and radiation risks. These exploration roadmaps assume a ten-year precursor mission development phase. The intended launch date for these missions is 2020 and a two-year robotic Mars mission follows. Cargo launches will start to follow in the next two years, with the implementation of the first international human mission to Mars in the late 2030s depending on human flight technology development. The 900-day human mission duration occurs from launch to return to Earth and considers a crew size of six or four in the case of the ESA DRM. Oxygen, water, methane and nuclear-thermal power are consumables in both life support and propulsion systems for a mission to Mars. The Moon acts as a test-bed for in-situ resource utilization capability, followed by further testing on the Martian surface. Both pressurized and unpressurized rovers providing surface transportation support scientific exploratory sorties from the main habitat.

1.4.2 Robotic Mission Overview

Robotic missions to Mars have included both rovers and orbital spacecraft. NASA previously tested non-human surface mobility on Mars via the Mars exploration rover Sojourner in 1997. This was the first vehicle to drive off-road on another planet (Bajracharya 2008). Furthermore, two vehicles named Spirit and Opportunity landed at different locations on Mars in 2004. These two rovers searched for evidence of past water activity inside craters. Other missions include Mars Express, Mars Global Surveyor, and the Mars Reconnaissance Orbiter. Future Mars reference missions are considered for robotic precursor missions to investigate caves on Mars.

1.5 Report Purpose and Outline

The structure of this report outlines the entire infrastructure of a mission to Mars intending to explore caves as a feasible habitation solution in comparison to proposed surface alternatives. The report includes the examination of current reference missions from various space agencies, required robotic precursor missions to locate and select caves, human missions to Mars to establish an initial settlement, and comparisons to an alternative cave mission scenario for future reference by national space agencies. This other scenario outlines possible timelines and crewmember structures that are made possible for a mission to Mars as a direct result of cave habitation.

Chapter 2 examines characteristics and properties of Martian caves. These include types of Martian caves (specifically focusing on lava tubes), cave material properties, cave thermal properties, and Martian hazard mitigation from radiation, meteoroids, dust, and wind. This chapter also explores possible locations of caves on Mars, in-situ resource utilization (ISRU) via locations of ice and other energy resources, and specific cave site selection processes. We also suggest that exploration be tightly linked to scientific merit, with a particular emphasis on astrobiology. Finally, this chapter includes descriptions of possible precursor missions and platforms using remote sensing equipment necessary to select a final cave.

Chapter 3 outlines requirements for a human mission to Mars to establish an initial settlement in caves. Human missions, from an operation, planning, and training perspective include factors such as launch masses, cargo flights, entry, descent, landing, robotics, communications, and navigation. The cave habitat design and layout is provided, focusing on living requirements and the life support system. Finally, Martian exploration deals with planetary protection issues during both precursor robotics missions and human missions. Requirements from both engineering and life science perspectives in regards to extravehicular activity (EVA) are discussed.

Chapter 4 encompasses the governing architecture for a Mars mission. This includes legal considerations and the applicability of space treaties and agreements concerning Martian exploration. Policy directives include international cooperation, lessons learned, and integration of existing space legal infrastructure. Other factors involved are public opinion and the necessity to address target groups to promote global awareness and support of a Mars-bound mission.

Crewmembers' traveling on a 900-day round-trip journey to Mars is a base-case for a reference mission to establish an initial settlement in a Mars cave. Chapter 5 discusses variations of this reference mission as a comparison for cave habitation. A key deliverable for ACCESS Mars is a comparative analysis between the reference scenario and an alternative mission scenario. The other scenario includes a crew overlap allowing twelve crewmembers to reside on the surface simultaneously. This section lists the advantages and disadvantages of each scenario from engineering, physical science, life science, legal, business, social, and policy perspectives. Chapter 5 also suggests that as a direct result of cave habitation, it is possible to consider many different mission scenarios with variations in crew numbers and mission durations. All mission details as presented in Chapters 2 and 3 refer to the ACCESS Mars reference scenario.

The final chapter discusses our conclusions regarding the feasibility of using Mars caves for habitation as opposed to surface habitation. We offer recommendations to optimize caves as a habitation solution.

2 MARTIAN CAVES

The use of caves as habitats on Mars poses new and interesting challenges. What types of caves are best? Where are these caves? How do we find these caves? We aim to address these and other questions in this chapter. We provide background information on the types and properties of caves on Mars. We will analyze the hazards both mitigated and introduced by caves. We discuss the scientific merit of different cave sites as well as the possibilities for In Situ Resource Utilization (ISRU). Finally we will present a summary of detection methods for both resources and caves and outline site selection mission architecture.

2.1 Physical Characteristics

2.1.1 Types of Martian Caves

As described by Boston (2003), several types of caves may exist on Mars ranging from glacial caves, ice volcanism caves, dissolution caves, and lava tubes. The large environmental differences between Earth and Mars may lead to cave formation mechanisms on Mars not found on Earth. Such mechanisms include the melting of super-cooled water ice, liquid carbon dioxide erosion, and boiling of ground ice. A type of cave that is present on Mars, Earth, and potentially the Moon, is lava tubes. Recent Mars Orbiter Camera data have proven the existence of lava tubes on Mars (Boston, 2008; Cushing et al., 2007). Lava tubes are chosen as the focus of this report because to date, they are the only type of caves observed on Mars (Boston, 2004). An example can be seen in Figure 2-1. The simple shapes of lava tubes in comparison to other caves along with characteristics mentioned in the following sections makes subsurface habitat planning easier.

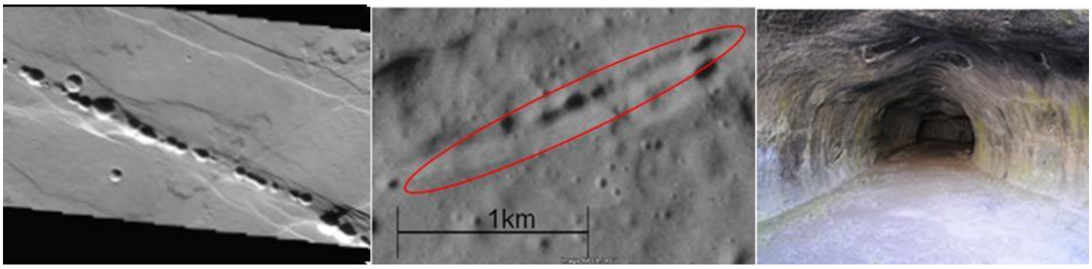


Figure 2-1: Lava tubes on Earth and beyond
Left - Mars lava tube (Photo: ESA, NASA), Center - likely lava tube on the Moon (Photo: Google moon image -NASA/ASU/LPI/USGS/JAXA/SELENE), Right – Interior of a lava tube on Earth (Photo: Line Drube)

2.1.2 Cave Properties

Lava Tube Characteristics

A lava tube is a cave created when low viscosity basaltic lava flows from a non-explosive volcano (Greeley, 1975). Basalt is a volcanic material made up of fine mineral grains packed tightly (Alden, 2009). This very fluid lava can create lava tubes in three different ways. First, the outer layer of a lava river can cool off and solidify thereby building a roof over the river. Second, in a turbulent flow, lava can splatter and start building up walls on the side of the channel, and these can end up closing over the top of the channel. Third, the very fluid lava streams can flow inside a more viscous lava flow, resulting in internal lava "rivers" within the other more viscous lava. After the eruption dies out, the lava will continue to flow out of the tube. This action leaves an empty tube coated with lava on the floor, walls and ceiling, typically creating a relatively smooth surface (Greeley, 1971).

Terrestrial lava tubes have a diameter typically less than 15m (Hörz, 1985), but on Mars and the Moon lava tubes are believed to exist that are more than several hundreds of meters in diameter. The primary explanation suggested for this discrepancy is the lower gravity. It is expected to find lava tubes on Mars of much smaller diameter, but these have yet to be identified (Boston, 2009).

The shape of the inside of a tube will depend partly on how many different eruptions occur within the same pathway. If only one eruptive event occurs, the tube will usually have a very round cross section. If several eruptions have used the same lava tube to channel their flow, then the tubes can be horizontally flattened ovoids or layered with multiple tubes on top of each other. The walls and ceiling of the tube can vary from being smooth to complex with hanging lava stalactites. The floor can vary from being very smooth, to having solidified pieces of lava protruding from the floor, to a very rough surface (called a'a type lava). After formation, the ceiling and sides of the tube can collapse partly or fully and thereby leave rocks on the floor (called breakdown). Some roofs collapse later because of weathering (see Section 2.2.2).

A lava tube can have several types of entrances. Such entrances have been described by McGown et al (2002) (see Figure 2-2):

- A rille is an unroofed lava river with an entrance that can be at the draining exit of the structure, a collapsed section of the rille wall, or possibly where a rille changes into a roofed lava tube. This means that a rille entrance penetrates diagonally into the ground with many rocks near the opening in a ramp like structure or sometimes a mound (see Figure 2.2). Dust and sand piled up between the rocks could help smooth the entrance floor. On Mars where global seasonal dust storms are frequent, it is expected the entrances will have dusty floors (Boston, 2009). This entrance type is being considered primarily in this report for an initial settlement. Some rille entrances are the start of a lava fan or field, where lava has spilled out onto the surface (Bleacher, 2007). Rille entrances could potentially be found by looking for these lava fans/fields.

- A skylight is formed when a section of a cave roof has collapsed. Pupysheva et al. (2006) found that the skylights they examined on Mars were between 130–270 m wide and 10–22 m in depth. There can be many skylights for each lava tube. Under the skylight there is typically a pile of debris, which may impede access.

- An hornito is a former gas pressure explosion site. These often have a strong rim from where the gas bubble under the ceiling burst and deposited splatter. On Earth hornitos are usually a few meters across, but it is not yet known if they are bigger on Mars.

Figure 2-2: Lava tubes
1) Inside a skylight entrance (Surtshellir Cave, Iceland, eighteenth century engraving). 2) Inside a lava tube (Hibashi Cave, Saudi Arabia, credit John Pint).

Cave Thermal Properties

An annual mean thermal structure for Mars can be modeled on a latitude-height averaged basis, as presented in Read (2004). Data from the zero log-pressure height from the mentioned model is used in Figure 2-3 below to approximate the mean annual surface temperature. Bessone (2004) gives a slightly larger range of temperature differences from 155 Kelvin (K) at the poles to 220 K at the equator.

According to Wynne (2007), studies of underground caves on Earth such as the Cavernas de Quitor and the Cueva Mina Chulacao indicate that cave wall temperatures can be roughly approximated by the mean annual surface temperatures for very dry caves. This approximation is expected to be more accurate on Mars due to the lack of Earth related factors. Additionally, the depth into the Martian basalt at which the surface seasonal and diurnal temperature oscillations are damped by a factor of *e*, called the thermal skin depth, is estimated to be approximately several centimeters (Mellon, 2004). To provide adequate hazard protection only lava tubes with basalt ceilings at least several meters thick are considered for habitation (see Section 2.2). It is expected that the thermal environment in these caves will be very stable and can be approximated by the mean annual surface temperatures.

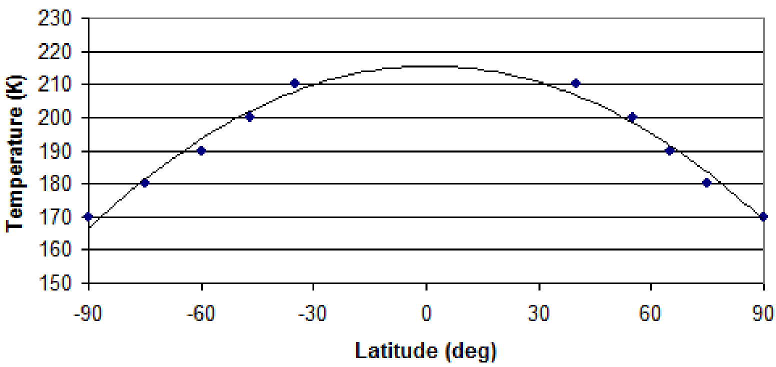


Figure 2-3: Latitude averaged mean annual surface temperature on Mars (data from Read, 2004)

A small vertical temperature gradient is expected due to internal heat sources on Mars (Roberts, 2005). Comparing measurements of the gravity and topography of Mars from the Mars Global Surveyor mission, a global reference lithosphere thickness of 50 km is estimated (Zuber, 2000). The temperature at which the rock softens and starts to creep elastically delineates the extent of the lithosphere from the surface and is estimated at 1300 K for the 50 km model (Roberts, 2005). With these temperature and depth values and a surface temperature of 220 K, a linear temperature gradient of 22 K/km is approximated. With this estimate, a cave at a depth of one kilometer will be 22 K warmer than a cave near the surface such as lava tubes, which are generally shallow features.

Although several models are available in the literature on the thermal structure of Mars, more data are necessary from on-orbit remote sensing, terrestrial measurements and Mars surface measurements to better quantify the expected thermal environment within Martian caves. The HP^3 instrument package onboard the future ESA ExoMars mission will assess the Martian subsurface thermal properties to a depth of five meters (Grott, 2009). These measurements will be the first thermal measurements collected below the surface of Mars. A NASA astrobiology project led by N. Cabrol (NASA, 2009) will make use of aerial infrared thermal measurements of caves on Earth to determine their thermal signature from an aerial platform compared to the surrounding non-cave features. Dr. Boston and her team at the New Mexico Institute of Mining and Technology are conducting work in characterizing the thermal environment in caves on Earth based on size, shape and material composition through thermal modeling and field measurements primarily at the Carlsbad Cavern, El Malpais lavatubes, and Ft. Stanton/Snowy River in New Mexico (Boston 2009; Shindo 2005). Research is also being conducted on cave airflow on Earth (Pflitsch, 2003). These efforts will give some insight into the thermal environments of Martian caves.

2.2 Martian Environment Hazards: A Comparative Analysis

The physical and thermal properties of lava tubes indicate benefits for cave habitation; however, their feasibility is still largely assessed through the potential for hazard mitigation. While many risks to crew are reduced in a cave habitat, other risks may be introduced or even enhanced. The relative trade-offs between these differential risks are explored in this section. Radiation, meteorites, dust storms, cave instability, risk of injury during Extravehicular Activities (EVA), and electric discharging are all identified as hazards that may have different effects within a cave as compared to those on the Martian surface.

2.2.1 Mitigated Hazards

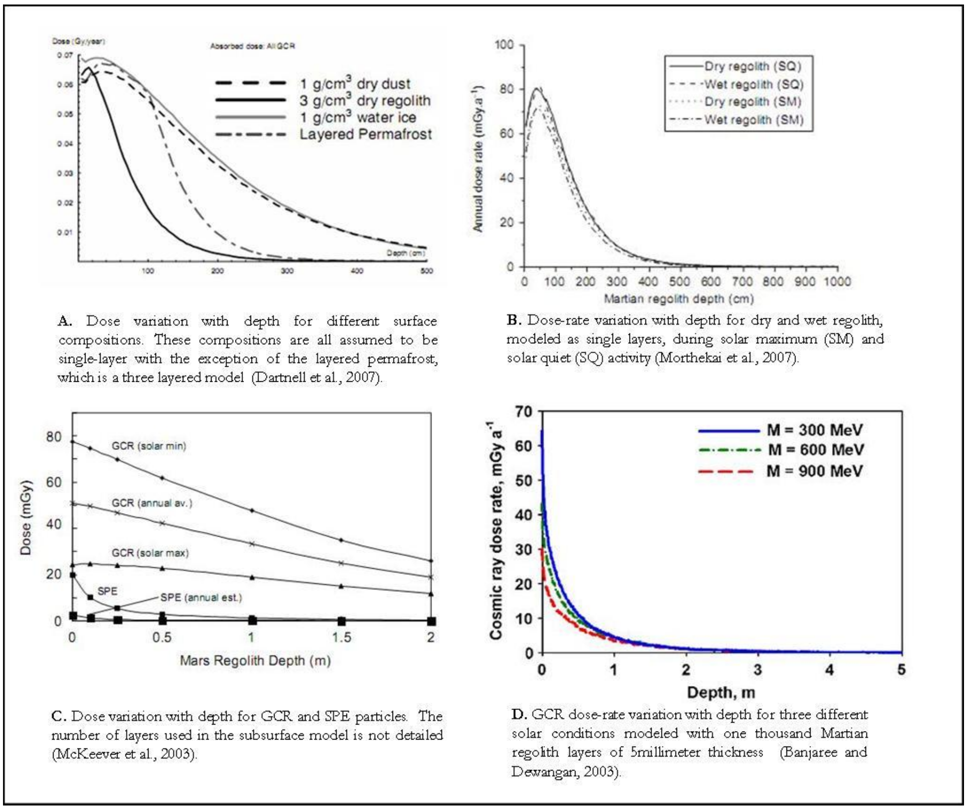
Radiation

Crewmembers traveling on long-duration missions to Mars will face extreme levels of radiation both in transit and on surface. The health effects of overexposure to radiation sources include cataracts, genetic mutations, cancer, and death (Langell et al., 2008). Radiation energy is measured in units of Grays (Gy), but the complex biological effect of an absorbed dose depends on the tissue type and is measured in Sieverts (Sv). All current NASA and ESA Mars mission decisions relating to radiation follow a 3% Risk Exposure Induced Death (REID) limit. The REID limit indicates that an astronaut's risk of developing a fatal cancer during their lifetime is increased by no more than 3% on such a mission (Townsend, 2000). These standards estimate the REID level within a 95% confidence interval and result in an allowable career dose limit between 1–4 Sv/year depending on age and sex. Significant uncertainties arise from radiation modeling inaccuracy, unknown effects of secondary radiation from space materials, and unknown effects of radiation on the human body (Ahlf et al., 2000). It may be necessary to increase the REID limit for missions to Mars but the implications of such a change on the human body are unknown.

The radiation on Mars is a combination of three sources: Galactic Cosmic Rays (GCRs), Solar Particle Events (SPEs) and secondary radiation (Wilson et al., 2004). GCRs are highly energetic background radiation, SPEs are sporadic, lower-energy higher-flux-density occurrences, and secondary radiation is caused by the interaction of GCR and SPE with the Martian atmosphere and surface (Dartnell et al., 2007). GCRs and SPEs vary with the solar cycle. There are a large number of SPEs at solar maximum but the levels of GCRs are minimal during this period (Committee on the Evaluation of Radiation Shielding for Space Exploration [CERSSE], 2008).

High-energy GCR particles interacting with nuclei in the Martian atmosphere and surface produce energetic secondary radiation particles, which can collide with other nuclei (Dartnell et al., 2007). Secondary radiation is poorly understood and difficult to characterize, with collisions producing multiple and multidirectional fragments with differing energies. In any thick shielding material, such as the top layer of the Martian regolith, these interactions are incredibly complex and difficult to predict (CERSSE, 2008). In addition to ionizing radiation from space, there is the possibility of natural radiation sources. More research is required to characterize the exact composition of the caves to ensure that natural radiation sources are minimal. Martian lava tubes are unlikely to contain high amounts of uranium compared to igneous or metamorphic rock types, which so far have not been identified in Martian surface outcrops (Boston, 2009; McDowell & Hamilton, 2009; Schmidt et al., 2009).

On Mars, the thin atmosphere attenuates some of the radiation incident on the surface. Despite this, the surface radiation levels are still much greater than those on Earth and hence surface radiation shielding is vital to the success of a human Mars mission (Saganti et al., 2004). In this section, we describe the natural sub-surface shielding offered by caves. There have been no direct measurements of the surface radiation levels on Mars. Numerous in-orbit radiation measurements have been recorded by the Martian Radiation Environment Experiment (MARIE) onboard the Mars Odyssey spacecraft (Morthekai et al., 2007). Martian surface radiation levels of both GCR and SPE radiation are calculated using a variety of numerical models. Such models use three primary particle physics computational codes, the baryon transport code, BRYNTRN, the combined nucleon and heavy ion code, HZETRN, and the geometry and tracking Monte Carlo code, GEANT4 (Dartnell et al., 2007; Morthekai et al., 2007; Simonsen, 1991). Typically, these are used to model SPE radiation, GCR radiation, and secondary cascades. The results of the numerical models are validated via extrapolation and comparison with recorded in-orbit Mars data. Additionally, many models are verified through simulation of the terrestrial radiation environment for which there exist actual measured values. The results of these four numerical models are presented in Figure 2-4. These results provide graphical representation of the variation in radiation with depth beneath the Martian surface regolith.



A. Dose variation with depth for different surface compositions. These compositions are all assumed to be single-layer with the exception of the layered permafrost, which is a three layered model (Dartnell et al., 2007).

B. Dose-rate variation with depth for dry and wet regolith, modeled as single layers, during solar maximum (SM) and solar quiet (SQ) activity (Morthekai et al., 2007).

C. Dose variation with depth for GCR and SPE particles. The number of layers used in the subsurface model is not detailed (McKeever et al., 2003).

D. GCR dose-rate variation with depth for three different solar conditions modeled with one thousand Martian regolith layers of 5millimeter thickness (Banjaree and Dewangan, 2003).

Figure 2-4: The Martian sub-surface radiation profiles predicted by four different models

In the models presented in Figure 2.4, the Martian regolith has an assumed depth of at least five meters. The composition of the regolith is consistent with that measured by Viking (McKeever et al., 2003) and Pathfinder (Dartnell et al., 2007; Banerjee and Dewangan, 2008; McKeever et al., 2003; Morthekai et al., 2007). It has been shown that slight variations in this assumed Martian regolith composition have negligible effects on the shielding properties (Kim et al., 1998). Hence, the results of Figure 2.4 are valid if a lava tube is shielded by solid basalt rock rather than the simulated regolith. El Taher et al. (2007) found that attenuation rates in two other related volcanic rock types (andesite and diorite) were proportional to the density of the material. Basalt, and diorite have densities ranging from 2.8 to 3 g/cc and andesite is slightly less dense at 2.5 to 2.8 g/cc (Hall, 1996).

Figure 2-4 shows that the GCR radiation penetrates the Martian surface to a greater depth than the SPE radiation. Therefore, the penetration of the GCR radiation dictates the required thickness of the cave roof to ensure adequate shielding. It should be noted that the ratio of solar minimum to solar maximum surface GCR radiation used by Morthekai, et al., (2007) is significantly different to that used in other simulations. Thus, the prediction of five meters depth to mitigate radiation effects in that simulation is considered conservative and our initial recommendation is to select caves with a roof thickness of 2-3 m. Ultimately, *in-situ* radiation measurements are necessary to validate these models, but these simulations can guide our initial investigations.

Meteorites

Meteorites impose hazards to all Martian surface missions (Committee on Precursor Measurements Necessary to Support Human Operations on the Martian Surface [COPM], 2002). Currently, the details of meteoroid flux and mass distribution in both Martian orbit and on the surface are unknown but some calculations have been made (Bland and Smith, 2000).

The scientific consensus is that Mars has a significantly higher probability of meteorite impacts than on the Earth or the Moon. This is a result of the proximity of Mars to the asteroid belt, the thin Martian atmosphere and the lack of a Martian magnetic field (Boston, 2009; Bland and Smith, 2000; Schroeder et al., 2008).

It has been calculated that no meteorites smaller than approximately one kilogram in mass are capable of reaching the Martian surface because of protection provided by the atmosphere (Carrermole, 2001). This parameter and the risk of meteorites vary with altitude. The precise flux of meteorites and how to calculate these values is still a subject of active debate even on Earth (Zolensky et al., 1990). Secondary fragmentation risks would further depend on the impacted terrain. It is anticipated that lava tubes buried by tens of meters of basalt would provide excellent protection from most small impacts and secondary fragmentation (Clifford, 1997). Precursor missions are needed to quantify these values and thereby assist risk management.

Dust Storms

The global dust storm season on Mars occurs on either side of the Martian perihelion passage and lasts approximately 3-5 months (Martin, 2007). In the ESA report Human Missions to Mars (Bessone and Vennemann, 2004), a key constraint on landing and surface operations is the Martian dust storm season. Mars arrival often coincides with the global dust storm season, requiring the spacecraft to linger in orbit until major dust storms have subsided to an acceptable level. In the reference mission detailed by Bessone and Vennemann (2004) a key requirement of departure time from the Martian surface was before the beginning of the next global dust storm season.

Within a Martian cave, it is reasonable to assume that only minimal protection near entrances would be required to protect hardware from the Martian dust storms. Consequently, structures would likely require less repair and maintenance than those for surface habitation. Additionally, the cave might facilitate equipment enclosures, thereby increasing apparatus accessibility.

