Mars-X: Exploring Mars from Phobos

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Mars-X

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ABSTRACT

It is important for the advancement of the human species to leave the cradle of Earth and extend human presence to the rest of the solar system and beyond. Twenty seven graduate students have come together at the International Space University to research human exploration of Mars from Martian orbit. The team is highly diverse with students from sixteen countries collaborating in an international, interdisciplinary and intercultural (3I's) way. The Mars-X project identifies the problems associated with sending humans to a Martian moon and returning them safely to Earth. A framework is suggested for addressing these challenges by proposing an alternative to the International Space Exploration Coordination Group's Global Exploration Roadmap. This alternative advises going to Phobos as a preliminary step to explore Mars, instead of missions to the Moon and Near-Earth Asteroids.

The Red Planet is located at an enticing distance from the Earth and possesses characteristics which make it an appealing destination for the advancement of human space exploration. Mars-X focuses on investigating whether all the technologies required for a human mission to Mars can be tested on a single mission to Phobos. For the mission to achieve 439 days in orbit around Mars, a three-phase launch architecture is proposed, with the first phase launching in 2020. Mars-X outlines how technologies such as nuclear thermal propulsion, advanced radiation shielding, teleoperation of robotics, and artificial gravity will help achieve the goals of this mission. Political, legal, ethical, and economic aspects, such as fundraising through Public Private Partnerships are addressed. The potential for involvement of spacefaring nations in this international venture is also discussed. Investigating the Mars-X mission from the 3i's approach is vital for its success. Therefore, Mars-X brings a unique perspective to the challenge of advancing human exploration throughout space.

FACULTY PREFACE

One of my earliest memories is that of watching the legendary electric guitarist, Jimi Hendrix, on BBC TV's "Top of the Pops". He was living in London at the time and was, I think, performing a track from his celebrated "Electric Ladyland" album. Even as a small child, I marvelled at Hendrix's dexterity, originality and absolute command of his art. Despite musical convention being flouted, everything seemed to work meticulously and harmoniously. The performance was engaging and the electric hard rock sounded very different to that of his contemporaries. As an adult, I now look back on this early memory as my first recognition of brilliance. In fact, not merely brilliance but a singular and unrepeatable genius.

It seems that some level of supreme ability (genius) is necessary for great advances by humankind: be it launching a spacecraft into orbit (Sputnik 1 in 1957) or 'splitting the atom' (Cockroft and Walton in 1932). Sending human beings to Mars - and returning them safely to Earth - is an immensely ambitious project and will require the brightest and best team of men and women. A multitude of technical, managerial, financial, ethical, legal, and other issues need to be addressed. It is to the credit of the members of the International Space University (ISU), Team Project (TP), *Mars-X*, that they have tackled all aspects of a hypothetical, but potential, future human mission to the near-Mars environment.

The TP is an important component of ISU's M.Sc. degree and accounts for some 16% of the total marks for the program. It also encapsulates ISU's '3I's' educational philosophy: Interdisciplinary, International and Intercultural. Indeed, *Mars-X* is composed of a diverse and interesting group of 27 young people from 16 different countries. All realize the complexity of this project: not just the intellectual complexity but also the logistical complexity of working together as a functional team, as opposed to a group of disconnected individuals.

TP *Mars-X* started their research in the autumn (fall) of 2012 with a thorough Literature Review, which they presented to ISU's Faculty. With this academic foundation - and many organisational lessons learned - they moved to the next phase: original research. In just a few months, the team has reached a good level of maturity. For example, they now realize that when it comes to space missions, there is often no 'right' and 'wrong' way of executing projects. It is often just a case of contrasting and comparing the 'pros' and 'cons' of different options. Hence, one could suggest that the opinions and assessments of TP *Mars-X* are as valid as those of anyone else working in the field of future, Human Martian missions.

It is worth highlighting that TP *Mars-X* benefited enormously from the support and assistance of numerous, external colleagues, most notably our generous sponsors: NASA and Lockheed Martin. In conclusion, members of TP *Mars-X* are to be congratulated on their enthusiasm, persistence and industry. Will some of them work on a Human mission to Mars at some stage in their careers? Very probably!

Associate Professor Hugh Hill,
ISU Faculty Interface for TP *Mars-X*.

TEAM PREFACE

"As you set out on your journey to Ithaca,
pray that your journey be a long one,
filled with adventure, filled with discovery".
(from 'Ithaka' by C. P. Cavafy (1863-1933), 1911)

Humans are curious explorers by nature. Like Ulysses searching for Ithaca, they constantly strive to reach new heights and expand their horizons. When we think about space, about the Universe, this becomes even more literal. In the age of rapid technological advancement, when more and more of what was once thought inconceivable becomes possible, it is the time to break the chains that keep us stranded on our maternal planet Earth, and create our new celestial home among the stars.

The goal of the Mars-X team is to create a financially, technologically, legally and politically feasible concept for building a gateway and a scientific facility on the Martian moon of Phobos, operated by humans. The vision is to create a platform that will lead to future exploration of Mars, a path for humanity to reach to the Red Planet and beyond. Mars-X is the intermediate step between remote exploration of Mars through orbiters and rovers, and astronauts walking on the planet's surface. This document describes in detail an innovative approach, based on an in-depth analysis of historic space-related endeavors, such as the Apollo program, Mir and the International Space Station. It also offers the fruits of the team's original research, incorporating a plethora of technical calculations, an assessment of business models and management scenarios and an overview of the legal considerations of such a mission. This report stresses the need for more global coordination, blending the experience and political might of multiple national space agencies and combining those strengths with the energy and vision of private sector explorers. In this work, emphasis is placed on the enormous importance that humanities can play in promoting the benefits of the space sector to the public, while at the same time aspiring to motivate more individuals to follow space-related career paths.

The Mars-X team believes that this pioneering approach can revolutionize space exploration, science and commerce. The authors of this report originate from different corners of our planet and a diverse set of backgrounds, but have joined forces to produce this international, intercultural and interdisciplinary effort. It is with great pleasure that we integrate this report into the long and successful ISU Masters Program archive. Every year since its foundation in 1987, the International Space University has brought highly skilled individuals within the space domain together, linking different perceptions, harvesting different ideas and bridging the gap between distant cultures. This is unique in the world, an opportunity offered nowhere else, and that is the reason why we, the authors of Mars-X, are grateful and proud of this effort.

The first human mission to the surface of the Red Planet will constitute perhaps the most important page in the history of mankind's exploration, echoing the steps of legendary pioneers of yore. United in diversity, we strongly desire to be part of this colossal achievement. The dreams of old are slowly becoming reality, and this has both inspired and motivated us all to surpass ourselves in this wonderful endeavor. Our Ithaca is close.

To Mars and beyond - we were born to explore!

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A	
AOCS	Attitude and Orbit Control Subsystems
APXS	Alpha Proton X-ray Spectrometer
ARES	Aerial Regional-scale Environmental Survey
ASRG	Advanced Stirling Radioisotope Generator
ASTRA	Asteroid Mining Technologies Roadmap and Applications
AU	Astronomical Unit
B	
BCI	Brain-Computer Interface
BFO	Blood Forming Organs
BMI	Body Mass Index
BNTR	Bimodal Nuclear Thermal Rocket engines
C	
CARR	Concept Architecture Roadmap Requirements
CCTV	Chinese Central TeleVision
CELSS	Closed Ecological Life Support System
CFM	Cryogenic Fluid Management
CI	Confidence Interval
CME	Coronal Mass Ejections
COSPAR	COmmittee for SPAce Research
D	
DLR	Deutsches zentrum für Luft-und Raumfahrt
DRO	Distant Retrograde Orbit
DTN	Disruption Tolerant Networking
E	
EDL	Entry, Descent and Landing
EEG	Electroencephalography
ESA	European Space Agency
ESOC	European Space Operations Centre
EUV	Extreme UltraViolet
EVA	Extra Vehicular Activity
F	
FAA	Federal Aviation Administration
FBS	Fan Beam Sensors
FY	Fiscal Year
G	
GAP	Gas Analytic Package
GCM	Global Climate Model
GDC	Galactic Cosmic Rays
GDP	Gross Domestic Product
GER	Global Exploration Roadmap
GPS	Global Positioning System
H	
H2M	Humans 2 Mars conference

HabEX-1	Habitat EXploration primary
HabEX-2	Habitat EXploration secondary
HDPE	High Density PolyEthylene
HZE	High Z (Atomic Number) and Energy

I

IDAGSS	ISS Display And Graphics Standard Specification
IGA	InterGovernmental Agreement
IRG	Intelligent Robotics Group
ISECG	International Space Exploration Coordination Group
ISU	International Space University
ISRU	In Situ Resource Utilization
ISS	International Space Station
IT	Information Technology
ITAR	International Traffic in Arms Regulation
ITU	International Telecommunication Union

L

LEO	Low Earth Orbit
LET	Linear Energy Transfer
LIDAR	LIght Detection And Ranging
LRF	Laser Range Finder
LSS	Life Support System

M

Mars-GRAM	Mars Global Reference Atmospheric Model
MAV	Mars Ascent Vehicle
METERON	Multi-purpose End-To-End Robotic Operations Network
MGCM	Mars General Circulation Model
MLI	MultiLayer Insulation
MMO	Martian Moon Outpost
MMU	Manned Maneuvering Unit
MoU	Memorandum of Understanding
MSL	Mars Science Laboratory
MTGCM	Mars Thermospheric General Circulation Model
MXC	Mars-X Consortium
MXV	Mars eXploration Vehicle

N

NASA	National Aeronautics and Space Administration
NCPS	Nuclear Cryogenic Propulsion Stage
NCRP	National Council on Radiation Protection
NEA	Near-Earth Asteroid
NERVA	Nuclear Engine for Rocket Vehicle Applications
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket engines
NTREES	Nuclear Thermal Rocket Element Environmental Simulator

O

OST	Outer Space Treaty

P

PEM	Proton Exchange Membrane

PPP	Public Private Partnership
PUL	Phobos Unmanned Lander
R	
RAD	Radiation Assessment Detector
RF	Radio Frequency
RTG	Radioisotope Thermoelectric Generator
S	
SAM	Sample Analysis at Mars
SE	Systems Engineering
SGAC	Space Generation Advisory Council
SHARAD	SHAllow RADar instrument
SLS	Space Launch System
SPE	Solar Particle Event
STEM	Science, Technology, Engineering and Mathematics
STK	Satellite ToolKit
STS	Space Transportation System
STW	Surface Telerobotics Workbench
T	
THEMIS	THermal EMission Imaging System
TP	Team Project
TRL	Technology Readiness Level
U	
UAV	Unmanned Aerial Vehicle
UN	United Nations
UNCLOS	United Nations Convention on the Law Of the Sea
UNCOPUOS	United Nations Committee On the Peaceful Uses of Outer Space
US	United States
USA	United States of America
USD	United States Dollar
USSR	Union of Soviet Socialist Republics
W	
WSW	World Space Week

1 THE NEXT GIANT LEAP

The vision established by Werner von Braun has been realized. The Moon landing, the Space Shuttle, the Space Station, launched us from dreams into history, and the world is preparing for the next great space voyage. It is the destiny of humankind to stretch into the solar system in order to meet the growing needs of our expanding race. Science is yearning to breathe in the air of new atmospheres, while the current generation anticipates embracing the discovery of life beyond Earth. With souls poised to leap past the confines of this Earth and Moon, the hurdles of economics and national differences become distant as the fading blue marble becomes lost in a sea of starlight.

For centuries the red hue of Mars has captured the imagination of humanity. Now it is time to embrace whatever lies beneath the rough surface. The Mars-X team spans fields of engineering, science, human physiology in space, business, and the humanities. This includes law, policy and outreach concerns that relate to the exploration of the red planet and its moons. This interdisciplinary approach to understanding the surface, interior, exosphere, composition, origin, and the near-space environment of the Martian system will provide a foundation for human missions. Engineering core competencies and technological focus areas such as telerobotics, deep space communications, and advanced propulsion techniques will be synthesized into an orbital strategy. Optimal management methods and the techniques for integrating this diverse and international team will be defined. Throughout, galvanizing all our spirits behind the vision, outreach, and education will inspire the millions of minds and hearts required to make a journey of this magnitude a reality.

There is consensus among spacefaring nations that Mars is the next destination for human presence. Long-term, multi-national visions for the exploration of Mars have been championed by NASA, ESA, RSA, CASC and others identifying the exploration and development of Mars as essential. Mars-X proposes a scenario to explore Mars by landing humans on a Martian moon and returning them safely to Earth, in order to prepare the foundation for the first human mission to the surface of the Red Planet.

Mars-X combines the intermediate goals of a low gravity asteroid rendezvous with the preparatory goals of observing and preparing for a mission to the Martian surface. Phobos, believed to be an asteroid captured by Mars during the early years of the solar system, will help reveal not only the geological development of Mars itself but address numerous scientific answers related to the formation of the planets. This strategic policy objective will maximize the economic viability of the mission by combining available funding resources and minimizing technical risk by avoiding the complex Martian descent/ascent systems. Asteroid missions have arguably higher return to industry with in situ mining possibilities at a lower cost (ISU, 2011). Such a mission advances human deep space presence while bringing us a step closer to the final destination, Mars.

Mars-X proposes a comprehensive solution that includes interdisciplinary objectives, in which it provides a flexible architecture for human missions to Martian orbit and beyond. This report determined possible financial structures, both conventional and unconventional, in order to ensure program longevity and mitigate risks associated with a sustained interplanetary expedition. Based on the legal and proprietary model for data sharing and data ownership aboard the International Space Station, a template for engaging private industry as well as governments is provided.

Sustainability for such an endeavor requires a long-term outreach and educational vision as well. Boosting interest in STEM subjects and improving space awareness is essential to ensuring overall mission success.

The Mars-X team is ready to initiate its development of a human-tended base on Phobos capable of enhancing the scientific research of Mars. There is a clear plan and destination. All systems are go for launch.

Exploring Mars from Martian orbit is mankind's next duty to its destiny.

Though much is taken, much abides; and though
We are not now that strength which in old days
Moved earth and heaven; that which we are, we are;
One equal temper of heroic hearts,
Made weak by time and fate, but strong in will
To strive, to seek, to find, and not to yield.
Alfred, Lord Tennyson (1809-1892), 1833.

Mars-X Mission Statement

Mars-X proposes a scenario to explore Mars by landing humans on a Martian moon and returning them safely to Earth, in order to prepare the foundation for the first human mission to the surface of the Red Planet.

1.1 Mission Overview

Mars-X chose to adopt a method called the CARR (Concept, Architecture, Roadmap & Requirements) process as a basis for this report. This process consists of a systems level activity with the goal of going from nothing to something. It takes a broad objective, combines it with inputs from multiple disciplines and results in a baseline that can then be developed and iterated further into the project. It is in effect a large trade space activity, with decisions being made based on available information. This trade space is created and analyzed by the Systems Engineering team, with the other teams providing inputs, and offering their expertise when necessary. This trade space is analyzed at different levels, first in a qualitative way to initially narrow down the option tree, then in a quantitative way to start defining key variables; both physical quantities and time scales. The following section presents a summary of the findings, with more details provided throughout the report.

1.1.1 Operating Context

The Mars-X team started by identifying the context in which the mission would operate. The first step was to identify the primary objectives of the report. Two main paths were identified, the first being an overall study of the project while the second consisted of a more detailed study of a particular mission.

In the end it was decided to study one mission in detail and to place it in an already existing context. The Global Exploration Roadmap (GER) offers a flexible phased approach towards enabling human and robotic missions to Mars by considering first going to the Moon (Moon-Next approach), or a near-Earth asteroid (Asteroid-Next approach), as seen in Figure 1-1. According to various trade studies and the International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap, the next goal in the human exploration of the solar system is Mars (ISECG, 2011).

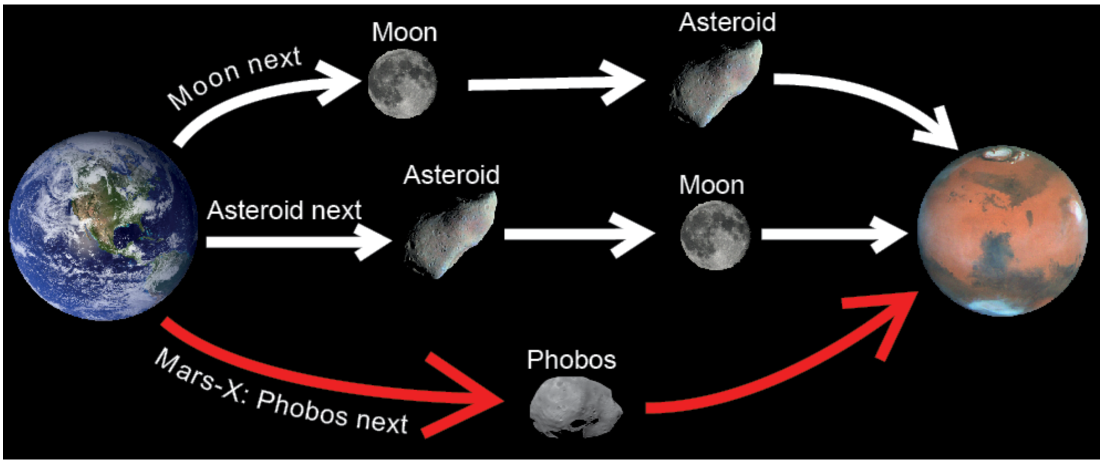


Figure 1-1: Optional Pathways in a Common Strategy [Adapted from ISECG, 2011]

It is important to outline that this mission does not claim to be a perfect substitute to the GER's existing scenarios. Mars-X represents a proposal to reduce the roadmap cost and to try to give clearly defined milestones. In order to fully meet all of the stepping stone requirements outlined in the GER it is essential to demonstrate all the technologies proposed in the Moon/Asteroid-Next scenarios in one mission: Phobos-Next. These technologies are outlined in Table 1-1. Only then will it be possible to fully justify this mission.

1.1.2 Demonstration of the Technologies Needed for Mars Compliance Matrix

The matrix shown in Table 1-1 identifies whether these technologies can be effectively demonstrated through the Mars X mission (duplications of technologies are eliminated).

Table 1-1: Key Technologies [ISECG, 2011]

Key Technologies	Level of demonstration during Mars-X mission compared to GER	Demonstration during Mars-X mission
Key technologies demonstrated in ISS/LEO in the GER		
Advanced EVA and robotics capabilities	Matching	EVAs and robotic teleoperations in the Martian moon environment will be performed (see Sections 3.2.3 & 4.3.1)
Long-term storage and management of cryogenic fluids	Matching	Cryogenic fluids will be used during the entire Mars-X's human mission phase (see Section 4.1.6.2)

Simulation of operational concepts	Exceeding	Operational concepts are similar to Martian surface mission in spite of lack of some key phases like EDL (see Section 1.2)
Key technologies demonstrated in cis-lunar space in the GER		
In-space habitation for long duration in the appropriate radiation environment	Exceeding	Long duration mission of similar length to Mars surface (see Sections 4.1.1 & 4.1.5)
Radiation protection and measurement techniques	Matching	The radiation environment experienced is similar (see Section 4.1.5)
Demonstration of beyond low-Earth orbit re-entry speeds	Exceeding	The re-entry speed is similar to that experienced from a Mars surface mission (see Section 4.1.1)
Automated delivery and deployment of systems	Matching	Demonstrates predeployment of systems to Mars orbit, but not to the surface (see Sections 3.2.1 & 3.2.2)
Simulations of NEAs mission operational concepts	Matching	Phobos is of similar size to NEAs, but the influence of Mars means the dynamics are not too closely related but the operational concepts about rendezvous and berthing are similar (see Section 4.2.1)
Key technologies demonstrated on NEAs in the GER		
Demonstration of advanced in-space propulsion systems	Matching	The nuclear thermal propulsion proposed would be the same as potentially used on a surface mission (see Section 4.1.6)
Subsystem high reliability and commonality, repair at the lowest level — living without a supply chain	Matching	Remoteness and reliability requirements are very similar to Mars surface mission
Demonstration of Mars mission transportation operational concepts	Exceeding	Transportation concepts are similar to a Mars surface mission but lacks EDL
Key technologies demonstrated on the Moon in the GER		
Surface habitation capabilities	Matching	Phobos surface environment and artificial gravity created in the spacecraft during the interplanetary transfer are similar to Martian surface (see Section 4.1.3)
Mars surface exploration scenarios, operations and techniques: long-range	Lacking	Lack of gravity on Phobos prevents from performing Mars surface exploration scenarios

mobility, automated predeployment		
Capabilities and techniques for extended operation in a dusty environment	Lacking	Lack of gravity on Phobos creates a dusty environment different from the lunar one
Advanced surface power if available	Matching	Power sources could be tested in the same way as in Martian orbit (see Section 4.1.7)
Extreme surface mobility	Lacking	Gravity levels and topology of Phobos' surface prevent from extreme surface mobility
Robust, routine EVA capability	Matching	Astronauts will perform EVAs during their stay on Phobos (see Section 4.3.1)
Precision landing and hazard avoidance	Matching	Berthing to Phobos provides experience, although gravity difference limits applicability (see Section 4.2.1)

1.1.3 Summary of Destination Assessment Activity Compliance Matrix

The GER identifies a large number of different science and technological objectives to be achieved through exploration based on different possible destinations. It is important to demonstrate how a human mission to Phobos satisfies these different goals instead of or in complimentary to other exploration destinations. Table 1-2 below table illustrates how the Mars-X proposal satisfies a large number of the objectives identified in the destination assessment activity of the GER.

Table 1-2: Key Objectives for Mars-X Mission

Key Objectives	**Level of Compliance during Mars-X mission compared to GER**	**Description of Mars-X mission compliance**
Objectives for Mars defined in the GER		
Search for life.	Matching	Teleoperated rovers will look for evidence of previous Martian life and return samples (see Sections 3.2.1 & 3.2.3).
Advance understanding of planetary evolution.	Matching	Understanding the origin of Phobos and robotic exploration of Mars would further the knowledge of planetary formation (see Section 3.2.1).
Learn to live on other planetary surfaces.	Lacking	Experience living on another celestial surface, although difference in gravity environment limits similarity with Martian surface.

Objectives for the Moon defined in the GER		
Characterize availability of water and other resources.	Lacking	The mission does not directly address this issue.
Test technologies and capabilities for human space exploration.	Matching	Mars-X demonstrates technologies and capabilities vital for future missions to the Martian surface (see Sections 3.2, 4.1 & 4.2).
Advance understanding of solar system evolution.	Matching	Understanding the origin of Phobos would further the knowledge of solar system formation (see Section 1.1.4).
Utilize the Moon's unique importance to engage the public.	Exceeding	The human exploration of a new world attracts the public attention (see Section 5.9.2).
Objective for a NEA defined in the GER		
Demonstrate innovative deep space exploration technologies and capabilities.	Exceeding	Demonstrates technologies and capabilities vital for future missions to Mars' vicinity, which are also applicable to other destinations (see Section 4.2.2).
Advance understanding of these primitive bodies in Solar System evolution and origin of life.	Matching	The possibility of Phobos being a captured asteroid would increase understanding of asteroids origin & evolution (see Section 1.1.4).
Test methods to defend the Earth from risk of collisions with near-Earth asteroids.	Matching	The possibility of Phobos being a captured asteroid allows characterization of their properties for developing methods (see Section 1.1.4).
Objectives for Lagrangian Points/Cis-Lunar defined in the GER		
Expand capability of humans to operate in this strategic region beyond low-Earth orbit.	Matching	Possibility of operating in unstable orbits between Martian Moon vicinity & Lagrangian points (see Section 4.1.1).
Demonstrate innovative deep space exploration technologies and capabilities.	Matching	See the NEA section above in this table.

1.1.4 Architecture

The CARR process has looked into a series of evaluation criteria in order to set the basis for the architecture of Mars-X. This section summarizes these criteria and outlines the mission phases.

1.1.4.1 Evaluation Criteria

In order to ensure a systematic and objective decision making process, a series of evaluation criteria were chosen, based on which all the trade-offs regarding the mission have been made. The following list summarizes the primary criteria considered to be drivers for this mission:

- Astronaut safety throughout the entire journey
- Availability for launch within a specific and attainable schedule, as early as 2024
- Demonstrations with the technologies proposed in the GER
- Martian exploration has to be beneficial for a future landing mission on Mars

1.1.4.2 Mission Stages

In order to satisfy the evaluation criteria, a three-stage mission was selected. Below are presented the main characteristics of each stage. A more in depth analysis of the each stage is provided in the Engineering section (Section 4.1) of the report. A graphical representation of the roadmap is shown in Section 1.2.

1) Preparatory Launches:
Prior to the mission there will be a preparatory launch (or more than one) by which communication relay satellites will be sent to Mars along with any rovers or other essential elements.

2) Spacecraft Construction:
This phase involves assembling the spacecraft in Low Earth Orbit (LEO). There will be a number of launches in this phase:

- *Unmanned phase:* Multiple cargo launches including engine, fuel tank, fuel, habitat blocks, rovers, scientific instrumentation, Martian surface landers, supplies, and other equipment.
- *Manned phase:* A single launch consisting of Orion or a similar crew capsule.

3) Phobos Mission:
The last phase is the actual manned mission: this involves a total mission duration of 919 days.

1.1.5 Analysis

This section provides an initial broad analysis of the key aspects of the mission. It was completed in order to build the basis upon which this mission relies. Many trade-offs were necessary in order to make decisions that defined the Mars-X mission and therefore affected all the subsequent subsections. The following sections highlight the most relevant outcomes of this process.

1.1.5.1 Short Mission versus Long Mission

The first key decision to define the Mars-X mission was to determine whether the short or long alternative would be selected. The short duration mission corresponds to a total duration of approximately 1.1 years including a four to five month cruise to Mars, up to two months' stay on Phobos, and six months returning to Earth. The longer trip has a duration of approximately 900 days: seven to ten months to go to Mars, fifteen months staying there, and seven to eight months coming back. The two missions have different delta-V totals associated with them. These are 25 km/s on average for the short mission and 10 km/s on average for the long one. Considering present and near future technology such as nuclear thermal rockets, it was calculated that a mission like this requires around 200 tonnes in LEO just for the spacecraft dry mass. For the purpose of this document every reference to tonne refers to a metric tonne of 1000kg. Considering the short duration, the amount of fuel required, when using the most efficient nuclear thermal rocket (with 950 s of specific impulse), is around 3000 tonnes. This mass is prohibitively high. This makes the short duration mission unrealistic and is the primary reason why the long duration mission was selected. Using nuclear propulsion, a long mission would require around 300 tonnes of propellant. When adding also the dry mass in LEO, a total of 500 tonnes will need to be transported from Earth. A more in depth analysis on these conditions is provided in Chapter 4.

1.1.5.2 Crew Number

The question of how many astronauts for the mission was analyzed under the following conditions: cost, scope for international cooperation, social wellbeing of astronauts, psychological wellbeing of astronauts, scientific usefulness, engineering complications associated with the crew size, and risk. Kanas and Manzey, (2008) mention that having an odd number of crew members is more desirable from a social and psychological standpoint; this was taken into account in the trade-off study shown in Table 1-3. The weighing ranges from 1 (lowest) to 4 (most important) and the score from +2 to -2. From this it was determined that having five crew members would be the optimal strategy for Mars-X going forward.

Table 1-3: Trade-off Summary for Crew Size

Criteria	Weight	Explanation of Criteria and Weighting	Crew Members		
			Five	Six	Seven
Cost to send entire crew to LEO	1	The difference in price for launching five or seven astronauts is in the order of USD 100-160 million (Whittington, 2012)	2	1	-1
Contribution to international cooperation	3	The promotion of international cooperation is one of the main aims of Mars-X The greater the number, the higher the likelihood that a variety of nationalities can be sent.	-1	1	2
Contribution to social wellbeing of the crew	3	Odd numbers make decisions easier because a majority is easily reached in situations where decisions need to be made by the entire group. Larger groups were found to be better than smaller ones because there is more social interaction and a greater tendency towards the formation of stable leader-follower relationships.	1	-1	2
Contribution to psychological wellbeing of individual	4	The importance of providing to the astronauts significant daily activities and a pleasant environment is paramount since the entire project hinges on their being content. Sending too many astronauts may	2	1	-1

members of the crew		mean that some of them have fewer activities to perform, leading to depression.			
Scientific usefulness of crew	2	This criterion assumes that more science can be performed with a greater number of crew members. The gathering of scientific data is one of the reasons for Mars-X but it is not central to the success of the mission.	-1	1	2
Engineering complication	1	The weighting for this criterion assumes that the increase in mass and volume when adding extra crew members is not a significant fraction of the total for the spacecraft.	1	1	1
Risk to astronauts	2	Here the assumption is made that the greater the number of astronauts, the greater the chance that injury or death may occur. It is impossible at this point to know exactly how a bigger crew will affect the likelihood of something bad happening to them therefore a medium weight is given.	2	-1	-2
Total Score (weight × score added)			**11**	**5**	**9**

1.1.5.3 Propulsion and Launch Systems

The most relevant current and upcoming heavy lift launchers were analyzed for use in the mission, with particular emphasis placed on the payload capacity and fairing volume. As can be seen from Table 1-4, both SLS and Falcon Heavy have a greater capacity than the other launchers and are the only two viable options for this mission. Angara rocket is at its very early development stage and there is no precise first flight date, nor price per kg, so it is difficult to consider this as a possible launcher, even though its capacity in LEO is similar to the Falcon Heavy. Research was also conducted on Chinese rockets; however the lack of information regarding the upcoming heavy lift Chinese rockets caused exclusion from the analysis. The finalists were Falcon Heavy and SLS and a second analysis was completed (Table 1-5) considering the optimal propulsion system that could be used for this mission once in LEO. Nuclear propulsion offers far greater efficiency than traditional chemical propulsion systems, although using a nuclear propulsion system could also introduce an element of extra risk.

Table 1-4: Comparison of Major Launchers

	SLS (NASA, 2013f)	**Falcon Heavy** (SpaceX, 2013)	**Delta IV Heavy** (Boeing, 1999)	**Ariane V** (Arianespace, 2011)	**Angara 7** (Russian Space Web, 2008)
Payload Capacity to LEO (tonnes)	105 (28.5˚ inclination)	53 (28.5˚ inclination)	23 (28.5˚ inclination)	21 (5.6˚ inclination)	40 (51.6˚ inclination)
Fairing Volume (m^3)	1000 (excluding the cone), 1500 (including the cone)	100 (excluding the cone), 150 (including the cone)	250	240	Lack of Information
Launch Cost (USD per kg)	20000-30000	1000-2000	9000-13000	10000-16000	Lack of information

Table 1-5: Number of Launchers Required Using Different Propulsion Systems, SLS and Falcon Heavy

Main Propulsion Stage	Number of launches needed from Earth	
Nuclear	SLS	6 + 1 crewed launch
	Falcon Heavy	12 + 1 crewed launch
Chemical	SLS	25-30
	Falcon Heavy	60-70

Falcon Heavy will be ready by 2015. SLS cargo will fly for the first time in 2024. Moreover a launch with SLS cargo will cost about half a billion dollars (NASA, 2013f), while one launch with Falcon Heavy will be about USD 125 million (SpaceX, 2013), meaning that Falcon is notably cheaper. Falcon Heavy allows the mission to begin earlier compared to using SLS due to this lower cost. However, one limiting factor of Falcon Heaving is fairing volume which is lower than SLS. The ideal solution identified in this trade-off is to use Falcon Heavy, and use a modified version of the payload shroud in order to allow the mission with fewer launches.

1.1.5.4 Phobos versus Deimos

A difficult choice was the selection of where to land: Phobos, Deimos, neither, or both. As an infrastructure is being established for future human missions to the Martian system, having a base and fueling station on Phobos would be easier to travel to than Deimos from Mars. From a base on Phobos it is possible to have line of sight communications with a location on Mars for 4 hours every 11.1 hours, whereas Deimos has line of sight for 2.5 days every 5.5 days (Hopkins and Pratt, 2011). It was initially decided that Deimos' longer access periods would be more advantageous, however it was then decided that, in order to help set up future infrastructure, a satellite communication network would be established. Having a satellite communication network around Mars offers continuous communication with the Martian surface from a possible base on Phobos. This mission will include a jumping rover, or a hopper, for geological research at geysers at the South Pole on Mars. However from Phobos it is only possible to have line of sight communications between latitudes of ±64.8˚ while from Deimos it is possible to see between latitudes of ±80.2˚ (Hopkins and Pratt, 2011). Nevertheless, to communicate with the polar regions it will be possible to use orbiters, such as Mars Atmosphere and Volatile EvolutioN (MAVEN) and ExoMars, as communication relays increasing the use of future infrastructure. Mars occults the Earth more from Phobos than Deimos, and this means that from Phobos there is less line of sight communication time with Earth, but the communication network nullifies this restriction.

By landing on one of the craters on Phobos a high level of protection from radiation can be provided. In addition, to get a sample return from Mars it requires a lower delta-Vs to go from its surface to Phobos (1.25 km/s from an altitude of 200 km at the equator) rather than Deimos (1.75 km/s) (Hopkins and Pratt, 2011).

1.1.6 Major Assumptions

The major assumptions for the Mars-X mission cover key technologies development and include:

- Nuclear engine development
- Radiation shielding
- Cryogenic fluid management and fueling infrastructure
- Closed life support system
- Low gravity and high radiation environment mitigation for humans
- Advanced EVA and spacesuits

These listed crucial technologies will be developed by participating members of the Mars-X consortium which is further outlined in Chapter 5 and it is assumed that development will occur by the time they are needed.

1.1.7 Conclusions of CARR

Mars-X combines the goals, efforts and aspirations of the current prevailing trends in human space exploration: putting humans on an asteroid and going to Mars. By embarking on the Mars-X adventure, humanity takes one step closer to conquering its dream of setting foot on the Red Planet. At the same time by landing on Phobos humans will have access to a planetary body strongly believed to be a captured asteroid, and exploration of all its features will be possible, including: investigating the nature of asteroid material for potential future utilization, demonstrating spacecraft berthing with an asteroid body, as well as living on it for a period of time.

The GER states that *"Decisions regarding destination sequencing will not be made by the ISECG, but will follow national policy decisions and international consultation on multiple levels"* (ISECG, 2011). That means agencies are open to a different path, such as the third option that Mars-X is offering to the GER ('Phobos next').