Surface operations cannot be conducted during a dust storm whereas cave habitation enables subterranean exploration and Extravehicular Activities (EVAs) for maintenance operations during dust storms. The use of caves potentially increases both the scientific output of the mission and the crew safety. Furthermore, caves can potentially be used for subterranean transport to regions of high In-Situ Resource Utilization (ISRU) potential or scientific interest during dust storms (Boston et al., 2004).

2.2.2 Hazards Intrinsic to Cave Habitation

Cave Instability

An intuitive disadvantage to residing in caves is a potential risk of cave-ins. The presence of skylights in known caves highlights this phenomenon. Caves of all lithological types have had geological periods of time available to reach gravitationally stable states. Thus, the potential for rock fall or collapse is quite small. As Hörz (1985) points out, the formation of caves is highly dependent on local gravitational fields. Further study and prospecting missions would be required prior to building a settlement. Some conclusions may be drawn from existing data about the size and structural integrity of the lava tubes. Having formed in an intermediate gravitational field, Martian lava tubes are likely to be smaller than lunar caves but larger than lava tubes on Earth (Coombes and Hawke, 1991).

Lava tubes have been assumed to have remained intact for millions of years of meteoric bombardment and seismic shaking (Coombes and Hawke, 1991). This assumption suggests a strong structural integrity, which, combined with the rarity of these events, results in a low probability of future high risk Martian volcanic activity or seismic disturbances. Increased human activity is the only likely remaining factor that may trigger a rock fall. Waltham and Park (2002) used analogue near-surface lava tubes in South Korea with highways and industrial complexes built above them to demonstrate that most can withstand "normal engineering loads". This durability criterion is less likely to be met at skylights and therefore any habitat should ideally be located away from skylights.

Cave instability is a hazard that can be largely controlled through appropriate training, prior research and site-assessment. The stability of rock that forms the roof of a lava tube depends on the thickness, the unsupported width over the tube and on how the roof was formed (Waltham et al., 2005). By development of operational guidelines for optimal cave assessment and selection, any cave-in risks could be minimized. These guidelines may in fact be primarily developed through Earth and Moon analog research. There are differences, however, that must be considered when using such comparisons. For example, there are large differences between the ratio of width to roof thickness on Earth, the Moon, and Mars. There are also differences between Martian basalt tensile strength that have not yet been investigated in-situ. Evidence of fracturing or surface craters would also indicate a higher risk of instability of the lava tube and would need to be determined prior to habitation. If there is any overlying crater with a depth 50% or greater than the roof thickness, then the lava tube was most likely penetrated by the impact and is likely to be unstable or collapsed (Hörz, 1985). Through detailed analysis of the surrounding geology of a tube, the risk of instability can be significantly reduced. Additionally, the mature fields of geotechnical engineering and mining engineering can provide stabilization techniques that are relatively easy to implement, even in challenging environments such as those of other planetary surfaces (e.g. Canakci and Gullu, 2009).

Extravehicular Activity

An additional hazard of cave habitation is the increased risk of crewmembers falling during an EVA due to changes in terrain and slope when entering or leaving a cave, especially when coupled with the changes in lighting conditions. Due to this hazard, it may be best to operate EVAs in the evening, or adjust artificial light in a cave to match the exterior. This hazard is thus easily mitigated, but is an important consideration for the operational approach. Furthermore, the gradient of the floor of any selected lava tube should be within set constraints to minimize crew risk. Volcanic materials within and surrounding lava tubes are typically sharp, therefore the possibility of damaging spacesuits during exploration and entry of the tube are significant. We anticipate that future spacesuits for planetary surface EVA use will be considerably more flexible and abrasion proof than current models (Jordan et al., 2006). Nevertheless steps to minimize falling will still be wise. Commonly used entrances and exits should be engineered into a safe path with solutions such as staircases, clearing of rubble and smoothing of the dusty surface by treatment or overlaying materials.

2.2.3 Undetermined Cave Hazards

Electric Discharging

Current estimates of risks from electric discharge are low for surface exploration on Mars

(COPM, 2002). Similar to the Moon, the dryness on the Martian surface inhibits natural discharging and conversely inhibits the prevention of charging. This leads to a lack of local electric ground, resulting in a build-up of potential differences to the habitat. These factors particularly affect EVAs; more specifically activities that electrically isolate crewmembers (COPM, 2002). Consequences of discharge may include damage to electronics, the EVA suit, or other mission critical equipment (COPM, 2002). Simple mitigation engineering and operational practices should be sufficient to avoid this charging for surface exploration. Scientists and engineers have concluded that knowing more about Martian electrical activity is not essential before the first manned mission to the Martian surface (COPM, 2002).

No studies have been performed to determine whether this situation would change within a Martian cave (Boston, 2009). Differences may result because in a cave environment, the human habitat is dissipating heat in an area of close proximity to permafrost. Additionally the habitat's water sources may increase local humidity. In a confined environment, the humidity of the air or the amount of water on surfaces may be increased. This leads to an increased likelihood of discharge occurring between static objects and those that have returned from EVA or rover missions. There is the possibility that living in a Martian cave poses no further risks of charging compared to a surface mission and may in fact reduce it, but there is not enough evidence or current data to draw valid conclusions. A lunar study may provide a good analogue for assessing the risks of electrical charging and discharging on Mars for surface and subsurface exploration.

2.3 Cave Location Considerations

To determine the best possible location for a human habitat on Mars, specific requirements and points of merit have been assessed. This exercise is necessary to identify the specific precursor missions as well as likely sites where habitable caves can be found. The assessment of regions of interest with respect to the mission objectives includes:

- Volcanic regions with evidence of lava tubes
- The potential for ISRU such as the presence of water ice, natural energy sources and minerals
- Features of scientific interest

2.3.1 Volcanic Regions

Lava tubes and basaltic caves are common features in volcanic terrains on Earth. On Mars, the largest volcanoes and volcanic provinces are located in the Tharsis and Elysium regions (NASA, 2000). In particular, regions of pahoehoe lava flows, which are generally very smooth and billowy, are more likely to contain lava tubes (Mars Global Surveyor, 2009). Between the boundary of the northern lowlands and southern highlands of Mars is a low relief-shield volcano called Sytris Mons. These areas are of strong scientific value, particularly in the terrain of Nili Fossae, which contains abundant aqueous minerals (Milliken et al., 2008), and the giant Isidis impact basin. Other regions that might be considered in terms of scientific merit are the east part of Hellas Montes and Mawrth Vallis. Carbonates have been detected in a number of these regions (Ehlman et al., 2008; Boynton et al., 2009).

2.3.2 In-Situ Resource Utilization

The goal of ISRU is to use indigenous resources on Mars in such a way as to reduce the amount of material that must be brought from Earth (Meyer, 1981; Meyer & McKay, 1989; Sridhar & Miller, 1994; Sharma et al., 1999). Mass savings can translate into cost savings or extra available mass for scientific payload (Reynerson, 2004; Drake, 2009; Landis, 2009). The cost of developing and proving the capabilities of the ISRU system as well as the precursor missions necessary for locating the Martian resources and investigating their accessibility must be taken into account (Garvin, 2001; Cockell, 2002; Reynerson, 2004; Diaz & Ruiz, 2006; Drake, 2009). It is important to identify regions on Mars that have advantages for ISRU, as an input for both the regional and the cave site selection process.

ISRU has three main objectives (Drake, 2009):
1 - Using local resources to meet needs/requirements (example: making own food)
2 - Obtaining fuel to produce power for habitat and propulsion from local resources
3 - Developing and testing ability to repair and manufacture items with local resources only

Derived Products

The main products derived from ISRU discussed in this section are oxygen, water and methane to be used for life support systems, for fuel, or both (Drake, 2009; Hu et al., 2007; Santiago-Maldonado and Linne, 2007; Mungas et al., 2006; Accettura et al., 2004; Frankie and Zubrin, 1999; Sridhar. & Miller, 1994; Zubrin, 1994). The use of ISRU in the production of propellant changes many elements of a mission design. For example, an ascent vehicle could be sent with the capability of landing and producing its own propellant for return ahead of the manned mission, thereby reducing the total transportation mass required. *In situ* production of fuel also allows a level of flexibility in the mission; EVA rovers for example, would not be confined by a limited fuel budget (Drake, 2009; Hu et al., 2007; Santiago-Maldonado and Linne, 2007). *In situ* production of life support consumables such as water and oxygen is essential for an extended human presence on Mars (Drake, 2009; Sridhar and Miller, 1994; Meyer and McKay, 1989).

On Mars atmospheric CO_2 can be harvested by one of three methods to produce oxygen: solid oxide CO_2 electrolysis, reverse water-gas shift, or the Sabatier reaction (Drake, 2009; Santiago-Maldonado and Linne, 2007; Sridhar & Miller, 1994). Oxygen can then be combined with hydrogen (extracted from the Martian soil, or having been transported from Earth) (Drake 2009; Rapp, 2008; Hu et al., 2007; Mungas et al., 2006; Sharma et al., 1999;) to produce water. The efficiency of this process is increased if used to produce oxygen and methane for use as fuel for the Mars Ascent Vehicle (Drake, 2009; Hu et al., 2007; Mungas et al., 2006; Sharma et al., 1999).

The simplest method of producing water on Mars is by extracting it from surface and subsurface ice (Drake, 2009; Rapp, 2008; Meyer and McKay, 1989; McKay et al., 1993). The abundance and distribution of subsurface ice is discussed below. Viking mission data show the accepted average H_2O content of Martian soil is 3% by mass. Mars Odyssey mission data suggest that in the upper meters of the soil the H_2O content could be 8–10% (Drake, 2009). Regions rich in clays and hydrated minerals such as gypsum could even have a water content of up to 20 or 30% by mass (Drake, 2009). Extracting water from soil and minerals involves excavating the material, heating it and collecting the steam in a condenser (Drake, 2009; Mungas et al., 2006; Sridhar and Miller, 1994). The slag left over at the end of this process may be suitable for use in the production of building materials (Drake, 2009; Santiago-Maldonado & Linne, 2007; Mungas et al., 2006). The in-situ production of O_2, H_2O and CH_4 fuel may be best achieved through a combination of methods (Drake, 2009; Rapp, 2008; Hu et al., 2007; Sharma et al., 1999). The efficiency of the methods and resources used will depend on a delicate balance among mass, volume and power. The exact way caves can affect these processes is still uncertain, as currently little is known about the interior atmosphere or soil composition (Rapp, 2008; Drake, 2009).

Ice

Access to water will be essential for any manned mission to Mars. "Evidence suggests that Mars is water rich and may store the equivalent of a global ocean of water of about 0.5–1 km deep as ground ice and ground water within its crust" (Boyce, 2002). Sites from where water can be extracted include the polar ice caps, subsurface ice, water-bearing minerals in the soil and the atmosphere. Most regions of interest considered in this report are located away from the polar caps so the following sections concentrate on the distribution of subsurface ice. Above 30° latitude the average surface temperatures are low enough for ground ice stabilization but too warm for surface frosts. During opposition, in the lower latitudes surface and subsurface temperatures are too warm for water ice to stabilize and thus sublimation and diffusion processes occur (Boyce, 2002). Farmer and Doms (1979) assessed the stability of water-ice under present-day Martian conditions; they assumed a frost point of -75°C (198 K) and average Martian values for the thermal inertia and albedo. Where temperatures below the surface exceeded the frost point the water-ice tends to sublimate and be lost to the atmosphere (Carr, 1996).

The most obvious factor controlling the global distribution of ice is latitudinal position and hence temperature. The depth of subsurface ice increases as latitude decreases from poles to equator. The known occurrence of permanent ground or subsurface ice is currently restricted to latitudes pole-ward of approximately 40°. This distribution profile is limited however by the methods of detection currently available, for example, the Gamma Ray Spectrometer (GRS) on board the Mars Odyssey spacecraft can only detect ice to a depth of 1 m. The measurements of the GRS appear consistent with a simple two layer experimental model (ice-rich >60% volume regolith under a desiccated layer of variable thickness) which predicted depths of ~13cm near poles to ~50cm at 40°-50° (Boynton et al., 2002). Recent work however has suggested that these depths could be up to five times shallower than previously thought (Mellon et al., 2004). The Phoenix Mars mission for example found ice at a depth of 5 cm at 68° North (Smith et al., 2009). At latitudes lower than 40° the depth of subsurface ice is thought to increase sharply. This is concluded using experimental models with results that range in value from hundreds of meters to a few kilometers depth closer to the equator.

A further contributing factor is the thermo-physical properties of the regolith. The ability of the overlying rock to act as a reservoir for ice is largely dependent on the pore size. This is influenced by the grain sizes, amount of mixing and compaction. Barriers to water movement through the regolith include mineralization horizons, for example, salt layers that could have a pore-filling habit. Fine particles can also fill pores of a coarse matrix and fine dust can coat grains again making the pores smaller. Fine dust regolith can have low density and thus good pore size or it can become closely compacted. The low mass of Martian regolith and poor chemical weathering processes can prevent dust from compacting (Hudson, 2008). The rate of sublimation out of the reservoir is mainly controlled by the thermal conductivity of the material. Regolith can also act as an insulating layer protecting a deposit of ice from sublimation. If a layer is a dust/ice mix, sublimation results in the burial of ice under a dust layer of growing thickness (Kossacki et al., 2006).

Debris flows and terrain softening are the two most suggestive indicators that ground ice is present in parts of the Martian surface. Both are attributed to the slow creep of ice-containing materials, and both occur primarily in the 30° – 60° latitude bands, roughly where ground ice is expected to be stable and to have significant rates of creep (Kargel, 2004; Squyres, 1979; Lucchitta, 1984; Squires and Carr, 1986; Carr, 1996). This is mainly in four longitude bands: in the Mareotis Fossae region (50° – 90° W), the Acheron Fossae region (130° – 140° W), in the Phlegra Montes (180° – 200° W) and Deutoronilus-Protonilus (280° – 360° W). In the southern hemisphere they occur at the same latitudes, mainly around massifs on the rim of the Hellas and Argyre basins. Other possible indicators of ground ice are polygonal fractures that occur mostly in the northern plains, patterned ground that is observed in the northern plains, fracturing and flow e.g. 34° N, 212° W, the northern edge of the volcano Hecates Tholus, and thermokarst e.g. 23° N, 36° W (Kargel, 2004; Carr, 1996).

The potential for subsurface ice in a specific region is highly variable due to local topography, the heterogeneous nature of Martian regolith and the geological history of the region. Evidence for past glacial activity can indicate a higher chance for ice at a depth shallower than the average for that latitude (Hudson, 2008). The potential for accessible subsurface ice in different regions is summarized in Figure 2-6 and Table 2-1.

Geothermal Energy Sources

Geothermal energy from the interior of Mars is potentially a useful source of energy for human settlements. On Earth, geothermal electric power plants are extremely reliable and flexible and are able to supply energy in an almost continuous way. The use of geothermal energy depends on the existence of exploitable geothermal fields, and it is unclear if these exist on Mars. Two recent instruments, the Thermal Emission Spectrometer (TES) on board Mars Global Surveyor and the Thermal Emission Imaging System (THEMIS) on board the 2001 Mars Odyssey spacecraft were used to detect temperature anomalies on the surface of Mars. The results of these observations did not yield any important temperature anomalies on the Martian surface, thus there is still no evidence of useful locations for geothermal exploitation (Arizona State University, 2008a; Arizona State University, 2008b). Taking into account the uncertainty in the data available, we do not recommend basing site selection on geothermal capabilities. Selected places with possible geothermal characteristics can be of interest for scientific investigation. A map with places likely to have geothermal activity is provided in Section 2.4.

Mineral Resources

Some resources, rare or in high demand on Earth, may be accessible and possibly abundant on Mars. Some of these include sulphates, elemental sulphur, semi-precious gems like olivines, possible uranium deposits (brought to the surface by hydrothermal fluids from the deep subsurface), calcite and carbonates, amorphous silica (Woo et al., 2008), xenoliths, allophane and halloysite (Kempe and Werner, 2003) and zeolites. Zeolites are a group of complex clays (Boston, 2009) that can be used in water filtration, but if chemically modified could be used in any filtration system to filter out numerous different properties (Bowman et al., 1995). Uranium deposits could potentially be mined to help power the ISRU plant as well as the habitat but there is as yet no evidence for any such deposits and the processing of such materials (enrichment) would be beyond the capabilities of a first habitation (Boston, 2009).

Risks

The most obvious risk involved with the use of ISRU is potential failure of in-situ production systems for fuel and life support consumables. The consequences could be fatal (Drake, 2009). If resources are brought from Earth as a back-up to the ISRU system, this simply adds mass and reduces the effectiveness of the mission (Drake, 2009; Hu et al., 2007; Diaz and Ruiz, 2006; Garvin, 2001; Sharma et al., 1999). One solution may be to begin ISRU autonomously before the crew leaves Earth (Drake, 2009). Possible risks to the operation systems can originate from the atmospheric dust (Drake, 2009); the dust in the air may hinder proper functioning of ISRU equipment, as fans and filters may suffer clogging and/or abrasion. Although a major study of dust abrasion properties was conducted in the mid 1980s (Greeley et al., 1984) a better understanding of the properties of Martian dust is needed to avoid this problem, as well as careful study of the cave systems to see if dust would be as big an issue as on the surface.

Terrestrial and Lunar Analogs

Equipment and techniques to use for Mars ISRU will have to be field tested prior to departure; both Earth and the Moon can be used as testing grounds, as a lunar failure is easily recoverable (Drake, 2009; Rapp, 2008; Diaz and Ruiz, 2006; Rodriguez, 2004). There are important differences between ISRU on the Moon and Mars, the main one being the lack of an atmosphere on the Moon to test atmospheric extraction methods (Diaz & Ruiz, 2006). The extraction of oxygen and hydrogen from basalt is still theoretical and so the technology must first be developed on Earth and tested on the Moon to evaluate if it is feasible and energetically efficient for use on Mars missions (Rapp, 2008; Drake, 2009).

2.3.3 Atmospheric and Geological Scientific Merit

One of the recent results to have caused more scientific interest is the detection of significant amounts of methane in the atmosphere. This finding may be very relevant to biology and geophysics. Since methane is not stable in the Martian atmosphere, the source needs to be in the subsurface (Atreya et al., 2006). Other gases such as SO_2, H_2S and HCN have a subsurface origin and are of interest for further study. Cave habitats could allow humans better access to the subsurface for these investigations.

Main topics of investigation include potential for past or present life, water presence, crater records and ages of Mars, igneous processes, surface-atmosphere interactions, chemical and mineralogical composition of the crust, tectonic history and present activity, determination of processes of regolith formation, crustal magnetization, and impact effects on the Martian crust. Different regions are more suited to different topics, for example volcanic areas with lava tubes are suited to volcanology and resource geology. Therefore the geological scientific merit of a mission depends on the location of the landing site and exploration team (Mars Exploration Program Analysis Group, 2008). A human presence would ensure a more effective and optimized sample collection, increased efficiency and access to the near subsurface of Mars by drilling much deeper than the previous robotic missions, thus enhancing the understanding of the above stated topics. Besides drilling, other methods for obtaining information include in-situ analysis, meteorological monitoring stations, seismic stations, diverse sampling, ejecta sampling or magnetometer analysis (Mars Exploration Program Analysis Group, 2008; Mars Architecture Steering Group, NASA Headquarters, 2009).

2.3.4 Astrobiology

The primary scientific goal of ongoing space programs is the search for and characterization of life beyond Earth. This would be one of the main scientific goals of the first human mission to Mars. In that respect the search for life in lava tubes or other caves would be conducted at two different levels. First, precursor robotic missions would investigate the microbial habitability and potential for life in targeted caves. Second, humans on the Martian surface would have a longer range of operations and the capabilities to continue investigating caves, as well as surface environments during EVAs. This dual scientific and exploration approach would impact both astrobiology and planetary protection. Planetary protection will be discussed in section 2.5.1.

Radiation and Astrobiology

The damaging effect of ionizing radiation on cellular structure is one of the prime limiting factors on the survival of life in potential astrobiological habitats (Dartnell et al., 2007). As discussed in Section 2.2.1, there is an increased exposure of the Martian surface and subsurface to ionizing space radiation, compared to Earth. Thus, to undertake with optimum scientific return the goal of searching for life on Mars, it is important to consider to what extent space radiation can be a limiting factor on the regions where extant or dormant life might exist today on the planet's surface and/or subsurface. UV radiation can be considered a potentially damaging agent for organisms directly exposed to it, but modest layers of Martian dust, of even just a few microns, can give a good protection against this radiation (Cockell and Raven, 2004). As for ionizing radiation in the form of SPEs and GCRs, current simulations indicate that radiation levels on Mars (0.85 Gy/year on the surface, biologically-weighted dose) would not be lethal to microbial life as we know it on Earth, even to radiosensitive life and on relatively long time-scales (Dartnell et al., 2007), as shown in Figure 2-5.

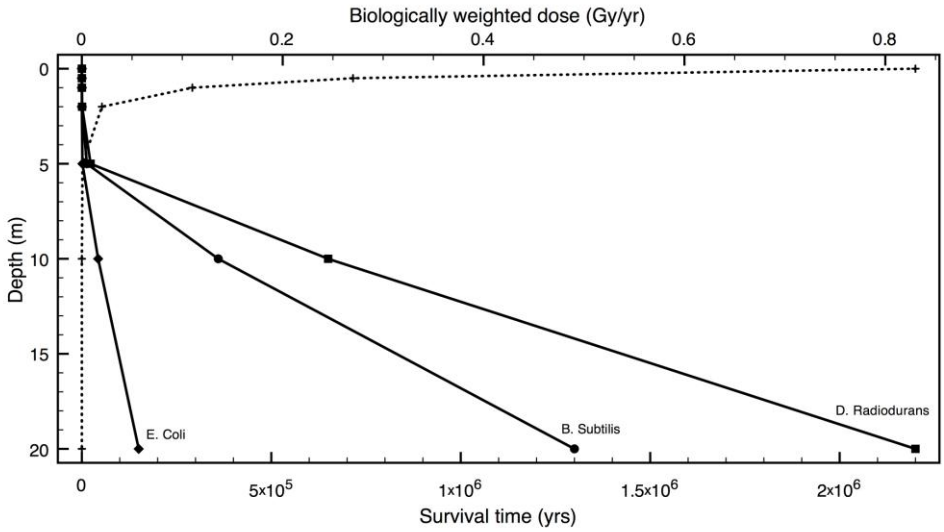


Figure 2-5: Absorbed dose with depth (adapted from Dartnell et al., 2007) Radionuclide decay of the regolith is not included. Microbial survival times, for dry homogeneous medium on Mars are also shown. Dotted line depicts doses; solid lines depict survival times for *Escherichia coli*, *Bacillus subtilis* and *Deinococcus radiodurans*.

On the surface or near subsurface, due to the present freezing conditions, most life (if it exists) will most likely have been in a dormant state over very long time-scales. If it lies dormant, normal cellular metabolic mechanisms would not have the opportunity to repair the accumulated cellular damage due to radiation, including damage from the intrinsic radioactive decay of the regolith (calculated at 4 x 10^{-4} Gy/year). In addition, the organisms would have the chance to reproduce, unless (for instance) episodic geothermal events allow transient bursts of metabolism and replication (Dartnell et al., 2007). Strictly from a radiation perspective, current models show that microbial life on Mars, and specifically metabolically active life, could survive quite easily close to the surface for thousands or even hundreds of thousands of years, and deeper into the surface for millions of years. For these longer time-scales the cumulative damage of intrinsic regolith radioactive decay would most likely render dormant life inactive, unless it is located in regolith-poor permafrost or in pure ice (Dartnell et al., 2007).

Given the strong astrobiological potential of caves and subsurface environments, (Boston et al., 2001) caves represent a scientific gold-mine. We recommend that precursor missions be strongly guided toward assessing the microbial habitability of the caves and the potential for extant life. The search for traces of extinct life would be a secondary objective of the precursor missions, since evidence for extinct life would not directly yield information about the nature of a Martian ecosystem. Precursor robotic missions would not only service upcoming human missions, but would have strong scientific value in themselves, and deeply impact our understanding of Mars. If microbial life were found to inhabit any or all of the lava tube caves tested by robotic precursor missions, then the scientific and planetary exploration communities would need to further debate the Committee on Space Research (COSPAR) Planetary Protection Policy (see section 2.5.1 in cave selection) before any further Martian cave activities could be undertaken (COSPAR, 2005).