The conclusion of the CARR process marked the first big milestone of the project and laid the foundations for the Mars-X mission. The rest of this report is built on these foundations.

1.2 Through Space and Time

This section summarizes the Mars-X roadmap. The first phase of the mission will consist in carrying mission support equipment into the Martian orbit and the rovers onto the Martian surface between 2020 and 2024. The second and third phase will consist in launching the crew vehicle to Mars in 2024 and back in 2027, as shown in Figure 1-2

There are major elements in this mission such as nuclear engines, cryogenic fuel tank (zero boil-off), rovers, life support system, and the berthing mechanism. They will follow several phases such as design, testing, certification, and operation in accordance with their individual time schedule.

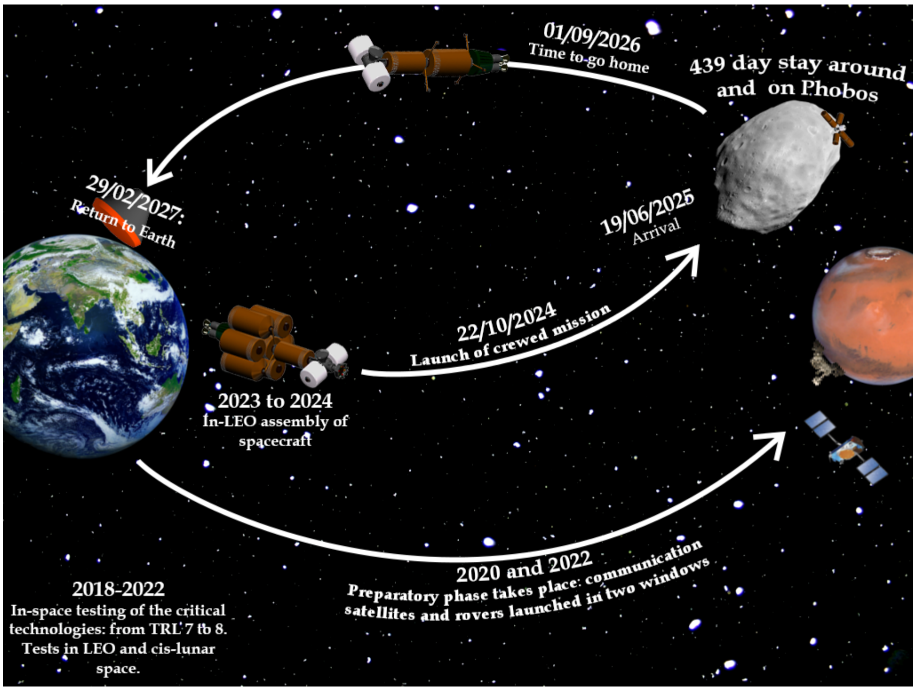


Figure 1-2: Mars-X Roadmap

Figure 1-3 demonstrates the overview of the Mars-X Mission timeline, which commences at the beginning of 2014 and finishes at the end of 2027. The main categories of the mission are shown in the orange box, which follow horizontally along the timeline in the yellow box. This figure visually summarizes the status of the manned space mission between the Earth and the Mars, including the launching vehicles, satellites, rovers, astronauts, spacecraft and other major elements.

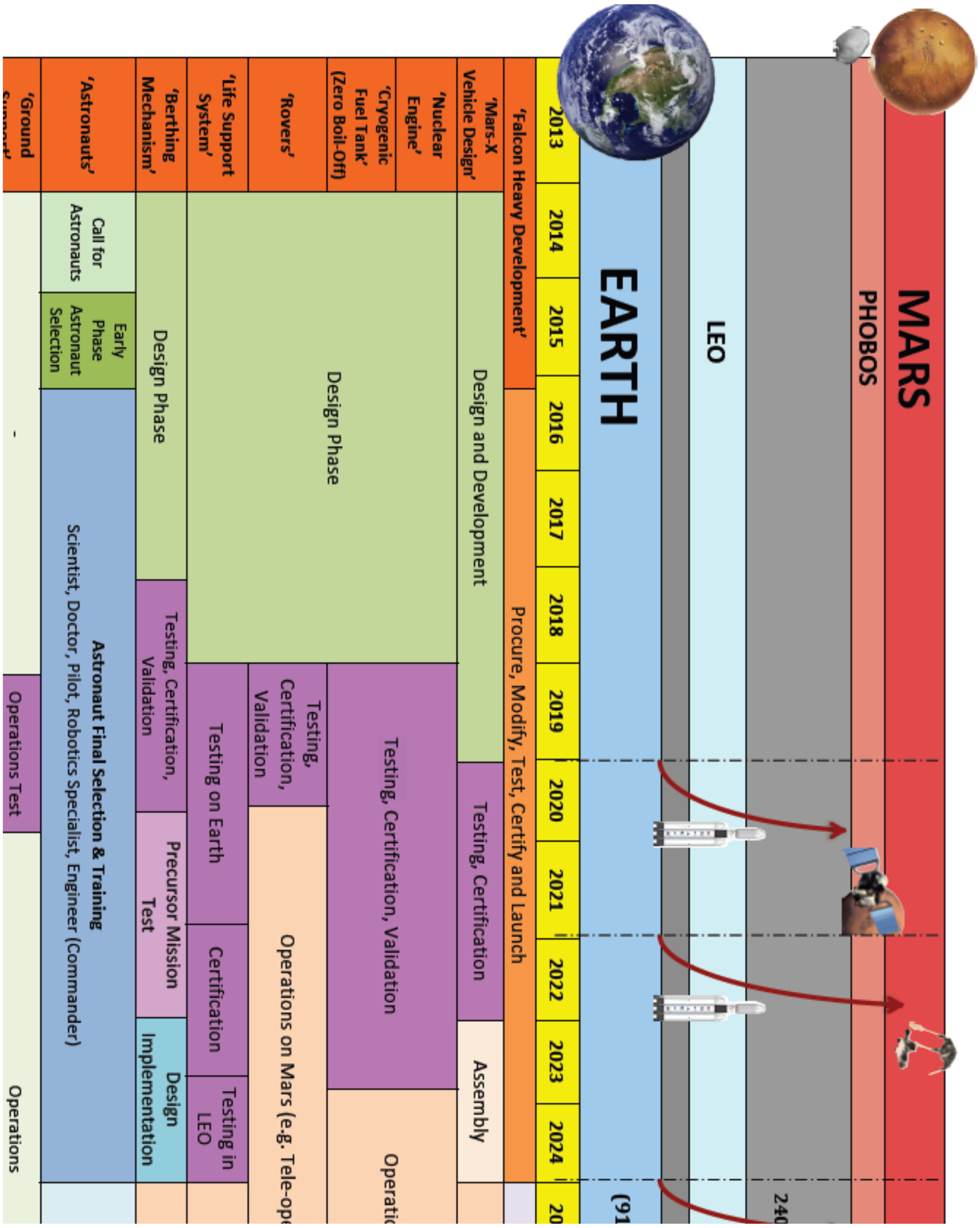


Figure 1-3: Timeline of Mars-X Mission

2 WHY EXPLORE MARS FROM ORBIT

2.1 For the Benefit of Humankind

In this project, there is an important question that has to be addressed: “Why are we going to Mars?” When trying to address this question, many generic and specific answers come to mind, however it has to be said that there is not a good solution for everyone and that “why go to Mars” may be addressed by another important question: “Why not?” This would summarize a feeling of exploration and the adventurous spirit of humans.

To try to answer the question, first it will be addressed in a more structured and analytical way, giving specific and tangible reasons that today's society is capable of understanding. Towards the end a more humanistic and abstract answer will act as a connection between all the possible answers.

Another point that has to be mentioned is that there is a difference between asking, “Why go to Mars?” and “Why Mars-X?” (the latter being specifically a mission to Phobos). The essence is, however, the same. Mars-X is a stepping-stone towards a final goal, Mars; therefore the reasoning has common motivations.

2.1.1 Importance of Exploration

The scientific aspect of the mission is an important motivator, further discussed in the next Section 2.2, for the continuation of discovery and exploration. It is always interesting to increase knowledge and to discover the unknown. As explained later, however, this exploration also provides some insights into the human species. The scientific data and knowledge obtained by the rovers, satellites, and the human experiments done on the surface of Mars or on the Martian moons, are all valuable for different reasons.

In terms of planetary science, Mars and Earth are very closely related. Learning about Mars, its origins and evolution, can provide insights into the processes that shaped the Earth. The atmospheric composition, what happened to the water assuming there were big rivers, what is the composition and structure of the planet: these are all valid scientific driving questions for exploring other parts of the solar system.

This project is expected to be a precursor mission to a human landing on Mars, therefore all this scientific knowledge is of considerable importance. The more information available about Martian characteristics and environment, the better the understanding of what future humans will face when they land on the surface and how they will overcome the possible difficulties.

The engineering and technological perspective links directly to the idea of a precursor mission. Humans like adventure, and at some point in history, assumed risks at any cost (and here cost is not only material). However, if risks can be prevented, or even assessed, the decision to go or not go forward on the adventure is easier.

A final mission to Mars would involve a huge amount of new technologies specifically tailored for such an endeavor. A mission to Phobos, or to an asteroid, can be used as a good test for a lot of the technologies needed for a human to walk on the surface of Mars. The characteristics of a life support system for a mission of around 900 days, the propulsion system selected, the radiation shielding and the artificial gravity are just some of the main technologies discussed in the following chapter that have to be designed, developed, and tested in situ in order to accomplish a further mission.

There is also a major ethical question, discussed in Section 5.10.3, about the risks for human life and whether or not putting humans in such conditions is ethical. All the knowledge obtained from this mission would be used to acquire more input in what happens to humans during a long period in a different gravity environment, for example how human bodies react to the radiation, what are the psychological effects on humans beings in an enclosed environment for two and a half years. There is much information to be processed and lots of conclusions that are important for next steps.

A challenge like a human mission to Mars brings another factor to the table: national prestige and political reasons to be part of it or not. In 1969, the United States of America (USA) won the "Space Race" against the Soviet Union (USSR) by achieving the first human landing on the Moon. Since then, the public image of the National Aeronautics and Space Administration (NASA) has been that of a highly prestigious space agency. People wanted to work for NASA, other space agencies were born, and Russia continued its activities as well. The landing on the moon demonstrated more power than any other political action, and sent a message to the world (US Information Agency, 1959).

In this case, a precursor mission for a human landing on Mars provokes not only the question "Who can take part in such an endeavor?" but also "Who doesn't want to take part?" The Mars-X Consortium will be discussed in the following chapters; this is a combination between private companies and governments joining their forces for this mission. If there is a big step forward, and if a major space agency signs for such a mission, the other potential actors will have to decide if they prefer to stay safe from the risks of failure on one hand, or if they want to be part of history and become another dominant space power on the other.

International and national policies and politics will likely play an active role in such an undertaking. In this project, it is suggested that every potential partner (private or public) that wants to participate, and fulfills some minimum requirements such as political and economic sustainability, should be considered as an equal partner of the consortium, as described in Chapter 5. It is believed that a human mission to Mars should be important enough to leave differences apart, and join forces, knowledge, technologies, and dreams for a common goal.

National prestige is more intangible than tangible and represents a strategic, a political, and an economic asset to be taken into account; in addition it drives a lot of the reasoning behind the answer to the question.

There is another interesting factor to mention; if different nations can contribute in their own ways to a mission like Mars-X, this could start new relationships, political partnerships and also set the basis and become an example for future such collaborations. The future seems to be easier if countries join forces to face major challenges, rather than facing issues without allies. It has been shown that the actions of some actors affect others, for example in the case of climate change.

Another question addressed in depth in the following chapters is the possible value return to the partners. Value returned does not strictly mean economic return, but the returned values would be in areas such as: education, national pride, space awareness, and inspiration.

2.1.2 Future Implications

Forecasting the future implications of this mission is not trivial and a lot of assumptions have to be made. First, the case in which the mission does not succeed must be considered, taking the extreme of failure to be the death of the entire crew; there are, however, many system failures that could occur across the critical spectrum. If the crew does not survive, which is the first top level requirement, it could have a huge detrimental impact on future exploration, and on the continuation of the roadmap. The other consequence could be similar to that of the Apollo program, where three astronauts died in Apollo I, but the program kept going successfully.

In both scenarios, the values returned to the population would be significant. This endeavor would bring a human feeling of being a part of something big, and the impression that humanity achieved another significant goal. All the technologies and spin-offs that would end up benefiting the general public are values gained.

The boost, in all the Science, Technology, Engineering and Mathematics (STEM) subjects, would result in a large number of engineers and scientists willing to continue the route, which is to put the first human on the surface of Mars. If the mission succeeds in its entirety, the knowledge acquired in all aspects would be an indicator of how far humanity would be from seeing a human being on another planet, which is something never before achieved.

Figure 2-1 shows an image of Planet Earth seen from the Moon. The impact on society of images like this one is immeasurable. It is part of human nature to explore, because humans are curious. It could be said that the current generation owes this to the next generation.

Figure 2-1: Earth Rise from the Moon [NASA, 2009]

Space is a challenge. Each new step taken in space exploration is something never done before. When facing something unknown, finding new answers to old and new questions is an obligation to our human curiosity. Standing up and facing new challenges has contributed enormously to living standards today, and is what should bring people to Mars and beyond.

The destinations are Phobos, followed by Mars. But maybe humanity needs a global mission in order to reach a common goal, and can start seeing Earth as astronauts see it: without borders, fragile, and vulnerable. Perhaps an external point of view is again needed in order to realize that conflicts between people are trivial in the larger scheme of things. Humans as a species should pursue a common goal and leave a better planet to future generations, giving an example of how to face challenges.

Space is there, we are part of it, and we want to explore it.

Mars-X chooses to go to the moon of Mars, not because it is easy but because it is hard.

2.2 Extending the Boundaries of Human Knowledge

2.2.1 Introduction to Martian Science

Equipped with his five senses, man explores the universe around him
and calls the adventure science.
– Edwin Hubble (1889-1953)

Ever since the early days of human civilization, the desire and dream to explore and the yearning for knowledge have gone hand in hand. From the days of Cook and Darwin, humanity has travelled far in search of understanding. The Mars-X project will realize advances not only for science, but also for humanity and future explorations into the cosmos. This will be done through several key areas of research; the Radiation Environment of Mars, Atmospheric Conditions on Mars, Martian Geology, Volcanism, In Situ Resource Investigation, and Life on Mars. From these fields of science, specific goals will be achieved in order to allow the advancement of humanity to this generation's New World: Mars.

In the following sections, current knowledge and opportunities for future research shall be discussed with an overarching theme of research for future human missions to the surface of the Red Planet and shall comply with the scientific objectives of this project.

2.2.2 Radiation Environment of Mars

2.2.2.1 Introduction

The radiation environment on Mars is a very important area of research for future human missions to the Red Planet. The main two sources of radiation on Mars are discussed below; Solar Particle Events (SPE) in Section 2.2.2.2 and Galactic Cosmic Rays (GCR) in Section 2.2.2.3. There is a third type, radiation caused by reactions of incoming radiation with the Mars regolith (Clowdsley et al., 2001), but this report will not focus on them. Section 2.2.2.4 will cover a recent discovery made by the Mars Science Laboratory (Curiosity), that atmospheric conditions on Mars correlate with the amount of radiation on the Martian surface. The protection of the astronauts is of utmost importance. Harmful radiation can severely damage their health. This is why the radiation environment must be researched thoroughly before sending humans to Mars. The effect of radiation on Mars on humans is outlined in Section 2.2.2.5.

2.2.2.2 Solar Particle Events (SPEs)

There are two main types of SPEs; Solar Flares and Coronal-Mass Ejections (CMEs). They are most commonly comprised of protons, hence sometimes being called Solar Proton Events, but can also consist of Hydrogen atoms, Helium ions and HZE ions. It has been reported (Reames, 1995) that during a solar maximum in the region of 100 solar flares per year have been detected, during solar minimum this number drops to approximately 2. Whereas at solar maximum only 10 CMEs per year have been observed. But it has been seen that these solar flares have smaller fluxes and exist for a shorter amount of time (approximately a few hours, whereas for CMEs approximately a few days) than CMEs (Reames, 1999).

SPEs can be harmful to astronauts and therefore, in order to send humans to the Martian surface, radiation levels from SPEs must be known. Models done by Leblanc et al. (2002) show that Hydrogen atoms and protons with an energy of >83 MeV when entering the Martian atmosphere will reach the surface with typically an energy of ~95% of their initial energy. For Helium atoms an initial energy of >335 MeV is needed and for heavier atoms such as Oxygen and Carbon the atmosphere of Mars is sufficiently thick to stop them reaching the surface (Leblanc et al., 2002). Protons of ≥30 MeV are thought to be dangerous to humans for exploration on Mars (Feynman and Gabriel, 2012).

It is worth noting that during a solar maximum when solar particle events are greatest, galactic cosmic rays, see Section 2.2.2.3, are at their least numerous. This is due to the higher than average number of solar particles scattering the incoming GCRs before they can interact with anything.

2.2.2.3 Galactic Cosmic Rays (GCRs)

Galactic Cosmic Rays are very high-energy particles which are thought to originate from the supernovae of massive stars (Ackermann et al., 2013). According to Schimmerling (2010) most of the observed GCRs are protons (85%), followed by Helium atoms (14%) and HZE particles (1%). As mentioned in Section 2.2.2.2 the flux of Galactic Cosmic Rays is anticorrelated with the solar activity and it is believed that the amount of GCRs of below about 1 GeV/nucleon are reduced by about 90% by the heliosphere (Klapdor-Kleingrothaus and Zuber, 2000).

The radiation environment for both SPEs and GCRs at one meter below the Martian surface has been modeled by Dartnell et al. (2007). The flux decreases as the energy increases; it is predicted that there is a flux of approximately 10^6 protons per cm^2 per year of 1 GeV, but only approximately 1 TeV occurs per cm^2 per year. Worst case solar minimum conditions of 1 TeV/nucleon GCRs and a range of 10-200 MeV solar particles were used for the generation of this model.

2.2.2.4 Radiation on Mars Due to Environmental Conditions

A recent discovery by the Mars Science Laboratory (MSL) (NASA, 2012c) has found that the radiation levels on the Martian surface is approximately the same to radiation levels in Low Earth Orbit and varies both on short and long term time scales. These radiation level variations are shown in Figure 2-2 and Figure 2-3.

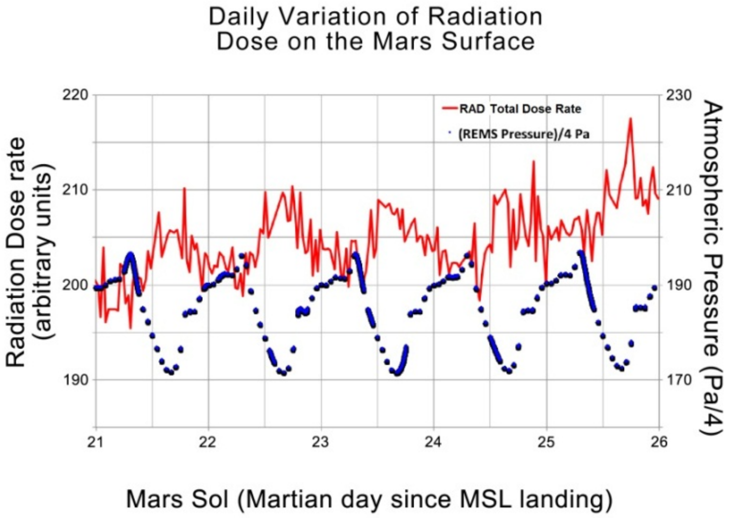


Figure 2-2: The Total Radiation Dose Rate and Atmospheric Pressure [NASA, 2012a]

Figure 2-2 shows atmospheric pressure and total radiation dose rate as measure by the Mars Science Laboratory over a short term time scale. It should be noted that the atmospheric data has been normalized and the radiation dose is in arbitrary units. It can be seen from Figure 2-2 that as the atmospheric pressure increases the radiation dose decreases by approximately 3-5%. This is due to the heating of the atmosphere by the Sun, as it is heated, the pressure and thickness of the atmosphere increases which leads to a "bulge" on the day side of Mars (NASA, 2012d). To equalize out on the night side of Mars the atmosphere becomes denser which corresponds to increased radiation protection on Mars (NASA, 2012c).

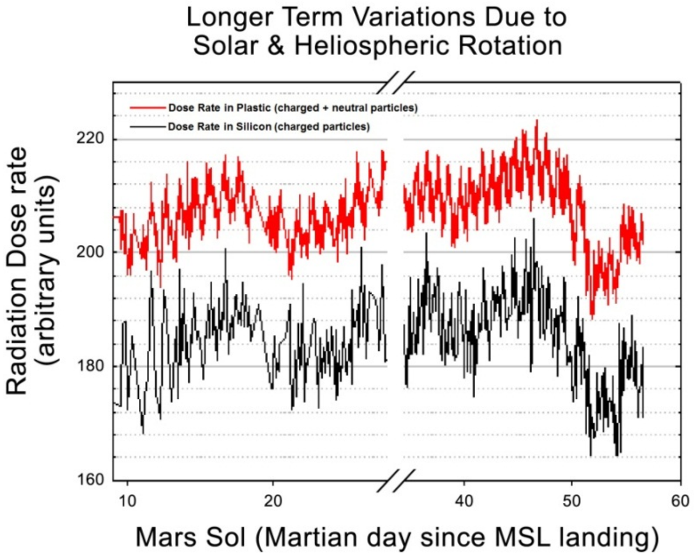


Figure 2-3: The Dose Rates for Only Charged Particles and Both Charged and Neutral Particles [NASA, 2012b]

Figure 2-3 shows the longer term radiation variation on Mars, as well as the daily fluctuations, as measured by the Mars Science Laboratory. It is believed that the long term variations are due interplanetary gas and plasma near Mars. This gas and plasma is magnetically linked to the Sun and rotates with the Sun with a period of roughly 27 days. The gas and plasma causes periodic shielding from galactic cosmic rays over the aforementioned 27 days. It should be noted these radiation measurements of the surface of Mars are the background radiation from space and do not include any detection of solar flares and CMEs.

2.2.2.5 Effects on Humans for Future Missions

The main reason for investigating the radiation environment on Mars further is to ensure a safe human mission to the Red Planet in the future. An important aspect of this research is how the amount of harmful radiation particles on the surface relates to the amount of radiation humans will receive in quantifiable figures. Saganti et al. (2008) provides a comprehensive model of the radiation environment on Mars; seen in Figure 2-4.

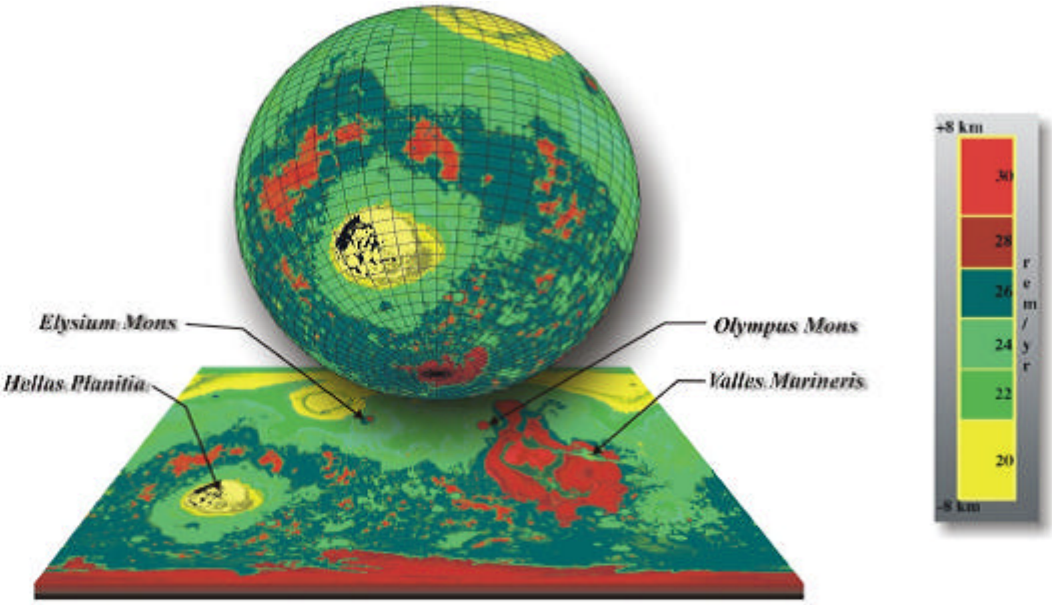


Figure 2-4: A Map Showing the Amount of Effective Total Skin Dose at the Surface of Mars [Saganti et al., 2008]

The above figure shows the amount of effective total skin dose at a solar minimum. It can be seen that it ranges from 20-30 cSv/year and relies heavily on the altitude. So for any future human mission to Mars it would be more advantageous to settle a colony in a lower altitude region or possibly sub-surface.

As this is just a simulated model it would be unwise to send humans to the surface of Mars until robotic missions such as Curiosity or ground and flying rovers proposed in this mission map the surface of Mars more accurately.

2.2.3 Atmospheric Conditions on Mars

2.2.3.1 An Introduction to Current Atmospheric Models of Mars

It is of key importance to have accurate models of the Martian atmosphere. Currently the two most accurate models of the Martian atmosphere are the Mars Global Reference Atmospheric Model (Mars-GRAM) 2010 (US model), shown in Figure 2-5, and the Mars Climate Database (developed jointly by the Laboratoire de Météorologie Dynamique, Oxford University and the Institute of Astrophysics of Andalusia) (ECSS, 2008).

Mars-GRAM is an engineering-oriented model of the atmosphere of Mars. The model is founded on input data tables based on information from the NASA Ames Mars General Circulation Model (MGCM) and the University of Arizona Mars Thermospheric General Circulation Model (MTGCM). These tables give variation of temperature, density, pressure and wind components with height, latitude, time of day, and solar longitude (L_s). The tables also provide boundary layer data at topographic surface as a function of longitude, latitude, time of day, and L_S. MGCM data tables cover altitudes from the surface to 80 kilometers. MTGCM data tables cover altitudes of 80 to 170 km. A modified, latitude-longitude dependent, Stewart-type thermospheric model is used for altitudes above 170 km, and for dependence on solar activity at higher levels. Recent documented applications of Mars-GRAM include aerobraking operations of Mars Global Surveyor, prediction and validation of Mars Pathfinder hypersonic aerodynamics, aerothermodynamics, and entry dynamics studies for Mars Polar Lander (Justus and Johnson, 2001). .

The Mars Climate Database is a database of atmospheric statistics compiled from Global Climate Model (GCM) numerical simulations of the Martian atmosphere. The database extends up to about 250 km in altitude; in addition to statistics on temperature, wind, pressure, and radiative fluxes, it provides data such as atmospheric composition (including dust, water vapor and ice content) and can represent the variation of dust in the atmosphere and solar EUV conditions. The models used to compile the statistics have been extensively validated using available observational data (Forget, Millour and Lewis, 2012).

Both models are in the process of being continuously revised as more data is acquired through atmospheric sampling by rovers and orbiters. The data acquired from previous Mars missions is not extensive enough to allow in-depth identification of the atmospheric regimes and an understanding of the patterns and the controlling processes (National Research Council, 2011). For example, the inter-annual variability of global dust events is not yet understood. Recent observations from Mars Global Surveyor, Mars Reconnaissance Orbiter, Mars Express, and Phoenix have also shown complex and not yet understood structures in the vertical profiles of airborne dust, unexpected distributions of water vapor, and surprising precipitating ice clouds (National Research Council, 2011).

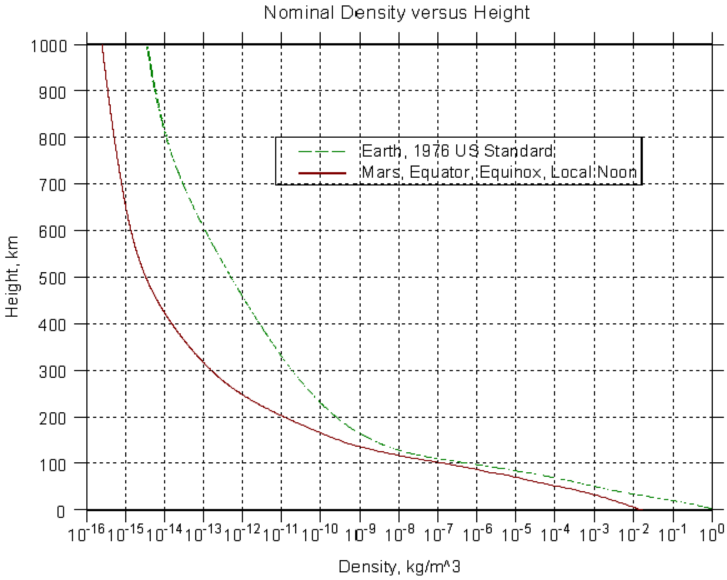


Figure 2-5: Comparison of Nominal Atmospheric Density versus Height for Earth and Mars [NASA, 2001a]

In Figure 2-5 Earth values are from the 1976 US Standard Atmosphere and Mars values are from Mars-GRAM1-4 at the Equator during equinox and local noon solar time (NASA, 2001a). In order for a human mission to accurately perform the aero-capture, Entry, Descent and Landing (EDL) and launch maneuvers on Mars it will require precise measurements of the atmosphere composition, density and the frequency and strength of the dust storms. All of these variables experience great variations with altitude from the surface of Mars because the atmospheric circulation is coupled to three cycles (National Research Council, 2011):

- Dust cycle: can modify radiative properties of the atmosphere.
- The carbon dioxide cycle: modifies pressure cycles.
- The water cycle: causes formation of clouds, hazes and frost.

Typically during a reentry trajectory the interaction of the Martian atmosphere with a reference surface (such as the spacecraft) can be categorized in four regimes: free molecular (particles of atmosphere can be modeled without interaction), transitional (collision among particles is important, but flow is not continuum), hypersonic continuum and supersonic continuum (Schoenenberger, 2005). As shown in Figure 2-6, there is currently a gap in atmospheric measurements at altitudes usually corresponding to the hyper and supersonic regimes. Such gaps could be filled by the use of UAVs, flying rovers, or ultra-low altitude satellites. Acquiring knowledge of the unexplored regime would ease the development of advanced aerobraking and reentry techniques. The measurements should take account of the variability of the Martian atmosphere on diurnal, seasonal and inter-annual scales in both ambient and dust storms conditions to support engineering designs, leading to a lighter heat shield (Mars Exploration Program Analysis Group [MEPAG], 2010). Current engineering models are not considered to be accurate enough to support a manned EDL maneuver (MEPAG, 2010).

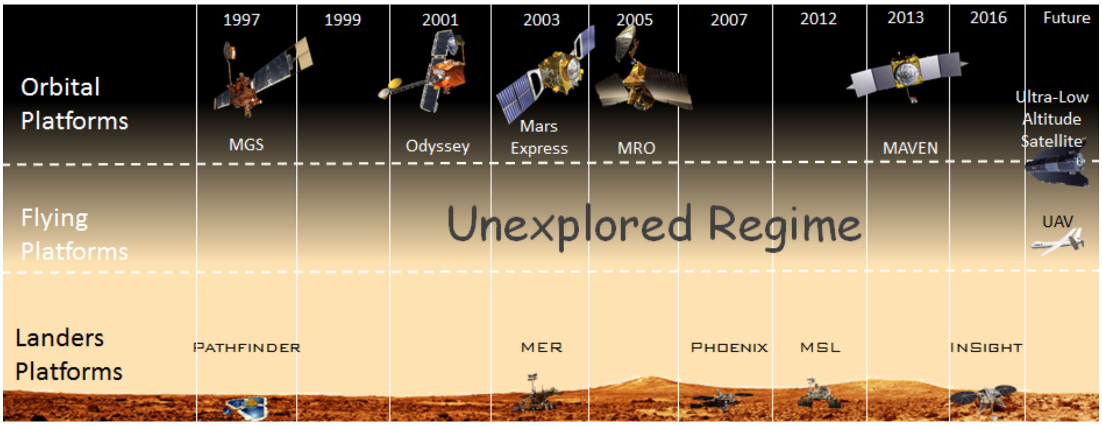


Figure 2-6: Gap in Atmospheric Measurements [Image adapted from Doddridge, 2011]

Currently the behavior of Mars' atmosphere is unpredictable due to the numerous dust storms and its density can fluctuate significantly from day to day. Dust storms can have a significant effect on low orbiters and landers. The intensity of dust storms varies on a yearly basis due to the absorption of different visible radiation doses and also on a seasonal basis, and it is typically stronger during Martian spring. In addition, in approximately two weeks a regional dust storm can evolve into a global dust storm and, depending on the particle size, Mars atmospheric dust can remain floating for months (Haranas and Pagiatakis, 2011). Dust not only reduces a satellite's lifetime, but also affects the electronics and communications systems of orbiters, landers and EVA suits; charges might be suspended in dust activity. The amount of charge contained in these events, their spatial and temporal variations, and discharge mechanisms remain largely unknown (MEPAG, 2010). Hence it is important to have more detailed studies about dust properties and atmospheric conditions.

2.2.3.2 Robotic Versus Human Missions

There is a critical reason behind sending humans in Martian orbit to operate rovers: reduced communication latency, which allows almost real-time communication. There are many ways in which this could benefit the mission:

- Humans would be able to immediately identify spots of interest and quickly redirect the flying rovers towards it
- Flying rovers or low orbiters would be at risk during dust storms. Humans could detect those dust storms and could make the flying rover land or could make the orbiter raise its altitude to go out of the storm reach. In this way the satellites would avoid getting damaged.
- In general, humans provide fast response to unanticipated events

2.2.4 Martian Geology

In this section, a few select features of the geological landscape of Mars will be discussed. The first part will outline what is known about Mars from previous exploration missions, both ground and space-based. The second part will pinpoint areas in which there are open questions relating to the origins of certain features. Finally, a number of potential experiments will be outlined for inclusion in the Mars-X mission architecture.

2.2.4.1 The Geological Landscape

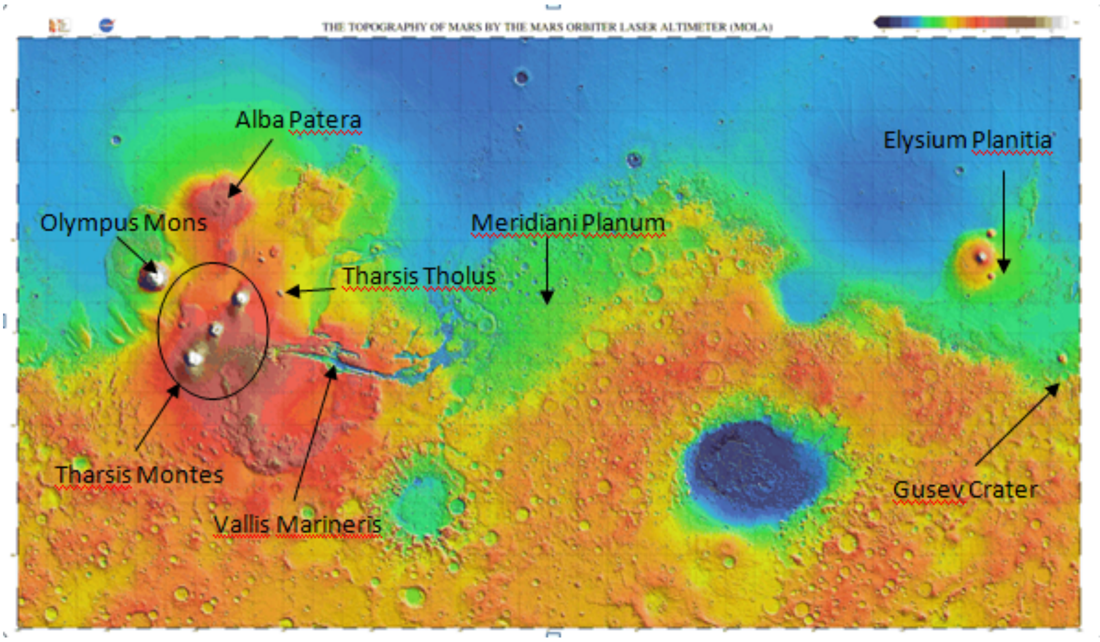


Figure 2-7: New MOLA High-Resolution Global Map [Adapted from NASA, 2001b]

Figure 2-7 shows a number of geological features of interest on Mars. The following is a brief summary of this selection.

Valles Marineris is an intriguing canyon system that runs along the Martian equator. It is over 4,000km long and 6.5km deep; by comparison, the Grand Canyon in Arizona is about 800km long and 1.5km deep. The image below (Figure 2-8) shows this system in more detail, extending from Noctis Labyrinthus in the west to even more chaotic terrain in the east.

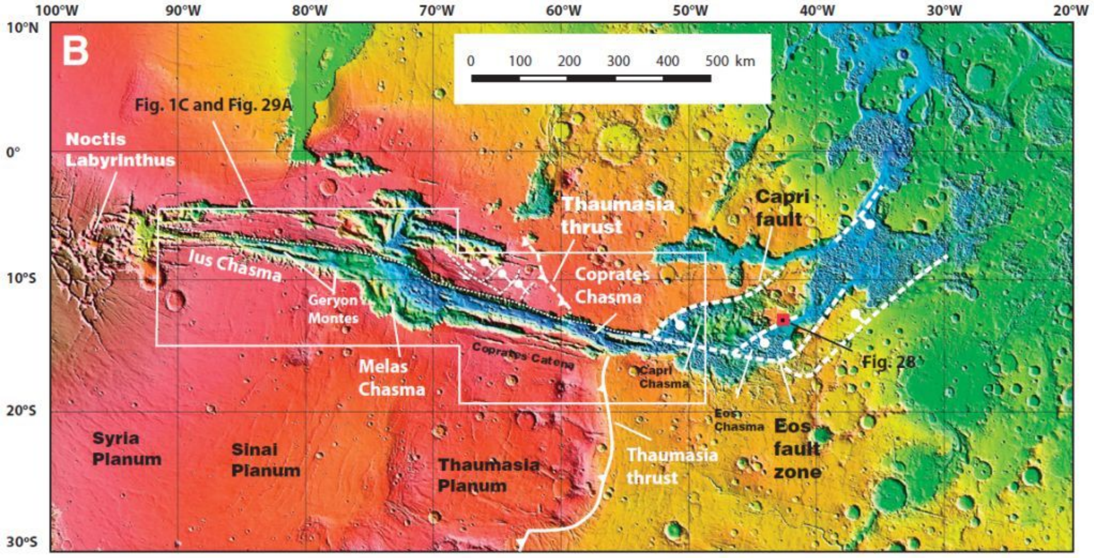


Figure 2-8: The Possible Fault Lines Across the Valles Marineris [Yin, 2012]

It is thought to be large crack or rift in Martian crust that formed as the planet's crust and interior cooled, affected by the more buoyant crust in the Tharsis region to the west, and subsequently widened by erosion (NASA, 2013b). There is much evidence in this canyon of features that were likely formed by the flow of liquid water.

Meridiani Planum is the landing site of NASA's Opportunity Rover. It is one of the smoothest, flattest places on Mars and is characterized by local surfaces rich in an iron oxide mineral called gray hematite, which on Earth usually forms in a wet environment.

Gusev Crater is the landing site of NASA's Spirit Rover, which has ceased communication with Earth since 2010. This crater is near the transition between the planet's ancient highlands to the south and smoother, lower plains to the north. Further discussion of the hemispheric dichotomy is given later in this section. The crater is about 160 km across and was about 7 km deep when it formed billions of years ago. Flowing water may have eroded the valley by cutting through the crater's rim and creating a lake inside. Indeed, Spirit found evidence that the local geology had been altered by small amounts of water, and cracks and coatings on rocks suggest water-deposited minerals. Spirit also discovered that the Martian dust in this region, which is typical of the dust throughout Mars, is magnetic (Bertelsen et al., 2004).

An interesting feature on Mars discovered by THEMIS on Mars Odyssey was the presence of caves and more specifically the skylights of collapsed caves on the surface. Several skylights were seen in the Tharsis Montes region ranging from 35 m to 180 m wide, with one skylight up to 178 m deep. It is believed that these cave systems are formed from lava tubes where lava once flowed.

2.2.4.2 Hemispheric Dichotomy

One of the striking characteristics of the surface topology of Mars is the dramatic change in altitude between the northern and southern hemispheres. The southern part of the planet is markedly higher in altitude than the northern plains. Figure 2-9 roughly traces the line at which the change in elevation occurs most prominently.

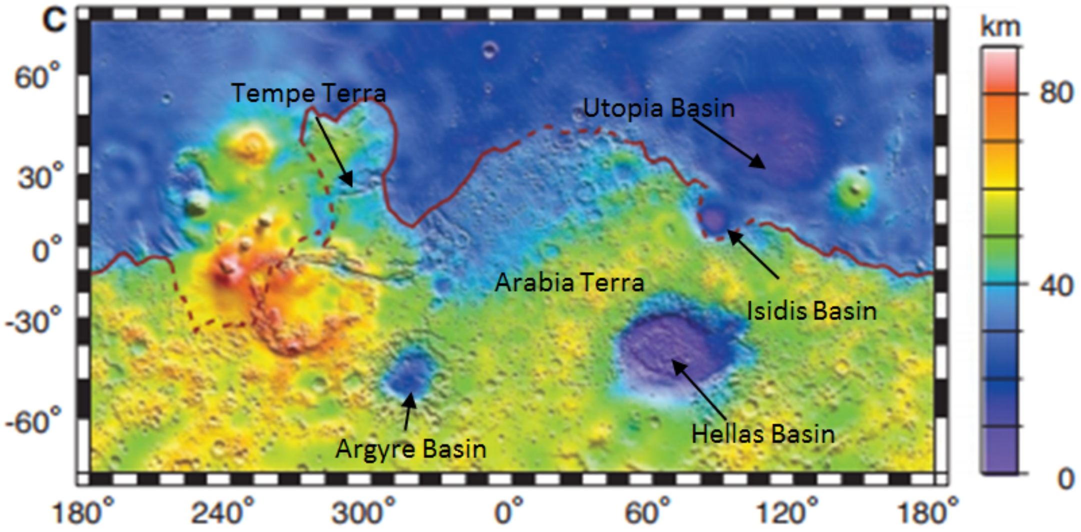


Figure 2-9: A MOLA Map Indicating the Areas of Interest Around the Hemispheric [Image adapted from Zuber *et al.*, 2000]

The three main theories for the origin of this dichotomy are creation by a single mega-impact, creation by several impacts or creation by an endogenic process such as mantle upwelling. However none of these theories on their own can accurately account for the observed topology (McGill and Squyres, 1991). Zuber et al. (2000) reported that free-air gravity maps of the planet show that there is a dichotomy present in the crustal structure as well as the surface topology, but that the dichotomies do not coincide for the bulk of the circumference of the planet. Andrew-Hanna et al., (2008) favor the single impact crater and explain that crustal flow may account for the northward shift of the dichotomy boundary. The same mechanism is invoked to explain the protrusion of the Arabia Terra region into the northern lowlands. They propose that a Borealis basin can be traced but has faded due to more recent processes. If this basin does exist, it would vastly dwarf the next largest impact craters, Utopia Basin and Hellas Basin, and the other major impact sites shown in Figure 2-9.

2.2.5 Volcanism

2.2.5.1 An Introduction to Volcanism

Volcanism on Mars is quite extensive with volcanic features covering large portions of the Martian surface. The volcanoes on Mars are basaltic in nature and are analogous to Earth's Hawaiian Island volcanoes; the main difference is scale with Martian volcanoes dwarfing those of Earth. The volcanoes are commonly shields and domes, but the environment of Mars allows for extensive lava flows to form plains. Some outstanding examples are described below and all can be located on Figure 2-7.

Alba Patera is a unique volcanic center on Mars. A patera is a flattened volcanic feature with a larger summit collapse crater. The planet's crust in this area behaves differently than in the Tharsis area. This will be addressed below in the discussion of the hemispheric dichotomy. Alba Patera could be the last of a family of giant, flat volcanoes that have been replaced by the larger shield volcanoes in the neighboring Tharsis region (NASA, 2013b).

Olympus Mons is famous for being the largest volcano in the solar system. It is roughly about the same size as the US state Arizona. It is a shield volcano, which is a type of volcano built almost exclusively from lava flows. The structure of the volcano is classified as a caldera, or a volcanic collapse crater. Olympus Mons has a base diameter of over 600 km, a height of 25 km and a summit width of 80 km (NASA, 2013b).

Tharsis Montes is the largest volcanic region on Mars, measuring approximately 3,800 km across and 10 km high. It contains twelve large shield volcanoes, with summits typically about the same elevation as Olympus Mons, which is the largest of the volcanoes within this region. Arsia Mons, a volcano in this area, has the largest caldera, measuring 120 km. The size of the volcanoes in this region is about 100 times larger than any such terrestrial feature (NASA, 2013b).

Tharsis Tholus is a partially buried shield volcano, first imaged by Viking 1 Orbiter and more recently by Mars Express. It is over 160 km in diameter, and a wide bench in the lower left of the caldera may be the remnants of an ancient lava lake. There is evidence of at least four episodes of structural deformation, and it is thought there may have been two magma chambers, allowing two volcanoes to grow simultaneously.

Elysium Planitia is the second largest volcanic region on Mars. It measures 1600 km by 2300 in area. A 2005 image from Mars Express provides compelling evidence that this region may be composed of ash-covered water ice. This region represents an uplifted region on a smaller scale than the Tharsis volcanic region. The three large volcanoes, Hecates Tholus, Albor Tholus, and Elysium Mons in this region are typically smaller than the volcanoes in the Tharsis region. Elysium Mons is the largest of the volcanoes in this region, measuring 675km across and climbing about 13 km above the surrounding plains. This volcano resembles the large shield volcanoes of Hawaii.

2.2.5.2 Methane

Since its discovery in 2003, it was established that the Martian atmosphere contains methane, a gas that is often associated with organic life. As seen in

Table 2-1 compared to Earth the average amount of Methane is very small but it has a much longer molecular lifetime due to the lack of an oxygen rich atmosphere and survives in the Martian atmosphere for between 300 and 600 years which is long enough for it to mix uniformly into the atmosphere. However Methane is not uniformly distributed across Mars, this therefore indicates that the gas is produced and/or destroyed at localized sources.

Table 2-1: A Comparison of Methane on Earth and Mars [Atreya, 2007]

Methane Data	Earth	Mars
Atmospheric Concentration	1,750 ppbv[1]	10 ppbv
Molecular lifetime in atmosphere (years)	10	600
Production rate needed to sustain constant amount (tonnes per year)	515 million	125
Main sources	Cattle, termites, swamps, rice paddies, natural gas	Bacteria? Rock-water reactions in aquifer?

[1] Parts per billion – volume fraction

Possible Sources of Methane:

Biological

- Methanogens are microorganisms that produce Methane as a metabolic byproduct during consumption of carbon-bearing molecules in the presence of water. Such organisms could in theory be present in the Martian aquifer.

Geological

- Serpentinization is a process in which ultramafic rocks react to produce hydrogen, which can then react with carbon to form methane. The conditions for serpentinization could occur by hydrothermal vents within the aquifer. Since volcanoes form over hotspots, then it is likely that the vents would form or formed in the past beneath or close by to volcanoes.

Storage

- A clathrate hydrate is a structure that is able to trap Methane and then slowly release it through fissures caused by volcanism or release it in bulk if affected by a large enough geologic event.
- The fissures and cracks in the volcanic regions of Mars could be slowly releasing methane generated deep in the aquifer; if any active sources could be identified then these could be flagged for future use as an in situ resource. One region known to expel a large quantity of methane is the Syrtis Major Planum, a shield volcano.

Some Known Sinks of Methane:

Dust devils

- Occasionally Martian winds form very statically charged dust devils. The static charge is generated by the rubbing together of dust grains; this charge can get large enough that it can degrade water molecules into peroxides which react with Methane to form Formaldehyde.

Sunlight

- At an altitude of 60 km and above, the UV splits Methane into Ethane and Hydrogen.
- Below the 60 km mark, sunlight splits water into oxygen atoms and hydroxyl radicals (OH), these oxidize methane into Formaldehyde.

2.2.5.3 Resources in Volcanic Soil

Mauna Kea is the name of a Hawaiian volcano that has been deemed a close enough proxy for the Martian volcanic environment. At Mauna Kea the soil contains the elements titanium, aluminum, iron, and magnesium among others; these could be a useful resource during future missions, and the problem is in how to change these metals to a usable state from grains of sand.

One solution worked on by Physical Sciences Inc. (2013) uses a solar concentrator to bombard a small area of the Martian soil proxy at Mauna Kea with photons, thereby raising the soils temperature and liquefying the metals. This is combined with careful computer control to create layered sheets of metal.

2.2.6 In Situ Resource Investigation

The Shallow Radar Instrument (SHARAD) was an instrument on board NASA's Mars Reconnaissance orbiter, launched in 2005. It was used to map the subsurface of the planet to a depth of one kilometer. The chief scientific objectives of using this instrument were as follows (NASA, 2007b):

- To map the dielectric interfaces in the Martian subsurface to depths up to one kilometer.
- To interpret these interfaces in terms of the occurrence and distribution of expected materials, including rock, regolith, water and ice.
- To determine the 3D distribution and state of subsurface H_2O.

The results of using this instrument over the North Pole of Mars revealed a small (approximately 100m) maximum deflection on the underlying substrate, implying that the present-day thickness of an equilibrium elastic lithosphere is greater than 300 km (Phillips et al., 2008). Soundings taken in the eastern Hellas region have revealed properties entirely consistent with massive water ice, representing perhaps the most extensive non-polar ice region yet found on Mars (Holt et al., 2008).

Using SHARAD on a Phobos orbiter will allow a good resolution (10-20 m vertical resolution, 300-1000 m along track resolution, 1500-8000 m cross track resolution) of subsurface structure and isolate areas of interest for deep drilling.

2.2.7 Life on Mars

2.2.7.1 Introduction

Even though the search for life on Mars is not one of the key research fields for landing humans on the surface of Mars, it is one of the essential activities that need to be undertaken in order to answer one of humanities most fundamental questions: are we alone in the universe? In the following sections the conditions for life on Mars (Section 2.2.7.2) will be detailed and the potential biomarkers and biosignatures for life (Section 2.2.7.3) will be discussed. Currently there has been no detection of intelligent life, but recent discoveries by the Mars Science Laboratory (NASA, 2013d) and reanalysis of Viking data (Navarro-González et al., 2010) suggest that there could have been habitable environments on Mars, which could have harbored life, but at the moment this is still speculative.

2.2.7.2 Conditions for Life on Mars

In order to search for life on Mars and attempt to answer the question stated above it is important to understand the conditions for life on Mars, and if they exist or have existed at any point on the Red Planet. For this several assumptions have to be made. According to the National Research Council's (2007) "An Astrobiology Strategy for the Exploration of Mars" the assumptions are as follows:

- Life is based on carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur and bio-essential materials.
- Life requires water.
- Life exists in the form of self-contained, cell-like entities.
- Life has physical characteristics that are determined by the same physical, chemical, and thermodynamic factors everywhere.
- Life employs complex organic molecules in biochemical roles.

These assumptions give a good baseline for searching for life on Mars, but one must also consider the Martian environment against these assumptions in order to see if these assumptions are valid and the environment on Mars is feasible to sustain life.

As Mars formed from the same carbonaceous chondritic material as Earth it can be assumed that life forming processes on Mars could have used the same elements as were used on Earth. Mainly those stated above in the assumptions. All of the elements listed above have been detected on Mars, however the scarcity of Nitrogen is of concern (Capone et al., 2006) regarding the evolution of life on Mars. Most of the initial Nitrogen could have been lost from the planet by impact erosion of the atmosphere during the heavy bombardment period or by photochemical processes (National Research Council, 2007).

An almost universally accepted environmental factor for the creation and sustainability of life is the presence of water. This need for the accessibility of water has implications on the temperature of the life-forming environment, and while this is not necessarily temperatures of between 273 K and 373 K this range can be taken as a good rule of thumb. While metabolism can continue down to temperatures of 233 K, there is no evidence of cell replication below 248 K or active cells below 253 K (Buford Price and Sowers, 2004; MEPAG, 2006). In laboratories on Earth life has been cultured up to temperatures of 394 K (Kashefi and Lovley, 2003). Current estimates of the temperature range state a minimum temperature of 130 K (Astronomy Café, 2004) and a maximum of 308 K (NASA, 2007a), with the mean being 210 K (NASA, 2010). Other environmental conditions such as water activity and radiation resistance are discussed in more depth (National Research Council, 2007).

2.2.7.3 Biosignatures of Life on Mars

Molecular Biosignatures

There are several fundamental components of life that, if found, would provide indisputable evidence of life on Mars. Such components include the four nucleotides of DNA, the 20 amino acids of proteins, lipids such as hydrocarbons, isomers, and nucleic acids. However while nucleic acids, carbohydrates, and intermediary metabolites are potential molecular biomarkers; they are rapidly recycled and chemically fragile. Also, on Earth they are not known for surviving intact over geological timescales. Lipids and hydrocarbons are renowned for their stability in harsh conditions and over billion year timescales (Engel and Macko, 1993; Brocks and Summons, 2003; Peters, Walters and Moldowan, 2004). Also it should be noted that the lower temperatures on Mars would aid in the preservation of hydrocarbons (National Research Council, 2007). The National Research Council also offers various chemical characteristics in order to help identify molecular biosignatures for carbon-based life:

- Chirality.
- Diastereoisomeric preference (a kind of isomer that is not a mirror image but can be differentiated in the spatial arrangement of atoms in the molecule).
- Structural isomer preference.
- Repeating structural subunits or atomic ratios.
- Uneven distribution patterns or clusters of structurally related compounds

Isotopic Biosignatures

In organic chemistry the elements of greater importance are those that have multiple isotopes. These multiple isotope elements, their isotopic patterns and ratios can constitute biosignatures. This is due to isotopic fractionations due to biological processes and depletion or enrichment of certain isotopes from expected values can be used as biosignatures. However, warns the National Research Council, isotopic fractionations are only useful in revealing biological activity if all the components of a system are available for measurement. In order for an isotopic biosignature to be viable the components of the system must not be fractionated further by physical and/or chemical processes.

A good example of an isotopic biomarker is the $^{18}O/^{16}O$ ratio in phosphates (Blake, Alt and Martini, 2001), as phosphorus in the form of phosphates (PO_4^{3-}) can be used as a genetic material and as cell membranes. The $^{18}O/^{16}O$ ratio of PO_4^{3-} records temperature and high-temperature exchange reactions with water. This therefore makes PO_4^{3-} a potential indicator of past hydrothermal activity on Mars (Blake et al., 2001).

Morphological Biosignatures

Indicators of life based upon size, shape distribution and provenance are divided into two fields: macroscopic and microscopic. Examples of macroscopic morphological biosignatures are intact microbes, microbial mats and stromatolites, whereas microfossils are examples of microscopic morphological biosignatures. Whilst the inference of biogenicity simply based on morphology is difficult (García-Ruiz et al., 2003), aside from the presence of absolute proof, it should be noted that morphological research is valuable for detecting targets of interest for future investigation.

Mineralogical and Inorganic Chemical Biosignatures

It could be potentially possible for mineralogy and inorganic chemistry to indirectly provide evidence for life on Mars. However it is advised that, similar to morphological biosignature research, additional study is conducted on samples where possible. This being said there are a few mineralogical and inorganic chemical biosignatures that could provide evidence of biological processes. A process could be inferred in some cases from the characteristics of aggregations of minerals, such as Fe minerals on Mars precipitated by bacteria. It is thought that both the size distribution and the aggregation of magnetite crystals could be biosignatures (Thomas-Keprta et al., 2000). However these processes have also been linked to abiotic processes (Treiman, 2003), which shows the difficulty in using mineralogical biosignatures.

3 MARS EXPLORATION

3.1 Potential Discovery of Mars

Scientific research for the future is a cornerstone of this mission and to echo this, the science objectives have been chosen so as to maximum the impact the research will have for landing a human on the surface of Mars. These objectives are listed below. It is worth noting that between the time of writing and the start of the mission many new technologies and instruments may become available for use. Any advancement in the technologies will be welcomed and encouraged. The project aims to:

Radiation Environment on Mars (Section 2.2.2)

- Measure radiation levels on the surface to verify or deny current models and to determine whether or not radiation levels are suitable for human habitation.

Atmospheric Conditions on Mars (Section 2.2.3)

- Make long term observations of certain properties of the global atmosphere, such as the vertical profile of aerosols, surface pressure, the location, magnitude and dynamics of electric fields, and the coupling behavior of atmospheric electricity and dust storms.

Martian Geology (Section 2.2.4)

- Study the geysers and their compositions to gain a greater understanding of their origins.
- Have a greater understanding of the elements and compounds present on the floor of the canyon system, which will allow a more comprehensive understanding of its origins.

Volcanism (Section 2.2.5)

- Locate regions of high concentration of methane expunged from the volcanic regions of Mars and to determine if it can be used for future In Situ Resource Utilization.
- Test the Solar Thermal Power System, developed by Physical Science Inc., on Martian tephra and to construct the first structure on a non-Earth planet out of in situ resources.

In Situ Resource Investigation on Phobos (Section 2.2.6)

- Understand the properties of, and differences between, the distinct red and blue units of regolith on Phobos.

Life on Mars (Section 2.2.7)

- Discover basic carbon-based organic compounds on Mars.

The following sections detail and outline the scientific objectives stated above and how they will be achieved experimentally. In order to achieve these scientific objectives a robotic network shall be utilized; this is detailed in more depth in Section 4.1.1. This network shall consist of two rovers (L1 and L2) searching for life on Mars, one rover (G1) and one hopper (GH1) for geological research, one rover (V1) to detect methane, one “Ares-type” flyer (A1) to measure atmospheric and radiation environments (see Section 4.1), and one balloon (C1) to explore the cave systems. Finally there will be a sample return lander (SR1). The locations of the sites of the robotic network are shown in Figure 3-1.

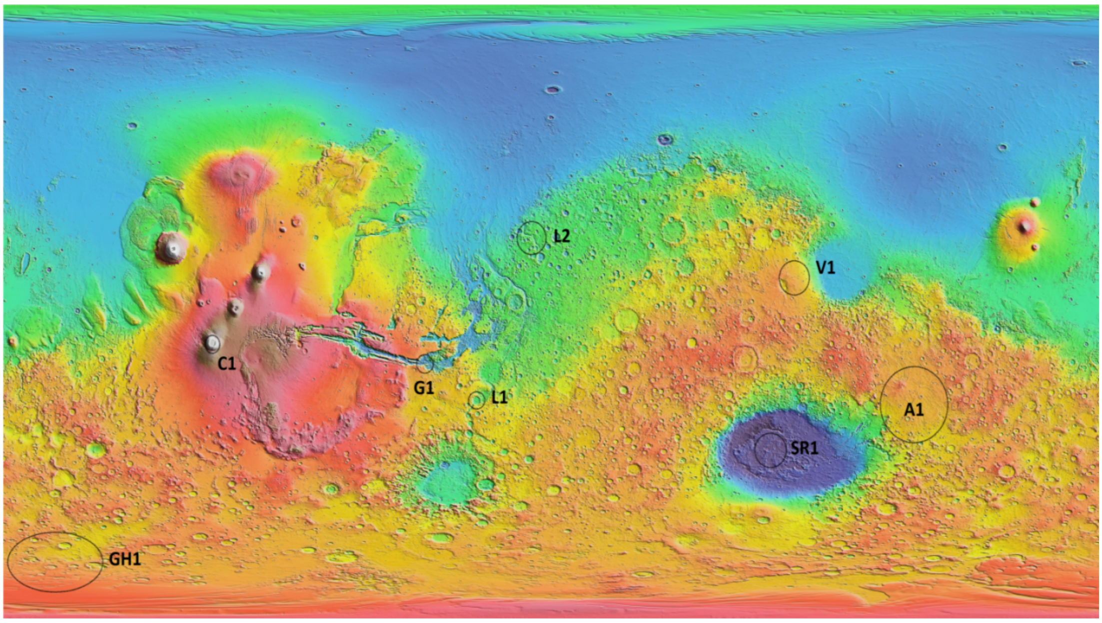


Figure 3-1: The Sites of the Robotic Network [Adapted from NASA, 2013c]

L1 is at the Holden Crater, L2: Mawrth Valles, G1: Eos Chaos, GH1: Il Thyle I, V1: Syrtis Major Planum, A1: Southern Highlands, C1: Arsia Mons, SR1: Hellas Planitia.

3.1.1 Radiation Experimentation

As stated above, the aim of the research on the Radiation Environment of Mars is:

- To measure radiation levels on the surface to verify or deny current models and to determine whether or not radiation levels are suitable for human habitation.

In order to meet this scientific objective the research to be conducted will revolve around several key experimental parameters. The instrumentation onboard will be able to detect radiation across a broad range of the energy spectrum and from many different sources, such as Solar Particle Events and Galactic Cosmic Rays, as outlined in Section 2.2. By covering a broad energy range the instrumentation will be able to detect the major particles in space radiation as shown in the energy coverage of the current RAD (Radiation Assessment Detector) instrument onboard the Mars Science Laboratory in Figure 3-2.

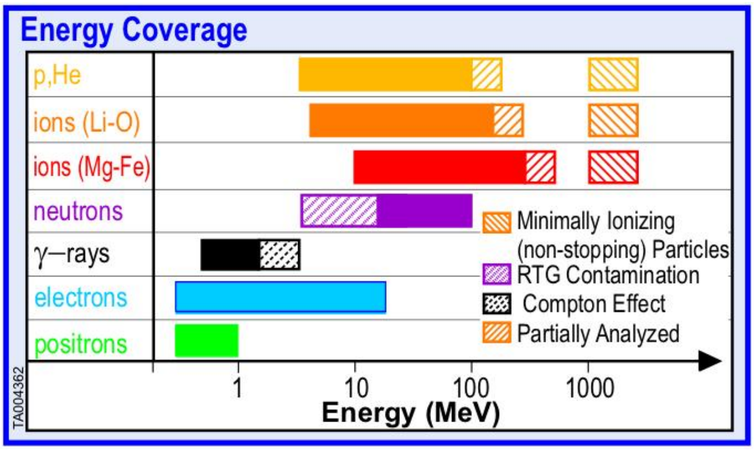


Figure 3-2: The Energy Coverage of the RAD Instrument on the Mars Science Laboratory [Hassler *et al.*, 2012]

The instrumentation will measure the background radiation as well as those mentioned previously to determine the radiation dose that a human would receive on the surface of Mars. By doing this it will be possible to verify or deny current radiation models of Mars from Saganti *et al.* (2008) that suggest the radiation level on the surface of Mars is lower than previously detected.

The primary radiation detecting instrument onboard will be an analogy of the RAD instrument currently operating on the Mars Science Laboratory. As radiation particles pass through the detectors they lose energy and produce electrons or light pulses which then can be analyzed to determine the original particle and its initial energy. From this process an accurate representation of the radiation level can be determined which will be used to complete the scientific objective of this research and progress the knowledge of humanity towards facilitating a successful landing on Mars.

3.1.2 Atmospheric Condition Research

When identifying what types of atmospheric experiments are needed to prepare for a future mission landing on Mars, it is important to answer the following questions (National Research Council, 2011):

- What are the processes controlling the variability of Mars' climate, what are the atmosphere's photochemical reactions and what key chemical or physical processes are missing in the current models?
- What is the distribution of chemical species in the atmosphere, and what are their sources and sinks?
- What is the 4-D structure of the winds in the atmosphere, and what are the causes behind global dust storms events?

A more complete understanding of the structure of Mars' atmosphere will come from global measurements, ideally being a combination of wind, surface pressure, and temperature measurements from orbital payloads. Surface measurements are also required in order to characterize the boundary layer. These data will be used to develop more realistic models. In order to achieve the scientific objective for atmospheric research the experiments should:

- Make long term observations of the global atmosphere at all local times. Measurements should have 5 km vertical resolution and 10 km horizontal resolution as suggested by (MEPAG, 2010). This is necessary for the EDL (Entry, Descent and Landing) systems.
- Make global measurements of the vertical profile of aerosols at all local times, with 5 km vertical resolution (MEPAG, 2010). This is necessary for the mission's guidance system.
- Monitor surface pressure in diverse areas. Measurements should be continuous with a full diurnal sampling rate > 0.01 Hz and a precision of 10^{-2} Pa (MEPAG, 2010). This is necessary for the EDL systems.
- Globally monitor the dust and aerosol activity. This is aimed at understanding the statistical frequency of events and their expected durations (in order to determine margins for avoiding them).
- Study the location, magnitude and dynamics of electric fields.
- Determine the coupling behavior of atmospheric electricity and dust storms.

The main way that the atmospheric measurements can be made is by using flying rovers similar to NASA's Aerial Regional-Scale Environmental Survey of Mars (ARES) (Guynn and Croom, 2003). The payloads will be composed of spectrometers and magnetometers.

3.1.3 Geology and Volcanism Experiments

In 1992, NASA launched their Discovery Program, in which lower-cost, scientifically focused missions could be proposed (NASA, 2013a). Using the model of these Discovery missions, there are a number of specific projects that Mars-X is proposing. Small rovers akin to Mars Pathfinder could be sent to explore features of the Martian landscape and could be remotely operated in real time by astronauts in the habitat on Phobos.

Placing two small rovers at either end of the Valles Marineris, one at the Noctis Labyrinthus and another at the Eos Chaos, each with a different complement of analysis instruments could help gain a broader understanding of such geological features that could be of use in future human missions to Mars. This understanding could help define new techniques to develop in situ resource utilization factories in the future manned or unmanned missions in the nearby areas or in a similar type environment.

3.1.3.1 Hemispheric Dichotomy

Much work has been done in recent missions aimed at attempting to better understand the causes for the hemispheric dichotomy, with the most thorough analysis to date performed by Andrew-Hanna et al. (2008), by combining topology maps with free-air gravity maps to analyze the crustal structure. The next step in advancing our understanding of the origin of this feature is to gain a thorough knowledge of the compositions of the various landscapes. It is, however, difficult to gain an overall picture, as samples taken by rovers can only represent the composition of the soil locally. It is unlikely that a rover could travel from one side of the boundary to the other, as the width of the boundary is ~700 km on average. Exploration ground-based rovers have not been designed to travel such large distances.

3.1.3.2 Geysers

NASA Glenn Research Center commissioned a study for a small-scale mission to explore this region, using a 'Geyser-Hopper' exploration rover. Using an Advanced Stirling Radioisotope Generator (ASRG) power system, this hopper would be able to move among the geysers to collect and analyze samples that could benefit future human missions to Mars for both landing sites and ISRU. The detailed report by Landis et al., (2012) does not appear as part of NASA's Mars Exploration Strategy, however the mission concept is sufficiently well developed for inclusion in Mars-X.

3.1.3.3 Methane

Methane vents are a potential source of concentrated methane on the Martian surface; these can serve as an in situ resource for future missions to Mars. The logical rover instrumentation setup would contain instruments as seen in Section 3.1.4, Table 3-1, especially the Gas Analytic Package (GAP).

Another instrument not included on the above list would be either a flow meter or some way of trapping methane seeping from the vent using a semi-permeable membrane, before separating and quantifying the amount gathered within a time period. The results of these measurements, if repeated at different vents, will determine the viability of ground based methane harvesting or if it is more efficient to filter it from the atmosphere.

3.1.4 In Situ Resource Utilization on Phobos

There remain several scientific questions regarding the structure and formation of Phobos. Is Phobos primarily made of one material represented by the blue unit, and largely covered by the other red material? What is the connection between the origins of Phobos and Deimos? What is the true origin of the grooves around the Stickney crater? What can the study of Phobos and Deimos reveal about the early history and sources of volatiles (chemical elements and compounds with low boiling points that comprise the crust and atmosphere of celestial bodies) of terrestrial planets? Mars-X proposes the following experiments focusing on Phobos:

- Using SHARAD on a Phobos orbiter will allow a good resolution (10-20 m vertical resolution, 300-1000 m along-track resolution, 1500-8000 m cross-track resolution (NASA, 2007b)) of sub-surface structure and isolate areas of interest for deep-drilling.
- Given the proximity of the astronauts, a sample return mission is an obvious addendum to Mars-X. The ideal samples to return from Phobos would be a sample of the blue material at the base of the Stickney crater, a sample of the red clay from the surface of Phobos, and perhaps a sample of the grooved region to detect any connection between the two types of material.