2.4 Site Selection Process

Table 2-1 summarizes different considerations for site selection at various locations and lists sites of interest with particular mention of the evidence of caves, local resources, terrain and scientific merit. These sites and their surrounding regions of interest are shown in Figure 2-6 superimposed over a map of Mars. Final considerations regarding local environmental conditions such as wind speeds, dust storm frequencies, and temperature will need to be assessed through in-situ measurements for site selection validation. A global environmental variable not considered below is radiation. Higher regions of Mars experience less atmospheric shielding than lower regions and hence the surface radiation levels vary according to the altitude of the topography (Saganti et al., 2004). This may be of concern for all activities that take place outside the radiation shielding environment of the cave such as EVAs and rover excursions.

Table 2-1: Summary of Site Selection Considerations

Region Name	Evidence of Lava tube / Volcanic area	Ice potential	Scientific Merit (Geology)	Scientific Merit (Astrobiology)
Alba Patera	Yes - area with high concentration of lava tubes (Riedel, 2001)	High potential for shallow subsurface ice	Boundary of volcanic terrain and Northern Plains	Potential for organic molecules/cells preserved in ice (Steven et al., 2006)
Arsia Mons	Yes - identified lava tubes with skylights (Cushing, 2007; Christensen, 2007)	Possible subsurface ice core in lobed feature (Head et al., 2003)	Layered lava flows (Mouginis-Mark et al., 2008)	Potential for organic molecules/cells preserved in ice (Steven et al., 2006)
Elysium Fossae	Yes - identifed lava tubes (Wilson, 2001)	Possible subsurface ice remnents (Kossacki et al., 2006)	Extensive anicent fluvial activity (Plescia, 2003; Mouginis-Mark, 1985)	Unknown
Hellas Eastern Rim	Yes - lava tubes along the rim	Debris aprons and other geomorphic features indicate debris covered glaciers (Head et al., 2005)	Fluvial/glacial activity possibly continuing to present day (Kostama et al., 2009)	Potential for traces of life in water related minerals, (e.g. Cady and Farmer, 1996; Visscher and Stoltz, 2005)
Nili Fossae	Volcanic area with unknown potential for lava tubes	Unknown potential for shallow ice	Horst-graben structure, large area of exposed olivine (Hoefen, 2003)	Methane plumes of unknown origin and potential for traces of life in water related minerals (carbonates and phylosilicates) (Mumma et al., 2009; Mustard et al., 2008; Ehlmann et al., 2009)
Olympus Mons Northern flank	Yes - identified lava tubes (Sakimoto, 2008; Bennett, 2009; Richardson, 2009)	Small area of shallow subsurface ice (Bellucci et al., 2007)	Igneous petrology, recent glacial deposits	Potential for organic molecules/cells preserved in ice (Steven et al., 2006)
Syrtis Major Planum	Yes - indentifed lava tubes	Unknown potential for shallow ice	Igneous petrology, stratigraphy of lava flows, tectonic structures	Possibility for recent habitable conditions in impact induced hydrothermal environments (Fairen et el, 2009; Marzo et al., 2009; Cockell et al., 2003))
Tyrrhena Patera	Yes - identifed lava tubes (Greeley and Crown, 1990)	Unknown potential for shallow ice	Igneous petrology, stratigraphy of lava flows, anicent river channels on flanks (Gregg, 2006)	Unknown
Valles Marineris	No lava tubes - unknown potential for dissolution/tectonic caves	Possible subsurface ice and transient liquid water at depth	Access to geological strata, evidence of water-cut channels, landslides	Potential for traces of life in water related minerals (sulphates and phylosilicates), strong indications of magma/water interactions likely conducive to hydrothermal activity and habitable conditions (Dohm et al., 2009)

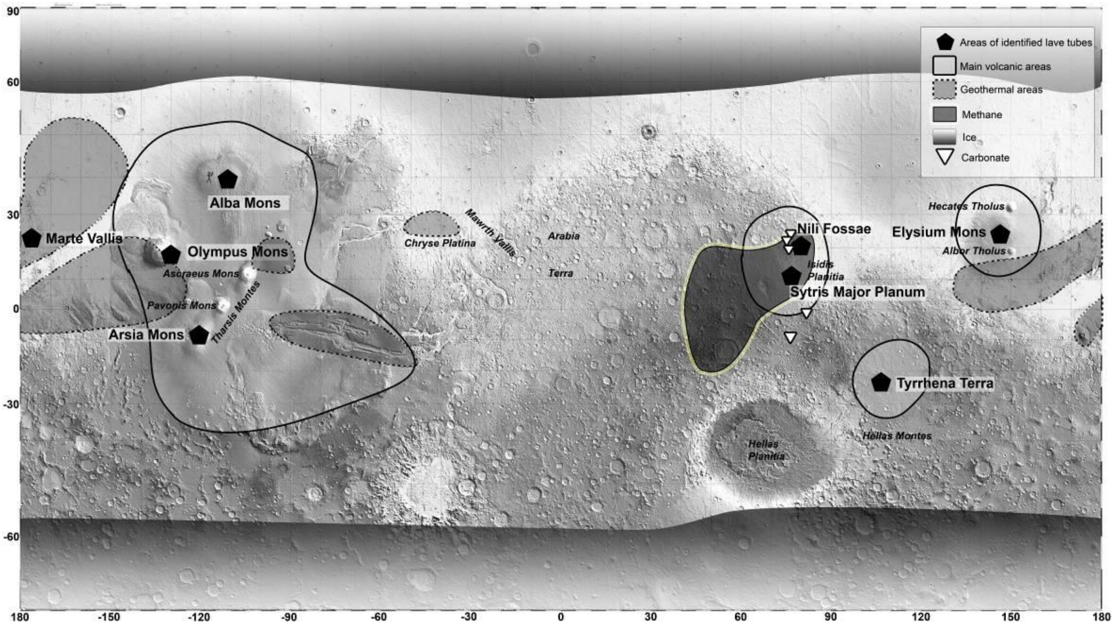


Figure 2-6: Mars map showing regions of interest.
Map: NASA JPL. Ice data from Mellon, et al., (2004). Geothermal data from Martyn (1996). Methane data from Mumma, et al., (2009), Carbonate data from Ehlmann, et al., (2009)

2.5 Cave Selection Processes

2.5.1 Planetary Protection

Precursor life-detection missions inside caves would service the upcoming human mission by directly addressing planetary protection concerns. The Committee on Space Research (COSPAR) is an international scientific committee focusing on international collaboration and information exchange in space research. In 2005, it drafted the latest version of the COSPAR Planetary Protection Policy that addresses planetary protection, with a focus on biological contamination and spaceflight. However, COSPAR policy is neither law nor state policy at present. Since Martian cave exploration is subject to COSPAR Planetary Protection Policy (COSPAR, 2005), careful instrument-sterilization and anti-contamination procedures would need to be implemented for each precursor mission. Since several areas of scientific interest have been recommended as good examples of landing sites in this report (all in close proximity to potential lava tubes), we recommend sending robotic precursor missions to lava tubes at more than one of these proposed locations. Having comparative data from several landing sites would increase the scientific value of the precursor missions, and would also help to ensure that the most effective cave selection is made. While ensuring the utmost care and attention to COSPAR Planetary Protection Policy, having preliminary exploration data from more than one lava tube cave on Mars would have the following important programmatic advantages: 1) If all caves explored are shown to harbor life, the scientific and planetary exploration communities would need to re-assess the follow up strategy for sending humans. Having multiple caves with indigenous microbial colonization could lead to the decision of turning caves and other sub-surface environments into “out of bounds sanctuaries”. Alternatively the presence of a widespread cave biosphere could be used as an argument to relativize the impact of humans on the microbial habitat. 2) If instead, some Martian caves are found to harbor either extant or extinct microbial life, while others do not, then one of the sterile caves might still be suitable for an initial human settlement. This choice would help minimize the chances of forward contamination of Earth-derived microorganisms to a microbial habitable environment and backward contamination of possible Martian organisms to a human crew. Furthermore, the establishment of a human habitat in a sterile cave would help uphold current COSPAR Planetary Protection Policy by providing some natural containment of human-associated contaminants.

A human settlement in a lava tube on Mars would in effect create a bio-geographical island scenario; a habitat suitable to human (and therefore microbial) life in the lava tube would be surrounded by the unsuitable self-sterilizing habitat of the Martian surface (Cockell, et al., 2000). In that respect, provided there are suitable and efficient sealing mechanisms, the natural confinement of caves would be of great advantage to constrain and control both forward and backward contamination between the human cave habitat and the surrounding regions of astrobiological interest. Caves could therefore be seen as contamination containment environments. This is in stark contrast to proposed surface habitation scenarios, which are more difficult to confine and isolate. These more likely sources of contamination and waste could propagate more easily to unexplored areas of the planet. Finally, if precursor missions determine that Martian lava tubes do not extend to great depths underground, then contamination between the potential human cave environment and deeper subsurface regions of interest would be minimized. In studying and exploring outer space, Article IX of the Outer Space Treaty (OST) requires that States avoid "harmful contamination" of the Martian environment, as well as adverse inter-planetary contamination on Earth. "Where necessary" the OST requires States to "adopt appropriate measures for this purpose." In practice, space agencies and industries have adopted standards for maintaining and preserving an extraterrestrial environment, as well as taking precautions for Earth's safety (e.g. containing the harmful lunar dust from lunar missions).

2.5.2 Desirable Cave Characteristics

Roof Thickness and Stability

- A roof thickness sufficient for the required level of radiation protection. *Refer to Section 2.2.1 Radiation*
- Large roof thickness to tube width ratio
- Minimal fractures in surrounding rocks or roof
- Minimal craters above the roof; no crater depth of 50% of the roof thickness or greater
- Habitats should not be constructed under or in close proximity to skylights to minimize rockfall risk. *Refer to Section 2.2.2*

Cave Accessibility:

- Large natural opening of sufficient size for inserting habitat, or easily enlargeable
- An open rille or major collapse pit entrance with a ramp-like structure without boulders that could impede access
- An area with a lava type that doesn't create a very rugged surface with a sharp structure, to minimize hazards to EVA suits and vehicles, e.g., a pahoehoe type flow
- Smooth and flat cave floor with no or minimal breakdown to be removed

Cave characteristics:

- In situ resources present in the cave or in the vicinity are desirable
- A lava tube that extends into a long and traversable network of tubes is preferable, to facilitate subterranean exploration and transport

Cave Width:

- The desired cave width will be an important consideration for cave site selection. This width will likely vary depending on the type of missions wanted. An analysis of what different lava tube widths can be used for is shown in Table 2-2

Table 2-2: Analysis of Lava Tube Widths

Lava tube width	Advantages	Disadvantages	Moon analogue?	Required technology
~200 m	Practically no space limitation. Has possibility of expansion up to city size settlement. In the future it might be possible to land directly into a large skylight.	Difficulty getting in and out of the lava tube.	Yes	Precision landing through a skylight requires a real time obstacle avoidance system
~30 m	Easy to get in and out. Possibility of closing off a section of the tube with a cave liner and pressuring it, if the settlement grows in the future.	Space limited, so no possibility of expansion to city size.	Yes	Development and testing inflatable habitats
~10 m	It is possible to use light weight cylinder-like inflatable habitat that uses the tube walls as the outer shell and insulation. Could lower mass of habitat. This idea has been tested on Earth. (Boston et al., 2004)	Requires significant advanced knowledge of the cave. Cramped space with no room for expansion. Difficult for initial settlement	Yes	Development and testing inflatable habitats

2.5.3 Remote Sensing Cave Detection

Whilst there is a lot of evidence for the existence of lava tubes on Mars, direct measurement of their location, size and entrances with Remote Sensing (RS) will be required before more detailed and expensive robotic precursor or human missions are launched.

Platform options

Remote sensing can be conducted from either a satellite or an aerial platform. Currently all remote sensing of Mars is conducted from spacecraft in orbit. This technology is well understood and relatively low risk and low cost compared to any other platform options.

Different types of aerial vehicles have been proposed for the exploration of Mars. Remote sensing for the detection of caves is required to take place over many different locations for long periods of time, meaning that one flight missions are not an option. Another desirable requirement for cave detection is the ability to guide the aerial vehicle. Two proposals meet both of these requirements. The first proposal is a helium-filled guided balloon as described by Pankine, et al., (2006). The second proposal is a solar powered vertical takeoff, fixed wing airplane described by Song and Underwood (2007). The balloon platform will orbit Mars at a 10 km altitude with the sensor and guidance system mounted at a 7 km altitude. It will travel with the prevalent winds in a west to east orbit around Mars, completing one revolution roughly every 10 days. The latitude of the balloon will be controllable with the guidance system mounted below the balloon. It is expected the balloon will be able to stay aloft in the order of 700 days and will be able to carry a payload of 35 kg (Pankine, et al., 2006). Some development has been done on this technology, in particular the Mars Balloon Validation Program, however the technology is still very much in its infancy and will require a significant design and testing period.

The vertical takeoff fixed wing airplane will fly at an altitude of 2 km for one hour, allowing it to cover 300 km before having to land and recharge its batteries (Song and Underwood, 2007).

The proposed airplane will only be able to carry a payload of 3 kg hence this design would have to be scaled up to be able to carry a significantly powerful sensor. While some work has been done on single flight fixed wing aircraft (Braun, et al., 2004), vertical takeoff rechargeable airplanes are currently entirely theoretical. As a result this design would require a lengthy and costly development period.

Compared to a satellite platform, both of these designs will result in a greatly increased mission cost and risk, due to development, testing and atmospheric insertion. The benefits an aerial platform can provide must outweigh these disadvantages.

Detection options

The two most promising methods for detection of caves are thermal imaging and ground penetrating radar (GPR).

Thermal detection of lava tubes is a means of detecting cave entrances and determining characteristics of the cave from the thermal variations of the entrance. The theoretical motivation for this detection method is due to the thermal regulation of the cave entrance as discussed in Section 2.1.2. Candidate caves are identified in the visible spectrum. The current RS capabilities orbiting Mars have sufficient resolution for this purpose (e.g. THEMIS visible camera with a resolution of 18 m or the High Resolution Image Science Experiment (HiRISE) with a resolution of 1 m). Once a candidate is identified, it is imaged in the thermal infrared spectrum over a period of time to confirm it is a cave. This technique is currently being used with the THEMIS and various visual sensors (Cushing et al., 2007; Wynne et al., 2008). The biggest problem with this method is the poor understanding of the processes that determine the thermal properties of a cave entrance. As discussed in Section 2.1.2, only very basic models of the thermal environment are currently used that cannot differentiate between a cave entrance and a pit in the ground. Data from cave entrances on Earth suggests that the difference between these two can be detected (Wynne, et al., 2009) and hence it should be possible to derive cave parameters from the thermal data of a cave entrance. Before thermal detection can reach its potential, a detailed thermal model of a cave must be developed and tested.

The second major obstacle is the spatial resolution of the thermal sensor. From Section 2.1.2, the lava tubes we are interested in are between 10–100 m in diameter. THEMIS is the only thermal sensor currently in Mars orbit and has a spatial resolution of 100 m (Cushing, et al., 2007), which is insufficient for these types of caves. Since the launch of THEMIS, a new technology known as a Quantum Well Infrared Photodetector (QWIP) has been developed. This technology is being used on the upcoming Landsat Data-Continuity Mission (LDCM) (Jhabvala, et al., 2009) and it is believed that spatial resolution on the order of 1 m is possible from Martian orbit, sufficient for cave detection (Wynne, 2009; FLIR Systems, 2009). For thermal detection there are two benefits of an aerial platform over an orbital one. First, it allows for far greater spatial resolution due to increased proximity of the sensor to the target. This would allow for thermal images of tens of centimeters as opposed to meters from orbit. Second, it allows for more data to be obtained for a site of interest as it can be revisited on demand. This is of great use as the thermal detection method relies on temporal information to distinguish between caves and anomalies (Wynne, et al., 2009). Given that the resolution of a thermal sensor in orbit should be sufficient for cave detection, these benefits probably do not outweigh the additional cost and risk of an aerial platform. Hence an orbital platform would be the best option for a thermal sensor.

Ground Penetrating Radar (GPR) is used to directly measure the cave itself. When an emitted radiation wave encounters a boundary between two electrically different materials, some of the radiation will be reflected. The boundaries of interest for cave detection are the roof boundary of basalt and air, and the air and basalt floor boundary. A GPR can therefore determine the dimensions and layout of a cave based on the timing of these reflections. In contrast with thermal imaging, the problems with GPR are very much on the technological side. The key parameters of a radar system are the vertical resolution, the penetration depth, the cross-track resolution and the along-track resolution. There is an inherent tradeoff when selecting the frequency of radiation between penetration depth, vertical resolution and spatial resolution. The higher the radar frequency, the better the radar can be focused, the better the vertical resolution, but the lower the penetration depth. The penetration depth can be increased by increasing the radar power (Skolnik, 2008). Two GPR instruments are currently in operation around Mars, the Shallow Radar (SHARAD) and the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS). Table 2-3 identifies the key parameters of each.

Table 2-3: Key Parameters of the MARSIS and SHARAD GPR Instruments (from Seu, et al., 2004)

	MARSIS	SHARAD
Frequency	1-5 MHz	15-25 MHz
Penetration Depth	0.5-5 km	0.1-1 km
Vertical Resolution	70 m	7 m
Cross-Track Resolution	15-30 km	3-7 km
Along-Track Resolution	5-9 km	0.3-1 km

As the caves of interest are expected to be between 10-100 m wide and up to 150 m deep, we require a penetration depth on the order of 200 m and a spatial resolution on the order of 50 m. The penetration depth restricts the frequency to being similar to that of the SHARAD instrument. As the spatial resolution of SHARAD is far too large, some form of focusing of the radiation will be required. At these frequencies, the large wavelength (on the order of meters) means we cannot focus the wave using a parabolic dish. This leaves the three options of directional antenna design, synthetic aperture data processing and decreasing the altitude of the sensor. Synthetic aperture data processing is currently used on both the MARSIS and SHARAD satellites to increase the along-track resolution by roughly a factor of five (Seu, et al., 2004). This would be useful if we could guarantee the satellite ground path crosses the lava tubes perpendicularly but this will not be the case. Directional antenna design could provide significant increases in resolution. SHARAD and MARSIS use a simple dipole antenna design (Seu, et al., 2004) and so there is room for improvement here. The downside to directional antenna design is the increased antenna mass required.

The altitude of the sensor could be reduced by moving from a satellite to an aerial platform. The size of the antenna required (on the order of meters) means that a fixed wing craft would not be possible; however it could be placed on a balloon. Using the SHARAD as a reference, this reduction in altitude would result in a spatial resolution on the order of 100 m. As noted above, this could be further improved through directional antenna design and synthetic aperture data processing. Hence moving to a balloon platform should give a radar sufficient penetration and spatial resolution to be able to detect caves. A balloon platform is therefore recommended as the best option for GPR.

Precursor mission recommendation

The above considerations have limited the precursor mission to either a satellite based thermal sensor focusing on the detection of cave entrances, or a balloon based GPR focusing on the direct detection of cave structure. Table 2-4 outlines the advantages, disadvantages and technology status for each. There is not a clear choice between the two, but the lower cost and risk of a satellite based thermal sensor along with its direct detection of a cave entrance probably make it the better option. A balloon based GPR could potentially be used as a follow up mission to map out caves identified by the thermal sensing. An important capability for the thermal sensor should be the ability for off-nadir pointing. This would allow for a greater range of coverage and for the detection of horizontal entrances, rather than just vertical.

Table 2-4: Satellite Based Thermal Sensor and Balloon Based GPR for Cave Detection Comparison

Mission	Cost and Risk	Detection Capability	Technology Status
Satellite based thermal sensor	Low - well understood technology	Direct detection of cave entrances. Inferred cave parameters.	QWIP technology is capable enough. Theoretical models need significant development and testing.
Balloon based GPR	High - untested balloon technology and atmospheric insertion	Direct detection of cave parameters. Can possibly search for entrances with orbiting visible sensors.	Radar technology is capable enough. Theoretical model well understood. Balloon technology requires significant development and testing.

2.5.4 ISRU Detection

This section describes the types of instruments needed for both precursor and future missions. The instruments are the ground penetrating radar (GPR), the mass spectrometer, the Alpha Particle X-Ray Spectrometer (APXS), the X-Ray diffractometer (XRD) and Mini-TES. As discussed in Section 2.5.3, the GPR can be used to detect different layers in the ground. This technique can be used for the detection of subsurface ice. As we are interested in accessible ice within ten meters of the surface, a high frequency GPR with a vertical resolution on the order of 1 m is required (Daniels, 2007). Specifications would require a radar frequency of 250 MHz resulting in a penetration depth of 5 m (Sensors & Software Inc., 2009).

Mini-TES (MER Spirit and Opportunity) is an infrared spectrometer which determines the mineralogy of rocks and soils from a distance by detecting their patterns of thermal radiation (Jet Propulsion Laboratory, 2009a). The Alpha-Particle X-Ray Spectrometer (APXS) used with the Mössbauer (Pathfinder 96, Spirit, Opportunity 2004, MSL, Exomars) is a device that analyses the chemical element composition of a sample from the scattered alpha particles and fluorescent X-rays after the sample is irradiated with alpha particles and X-rays from radioactive sources. The Mössbauer Spectrometer is an instrument that studies iron-bearing minerals to a high level of accuracy. This ability can also help understand the magnetic properties of surface materials. The APXS and the MB can share the electronics on board, as on MER rovers (Jet Propulsion Laboratory, 2009b).

A mass spectrometer (e.g. SAM – Sample Analysis at Mars on MSL) is an instrument which can measure the masses and relative concentrations of atoms and molecules. It makes use of the basic magnetic force on a moving charged particle (National Aeronautics and Space Administration, 2009a)

The X-ray diffractometer (XRD/XRF e.g.: CheMin on MSL) uses a versatile, non-destructive technique that reveals detailed information about the chemical composition and crystallographic structure of natural and manufactured materials. Past or present water activity on Mars will be revealed by the discovery and analysis of hydrated minerals, clastic sediments, hydrothermal precipitates and chemical sediments (Vaniman et. al., 2003).

2.5.5 Robotic Investigation

Following the remote satellite operations, the next step a robotic surface mission to investigate potential caves. Rovers similar to Mars Exploration Rover (MER) class could be sent to provide a near view of the cave's access and interior. The rovers could be human-controlled for high level decision and autonomous for low level decision. A 10 to 15 km range for the rover surface journey is envisioned. To acquire data, each rover will stay outside of each cave, act as a telecommunication relay and send one small autonomous reconnaissance vehicle (ARV) into the cave. The ARV may use aerial or ground based propulsion systems depending on the tradeoffs between cost, effectiveness and engineering complexity. Specific ARV examples are: wheeled or walking machines (Brian, 2004), tethered robots (Nesnas, 2008), hopping microbots (Boston, 2005; Dubowsky, 2008), rotorcraft (Young, 2002), and flying robots (Thakoor, 2002).

Our mission will include three or more MER class rovers, although the exact number of rovers needed will depend on the quality of the information provided by the satellite remote sensing.
The cave entrance is a major concern. It might be an unstructured surface with boulders and other debris. The robot's mechanism should be able to move in such terrain and deal with stability and traction issues. There can be different cave entrances varying from horizontal to vertical ones. Most rovers will experience difficulties with vertical caves, thus, for high steep or vertical entrances, tether rovers and aerials ARV may be suitable. Obviously, low steep or horizontal caves will be easier to access with leg or wheel-based rovers.

2.5.6 Precursor Mission Architecture

A proposed precursor mission architecture is shown in Figure 2-7.

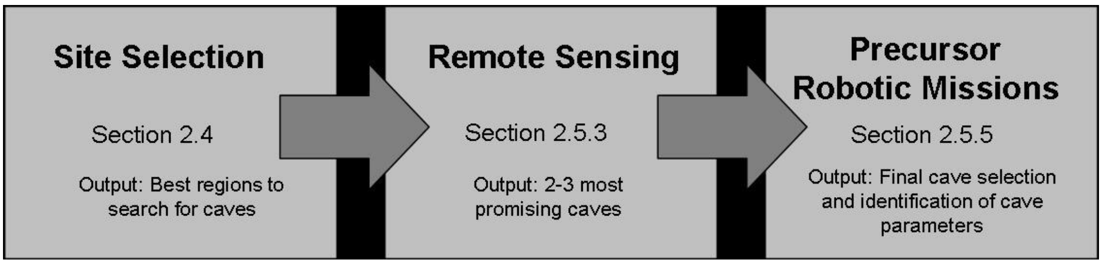


Figure 2-7: Precursor mission architecture

The most promising regions identified in Section 2.5 will determine the orbit of the thermal sensor recommended in Section 2.5.3. The data produced by this sensor, in correspondence with the desirable cave parameters identified in Section 2.5.2 will identify 2 to 3 of the most promising caves and cave entrances for further investigation. The MER class rovers recommended in Section 2.5.5 equipped with astrobiological instrumentation and ISRU instrumentation recommended in Section 2.5.4, will visit each of these caves. Based on the resulting data, the final cave for human habitation will be selected.