Table 3-1 details the instruments that were included in the ill-fated Phobos Grunt mission of 2012. The entire suite of instruments listed weighs about 50 kg. The mass of the Sojourner rover of the Mars Pathfinder mission was 10.6 kg and carried a 5 kg scientific payload including three cameras, an Alpha Proton X-Ray (APX) Spectrometer and a series of experiments for the Martian dust along with a set of lasers for navigation (NASA, 1999). Considering the improvements in technology over the past two decades, it is reasonable to expect a similarly sized rover or Robonaut to be capable of much more scientific experimentation than was the Sojourner rover of 1997. For example, as seen in Table 3-1, the APX spectrometer is only a part of a set of instruments with a total mass of 1.3 kg.

Table 3-1: In Situ Analysis Instruments [Marov et al., 2004]

IN SITU ANALYSIS INSTRUMENTS		
Instruments	**Scientific Objectives**	**Mass**
Gas Analytic Package (GAP): -Thermal-Differential Analyzer -Tunable Diode Laser Spectrometer -Gas-Chromatograph -Mass-Spectrometer	Mineralogical analysis of soil Inventory, chemical and isotopic composition, of volatiles Search for organics	8.7 kg
Manipulator Instruments Set: -APX spectrometer -Mössbauer spectrometer -Micro-TV	Elemental and mineralogical composition of soil	1.3 kg
Neutron Spectrometer	Hydrogen content of Phobos soil	4.0 kg
IR Spectrometer	Regolith mineralogy	4.0 kg

Thermal Sensor	Regolith thermal characteristics	0.3 kg
Long-wave penetrating Radar	Phobos inner structure, electric characteristics	3.5 kg
Seismometer	Phobos inner structure, gravimetry	0.5 kg

OPTIC INSTRUMENTS		
Instruments	**Scientific Objectives**	**Mass**
Navigation TV system	Landing support; Phobos surface mapping	3.0 kg
Panoramic TV camera	Panoramic images of Phobos; sample selection	0.5 kg
Visible Optical Spectrometer	Mineralogy of Phobos ground	2.5 kg

INSTRUMENTS FOR MARS ENVIRONMENT STUDY AND CELESTIAL MECHANICS EXPERIMENTS		
Instruments	**Scientific Objectives**	**Mass**
Solar occultation spectrometer (TIMM-2)	Trace gases of Mars atmosphere	3.5 kg
Plasma Science Package -Planetary Ion Spectrometer -Electron Spectrometer -Magnetometer	Interaction of the solar wind with Phobos and Mars	3.0 kg

Lee et al. (2010) have proposed a sample return model for launch in 2015. Their instrument suite includes a high-resolution panoramic and microscopic imager, CHAMP (Camera Hand-lens and Microscope Probe), a carbon-sensitive APX spectrometer, a neutron detector/gamma ray spectrometer and a radiation dosimeter. For analysis of material on Phobos, many of the above instruments could reside in the habitat, reducing the complexity of the sample return and analysis from Phobos.

3.1.5 Search for Life on Mars

As can be seen at the beginning of Section 3.1, the aim of the Life on Mars research is stated to be:

- To discover basic carbon-based organic compounds on Mars.

To complete this scientific objective, specific tasks and means to undertake and complete these tasks have been outlined by the National Research Council (2007). Instruments onboard shall be able to identify specific samples of interest from a distance and perform both initial analysis to determine the validity of the sample to the research and more in-depth analysis which will be the main objective of the research. This can be done most efficiently using humans to guide the rovers.

The instruments shall be capable of making the following observations and measurements to achieve the tasks outlined above; these observations and measurements are given in more detail by the National Research Council (2007):

- Comprehensive Imaging.
- Definitive Mineralogy and Chemistry.
- Redox Potential.
- Fine-Scale Surface Analyses.
- Subsample Biosignature Analyses.

To achieve the main science objective for the Life on Mars research and the subsequent tasks, several technologies will be utilized. As noted before, any advances in technology before the launch of Mars-X will be incorporated to enhance the analyses.

Imaging Spectroscopy

Imaging Spectroscopy, the combination of imaging and spectroscopy, can be a very useful tool in determining the chemistry of a sample. For example, using an imaging Raman system, reduced carbon was detected in the meteorite ALH 84001 (Steele et al., 2007).

Mass Spectrometry/Gas Chromatography

Currently this is the preferred method of detection and identification of organic molecules. This technology is useful to resolve and obtain the spectra of isobaric compounds and to determine their relative abundances.

Biotechnology

It is believed that the best way to detect life in a target of interest will be to use probe molecules. Probe molecules, such as antibodies, DNA/RNA aptamers and molecular imprinted polymers, interact specifically with the target of interest. This will allow determination of the concentration and detection of certain biosignatures (stated in Section 2.2.7.3) (National Research Council, 2007).

Sample-Handling Technology

A key technology that needs to be developed is sample-handling technology. In general, measurements for biosignatures require that the sample be pretreated. Care will need to be taken to ensure there is no contamination of samples within instruments and also that there is no pollution of samples by humans or other external factors (National Research Council, 2007).

3.1.6 Further Scientific Experiments

Another possible future experiment is soil resources in the Volcanic Plains. Through the use of a solar concentrator such as the one designed by Physical Systems Inc. (Nakamura and Smith, 2011) and a remotely controlled manipulator, it is possible to construct the first structure on a non-Earth planet out of in situ resources. By having the quartz prism on the base at the end of a flexible guide it will be possible to manipulate it with the manipulator on the rover in order to create sintered sheets of a desired size. The structural properties of a sheet change with thickness and rigidity can be increased by layering new tephra over a finished layer and sintering again. These sheets, with the help of a second manipulator, can then be welded together into structures using the concentrator.

3.2 Through Our Robotic Eyes and Hands

3.2.1 Robotic Network to Explore Mars

The network of rovers deployed on the Martian surface will provide the crew with the possibility to explore Mars via the teleoperation of robotic vehicles. Teleoperations from orbit bring the astronauts near the sites of scientific interest and give them the advantage of real time decisions concerning control of operations, experiments and command. In this section, Mars-X proposes a scenario with four ground rovers, one hopper, one balloon, one flying robot and one sample return vehicle exploring various scientific sites of interest on Mars. Landers will also perform scientific operations and the astronauts will receive the data provided by the entire robotic network in real time in order to adapt the command instructions. The robotic network design is shown in Figure 3-3. This figure demonstrates the communication link between the orbiting spacecraft, the base on Phobos, relay satellites, and rovers on both Mars and Phobos. A detailed description of the spacecraft and Phobos base is described in Section 4.1.1.

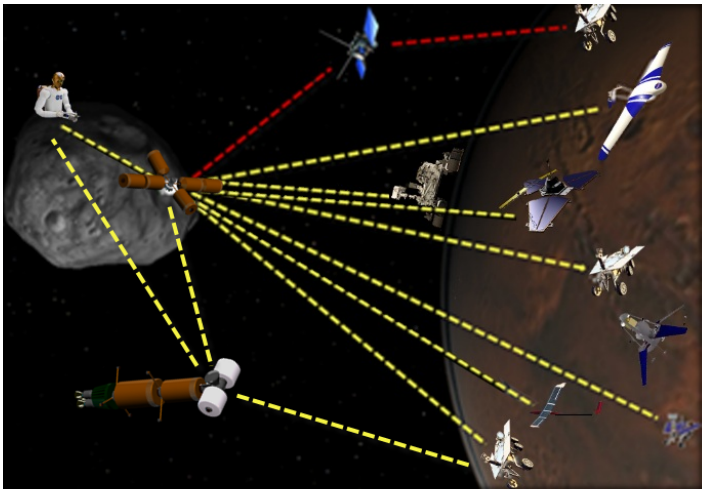


Figure 3-3: Communication with Robotic Network on Mars

Up to three astronauts will be able to control rovers once at a time, combining the advantages of working autonomously through the implemented artificial intelligence in the software and through the capability of being controlled remotely thanks to real-time orders, path corrections and new target acquisition. It is known that human beings take decisions with a maximum latency of 100 ms (Feng *et al.*, 2010). Phobos orbits Mars with an average distance of 6,000 km and therefore the effective teleoperation signal will need up to 40 ms to reach the rovers. Using a satellite relay and adding hardware delay, this duration can be up to 200 ms. These added delays of 300 ms maximum will not impair the communication with rovers and will not prevent from taking the appropriate decisions at a vital moment. Table 3-2 demonstrates the types of rovers that will be used for this mission. The landing mass of the entire robotic network is estimated to be around 5,000 kg on the surface of Mars.

Table 3-2: Mars-X Robotic Network Definition

Type	Rover Functions	Basic Assumed Parameters Per Rover	Rover Examples
Rovers (4x)	In Situ Detection, Organic Compounds Search Detection, Imaging, Soil Analysis	*Total Mass:* 15 kg *Payload:* 5 kg *Battery:* ASRG[1] *Max Speed:* 5 m/s *Size:* 50 x 50 x 50 cm^3	MAX - Type
Landers (4x)	Communication Relay, Drilling, Sample Analysis	*Total Mass*: 500 kg *Payload:* 25 kg *Battery:* ASRG *Drill Depth:* 2-5 m *Size:* 100 x 100 x 100 cm^3	Pathfinder, Viking 1 & 2, Phoenix
Flying Rovers (2x)	Atmospheric Data, Radiation, Collection, Imagery	*Total Mass:* 200 kg *Payload:* 0.5 kg, 25 kg *Battery:* Li-Po batteries, ASRG *Max Speed:* ~60 m/s *Size:* 250 x 250 x 200 cm^3 320 x 320 x 70 cm^3	Sky-Sailor ARES
Hopper (1x)	Geology and Atmosphere Analysis	*Total Mass:* 500 kg *Payload:* 25 kg *Battery:* ASRG *Hop Range:* 2 km *Size:* 250 x 250 x 200 cm^3	Mars Geyser Hopper
Balloons (1x)	Mars Cave Exploration, Atmosphere Analysis, Imaging	*Total Mass*: 70 kg *Payload:* 30 kg *Battery:* ASRG *Max Speed:* 10 m/s *Size:* 200 x 50 x 50 cm^3	Mars Geoscience Aerobot
Mars Sample Return (1x)	Lander, Sampler, and Mars Ascent Vehicle to Phobos	*Total Mass*: 1800 kg *Sample Return Mass:* 0.5 kg *Size:* 100 x 10 x 100 cm^3	NASA - Mars Sample Return Concept
Humanoid Robots (2x)	Phobos Sample Collection and research, EVA operations assistant outside the station	*Total Mass:* 150 kg *Carrying Payload:* 20 kg *Size:* 100 x 100 x 50 cm^3	R2 Humanoid

[1] ASRG: Advanced Stirling Radioisotope Generator

The main drivers of this robotic network are the wheeled ground rovers. Their design will be functional and based on parameters like low cost, reliability, extended life, modularity and reprogramming abilities. The design will be based on the open platform Max rover, developed by the American company Senseta. Its software can be enhanced using algorithms developed by students all over the world, which can also be used as an outreach strategy. This robotic platform is ideally suited for supporting research relevant to intelligent teleoperation and provides a low cost test bed. Its suspended wheels allow it to be driven on rugged surfaces and slopes. Its basic sensors are ultrasonic and infrared telemeters, a video camera and a microphone. The rover will also carry a scientific payload with a maximum mass of 5 kg, adapted to its target and to the measurements it will perform on it. Its cameras will help map the ground surface and will contribute to design a 3D mesh that will enhance the knowledge of the terrain for a possible future settlement (Ippolito et al., 2010).

The landers will be used in order to allow the rovers to land smoothly on Mars' surface. Some of these landers will be able to drill the soil very deeply and will act as local laboratories in order to analyze different layers of the Martian surface. Advanced laboratories similar to the successful SAM (Sample Analysis at Mars), equipping MSL (Mars Science Laboratory), will be in charge of identifying various soil compositions and properties from volcanic, biological, atmospheric, magnetic, geological and radiation samples. The landers will also analyze the samples collected by the rovers. They will include an auxiliary power supply system and a robotic arm, which will be able to provide basic mechanical maintenance locally and to the rovers.

Whereas Opportunity and Spirit were equipped with a grinding tool able to peel away rock layers, some of the landers and rovers in this mission will use fast-spinning percussive drills allowing them to bore up to 2.5 cm into rocks, like Curiosity (SPACE.com, 2012). They will also be equipped with electromechanical moles like the one developed by the German Space Agency (DLR) for NASA's future InSight mission to Mars to be launched in 2016. The mole will be able to penetrate up to five meters deep into the Martian soil thanks to an internal hammering mechanism (DLR, 2013). It will then bring powder back to the surface and transfer it to the rover's onboard chemistry lab for analysis.

Losing the drill bit, breaking the drill string or impairing the rock samples by forcing the drilling fluid into the rock are the most common issues encountered during drilling operations. To avoid these troubles, companies like the Slovakian Geothermal Anywhere provide solutions for deep drilling (5-10 km) using innovative techniques based on a plasma generator with a high rate of penetration (Geothermal Anywhere, 2010). Provided they reach a sufficient Technology Readiness Level (TRL) and after being extensively tested on Earth, these technologies could be used by Mars-X's landers and rovers on Mars and Phobos.

One of the landers will be equipped with a device collecting samples and an MAV (Mars Ascent Vehicle). Once this device or a rover has collected relevant soil materials, the sample will be launched and sent back to the Martian Moon Outpost. The astronauts will collect the samples and will conduct experiments on board in order to determine their main compounds and the possible hazardous elements (radioactive or biological). Such an operation will require the development of new technologies dealing with the identification of landing sites and dealing with sample sizes, collection and protection. ESA and NASA have started developing these concepts but these developments are still in an early phase of study (Oh, 2009). In order to conduct scientific experimentation on the Martian atmosphere's composition and structure, the Mars-X project will use UAV (Unmanned

Aerial Vehicles) with different characteristics:

Fast aircraft: Currently there are two technological approaches to solve this requirement. Firstly, there are models based on NASA's ARES prototype, a self-deployable UAV which has flight autonomy of one hour and can carry samples up to the base stations. These characteristics are in the process of development and might be improved in the next few years. The second option is to use ESA's Sky-Sailor light aircraft (Noth et al., 2004), powered by solar panels. It flies at high speed and provides a basic laboratory capable of collecting atmospheric samples. It is also equipped with cameras and ultrasound devices, which will contribute to the high resolution mapping of the Martian surface. The main issue with these vehicles is to design a system capable of being constantly remotely controlled at high speed. Nevertheless, this can be easily performed thanks to an efficient communications network.

Robotic balloon: This slow robot is used in rocky areas and will help for the exploration of Martian caves in the Arsia Mons region. It can include a system in which the balloon deposits a transmitter at the entrance to the cave to be explored and remains attached via a long power cable. After accomplishing its mission, it rolls the cord and picks up the transmitter, before travelling to its next destination. The robotic balloon will have to be filled with helium, as Mars lacks the atmospheric air that can be used as a driver as happens for traditional hot air balloons on Earth.

Hopper: Vehicle designed to perform soil sample collection during different phases of the mission by hopping up to two kilometers. The research has proved to be a good system for investigating geysers, given the variability of the terrain in different areas and its inclination, and can access difficult areas not accessible for rovers (Landis et al., 2012).

On Phobos' surface, it will become necessary to use an assistant robot to perform EVA operations outside of the station. In order to achieve this, two humanoid robots will be included, based on R2, the current advanced Robonaut, developed in 2010 (Diftler and Ambrose, 2001). It extends its capabilities compared to the previous version in order to become a dexterous robot and it will be improved even further in later versions. It is expected to evolve to station maintenance tasks, such as performing maintenance on the outside of the station, cleaning and vacuuming filters, or helping astronauts during EVAs. On Phobos, it will use a jetpack transport combined with a crawling system and will perform operations too dangerous for the astronauts. This humanoid robot will be controlled remotely or work autonomously on Phobos' surface with periodic status checks.

3.2.2 Martian Satellite Support

One of the greatest benefits of Mars exploration from Martian orbit is the lack of or significantly lower communication delay caused by vast distances between the transmitter and receiver. One of the rationales behind establishing a moon base on Phobos was its orbital period and distance from the Martian surface, which all together gives a single communication window with a time duration of approximately four hours every eleven hours (Hopkins and Pratt, 2011). Moreover, given the distance between Mars and Phobos the expected delay should not exceed 200 ms, as mentioned earlier. Such a small latency creates near-real time connection capabilities and allows very efficient surface rover operations from Martian orbit. In order to extend the connection time with Martian surface rovers, relay satellites are included in the mission architecture. This section outlines recommendations with regard to the communication network for the Mars-X mission in the context of past, present and future missions, such as: NASA Laser Communication Relay Demonstration, Mars Laser Communication Demonstration and including innovative concepts and technologies such as Disruption- and Delay-Tolerant Networking. Lastly, the results of coverage simulation using STK (Satellite Toolkit) software are presented.

3.2.2.1 Network/Communication Architecture

The mission architecture design, specifically Phobos' moon base, grants four hours near-real time communication every eleven hours, as mentioned before. However, to fully exploit latency free connection, use of relay satellites is envisioned. The Mars-X network concept is depicted in Figure 3-4, where yellow lines represent communication to/from Mars' surface and red lines represent relay links between satellites and the moon base established on Phobos. The exact number of satellites, the detailed coverage area and time data are presented in the last section of this chapter.

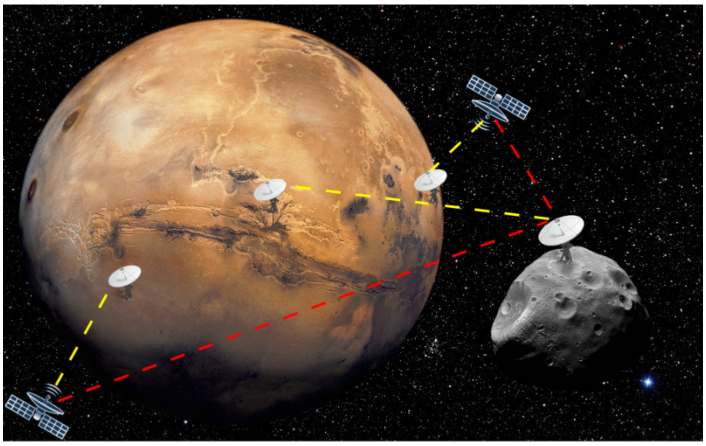


Figure 3-4: Mars-X Network Architecture

Laser communications may significantly improve the way data is being sent and received in space by increasing the transfer rate in comparison to radio, or by lowering the mass and power requirements while having the speed equal to the fastest modern RF radios. The upcoming NASA Laser Communications Relay Demonstration led by NASA Goddard Space Flight Center (NASA, 2011) is supposed to launch a commercial satellite in 2016 in order to present, and improve, the use of optical communication transmission that is 10 to 100 times faster than radio communication, with potential future implications for use in near-Earth and deep-space missions (Williams, 2006).

Mars-X will implement laser relay satellites in order to optimize data acquisition and enable near-real time connection with the Martian surface. Moreover, laser communication implies lower mass and power requirements (Williams, 2006); both are very crucial factors in deep space missions. The mission architecture foresees the crew staying 439 days around Phobos, however the entire infrastructure (e.g. rovers, moon base and relay satellites) should still be operational and capable of performing further experiments and transferring data back to Earth afterwards. Therefore, all Mars-X network architecture components will implement a set of protocols and standards recommended by the DTN specifications, in order to ensure compliance and compatibility with future Mars missions.

3.2.2.2 Coverage Simulations

The STK simulations show that placing two relay satellites on the same orbit as Phobos with a true anomaly difference of 120 degrees would result in having continuous near-real time connection with the Martian surface latitudes of ±65˚. Figure 3-5 presents both 2D and a 3D map of the coverage of the Martian surface. It can be observed that two satellites (or Phobos' moon base and satellite) provide coverage over the same area for a short period of time. This guarantees a smooth connection transition during the switching between the link path from one satellite to the next.

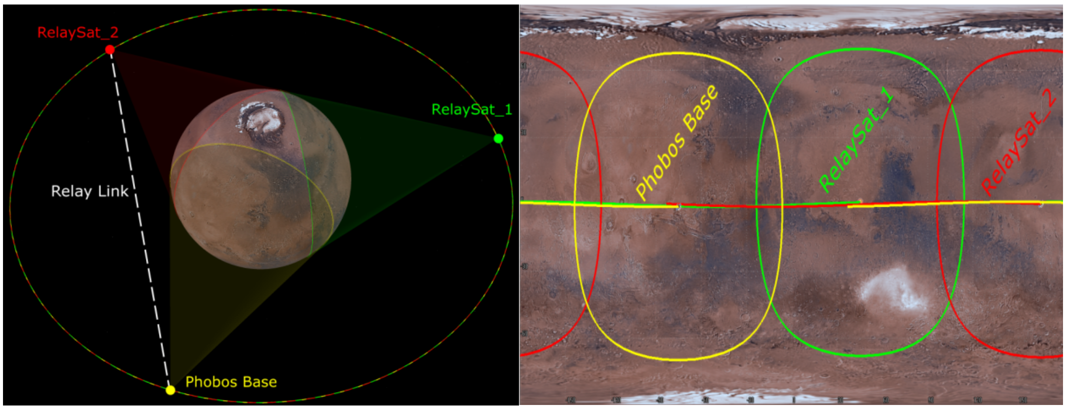
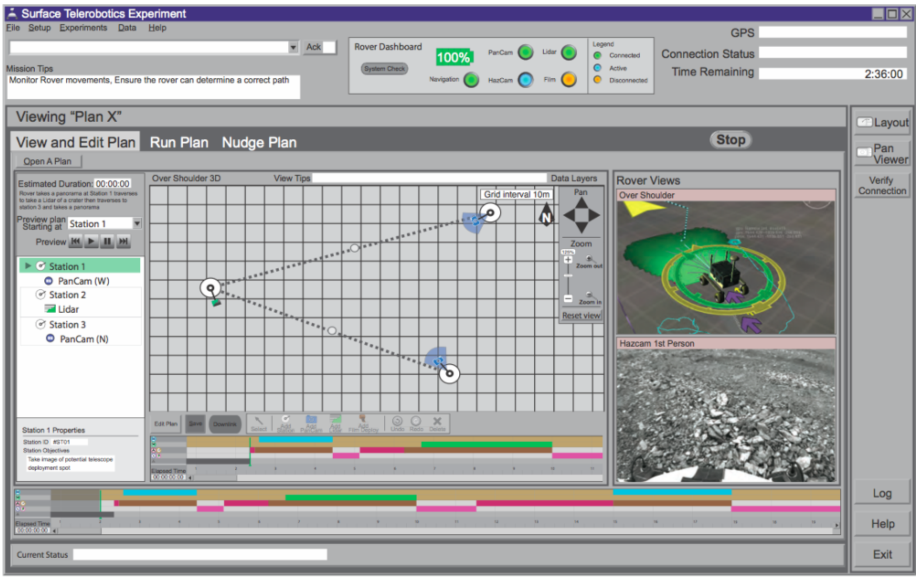


Figure 3-5: Two and Three Dimensional Coverage Map of the Martian Surface

3.2.3 Human-Machine Interface

The robotic network that this mission aims to deploy on Mars is composed of six ground landers with rovers and two flying vehicles: one plane and one balloon. These semi-autonomous rovers will explore various sites on Mars, drill into Mars' surface and perform scientific analysis, receiving real time commands by astronauts in orbit and finding appropriate paths between assigned waypoints autonomously.

During the stay in the Martian environment, the rovers will be monitored and commanded through conventional computers via the Surface Telerobotics Workbench (STW). This software user interface developed by the Intelligent Robotics Group (IRG) at the NASA Ames Research Center is powered by 3D graphics which allows it to display accurate information about the current location of the rovers and their attitude in the local environment (Henry, 2012). The interface also provides the astronauts with visual representation of the rovers' subsystems status, as shown in Figure 3-6 (Henry, 2012). The Surface Telerobotics Workbench is compliant with the ISS Display and Graphics Standard Specification (IDAGSS) and therefore uses agreed standards regarding colors, modes of interaction and button design.



Mission Tips
Monitor Rover movements, Ensure the rover can determine a correct path

Time Remaining 2:36:00

Estimated Duration: 00:00:00
Rover takes a panorama at Station 1 traverses to take a Lidar of a crater then traverses to station 3 and takes a panorama

Preview plan Starting at Station 1

Station 1 Properties
Station ID #ST01
Station Objectives
Take image of potential telescope deployment spot

Elapsed Time 00:00:00:00

Figure 3-6: Interface Seen by Astronauts when Using the Surface Telerobotics Workbench [Henry, 2012]

Real time operations like sampling (digging or drilling) and manipulating objects with a robotic arm will be performed using force feedback joysticks and wearable electromechanical trackers (i.e. gloves equipped with displacement and deformation sensors) in addition to the use of conventional computers. The DataGlove proposed by the American Branwyn (1998) or the ExoHand proposed by the German Festo (2012) will be synchronized with rovers' robotic arms on the Martian surface and will allow astronauts in orbit to control them. Regarding EVAs performed in the vicinity of the spacecraft or on Phobos, astronauts will be assisted by NASA's android-like Robonaut 2 (Figure 3-7) or DLR's Justin. In a first possible operating mode, the android will work autonomously with periodic status checks. An astronaut inside the spacecraft will remotely monitor and run use cases (i.e. predefined sequences of instructions) based on feedback status indicators. In a second possible operating mode, the android will be fully controlled via haptic telepresence by an astronaut wearing an exoskeleton inside the spacecraft. The exoskeleton developed by ESA's Telerobotics and Haptics Laboratory allows the full range of human arm motion, produces force feedback just on the arm joints and not on the whole body and has a total mass below 10 kg (ESA, 2006), making it fully adapted to this mission. Furthermore, an augmented reality headset worn by the astronaut will allow the display of additional information in order to facilitate operations.

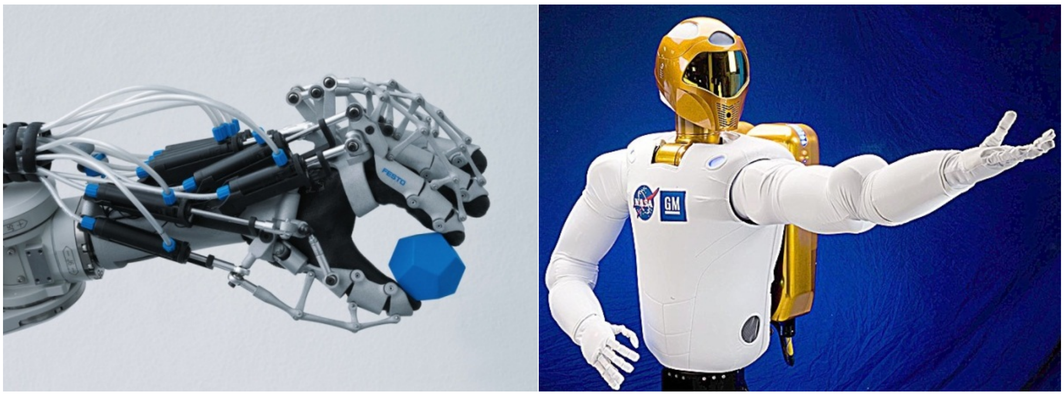


Figure 3-7: Festo's ExoHand (left) [Festo, 2012] NASA's Robonaut 2 (right) [NASA, 2013e]

In addition and in parallel to the techniques described previously, speech recognition will be used extensively through microphones and processing software. Control of cabin instruments and equipment or orders to the spacecraft's life support system will also be given using voice recognition. On the other hand, due to long user training and high susceptibility to noise, techniques like Electroencephalography (EEG), Brain-Machine Interfaces (BMIs) and Brain-Computer Interfaces (BCIs) will not be used during the mission.

Many challenges associated with rover operations on the ground by astronauts in microgravity have yet to be identified. It is already known that the human body's behavioral and physiological responses are different when put into weightlessness, and that the senses of force and touch are not the same as under Earth's gravity. But what is the exact level of operational difficulty implied by these differences? In order to address these issues, NASA and ESA are paving the way for rover teleoperations by astronauts in orbit. In late October 2012, while in orbit ISS expedition 33 commander Sunita Williams successfully drove a small rover at the European Space Operations Centre (ESOC) in Darmstadt, Germany. This collaborative experiment led by NASA and ESA used NASA's Disruption Tolerant Networking (DTN) protocol to demonstrate the possibility of interplanetary internet-like communications to command space vehicles remotely (Kraft, 2012).

In June 2013, the Eurobot rover and the Justin android will be controlled remotely by astronauts from the Columbus laboratory in the International Space Station. This initiative, named Meteron (Multi-Purpose End-To-End Robotic Operations Network), aims to help turn robotics and telepresence into a standard tool for remotely controlled missions (ESA, 2011).

The IRG at NASA Ames Research Center is also performing an analog study called the Surface Telerobotics project. According to their scenario, a semi-autonomous K10 rover (a collaborative development of the IRG with Carnegie Mellon University) will be receiving commands from the ISS and will be deploying an antenna on the surface of the MarsScape at Ames (Henry, 2012). NASA is already considering the construction of an inhabited outpost orbiting the Earth-Moon Lagrange Point 2 above the far side of the moon in order to deploy a lunar radio telescope using semi-autonomous teleoperated rovers (Houdu, 2012).

By extensive experimentation with rovers and training of astronauts in the coming years, the teleoperation of robots from orbit in interplanetary exploration missions will become a reality. Countermeasures will be needed to account for the challenges that will be faced by the operators, but there is no doubt that the astronauts from the Mars-X project will take advantage of robotic assistance upon docking with Phobos, which will enable them to bring back samples from the Martian surface.

4 TO ORBIT, THERE AND BACK AGAIN

4.1 Spacecraft and Mission Design

4.1.1 Mission Overview – Trajectory Description

According to the general architecture, the whole Mars-X mission will be operated with both robotic and human presence in Mars and Martian orbit from 2020 to 2027. It includes a series of scientific missions, which carry the Martian landers with rovers and satellites to Mars throughout the three launch windows in 2020, 2022, and 2024. Following the scientific payload missions, the Mars Exploration Vehicle (MXV) will transport five astronauts to the Martian moon, Phobos, and back to Earth. The design of MXV was completed after several iterations of ΔV budgets and trajectory selection. These iterations considered different travel times and the duration of stay in Martian orbit. The resulting mission duration was found to be 919 days with a 240 day trip time to Phobos, a stay of 439 days and a return trajectory of 240 days.

The sequence for the defined mission will commence with the assembly and testing of MXV in lower Earth circular orbit at an altitude of approximately 400 km. The designed trajectory for the human mission to Phobos and back is shown in Figure 4-1. In October 2024, the nuclear thermal engine will operate and propel the piloted spacecraft into Earth-Mars transfer orbit, during which the spacecraft will rotate, generating artificial gravity to maintain astronaut health. After a series of trade-off studies involving the total velocity, total mass, radiation protection, schedules, and cost, a Hohmann transfer orbit was selected for both going to Mars and returning to Earth. The crew and vehicle will arrive at Mars in June 2025. The initial capture orbit is around 400 km by 80,000 km with an inclination of approximately zero degrees. The velocity requirement for Mars orbit insertion is approximately 1.02 km/s.

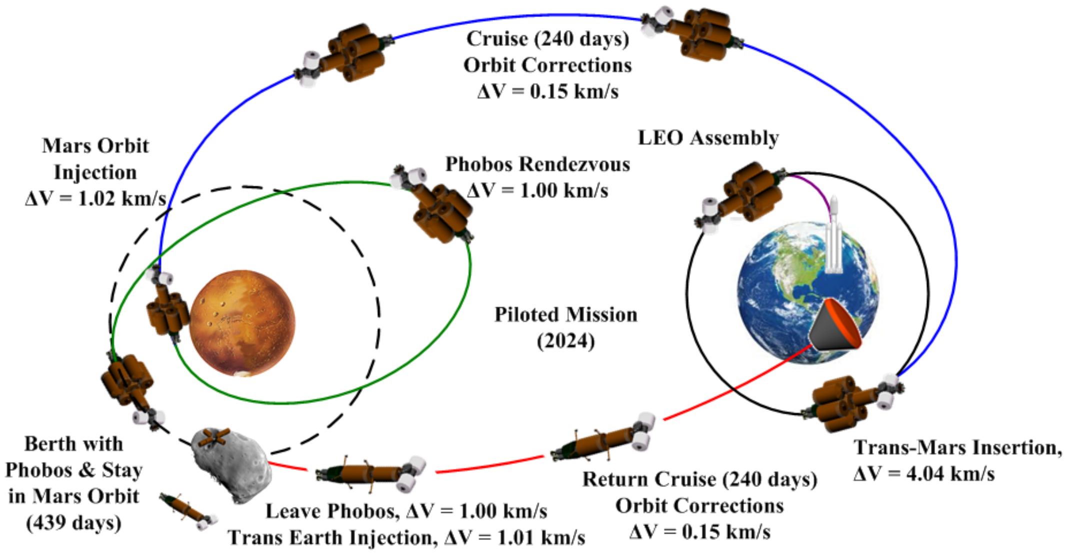


Figure 4-1: Trajectory of Piloted Mission in 2024

In order to rendezvous with Phobos, a bi-elliptic transfer will be used (Hopkins and Pratt, 2011). At apoapsis of the initial orbit, MXV performs a burn to raise periapsis to the altitude and orbital plane of Phobos, around 5,980 km and 1.1˚. MXV will then perform another burn to circularize the orbit. After arriving in the orbit of Phobos, the duration of stay will be 439 days, for which procedures must be defined. It was decided that Lagrange points L1 and L2 of Phobos would be used in order to park MXV in a stable Distant Retrograde Orbit (DRO). This DRO orbit is defined in Figure 4-2, in conjunction with a halo orbit, which is a type of orbit which is unstable orbit and would require hourly orbit maintenance on the order of 0.30 m/s/day. The DRO is considered to be a stable orbit with a period of around five hours at altitudes of approximately 20 km from Phobos' surface. Therefore maintenance is not required for months (Wallace et al., 2012).

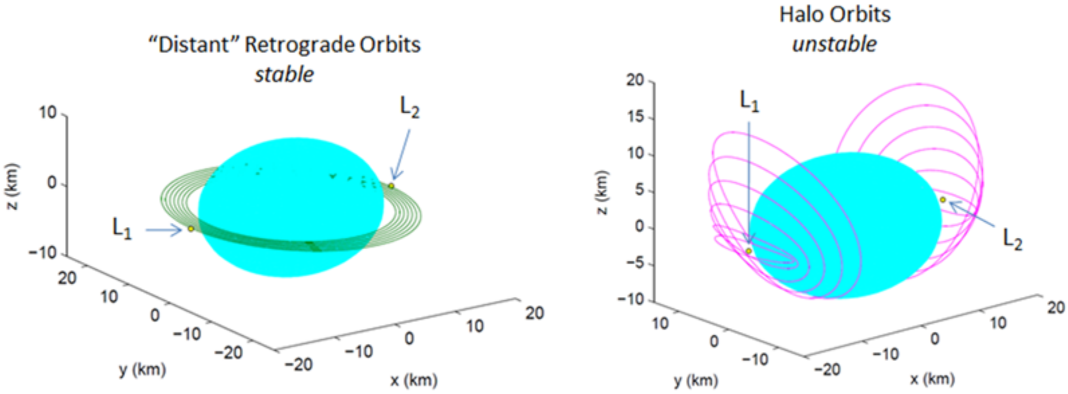


Figure 4-2: Orbits around Lagrange Points of Phobos [Wallace *et al*., 2012]

After arriving at DRO orbit, the Phobos Unmanned Lander (PUL) will then be deployed to establish the first Martian Moon Outpost (MMO) on Phobos. The lander will perform a berthing maneuver with Phobos, as described in detail in Section 4.2.1. The landing site for MMO is within the Stickney crater, at a specific location defined in Figure 4-3. This figure shows regions of continuous sunlight in yellow. The region inside the green boundary has line of sight to the full disk of Mars, while the region between green and red boundaries has visibility to parts of Mars. The Stickney crater location was chosen partly for the scientific interest in Stickney and Limtoc craters but also because there is better radiation protection within the crater, and it does not impede full visibility of Mars' disk throughout the Martian year. Around 10 km from the landing site there is a monolith, seen in Figure 4-3, which is a point of interest that could be reached by teleoperation of a robotic humanoid, such as Robonaut, capable of extracting samples on Phobos.

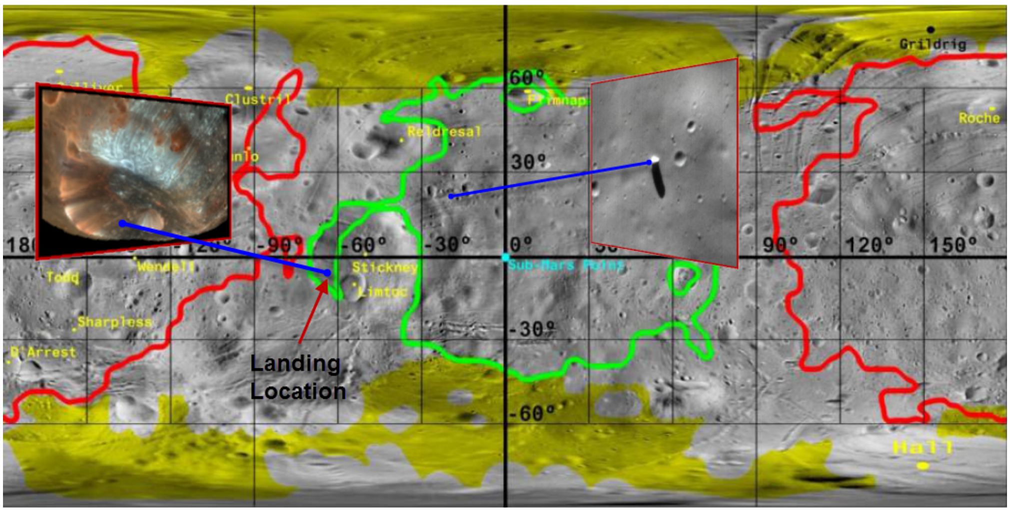


Figure 4-3: Landing Location on a Map of Phobos [Adapted from Hopkins and Pratt, 2011]

Once the lander has successfully berthed with Phobos, the empty fuel tank modules will be docked with it, assembling the first MMO, as shown in Figure 4-4. This step will be followed by sending one of the two habitats, with two astronauts, for an exploratory mission to the surface of Phobos for approximately 40 days. These 40 days will involve making the MMO operational, as well as performing EVAs at nearby places of interest to obtain samples for analysis. This phase of the mission will be very stressful and perhaps the most difficult due to the high importance of the tasks to be performed; berthing with Phobos, disassembly/assembly of fuel tanks, undocking and then docking of the habitat to the MMO, performing EVAs, sample analysis, and robotic teleoperations, among others. It is expected that after approaching Mars, at least three months will be required to complete the construction of the MMO and perform human exploration of Phobos, after which the crew could return to the artificial gravity module. After completion of the MMO, the astronauts will start performing telerobotic operations on the Martian surface.

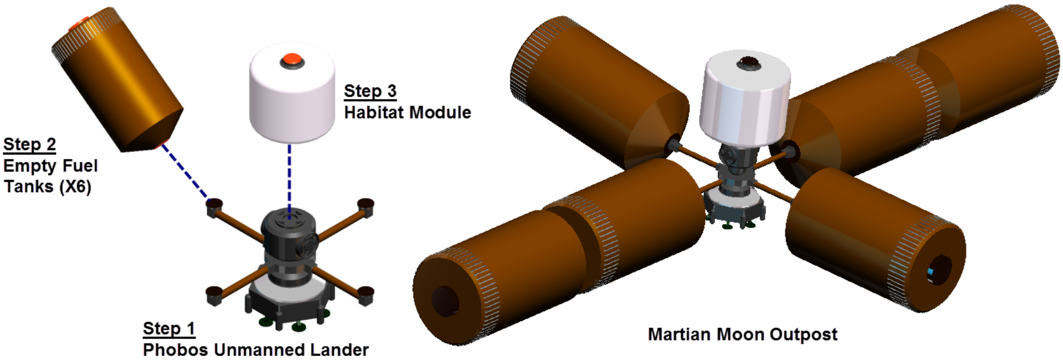


Figure 4-4: Martian Moon Outpost on Phobos

After staying in Martian orbit around Phobos for approximately 439 days, the MXV will adjust its orbit to fire its nuclear thermal engines in September 2026 for a return trajectory to Earth. Finally, the return capsule will reenter Earth's atmosphere with a maximum reentry velocity of 13 km/s in April 2027, returning the astronauts along with samples from Phobos and Mars.

4.1.2 Mars Exploration Vehicle Design

The design of the Mars Exploration Vehicle and mass breakdown of major components are illustrated in Figure 4-5. Through an iterative design process it was decided that there would be two small sized habitats separated by an airlock for emergency situations. These two habitats each have a volume of approximately 200 m^3 and need to support five crew members for 919 days which will be achieved through a Controlled Ecological Life Support System (CELSS), as described in Section 4.1.4. The Phobos Unmanned Lander will be docked to MXV, along with the return capsule and scientific payload equipment, which carries a flying robotic payload to be inserted in the Martian atmosphere. This design uses three Nuclear Thermal Rocket engines (NTR) with specific impulse (I_{SP}) of 975 s for its propulsion. A total of eight liquid hydrogen fuel tanks, capable of storing a total of 285 t of propellant are required to successfully complete the Mars-X mission. MXV will be rotated about its center of gravity to produce artificial gravity with Martian gravity levels varying between 0.38 g to 0.55 g.

MXV Components		**Mass Breakdown (Metric tons)**
HabEX-1 with Docking Module		25 t
HabEX-2		20 t
Phobos Unmanned Lander		15 t
Return Capsule		10 t
Payload Equipment to Mars		2 t
NTR	3X Engines (Isp-975s)	7 t (X3)
	Shielding	10 t
	Fuel Connectors	4 t
Artificial Gravity	Attitude Thrusters (Isp-450s)	3 t
	Fuel Req. - (min. 8 cycles)	5 t
Fuel Tanks	LH2 Tank 1, cap. - 37.5 t	12.5 t (X7)
	LH2 Tank 2, cap. - 27 t	8.5 t (X1)
	Fuel Connectors	4 t
Total Dry Mass		**215 t**
Total Fuel Mass		**285 t**
Mars Exploration Vehicle Mass		**500 t**
Mass on Phobos	LH2 Tank 1, cap. - 37.5 t (X6)	**90 t**
	Phobos Unmanned Lander	
Return Vehicle Mass		**125 t**

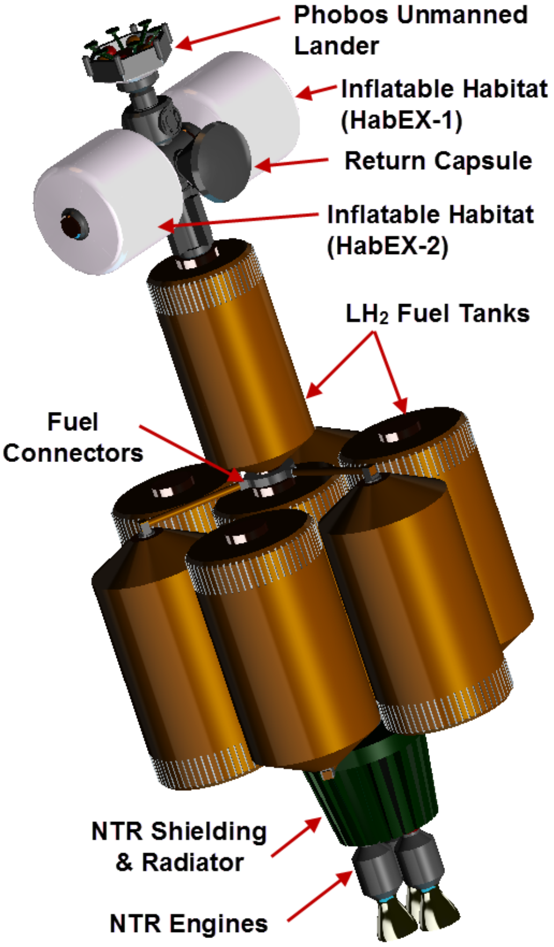


Figure 4-5: Mars Exploration Vehicle Design

The initial dry mass in LEO for the Mars Exploration Vehicle was estimated based on previously designed components, such as nuclear thermal engine mass, habitat mass, and return capsule. Other specific parameters for this mission were also taken into account, such as the mass of the Life Support System (LSS) and artificial gravity propellant requirements. After computing the ΔV required (Figure 4-5) for the mission, the required propellant mass was found, while taking into account 3% residual fuel and a 5% fuel margin at each burn. The sizing of the components, such as the number of fuel tanks, was completed based on the modified Falcon Heavy launcher or a newly developed launcher for this mission. Each fuel tank module was designed assuming the maximum mass that could be launched to LEO is 50 t with the shroud diameter of 8 - 8.4 m. The propellant to be used is liquid hydrogen which has a very low density of approximately 70 kg/m^3. This requires a large amount of volume, around 550 m^3 for each fuel tank. Therefore, from the eight fuel tank configuration, six will be expended prior to arrival at Phobos and will be docked with the Martian Moon Outpost. In accordance to this the return configuration of the vehicle is different, as shown in Figure 4-6.

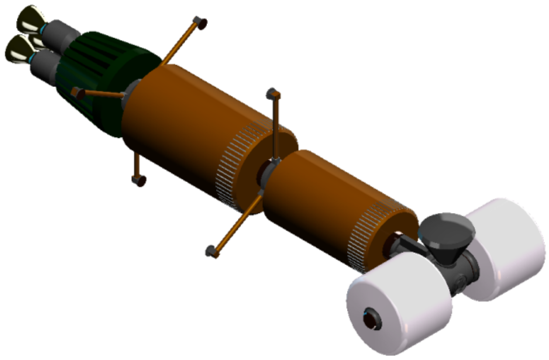


Figure 4-6: MXV Return Configuration

4.1.3 Mitigating Microgravity

During long term spaceflight, microgravity has adverse effects on human health which are evident both physiologically and psychologically. Bone demineralization and muscle atrophy are amongst the most significant physiological effects. Loading on weight bearing bones is required for re-calcification which is not provided in microgravity; as a result calcium is lost at approximately 1% per month, observable through loss of bone mass and density (Clément, 2011). It is predicted that on a two year mission without significant mitigation, a loss of 40% may occur (Young, Yajima and Paloski, 2009). Muscle atrophy also occurs from a lack of loading and use. During short term (7-10 days) flights astronauts lose approximately 10-20% of their overall muscle mass, however on long term flights (greater than six months) this may increase to around 50% (Clément, 2011). Other effects of microgravity include: reduction in strength, vision changes, decrease in cell-mediated immunity and T-cell response, reduction in heart size and plasma, hyperreflexia, cardiovascular deconditioning, and sleep restriction, among others. The longest exposure a human has had to microgravity is 438 days, which is considerably shorter than the Mars-X mission of 919 days (Buckey, 2006). The effects of microgravity on humans are unknown for such an extended period of time and questions arise as to whether it is possible for astronauts to embark on a mission to Mars and return safely and healthily to Earth. Implementing a simulated gravity environment, or artificial gravity, could mitigate these effects on the Mars-X astronauts. For future long term spaceflight artificial gravity will be essential (Clément and Bukley, 2007).

A centripetal force, which is exerted by a spinning body, can simulate the gravity-like effect and substitute the Earth's gravitational pull in the space environment. It is unknown whether partial constant gravity will be enough to counteract the adverse effects of microgravity, or whether complete Earth gravity (1 g) is required. There are also questions as to the requirement of constant gravity or whether periodic artificial gravity would suffice for astronaut health (Clément and Bukley, 2007). From studies it has been suggested that 0.5 g is implemented to maintain normal human performance and that the minimum required level is 0.3 g (Young et al., 2009). To test these parameters during the Mars-X mission the spacecraft will be spun to achieve Mars gravity of 0.38 g.

Numerous designs of artificial gravity systems have been proposed, however the only implementation was the tethering of an Agenda rocket to a Gemini spacecraft which, due to technical problems, was unsuccessful and caused an uncontrollable spin (Young et al., 2009). There are two main types of design concepts: tethering systems with a long rotational radius, and short rotation radius systems. The disadvantages of a tethered system include deployment systems, possibility of tether breakage, lack of precision during spin-up and spin-down, and large complications in control of the spacecraft. Short radius centrifuge systems also have disadvantages, including large gravity gradients which increase motion sickness. Implementation of a short radius centrifuge system may be more beneficial in intermittent exposure to artificial gravity rather than constant exposure (Clément and Bukley, 2007; Young et al., 2009).

A rotating environment adds complexity both to the spacecraft design and to human performance. Coriolis force is a force felt by astronauts as a result of their linear movement in a rotating reference frame. Therefore, due to the angular velocity, limb movements become more complex and eye-head movements are altered, which can cause motion sickness. The greater the rotation, the more Coriolis effect the crew needs to account for, which could be potentially hazardous (Clément and Bukley, 2007). Effects of prolonged exposure to a rotating environment are also unknown. Further experimental data on this will be acquired through the Mars-X mission.

To achieve simulated Martian gravity onboard the spacecraft, the rotation rate and rotational radius, along with the comfort zone of the astronauts, must be considered. Figure 4-7 demonstrates the comfort zone as a function of rotation rate in revolutions per minute and radius in meters. The head-to-foot gravity level will affect the comfort level of astronauts. This parameter results from the outer radius of rotation having a greater magnitude than the inner radius and depending on the design of the working artificial gravity environment the gravity felt by astronauts at their heads and feet can be drastically different. This can result in posture alteration in the astronauts and it has been estimated that less than 15% gravity gradient between the head and foot is acceptable, however this may be more conservative than necessary. In order to keep the gravity gradient between the head and foot of an astronaut at no more than 15% difference, a radius of 12 m was specified. As previously mentioned the lower limit for the gravity level is 0.3 g, which is indicated in Figure 4-7, and the upper limit is 1 g, with a maximum rotation rate of 6 rpm (Clément and Bukley, 2007).

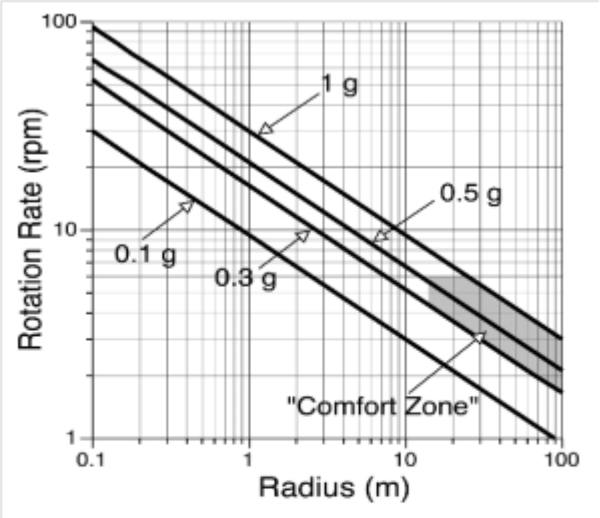


Figure 4-7: Comfort Zone [Clément and Bukley, 2007]

The spin-up and spin-down periods and frequencies must also account for the effects of human adaptation. Adaptability to a rotating working environment is considered to be relatively easy at levels of 2 rpm, however, when moving to higher levels it can become more challenging. Therefore, staged increases of 2 rpm at 12-24 hour intervals are recommended (Young et al., 2009).

The spacecraft design for the Mars-X mission is illustrated in Figure 4-8 showing the axis of rotation and the changing gravity level along the spacecraft habitable area. The entire spacecraft will be spun in order to create the centrifugal motion needed to generate artificial gravity. The two white modules in the design are crew accessible areas in which Martian gravity of 0.38 g is achieved. This will enable scientific experimentation at Martian gravity levels to occur at this specific location in the module. At the initial mass distribution of the spacecraft, on the way to Mars, this gravity level will occur at a rotational radius of 17.5 m and at a rate of 4.4 rpm. The outer radius of 24.5 m will have a gravity level of 0.53 g and, therefore, as an astronaut travels through the spacecraft, the maximum change in gravity level he will experience on the way to Mars is 0.15 g. However, throughout the mission phases and different fuel burns the location of the axis of rotation changes and could vary by up to four meters. These changes would affect the rotational rates of the spacecraft and the fuel required to do spin-up/spin-down cycles. These changes are also outlined in Figure 4-8. The mass of the propellant needed was calculated and it was found that for attitude thrusters using chemical propulsion with an I_{SP} of 450 s, approximately 305 kg of fuel will be needed for one spin up or spin down. The system will need to complete at least four spin-up/spin-down cycles throughout the mission. However, enough propellant will be carried to achieve eight complete cycles, which requires 4,880 kg of fuel to be carried for artificial gravity. As previously mentioned, it is important that the amount of rotation is slowly increased or decreased to allow astronaut adaptation to the environment. Therefore, an increase/decrease of 2 rpm will occur every 16 hours during transition periods, meaning that the maximum time a complete spin-up/spin-down will take is 40 hours.

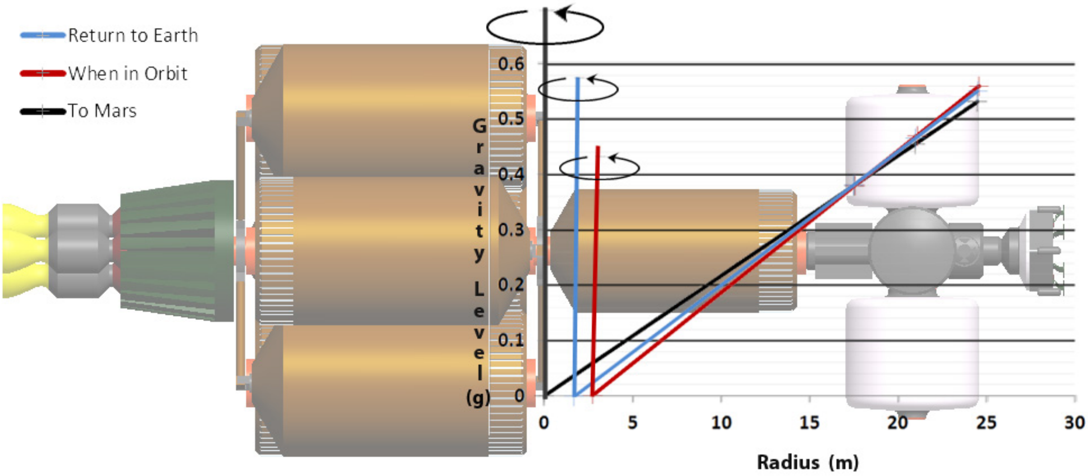


Figure 4-8: Artificial Gravity Level Variations throughout Different Mission Phases

Artificial gravity adds significant mass and complexity to the design and maintenance of the Mars-X spacecraft; however without incorporation of this system the effects of microgravity on humans may be detrimental to the success of the mission. The simulated Martian gravity environment that will be present on the mission will help increase the level of knowledge of the effects of partial gravity on astronaut health and provide building blocks for more advanced microgravity mitigation techniques.

4.1.4 Habitat Module Design

4.1.4.1 Design of Life Support System (LSS)

The basic functions of the Life Support System include environment control for the pressurized spacecraft and the crew's requirements for habitation. According to the trend of technological research and development (Larson and Pranke, 1999), LSS includes three main types:

1) Non-regenerative or open-loop LSS
2) Regenerative or Physical & Chemical semi-closed-loop LSS
3) Controlled ecological or closed-loop LSS, or CELSS

Controlled ecological LSS follows the principles of ecology; closely related to the ecology of the Earth, and uses the parts of higher plants, i.e. plants that produce fruit or vegetables, and organisms to produce food, oxygen, water and some other necessities for life. The application of higher plants can establish a harmonious environment which suits human habitation. The growing of food from higher plants on board the spacecraft will help benefit the psychological state of the crew as it helps mitigate the mental pressure and isolation associated with long term spaceflight. Cultivation of the plants can form part of the crew members' routine and the sense stimulation brought by fresh vegetables will be enjoyable for crew members.

4.1.4.2 Mode Selection on LSS

According to the current developments of LSS, controlled ecological LSS is a trend for future applications, especially for long term human spaceflight. Its technical stability and reliability has been proven sufficient for practical applications. However, despite the developments and progress, the closure of the whole CELSS cannot reach 100% in the 2020s. Even if it does, in order to keep the system reliable, some redundancy will be required by providing extra storage of resources. So based on CELSS, there is a trade-off between technical maturity, application reliability, and system robustness. Therefore, selecting the degree of closure is very important. In CELSS, the key technologies that must be addressed are firstly, regulation and control of a dynamic balance between oxygen and carbon dioxide, and secondly, a comprehensive process of recycling metabolites based on microorganisms.

4.1.4.3 Requirements on LSS

The general design principles of LSS as described by Larson and Pranke (1999) are explained here. First, the LSS must stabilize atmospheric pressure and apply partial pressure to oxygen in the manned modules of the spacecraft. Then it must provide oxygen for the crew, remove carbon dioxide metabolized by the crew, and it must control and remove harmful gases from the cabin for the crew's safety. Temperature control and humidity of the cabin must be regulated to provide a suitable living environment and ventilation conditions. Food and water management is crucial for sustaining living conditions in the module, while collecting, handling and recycling the metabolized waste of the crew and other waste in the spacecraft is as important. The LSS must also ensure protection against smoke and fire hazards, while regulating emergency pressure control in the cabin during accidental leakage to protect the lives of the crew. Aiming at the long term mission, the performance of the LSS should attain the following level:

- Atmospheric environment for the crew in the spacecraft should be:
  Environmental pressure: 101.3±1.4 kPa.
  Partial pressure of oxygen: 21.3±1.8 kPa.
  Partial pressure of carbon dioxide: less than 0.3 kPa.
  Temperature: between 18 to 27°C.
  Relative Humidity: around 30 to 70%.
- Food management and regeneration:
  Provide 0.7 kg of food for each crew member per day (calculated by dry mass after dehydration).
  20% of food should be provided by plant regeneration.
- Water management and recycling:
  Provide 30 kg water for each crew member each day for food, drinking and hygiene.
  All water can be recycled. 90% can be recycled for reuse by humans, while the remaining 10% would be considered waste.
- Waste management:
  According to the definition of closure, the waste produced by the LSS is the final output processed after ecological recycling, which is outlined in Figure 4-9.

4.1.4.4 Conceptual Design of LSS

The conceptual design of the LSS is shown in Figure 4-9. In this system, the oxygen and carbon dioxide will be balanced between crew and plants. So, the generation of oxygen will be fully recyclable throughout the mission, while having stored oxygen for emergency depressurization and EVA activities. The plants can be used to provide 20% of food recycling and the microbial bioreactor can be designed to achieve 90% of water recycling. The area for plants is expected to be less than 10 m^2 per crew member. The rest of the required food and water will be provided by supplementary storage resources.

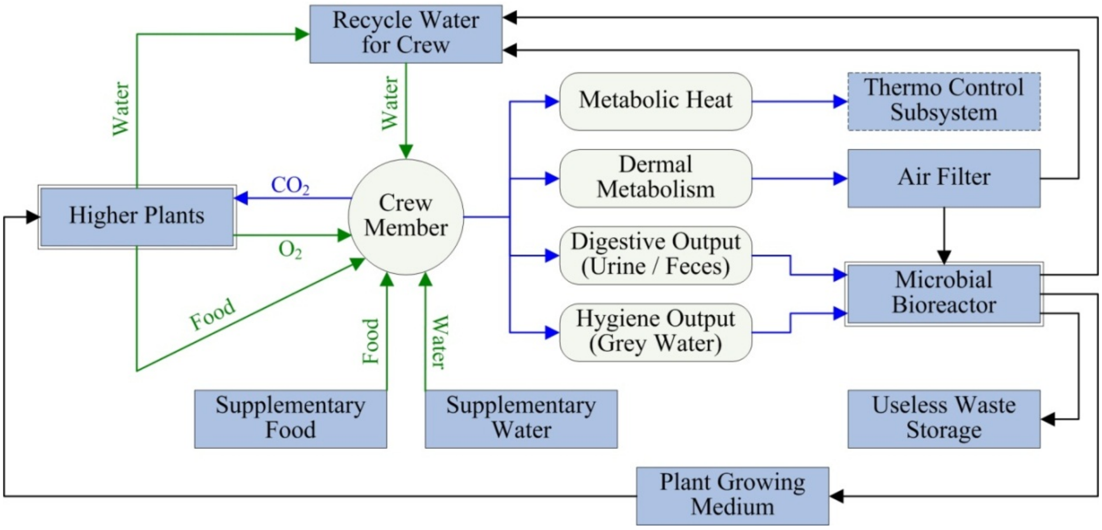


Figure 4-9: Design of LSS

4.1.4.5 Outcomes of LSS Design

In order to estimate the total mass of the CELSS the following equation was derived, based on consumable materials, hardware and equipment, the mission duration, the number of crew members and the recycling closure level of LSS. This equation takes into account the recycling closure level of the system, C_i, so as to calculate the mass difference between the closed-loop LSS and the open-loop LSS based on the degree of closure, assuming a linear relationship.

$$M = \left(\sum_i M_{Ri} \left[C + (1 - C_i) D \right] P \right) + M_P \cdot P + M_D \cdot D + M_A$$

Where: M is the total mass of the CELSS
M_{Ri} is the mass of consumables per person per day
M_P is the mass of hardware depending on crew number
M_D is the mass of hardware depending on mission period
M_A is the mass of the CELSS architecture and fixed equipment
D is the mission period
P is the number of crew members
C_i is the recycling closure level of LSS
i is the material type of human requirement, which can be recycled, such as, food and water.

In this equation, the mass of dynamic allocation (recyclable material) and static allocation (hardware and equipment) are all contained. The mass of dynamic allocation depends on the crew number and mission period. The static allocation depends on the project requirements and system architecture.

4.1.4.6 Habitat Structure

In addition to the LSS, the environment for the crew's habitation must include personal stowage, cleaning devices, sleeping quarters, and medical facilities. Personal stowage is used for the individual belongings that each crew member has for their personal use, including entertainment during the long spaceflight. Habitat environment cleaning devices are used to clean the living and working environment in the module by crew members. The medical room and equipment is a key element for medical, surgical or dental care, for both regular check-ups and emergencies. Physical exercise quarters must also be present in the habitat design. Including the items already discussed and referring to relevant literature (Larson and Pranke, 1999; Taylor, 2010) while evaluating the system requirements, the mass allocation for the CELSS is depicted in Table 4-1. The table shows all of the consumables and equipment which were taken into account when calculating the total mass and volume of the CELSS for the Mars-X mission.

Table 4-1: Mass Allocation of CELSS

Category	Contents	Mass Distribution	Volume Distribution	Comments
Consumables	Food	0.7 kg/p/d	0.003 m^3/p/d	Calculated by dry weight after dehydration.
	Water for ingestion	3.5 kg/p/d	0.0035 m^3/p/d	Drinking: 1.6 kg/p/d Preparing food: 0.75 kg/p/d Water in food: 1.15 kg/p/d
	Water for hygiene	25.5 kg/p/d	0.025 m^3/p/d	Water for personal hygiene: 7 kg/p/d, For environmental hygiene: 18.5 kg/p/d
	Reserve oxygen	200 kg	0.2 m^3	Emergency oxygen supply of the overall mission period for crew's safety.
Food and Water Hardware	Food freezers	400 kg	2 m^3	For dehydrated food in low temperature storage.
	Food cookers	120 kg	0.6 m^3	Devices for food hydration and heating.
	Cleaning tools for food	60 kg	0.6 m^3	Device, such as dishwasher.
	Water storage device	100 kg	14.5 m^3	The initial water storage device, which is divided, with recycling system.
	Recycling water storage device	50 kg	0.2 m^3/p	The recycling water storage device (one week storage)
Controlled Ecological LSS Hardware	Planting chamber	100 kg/p	0.5 m^3/p	These items are the key items of equipment for the CELSS.
	Air circulation device	100 kg	2 m^3	
	Microbial bioreactor	200 kg	2 m^3	
Waste equipment	Waste storage device	0.5 kg/d	0.1 m^3/d	According to the mission design, it is calculated through the maximum capability of payload.
Hygiene equipment	Personal hygiene devices	85 kg	1.5 m^3	Due to the use of water, these items are involved in the loop of the CELSS.
	Personal hygiene consumables	0.075 kg/p/d	0.0015 m^3/p/d	
Personal equipment	Clothing	100 kg/p	0.3 m^3	Due to the use of water, these items are involved in the loop of the CELSS.
	Clothing cleaning devices	160 kg	1.5 m^3	

Personal stowage	Personal belongings	50 kg/p	0.75 m^3	Individual recreational devices and personal belongings.
Habitat environment cleaning devices	Housekeeping devices and tools	20 kg	0.1 m^3	Vacuum, disposable wipes and cleaning tools for habitat environment.
Sleeping quarters	Sleep provisions	9 kg/p	0.1 m^3/p	Sleeping provisions including sleeping-bag, bedclothes, etc.
Medical room and equipment	Medical suite and consumables	1500 kg	6.5 m^3	For the medical, surgical and dental care of crew members.
TOTAL for Mars-X		**21,175 kg**	**135 m^3**	Calculated for a mission of 919 days with five astronauts

The total mass of the designed CELSS (recycling level of 90% water, 20% food and 100% oxygen) for the Mars-X mission of 919 days with five astronauts on board is calculated to be 21,175 kg with a habitat volume of no less than 135 m^3. This volume does not include free space for the astronauts, such as living quarters, working area, kitchen, exercise room, plant room, corridors, etc. which was assumed to be 50 m^3 per person. Thus the resulting design for the two habitats will have a combined volume of approximately 400 m^3. For comparison, the habitable volume for Mars500, ground analog of a Mars mission, was 550 m^3 for a crew of 6 astronauts (Voloshin, 2013). The mass of each habitat was assumed to be 20 tonnes, of which half would be the mass of the CELSS.

4.1.5 Radiation Shielding

Space radiation is considered to be one of the major hazards in deep space missions for the astronauts as well as to the spacecraft systems. Although space radiation remains one of the most critical issues to be resolved, with the advancements in present day technology interplanetary travel will become a reality. In this section the radiation exposure limits for astronauts are discussed, along with the various shielding methods and their capabilities, feasible materials that could be used for shielding the spacecraft, and also risk of the astronauts developing cancer after the Mars-X mission. Table 4-2 analyzes three different methods of shielding the spacecraft from Solar Particle Events (SEP) and Galactic Cosmic Radiation (GCR).

Table 4-2: Analysis of Radiation Shielding Methods [Parker, 2006]

Shielding Method	Description	Pros	Cons
Material Shielding	A large amount of material mass is added around the astronauts to reduce the penetration of the incoming cosmic radiation by absorbing it.	Simple Guaranteed to work	Much too heavy Cascade of secondary particles in the case of heavy nuclei materials
Magnetic Shielding	An electromagnetically induced magnetic field is used to deflect the incoming charged particles back out into space.	Much lighter than material shield	Offers no protection along axis Strong magnetic field (20 T) may itself be dangerous to the crew
Electrostatic Shielding	The spacecraft is charged electrically in order to repel the incoming cosmic ray protons	No gaps in coverage No hazardous magnetic field	Creates nasty influx of negatively charged particles Requires gargantuan voltage of 2 billion volts

After weighing the above shielding methods, in Table 4-2, over a number of criteria such as shielding capabilities, technology readiness, power requirements, safety and reliability, the material shielding method was selected. The effectiveness of the shielding material that can be used depends on the basic atomic/molecular cross sections and also the nuclear cross sections, which in turn depend on the density of electrons per unit volume, the electronic excitation energy, and also the tight binding corrections of the inner shell electrons (Wilson et al., 2001). Materials such as water and polyethylene, that have higher electron density and the least electronic excitation energy, were selected for a trade-off analysis to compare the radiation dose levels with the required shielding. However, prior to looking at shielding methods the limits of the human body must be discussed first. Table 4-3 illustrates the current exposure limits for astronauts and flight crews recommended by the National Council on Radiation Protection (NCRP) issued in 1989, considering low earth orbit conditions.