3 HUMAN CAVE PROGRAM

The programmatic, technical, and medical complexities of sending humans to a new planet are staggering. This chapter outlines the strategy recommended by the ACCESS Mars team to begin the journey to a new planet. The logistical aspects of sending both cargo and crew to Mars are identified. The requirements for both habitats and transport vehicles are described, with a focus on available materials. The problems of crew selection, training, and operations are analyzed in conjunction with a summary of critical and acute space medicine issues that need to be addressed, and if possible, overcome.

3.1 Description of the ACCESS Mars Reference Mission

Both NASA and ESA follow similar Mars mission scenarios (Mars Architecture Steering Group, 2009; Mongrad 2008). We will use the NASA and ESA scenarios with six crewmembers for a 540-day surface stay as the baseline for the ACCESS Mars design reference mission (AM DRM). The difference between the NASA/ESA reference missions and the ACCESS Mars reference mission is surface versus cave habitation respectively. Our reference mission will serve as a starting point for the consideration of alternative mission scenarios, which will vary in duration and number of crewmembers. This chapter and the following describe the social, technical, and programmatic aspects of the AM DRM. Chapter 5 details a comparative analysis with an alternative mission architecture proposed by ACCESS Mars known as the ACCESS Mars Extended Duration Reference Mission (AM EDRM). Figure 3-1 below gives an overview of the ACCESS Mars reference mission and specific descriptions of the required missions, operations, and analysis of this mission immediately follow.

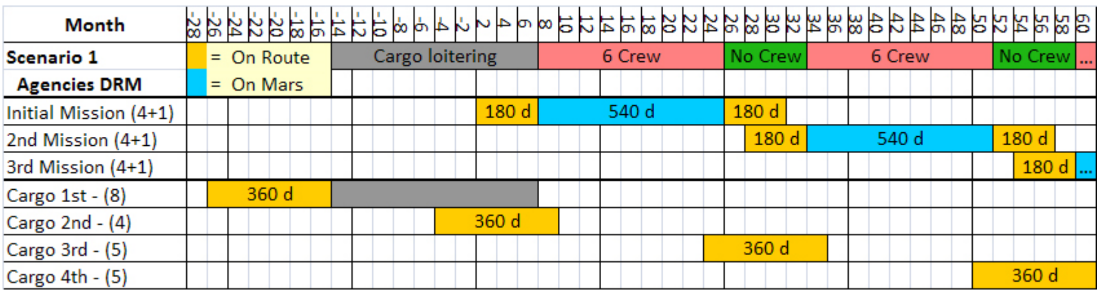


Figure 3-1: Timelines and Descriptions of ESA & NASA DRM and AM DRM

The success of both the AM DRM and the alternative AM EDRM depend on the robustness of missions, operations, and analysis protocol. The key elements of each of these three phases are presented in the following sections.

3.2 Missions, Operations, and Analysis

Mission aspects of the reference mission to Mars involve careful planning of trajectories to transport both human and material resources to another planet. The key targets for mission planning incorporate the crew and cargo transfer trajectory to get to Mars and constraints on the landing site selection. A cargo mass summary for transport to Mars without a crew will be identified.

3.2.1 Crew and Cargo Transfer Trajectory

All transfer vehicles will use thermonuclear propulsion because this option offers the best trade-off between thrust and specific impulse. Thermonuclear propulsion is needed for the crew transfer but can also be used for the cargo transfers. It is possible and more cost efficient to send cargo on a longer, low energy transfer to Mars using cheaper propulsion options. Chemical and solar electrical propulsion were considered as alternatives but have drawbacks in terms of launch. The chemical propulsion option would increase the total launch mass drastically because of the relatively low specific impulse whereas solar electric propulsion would increase the transfer times.

3.2.2 Constraints on landing site selection

Table 3-1 below gives the current AM DRM status, constraints, and necessary capabilities extrapolated from Braun (2006).

Table 3-1: Summary of Present and Future EDL technologies

	Max. Touchdown Mass (Metric Ton)	Max. Touchdown Elevation from Mars Laser Lunar Altimeter (MOLA) (km)	Technology Baseline
Current Capability	1	2	-Viking EDL technology
ACCESS Mars Constraints & Extrapolations	40	6	-Lift/Drag = 0.18 - 0.25 -Inflatable Thermal Protection System to lower ballistic coefficient -Powered supersonic descent -Supersonic (Mach 2.7) parachutes

Terrain, elevation, and limited maximum touchdown mass are the main constraints for landing site selection on Mars because of its thin atmosphere. This limits the amount and type of robotic equipment that can be deployed prior to human landing. To be able to land hardware for a human Mars mission with the adequate accuracy, the EDL capabilities have to be expanded to a 40 metric ton touchdown mass and to 6 km landing site elevation. This accuracy will require development of new technologies including vehicles using lift and an inflatable TPS to reduce g-loads and maximum heat flux on the vehicle. Other future solutions include powered supersonic descent and new supersonic parachutes to slow down the lander enough to land heavy payloads at high elevations. This improvement in technology will be useful when transporting cargo mass to Mars.

3.2.3 Cargo Mass Summary

The following table shows a mass summary and comparison between NASA and ACCESS Mars for the Descent and Ascent Vehicle Lander and Habitat Lander using data from the AM DRM. Given the touchdown masses outlined in the table above, the corresponding specific cargo launch masses are detailed in Table 3-2.

Table 3-2: Nuclear Thermal Rocket Launcher Manifest

Ares V Launches		NASA DRM	ACCESS Mars	
Launch Number	**Launch Manifest**	**Launch Mass (t)**	**Launch Mass (t)**	**Notes**
Cargo				
1	NTR Core Stage 1	96.6	96.6	same as DRM
2	Cargo Lander	106.1	106.1	same as DRM
3	NTR Core Stage 2	96.6	96.6	same as DRM
4	Habitat Lander	113.8	113.8	same as DRM
5	Twin In-Line LH2 Tank	93.2	93.2	same as DRM
6	NTR Core Stage 3		96.6	
7	LH2 Tank		46.6	
8	Cave Lander		99	
Total Cargo Mass		506.3	748.5	
Cargo Mass Increase			242.2	
% Increase			47.838	
Crew				
1	NTR Core Stage 1	96.6	96.6	same as DRM
2	In-Line LH2 Tank	91.4	91.4	same as DRM
3	Drop Tank	96.0	96.0	same as DRM
4	Crew Payload	108.0	108.0	same as DRM
Total Cargo Mass		392.0	392.0	

As can be seen from Table 3-2 above, the ACCESS Mars DRM requires three extra launches as compared to the NASA DRM because there is a 47% increase in launch mass. This extra mass is a direct result of the differences in infrastructure required to establish a cave habitat versus a surface solution. Therefore, two of the launches are required for the core delivery system into orbit via the NTR Core Stage 3 and LH2 Tank, and the other launch is required for the cave lander payload. A mass summary for the cave lander payload is provided in Table 3-3.

Table 3-3: Cave Lander Ares V Content

Manifested Item	**Quantity**	**ACCESS Mars Scenario 1** *Mass (tons)*	**Notes**
Cargo Rover	1	12000	See Robotics and Cargo Section in 3.4
Main Habitat	1	20000	See Habitat Section in 3.5
Descent Stage (wet)		23300	
Aeroshell		43700	
Total IMLEO Mass (tons)		**99000**	

To summarize, the addition of a cargo rover and the cave habitat infrastructure increases, the total mass of the ACCESS Mars reference mission is 32 tons heavier than the cargo of the NASA DRM.

3.3 Mission Operations

The real-time operations of both in-orbit and on-surface tasks follow suit once the cargo and payload are launched into space. The operational aspects of a human settlement on Mars are complex and multi-disciplinary. Lessons learned from ISS are applied to outline a new approach, which can be broken down into two groups of operations: Mars-Mars and Earth-Mars as described in the following sections.

3.3.1 Operations Concept

The Mars Control Center (MCC) for Mars-Mars operations consists of one main room in the habitat. From there, vital equipment is monitored and problematic conditions are flagged. All Telemetry (TM) flows directly or indirectly to the MCC and then is relayed back to Earth. Habitat real-time status and triggered alarms are echoed in strategically-placed displays throughout the habitat. The MCC is highly automated to reduce surface/sub-surface support.
One Earth Mission Control Center (EMCC) and one Back-Up (BU) center for Earth-Mars centralizes and displays all TM from the habitat and deployed equipment. Given the light round-trip delay of 8-44 min (NASA 2006), real-time crew support cannot be applied. Crew on Mars is essential for monitoring key parameters and responding to malfunctions.

3.3.2 Operations planning

Three phases of operations planning have been identified, with different approaches as outlined as follows. Robotic precursor missions can be conducted in the same fashion as current Mars robotic missions. Earth based mission control centers can direct robotic rovers to perform exploration tasks. The habitat construction phase is a complex operation that must be carefully sequenced to reduce the risk of potential failure. During the routine operations phase, the Mars crew will be operating in a more autonomous manner, with Earth personnel assisting in troubleshooting system anomalies, monitoring system telemetry for signs of degradation and keeping track of necessary preventive maintenance. Scientific results and samples will be sent to Earth for further analysis by Earth-based scientists.

3.4 Robotic Transportation Solutions

We anticipate that the main habitat and the cargo surface transportation system (CSTS) will be sent to the surface of Mars once a landing site is selected. The robotic cargo will land within 7 - 10 km away from the selected site, based on current experience with Mars rover missions. The main issue is transporting the habitat in a rover over long distances in an extreme environment.
The CSTS rover has to be designed with a heavy payload capacity because of the large habitat mass.

Based on the specifications of the nuclear power generator for the habitat (discussed in 3.7) and previous NASA and ESA mission profiles, the CSTS rover will weigh around 8.5-12 metric tons. The CSTS should be capable of robotic, manual, and remote teleoperation, especially during the construction phase of the cave habitat. Operators located on Earth should remotely control transfer from the landing site to the selected lava tube. Furthermore, in subsequent missions, the complexity of the rovers can be increased to better accommodate needs of the crew within the cave. After deploying the habitat, the CSTS rover could be re-used as a general purpose unpressurised vehicle for medium to long range EVA missions.

3.4.1 Human Subsurface Transportation

The potential mobility architecture for subsurface exploration may include unpressurized and pressurized rovers and a variety of robots that can navigate over rough terrain. Aerial and climbing robots can be used to travel lengthy distances in caves, explore hazardous subsurface terrain, and study sites of scientific interest. Autonomous robots, such as microbots (Boston, 2005), and flyers (Thakoor, 2002), may easily be used for sensing, telemetry, and reconnaissance missions. Therefore these microbots are advantageous in confined cave environments. Table 3-4 presents the advantages and disadvantages of the proposed vehicles for subsurface exploration.

Table 3-4: Comparative Analysis of Potential Vehicles for Subsurface Exploration

Type	Advantages	Disadvantages
Microbots	-Small and lightweight -Collective group behavior -Low power consumption	-Fundamental limitations of component technologies in extreme environments -Laboratory and field demonstrations of key technologies still required -Payload limitations
Flyers	-Small and lightweight -Low power consumption -Adaptive control and reconfiguration	-Fundamental limitation of component technologies in extreme environments -Limitations for long-range missions Payload limitations
Small Rotorcrafts	-Simple and field-tested solution -Human/Robotic symbiosis	-Small operational radius -Relatively high-energy expenditure -Payload limitations
Medium-Large Rotorcrafts	-Large payload capacity -May be human operated -Human/robotic symbiosis	-At conceptual design level -High-energy expenditure -Complex engineering solution

The performance of the unpressurized surface mobility architecture is not limited by energy storage capabilities of the vehicles or by the subsurface environment, but by contingency constraints and limitations on EVA capabilities (Hofstetter, 2008). For longer excursions, a pressurized rover might be a better approach given greater autonomy than unpressurized rovers. Table 3-5 presents the robotic specifications for subsurface exploration.

Table 3-5: Robotic Specifications for Subsurface Exploration

Type of robot	Mass	Payload (% of Total Mass)	Range	Peak power	Cost
Flyers	0.650 – 25 kg	~10	10 – 1000 km (cooperatively)	~40 mW	$500-$3000
Medium - Large rotorcrafts	1000 – 2750 kg	10	225 km (110 km radius from home base)	N/A	N/A
Microbots	150 g (100-1000 units are needed for a mission)	60-70	60 hops of 1.5 m (0.009 km/h)	1.5 W	N/A

Analog terrestrial sites (deserts and lava tubes) provide risk-free and affordable environments to test, operate, and evaluate the performance of robots, rover systems, and the overall precursor mission profiles. Issues like robotic communication and navigation and ways through which humans can effectively use mobile robots for cave or scientific exploration could be tested.

3.5 Habitat Program and Layout

A temporary habitat (on-surface, which is the DRM surface habitat) is to be deployed to house the first humans on Mars and allow them to establish the primary habitat inside the cave. This temporary habitat can be powered using the nuclear power systems delivered with the primary habitat. The complete habitat requirements will be one initial surface habitat, delivered on site by precursor cargo mission and verified as functional prior to launch of the crew, capable of supporting the crew during construction of the primary cave habitat.

Existing mission typologies and analogue design habitats provide insights on future requirements involved in a new mission environment such as the caves on Mars. Four such habitats are described in Table 3-6.

Table 3-6: Summary of Mars Reference and Analogue Habitat

	NASA Mars Design Reference Mission (DRM)	Flashline Mars Arctic Research Station (FMARS)	Mars Desert Research Station (MDRS)	Mars Base 10
# Intended Crew	6	7	6	10
Total Habitable Area (m²)	41.2	77	84.1	248.5 (542.5 with Greenhouse)
Total Pressurized Volume (m³)	198	258	281.7	571.9 (1747.9 with Greenhouse)
Total Pressurized Volume per person (m³/person)	33	36.8	46.9	57.2 (174.8 with Greenhouse)
Description	Expanded from Lunar design Includes 2 drop-locks, 1 suit lock	7 crew Mimics time delay of Mars communications Similar size to DRM	6 crew Similar size to DRM	10 crew Closed Life Support System

Compiled from (Drake, 2009; Osburg, 2004; Gregory, 2007; Doule, 2009)

It should be noted that the NASA DRM habitat is based on a 1.5 multiple of the proposed lunar habitat size (Drake, 2009). A Mars mission will last up to three times the length of a Moon mission. This extra duration was not taken into account when sizing the Martian habitat. The 50% increase in crew size was the influencing factor. Therefore the feasibility of a Mars habitat just 1.5 times the size of a lunar habitat is cast into doubt.

3.5.1 Effects of Cave Environment on Habitat Program and Layout

When fitting existent habitat designs to cave specific conditions, we identified several key changes to the program and layout. In each case, there is a rigid structure and exterior shell designed to withstand both Martian weather phenomenon and high radiation conditions caused by SPEs and GCRs. When the habitat is moved into a cave, the threat of radiation is removed. The lightweight inflatable structure is only required to support itself, which is a primary advantage in housing a habitat in a naturally sheltered environment (Hörz, 409). With no rigid structure required, the habitat can transform from multiple stories to a single story, allowing for more interior freedom and the possibility for continued spatial reorganization over the course of a long duration mission. This is desirable as it may prevent monotony within a confined space over time.

Though the program and required zones of the habitat may not change from surface to cave occupation, the accessibility of both interior and exterior spaces of the habitat will increase. Fewer environmental hazards will allow increased access to exterior lab zones, robotics, and other exploration applications. One aspect that changes greatly when moving the habitat into a cave is the view outside any fenestration. However, the fenestration will be small due to engineering constraints. By removing the crew from the landscape they originally came to explore and placing them in a dark, cavernous space, feelings of confinement and claustrophobia increase. This may affect the success of the mission. It is therefore important to consider this factor when organizing recreational spaces in the habitat to increase the feeling of spaciousness. An artist's rendition of the primary habitat is shown in Figure 3-2.

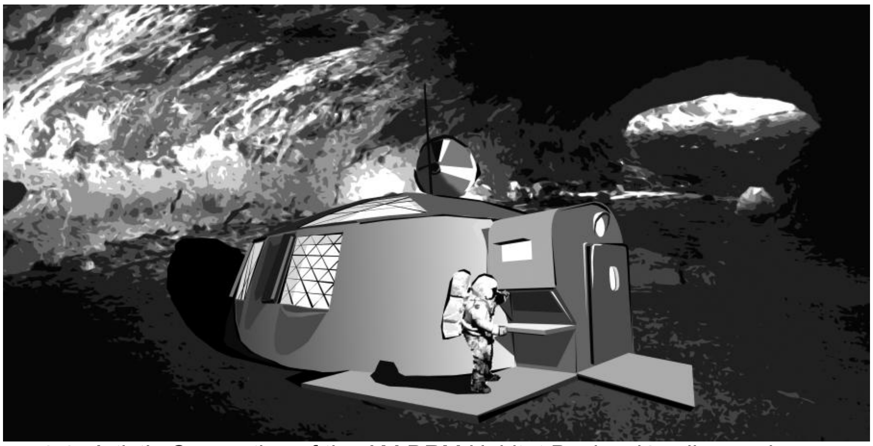


Figure 3-2: Artist's Conception of the AM DRM Habitat Design (Credit Reggie MacIntosh)

3.5.2 Effects of Cave Environment on Habitat Area Allocation

As was shown in Table 3-6, habitat area and volume varies a great deal between the example habitats. Where the focus of Mars Base 10 is human comfort and a Closed-Loop Life Support System (CLLSS) the volume of NASA Mars DRM is determined heavily by current launch load capacities, an Open-Loop LSS (specifically with food), and a requirement to achieve the most effective delivery of mission requirements in the least amount of launches. FMARS and MDRS are also not focused on a CLLSS. It should be noted that mission durations within the FMARS project bases are limited to durations of two to three weeks and while the provided volume may be adequate for a short duration mission, it may not when the mission is close to 2 years in length, or longer. It is important to keep in mind that the success of a mission is reliant on a crew that is kept safe and comfortable in a secure habitat. They must feel "at home" enough that they are able to perform their duties without the threat of major conflict between crewmates caused by undesirable habitat conditions. In addition, lighting plays a significant role in allowing crewmembers to feel comfortable in a confined and dark environment. An artist's conception of the habitat interior is shown in Figure 3-3.

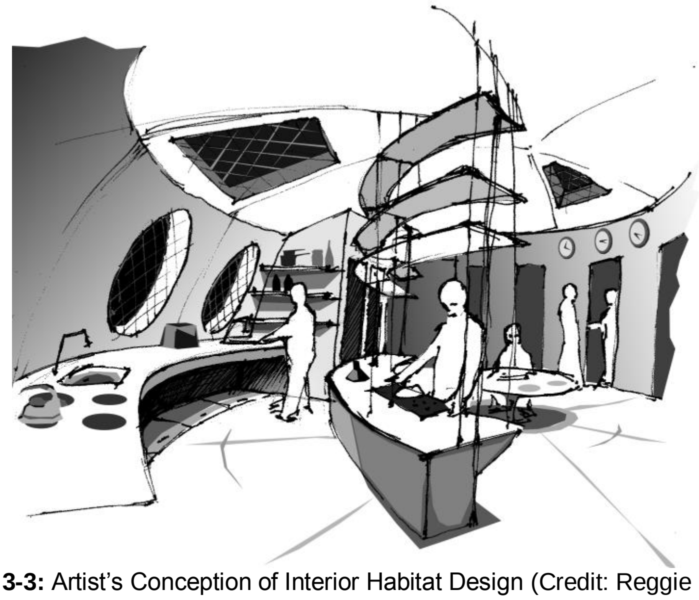


Figure 3-3: Artist's Conception of Interior Habitat Design (Credit: Reggie MacIntosh)

3.5.3 Lighting Design & Daylight

Lighting design and requirements differ depending on the individual task. Visual comfort, visual performance, and visual ambience are the three fundamental features to be combined for good quality lighting design (FGL, 2004). The cave will require emergency lighting to ensure tasks can be continued or postponed safely if a power failure occurs. The recommended illuminance for specific tasks is available from the "IESNA Lighting Handbook" (NASA, 2006). Supplementary lighting will be required in the cave to ensure the required illuminances are maintained for both day and night. A Digital Addressable Lighting Interface (DALI) system will be used to ensure maximum energy efficiency and provide appropriate integration between electric lighting and daylight in the cave. The DALI system includes light sensors that control the lamp output depending on the available daylight and occupancy, which maintains the required illuminance with artificial lighting (CEN/TC 169, 2002).

If crewmembers do not receive sufficient daylight during their missions, they could experience disturbances in their sleep/vigilance, mental and physical performance, and metabolism (Wolf, 2009). Simulating daylight in the cave will be an important factor for humans to live and work in a healthy in a cave environment. Glazing material should maximize the illuminance and minimize the harmful radiation while being able to withstand the harsh environment (Eckard, 1994). By using other technology (e.g. fiber optic cable, light tubes), natural daylight will be utilized effectively and efficiently in the cave while ensuring the safety of the crew from radiation.

3.5.4 Structure Types

There are currently several types of construction technologies useful for a human habitat on Mars. Lunar and Mars analogue environments also consider many of these technologies. A detailed analysis of these habitats aids in understanding the most favourable structural design options. Inflatable structures are collapsible pressure vessels deployed on-site and consisting of a membrane-like fabric. Metallic self-erectable structures deploy on-site and unfold in order to form a pressure vessel. These metallic structures have also been proposed for lunar bases (Eckart, 1999). Metallic and composite modular structures assemble manually on-site and are a more conservative approach. Brick and concrete construction from ISRU (Kozicka, 2007) utilizes local Martian soil, requiring only machinery brought from Earth. Soil blocks with ISRU (Kozicka, 2007) are cut from larger blocks before use in habitat construction. A final option for an OCH is Underground Tunnels (Kozicka, 2007), which would require either heavy tunnel boring machines, explosives, or a combination of both. Using these available materials, different configurations of habitat designs can be considered and are described below.

Comparative Analysis of Habitat Design Concepts

Table 3-7 outlines a comparative analysis between the different types of potential habitats on Mars. The types of habitats are the lava tubes, and the artificial caves or surface habitats, either rigid or inflated. The habitat designs developed thus far are mostly focusing on the lunar environment. Both the Moon and Mars are taken into consideration because they have common elements.

Table 3-7: Comparative Analysis Between Different Types of Habitat

Advantages	Disadvantages
Lava Tube: Pressurized pneumatic habitat within a natural lava tube.	
- Readily available radiation shielding (§ 2.1) - No excavation required (Boston, 2003) - Lightweight construction (Boston, 2003) - Structural stability (§ 2.1) - Scientific merit (§ 2.1) - Expandable within cave network (Boston, 2009) - Potential access to underground resources (§ 2.1) - Deeper drilling capability (Boston, 2009) - Natural stable temperature environment (§ 2.1.2)	- Location specific (§ 2.1) - Limitation for landing site (§ 3.2.2) - Limitation for mobility and access to surface resources (§ 2.1) - Fixed entry way (§ 2.1) - Precursor mission needed (§ 2.2)
Artificial cave: Pressurized pneumatic habitat within an excavated cavity.	
- Readily available radiation shielding (§ 2.1) - Lightweight construction (Kozicka, 2007) - Flexible size and shape (Kozicka, 2007) - Flexibility of location (Kozicka, 2007) - Flexibility of entry way (Kozicka, 2007) - Expandable through excavation (Burke, 1985; Schrunk, 2008)	- Risk of cave instability (Boston, 2009) - Difficulty in excavation (Land, 1985) - Heavy drilling equipment required (Boston, 2009) - Labor and time intensive (Boston, 2003) - Hazardous efforts (Boston, 2003) - Size limited by excavating equipment (Boston, 2003)
Rigid surface habitat: Preassembled habitat covered with regolith for protection.	
- Flexibility of location - Easily expandable (Land, 1985; Johnson, 1999; Ruess, 2006; Beneroya, 2008) - Modular sections (Johnson, 1999; Ruess, 2006; Beneroya, 2008)	- Radiation shielding difficult because of thick regolith requirement (§ 2.1, Land 1985) - Heavy structure required for regolith support and shielding (Johnson, 1999; Boston, 2003) - High cost due to large mass (Land, 1985) - Labor intensive (Land, 1985; Boston, 2003) - High risk operations (Boston, 2003) - Canopy relies on regolith property assumptions (Ruess, 2006)
Inflated surface habitat: Pressurized pneumatic habitat covered with regolith for protection.	
- Flexibility of location - Easily expandable (Land, 1985) - Lightweight construction (Boston, 1981)	- Radiation shielding difficult because of thick regolith requirement (§ 2.1, Land 1985) - Labor intensive (Johnson, 1999; Boston, 2003) - High risk operations (Boston, 2003) - Canopy relies on regolith property assumptions (Ruess, 2006) - Hazard of habitat collapse from depressurization (Johnson, 1999; Land, 1985)

The main arguments for using lava tubes are their readily available radiation protection and rapid use for habitation, where no labour intensive and hazardous excavation will be required (Boston, 2003). Based on Table 3-7, we recommend using lava tubes with a pressurized pneumatic interior. Although this will require more investigation through precursor missions for site selection, the initial establishment of the habitat poses lower risk to crew and leaves more time for accomplishing key scientific and exploration objectives.

From precursor missions as described in Section 2.5.3, specific lava tube locations, nearby accessible resources, and terrain will determine the ultimate feasibility of their use. Future habitats following the initial settlement will most likely be constructed from Martian materials as described in Sectio by Zubrin (1996) and Lin (1985). Such habitats have not been considered in this comparative analysis as enormous infrastructure and significant in-situ experimentation will be required before this is possible.

Comparison of Mass and Volume

The cargo mass specifications outlined in previous sections determine the allowable masses for the habitat structure and all supporting systems. To come to a reasonable estimate for ACCESS Mars mission masses, the system masses - as specified by the Lunar Database, The Lunar Base

Handbook, NASA's Lunar Architecture Team (LAT), and the NASA/ESA Mars DRM - were all consulted. The AM DRM will use the same mass definitions as these existing architectures except for the radiation shielding and specific habitat structure type. The mass of the radiation shielding was assumed negligible because shielding is not required in a cave environment. The structural mass of the habitat was calculated using approximate values for the volume, wall thickness, and density. Data from the Mars DRM, LAT reference missions, and AM DRM are included in Table 3-8.

Table 3-8: Comparison of Mars DRM, LAT, and ACCESS Mars Habitat Mass and Volume

Habitat Element	Mars DRM (C&TC) Mass (kg)	LAT Mass (kg)	AM DRM Mass (kg)
Structures	8174	5679	1225
Protection	863	489	0
Power	599	646	599
Thermal	785	445	785
Avionics	222	169	222
Life support	2767	2554	2767
Suit Locks	964	582	964
Outfitting	8966	246	8966
Science Equipment	1200	5679	1200
Sub Total	24540	10810	16728
Growth (20%)	4908	2162	3345
Total	29448	12972	20073

As can be seen from the tables, the total mass of the primary cave habitat is 20 tons, which is lighter than the Mars DRM. As stated previously, to establish an initial settlement, we will use one surface habitat and one cave habitat.

3.6 Thermal Systems

The thermal (and power) buses are additional systems necessary for both cave habitation and Martian exploration. Thermal control systems are used to maintain temperatures inside the cave habitat and during exploratory activities.

3.6.1 Rover Thermal Control

Rovers must possess thermal control systems to keep components within recommended operating temperatures given variable temperatures. Rover subsystems often have different operational and critical temperature limits (Charles Phillips, 2002), further complicating this task. On the Martian surface, special thermal coatings will provide protection from the harsh environment (Daniel P. Thunnissen, 2004). The main difference when operating in caves is the more stable thermal environment, which allows for a smaller range of operating temperatures compared to the surface. This smaller temperature range simplifies component design.

3.6.2 Habitat Thermal Control

Thermal control systems designed specifically for the Martian environment will provide temperature management so that humans can inhabit caves. The thermal control system must maintain the environment temperature between 18-24°C (De Rose, 2003) for comfortable habitation. In contrast to surface habitations, the sub-surface environment is characterised by constant temperature with a minimum amount of wind. The thermal control system for subsurface habitats will not need to protect against fluctuating external climates, as is the case for surface missions (De Rose, 2003).

Coatings, paints, fans, multilayer insulators, louvers, fluid loops, heat tubes, and radiators are possible technologies that can be used to maintain habitat temperature (De Rose, 2003). Coatings or paints on the habitat are required in order to enhance temperature retention because the nominal cave temperature is below -50°C. Due to the low ambient temperature, convective heat transfer to the surroundings will be dominant, so heating will be required within the habitat (Moran & Shapiro, 2004). In the event that excess heat rejection is required from the habitat, a system of fluid loops and radiators will be used due to their power efficiency and low maintenance. Fans can be used to maintain a uniform, comfortable atmosphere within the habitat, by removing hot spots around equipment and ensuring proper ventilation.

3.7 Power Systems

Reliable power systems are required to run human life support systems in the cave habitat. The cave environment offers radiation protection, limited solar illumination, and practically no wind influences as compared to the surface. Several power systems can operate above and/or below the surface. The optimization of power systems will be a trade-off between reliability, limiting intermittent generation and distribution, and ease-of-access. Table 3-9 lists the advantages and disadvantages of various power sources as they apply to both rover power systems and habitat power systems. This table will be used as a reference for making recommendations for both habitat and rover power systems as discussed in the following subsections.

Table: 3-9: Advantages and Disadvantages of Power Sources

Power Source	Advantages	Disadvantages	A	B	C	D	E
Primary Batteries	-Cheap,reliable, full-time operation -No energy capture required	-Very short lifetime -Low power output	-	-	-	-	-
Solar power and Secondary Batteries	-High reliability -Mature technology -Renewable energy	-Low efficiency and large area -Degradation and damage -Intermittent power generation -Need to transport solar arrays	R	S	-	-	-
Solar power and RFCs	-Renewable fuel -Lower array area required	-Degradation and damage -Intermittent power generation -Need to transport solar arrays	S	-	R	R	R
Wind Energy	-Renewable energy	-Low atmospheric density - -Large structures required	-	-	-	-	-
Geothermal	-High efficiency -High reliability	-No proof of concept (Arizona State University, 2009a; Arizona State University, 2009b)	-	-	-	-	-
Nuclear Fission and Nuclear RTG	-Optimal for large-scale, high-power missions -Full-time operation and long lifetime -Compliments nuclear propulsion -High reliability	-Ethical and safety concerns -Radiation shielding -Low specific power	-	-	S	S	S, R
ISRU	-Sustainable energy source -Long lifetime -Abundance of fuel	-Insufficient knowledge and access to resources -New technology	-	-	F	F	F

A: Surface rovers D: Human transport vehicles -: Not suggested
B: Microbots E: Habitat R: Suggested redundancy
C: Cargo delivery rovers F: Future concept for settlement S: Suggested solution

Habitat Power Systems

We recommend using nuclear fission power systems for habitats because of their long lifetime, high power output, and mobility. Solar panels and RFCs can be used for smaller systems in the primary habitat. The preliminary habitat can also be powered using the nuclear power systems delivered with the main habitat.

The first Mars Reference Design Mission prepared by NASA (Weaver & Duke, 1993) merely stated a 160kW nuclear reactor would cover all ground-based power requirements. Hoffman and Kaplan (1997) revised this requirement to two 160kW reactors for hot-standby redundancy. The work by Strategy and Architecture Office, ESA (2008) quotes habitat modules at a maximum of 30kW, closer to Huckins & Ahlf (1994)'s estimation of the ISS habitation module at 12.5kW. The work of Mars Architecture Steering Group, (NASA Headquarters, 2009) investigates quantitative power requirements, as outlined in Figure 3-4. This also included a breakdown of subsystem requirements based on different phases.

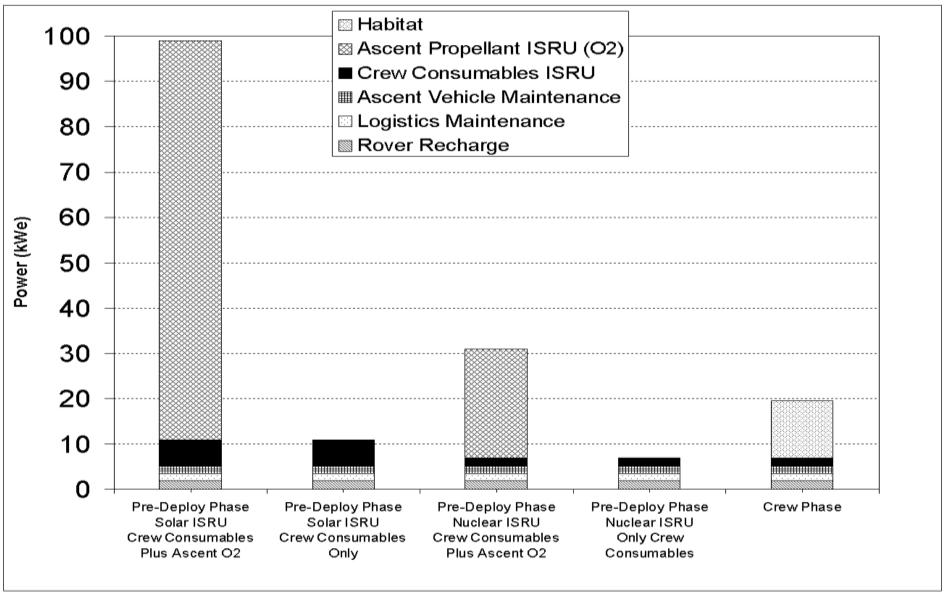


Figure 3-4: Quantitative Power Requirements

The foreseen increase in power requirement at night for a surface habitation is avoided due to the thermal protection offered by the cave because the cave temperatures remain relatively constant. Physical protection offered by caves reduces the extra load on environmental processing during dust storms. The power consumption of extra lighting in caves is minimal.

3.7.1 Martian Exploration Power Systems

Our recommendation for surface rovers is to use photovoltaics for energy capture as on past Lunar and Martian surface missions (Jet Propulsion Laboratory, 2009). RFCs are also proposed, since they provide increased efficiency and require lower solar array area. Rechargeable secondary batteries will provide redundancy.

The recommended power systems for microbots are primary batteries for very short duration excursions or solar cells and secondary batteries for longer mission lifetimes, as the technologies are fully developed and ready for implementation on precursor missions.

Cargo delivery robots require very high power levels and long life-expectancies so nuclear RTGs are recommended, given sufficient radiation protection. Nuclear RTGs provide up to 10kW of power (Wertz and Larson, 1999) for over a decade, do not rely on solar illumination, and are recommended for use on large-scale rovers. They also allow long sorties and can act as mobile power systems. Since such vehicles are likely to operate both above and below the surface, solar panels with RFCs can also be used as a redundant power system able to recharge during surface operations. This power system architecture is also suitable for use on human transportation rovers.

To improve power supply technology for future missions, two long-term solutions are proposed. The first involves the development of ISRU technologies to generate power both above and below the surface at any time of day regardless of wind conditions. This would lead to the establishment of a sustainable power supply and reduce launch requirements. Power generated using ISRU could be applied to second-generation vehicles (i.e., those beyond the scope on initial settlement). The second solution proposes the setup of nuclear RTG or ISRU power generation outposts. Outposts would be capable of recharging a fleet of second-generation vehicles, which would rely only on secondary batteries and could be used for long term excursions into cave systems.

3.8 Communications and Navigation

Communications can be split into four main areas: In-Transit, Mars-Earth Link, Mars Communication Network, and Subsurface. Navigation can be divided into surface and subsurface.

3.8.1 In-Transit Communications

During the Earth-Mars cruise, the Deep Space Network (DSN) (NASA, 2009c) will provide the spacecrafts with basic telemetry, tracking, and communications (TT&C) through an X-band link (50-500 kbps) and high-data-rate communications through a Ka-band link (350 kbps-6 Mbps). A laser based communication system (Boroson, 2004) has also been foreseen as a mean of achieving high-data-rate transmissions (10-100 Mbps). Independent of the type of system used, the round-trip delay depends on the distance between the planets, ranging from 8 minutes to as long as 44 minutes.

3.8.2 Mars-Earth Link

An important factor to consider is the time the communications are blocked during solar conjunction. Measurements from the European Space Agency (ESA) during the Mars Express mission show that a conventional S-band radio link with a Mars orbiter may suffer an outage as short as four days in favourable, solar minimum conditions (Reboud, 2006). For an optical communications system, however, the outage is expected to last longer (approximately 25 days) as the telescopes and other hardware must be deactivated to prevent damaging the equipment when the Sun-Earth-Mars angle is less than 3° (Boroson, 2004). Different solutions have been considered to improve the communication capabilities of future Mars missions (Bashin, 2001a). Mid-to-far-term solutions include Mars orbiting MicroSats (for communications and navigation purposes) and Aerosynchronous Mars Orbit (AMO) communications satellites (for monitoring and relaying). To increase the availability and capacity of the DSN, Earth orbiting relay stations are also being considered. Finally, one or more relay satellites could be placed at Earth-Sun Langrangian points (L4 or L5) to prevent solar conjunction outages and ensure a permanent Earth-Mars link for human missions.

3.8.3 Mars Communications Network

There are three types of communication networks that can be deployed on the surface and in the vicinity of Mars. These are: access networks, inter-spacecraft networks, and surface networks (Bashin, 2001b). These networks include all possible wireless (radio or optical) communication links from all vehicles situated within a relatively short range of the surface.

The access network interconnects all exploration units deployed on the surface of Mars (out of cave habitat, rovers, humans, aerial vehicles) with the spacecrafts in orbit. The inter-spacecraft networks are ad hoc networks (decentralized networks) that interconnect all spacecrafts clusters (constellations) orbiting Mars that require the exchange of information for cooperative actions. Finally, the surface network manages the data interlinks for surface exploration units (out-of-cave habitat, landers, robots, rovers, aerial vehicles, and sensors) in an ad hoc fashion.

3.8.4 Surface Navigation

A compass will not work on Mars because there is no magnetic field. However a Global Navigation Satellite System (GNSS) will. This solution requires the deployment of a satellite constellation to obtain partial (four satellites) or full (seven satellites) positioning on the Martian surface. It would also take a long time until it is completely set up and fully operational so this solution may be unfeasible for near-term missions (Dabrowski, 2007). Instead, a GPS-based local area positioning system (Lemaster, 2003a,b) can be deployed using an array of pseudolites (pseudo-satellites) as ground emulators of GPS satellites, providing an accurate positioning with a centimeter level precision. This system is simpler and less costly than the constellation solution and allows precise navigation and positioning in bounded areas of exploration (i.e., within a certain area around a cave or lava tube entrance.) This GPS system would not be suitable for longer distance excursions as the required number of pseudolites increases to a point where it is no longer cost effective.

3.8.5 Subsurface Communications

Deploying a reliable and relatively simple communications network in a Martian cave or lava tube may not prove to be an easy task. A wireless ad hoc solution may be preferable, but a few factors must first be considered as the underground environment is known to be adverse to radio frequency (RF) propagation (multipath fading).

For a Mars expedition, different subsurface communication solutions must be investigated prior to the mission in analogue Earth locations. In the study of Boston (2003), a simple multi-hop wireless network was deployed in a cave in New Mexico. Off-the-shelf equipment was used to establish a wireless link between two laptop computers. Acceptable results were obtained, but occasional drop outs and variable traffic speeds were experienced. This proof-of-concept experiment showed that the reliability of an underground link is highly dependent on the shape, size, and configuration of the environment. For example, if a bend in a tunnel blocks the line-of-sight link, the signal will be degraded and potentially lost if the distance is too great. This increases the complexity of the design, as caves and other natural subsurface locations are uniquely shaped. The solution adopted for the mission robotics is to set up an ad hoc wireless network using the explorers as communication relays to the operator (human or main robot). The link between the in-cave units and the Mars orbiting satellites will be carried out by the operator placed at the entrance of the cave or lava tube.

Extensive research is ongoing in the underground mining industry to mitigate some of the issues mentioned before. Consequently, various spin-off and spin-in opportunities are foreseeable (advanced antennas, self-deploying and autonomous systems, underground worker safety).Comprehensive propagation measurements campaigns have also been undertaken by various research groups. For example, measurements in an old gold mine in Val-d'Or, Canada (Boutin, 2008), have already established that underground communications are unlike conventional indoor communications (inside buildings). Moreover, the propagation channel seems to be frequency selective (i.e., electromagnetic waves of diverse frequencies interact differently with the surroundings.)

In this perspective, future Mars subsurface communications assets should also be tested in analogous Earth locations and, if possible, in Mars-like environmental simulators (simulated basalt walls, carbon dioxide atmosphere). Ideally the testing of subsurface communication technologies should be a mission milestone during the Lunar program.

3.8.6 Subsurface Navigation

For early human missions, precise subsurface navigation and positioning may not be as critical, especially if the area to cover is limited and there is full communications coverage. For crew safety purposes, a simple and cost-effective tracking solution would be to use small wearable devices that send beacon signals to the subsurface communications system to provide periodical location updates.

In the mid-to-far term, as the habitat expands and the underground exploration intensifies, an advanced underground communications and navigation system should be implemented using self-deploying, self-recharging, and self-repairing robots (Boston, 2003) to establish an in-cave cellular network. Additionally, other solutions based on latest advances in indoor positioning techniques and technologies should be adapted to subsurface navigation.

The needs for subsurface navigation will vary as the mission progresses. At first, autonomous robots will most likely be used to explore caves or other subsurface environments. Various exploration algorithms will therefore be implemented to accommodate different mission objectives (cave mapping, resource localization, and so on). Once again, the mining industry could provide valuable knowledge in this field as various solutions have already been investigated in past studies. Unfortunately, at the moment, most existing autonomous underground navigation algorithms assume a prior knowledge of the environment such as a map of the area to navigate (e.g., Bakambu, 2007).

Different sensors (visual, sonar, infrared, laser) are used to navigate robots in indoor environments (Sikking, 2004). For cave exploration, a laser based device such as a LiDAR would seem to be the best solution as it has a greater range than infrared, it is faster and less sensitive to atmospheric changes than sonar and it does not require an external light source as a visual sensor would. It does require more power and data; either way, these sensors can be combined with an internal inertial navigation system (accelerometers and gyroscopes) and odometry sensors to improve position awareness and track the path travelled by the robot.

3.9 Life Support Systems

As a consequence of the long-term nature of a Mars mission, the mass of Life Support Systems (LSS) can comprise a large portion of the payload and propulsion costs (Drysdale, 2007), therefore their mass should be optimized. Additionally, the challenges and opportunities presented by the choice of caves as habitat shall be addressed in this section.

3.9.1 Human Requirements

While LSS may take many forms, human requirements remain essentially invariant, as indicated by Figure 3-5. NASA's DRM (2009) aims to minimize mission dependency on resupply from Earth with no feasible options for rescue and recovery and two layers of functional redundancy are recommended. The DRM also proposes having untested options, with low Technology Readiness Levels (TRL) to be used as second backup to guarantee crew safety. Since closing the LSS loop can significantly reduce mission payload, physical/chemical, bioregenerative, and ISRU techniques are considered. We propose the testing of bioregenerative approaches on the ISS and the Moon to qualify them as primary systems on a Mars mission.

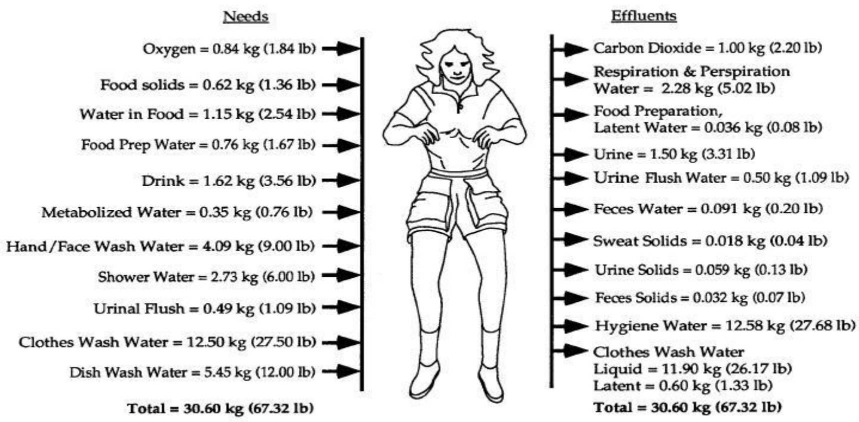


Figure 3-5: Human Input/Output Requirements (Kubieck & Woolford, 1995)

3.9.2 Atmospheric Management

Air Composition & Pressure

To eliminate the need for a pressure suit to be worn by crewmembers in the cave, it is desirable to have the habitat total pressure and partial pressures within the Constellation program recommendations (NASA, 2006), indicated in Table 3-10. If the selected cave's diameter is small enough, cave walls can be used to naturally bear habitat pressure (Boston, 2003).

Table 3-10: Constellation Program Atmospheric Pressure Requirements (NASA, 2006)

Type	Total Pressure	ppO$_2$	ppN$_2$	ppCO$_2$
Lower Bound (kPa)	51.711	18.616	10.332	-
Upper Bound (kPa)	103.421	23.442	82.793	0.666

Since argon and nitrogen are readily available in the atmosphere, they can be used as a buffer gas to pressurize the cave upon elimination of CO_2 by compression and cooling (Boston, 2003). The energy intensive nature of argon/nitrogen separation has led to proposals on studying the biological effects of breathing Argon by humans. If it is found to be safe, energy required for this process can be conserved. However, altering the cave's atmosphere must not violate planetary protection guidelines, particularly if life is found to exist inside.

Air Revitalization (CO_2 removal and O_2 generation)

The use of caves also has an impact on CO_2 removal strategies. For example, Temperature Swing Absorption is characterized by low-power operation by exploiting the diurnal temperature fluctuations of the Mars surface which span 70° Celsius (Boston, 2003). Since temperature fluctuations are absent inside the cave, more energy would be required through active heating and cooling. Alternatively, equipment could be located on the surface at the cost of its subjection to radiation effects and micrometeorite hazards. The Sabatier reaction is an attractive option, because of its exothermic conversion of CO_2 into CH_4 and H_2O (Murdoch et al., 2005). Testing this method on the ISS and the Moon can help increase its TRL for Mars use. Cave typology could help satisfy ventilation requirements indicated in Table 3-11.

Table 3-11: Constellation Program Ventilation Requirements (NASA, 2006)

Ventilation Rates (m/s) – Measured 0.15 m from habitat walls	
Lower Bound	0.079
Upper Bound	0.610

If it is a horizontal cave, conventional approaches may be sufficient. For vertical caves, however, the high density of CO_2 coupled with gravity of Mars may result in CO_2 and trace contaminant concentrations at the bottom of the habitat. CO_2 partial pressure must therefore be monitored and controlled via fans, ducting, or valves (Aponte et al., 2002).

3.9.3 Water Regeneration

While 100% water closure is not currently feasible, various techniques for water reclamation can be used to close the water loop; an example being the Sabatier process used for CO_2 reduction. While dehumidification of Martian air requires large volumes of air and high energy (30 kW-hour/kg H_2O), the choice of caves as habitat may improve this method's feasibility (McKay et al., 1986; Boynton et al 2006). Other ISRU techniques can be used to recover water from the surface layer, as well as cave ice (if found) (Garvin, 2001). Planetary protection guidelines would need to be respected, as the cave may contain microbial life. Water reclamation through processing of urine and feces is discussed in the next section. Alternative means –not specific to caves- include Zirconia Electrolysis Cell Units, Water Vapour Electrolysis and biosystems (Aponte et al., 2002).

3.9.4 Waste Management

Waste management in the context of caves would not be significantly different from surface approaches, with methods of choice being mostly a function of mission duration and food closure (Drysdale, 2003).

Any waste to be dumped must first be sterilized to avoid forward contamination through terrestrial micro-organisms, as caves are more likely to bear life than the surface (Hogan et al., 2005). Once sterilized and packaged, it is recommended that caves be considered as potential storage sites for waste packages, as an alternative for leaving them exposed on the Mars surface or stored permanently inside the habitat for containment purposes. In terms of water recovery, drying, pyrolysis or other physiochemical processes can be used on biologically decomposable solids (faeces, urine, hygiene water..etc) (Aponte et al., 2002). Electrolysis could then be conducted to yield O_2 and H_2, with the resulting H_2 feeding the Sabatier process for the CO_2 reduction subsystem. Since bioregenerative systems are suggested inside the cave, the ability to process large quantities of inedible biomass is of importance. Suggestions for using biomass for the production of sugars, single cell oil or crops have been suggested in literature and would reduce the food payload burden and so should be further investigated (Strayer et al. 1900, Hunter et. al, 1997).