Table 4-3: Radiation Exposure Limits for Astronauts in Low Earth Orbit [Campbell, 1992]

Exposure Interval	Blood Forming Organs (cSv)	Ocular Lens (cSv)	Skin (cSv)
30 days	25	100	150
1 year	50	200	300
Career	100-400*	400	600

*Depends on crew member sex and age

Table **4-4** shows the shielding effectiveness against both GCR and SPE on the human tissue at the skin level and at the 5-cm depth, described as Blood Forming Organ (BFO) dose. From this table it is evident that traveling during a solar maximum is better to minimize radiation risk to the astronauts from the GCR. This is supported by the fact that the strong magnetic field of the Sun during solar maximum reduces the flux of the cosmic rays entering the inner solar system (Hopkins and Pratt, 2011). The next solar maximum is expected to be around 2024 (based on the 11 year solar cycle); hence the piloted mission of Mars-X is scheduled for 2024.

Table 4-4: Annual Dose Equivalents for GCR at Solar Minimum and Maximum in Free Space at 1AU from the Sun [Campbell, 1992]

	Skin Dose Equivalent for GCR[1] (cSv/year)	**BFO[2] Dose Equivalent for GCR (cSv/year)**	**Skin Dose Equivalent for GCR (cSv/year)**	**BFO Dose Equivalent for GCR (cSv/year)**	**Skin dose Equivalent for SPE[3] (cSv)**	**BFO Dose Equivalent for SPE (cSv)**	**Shielding g/cm^2**
Material	**Solar Minimum**	**Solar Maximum**	**Solar Minimum**	**Solar Maximum**	**N/A**	**N/A**	**N/A**
Water	22.56	10.97	21.86	10.69	0.32	0.38	50
	30.29	14.28	27.62	13.16	12	7.29	25
	49.6	21.31	40.16	18.11	105.6	42.88	10
	65.6	25.92	49.6	21.3	411.4	105.6	5
	111.45	40.02	65.6	25.27	19 800	391.5	0
Poly-ethylene	21.99	9.94	16.18	9.65	10.02	6.3	25
	40.81	17.36	33.9	15.1	90.89	39.05	10
	58.74	23.15	45.06	19.26	360.3	99.23	5

[1] GCR: Galactic Cosmic Ray
[2] BFO: Blood Forming Organs
[3] SPE: Solar Particle Event

It can also be seen in

Table **4-4** that among the two materials, polyethylene has the highest shielding capability and is the main driving factor for selecting polyethylene for protecting the transit habitat from GCR. HDPE (High Density Polyethylene), with a density of 0.97 g/cm^3, will be used to shield the two human modules. HDPE is known for its high specific and tensile strength. It is opaque and withstands high temperature. Polyethylene with shielding capability 10 g/cm^2 will be sufficient to keep the equivalent GCR dose well within the limits. The corresponding shielding thickness of polyethylene will be approximately 11 cm contributing an additional mass of 6000 kg.

Though the SPE doses in

Table **4-4** were estimated using the fluence at 1 AU, while in the vicinity of Mars (approximately 1.6 AU) the fluence of these SPEs is expected to be much less. This can be supported by the fact that SPE flux is inversely proportional the square of the distance from the sun (Rapp, 2006). Nevertheless, to minimize risk the spacecraft will have a special shielding chamber in one of the habitat modules. This chamber is designed to be spherical (non-spherical shapes would require more mass) and encloses a volume of 40 m^3 (Campbell, 1992). It is estimated that the spacecraft is going to encounter five large SPEs, two during the transit to and from Mars, two while in Martian orbit, and one while on Phobos. The spacecraft will use a 50 cm thick layer of de-ionized water (around 5.3 metric tonnes) that is going to be continuously circulated around the solar storm protection chamber in polyethylene pipes. The water in this circulation system is derived from the closed loop life support system. In this way, the dual use of water solves the problem of spacecraft mass overrun. In addition to water the food supplies and other storage products will be packed in this chamber to provide additional shielding.

The forecasting of large SPEs will be a vital part of the mission to warn crew members of potentially lethal doses. By continuous monitoring of various aspects of solar activity (x-ray and radio emissions, sunspot number, etc.) the likelihood of a proton event will be accurately predicted with a 20 minute warning time. This means a warning signal will be sent out to the crew to hide in the solar storm shelter chambers and protect themselves from large SPEs (Rapp, 2006).

Biological radio protectors have been considered in the past for low LET (Linear Energy Transfer) radiation and in radiation cancer therapy for the purpose of reducing the effects to normal tissues in patients (US Department of Energy, 2012). It is, however, unknown if these are effective for heavy ions and neutrons in deep space. A combination of lower doses of radio protectors with dietary factors that include anti-oxidants such as vitamins E and A is a promising approach that will be explored in this mission. The use of chemo preventers that function to inhibit the promotional effects of both radiation and pre-malignant clones in a target tissue will be tested and studied in ground based radiation experiments before the Mars-X mission (Cucinotta et al., 2001). Taking into account the polyethylene shielding and water shielding the equivalent radiation dosage breakdown for the entire mission is given in Table 4-5.

Table 4-5: Total Equivalent Radiation Dosage Breakdown for the Mission

	Skin Dose Equivalent (cSv) for GCR	**Body Dose Equivalent (cSv) for GCR**	**Skin Dose Equivalent (cSv) for SPE**	**Body Dose Equivalent (cSv) for SPE**
Transit to Martian Orbit (240 days)	11.42	9.93	0.32	0.38
Martian Orbit (399 days)	18.98	16.5	0.64	1.52
Phobos (40 days)	0.95	0.83	0.16	0.19
Transit to Earth (240 days)	11.42	9.93	0.32	0.38

An additional radiation dose of 1.5 cSv is expected from the NTR for the duration of the mission (Nealy et al., 1991). It has been uncovered that conventional dose limits have a large biological uncertainty associated with them. In addition the equivalent doses compiled in the above tables are estimated for free space at 1 AU from the Sun. Hence it is necessary to multiply the doses by a factor of ~3.5 to obtain a rough approximation of the

95th percentile radiation confidence interval (CI) dose equivalent while calculating point estimates (Rapp, 2006). By incorporating the 95th percentile CI dose, a total radiation exposure for the mission of 2.5 years is found to be within 53-160 cSv (skin dose equivalent) and 48-145 cSv (BFO dose equivalent).

These levels are considered to be under the limiting levels for the career exposure guidelines as outlined in Table 4-5. This in turn implies that the radiation exposure is within the limiting level of 3% of the excess cancer fatality risk set by NCRP. This means that the cancer fatality risk for astronauts after the Mars-X mission is not more than 3% (Cucinotta et al., 2001).

To conclude this section, radiation will still remain one of the biggest risks of the Mars-X mission due to the existing uncertainties in biological effects of radiation as well as the uncertainties in the radiation environment in deep space beyond 1 AU. More ground based radiation experiments should be implemented to overcome these uncertainties and to make missions to Mars less risky.

4.1.6 Nuclear Thermal Engines

The Nuclear Thermal Rocket (NTR) engine is a leading propulsion system for human Mars missions. For this mission, having researched NTRs a decision was made to use this technology as the main transportation method, because of its proven technology, higher performance, and lower overall launch mass in LEO. As an example, if chemical propulsion (I_{sp} of 450 s) was chosen for this mission then the LEO mass in orbit would have to be around 1,340 tonnes and not the current 500 tonnes. Nuclear Thermal Propulsion (NTP) allows greater future growth capability including the use of “bimodal” engine operation, which can eliminate the need for deploying and operating large Sun-tracking photovoltaic solar arrays. As discussed in Section 4.1.7 on power supply, this is a preferable power supply solution for our mission.

Unlike conventional chemical rockets which produce energy through chemical combustion, the NTR derives its energy from the nuclear fission reaction of uranium-235 atoms. By using an “expander” cycle for turbopump drive power, propellant such as liquid hydrogen is raised to a high pressure and pumped through coolant channels where it absorbs heat to become superheated, then it is expanded out a supersonic nozzle to generate high thrust. By using hydrogen for both the reactor coolant and propellant, the NTR can achieve specific impulse values of ~900 s or more; twice that of today’s best chemical rockets (Borowski, McCurdy and Packard, 2012). From 1955 to 1972, 20 rocket reactors were designed, built and ground tested in the Rover and NERVA (Nuclear Engine for Rocket Vehicle Applications) programs. Key performance parameters like thrust level, sustained engine operation, and restart capability were demonstrated (Robbins and Finger, 1991; Koenig, 1986).

Research and development work on NTR started in the former Soviet Union in the 1950s. From 1959-1960 advances in the development of high temperature, corrosion-resistant, ternary carbide nuclear fuels finally resulted in a heterogeneous core design (Zakirov and Pavshook, 2007). Except for the inside fuel element bundles, this engine operates at moderate temperatures. Another temping advance is a power generation loop, which can be integrated inside the core to provide electric power for the spacecraft and enable smoother propulsion system operations. Ternary carbide fuels developed in Russia may have the potential for providing even higher specific impulses.

4.1.6.1 NTP Technology Status and Performance

In contrast to other advanced propulsion options, no large technology scale-ups are required for NTP. It will only be utilized if it is affordable. An important issue is the test facilities needed for developing nuclear thermal propulsion engines. Those test facilities built during the 60's and 70's are no longer available. The solution could take advantage of analytical techniques, utilizing or adapting existing facilities and infrastructure, and developing a limited number of new test facilities.

The goal of NASA's Nuclear Cryogenic Propulsion Stage (NCPS) project, initiated in October 2011, was to assess the affordability and viability of the first generation of NCPS based on NTP (Houts et al., 2012). Key elements of the project include development of a high power (~1 MW input) Nuclear Thermal Rocket Element Environmental Simulator (NTREES) and an affordable NCPS development and qualification strategy. NASA restarted the NTP technology development and demonstration effort in 2011. System level technology demonstrations will be required, including ground testing of a small, scalable NTR before 2020, followed by a flight test shortly thereafter (Borowski et al., 2012).

With well proven NTP technology, developing and implementation of NTR for the Mars-X mission is more dependent on policy factors. Unlike other mission architecture, Mars-X is not restricted to ground rules which depend on only one space agency. Nuclear Thermal Propulsion systems produced by any available entity can be employed during the mission implementation phase. Effort must be made to promote international cooperation. As a relatively independent subsystem of the Mars-X spacecraft, there exists more flexibility to integrate NTR to other subsystems. Nuclear thermal engines and propellant tanks from different producers can also be integrated. An I_{SP} of about 975 s is used in transportation performance analysis as higher performance is to be expected from the predecessor engine designs, that is, engines which have previously been built and upon which the new engines will be based.

4.1.6.2 Cryogenic Fuel Storage Considerations

Cryogenic Fluid Management (CFM) is an important technical area that is needed for the successful development of Mars mission architectures. The first challenge is the storability of propellants for long duration missions. Regular venting to prevent over-pressurization will cause propellant losses. The key figure of merit for propellant storage is usable mass fraction, F_u, which is the ratio of the usable mass of liquid hydrogen (LH_2) to the initial mass of the system including the propellant and the storage system.

A passive thermal protection system utilizing multilayer insulation (MLI) material is widely used in short duration missions. It is quite difficult to get a monthly boil-off rate under 3% using MLI, or to have a F_u of more than 0.7 (Rapp, 2008). This boil-off rate of 3% per month would make a mission such as Mars-X unfeasible, without an external resupply in Martian orbit, as most of the H_2 would escape from the fuel tanks.

Many studies utilizing NTR transportation systems take active cryogenic fluid management/Zero Boil-Off LH_2 propellant systems as a mission ground rule. Both MLI systems and active cooling components such as cryo-coolers are rapidly advancing in capability, and have gradually replaced cryogenic dewars for space telescope applications

(NASA, 2009). Although these developments have not been applied to cryogenic propellant applications, particularly to the size of the tanks that would be needed for the Mars-X mission, the core supporting technology needed for future propulsion systems will be ready as planned in NASA's propulsion road map (Meyer et al., 2010) and will be available for use in this mission. For the Mars-X mission analysis and system design, Zero Boil-Off system for LH_2 propellant storage was assumed, with F_u ~0.75.

4.1.7 Power and Thermal Design

In this section, the characteristics of the power system needed for the spacecraft will be considered. A number of points have to be taken into account when designing such a system. Firstly, the power produced by a power source decreases over time due to degradation and other perturbations. For instance, Si solar cells have an efficiency of 88% after two years of mission (Larson and Pranke, 1999). Therefore, it is required to size the components of the system in a way that the requested amount of power will still be delivered by the end of the mission. Secondly, it is important to make a difference between *baseline power*, which is needed continuously, and *peak power*, which is needed only during short surges. The values in Table 4-6 below are estimates based on past STS and current ISS missions (seven and six crew members respectively). The Mars-X project considers a spacecraft with five astronauts traveling with instruments for scientific experimentation.

Table 4-6: MXV Power Requirements

Baseline Power	**Power Required**	**Engineering margin**	**Utilization coefficient**
Housekeeping - Maintenance	5 kW	+25%	100%
Spacecraft lighting	0.5 kW	+25%	100%
Life support - Crew health care	15 kW	+25%	100%
Communication	1 kW	+25%	30%
Spacecraft AOCS[1]	2 kW	+25%	20%
Scientific experimentation	2 kW	+25%	100%
Total	**25.5 kW**	**31.9 kW**	**29 kW**
Peak Power			
Crew discretionary	15 kW	+25%	30%
EVA lights	1 kW	+25%	30%
ISRU equipment	8 kW	+25%	30%
Total	**24 kW**	**30 kW**	**9 kW**

[1] AOCS: Attitude and Orbit Control Subsystems

Applying an engineering margin of 25% to account for unanticipated growth and for safety, the results become:

- Total baseline power: 29 kW
- Total peak power: 30 kW

Making the assumption that the power system must also be able to provide peak power for occasional surges 30% of the time, the total amount of power required is 38 kW, rounded to 40 kW.

4.1.7.1 Solar Arrays

Solar arrays have been used for decades in space applications and the solar modules powering the ISS have proven their efficiency. When considering the use of solar power, an important factor to take into account is the distance from the Sun, which affects the production of energy as the solar flux received decreases proportionally to $1/D^2$ (where D is the distance from the Sun). Typical flux values are 1.4 kW/m^2 on Earth and 0.6 kW/m^2 on Mars (Larson and Pranke, 1999). In order to generate the required 40 kW by MXV, the surface area of the solar cells needed would be a few hundred square meters. Such large solar panels could prevent the use of artificial gravity; that is why a technology like bimodal NTR (BNTR) will be the considered option for powering the spacecraft. BNTR can be combined with secondary power systems such as fuel cells, to be used as emergency backup power in case of power distribution issues or even outage.

4.1.7.2 Bimodal NTR

In addition to being considered among the leading propulsion options for future human exploration mission, BNTR can also be configured for power generation. Recent systems and mission analysis studies carried out by NASA at the Glenn Research Center, a family of modular BNTR vehicle concepts has been developed (Borowski, McGuire and Dudzinski, 2005). They utilize a common core stage powered by three ~67 kN engines which are also able to produce electrical power. Each engine is equipped with a closed-cycle Brayton rotating unit, which is a thermodynamic cycle between hot and cool sources, used to generate electricity, and is able to provide up to 25 kWe. Considering that each Brayton rotating unit operates at two-thirds of the rated power under nominal conditions (~17 kW), three engines would provide the power of 40 kW required by the CELSS, telecommunications systems and scientific experimentation. Following propulsive burns of the NTR, a radiator system rejects waste heat and reduces decay heat propellant loss. The NTR turbine is directly connected to a heat exchanger which is itself linked to the radiator.

4.1.7.3 Power Consideration for the Martian Moon Outpost

In a first consideration, an assumption is made that the power needed by the two or three crew members on board the landing habitat (HabEX-2) is less than half of the total power needed for the whole MXV spacecraft. Therefore, between 15 kWe and 20 kWe would need to be generated during 40 days by the power source of HabEX-2 after docking with the Martian Moon Outpost.

Three options are studied in order to supply the lander with the required amount of power. The first one uses multiple Radioisotope Thermoelectric Generators (RTG) and ultra-thin solar arrays deployed on the surface of Phobos by the astronauts. Research done by NASA includes the development of an advanced thermoelectric converter with a goal of 6-8 We/kg specific power (Misra, 2006). An embedded mass of 1.4 t would then generate 10 kWe, the 7-8 kWe remaining being generated by solar thin films. A second option uses a separate BNTR with a single engine and a Brayton rotating unit, producing in total ~17 kWe of electrical power under normal conditions. A third option considers NASA's current research in aerospace power generation and Proton Exchange Membrane (PEM) fuel cells. Capable of providing between 1 and 10 kWe with a compact size (250 to 350 W/kg), they have a lifetime of 10,000 hours (>400 days) (NASA, 2009).

Future research in power supply for aerospace systems and the associated extensive testing will qualify new technologies in the coming years. The Mars-X project intends to take advantage of these technologies and will consider a combination to identify the best solution for the mission to Phobos.

4.1.8 3D Printing

Embarking on a 919 day journey, means that humans are sent to distances beyond any help or potential rescue. The risks of component failures can be mitigated through 3D printing technology by fixing, repairing and upgrading internal MXV components. This technology is evolving at an exponential rate and currently it is possible to create micro-electromechanical systems through 3D printing using a combination of materials and methodologies such as electron-beam or laser nano-lithography (NANOSCRIBE, 2012). In this way printing a new chip or even manufacturing a computer damaged by SPEs or GCRs is completely within the reach of the Mars-X mission. What remains is the ability to repair the most precious systems of this mission, the human body. As described by Kooser (2013), the extant terrestrial examples of successfully printing replacements of entire organs, from dentures to an entire liver and other vital organs, show that this technique could also be viable in space. Other than in-flight repair of man and machine we can imagine printable food. Food variety matters for astronauts and fresh meat can only be available using this novel approach (Thompson, 2012). The emerging micro-gravity 3D printing companies, such as Made In Space and Deep Space Industries, provide an example of future development and uses of 3D printing in the space industry. Also, ESA has just commissioned a study on the use of 3D printing of regolith for ISRU to create surface infrastructure (ESA, 2013). The Mars-X mission could test some of these 3D printing technologies on Phobos, which in the future will enable in situ production, mainly for structural construction and radiation shielding as well as mining of potential volatiles.

4.2 Landing and Staying on the Moon

4.2.1 Phobos Rendezvous and Berthing

Due to a very low gravity and uncertainty regarding the surface properties of Phobos, landing on it will be more difficult than landing on a planet or a large moon. Upon approaching Phobos, the narrow angle camera (ONC-T), wide angle camera (ONC-W) and Light Detecting and Ranging (LIDAR) instruments will be used together to map and monitor Phobos, measure the altitude and establish the dynamics model relative to the spacecraft. The measuring range of the LIDAR is from 50 m to 50 km. When the distance is within 100 m, the Laser Range Finder (LRF) will be utilized to generate the height and attitude information relative to the surface of Phobos. In addition, several sets of Fan Beam Sensors (FBS) will be equipped onboard as alarm sensors to detect potential obstacles which may hit the approaching Phobos Unmanned Lander (Kubota, Hashimoto and Kawaguchi, 2008). When the lander craft connects with Phobos, some thrusters in the opposite direction will still operate to provide contact force, because the gravity of Phobos is nearly negligible due to its small mass. Simultaneously, the drilling equipment in each leg of the lander craft will drill into the soil to fix it on the surface of Phobos.

Mars-X proposes that a lander craft with a berthing mechanism on each of its six or eight legs be designed and developed for this mission. The lander will be semi-autonomous and it will be teleoperated by the crew who will stay in orbit around Phobos, in case an abort sequence is required. In each leg, the damping mechanism and berthing system must be implemented. At touchdown, most of the impact energy will be absorbed by the damping mechanism, as described by Marov et al. (2004). The dimensions of the berthing equipment, as shown in Figure 4-10, is about 0.6 m in length with a drill-bit of 0.2 m, each implemented in the legs of the lander. It is designed such that the screw is unidirectional, so that the retraction is blocked (Ulamec and Biele, 2009).

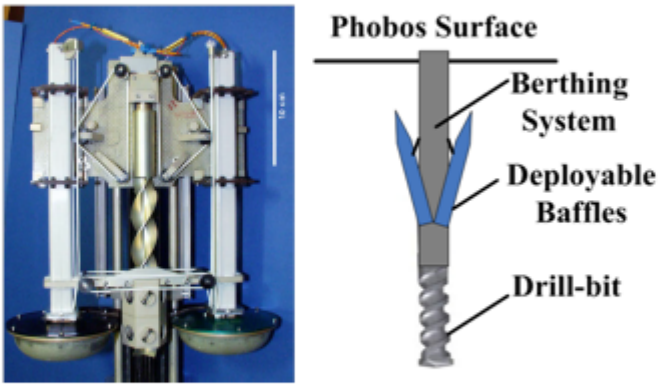


Figure 4-10: Berthing Mechanism Design (left) [Ulamec and Biele, 2009], Proposed Berthing Mechanism (right)

In order to ensure the reliability of the system and to strengthen the fixing force, the proposed design will include deployable baffles, as in Figure 4-10. These deployable baffles with sharp heads are mounted in the middle of the berthing equipment, and can unfold and fasten when the drilling operations are completed. An extra component could be added to enhance the fixation performance, which is some liquid material that would expand into the gaps. The berthing mechanism is a very complex set of equipment, which must be tested comprehensively and reliably. One proposed method would be to test a scaled model of this landing system on a near Earth asteroid with a robotic mission or with a probe to Phobos, similar to Phobos Grunt.

4.2.2 Infrastructure for Future Missions

One of the main goals of the Mars-X mission is to prepare and test key technologies for future human landings on Mars. The mission duration is designed to be 919 days, however most of the Mars-X infrastructure is expected to significantly exceed mission lifetime, thereby contributing to any future Mars mission and potentially to other deep space missions. This section will explain and discuss key features and innovative concepts implemented in Mars-X for exploitation in future missions to Mars and beyond.

4.2.2.1 Establishing an Interplanetary Network

The overall objective of the mission is to observe Mars from Martian orbit. For that reason architecture exploits rovers and flyers placed on the Martian surface to great extent. A human Phobos moon base along with two optical communication relay satellites will grant constant near-real time communication to the Martian surface, Martian orbit and Earth. In order to enhance the communication the delay- and disruption-tolerant network (DTN) protocols will be implemented, during the mission these protocols will ensure proficient communication within the architecture. Once the mission comes to an end all the rovers and flyers placed on the Martian surface will be toggled to (semi-) autonomous mode and will remain fully operational and capable of performing further scientific experiments; thus DTN will grant an efficient and reliable connection between the Martian surface and Earth. DTN efficiency increases along with the number of nodes (e.g. spacecraft, satellite, rover with DTN communication protocols); thus the Mars-X architecture would likely be a first step in establishing an interplanetary network (interplanetary internet) that would significantly improve deep space communications in the context of reliability and data transfer rates.

4.2.2.2 Architecture Reusability

One of the greatest challenges of any human deep space mission is the mass requirement. Mars-X incorporates a modular approach creating the possibility of leaving some parts of the architecture on Phobos, such as the Martian Moon Outpost, for use in future missions. The base established on Phobos during the Mars-X mission will also act as a storage depot. In the event that water is discovered on Phobos, empty fuel tanks could be filled with liquid hydrogen via electrolysis for use in future missions. This process would require adequate power generation by MMO, either installed during this mission through ultra-thin solar panels or with the future upgrades to the station. Also, given the recent progression of asteroid mining companies, some of the technologies used to berth with Phobos can be turned to commercial products and sold to the industry.

4.2.2.3 Scientific Experiments

BioRacks could be one of the moon base scientific modules left by the astronauts in the Martian Moon Outpost. After the crew's departure, a few experiments could be started and remotely monitored via previously established relay satellite networks. These experiments could potentially look into the following areas, which not only have scientific value, but could also be used in the outreach campaign:

- Initiating slow growth of algae that can be further exploited in biological hydrogen production or used as a fertilizer for growing food and for other experiments. Algae also provide vital nutrition elements.
- Terraforming reactions could be initialized in small autonomously operated factories in order to produce some oxygen for future missions, e.g. leaving cyanobacteria in controlled compartments.
- In order to decrease the overall mass of the return vehicle, some waste will be left on Phobos. Human biological waste can be recycled i.e. within the two aforementioned experiments

4.3 Living and Working Away from Earth

4.3.1 Astronaut Schedule

The astronauts will be assigned to perform a number of experiments during the journey to Mars and while on Phobos. During the journey to Mars and back the experiments will vary, including microgravity experiments, and localized experiments. To study the effect of Martian gravity on the human body the astronauts will perform experiments similar to those currently performed on the ISS. The crew will also be involved in rigorous training such as robot teleoperations, including use of the sampling equipment to develop competency and prepare before reaching Phobos. This approach will keep them occupied, since an underloaded crew performs as poorly as a crew that is overloaded (Kanas and Manzey, 2008). Figure 4-11 gives a brief description of daily astronaut activities throughout the mission. Such activities include daily exercise, medical exams, status updates, work time, personal time, meal breaks, and sleep time allocations. Regular physical exercise is necessary to counteract the understood harmful influence of microgravity (e.g. bone and muscle mass loss) and sustain overall good physical condition. The time devoted for conducting scientific experiments must be balanced with environmental maintenance, such as plant care, for constant psychological support and stability.

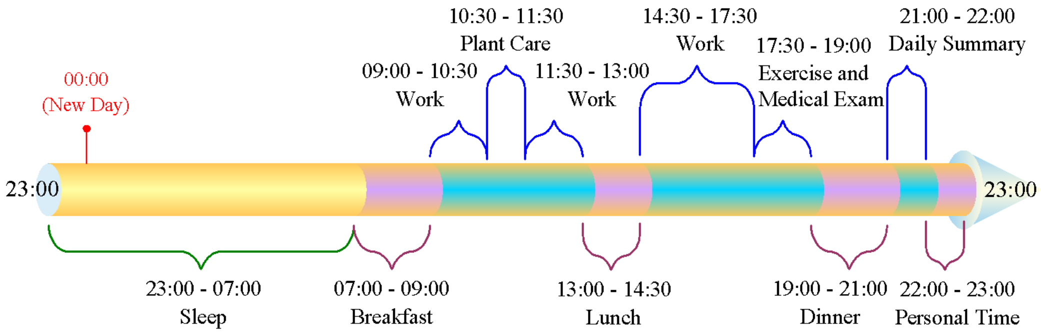


Figure 4-11: Astronaut Daily Schedule

Once the crewed habitat has docked with the Phobos base, the astronauts will have time to conduct experiments within the habitat, as well as outside the pressurized habitat. Collecting samples from the Martian moon, among with other activities, can only be carried out by Extra-Vehicular Activities (EVA). Astronauts on Phobos will be equipped with personal propulsion units in addition to their EVA suits. This is important in order to maneuver in the almost non-existent gravity of Phobos. The desire is to keep the astronauts untethered in order to allow maximum autonomy, as they might have to travel up to 500 meters. Using propulsion to stay close to Phobos' surface is more practical than using an umbilical. A design similar to the US Manned Maneuvering Unit (MMU) can be followed (Millbrooke, 2001). Moreover, if EVA on the main spacecraft is needed (e.g. maintenance and repairs), astronauts can use the same propulsion units or be tethered and moved around by robotic arms. For distances further than 500 m on Phobos the risk rises, so robotic assistance can be utilized. For example, astronauts can remotely operate Robonaut, equipped with boosters to collect samples from distant sites; the difference being that if something goes wrong far away from the Habitat a robot will be lost instead of a human life.

4.3.2 Psychological Considerations

The proposed mission that will bring humans to Phobos will have a duration of 919 days, as discussed in Chapter 1. This could present extraordinary challenges for the psychology of astronauts aboard, as never before have humans been isolated and confined in space for so long. Stress also stems from the high risk factor, work demands and, at times, from having to cooperate with people from different cultures and backgrounds (Kanas and Manzey, 2008). Many more preparatory studies have to be conducted to test how humans behave in similar situations and also if countermeasures proposed are effective enough:

These begin, naturally, with astronaut selection. Ideally, potential crew members would vote to select the rest of their team, as demonstrated effectively in the Mars 500 experiment (D. Urbina, personal communication, January 15, 2013). Current standards for crew selection are, however, considered inadequate. One main characteristic that all Mars-X astronauts should have is being highly excited and enthusiastic. People inspired deeply by science and exploration, who will long not only to set foot on Phobos, but also to perform even mundane tasks for the benefit of mankind, are deemed as the only ones capable of coping with the challenges. On top of that, the Mars-X crew must receive special training to withstand the deep psychological effects of this endeavor. During the mission itself, leisure activities can be of great importance to stabilize morale and develop a positive intra-crew atmosphere.

The Internet, specifically, can be a great asset in the battle against isolation, as a portal to the rest of civilization. With current advancements in the development of Disruption Tolerant Networks (DTN), it could be possible for astronauts to surf the Worldwide Web with a small time delay, but otherwise naturally and efficiently. This can prove particularly helpful for the crew to read the news or even watch sporting events. In time, a more stable, interplanetary Internet could be established (BBC, 2012).

The internal architecture of the spacecraft can play a pivotal role in maintaining crew morale over extended periods of time. It is here that the latest advancements in *Sensponsive (sense-responsive) Architecture* can help turn the emotional tide; these aim to adapt the flexible, transformable spacecraft interior in response to the behavior that astronauts display. The target is to minimize their stress and maximizing their comfort, stabilizing crew psychology in the process (Oungrinis et al., 2012).

Sensponsive Architecture detects the facial expressions and body movements of the crew, sensing discomfort, and it can also monitor hormone levels via implants in their bodies. It then processes these data through advanced software, compiles behavior patterns and resolves to use the proper response in each situation. Unlike “responsive-only” systems, it is dynamic, with the ability to iterate and learn – and thus it can even earn the “trust” or “friendship” of the crew, as with time, it adapts to accommodate their personal needs better. Since the sensponsive system improves with time to each astronaut, it is advised that the crew trains with it from the very beginning. Examples of how Sensponsive Architecture can react to crew member stimuli include primarily the use of actuators to alter the distribution of space elements around the astronaut, as shown in Figure 4-12. Also, changes in the intensity of light, background music, temperature level or even texture of working surfaces and release of specific odors can prove to be useful tools in order to manipulate the human senses and suppress psychological extremities. More intense lighting and rhythmic music can be in turn used to counter astronaut hypokinesia. In this design, crew quarters would be fashioned to look like an Earth-like retreat: familiar textures, smells, sounds and colors create a cozy feeling for the astronauts.

The design to implement such architecture in small segments is already available (Liapi, Linaraki and Voradaki, 2012). Tests in a full spacecraft design should be conducted soon.

Figure 4-12: Geometry Changes through the Sensponsive System [Liapi et al., 2012]

Another issue that can affect crew psychology is that Mars-X proposes a multinational, mixed gender crew; this can add complexity to interpersonal relations. However, in the long run this diversity can be have a positive impact on the psychology of the astronauts, as Diego Urbina and Romain Charles of the Mars 500 experiment have reported. Equally important is to counter repetitions in the crew's daily schedule, e.g. by adding flexibility in meal choices during the mission, as well as ensuring availability of the astronauts' national dishes (Charles and Urbina, 2012). Another solution is to make use of pleasant surprises every now and then. Presents could be stored aboard the spacecraft and handed out by the Mission Commander on special occasions. A regime of "increasing returns" could be implemented to counter the rising discomfort as the mission progresses. For instance, an astronaut rewarded with 20 minutes of free time for successfully completing an experiment in the beginning of the mission would get 40 minutes towards the end of the journey. In this way, as the angst increases, so does motivation.

One largely neglected issue in terms of psychology has been the crew's sexual activity during the mission. For a mixed gender crew this is something that needs to be taken into careful consideration. While sexual activity can be excellent for psychology, the complete lack of it for 919 days could be a blemish. Certain precautions have to be taken to ensure harmony between the crew as well as with their families on Earth. Astronauts have to be of the right mindset and apply caution in their relations with their partners. Flirtation and interaction are perfectly possible with loved ones, be them in the spacecraft or on Earth, and a significant other usually can support the crew and motivate them further.

Learning from Earth analogs, the inclusion of women in a confined group has positive effects, especially if women are older than men and adopt the role of the "mother". However, it can be a stressor for both genders if the ages of males and females are similar; then it can lead to rivalry, frustration and possibly sexual harassment. Coping strategies must be further researched and developed and the astronauts' select-in criteria should probably take this into account (Kanas and Manzey, 2008).

Due to the time delay between the Earth and Mars' neighborhood, utilization of psychotherapy is restricted mainly to fellow crew members on board the spacecraft. It is essential that certain members of the crew undergo special training in order to be able to deliver help, counseling and treatment when necessary. Psychiatric medication should be available on the spacecraft and perhaps a detainment chamber in case a crew member develops violent, impulsive or suicidal behavior, to avoid jeopardizing the entire mission. If implemented in the design, this chamber should allow living in humane conditions. Perhaps it could serve two purposes to save space; more specifically, it could be the same room as the highly shielded chamber available for sheltering the crew in the event of a solar particle event.

It is also worth noting that a long stay in space can still offer opportunities for salutogenesis – psychological self-promotion of health, as astronauts feel like achievers and pioneers. It could be worth discovering salutogenetic activities, as is now manually photographing the Earth from the ISS, and proposing them to the future Mars-X astronauts.

4.4 Ground Support and Supply Chain

4.4.1 Ground Supply Chain

The ISS model is very practical for the management of on-the-ground infrastructure. The executive agency of Mars-X will be responsible for all agreements. For instance bilateral purchase agreements will be signed directly between all contractors. Counter purchase agreements will be signed between each member agency in order to keep accounts and guarantee the geographic return rule (ESA, 2007). Barter agreements (agreements in which services are exchanged as currency) will also be signed between the space agencies, in case the contributing space agency would like to participate in the program by delivering some important parts to the mission, instead of playing just a financiers role. The executive agency will also be responsible for the organization of all supplies to space through its partners' space ports and chosen launch vehicles.