3.9.5 Food Supply

With open-loop dry food requirement for a 6 person crew being 6.84 kg/day, a 550-day stay on Mars would require 3,762 kg of food (Messerschmid & Bertrand, 1999). Bioregenerative approaches therefore become desirable to increase food closure and reduce payload. In the context of cave habitation, a sub-surface greenhouse would require more artificial lighting than its surface counterpart. In addition, energy requirements for a sub-surface greenhouse would depend on plant species and whether daylight is integrated into the design. The scale of the greenhouse would be determined on mission length and crew number. For reference, a crew of 5-6 it is expected that 40 m² of plant growth will be required for producing 25% of the food mass (Drysdale et al., 1993). In conclusion, advanced bioregenerative life support systems designed to grow food and regenerate water and air in Table 3-12 while helping the recovery of the waste are strong candidates for a long term human mission to Mars.

Table 3-12: Requirements and Productivity of Higher Plants (Scott C et al., 1992)

Plant Requirement Values		Plant Performance Values	
Parameter	**Amount**	**Parameter**	**Amount**
CO_2	40-300 g/m²/day	**O_2**	30-220 g/m²/day
Water	5-10 kg/m²/day	**Transpiration water**	5-10 kg/m²/day
Minerals	10-100 mg/m²	**Edible biomass**	20-40 g/m²/day
Lighting period	8-24 h	**Inedible biomass**	4-20 g/m²/day
Lighting power	13-170 W/m²		

Lighting for greenhouse and food supply

There are lamps designed specifically for the photosynthesis process. Photosynthesis occurs between 400nm and 700nm (PAR area) on the electromagnetic spectrum. The PAR value is measured in micromole per second (μmol/s). The higher the PAR value per Watt, the more efficient the light source is for plant growth. This is the only reliable way of measuring if a light source is suitable for growing plants (Philips &Verhoeven, 2002). PAR meters are employed to measure how much useful energy is entering the greenhouse. Artificial lighting can supplement the natural light to maintain the PAR if it's required (L .Ellington, 2003). Different plants require different levels of PAR and it is fundamental they have the suitable requirements. A control system can be employed to integrate with a life support system. High pressure sodium (HPS) lamps are dominant in present horticultural applications. LEDs are currently under ongoing research for the use in horticulture due to their high efficiency, longer lamp life and low mass (Drysdale, 2008). The available daylight into the Martian greenhouse depends on the site location and typology which is explored in 'Advances in space research 41' (J.Kozicka, 2008).

3.10 CREW

3.10.1 EVA Scenarios and Planning

Extravehicular activities (EVAs) will play a very important role for the initial settlement in caves on Mars. The main activities performed during the first settlement will involve building the habitat, performing science and exploration, with a particular emphasis on the search for life. Therefore, EVAs will be performed both inside the cave system and on the Mars surface. Considering the overall reference mission with 550 days on Mars, different tasks will require four different EVA scenarios to achieve mission objectives involving either on-foot or rover activities on the planet and inside the caves.

3.10.2 EVA Inside Caves

EVAs will be performed in both the habitat cave and in adjoining cave systems for surveying and mapping purposes. This will allow crewmembers to explore caves to search for life and any other entrances or zones for future cave habitation. Some of the caves selected for the habitat could be very large and a rover will be required for transportation. EVAs on foot will include construction and maintenance of the cave habitat and conducting nearby experiments.

3.10.3 EVA outside Caves

The EVAs conducted outside the caves will focus mainly on the search for other caves, areas with in-situ resources, and conducting scientific activities. Exploration missions to search for caves several kilometers away from the main habitat will require rover EVAs. An important factor for rover EVAs is the access to the cave. Depending on the entrance orientation (horizontal, vertical, or diagonal), different strategies and equipment will be considered for the EVA. The frequency of each EVA scenario is summarized in Table 3-13.

Table 3-13: Frequency and Duration of EVA In Each Scenario

Scenario	Duration	Frequency	Critical Path (Time)	Min. Path (Time)
Rover inside other caves	10-15 days, with maximum 8 hours inside other cave	1-2/month	720h/month	240h/month
Rover inside main habitat cave	1-5 days	4-5/month	600h/month	96h/month
Foot inside cave	2-8 hours	3/week	24h/week	6h/week
Rover outside cave	10-15 days	1-2/month	720/month	240h/month
On foot outside cave	2- 6 hours	3/week	18h/week	6h/week

Each EVA will be performed by two or three crew members on a rotational cycle (exposing each crew member to the same amount over the mission duration) to limit radiation dose and physiological consequences during the mission. EVAs will be carried out on average every two to three days; however, the frequency of on-foot EVAs inside the cave may be once per day. Since radiation levels are low inside caves and crewmembers inside caves will be very close to the main cave habitat, the EVA frequency can be increased.

The EVA spacesuits worn by crewmembers will be designed for both the inside and outside cave scenario to accommodate for comfort, flexibility, radiation levels, and probably of penetration by debris. There should be six spacesuits in order to perform activities simultaneously inside and outside caves, with two back-up suits. Requirements for a cave-suitable spacesuit will include more lightweight materials and the ability for resupply and recharge even in the dark cave environment. The spacesuits will require more maneuverability within the cave environment because of space constraints. Therefore, the flexibility of the spacesuit and mobility of the gloves used for performing tasks inside the cave are the most important parameters. The main requirement of spacesuit design suitable for cave exploration will be to increase the mobility by adding a waist joint that provides forward bending abilities, hip joint with two degrees of freedom (flexion-extension and abduction-adduction), an ankle joint with two degrees of freedom, and a new knee joint (to support climbing or crawling in caves)(Abramov I.P., 2003).

To prevent leaks, a separate fabric layer could be added to the ortho-fabric layer (Christiansen E.L., 2001). Still, the high frequency of EVAs can increase the probability of contamination. A method to avoid planetary contamination is using suitports rather than a STS or Transit Airlock (Cohen M.M., 1987). Suitports facilitate detachable spacesuit ingress and egress from the habitat via a sealed hatch (NASA, 1989). Suitports also offer additional advantages for contaminant isolation and control, whereas common airlocks require decontamination before entering the airlock (Cohen M, 1995).

There is little information in existing literature concerning the medical effects of regular EVAs on Mars. To try and gauge these effects one must take into account health risks identified in previous design reference mission, which indicate that physical capabilities of crew are reduced during long-duration missions. This has implications for the ability of the crew to conduct EVAs. [R.S. Johnston 1977] have recommended 300 EVAs as a maximum for a 500 day surface stay. Simulations show that EVAs induce a 1.5% added risk of an arrhythmia or heart attack [A Perez-Poch 2006]. This risk will remain constant regardless of the duration of the mission if adequate aerobic exercise regimes are performed. To minimize the stress applied to the body it is recommended that most EVAs take place during the first months of the mission.

Radiation exposure during EVAs is a major concern. The Martian atmosphere cannot provide adequate radiation shielding for crewmembers. Crew radiation dosage must be continuously monitored, especially during EVAs (Benghin et al., 2003). Crewmembers on an EVA could receive a fatal dose of radiation from an SPE if they fail to find appropriate shelter (Managing Space Radiation Risk in the New Era of Space Exploration [MSRRNESE], 2008). The worst SPE to date occurred in 1959 with a proton fluence greater than 30 MeV (Space Radiation Hazards and the Vision for Space Exploration [SPHVSE], 2006). Dangerous SPEs occur one to three times per 11 year solar cycle (CERSSE, 2008). To prevent such a catastrophe a warning system is necessary to provide crewmembers on an EVA adequate time to seek shelter during an SPE. Consequently, any EVA must incorporate a fully operable communications infrastructure both interior and exterior to the cave system. Such a system could utilize the Moon as an initial test-bed. We recommend that future missions survey and map local underground cave systems to allow crewmembers to find shelter in locations other than the main habitation cave in the event of an SPE during an EVA.

The differences in the total radiation absorbed per crewmember for a cave habitation scenario versus a surface habitation scenario were calculated. The sum of the radiation absorbed inside the cave, inside the rover, and during an EVA yields the total dose of radiation for the 540-day reference mission. Table 3-14 summarizes our results. Any absorbed radiation in-transit was not included in the calculations because this value is independent of habitation scenario. The maximum surface radiation level was estimated using data acquired from the Mars Radiation Environment Experiment (MARIE) instrument (NASA, n.d.). The measured data indicates a worst-case surface radiation estimate of 200 mSv/year.

For routine exploration activities, previous lunar spacesuits provided about one quarter reduction in radiation dosage (NASA, n.d.). This level of shielding was assumed for all Martian EVA spacesuits in our calculations. It is expected that the Mars excursion vehicle will provide a one-twentieth reduction in surface radiation (NASA, n.d.). Caves reduce primary radiation to a negligible value for depths between 2-3 meters as indicated previously in this report. The background radiation within the cave was taken to be 0.8 mGy/year (Morthekai et al., 2005).

From Table 3-14, it is evident that for the cave scenario, the total cumulative radiation level is lower than the radiation absorbed during surface habitation. From our calculations of the ACCESS Mars reference mision, crewmembers absorb 14.8 mSv of radiation given 24-hour days on the surface. Comparatively, crewmembers only absorb 0.012mSv of radiation during constant cave habitation. Current estimates indicate that crewmembers absorb 1.21Sv of radiation during a 600-day swing-by mission to Mars (Cucinotta et al., 2006). Performing a ratio of these rates for the 360-day in-transit time for the ACCESS Mars reference scenario yields a 726mSv in-transit radiation dose. This verifies that in-transit radiation absorption rates are orders of magnitude larger than both surface and cave habitation absorption rates. Any successful mission to Mars will require advancements in radiation countermeasures for mitigating the harmful in-transit effects. These countermeasures are less critical on the planet because cave habitats provide adequate radiation shielding.

Table 3-14: Radiation Path Time and Total Absorbed Cumulative Radiation Dose

Scenario	Path Time	Total Cumulative Radiation Dose (mSv)
Surface Mission	24 hours per day	14.795
Cave Habitat	24 hours per day	0.012
Minimum EVA on Foot	6 hours per week	2.653
Maximum EVA on Foot	18 hours per week	7.936
Minimum EVA in Rover	240 hours per month	4.939
Maximum EVA in Rover	720 hours per month	14.795

Possible radiation countermeasures can be used to mitigate the harmful effects of both acute and chronic radiation exposure. Chronic radiation doses can be mitigated by incorporation of naturally occurring radioprotective compounds, such as Terpenes, ascorbic acid, N-acetyl-cysteine, carotionoids, and antioxidants into daily diet programs (ESA Humex Study 2003). Newly developed drugs such as CBLB502 that aid in prevention of cell death and activation of DNA repair mechanisms, may be used to mitigate acute radiation exposures (Gudkov A. V. et al 2008). Testing of CBLB502 is already underway with positive initial results indicating a lack of human side effects and effective radiation shielding in mice and monkeys (Gudkov A. V. et al 2008).

3.11 Precursor Habitat Missions

As a preparation for a long duration stay on the Martian surface, different preparatory training missions will be vital to increase the confidence of working and living in a confined environment. These studies will quantify the following main aspects:

- Psychological well-being of a crew in a confined environment
- Social interactional behavior between crew members (group forming vs. individuals)
- Psychological problems caused by disconnection from family & friends
- Home sickness effects induced by long term off-world activities

To enable the monitoring of these effects and enable the building and testing of a habitat on a remote location, a preparatory training program should be established which contains, among others, the following elements in chronological order:

- Long duration studies in habitats placed within caves/lava tubes on Earth
    - Experience generation with building on-site habitats in caves/lava tubes
    - Training of living in a confined environment
- Long duration studies in a habitat placed inside caves in Antarctica
    - Experience generation with building up habitats in caves under harsh conditions
    - Training of living in a confined and remote location
- Long duration studies in a habitat placed and built within lava tubes on the Moon
    - Experience generation with building up habitats on other celestial bodies
    - Training in living in a confined and remote location
    - Training in off-world habitation
    - Observation of the physiological effects generated by being away from Earth

3.12 Crew Selection

The majority of crew activities throughout the Mars Cave mission fall into four categories including training, science and exploration, systems operation and maintenance, and programmatic considerations. It should be noted that the crew composition requires variety and redundancy for optimal functioning. The Mars cave specific skill requirements fall in the following three categories (Hoffman & Kaplan, 1997):

1) Medicine specific medical issues treatment and robotic surgery
2) Engineering cave habitat construction and architecture
3) Geosciences cave geology and environment

3.12.1 Crew dynamics

A good understanding and knowledge of the leadership qualities, the diversity of crew composition and crew dynamics will help the designers in the planning and preparation for the Mars mission. Data on crew dynamics in environments such as caves are sparse, especially for long durations, therefore it is recommended that long term Earth and lunar studies are performed.

3.13 Crew Training

Crewmembers need to be familiarized with the cave habitat and its components. Furthermore training in Mars analog environments like the Arctic or desert like environments is a necessary part of the crew preparation. Current ISS crews could perform Mars cave-specific Intravehicular and Extravehicular activities (Ball & Evans, 2001). Current technology already allows simulating of specific operational scenarios like the lack of real time communication or unforeseen emergency events.

Crewmembers must be capable of acting autonomously and reacting accordingly to unforeseen events, since this is the first time that extraterrestrial subsurface exploration will be undertaken. The Apollo missions were only focused on the surface exploration of the Moon. As the crewmembers will perform a lot of EVA's during this mission, they need to be trained as field scientists (Lim et al., 2009).

3.14 Space Medicine

A long duration manned mission to Mars constitutes a major challenge to the health of crewmembers. On such a mission the long-term exposure to microgravity, particularly during Earth-Mars/Mars-Earth transit must be taken into account. The crewmembers will be exposed to different transitions between varying levels of gravity on the course of the mission. On Mars, crewmembers will be exposed to a reduced level of gravity, roughly one third of that on Earth (ESA Humex, 2003). The impact of microgravity on health is a very complex issue, comprising effects on the different organs and systems in a highly complex manner.

As an initial response to gravitational change, cardiovascular de-conditioning is a major issue. In a long-term mission, countermeasures such as exercise and diets do not fully compensate for the loss of physical capabilities. Similarly, the bone and muscle loss is associated with long-duration exposure to microgravity and low light levels and it should be taken into account (Charles et al., 1994). In the worst case, the total bone loss may be up to 36% after such a mission, and the accepted loss for a significant risk of fracture is 15% (ESA Humex, 2003). Gender differences related to countermeasures are appeared to be minimal (A Perez-Poch, 2008). The main difference predicts that females appear to benefit more from exercise to minimize the effects of cardiovascular problems.

Although it is not totally understood that if it is due to the fact that the muscular mass loss is less in females than in males. Due to the partial ineffectiveness of current countermeasures against these highlighted health issues, it is recommended that artificial gravity, use of a short-arm artificial centrifuge and fluid intake before landing should be considered as countermeasures. Pharmacological countermeasures both in transit and on surface will also be advisable (Charles et al., 1994).

Both NASA and ESA have initiated studies to evaluate health risk probabilities for proposed Lunar and Mars reference missions (J. Rhatigan et al 2006; ESA Humex Study 2003; R. White 2007). There is a significant probability of diseases and injuries occurring in such missions. Results are shown in Table 3-15.

Table 3-15: Health Risk Probabilities for the Scenario 1 Mission. (ESA HUMEX, 2003)

Gravity-Related Disorders	%	Gravity-Related Disorders	%
Bone demineralization	unknown	Ischaemic heart disease	0.06
Back Pain	unknown	Digestive disease	0.04
Space Motion Sickness	10.20	Appendicitis	0.04
Intestinal Diseases	0.01	Liver & Gall Bladder	0.07
Viral diseases	0.01	Urinary calculus	0.03
Acute respiratory infections	54.95	Male Specific	0.03
Pneumonia and influenza	0.14	Female Specific	0.71
Cystitis	12.37	Fracture of skull, spine or trunk	0.03
Skin Infections	12.37	Fracture of upper/lower limb	0.03
Neoplasms	0.01	Head injury	0.03
Endocrine, nutritional, metabolic, immunity	0.04	Open wounds	0.14
Disorder of thyroid gland	0.00	Burns	0.14
Diabetes mellitus	0.01	Dental diseases	0.14
Diseases of Blood	0.03	Toxic effects	0.07
Cardiovascular disease	0.14	Reduced Temperature effects	0.07
Hypertensive disease	0.01	Heat & Light effects	0.10

Aside from bone loss and radiation, behavioural adaptation is one of the most important health issues in exploration class missions (Ball & Evans, 2001) It can be predicted that travel to Mars presents the risk of developing major psychiatric conditions such as adjustment disorders, somatoform disorders, mood disorders and other thought disorders (Manzey, 2003). The reduced lighting associated with the use of caves may increase risk of suffer from Seasonal Affective Disorder (SAD). Treatments include the use of light boxes and administering the hormones cortisol and melatonin (Avery D. et al., 2001). Still, due to the lack of data on cave habitation it is recommended that Mars cave analogue studies, including sleep-wake cycles and seasonal changes be conducted. In the case of cave-oriented missions, analogues for instance in polar over wintering, terrestrial caving, submarines, underwater laboratories and industrial mining contexts should be taken into account. Preparatory measures for crewmembers should include exposure to and familiarization with these environments, especially to develop coping strategies for increased isolation and confinement, unusual photoperiodicity, the interplay of both high workload and long-term sensory and social monotony and awareness of increased risk of operational hazards.

Medical operations dealing with mentioned issues comprising self-management will become one of the first principles of Martian crew activities. Transfer of appropriate medical equipment and training of non-physician members of the crew should be considered. Real-time telemedicine operations will not be possible because of time lag in communications, so primary basic diagnosis equipments and surgery kits should be transferred to Mars in advance. Tele-mentoring should also be considered for the conduction of medical activities and dealing with medical emergencies on Mars. One possible solution to the problem of medical emergencies is hibernation. It has been shown that an induced hibernation state can be triggered in cells, tissues and even in whole organisms (Roth M.B., 2008-2005). Use of hibernation can be crucial for the stabilization of medical status in case of an emergency such as unexpected traumas, infections and sicknesses, severe radiation poisoning and decreasing life support supplies. As an instance of severe trauma or sickness during the mission, vital stabilization of the crew member(s) for long periods of time could be possible by induced states of hibernation, allowing transport to Earth. Hibernation is also a radioprotectant application.

Choosing caves as a habitation option, compared to the other surface-based solutions would have an effect on communications that may be crucial for emergencies and may increase the risk for traumas. The use of lunar missions for the development of reliable and safe medical procedures must be viewed as a compulsory milestone before embarking on a Martian expedition. It has been known since Apollo missions that lunar dust poses risks to both crew health and EVA systems. Experiments conducted with lunar and Martian dust stimulants demonstrated the adverse effects of both in triggering inflammatory lesions in the pulmonary system (Chiu-Wing Lam et al., 2002; Gaier J.R. 2005). Before attempting a Mars missions protocols for minimizing the effects of dust must be developed. As with medical procedures, this should be a focus of lunar missions.

Finally, the use of caves as opposed to the Martian surface as a habitat does not increase the physical health risks to humans as outlined above (with the possible exception of bone fracture depending on habitat design). The improved radiation shielding and protection from Martian dust and air filtering provided by caves are major advantages and could significantly increase efficiency of the mission. It should be emphasized that a Mars exploration mission shall bring several major challenges for maintaining the crewmember's health, in spite of being protected in a cave habitat, as reduced gravity will still be playing a major role in many physiological disorders.

4 GOVERNING FRAMEWORKS

"Laws and institutions must go hand in hand with the progress of the human mind."
–Sir Francis Bacon

The foundational framework for any international space initiative is inherently based in law, policy, and society. Thus, a human mission to Mars requires authorization and support in all three areas. An analysis of the relevant legal, policy, and society considerations for a Mars mission is provided here.

4.1 Legal Considerations

The United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) has codified principles and guidelines in several space treaties. They are the Outer Space Treaty (OST), the Rescue Agreement, the Liability Convention, and the Registration Convention. The Moon Agreement is only briefly mentioned because it lacks significant international acceptance and ratification. These primary space law instruments set the rights and obligations for States in conducting space activities. States that have signed these treaties then implement these obligations in their national laws and licensing regimes. Space related intergovernmental agreements (IGAs) and memorandums of understanding (MOUs) also reflect adoption of these State obligations and principles in customary practice.

A human mission to Mars, regardless of mission duration, raises certain legal issues for compliance under both international and national law. For example, the exploitation and use of Mars resources (to include Martian caves) by both States and private entities, as well as the role of States and private industry with regard to the technological preparation and innovation required for a human expedition to Mars. Moreover, States have a mutual obligation not to harmfully interfere with the rights of other States in conducting space activities and exploring or exploiting other celestial bodies.

4.1.1 Exploitation and Use

Most important, under Article II of the OST, Mars "is not subject to any national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." Significantly, this means that States cannot claim any Martian land for themselves, and international organizations and private entities cannot claim possession either. Likewise, any private entity or international organization on Mars must conduct their space activities under the authority and supervision of an appropriate State. In this regard, private entities must comply with the relevant national laws and licensing regimes for conducting space and related activities.

In accordance with the OST, everyone has an equal right to resources in space, but there is no system for resource allocation among States and their private entities. The Moon Agreement was adopted in 1979 with the intent to provide an idealistic system for allocating extraterrestrial materials. However, this treaty has failed to obtain international support and significance. As a result, future mining, water extractions, and other ISRU activities on Mars, whether by a public or private entity, remain an issue for discussion and agreement among States. This issue can be appropriately addressed in the IGA between participating States in the Mars mission.

4.1.2 State Responsibility and Liability

The OST also solidifies State responsibility for national activities in outer space, including the Moon and other celestial bodies. National activities include all space activities conducted by governmental agencies as well as non-governmental entities (such as private enterprise). Consequently, States have an obligation to both authorize and continually supervise commercial space activities. Furthermore, the Liability Convention defines the liability regime and the launching States.

4.1.3 International Participation and National Concerns

All international space initiatives inherently require an international agreement. As experienced with the International Space Station (ISS), an IGA is an appropriate instrument for incorporating the initial contractual rights and obligations of all participating parties to a collaborative space project. Further issues may also be addressed in bilateral/multilateral MOUs, as appropriate. No framework currently exists for an interplanetary human space mission; however, some essential elements for such an agreement include: a code of conduct for the mission participants, an intellectual property and copyright regime for discoveries made on Mars (e.g., whether to apply the national law of the astronaut's flag State or other arrangement), cost and risk allocation, crew slots and selection, and agreements pertaining to ISRU, especially pertaining to scarce resources on Mars).

4.1.4 Astronauts

While there is no unified consensus on the definition of "astronaut", Article V of the OST defines an astronaut as an "envoy of mankind." The cultural and technological context at the time of drafting reflects how astronauts were, in fact, representatives of their sponsoring nations. For purposes of this report, astronaut crew members are assumed to be State selected and trained individuals, not private persons. Consequently, the definition of 'astronaut' and the Rescue Agreement, would apply to the 'crew members' of a public-sponsored Mars mission as described in this report.

On the other hand, with the emerging new phase of commercial space flight participation, the issue of defining who is an "astronaut" is ripe for re-discussion in the international community. A new definition and regulatory regime will inherently be required with the addition of commercial space flight participants and inhabitants on Mars. Alternatively, the IGA governing the Martian expedition may adopt additional relevant terms and definitions from existing national space law, regarding commercial individuals in space.

4.1.5 Security Concerns

Several major security considerations arise with a mission to Mars. They include dual use technologies; the role, if any, of military in space; and remote sensing.

<u>Dual Use Technologies</u>: Contemporary dual use technologies are governed by national licensing and export regimes. In regard to U.S. involvement in a human Mars mission, export law,

particularly the International Traffic in Arms Regulations (ITAR) will affect the success of the mission for dual use technologies. ITAR specifically applies to the transfer of spacecraft systems and related equipment through services, hardware, data, and the sharing of knowledge with foreign entities and persons. While technical assistance agreements and academic research waivers may facilitate international cooperation for some space activities, other national restrictions must also be considered. For instance, a nuclear powered space transport vehicle will inevitably pose concerns for national security due to the dual nature aspect of the technology, not to mention a heightened liability in case of launch failure. Moreover, the presence of a significant nuclear energy source in orbital space, or near Earth trajectory, may also pose planetary environmental issues that threaten nations' safety and security on Earth, for example, issues regarding space collisions and falling debris.