4.4.2 Interplanetary Supply Chain

In preparing missions to planets and other celestial bodies, interplanetary logistics and supply chain management is an important issue which must be taken into account during early design phases (Shishko, 2013). The supplies necessary for space missions can be categorized into subgroups depending on their nature, which extends from basic requirements such as astronaut sustenance to complex supplies such as the transportation vehicle (Shishko, 2013). For the purpose of this project, Mars-X will be focusing on a few important subgroups.

There are three main options in organizing interplanetary logistics. In the first, all necessary supplies are carried from the start of the mission. The second is scheduled re-supply, where supplies are shipped to a specific location by a specific time when it is estimated that they will be required. The third is prepositioning, which is when the supplies are sent to a specific location on the celestial body or orbital nodes, where they await utilization (Interplanetary Space Logistics, 2007). Resources at orbital nodes or celestial bodies will add extra value to the mission only when they can be accessed (Shishko, 2013).

For engineering and science purposes various types of observation equipment will be implemented on Mars and into Martian orbit. This equipment will be prepositioned at the defined locations, both on the surface and in orbit, on a mission separate to the main spacecraft as it is not necessary to carry all this equipment along with the main spacecraft during the journey to Martian orbit. This will reduce risk and minimize complexity of the mission. All empty fuel tanks with a hydrogen cooling system will be attached together on the surface of Phobos. The fuel tanks will be reusable and accessible from space during future automated In Situ Resource Utilization (ISRU) missions. This will prepare fuel supplies for future human missions to Mars or Martian orbit. Together with the interconnected fuel tanks rack, a Mars and Earth communication satellite will be left behind on Phobos, as well as some equipment for Mars observation. The transportation of communication and observation equipment to Mars is an opportunity to gain additional income for the mission. There are also future trade opportunities of the empty fuel tanks; this could be of interest for private companies whose business model involves providing interplanetary supply services for future public or private exploratory missions (Keravala, personal communication, February 1, 2013)

4.4.3 Mission Operations

The importance of mission operations and ground support should not be underestimated. It is vital to have a continuous communication link, especially with human missions in deep space. From Mars signal propagation delay may reach from 3 up to 17 minutes for a single round trip, which therefore allows a minimum of three sessions per hour. In accordance, emphasis will be placed on effective ground infrastructure in order to be well prepared for every predictable situation which will reduce risk. Using the existing ground station network and infrastructure can facilitate cost-saving (Wertz and Larson, 1996). In order to have continuous communication with the spacecraft, at least three ground stations on Earth will be needed to provide up- and down-links between the mission control center and the crew. Back up communication links will be prepared, by additional existing ground stations on Earth, with priority agreements for emergency situations. To improve the link quality, space based communication relay satellites may also be used. They would enhance bandwidth and signal strength by additional amplification as well as providing intermediate storage and signal correction. Table 4-7 demonstrates staff allocation for effective ground operations for higher risk stage missions, which has to be finally defined during detail design phases and after frequency allocations (Boden and Larson, 1996).

Table 4-7: Ground Operations Staff Allocation

Facility	Function	Number of full time staff
Primary Mission Control Center	Mission command center	40
	Telemetry tracking and analysis	20
	Communications	30
	Crew schedule planning	30
	On-board experimentation planning	30
	Consumables record-keeping	10
	Guidance navigation and control	28
	Support staff	45
West Control Center	Command center	10
	Telemetry tracking and analysis	8
	Communications	10
	Guidance navigation and control	8
	Support staff	15
East Control Centre	Command center	10
	Telemetry tracking and analysis	8
	Communications	10
	Guidance navigation and control	8
	Support staff	15
	TOTAL STAFF:	**335**

4.5 Technology Requirements Summary

The engineering aspects of Mars-X mission were discussed within this chapter and a broad overview of the required technological progress was developed. This progress must be completed within the allocated time frame of the designed architecture. As this report is not solely an engineering report it was not possible to cover every engineering topic and as such the most important technologies and their associated challenges were summarized.

Launch Vehicle: A mission to Mars will require a new type of launch vehicle. It is proposed to upgrade the shroud of Falcon Heavy increasing its diameter to 8-8.4 m, with volume capability of 550 m^3 and assuming it will be capable of lifting 50 tonnes into a 400 km LEO orbit. This is a strict assumption, which must be further analyzed to establish the feasibility of this proposal.

MXV LEO Assembly: Increasing the number of launches required to complete MXV will make the mission more difficult. Current restrictions are the mass and volume of the fuel which require at least 8 launches in the current MXV configuration. The fuel tank module spacecraft will need to have automatic docking capabilities, while keeping the cryogenic fuel thermally stable.

Cryogenic Fuel: Liquid hydrogen is very difficult to store without any leakage during the mission duration. An excess amount of fuel will be required, even if the fuel tank modules will have zero boil-off technology implemented. It was assumed that this technology will be developed in the following years.

Nuclear Propulsion: The cryogenic fuel is required to increase performance of NTR. It was assumed that bimodal engines with I_{sp} of 975 s and generating 25 kWe will be produced and developed within the project schedule. Other NTR requirements such as thrust or nuclear material mass were not analyzed and must be addressed in future studies.

Inflatable Habitats: The habitats can be launched on currently available launch vehicles, making use of inflatable technology, which has already been developed. The internal spacecraft configuration will need to be designed to incorporate the architecture for the artificial gravity effects.

Artificial Gravity: The MXV will rotate at a rate of 4.4 rpm creating a gravity gradient through the habitat in the range of 0.38 - 0.53 g. This poses many technological challenges on the spacecraft and human behavior. Future tests must prove the adaptability and compatibility of this design, simulating a similar environment on Earth.

CELSS: The development of closed ecological life support system will need to incorporate space agriculture, which was assumed to produce 20% of food and 90% of water recycling. This is a complex system, which could be very costly, but is a necessary step for any future deep-space missions.

Radiation Shielding: The initial research shows that it is possible to keep radiation exposure of astronauts at an acceptable 53-160 cSv range. Polyethylene shielding will have to be integrated within the inflatable module walls for GCR protection, while a special chamber must be designed for protection from SPEs.

Sensponsive Architecture: Psychological effects are a very important aspect of long duration missions. The proposal to use sensponsive architecture adds complexity to the design, but it must be developed for missions to Mars to reduce psychological stress.

Berthing Mechanism: Berthing in a low gravity environment of Phobos will be essential for Mars-X mission and for future missions to asteroids, so a mechanism combining unidirectional drilling, deployable baffles, and liquid material was proposed for further investigation. This mechanism could be tested either with a mission to Phobos or to a near-Earth asteroid.

3D Printing: Increasing interest in 3D printing technology could prove very beneficial for a mission to Mars. If mature enough, this technology will provide ability to fix, repair and upgrade internal spacecraft components, with possibility to print food or even internal human organs.

MXV Subsystems: The presented MXV design does not cover attitude and orbit control, communication, command and data handling, and thermal subsystems. Although some areas of these subsystems were presented, future analysis of these will need to be performed.

All of the above mentioned components of MXV design represent an overall view of different technological challenges behind the Mars-X mission. The rapid development of these technologies is required in order to meet the demanding project timeframe of launching the mission in 2024. All of these items must be addressed and researched in more details, from which the cost estimate can be obtained. The following chapters of this report present an overview on how all of these technological aspects of the mission can be approached from the political, management and financial disciplines, which are required to make this mission a success.

5 FROM DREAM TO REALITY

5.1 Governing Parameters

There is consensus among space faring nations that Mars is the next destination for human presence and therefore the policy for the exploration is already established. Long-term, multi-national visions for the exploration of Mars have been supported by agencies including NASA, ESA, RSA, and CASC, which have identified the exploration and development of Mars as essential. Mars-X combines the intermediate goals of a low gravity asteroid rendezvous with the preparatory goals of observing and preparing for a mission to the Martian surface. Phobos, an asteroid captured by Mars during the early years of the solar system, will help reveal the geological development of Mars itself and address numerous scientific questions related to the formation of the planets in the solar system. The strategic policy of this mission will maximize the economic viability by combining available funding resources and minimizing technical risk by avoiding the complex descent and ascent systems. Asteroid missions have arguably higher return to industry with in situ mining possibilities at a lower cost (ISU, 2011). The technology required for the habitation of an asteroid will be cross compatible with missions to Phobos and will adhere to the severe budgetary limitations impeding human surface exploration (ISECG, 2010). The policy for observing Mars will be the pursuit of biological and geochemistry knowledge of the planet for the next ten years. The cancelled Mars Astrobiology Explorer Catcher MAX-C was to follow the successful design of Mars science laboratory while the Trace Gas Orbiter will endeavor to more accurately describe the composition of the planet and its history. Sample return missions will be of the highest priority making Martian moons increasingly attractive (ISU, 2011).

Vision and Voyages, the NSF/NASA requested decade study is in agreement with the long term Mars exploration initiative announced by President Obama in 2012. This report specifies two Mars flagship missions, a low cost Mars Trace Gas observer mission with ESA and a USD 2.5 billion Mars Astrobiology Catcher which endeavored to determine how life existed on Mars (ISU, 2011). These budget limits arise from economic factors with an emphasis on international consensus and partnership (ISU, 2011). Phobos next will accomplish all scientific objectives outlined in this document. Private corporations such as SpaceX, Moon Express, Shackleton Energy, Planetary Resources, Inspiration Mars, Lockheed Martian, and The Boeing Corporation have announced private initiatives to explore, invest and profit from the resources contained in and around the Red Planet. It is clear that there is a unified goal to accelerate and expand human presence throughout the solar system. These major space agencies share insights into the existing and emerging policies within their nations, which are necessary to understand to reach a strategic consensus. Within this section the political, economic, legal and management challenges of the Mars-X mission will be addressed.

5.2 Mars-X Political Steps

The Mars-X plan endeavors to remove the divisions that have prevented missions to the stars for generations. In this spirit Mars-X addresses not only numerous technical issues, but the challenge to integrate the nations and corporations that will execute a mission of this complexity, cost, and schedule. It is evident through the cancellation of numerous recent missions that there is a higher failure resulting from financial, managerial, and political insufficiencies, and that few fail for technical reasons.

To secure the project vision and enable mission success, a framework of political initiatives have been identified that will offer governments and corporations a platform for cooperation. Strategic planning methods have been established with careful consideration placed on previous mission experience, as well as momentum building in the space sector led by entrepreneurs around the world.

5.2.1 ISECG as a Starting Point

In 2006, a series of discussions were initiated by 14 space agencies on global interests in space exploration. They elaborated a vision for peaceful space exploration by both robots and humans, and they formed the International Space Exploration Coordination Group (ISECG). ISECG has identified Mars as the next destination for man. Within ISECG, the most influential and advanced space-faring states are represented and is the ideal starting point to promote and support the Mars-X project at a state level. Building on the policies and plans defined by the ISECG, the common elements, and the common trends, Mars-X defines a strategic consensus among vital contributors (Kawaguchi et al., 2011).

5.2.2 International Cooperation

There are multiple important political benefits for the states that embark on an international project. One of these is international cooperation, which in space activities has the potential to reduce a partner's costs by spreading the burden to other nations. Although additional overhead costs may increase, these costs are spread among the partners. Furthermore, international cooperation generates diplomatic prestige while encouraging political sustainability. Another very important benefit is a resulting increase in workforce stability; one large program brings a relatively large number of jobs and amount of revenue. With private industry participation this employment boom can be extremely beneficial to recovering economies. Legally the industrialization of outer space must be available to all mankind. Mars-X encourages every nation to join the voyage and each citizen to invest.

5.3 The Mars-X Model

5.3.1 Scope of Political and Legal Entity

Mars-X has defined the governing authority for the viable execution of the proposed gateway on the Martian moon of Phobos. The ISECG provides the initial forum for member entities to share their objectives, plans, explore collaborative concepts, and formulate preprogram international partnerships. However, every nation will be permitted to enter the consortium upon meeting the required commitment levels.

Several models were researched; however, the intergovernmental organization-transnational corporation provides the most practical legal and business case for Mars-X. This innovative public-private partnership model involves the creation of a new intergovernmental authority, the Mars-X Consortium (MXC). MXC will consist of, at a minimum, the fourteen ISECG members and the transnational corporations wishing to develop the project. This commercial entity combines state reliability and legality with the flexibility of industry on an international level.

In addition to the acquisition and distribution of scientific data, MXC will be responsible for resource speculation and allocations, ingress and egress routes, and mission resupply making a "Port Authority" model an ideal analogue. Similar to the Suez seaport this model allows a public entity to plan, facilitate, and regulate the initial construction and port extension, acquiring the large amount of capital needed. The port operator is managed by a private entity which operates, develops, and provides services to customers. The model combines creation of vital connections for customers, acts as a commercial space business incubator, provides safety management and allows creation of values and taxes incomes for member entities.

5.3.2 The Governing Authority

From a top level perspective, the political questions that must be answered involve determining the necessary framework to enable international participation. The governing body therefore must be international, providing a framework for enabling negotiations and conflict resolution (internal and external), and it should regulate the Phobos Next Gateway.

To determine the best strategy and political framework for the MXC governing authority, it is necessary to take into consideration the lessons learned from the International Space Station (ISS) and International Telecommunications Union (ITU). The feasibility of this project relies on accommodation of a partner's own objectives and establishment of realistic expectations. Other important aspects to feasibility include: usage of clear mission objectives to drive support, establishment of dependencies, planning of public policy and early achievements, application of common standards , identification of milestones that demonstrate tangible benefits to the public, and employment of reference missions in order to define requirements (Laurini et al., 2011). Several models were considered including a lead agency approach and a public private partnership model.

The Mars-X lead agency model considered the United States of America National Aeronautics and Space Administration (NASA) as leader in an international cooperative similar to the structure honed during the International Space Station endeavor. The political history of this model will be detailed through a closer examination of the International Space Station and his origins. On January 24, 1984 US President Ronald Reagan directed the NASA to build the ISS within a decade (NASA, 2007). Within two years Canada, Japan and the European Space Agency (ESA) accepted this invitation to collaborate. This was followed by Russia's joining in 1993 (Logsden, 1998).

Primary lessons learned through this success in human spaceflight include:

- Ensure stability through a formal Intergovernmental Agreement (IGA).
- Data-sharing and Export-control issues must be mitigated in early stages.
- Balance specificity and flexibility in program agreements
  (International Space Station (ISS) Multilateral Coordination Board (MCB), 2009)

Mars-X considered a consortium led by NASA for the following reasons:

- NASA has a demonstrated history of human exploration and the culture of the organization is within the mission objectives laid out by Mars-X mission designers.
- This mission fits within NASA's current 2013 directives from the US Executive Branch.
- The Global Exploration Roadmap (GER) was headed by NASA and is being used by the agency as a current development guide. Mars-X accomplishes much of the GER objectives in an alternative way.

- The financial requirements identified by the budget require the buy-in of a space agency capable of significant investment over a ten-year period.
- Nuclear propulsion has been established as a critical technology. It is non-exportable and thus must be provided by the launching and host agency. Russia is the only other agency that has the technological and political ability to support this choice, but ranks lower against other criteria.
- The choice of SpaceX launchers, which is based on lowering the cost to make the mission feasible, launches from the Kennedy Space Center in Florida making NASA an ideal launch coordinator.
- The choice of the US as the launching state mitigates US ITAR constraints.

Ultimately this solution suffered from several constraints. NASA is currently suffering from massive budgetary constraints. Numerous international missions and cooperative agreements in the space sector have been canceled. If the weight of the entire mission rest solely on its capabilities, a short political cycle and highly susceptible economic structure make the United States a risk. The management and execution of the ISS program creates serious concern itself due to the deployment schedule and budget overruns. Additionally, a NASA led endeavor linked to US politics has alienated many Asian nations from participating in the Space Station. As an orbiting vehicle these exclusions were legal, whereas Mars-X is subject to the Outer Space Treaty. However, when applied to the Mars-X model there were serious legal ramifications which will be discussed.

The MXC partnership model seeks to bring all nations to the endeavor which will increase funding levels. Extensive partnerships with the private sector composed of numerous transnational corporations, enables MXC to engage resources previously untapped. A request for proposals or call for tenders by MXC will invite private industry buy-in as equal voting members in the consortium. Once added, these members will be made identical financial contributions as the member states themselves.

The political benefits from such a partnership include: development of local private sector capabilities through subcontracting opportunities and exposure of state owned enterprises. It also creates diversification in the economy by making the country more competitive in terms of its facilitating infrastructure base as well as boosting to its business and industry associated with infrastructure development, while also supplementing limited public sector capacities and preparing for future demand.

The MXC will have sole proprietary rights to the application of technologies resulting from this mission. Land will be leased to the company for utilization whether through ISRU commodity production, gateway services or habitation. The company will retain the right to use member logos and reserve sole access to media and distribution rights for profit. Distribution of data such as maps, genetic life found, scientific data and more will be available for sale by the company. Given the potential profitability of the project demonstrated in business studies, private entities will have access to the MXC capital as a way to leverage additional financial capabilities, resulting in public private shareholders. MXC will also be traded publically, opening up increased public investment motivated by the above incentives.

5.3.3 The Agreements

The lead agency model would select partners based on a number of criteria including: financial ability, technological inputs, space program history, governmental stability, and inter-governmental relations. Further study must be undertaken to identify potential compatible agencies but historical precedence identifies Agenzia Spaziale Italiana (ASI), European Space Agency (ESA), Centre National des Etudes Spatiales (CNES), Canadian Space Agency (CSA), German Aerospace Center (DLR), Russian Aviation and Space Agency (FKA), Japanese Space Agency (JAXA), and United Kingdom Space Agency (UKSA) as potential contributors. Additionally, China, India, South Korea and Ukraine would be considered. There is an understanding and drawback that comes with choosing a certain nation as host, as capable member nations will not participate due to governmental conflicts or compatibility issues.

In the PPP model the MXC will be created by the unification of the ISECG members. A Memorandum of Understanding (MoU) will be signed among the states at the highest presidential levels and ratified by the peoples governing body, providing the initial framework for smooth operation and long-term commitments. All basic norms and principles will be in this “treaty”; for instance, all MXC members will participate in an equitable manner, regarding their financial contribution. The distribution of power in MXC and therefore decision-making will be equal as long as the member makes the minimum required financial contribution. Members will vote on vital decisions, contract selection, and regulatory decisions.

Similar to all intergovernmental organizations, after the initialization of Mars-X activities and in order to provide a long term secured framework, MXC will need to rule by a binding intergovernmental agreement designated as the MXC Treaty. It is recommended that creation occurs under the United Nations Vienna Convention on the Law of Treaties and will be based on the already existing MoU. The agreement states the scope of activities, regulates Mars-X scientific activities, enables efficient international cooperation and duties, and provides an equitable platform for decision making and conflict resolution. The following will be incorporated into the MXC Treaty:

- Participating members should be involved in the space business either directly or indirectly.
- Should be willing to share and demonstrate their technical capabilities which can be used for Mars-X project.
- Should be willing and adhering to the agreements of the MXC.
- Willing encourage democracy and transparency.
- Equal participation in terms of investments.

This authority will enable an integrated program, which will facilitate more efficient sharing of costs while reducing duplication of effort in areas of: research and technology development, design, production, and infrastructure. MXC will independently manage the funding and securing of full cooperation between states. Through recommending space objectives to its member entities, MXC will also combine the policies of these states with respect to other national and international organizations to develop and implement a long-term space policy. By using the existing industrial potential of all member states, MXC ensures that space technology will be developed and maintained and licensed to partners both during and after the mission. MXC will provide the regulatory framework for diplomatic relations, negotiations, contractor selection, state-to-state/corporate reciprocity, and conflict resolution. Each member entity will receive a vote on such issues. The MXC will represent every continent, including ISECG members, and shall be open to all states and corporations whether from developed or developing space programs. Membership entities cannot be under sanctions by the United Nations or under adverse legal status in their registered state.

5.3.4 Voting Authority Example: Astronaut Selection

International cooperation is distinguishing elements of Mars-X, not only different nations, but private agencies are presented with partnership opportunities. Five astronauts will embark on this mission with an additional five crew members proposed as backup. The extreme difficulty and long duration of the Mars-X flight requires the right mix of crew and a rigorous eight year long training. Every partnering nation will have an interest in having an astronaut participant for the purpose of national prestige and justification of the economic return in the eyes of its citizens. A private entity may be interested in using the astronaut image as an asset for sponsorship or technology demonstration.

The International Space Station (ISS) program was completely public funded with different partners having different shares. According to the Space Station Agreement (1998): “Each Partner has the right to provide qualified personnel to serve on an equitable basis as Space Station crew members.” The selection was carried out according to the procedures laid out in the MoUs and the agreements signed between the partners. ISS is a long-term human space flight program where each partners’ crew assignment opportunity gets satisfied over a period of time and not necessarily with every rotation. To have a crew selection and training process that meets the requirements of public as well as private partners needs a democratic system. Participating entities will be able to take part in the decision of selection of the candidates for Mars-X Crew. Following considerations are some of the few that will impact the decision:

- Mars-X will be one single mission with a limited number of crew positions but many partnering entities.
- Having the best crew for aspects such as brand endorsements, advertisements, and product demonstration, could be of more interest to private partners as opposed to having an astronaut participant.
- Competitive selection and training process meeting all the requirements.

The following procedure could be adopted to have a fair, transparent, competitive selection process for the primary and backup crew:

1. Invitation for applications for the crew position of Mars-X will be open to all qualified personnel without restriction of their nationality. All the participating entities will be free to provide candidates.
2. Amongst the top most applicants, the partnering entities will be allowed to reach a consensus on the finalist candidates who will undergo training. In absence of consensus, voting will be conducted to select the finalist candidates.
3. All the candidates selected will start the transparent training process to become Mars-X crew. Performance feedbacks of candidates and their competitive standings will be made available to them.
4. The highest performing candidates will continue through the 8 year long process.
5. At the end of 7 years, the primary and backup crew will be announced and will undergo the final year of training together.

5.4 Securing the Project from a Legal Perspective

To provide a securing legal framework to enhance the feasibility and efficiency of the activities, Mars-X has taken into consideration both general law principles as well as specific notions that may be relevant in the different stages of the project.

5.4.1 General Legal Framework

The PHOBOS NEXT gateway must establish public and private regulations, with international cooperation to ensure its legal feasibility and sustainability. On an international level, 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, 1967), the Rescue Agreement (1968), the Liability Convention (1972), and the Registration Convention (1975).

By carrying out activities in outer space the MXC shall be compatible with current space law. As a "province of all mankind", the OST Article I enacted the right of free exploration of outer space, that can be used by any public or private entities without "any appropriation or claim of sovereignty" or "harmfully interfere with the right of other states". The Mars-X model protects the spirit of this act by making participation in the mission open and available to all mankind.

The OST and the Liability Convention outline the responsibilities and liabilities of Treaty members. MXC and the states of registry bear the liability for any damages occurred by the Phobos gateway activities and also the duty to supervise it. However, state parties to the MXC are not directly liable for damages caused by MXC, but are jointly liable inside. OST provides that states shall authorize and provide continuing supervision of the activities of their non-governmental entities in space, and there is international liability for damages. This primary state liability along with the framework of the Liability Convention does not have a maximum cap for the imposition of damages. However, primary state liability promotes responsible state legal regimes that can be expressed by domestic licensing or other authorization mechanisms. Under our legal model, the MXC is a transnational private company registered in all MXC member states as shareholders. As such, all MXC proprietary rights will be protected under the intellectual property law of each participating entity. Land claims will be respected both internationally and nationally. Though space programs costs are under more scrutiny, the use of public-private partnerships (PPP) allows development of infrastructure with a minimum public investment (ISU, 2011).

As a private entity registered in each member state, all activities of the MXC shall be monitored by its states of registration and/or any launching states contributing to the assembly and execution of the Phobos Next Gateway. The MXC shall deliver customer authorizations to approach facilities under a licensing regime of technical regulations, control insurance, and indemnification warranties, following the example of the Federal Aviation Administration (FAA) and International Telecommunications Union (ITU). That is why unlike the International Space Station Intergovernmental Agreement (ISS IGA) which creates a cross waiver of liability between States parties, this model enables the MXC to sue any customers creating damages to Mars-X Gateway. In the case of a breach of the MXC Treaty, the principles of Article 60 in the Vienna Convention on the Law of Treaties apply, which concern termination or suspension of the operation of a treaty as a consequence of its breach.

5.4.2 Nuclear Thermal Propulsion

Out of all of Mars-X required technologies, the choice of nuclear thermal propulsion proposes the greatest challenge in terms of garnering political support from both domestic and international perspectives. Nuclear propulsion is a primary driver of the mission due to launch mass restrictions, as the amount of propellant required through traditional chemical propulsion is prohibitive from the engineering and financial perspectives.

Russia and the US have previously tested nuclear thermal propulsion. Although in the past it was stopped due to financial and political pressure reasons, there is nothing legally prohibiting the use of this propulsion type. The United Nations adopted a principles document outlining the use of nuclear energy sources in spacecraft but excludes propulsion in the agreement. Although this is not binding and does not ban the use, The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space and The International Atomic Energy Agency (IAEA, 2005) has identified states friendly to nuclear propulsion and outlined the history, current state and potential future applications of the technology.

On-orbit construction in low earth orbit (LEO) could also be an area of sensitivity, as there may be significant political pressure against having fissile material in LEO for substantial amounts of time. Mars-X is continuing studies into mitigating any potential pressures this may create politically.

5.4.3 Principle of Freedom of Exploration and Use

OST Article I demonstrates the freedom of exploration and use of outer space. However, there are two main issues from this principle that are relevant to Mars-X. One is "in case of permanent space structures on a particular site, the use of the underlying surface would in practice amount to appropriation; yet according to Article II of the OST one cannot appropriate space or celestial bodies" (Viikari, 2012). The principle of non-appropriation will be further discussed in Section 5.4.5.

5.4.4 Export Control Implications

Mars-X proposes dealing with export controls both at an international and a national level. On the international level, states typically implement internationally agreed upon principles in their legislation, while at a regional level they define specific example cases of control or partner-states that are exempted. Export control legislation has a considerable influence on the space industry, as many of the technologies can have are dual use. The USA International Traffic in Arms Regulation (ITAR) places restrictions on the transfer of high technology and items of a military nature mainly for protecting the geopolitical, strategic and economic advantages of the states (Code of Federal Regulations, title 22, sec. 120).

In a project that proposes the development of a planetary gateway, export control issues will play a challenging role. Since Mars-X is a project requiring international cooperation and MXC will be based on an international treaty, the concept of a Memorandum of Understanding (MoU) or other type of bilateral agreement system should be included. This system can be developed so that different levels of regulations can be agreed upon among the states. The MXC will specify specific technologies from the ITAR munitions lists that will be excepted from typical restrictions providing international partners greater access and transparency for the development of the project. Care will be taken by the national or corporate partner to reduce transmitted technologies to the interface level providing only the data required by the participants.

5.4.5 The Principles of "Province of Mankind" and "Non-Appropriation" in Relation to Use of In Situ Resources

Mars-X includes activities on the planetary surface that might include use of in situ resources. In accordance there are some basic principles dictated by international space law that need to be considered. The concept of 'province of mankind' was first introduced in Article I of the OST (1967) stating that "exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries... and shall be the province of all mankind." This concept does not necessarily require equal sharing of all benefits obtained from space activities.

The Common Heritage of Mankind (CHM) principle deals with international management of resources within a territory, rather than the territory itself. It appears indifferent to ownership of designated areas, but rather focuses on the "uses of them for the benefit of humankind, to serve the common interest of peoples everywhere." Kerrest (2001) associates the term "province" with the idea of a territory or the responsibility over a territory which gives the notion of control rather than "property and possible wealth."

The Outer Space Treaty, which governs outer space, prevents national sovereignty claims, but does not expressly prohibit private appropriation. Although OST prohibits national appropriation, the Moon Agreement is the only regulating document that addresses the problem of non-appropriation. However, the Moon Agreement is in the line of OST principles and has not been ratified by the majority of the space-faring states.

There are some precedents that may have value as customary law. An example of this is where Sterns and Tennen (1999) show that there was "no objection to the ownership of the materials by the state, which had collected them, was presented" when the USA and USSR first returned rocks and other samples from the Moon in the late 1960s (Viikari, 2012). Other precedents show the possibility "to remove lunar samples for economic gain if they are also used for scientific purpose." (ISU, 2007)

An alternative solution could be to distinguish land appropriation from resource appropriation since "the ban on appropriation only concerns the exclusion of sovereignty, not of possession" (Viikari, 2012). That is "celestial bodies cannot be subjected to the sovereignty of any state" (Viikari, 2012). However, "once removed, these may be regarded as property" (Badescu, 2012).

Article 2 of the OST (1967) states that "The use of in situ resources on celestial bodies to build a facility challenge the definition of a space object as well as the registration and ownership, whereas in the spirit of the OST, "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means."

Mars-X has developed to incorporate commercial services as well as collect scientific data for profit. The OST contains only general principles and as Viikari (2012) indicates there is "no specific reference to private activities in outer space". Therefore, MXC is a good opportunity to establish a new legal regime, instead of amending the existing one.

5.4.6 Non-Interference

Another issue that should be taken into consideration is the implication of an outside public or private entity interfering with Mars-X activities on the celestial body's surface, or independently starting a similar activity. In the case a non MXC member starts a new commercial activity on a celestial body which uses in situ resources, it falls under the general legal regime and any kind of such activity is considered to breach the OST as well as the Moon Agreement. No matter if it is a public or private entity, the State is immediately accountable for the breach on the international plane as if it had breached the international obligation (Hermida, 2004). The MXC treaty will be the only one that provides the legal framework and facilitates such activities. Furthermore, if an entity tries to use Phobos gateway infrastructure or interferes with Mars-X activities without previous notice and approval, it will be seen as a breach of the notion of non-interference with space objects on the basis of Article IX of the OST (1967) and Article 45 of the Constitution of ITU (2011).

5.5 Benefits of Mars-X Consortium

The MXC model is innovative, combining the experience and vision of the worlds' national space agencies with the determination and momentum of leading corporations. The equal voting structure and international legal protection for both land and proprietary rights give MXC the authority to incentivize new sectors of industry. A profit based infrastructure insures that the investment made by both public and private sectors returns value back to their shareholders or taxpayers. Traditional leadership models such as the space station took more than 30 years to complete, almost three times the initial projection, and at triple the price (NASA, 1992). In this international endeavor many spacefaring nations such as India and China were excluded from participation. The MXC will address this issue by requiring its partners to only meet a minimum contribution threshold. Having met this requirement they will then be considered active and equal participants. Working within the established boundaries of the Outer Space Treaty, the Mars-X Consortium of governments and corporations has established a framework for the distribution of land, capitalization of Martian resources, and protection for associated intellectual rights for the invested partners. With these securities in effect the capital required for missions to Mars will be exceeded and the political will to go to Mars will be firmly established. The MXC represents the ideal way to build a solid economic sustainability for this endeavor.

5.6 Economic Aspects

5.6.1 Principles for Optimizing Budget Management

When it comes to the funding of public space programs, there have historically always been some contradictions. On one hand there is a client, i.e. policy makers, who want results as quickly as possible to inform the public and gain additional support for their political campaigns. On the other hand, there are industrial contractors, who are willing to provide their services, but often at the highest possible cost.

It is therefore necessary to agree on the most common budgetary requirements during initial negotiations with the consortium. The resulting agreements from these negotiations will assist in keeping program costs at a reasonable level. The Mars-X mission is designed to be an international endeavor and as a result it is important that opportunities are equalized in accordance with the different economic conditions and technological capabilities of different contractors from different countries. The geographic return principles practiced by European Space Agency is a useful model which can be incorporated to assist in accomplishing these goals (ESA, 2007). As was previously mentioned it was proposed that an international consortium be established in the form of juridical persons instead of an association. One of the main reasons for this decision was to give the project management body decision-making power in all matters below top level requirements within given amplitude of budget and time schedule.

Similar to the methods practiced by Lockheed Skunk Works, the application of many unconventional methods in the research and design phases can be applied to space missions to reduce costs and enhance the development speed (Wertz and Larson, 1996). The Lockheed Skunk Works program established in 1943 is known for its capability for astonishing achievements in world aviation history. Examples of these include the U-2 spy plane, the Mach 3.2 reconnaissance plane SR-71, and the first stealth fighter F-117 A (Wertz and Larson, 1996). All of these aircraft were well ahead of their time. The techniques employed allowed for the development of some of the most remarkable flying vehicles, below allocated budgets and time schedule. Some of the unconventional methods which can also be applied to space exploratory missions include (Wertz and Larson, 1996):

a) The program manager must be delegated to have complete control over all aspects of the program
b) A smaller number of capable people who are connected to the project should be utilized
c) The number of reports should be kept to a minimum. However, all important work must be thoroughly recorded and files must be easily accessible to all relevant personnel by several different search parameters
d) Monthly cost and budget reviews; invoices should be processed as quickly as possible
e) Bidding and procurement procedures should be kept as simple as possible
f) Basic inspections should be delegated to subcontractors and vendors where applicable
g) Representatives of contractors should have access to the progress status continuously
h) Hardware specifications should be given in advance of contract agreement with indication of the rationales behind the specifications
i) The contractor must be delegated to have the authority to test the final products developed by them. Testing is also very important in early phases to keep the competency and confidence in a particular field
j) Access to project sites by outsiders must be strictly controlled by appropriate measures of security

k) A motivating reward system should be applied for good performance at all administrative levels
l) Building of trust and friendship between the client and the contractor through close daily communication will help to avoid many misunderstandings

This mission should be neither the highest cost mission nor the lowest cost mission. The target area in terms of performance and cost relation curve should be in the middle - between the design-to-cost and design-to-requirements, giving a reasonable performance per unit cost (Boden and Larson, 1996).

5.6.2 Mission Cost and Margins

It is important to agree about the order of magnitude of the program budget with all of the consortium partners as early as possible. This will give the consortium enough time for negotiations with local policy makers and parliaments.