Military in Space: With particular regard to military forces on Mars, the international consensus and treaty law are adamant about using space for peaceful purposes. While Article IV of the OST does allow for the "use of military personnel for scientific research," it strictly prohibits military uses such as military bases and maneuvers on celestial bodies, as well as the placement of nuclear weapons or any kind of weapons of mass destruction anywhere in space.

Chain of Command: The chain of command requirements and procedures for astronauts of a public space mission to Mars must be agreed upon and established by the States Parties and/or space agencies. The IGA may also refer to existing program procedures, astronaut codes of conduct, emergency measures and procedures, or other applicable documents.

Remote Sensing: Remote sensing activities on Mars fail to raise any national security concerns on Earth. The principles of non-sovereignty and non-appropriation of space and celestial bodies impede any application of national rights in this regard. Consequently, the existing international Principles on Remote Sensing apply only to Earth and not to other celestial bodies. Therefore, no legal impediments currently stand in the way of any State or private entity, from conducting remote sensing activities on Mars for resource location etc.

4.1.6 Conclusion

Diverse fact patterns, including various States' involvement, as well as new and developing space policies, inherently affect the interpretation and application of existing international and space law. While certain major legal issues were necessary for deliberate discussion and explanation here, other legal issues exist with regard to a human mission to Mars and must be considered. Table 4-1 identifies some of the important legal elements and applies the current framework(s) applicable to the issue.

Table 4-1: Legal Framework

Issues	Framework	Implications & Comments
State Sovereignty	OST Art. II	Mars is not subject to national appropriation by claim of sovereignty.
Private Possession	OST Art. II	Mars is not subject to national appropriation by claim of sovereignty.
	OST Art. VI	State parties shall bear international responsibility for non-governmental space activities.
Facility	OST Art. IV	The use of any equipment/facilities necessary for peaceful exploration on Mars is not prohibited.
	OST Art. XII	All equipment/facilities on Mars are open to other States Parties on a basis of reciprocity.
	OST Art. VIII;	Launching States have jurisdiction and control over their registered space objects/personnel.
Natural resources	OST Art. I	Mars is free for exploration and use by all States on a non-discriminatory basis and in accordance with international law.
Scientific Data/Resource Sharing	OST Art. I, III	The OST promotes international cooperation for scientific investigations. However, no obligation to share acquired space resource/data now exists.
ISRU by private entity	OST Art. VI	State parties also bear responsibility for non-governmental space activities
IP & Copyright	National law; IGA (e.g. ISS IGA)	There is no definitive law on this issue. Earth-based discoveries: governed by *lex loci*. Discoveries made on Mars: governed by *lex loci* or by IGA arrangement.
Jurisdiction and Control	OST Art. VIII	A State Party retains jurisdiction and control over their registered space object/personnel.
Registration of Space Object	Registration Art. II	The launching State must register a space object launched into Earth orbit or beyond.
Supervising Commercial Activities	OST Art. VI	States must ensure Treaty compliance, and non-governmental entities require authorization and continuing supervision.
Supervising International Organizations	OST Art. VI	The international organization and States Parties to the Treaty are both responsible for ensuring Treaty compliance. (e.g., ESA)
Liability	OST Art. VII, VIII	Covers overall international liability requirements.
	Liability Art. II	Earth Surface: absolute liability for damage.
	Liability Art. III	Elsewhere than on Earth surface: fault-based liability for damage.
	Liability Art. IV; National Law	Third Party Liability: usually covered by national regulations on insurance requirements.
Environmental issues	OST Art. IX	On Mars: States shall pursue outer space studies on Mars, and conduct exploration of them so as to avoid their harmful contamination.
	OST Art. IX	On Earth: States shall avoid adverse changes in Earth's environment resulting from the introduction of extraterrestrial matter.
Astronauts	OST Art. V; Rescue	Astronauts are envoys of mankind in outer space.
Governance of Mars	Space Law & Treaties	State(s) sponsored settlements on Mars will be governed by space law, national law, & IGAs.

4.2 Socio-political Considerations

4.2.1 POLICY

Several major policy considerations are embedded in the planning of any human space mission. They include the potential for international cooperation and contribution, an analysis of the significance or benefits of a combined Moon/Mars exploration strategy, as well as an overview and benefits analysis of precursor missions.

Potential for International Cooperation

The scale of a program that would allow for an initial human settlement on Mars is unprecedented. For this reason it is very likely that only a worldwide cooperation effort within a concerted international exploration strategy could succeed. This section assesses the potential of countries to contribute to an international human mission to Mars in terms of technical and financial capabilities. An overview of the relevant technical space capabilities for current space-faring nations is included in Table 4-2.

Table 4-2: Overview of Relevant Technical Space Capabilities as of 2009

Capacity	*USA*	*Russia*	*China*	*Europe*	*Japan*	*India*
HUMAN						
Access To LEO	Yes	Yes	Yes	No	No	No
Earth Re-Entry	Yes	Yes	Yes	Anticipated	Anticipated	No
Life Support System	Yes	Yes	Yes	Anticipated	No	No
LEO Rendezvous	Yes	Yes	No	No	No	No
Transfer to Moon/Mars Orbit	Yes	No	Anticipated	No	No	No
Mars EDL	Anticipated	No	No	No	No	No
Moon Landing	Yes	No	No	No	No	No
Surface Habitat	Anticipated	No	No	No	No	No
Rover/Mobility Capability	Yes	No	No	No	No	No
Moon Surface to Low Lunar Orbit	Yes	No	No	No	No	No
Mars Surface to Low Mars Orbit	No	No	No	No	No	No
ROBOTIC						
Access To LEO	Yes	Yes	Yes	Yes	Yes	Yes
Transfer to Moon/Mars Orbit	Yes	Yes	Yes	Yes	Yes	Yes
Earth Re-entry	Yes	Yes	Yes	Anticipated	Anticipated	No
Moon Landing	Yes	Yes	Anticipated	Anticipated	Anticipated	No
Mars EDL	Yes	Yes	No	Anticipated	No	No
Rover/Mobility Capability	Yes	Yes	No	Anticipated	No	No
Autonomous Rendezvous	Anticipated	Anticipated	No	Yes	No	No
Moon Surface to Low Lunar Orbit	Yes	Yes	No	No	No	No
Mars Surface to Low Mars Orbit	No	No	No	No	No	No
Yearly Foreseeable Budget ($ Billions)	**18**	**1.5**	**n/a**	**7**	**2**	**1**

While most of the capabilities listed above already exist or are anticipated, some are missing. Some capabilities, like cargo transportation to LEO, are available worldwide; other capabilities, such as an Entry, Descent and Landing on Mars, are limited to a small number of space faring nations. In addition, some countries may offer specific expertise, such as space robotics in Canada, which is another factor to take into consideration for international cooperation.

These factors, combined with the foreseeable budget of each country with respect to the overall cost of the entire program, demonstrate that international cooperation is absolutely required to ensure a safe voyage and landing on Mars. International cooperation can provide the redundancy needed in the mission critical path to achieve the high level of safety required for such a mission. For example, redundancy in the ISS transportation architecture (having the Shuttle and Soyuz) has proven to be vital to the program. Likewise, a concerted global exploration strategy should be established for a human Mars mission, where responsibility for each part of the mission is assigned to a given country, or countries, when redundancy is deemed necessary and financially viable.

A Combined Moon/Mars Exploration Strategy

This section analyses the value of lunar exploration as a stepping stone for Martian exploration. For each technology, exploration of the Moon is show in Table 4-3.

Table 4-3: Relevance of Lunar Exploration to Mars Mission

Technology/System needed	Tested on and/or gain information from:		
	Earth	*ISS*	*Moon*
Moon Unnecessary			
Aerobreaking Technology	No	No	No
Balloon-based Exploration	Partial	No	No
Power Source & Infrastructure	Partial	Yes	Yes
Manned Operation Experience	No	Yes	Yes
Radiation Shielding	No	Yes	Yes
Legal International Framework	No	Yes	Yes
Moon Desirable			
Earth Re-entry Technology	No	Partial	Yes
Long Term Reduced-G Impact on Human Physiology	No	Partial	Yes
Space Suits Technology	No	Partial	Yes
Mars Final Landing Technology	No	No	Partial
Moon Needed			
Manned Roving/Mobility Technology	Partial	No	Yes
ISRU (Oxygen and/or Water)	No	No	Yes
Habitat Deployment and Living Experience	No	No	Yes
Planetary Take Off Technology	No	No	Yes

Based on the above table, there is a solid case for a combined exploration strategy, first optimizing the ISS experience, then landing on the Moon, and eventually setting foot on Mars.

Precursor Missions

Precursor missions are a major cost input for the overall Mars program. Therefore, the success of developing a viable cave-based Mars mission will depend largely on the additional precursor missions it requires, and their associated costs. Precursor missions can be broken down into exploration missions to obtain data and scientific information required before a human mission, and technology demonstration missions used to test the fidelity of a given set of technologies.

The biggest challenge lies in safely and successfully establishing the infrastructure to live in the caves on Mars. Creating a long-term program, based upon existing and developing technologies allows for the development and demonstration of the required infrastructure without prohibitive costs. This again highlights the need for international cooperation in executing a space exploration program to the Moon and then onwards to Mars.

4.2.2 International Cooperation

In building an international cooperation model, many lessons can be taken from the model for the ISS. Currently, the ISS is managed through time allocation of the ISS modules and assets. This designation of use is derived depending on which agency paid for the equipment, which agency the asset is registered to, and which country launched the asset. While this model proved to be functional for a modular space station, this approach will not be ideal on Mars.

Any human program to Mars will need to be an international effort without specific division of facility space or use. Instead of focusing on the habitat or asset time allocation, the Mars model should focus on allocation of a crewmember's time. Each crewmember's time could be divided in the same manner that private company stock is used for voting purposes. Shareholders in the Mars Program would have the ability to sell their crewmember's time to any other countries wanting to enter into the program or purchase time for their own experiments. This exchange of time may or may not be done with an exchange of money, but could also be conducted on a no exchange of funds basis for services, hardware, or software.

4.2.3 Public Private Partnerships (PPP)

An initial human settlement on Mars will involve industry in order to meet mission technology goals. One way to do so is to provide seed funding to address barriers and initiate joint-development partnerships. One model to handle such PPPs is NASA's International Partnership Program (IPP) that issues request for proposals to industry, universities and research institutions (NASA 2009). In cave-based and surface-based solutions, the technological opportunities are similar and it may be advantageous to involve PPPs.

4.2.4 Public Opinion

An initial human settlement on Mars is a venture that can only be enabled by international collaboration. This enterprise involves not only the crew, or the thousands directly working for the success of the mission, but it also involves all people on Earth. Furthermore, different cultural aspects must be taken into account to stimulate public opinion (Ehrenfreund et al., 2009). A stakeholder analysis was undertaken to identify the primary groups that form public opinion and identify where efforts should be focused.

<u>Governments</u>: Governments have a unique opportunity to ensure that this generation is remembered as pioneers of human exploration of the solar system. For this reason, government interest in undertaking a human mission to Mars is to gain votes and support from their citizens, to establish stable international alliances to ensure freedom, and to support the exploration vision. Involving governments from all over the world will help to discourage short-term thinking by government officials for personal political gains.

<u>Non-Government Organizations (NGOs)</u>: NGOs will generally be in favor of a mission that expands mankind's horizons. However, some mission aspects such as nuclear propulsion may raise concerns from environmental policies of NGOs.

<u>Space Agencies</u>: Space agencies act to transform the goals of the space science community into reality, while succeeding to the political will of their supporting nations. Their main interest is to conduct space missions in accordance with their space rationales, within budgetary constraints,

and to safeguard jobs within national space industries. With international cooperation space agencies can profit in many ways.

Large Aerospace Companies: Large aerospace companies are the integrators of future missions to Mars, directly delivering the mission for the space agencies. Their interest in the success of such missions relates to new business opportunities and job creation.

Small and Medium Aerospace Companies: Small and medium sized aerospace companies will be indirectly involved in the mission. They will be mostly subcontractors for the integrators. Their interest in the success of human missions to Mars relates to new business opportunities, job creation, and access to knowledge through technology transfer from the integrators.

Private Entrepreneurs: There is a unique window of opportunity for private entrepreneurs from different business areas to use their participation as a showcase for worldwide exposure. Furthermore, the outlook for future spin-ins and spin-offs will certainly be interesting for this stakeholder group, as space technology is already an inducer of cutting-edge technological advancements.

Taxpayers: A program such as human missions to Mars will have costs of such magnitude that will impact taxpayers to a great extent. Taxpayers will desire that their money be spent rationally and with visible results.

Space Lobbyist Organizations: Space lobbyist organizations such as The Mars Society actively advocate for a human mission to Mars. They have high interest in the complete success of this mission.

Scientific Foundations: Scientific foundations collect funding from governmental budgets or private donations and allocate these resources through researchers in the scientific community. The success of a human mission to Mars will provide scientific foundations with increased funding and negotiating power.

Academia: The scientific and technical community is the main advocate for a human mission to Mars. Mars is the prime location for seeking answers to the question of whether there is or was extraterrestrial life. The technical community will benefit from the challenge of developing new technology for this mission.

Entertainment Industry: The entertainment industry has great potential to influence large sectors of the public opinion through their products. Their main interest is to be inspired and acquire stories for their projects and sell them worldwide. Also, entertainment industry celebrities have the potential to become effective advocates for space exploration.

Cultural Institutions: Artists reflect the different cultures on Earth, and culture is the only rationale for space exploration. (Dator, 2009). Artists are stakeholders in the sense that they will want to translate the first missions to Mars into a shared human experience.

Mass and Social Media: A human mission to Mars has the potential to become the greatest story of its generation and the main interest of mass media. Journalists will report on every aspect of the mission. Mass media have a major role in influencing public opinion. Furthermore, social media like blogs, micro-blogs (e.g., Twitter), social networks and social news have the potential to become the primary influence on public opinion as they acquire news in real-time and spread it though their networks.

4.2.5 Stakeholder Matrix

The purpose of the Stakeholder matrix is to determine the importance of each interest for the type of stakeholder. The significance of each interest relative to a specific stakeholder and the overall importance of that interest to the mission were determined. This was done by allotting an opinion based interest value to each stakeholder and weighting these values by multiplying by a power value for each stakeholder. These results were summarized to form the stakeholder matrix in Table 4-4.

Table 4-4: Stakeholder Matrix

Interest\ Stakeholder	Governments	Non-governmental organizations (NGOs)	Space Agencies	Large aerospace companies	Small space companies	Private entrepreneurs	Taxpayers	Space lobbyist organizations	Scientific foundations	Academia	Entertainment industry	Cultural institutions	Mass and social media
Science discovery	37	14	62	37	14	1	23	22	27	24	36	6	31
Technology engineering	37	7	62	62	34	3	35	22	27	24	27	2	21
Social impact	62	34	49	25	21	2	58	22	22	10	45	10	51
Political	62	34	62	49	21	2	47	27	11	10	9	4	31
Educational	49	27	49	25	14	1	47	16	22	24	18	8	21
Cultural	25	27	37	25	14	1	47	16	16	14	36	10	41
Financial	49	7	37	62	34	3	47	11	11	10	45	4	21
Economical	62	21	37	62	34	3	47	5	11	10	27	6	41
Legal/insurance	49	14	37	49	27	2	23	11	5	10	9	2	21
Regulatory / policy	62	27	49	37	21	2	12	27	5	10	9	2	10
Environmental impact	37	34	37	25	21	1	35	16	22	19	18	8	41
Total	**530**	**247**	**518**	**456**	**253**	**23**	**419**	**197**	**181**	**163**	**276**	**64**	**329**

The main stakeholders that should be focused on are governments, space agencies, large aerospace companies, public taxpayers, and mass and social media especially in the areas of social impact, technology engineering and economical prosperity. These results show the areas of society that have the most influential impact on the Mars mission; thus, time and effort need to be dedicated to these stakeholders to ensure a successful mission.

4.2.6 Martian Life & Society

Whether microbial life was to be discovered in Martian caves or elsewhere on Mars, it would profoundly affect human society. The discovery of extraterrestrial life would have an impact on world religions, space policies (particularly those related to exploration), philosophical thinking, cultural imaginings, scientific theories, cosmological conjectures and numerous other aspects of human thought. Human civilization would experience a profound paradigm shift with respect to our perceived place in the universe. This would be comparable to a Copernican shift of consciousness. If extraterrestrial life does or did indeed exist, or even if we are alone in the universe, the innate human drive to explore and discover compels us to expand into space. An initial human settlement on Mars would pave the way for further planetary and space exploration, as we seek to further our understanding of the origin of life in the universe.

4.2.7 Risk Acceptance

Danger is a part of all human endeavors (Greene, 2009). From a societal perspective losing a crew member could have a huge impact on public reaction and influence the direction of future missions. Therefore, this issue must be addressed in the strategy for a global public campaign.

Another issue that could lead to a lack of public support is the use of technologies perceived as dangerous, such as space nuclear propulsion. In the case of space nuclear propulsion, Fridensen (1998) argues that the public's risk perception related to the launch of such technology must be reduced through an increase in confidence level by the use of the technology. Public perception of risk depends not only on the novelty of the risk, but also on the voluntary nature of the exposure and the negative quality of the risk (Fridensen, 1998). Finally, social risk acceptance depends on the perceived benefits when compared to the associated risk. These arguments largely support the need for a Moon settlement mission as a precursor to Mars to increase the risk acceptance level of a human Mars mission when assessing familiarity, technology readiness and social and economic benefits.

A strategy for risk acceptance should also be targeted to space agencies, as these will be the main integrators and operations managers for human missions to Mars. Three main risks should be considered:

- The risk of losing precursor missions, which would delay collection of vital data.
- The risk of losing cargo missions, which would delay the deployment of supplies, power sources or habitats for the crew.
- The risk of loss of one or more crew members and/or vehicle during the mission, which could result in public and political pressure that could seriously compromise the entire program.

Space agencies tend to overlook risks associated with early missions of a program, for which there is little or no flight heritage. For example, initial risk assessments by NASA for the space shuttle indicated a loss of vehicle and crew risk of 1 in 100 to 1 in 100,000 (Paté-Cornell et al., 2000). Considering that two catastrophic losses occurred in 127 flights so far, it can be said that risk estimation strategies for a mission to Mars should be as conservative as possible. Any human mission will include inherent risks that cannot be completely mitigated with the technologies and funds available. These risks will have to be accepted by the space agencies involved if such a mission is ever to take place.

5 ALTERNATIVE MISSION ANALYSIS

The use of caves as a habitat solution enables other mission scenarios, which are different from NASA or ESA reference missions. This chapter describes an alternate scenario, ACCESS Mars Extended DRM, outlined in section 5.1.3. A comparative analysis with ACCESS Mars DRM, described in section 5.1.1, is conducted highlighting the relative advantages and disadvantages.

5.1 Alternate Mission Scenario Descriptions

5.1.1 ACCESS Mars DRM (AM DRM)

ACCESS Mars DRM is an adapted NASA DRM for a cave habitat. A schematic of ACCESS Mars DRM is shown in Figure 3-1 in Section 3.1.

The first cargo campaign launches will send two cargo vehicles carrying the infrastructure stated in the NASA DRM, plus one additional cargo vehicle that delivers the cave habitat, the cargo rover, and additional unpressurized rovers.

The crewed flights are identical to the NASA DRM for both scenarios, using four Ares-V launches and one Ares-I launch.

Subsequent to cargo campaign 1, only five Ares-V launches are required to build two cargo vehicles every two years for re-supply, with the exception of cargo campaign 2, which will only require four Ares-V launches because an extra in-line LH2 tank will already be in orbit from cargo campaign 1. For this scenario, the cave habitat is not expanded beyond the single six person module. The first cargo vehicle delivers the Ascent Vehicle, a second ISRU plant, and a third nuclear power plant to the Mars surface. The second cargo vehicle will stay in Mars orbit. When the crew arrives, they transfer to the second cargo vehicle with the Orion spacecraft, dock, and land with a small descent vehicle that also carries consumables, spares, and a fourth power plant.

5.1.2 Cargo Mass Summary

The following two tables show a mass summary and comparison between NASA DRM and ACCESS Mars DRM for the descent/ascent vehicle lander and habitat lander. This comparison was completed for a crew of six people as described in Section 3.1. The mass budget was summarized in Table 3.2. The cave habitat vehicle mass is summarized in Table 5-1.

Table 5-1: Cave Habitat Cargo Vehicle Contents

Manifested Item	Quantity	Mass (t)
Cargo Rover	1	12.0
Cave Habitat	1	20.0
Descent Stage (wet)		23.3
Aeroshell		43.7
Total IMLEO Mass		99.0

The addition of a cargo rover and a cave habitat makes the total cargo mission of ACCESS Mars DRM 32 tons heavier than the cargo of the NASA DRM. This requires three additional Ares-V launches.

5.1.3 ACCESS Mars Extended DRM (AM EDRM)

In the ACCESS Mars Extended DRM, a six-person crew is launched every launch window and stays for two turns totaling 1320 days, which will create a crew-overlap on the surface. The crew size will alternate between six crewmembers for 240 days and twelve crewmembers for 540 days. The only exception to this schedule is that the initial crew will be on the surface for 780 days before the second crew arrives. All six crewmembers leave and return to Earth together. Figure 5-1 (where time zero indicates the time that human leave Earth) and Table 5-2 detail the extended duration scenario.

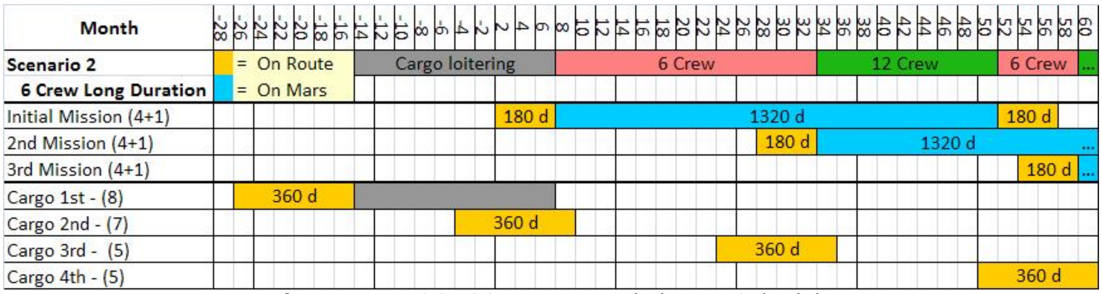


Figure 5-1: ACCESS Mars Extended DRM Schedule

Table 5-2: AM EDRM Phase Description

Stage	Time (months)	Description
1	-14	Cargo, Cave Habitat Mars Transfer Vehicle (MTV), Surface Habitat MTV arrives. Cargo and Cave Habitat MTV land on Mars. Habitat MTV stays in orbit.
2	+6	Crew 1 MTV arrives. Crew Transfer to Surface Habitat MTV and lands. Crew 1 MTV stays in orbit.
3	+10	Second Cargo Cave Habitat and Descending MTV arrive. Cargo and Cave Habitat MTV land on Mars. Descending vehicle MTV stays in orbit.
4	+32	Crew 2 MTV arrives. Crew Transfer to descending vehicle MTV and lands on Mars. Crew 2 MTV stays in orbit.
5	+36	Third Cargo and Descending MTV arrives. Cargo MTV land on Mars. Descending Vehicle MTV stays in orbit.
6	+50	Crew 1 departure to Earth.

The AM EDRM cargo campaign uses the same initial sequence of flights and payloads as the DRM. This is possible because one Ares-V was not used to its full capability in the previous scenario. Here it will carry an additional in-line tank that will stay in LEO for 780 days to be picked up at a later time by the second cargo campaign. Since AM EDRM introduces crew overlap, the cave habitat will have to be expanded. Using the in-line tank launched earlier, one Ares-V launch can be saved, resulting in a total of seven for the second cargo mission. Beginning with Cargo Campaign 3, only five Ares-V launches will be used.

5.2 Engineering

5.2.1 Mission Analysis

The double duration of 1,320 days of AM EDRM might have undesirable effects on the ascent and return vehicles. The vehicle will stay 780 days longer compared to the NASA DRM, which remains unused and relatively unprotected on the surface or in Mars orbit. Special precautions must be taken to ensure the vehicles are fully operational after such a long period of time. For the Earth return vehicle, the problem can be mitigated by ensuring the returning crew uses the transfer vehicle from the new crew that arrived 540 days earlier.

5.2.2 Habitat Design

We have considered scaling the sub-surface habitat to allow up to twelve crewmembers at a time. Although the different scenarios may require a maximum occupancy range of six to twelve crewmembers, we will use a twelve crewmember cave habitat for AM EDRM. Two mission architectures were considered for the twelve crewmember habitat:

- Expanding the cave habitat in the AM DRM by landing a second habitat of equal size to double the crew capacity to twelve.
- Landing a single cave habitat capable of supporting twelve crewmembers.

When comparing architectures, it seems that two small cave habitats have roughly the mass equivalent of one twelve-person cave habitat: 2*20,000 kg as opposed to 38,000 kg respectively. Two modular six-crewmember habitats will have greater ease of transportation by robotic rovers as compared to a single twelve crewmember habitat. For this reason the modular six crewmember habitats were selected.

5.2.3 ISRU and power

Because of overlapping mission requirements, both mission scenarios require at least four power systems: one for redundancy, one for each ISRU plant to produce the ascent stage liquid oxygen, and one to power the modules, recharge rovers, and produce crew consumables. The NASA DRM assumes at least 300 days pre-processing to collect ascent stage liquid oxygen prior to crewmember arrival, so a secondary ISRU plant and associated power plant dedicated to ascent stage ISRU will most likely be required. AM EDRM settles into a pattern of six crewmembers leaving and six crewmembers arriving every 1,320 days, so ascent stage liquid oxygen requirements would be relaxed, and only one ISRU plant processing capacity and associated power generation would be required. Since the crews would be staying for double the duration, we would retain the four power plants and two ISRU plants for redundancy to reduce risk.

5.2.4 Operations & Planning

Periods of no crew in the habitat for the AM DRM have operations and planning implications. The crew will have to leave the base in a well defined, safe configuration with Earth support decreased to maintenance levels. Periods of twelve crewmembers, as stated in the AM EDRM, will require increased ground support, logistics, and planning. Some advantages would be an efficient on-Mars crew transition and increased science return. The main differences between surface habitat operations and cave habitat operations are cave habitat construction and utilization, emergency procedures, using less robust crew landing vehicles after the initial campaign, and crew training for living and operating out of caves.

5.2.5 Crew Training

It is recommended that the crewmembers of overlapping crews interact with each other during their training, to guarantee a better interpersonal understanding and a more effective knowledge transfer after the arrival of the second crew of six. This will facilitate the learning process, if relationships have already been formed.

5.2.6 Unchanged Aspects

There will be no substantial change in the power systems, thermal characteristics, or communication and navigation architecture between the two scenarios. We also expect no changes to the robotics or human transportation vehicles between the two scenarios other than the additional rover for the second six crewmember cave habitat.

5.3 Life Sciences

5.3.1 Crew Behavior and Performance

The AM EDRM can be compared to Antarctic overwinters with overlapping crews. Overwinters pose the challenge of differences in individual or crew situations in terms of mission phase. While a remote overwintering crew can be invigorated by new arrivals, the influx of more inhabitants can still be overwhelming (Carrère, Evans & Stokols, 1991). In mission scenario 2, the alternation between high and low habitat occupancy provides a change in workload and level of privacy. Future research activities in relation to sub-surface habitation could concentrate on circadian aspects and target the development of respective countermeasures in lighting design for habitability. Concerning different mission scenarios with multiple crew overlap, the effects and dynamics of crews that are operating in different mission phases could be investigated in polar and mining analogs, and in orbital and lunar outposts.

5.3.2 Habitation Design & LSS

To reduce the need for food resupplies and to improve crew morale we propose a greenhouse for food production. A minimum of 15 m^2 per crewmember is needed to produce a sufficient amount of food (Campbell, 1993), so for the AM EDRM with a crew of twelve, a 180 m^2 greenhouse with approximately 1160 kg of mass is needed. The plants in the greenhouse could also be used to assist with liquid oxygen production and carbon dioxide regeneration for the LSS.

5.3.3 Radiation

Previous reference studies have shown that one long-duration Mars surface mission will subject crewmembers to more than the career limit dosage of radiation, assuming that space agencies maintain a guideline of a 3% risk exposure induced death (REID) limit (Cucinotta et al., 2006). Given that Martian regolith, composed mostly basalt, can provide sufficient protection against the effects of primary and secondary galactic cosmic radiation and solar particle events, there is more flexibility in the length of a Mars mission if a cave habitat is the chosen solution.

Mars radiation calculations Table 5-3 in show the absorbed dose levels for the two scenarios. The total cumulative radiation dose is larger for the AM EDRM since it is longer than the reference mission. A general comparison between these missions for a subsurface habitat, assuming no EVAs, shows a cumulative total radiation dose of 0.012 mSv and 0.029 mSv for the AM RM and the AM EDRM respectively. Two other cases were evaluated: The surface habitat scenario and the worst-case on-foot EVA scenario.

It is important to recognize that radiation dose levels absorbed via surface habitation are not enough to exceed the 3% REID levels for crewmembers. However, cave habitation significantly reduces the dose of radiation absorbed in the same time period as shown in Table 5-3. Finally, whether crewmembers live in caves or on the surface, the radiation absorbed is insignificant compared to the radiation absorbed during transit, as discussed in section 3.1 Any successful mission to Mars necessitates the development of advanced countermeasures and technology to combat the in transit radiation effects.

Table 5-3: Radiation Dose Comparison

EVA Scenario	Mission (Days)	Total EVA Cumulative Radiation Dose (mSv)	Total MEV Cumulative Radiation Dose (mSv)	Total Cave Cumulative Radiation Dose (mSv)	Total Cumulative Radiation Dose (mSv)
Cave Habitat No EVAs	540 (AM DRM)	0.000	0.000	0.012	0.012
Cave Habitat No EVAs	1320 (AM EDRM)	0.000	0.000	0.029	0.029
Surface Mission No EVAs	540 (AM DRM)	0.000	14.795	0.000	14.795
Surface Mission No EVAs	1320 (AM EDRM)	0.000	36.164	0.000	36.164
EVA on Foot[1]	540 (AM DRM)	7.926	0.000	0.011	7.936
EVA on Foot[1]	1320 (AM EDRM)	19.374	0.000	0.026	19.400

[1]Maximum EVA duration on Foot of 18 hours per week

5.3.4 Space Medicine

Both the shorter and longer missions involve six months in transit (micro-g), 18 or 44 months on Mars (0.38g), respectively, and six months in transit (micro-g). The presence of twelve crewmembers on the surface may increase medical risks to unacceptable levels or place undue strain on the medical infrastructure. Table 5-4 shows the calculated worst-case health risk probabilities between the short and long-term ACCESS Mars scenarios. It is important to note that the uncertainty of these figures is higher for the longer mission compared to the shorter mission, as the extrapolation from the available data can lead to some uncertainty in the risk results outcome.

Table 5-4: Health Risk Probabilities (HUMEX study, ESA, 2003)

Estimated Probabilities of Health Issue Outcomes (%)					
	Scenario			Scenario	
Condition	DRM	EDRM	Condition	DRM	EDRM
Acute respiratory infections	54.95	85.99	Urinary calculus	0.03	0.04
Pneumonia and influenza	0.14	0.22	Disease of male genital organs	0.03	0.04
Neoplasms (pre & pose flight control)	0.01	0.02	Disease of breast or female organs	0.71	1.11
Endocrine, nutritional, metabolic, immunity	0.04	0.07	Heat and light effects	0.10	0.15
Blood diseases and blood forming organisms	0.03	0.04	Open wounds / bleeding	0.14	0.22
Cardiovascular disease	0.14	0.22	Ischemic heart disease	0.06	0.09
Hypertensive disease	0.01	0.22	Disease of liver or gall bladder	0.07	0.11

After the analysis of the risks for these mission scenarios, some concerns arise about the physical capabilities of the crewmembers in the second half of the mission. Current knowledge estimates a 1% loss of bone every month in microgravity (Buckley J., 2006). Little is known on how the reduced gravity of Mars may affect this estimation, but in the worst case these figures put the possibility of bone trauma during the mission beyond acceptable risk. There are also strong concerns about the cardiovascular deconditioning during the later months of the longer mission. Currently, it is known that countermeasures, such as aerobic exercise, only provide a partial reconditioning in microgravity. Further research is recommended, with a particular focus on new countermeasures such as artificial gravity.

5.3.5 Extravehicular Activities

The increase in the number of people present on Mars in the AM EDRM has implications for EVAs. Specifically, the number of space suits available should be increased from six suits and two back-up suits for the AM DRM, to twelve suits and five back-ups for the AM EDRM. If the cave habitats become uninhabitable, all crewmembers will need to leave the cave and take shelter in the surface habitats. There are some advantages to the longer mission scenario. Many more EVAs will be able to be conducted with 12 crewmembers. Additionally, multiple EVAs could be conducted simultaneously. The maximum number of simultaneous EVAs could be up to three to ensure at least one person per group always maintains control from the habitat.

5.4 Physical Sciences

A total crew of six would allow personnel the opportunity to conduct field surveys and possible excavation of resources. A crew of twelve would be ideal, as it would permit multiple geological field teams to be at work, possibly in multiple areas, conducting both experiments and valuable reconnaissance for future ISRU deposits. This work could also allow future expansions and longer duration stays. The increase in ice to be used in ISRU would be minimal and the handover between both crews would last approximately four months; thus, there would be no lag time, allowing the next team to hit the ground running and begin right away, instead of having to learn all locations on their own, and restart everything each time they get to Mars.

From a physical science perspective, the AM EDRM is the preferred option, as it would increase habitat use, as well as increase the speed at which habitat expansion would be possible. In addition, it would allow continuous and long-term science experiments to be conducted. Humans are going to Mars to help mankind, conduct science, and explore; none of these can be done without a constant human presence on Mars.

5.4.1 Site Selection

The primary site selection factors to consider for the AM EDRM are the size of the cave, which must be large enough to handle up to two cave habitat modules and the amount of resources nearby to support ISRU for up to twelve crewmembers.

5.5 Interdisciplinary

5.5.1 Scenario Cost Differences

Actual cost numbers could not be obtained, by ACCESS Mars, at the current development stage of the Ares-V and Ares-I launch vehicles. Instead of providing inaccurate cost estimates, the ACCESS Mars team elected to point out the differences between the NASA DRM and the ACCESS Mars DRMs. The shorter and longer missions would increase the cost of a human mission to Mars by three or five Ares-V launches, respectively, compared to the NASA DRM surface habitat option. These additional launches would also have to take place within the same two year window as discussed at the start of this chapter. Both scenarios have a maximum launch requirement of twelve Ares-V launches and one Ares-I launch for the first one or two launch campaigns. Other additional costs would be the development of the cargo vehicle, cave habitats, and the habitat rovers. These additional launches would enable the use of a subsurface habitat thus lowering the radiation doses for the crewmembers, and allow an initial permanent settlement on Mars. NASA's launch frequency capabilities for Ares-V and Ares-I vehicles are currently unknown, but it might be necessary to construct additional launch pads at Kennedy Space Center to facilitate such an ambitious launch schedule.

5.5.2 Policy

A permanent initial settlement on Mars, made possible by the AM EDRM architecture, would negate the possible cancellation of Mars exploration missions by the relative authorities.

5.5.3 Potential Social Issues

The main social issue for the AM DRM is the loss of continuity in human activity during the intermediate period of no human presence. The experience acquired by the initial crew would be lost, condemning the new crew to repeat the same mistakes and increasing the costs of starting a new learning process in such a challenging environment. Some issues may arise in the AM EDRM, especially during the phase of the mission when the twelve crewmembers coexist within the same habitats. Room in the habitats and life support resources are limited and the scarcity may cause conflicts among the crewmembers. Moreover, subgroup divisions may appear as a result of conflicts between crewmembers, especially during the longer duration mission.

6 CONCLUSIONS AND RECOMMENDATIONS

Throughout this report, we have shown that a human presence on Mars and the development of an initial settlement requires careful consideration of factors including technological and engineering constraints, planetary protection concerns, and crew safety. Developing the infrastructure to live in specific subsurface habitats such as lava tubes requires much analysis and planning. Furthermore, the planning phase will extend into exploratory activities so that crewmembers can perform key science and exploration tasks, warranting scientific merit for a cave mission to Mars. These activities must be optimized to realize the benefits of cave habitats while reducing the risks to crewmembers: the envoys of humankind.

6.1 Conclusions

"We are children of Earth… yet here we stand, in a lava tunnel on the planet Mars. We should not forget how strange a fate that is."

- (Robinson, K. S., 1994)

We have shown in this report that while several types of caves exist on Mars, lava tubes are the most feasible option for establishing a permanent settlement. The rationale for using specifically lava tubes includes adequate capacity to accommodate the habitat, structural stability, known occurrence on the planet, thermal stability, and accessibility (via orientation of entrance) for both robots and humans. Lava tubes offer significant protection from many harmful surface hazards such as minimizing the radiation dosage absorbed by crewmembers by almost three orders of magnitude as compared to a surface stay. This ratio assumes that the Martian regolith provides between 2-3 m of shielding as recommended in Chapter 2. Lava tubes also present significant protection against meteorites and dust storms. Rare cave instabilities may threaten crewmembers, but a significant disaster could be mitigated via proper training and site selection.

The lava tube location ought to be selected via access to ice, proximity to alternative energy sources, minerals of interest for use in the ISRU, proximity to suitable landing sites, and access to regions demonstrating scientific promise. Selection of a cave using these parameters will pave the way for an initial human settlement on Mars. Site selection involves consideration of planetary protection guidelines before exploring 'keep-out' zones. This necessitates robotic precursor missions prior to the construction of the initial settlement. Further lava tube requirements include a roof thickness ratio of 4:1, no major fractures in surrounding rocks, large natural openings, and a smooth floor. These lava tubes will be found via remote sensing equipment on orbiting satellites.

Further precursor missions to acquire more data and explore potential cave options include both small- and large-wheeled and walking robots, tethered robots, hopping microbots, rotorcrafts, and flyers. These rovers will have the most difficulties exploring caves with vertical entrances, but will provide valuable information regarding cave location and access to resources needed before a crew can be sent to the planet. These rovers will also be advantageous for completing scientific goals - specifically for exploring 'keep-out' zones identified from planetary protection strategies.

A significant element in the infrastructure for settling on Mars is the habitation, involving all habitat systems and subsystems including robotics, power, thermal management, communications, navigation, habitat structure and layout, LSS, and crew training and psychology. The successful implementation of our goals includes a meticulous operations phase combining precursor missions, habitat construction, and continuous human exploration. Each of these phases is considered for a base reference mission with comparisons drawn for an alternative mission scenario in Chapter 5.

Arguably, the most complex element of the human cave program is the habitat program and layout. In a cave system, the threat of radiation is removed and the weight of the exterior shell can be reduced significantly by employing inflatables or thin-walled structures. Without any constraints on rigidity, the habitat layout can accommodate greater freedom and spatial recognition over a long-duration mission. Based on a predetermined rating scale, we recommend inflatable structures for both the surface and subsurface habitats. Crew psychology is important for a cave environment because of potentially curtailed daylight cycles and confinement. Both preflight psychological preparation and the design of *in-situ* countermeasures are necessary.

Our reference mission uses a conjunction class fast transfer to reach Mars orbit with a subsequent entry, descent, and landing to reach the selected cave site within an accuracy of 10 km. Both surface and subsurface navigation systems are vital to cave settlement. Wireless networks are recommended for both rover and crewmember communication below the surface. Subsurface navigation may incorporate LiDAR and a cellular network. During surface operations, access networks, inter-spacecraft networks, and surface networks manage the data interlinks. Surface navigation can be managed via a GPS or GNSS-based local area positioning system. Furthermore, subsurface power and thermal systems could use nuclear and solar energy sources to power both the habitat and the rovers.

Specific importance will be placed on international cooperation, increased robustness of critical mission elements, and possible utilization of private-public partnership between commercial organizations and national space agencies. Crewmembers on a human mission that ventures to another planet will most certainly face many hazards. A stakeholder analysis identified governments, space agencies, large aerospace companies, and the public (taxpayers and mass & social media) as key targets that must be persuaded to accept a higher level of risk before the commencement of such a bold mission. This acceptance may require a change in the current perception of the risk involved with exploratory tasks.

Throughout this report, ACCESS Mars focused on several key tasks as presented in Chapter 1. These key mission tasks are presented in Table 6-1 along with a brief summary of our conclusions reached regarding each task.

Table 6-1: Task Identification and Recommended Solutions by ACCESS Mars

Program Task	ACCESS Mars Recommended Solution
Examination of current Mars Reference Mission Roadmaps	-Comparison between NASA/ESA DRMs -Important parameters include cargo launches and mass budget -DRMs assume a 10-year development phase and commencement of cargo launch for 2020 -Nuclear thermal propulsion with Mars aerocapture -Surface mission for two crew with a pressurized rover
Cave location and site selection	-Regions chosen close to ice, geothermal energy sources, and other minerals -The Mars atmosphere, geology, and tectonics yields scientific merit -Planetary protection guidelines must be considered when caves are 'keep-out' zones -Site selection from geologic context, ISRU, proximity to landing site, and science potential -Require caves without fractures or craters, 2-3 m regolith depth, large natural openings, smooth cave floor, possible access to a cave network -Cave detection via remote sensing (GPR and thermal imaging) -Thermal imaging provides enough resolution for cave detection -Ground penetrating radar may be limited by the penetration depth for caves
Establishing requirements to make caves a feasible habitation option	-CELSS -Views of the exterior, digital images of exterior, or skylights -Area larger than NASA MDRM -Designated leisure space -Inflatable structure to provide protection and pressurization -LSS will include a greenhouse for food production, improved waste and atmospheric management, and water regeneration
Comparison between cave-based and surface-based habitation solutions	-Physical cave parameters differ from surface conditions, which influences habitat design -Radiation protection requirements are removed -Structural requirements are minimised, allowing for inflatable structures -Caves introduce the possibility of geothermal power sources -Limited solar illumination -Increased difficulty of communications below the surface -Changes in psychological factors due to less illumination
Consideration of ethical, political, philosophical, and social factors	-Addressing issues of international collaboration -Redundant capabilities for increased robustness -Evaluation of lessons learned from previous international missions -Social risk acceptance for crewmembers exploring caves on Mars -Necessity to change planetary protection standards from a global perspective
A business case for private industry partnership	-Commercialization of satellite constellations around Mars -Developing infrastructure for commercial LEO segments
Evaluation of a combined Moon/Mars strategy	-Further knowledge of lava tubes -Test bed for ISRU capabilities and techniques -Testing for EVAs -Testing of inflatable structures in reduced gravity environments -Testing bio-regenerative technologies for the LSS -Testing the Sabatier reaction for converting CO_2 to methane and water -Testing subsurface communications -Testing electrical charging/discharging of shielding materials -Gain experience deploying and constructing habitats and living in confined spaces -Use the Moon as a pre-mission for risk acceptance
Application of terrestrial and lunar analogues for a Mars cave mission	-Testing operational capabilities and procedures in the case of a cave-in -Testing area for EVAs -Testing of inflatable structures for a combined Moon-Mars mission -Testing subsurface communications and procedures -Using terrestrial or lunar analogues to test structural capabilities of lava tubes

6.2 Recommendations

"Now was their chance, for all of them together in this present – ghosts could watch, from before and after, but that was the moment when what wisdom they could muster had to be woven together, to be passed on to all the future generations."

-(Robinson, K. S., 1996)

ACCESS Mars presented an alternative scenario to the reference mission, which opens the door not only to an initial human mission but also to a permanent human presence on the planet. We make the following recommendations for a Mars cave mission based on a comparison among the AM DRM, the AM EDRM, and current NASA/ESA DRMs. After much research and analysis, our team offers several recommendations for increasing the feasibility of inhabiting caves on Mars.

Improvements in techniques to detect, locate, and select Martian caves is the starting point for successful habitation of Martian caves. The development of international guidelines for optimal cave assessment and selection will be advantageous. More precursor missions for *in-situ* measurements would quantify hazard levels in addition to both the physical and possible biological environments within the cave. Further research into extraction of local minerals such as sulphates, zeolites, and copper oxides will support the argument for *in-situ* resource utilization on Mars. Furthermore, geothermal energy could provide a long term energy solution if harnessed in sufficiently large quantities. More research is necessary into regions of interest, including finding the source of the observed methane in the atmosphere and water and mineral composition such as carbonates and amorphous silica in the regolith. The best solution for detecting caves, as demonstrated from field measurements on Earth, would be a combined visual and infrared thermal imaging survey from an orbital or aerial platform. Ultimately, geological surveying by a human crew will be necessary to obtain more accurate cave data.

Even with improved methods for detecting and selecting caves, a human Mars exploration mission, let alone a mission to caves, will probably not be possible without global international support. A more in-depth stakeholder analysis is required to generate interest for supporting a cave exploration mission versus a surface mission. Attention must be given to outreach strategies targeting governments, space agencies, large aerospace corporations, and the public as identified from the stakeholder analysis. Future outreach options could include incorporating intercultural events into space exploration activities. Furthermore, artistic and social activities have the potential to inspire and generate public support for a manned mission to Mars, but specific emphasis must be placed on generating support for sending humans to caves. Even interactive social media such as Twitter can be used to spread the word on future Martian cave exploration. The entertainment industry can also be used as an instrument for familiarizing the public with human missions to caves via movies, computer games, or popular television shows. This social medium along with other outreach programs could be used to alter the current levels of risk accepted by society.

Extravehicular activities and the exploration of the unknown in the foreign environment of Mars is a natural progression of the curiosity of humankind. However, planetary protection policies are inextricably linked to planetary exploration. ACCESS Mars recommends better and more cost-effective instrument sterilization and anti-contamination procedures to satisfy these policies. Improved technologies may also help facilitate more astrobiology exploration missions, which should adhere to the COSPAR Planetary Protection Policy. Further debate pertaining to the evolution of planetary protection policies on a global scale will be beneficial given the international dimension of space exploration. Finally, if the right to explore protected or sensitive zones on other planets are thought of as earned privileges, a policy scenario might reward efforts in preventing forward contamination. As an example, we suggest the use of sterilization of robotic instrumentation while using the Moon as a test bed for practicing protection procedures.

Precursor missions to the Moon are necessary to identify trade-offs between the complexity and capability of implemented technology, the reliance on robots, and the dependence on local resources. Becoming self-sufficient will be of utmost importance on Mars, and using the Moon as a stepping-stone will only aid in successfully establishing an initial cave settlement. Learning to use local resources and making use of the environment in analogous locations on Earth and the Moon will also prepare us better for a human mission to Mars. Furthermore, the future use of both terrestrial and lunar analogue sites to prepare for the discovery of Mars caves will help to convince stakeholders of the feasibility of living in lava tubes.

Based on the above recommendations and experience gained from the reference ACCESS Mars mission architecture, additional cave habitats could be built. With additional habitats, longer missions could be planned leading perhaps one day to humans permanently relocating to Mars. Many hazards and surface constraints on Mars are mitigated by cave habitats, which will be very important until future technologies are developed.

Technologies that may enable and accelerate future colonization of Mars include:

- Radiation shielding, especially in the field of liquid hydrogen or any material with an atomic number less than aluminum, as it will reduce secondary radiation;
- EVA suit mobility, possibly in the form of mechanical counter-pressure suits;
- Technology to protect humans and equipment from dust storms;
- Advanced propulsion systems, which may make Earth-Mars transits faster and less costly. This will have significant implications for absorbed radiation doses and the length of time that crewmembers can reside on the surface;
- Advances in ISRU, which may enable the recovery of materials necessary for human life and habitat construction out of the Martian regolith and atmosphere;
- Advances in autonomous robotics;
- Rover designs capable of overcoming obstacles blocking cave entrances and volcanic terrain;
- Innovative communications systems to optimize propagation of signals within a cave;
- Research and development of inflatable structures and in situ repair methods;
- Development of Mars-based power sources;
- Remote manufacturing.

Other technologies developed on a long-term timescale that may facilitate a Mars colonization include:

- Space elevators;
- Terraforming technologies;
- Nuclear fusion reactors;
- Balloons for habitation and exploration;
- Advances in space medicine such as hibernation and radiation amelioration.

As humanity endeavors to become a two-planet civilization, the use of Martian caves can provide an excellent initial solution to some of the problems posed by the various hazards on both planets. With time, it is possible that new technologies will lead to more discoveries enabling the human species to thrive on Mars, thereby fully realizing a new era of space exploration. By Assessing Cave Capabilities and Establishing Specific Solutions, we will leave the cradle of Earth, effectively accepting the challenge of exploring the unknown and pushing the limits of knowledge beyond our home planet.

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