Due to the nature of the space industry and the differing criteria for each mission the cost always depends on multiple objective and subjective factors, making each case unique. Even interplanetary exploration missions can vary significantly due to their level of complexity. For instance, the Hayabusa asteroid mission, which delivered samples to Earth from 300 million km away, cost Japanese taxpayers approximately USD 100 million (2003 economic conditions)(NASA, 2012) while Mars Curiosity laboratory, being twice as heavy as Hayabusa, cost American taxpayers USD 1.8 billion (2012 economic conditions)(David, 2012) which is roughly eight times more expensive per kilogram of spacecraft (both figures excluded launch costs). In accordance with this, it is almost impossible to produce a reliable fixed cost figure for the Mars mission until all partnership and key technology procurement agreements have been signed (Hoffman and Kaplan, 1997). Even then, budget margins for up to a factor of 10 will be necessary to allow for inevitable fluctuations, as has been seen historically with the ISS. Based on fully and partially applicable analogies as referred to in Table 5-1, after making a small number of assumptions and considering that it is not a Mars surface mission, an estimate for the minimal reasonable cost to perform this mission at the lowest acceptable level of risk, is USD 60 billion (by 2013 economic conditions). It may easily become a bigger number due to unpredictable events as mentioned earlier. It is appropriate to start an open international discussion about the budgetary issues and realistic speculations about interplanetary and Mars related human missions.

5.6.3 Mission Cost by Analogy and Parametrics

Preliminary space mission costing can be estimated relatively accurately by using analogies from the past along with known parameters. Analogies must be applicable to the planned missions, in technical complexity as well as in their macroeconomic background. It is important for this costing technique that the information sources utilized are trustworthy. However, there is no costing analogy available for any manned missions to Mars. As a result a significant number of assumptions were incorporated based on how relevant the conditions to the Mars-X mission were. In real life, the situation is much more complicated. The price always depends on who is asking for the price and who is asked to make a proposal. For that reason it would be wise to maintain a delicate balance between becoming too independent of existing contractors and having good relations with back up providers who have the necessary technological capability.

In the mission cost analysis, the following main parameters and analogies were observed, with correction factors for subsystems and distinguishable parts of the program. These are indicated in Table 5-1, Figure 5-1, and Figure 5-2.

Table 5-1: Mission Budget Allocation by Cost Groups

Cost Description	Total Cost in Billion USD	Comments and level of confidence of each cost group
Cost of Facilities	0.8	100% analogy
Project Management	8	100% analogy and best practice
Design and Development	9.5	50% assumptions; 50% analogies
Manufacturing of Subsystems	28	10% assumptions; 90% analogies
Testing, Launching, Integration	8	75% assumptions, 25% analogies
Operations and Ground Support	3.5	25% assumptions, 75% analogies
Other Costs	2.5	75% assumptions, 25% analogies
Total:	**60**	**in 2013 economic conditions**

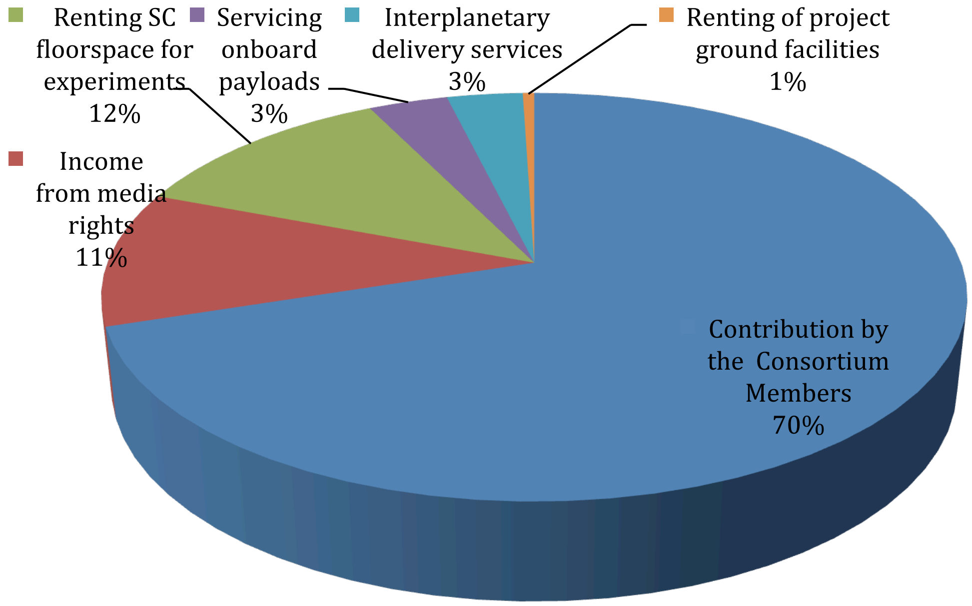


Figure 5-1: Project Income Sources

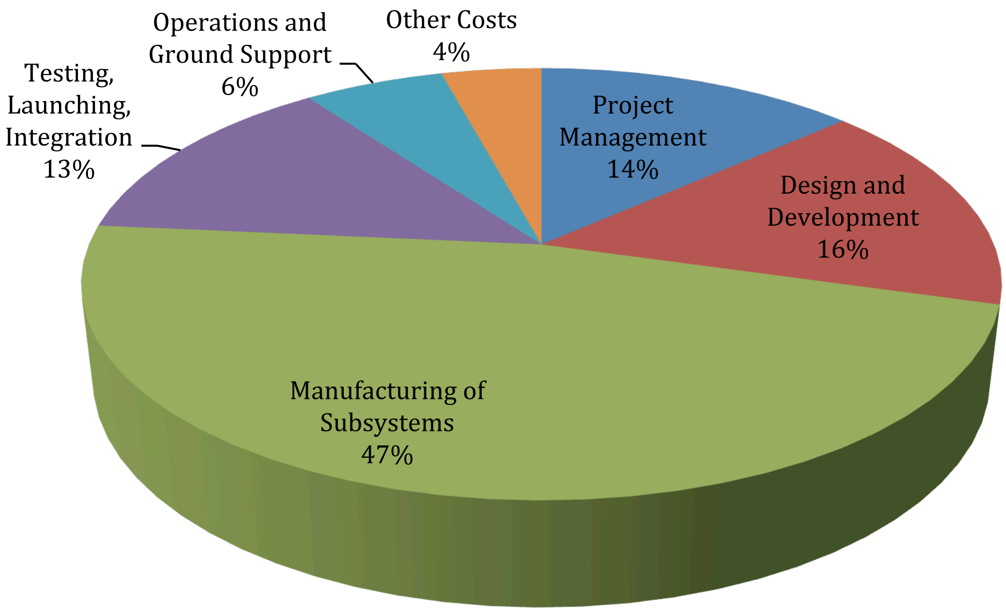


Figure 5-2: Project Cost

5.7 Investing in Mars

5.7.1 Potential Advantages and Disadvantages in Private and Public Sectors

An exploration mission to Mars faces several challenges both for the public and private sectors. Unlike the Apollo program dedicated to U.S. President John F. Kennedy's national goal of "landing a man on the Moon and returning him safely to the Earth," Mars-X lacks a dedicated leading public figure. With a global fiscal crisis and environmental issues mounting, the public sector is currently very terrestrially focused. Determining who will pay and benefit from this mission is a primary goal of the Mars-X Consortium and critical to mission success. Both public and private sectors must understand the potential benefits from this mission and how they could generate future value for investors. Potential benefits of Mars-X to both the public and private sectors is addressed in order to create awareness of positive value and to encourage participation. Governments should support the Mars-X mission by initiating and generating national or public leadership, creating incentives for increased investment. This is shown in Table 5-2:

Table 5-2: Advantages and Disadvantages of Public and Private Sector Participation [Livingstone, 2000]

	Public	Private	Both
Advantage	• Scientific discoveries • Public service opportunities for education and outreach • Entertainment, media, sponsorship • Creation of national or public leadership	• A favorable public image • Advertising • Opportunities for corporate growth • Service for established infrastructure (e.g. renting service) • Research and development of new products • Potential for untapped resource exploitation	• New technologies (spin-offs) • High-paying job opportunities • Employment opportunities • Revenue from media rights
Disadvantage	• High competition with respect to relatively cheaper and safer terrestrial projects for funding allocations from the budget	• High capital investment to reach profitability • High risk environment	• Costly and risky • Opportunity cost in the form of council programs or other areas such as health and education

5.7.2 Public Investment

There are several countries with an ambitious aim of exploring deep space for the benefit of the human race. The United States is the first country to place humans on the Moon and is still leading the world in space exploration under the guidance of NASA. According to Euroconsult research reports (Euroconsult, 2012) the United States stands on top of the chart with an annual budget of ~$16 billion per annum. The European Space Agency (ESA) has recorded many space achievements as well. In 1985, ESA launched Giotto which completed a close fly-by of Halley’s Comet. This was Europe’s first deep space mission. Planning is currently underway for the Rosetta mission which will study the comet Wirtanen. Probes to Mercury (BepiColombo) and Mars (Mars Express) are also in development (Oracle ThinkQuest, 2013). ESA currently stands in second place with an average annual space budget of $4.5 billion in the last few years (Euroconsult, 2012). Russia's outer space aspirations focus greatly on the Moon. In addition to that, Roscosmos is considering assembly of a space station in orbit around the Earth by 2030. The Russian space plan also calls for sending robotic probes to visit Venus, Jupiter and Mars by 2030 (SPACE.com, 2012b). Japan, being a member of the ISS and with asteroid sampling experience, has considerable expertise to share. China has been involved in space since the 1960's and has successfully launched a manned spacecraft to its space station. India has also developed launch vehicles and is very ambitious with its Mars project, with their first mission to Mars planned for September of this year (SPACE.com, 2012a). Canada has also had a long history in space. Canada’s Remote Manipulator system (Canadarm) has been used on Shuttle missions to deploy and retrieve satellites. Currently, Canada is contributing a robotic system to the ISS and many Canadian astronauts have flown on Shuttle missions.

All the countries shown have annual space budgets of over $1 billion (Euroconsult, 2012).

The above mentioned countries have the potential capability to be part of the consortium. Apart from these space agencies there are several private companies which have the potential to be part of this consortium. In the new age of space exploration, with the rise of new commercial space companies such as SpaceX, interest in Mars exploration has risen. Another commercial space company, Bigelow Aerospace, has launched two of its inflatable modules for technology testing and has also shown much interest in Mars exploration. Mars One is a not-for-profit organization that plans to take humanity to Mars by 2023 and the Inspiration Mars Foundation is an American non-profit organization which aims to launch a human mission to flyby Mars in January 2018. With the increase in private sector investment in space, private funding is becoming a popular option for future human missions.

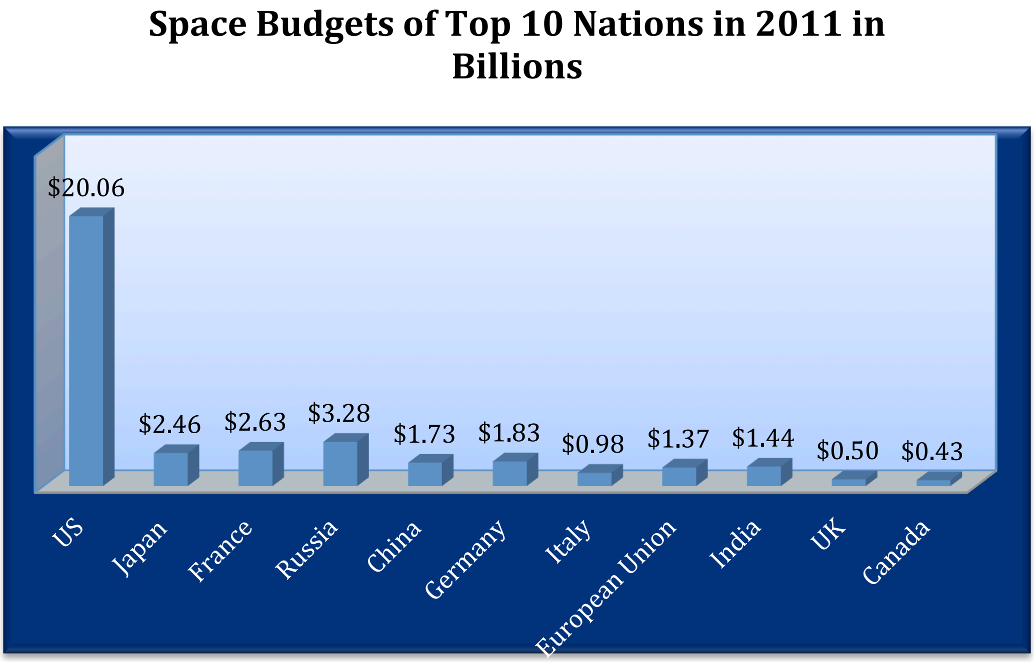

Space Budgets of Top 10 Nations in 2011 in Billions

Figure 5-3: Annual Budgets of Major Space Agency [Euroconsult, 2012]

5.7.3 Private Interest

The financial incentives for corporations working with the MXC initiatives are numerous and lucrative. As an example, many of America's defense contractors and industrial space partners today were fostered as emerging businesses under the Apollo era. However, business incubation is just one of the many areas that will profit from being a MXC partner.

5.7.3.1 Media and Marketing Rights

Media rights are one of the largest identified areas of potential economic return for Mars-X participating states. Increased globalization of products and the high visibility of the Mars-X mission will make those with the distribution rights instant global icons. For example, Tang is still a well-known drink from the Apollo missions though it is no longer manufactured; however, it made Kraft Foods a billion dollar international food corporation. Organizing the sale of media rights with the intention of creating television programming, large-scale social media interaction, films, product placement, and advertising, will provide significant profit for MXC partners. Additionally, presenting this mission as a social event for all humanity may lead to an indirect crowd sourcing effect if emphasis is placed on the marketing and product development aspects of commercial media. Since MXC retains the rights to all distribution and branding rights as well as the right to use member logos, it reserves sole access to media rights for profit.

The list of participants that would find interest in the use of MXC facilities and branding include commercial ventures as diverse as cosmetics (e.g., AXE, L'Oreal, Avon, Revlon), food (e.g., McDonald's, Coke, Pepsi, Pizza Hut), clothing (e.g., Uniqlo, Armani, Zara), sports (e.g., Nike, Adidas, Reebok, Puma), big technology companies (e.g., IBM, Microsoft, Apple), hospitals, travel agencies, etc. Facilities or mission footage will be used for filming movies in deep space for IMAX and other major movie studios to produce movies such as Hubble 3D or Armageddon, which made over USD 500 million worldwide (FindTheData, 2012). Models of space ships, toy licensing, accessories, jewelry and clothing with the MARS-X logo are among many potential revenue sources that would motivate private business participation in MXC.

Naming some projects or the facilities with prominent peoples' names willing to contribute large amounts of private capital is another media potential. An example is investor Burj Khalifa of Dubai whose name is now known in association with the world's tallest building.

5.7.3.2 Lease of Instrument Use

The ISS has demonstrated itself as a successful test bed for commercial ventures in space; including rental based experiments. The ISS-based Nanoracks science laboratory offers time-based usage of station resources. Mars-X will seek to lease instrument time use of its rovers' sensors, spacecraft instruments, and precursor Mars orbiters. The pricing of the product will help to offset operational costs and try to ensure close to 100% efficiency of instrument utilization.

5.7.3.3 Future Gateway Services

During the execution phase of the Mars-X mission, several terrestrial and extra-terrestrial facilities will be established. Once complete, the MXC will create future renting services such as test facilities on the ground and spaceflights to LEO (e.g., commercial LEO station by Bigelow), on-board experiments in-flight, and the utilization of Mars-X interplanetary infrastructures (e.g., radiation shielding on Phobos, telecommunications, reusable fuel tanks in Martian orbit). In other words, there could be exclusive rights to all test and building facilities during the mission.

5.7.3.4 Land Leases

MXC will have the legal authority to distribute land leases. Perhaps one of the most lucrative offers Mars-X plans to make is the right to capitalize for the first time on extra-terrestrial claims and have the legal and political protection to do so. Land will be leased by the company for utilization whether through ISRU (In Situ Resource Utilization) commodity production, gateway services or habitation. Use of this land has the potential to generate huge profits for MXC that will be used to fund the mission. Land speculation remains a major incentive for private investment the world over.

5.7.3.5 Return of Use of Regolith and Other Materials

Use of space-based technology for the extraction of natural resources will engage mining companies and energy companies. The natural resources on Phobos, particularly the atmospheric CO_2 but also subsurface ices, are thought to be potential sources of rocket propellants, mineral resources, and life support. If Mars missions could be launched relatively "dry" and refueled in Phobos, it will enable the reduction in launching costs to Mars in the future. After successfully landing on Phobos and then on Mars, future missions could incorporate drilling of the Martian surface. This could give rise to many potential benefits to humans such as natural resources (Klinger, Mosemann and Johnston, 2011).

Though Mars-X will not seek to return Mars system resources to Earth for profit in the near term; however, as usage of near-Earth resources like asteroids grow, MXC, via its Phobos gateway will be ready to sell resources to potential customers. ISRU is permitted by international conventions for scientific missions and should not be considered as a barrier; even if this mission does not incorporate ISRU in its critical design. Delivery of in situ resources both to current and future customers as well as cargo delivery services using propellant nodes has been identified as a major profit area.

5.7.3.6 Contract Acquisition

The 'lead agency' approach suggests participating space agencies would be the decentralized contact point for contractors, holding legal responsibility and arranging contract agreements. For example, if a European company is the contract supplier for attitude control systems, the contract would be initiated with the Mars-X administration through ESA. ESA would bear the liability for filling the obligations set forth in the supplier contract. Additionally, similarly to the ISS, if a country wishes to do so, it may establish PPP (Public Private Partnership) relationships within their own organizations to fulfill the obligations of the Mars-X contract.

However, in the selected PPP model the contract selection becomes a matter to be voted on by the MXC in the same fashion as any other major decision. Companies submit proposals related to the design, execution, operation and management of the mission components and in return may receive lucrative multi-million dollar contracts.

5.7.3.7 Spin-off Technologies

The economic valuation of the spinoffs from the Apollo program numbers in the billions. The MXC will have sole proprietary rights to the application of technologies resulting from this mission. Participating companies will be able to license their innovative technologies resulting in other technological spin-offs. Virtual reality in space is one example of a potential spin-off technology resulting from investment in Mars-X. Engaging the research domains of tele-medicine, tele-education, and tele-operations will be beneficial to the Consortium. The Mars-X mission will stimulate new markets based on space activities that benefit humankind.

5.7.3.8 Tourism/Astronaut Selection

Dennis Tito, a multi-millionaire entrepreneur and space tourist, is funding the Inspiration Mars Mission. In February 2013, Tito announced his intention to send a privately funded spaceflight to Mars by 2018 (Mack, 2013). MXC would invite wealthy individuals and charitable foundations to combine efforts and become partners as well. The use of MXC facilities to support tourism and additional private endeavors will generate additional partnerships and profit sources.

5.7.4 Conclusion

Given the potential profitability of the Mars-X mission, MXC anticipates raising more capital than governments alone can allocate to space initiatives at this time. Providing sound legal and financial assurances to potential partners is key to raising up-front capital. MXC capital can be leveraged to generate numerous financial opportunities, resulting in public and private shareholders. It is proposed that the Mars-X Consortium also be traded publicly, allowing every human being to be a part of the initiative. A space mission truly focused on returning value to its investors and citizens is a novel concept Mars-X will spearhead.

5.8 Management Structure and Governance

The MXC vision is to internationally coordinate human and robotic space exploration focusing on destinations in our solar system where humans may someday live and work. As a final model for MXC a consortium with international participation was selected that includes both government space agencies and private companies. These entities will be coordinated by MXC. MXC will act as the decision making body for all contract selections and major program decisions, however it does not perform the task of project management. Hence, all the programmatic decisions will take place at MXC. It will be headed by a chairman elected by the partner members. All partner members will have an equal right to participation.

5.8.1 International Consortium

Multi space agencies along with private player's participation (International Consortium): A consortium of private companies, national agencies, and investors will jointly manage all aspects of this Mars-X Consortium. The consortium will enhance the program to potential customers in a proficient manner and will include members of experienced space companies. One of the main reasons that potential Mars missions failed in the past was due to the heavy dependency on government funding from a single nation. However, the involvement of several nations working together along with industrial partners on a mission to Mars will benefit these nations in numerous ways including: technology spin-offs, job creation, and international trade, among others.

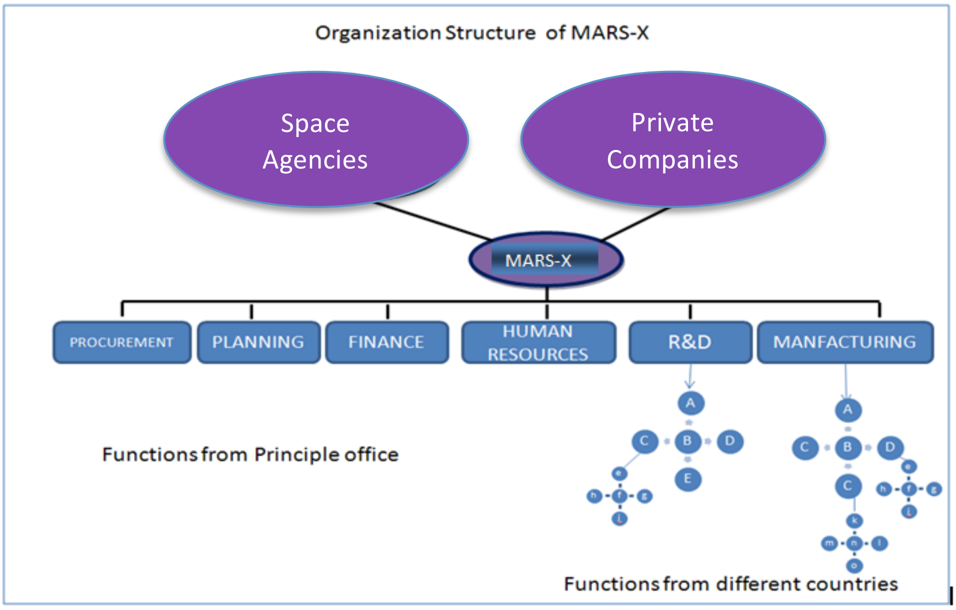


Figure 5-4: Organizational Structure of Mars-X

5.9 Risk Management

The objective of risk management is to identify the items or activities which show potential risk and then analyze their possible failures and frequency of these occurring. Understanding the correlation between the likelihood and consequences or damage can be caused is essential to risk management. The process identifies and assigns parties responsible for each risk response. Depending on the development phase of the project, the person responsible could be an agency planner, engineer, or construction manager. The process could also assign responsibility to a private sector contractor or partner, depending on the contracting method and risk allocation. This risk analysis has explored the activities with the highest activities and consequently has developed a risk response plan or mitigation strategy. In this mitigation strategy the policies, procedure, standards are defined. It demonstrates what options are available for trade-off in terms of costs and benefits. It also demonstrates the impact of current decisions on future options. There are several methods of analyzing the risk; for the case of Mars-X project a matrix method has been implemented. The scaling method used for the development of this risk matrix system is demonstrated in Table 5-3.

Table 5-3: Scaling System for Risk Matrix

Scale	Measure
1	Very unlikely to occur 0%-20%
2	Unlikely to occur 20%-40%
3	Likely to occur 40%-60%
4	Highly likely to occur 60%-80%
5	Near certain to occur 80%-100%

5.9.1 Consequence

Table 5-4 and Table 5-5 represent how a problem in terms of technical aspects, schedule and cost can cause damage to the entire project. Damage is divided into five classes, where class I has catastrophic effects and class V has negligible effects.

Table 5-4: Resource of Risk

Technical risk sources	Programmatic risk sources	Supportability risk sources	Cost risk sources	Schedule risk sources
S-I	II	III	IV	V
Physical properties	Material availability	Reliability and supportability	Sensitivity to technical risk	Sensitivity to technical risk
Material properties	Personnel availability	Training	Sensitivity to programmatic risk	Sensitivity to programmatic risk
Radiation properties	Personnel skills	Operation and support	Sensitivity to supportability risk	Sensitivity to supportability risk
Testing/ modeling	Safety	Manpower considerations	Sensitivity to schedule risk	Sensitivity to cost risk
Integration interface	Security	Facility considerations	Labor rates	Degree of currency

Software design	Communication problems	Interoperability considerations	Estimating error	Critical path items
Safety	Labor strikes	System safety	Exchange rate	Estimating error.
Requirement changes	Requirement changes	Technical data	Purchase power of parity	
Fault designs	Environmental impact			
Operating environment	Stakeholders advocacy			
Proven/ unproven technology	Contractor stability			
System complexity	Funding continuity			
	Regulatory changes			

Table 5-5: Impact of Consequences

Impact of Consequences			
Class	**Technical**	**Schedule**	**Cost**
Class I Catastrophic (Scale 5)	A condition that may cause death or permanently disabling injury, facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission	Launch window to be missed	Cost overrun > 50 % of planned cost
Class II Critical (Scale 4)	A condition that may cause severe injury or occupational illness, or major property damage to facilities, systems, equipment, or flight hardware	Schedule slippage causing launch date to be missed	Cost overrun 30% to 50 % of planned cost
Class III Moderate (Scale 3)	A condition that may cause minor injury or occupational illness, or minor property damage to facilities, systems, equipment, or flight hardware	Internal schedule slip that does not impact launch date	Cost overrun 15 % to 30 % of planned cost
Class IV Fair (Scale 2)	A condition that could cause the need for minor first aid treatment but would not adversely affect personal safety or health; damage to facilities, equipment, or flight hardware more than normal wear and tear level	Internal schedule slip that does not impact internal development milestones	Cost overrun 15 % to 5% of planned cost
Class V Negligible (Scale 1)	A condition that could cause the need for minor first aid treatment and facilities and system will continue without any interruption.	Internal schedule slip that does not impact internal design and development targets.	Cost overrun < 5% of planned cost

5.9.2 Activities

In Table 5-6 the activities which have the highest risk are listed. They are classified into categories of technical, schedule, and cost. The score of consequences and the likelihood are presented for each activity and depending on the scores a mitigation strategy was adopted. From the table it can be seen that before the mitigation plan, there is a high acceptance of risk. Hence, the research and testing has to be carried out using methods which minimize the risk. Two risk matrixes are illustrated in

Table 5-7, the first shows the risk before mitigation and the second shows the acceptance of risk after mitigation.

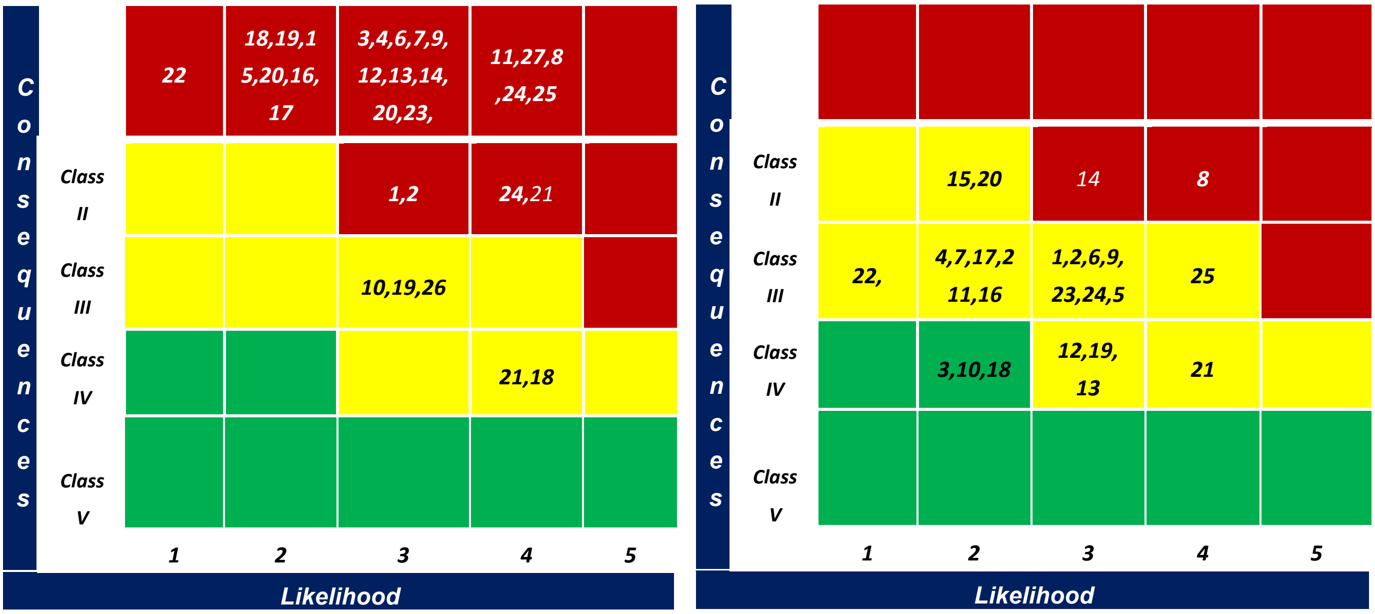
Table 5-6: Table of Activities

Serial No.	Risk Activity	Consequences	Likelihood	Responsive Plan
1	Behavioral and psychiatric risks	C-II	3	Special crew training to withstand isolation, confinement and stress; sensponsive architecture, cross-training the crew for psychotherapy.
2	Performance errors due to poor team cohesion and performance	C-II	3	Team building training, final astronaut selection will include the candidates' opinions/preference for each other.
3	Inadequate selection/team composition, inadequate training	C-I	3	As the astronauts call is open for the entire world, a great number of applications are anticipated; hence very stringent screening methods will be adopted for better selection and team composition. Rigorous training for astronauts for very long periods is adopted for better training and understanding between the astronauts.
4	Performance errors due to sleep loss or work overload	C-I	3	Redundancy in crucial spacecraft/robot commands, careful planning so that astronauts operate only when not tired, this can be detected by the spacecraft's sensponsive system.
5	Circadian desynchronization, fatigue	C-I	4	Light cycle simulating day-night on Earth, carefully planned schedule to imitate Earth days, medication to induce sleep and waking up (caffeine, melatonin, etc.).
6	• Radiation carcinogenesis • Acute radiation syndromes due to SPEs • Acute or late	C-I	3	For radiation carcinogenesis - The total radiation exposure of the mission is within the limiting level of 3% excess cancer fatality risk set by NCRP Acute or Late Central Nervous System Effects from Radiation Exposure - Material Shielding along with biological radio protectors. Acute

	central nervous system effects from radiation exposure			Radiation Syndrome due to Solar Particle Events - Specialized solar storm shelters with extra shielding from 25 cm of water.
7	Inability to adequately treat an ill or injured crew member	C-I	3	Detainment chamber to avoid disease transmission, diversity of medication available on board, good communications with Earth to acquire expert advice.
8	Error due to inadequate information	C-I	4	Long and complete astronaut redundant training and simulating the worst possible scenario. Independent and autonomous action precedes crew chain of command.
9	Reduced safety and efficiency due to inadequately designed vehicle, environment, tools, or equipment	C-I	3	Double redundancy for the most complex systems which cannot be repaired, and for the future programs use of self-healing material.
10	Error due to poor task design	C-III	3	Each astronaut is delegated with a defined job and ground management will be monitoring in order to eliminate any kind of difficulties and ensure optimal efficiency.
11	Inadequate food system	C-I	4	Long and complete astronaut training and with back-up surplus.
12	Compromised EVA performance and crew health due to inadequate EVA suit systems	C-I	3	Robonauts for the EVA activities on complex operations.
13	Operational impact of prolonged daily required exercise	C-III	3	Astronaut preparation must be optimal. Each of the astronauts has to know perfectly the tasks he is going to accomplish. Focus on astronaut training.
14	Nuclear radiation	C-I	3	Radiation dose are within considerable limits.
15	Failure of NTR	C-I	2	More redundant testing on ground and in space.
16	Failure of artificial gravity	C-I	2	Testing of engineering systems to ensure functionality. Additional propellant will be carried in order to account for additional spin-up/spin-down if required. Conventional microgravity mitigation strategies (e.g. exercise) will also implemented to maintain astronaut health in case of complete artificial gravity failure.
17	Failure of docking	C-I	2	Testing the docking techniques with nearby asteroids prior to the main mission.
18	Cost over-run	C-IV	4	The international participation would be both a problem and a solution in this case. Can be reduced by stringent regulations and contracts.
19	Schedule over-run	C-III	3	Ensure airtight legal contracts between contractor and supplier. Establish high accretive daily compensation for delay. Provide enough margin of error for each schedule element. Maintain strict supervision over suppliers and staff. Set firm deadlines.
20	Complexities of	C-I	3	Have an emergency aborting system prior to docking

	integrating the MXV at LEO			sequence in case of misalignments and failures. Then proceed with the docking sequence from the beginning.
21	Supply chain problems	C-II	4	Binding agreements with subcontractors of all levels. Back-up providers for all key supplies. Regular status monitoring and communication with all suppliers. Margins in schedule and budget.
22	Launch failure	C-I	1	Launch can be insured to mitigate the cost risks. Stringent quality assurance and operational plans could minimize the risk.
23	Communication loss with MXV	C-I	3	DTN (delay- and disruption-tolerant networking) protocols are exactly for this purpose, they ensure that data is stored and re-sent (re-routed) in the most efficient way as soon as the link is re-established. The DTN protocols are implemented throughout the architecture, meaning all communication is conducted with the use of DTN protocols, hence greatly increasing reliability, efficiency and effectiveness in case of communication problems.
24	Failure of robotics	C-I	4	General failures can be power supply interruption, communications failure, terrain difficulties, unexpected delays, and software and hardware interruptions. Flying rovers: especially the ARES-based model, in case of failure (power supply, telecommunications, accident, control loss) this model should be replaced. Another flying rover will be launched. Sample return: In case of failure a substitute lander will be launched. In the case of geology, volcano and life rovers, the network will provide enough information so all of them will be used as a back-up. Cave balloon: Not necessary and can be dismissed in case of failure.
25	Communication loss between MXV and robots	C-I	4	On-surface robots will have the capability of switching between two modes - 1. Manual: astronauts control the rovers remotely; 2. Autonomous: rovers are controlled by a set of Artificial Intelligence algorithms. In case of communication loss between mother ship and the robots, the second mode will be enabled hence ensuring that rovers are still continuing work (e.g. performing scientific experiments, conducting self-maintenance and testing etc.)
26	Political risk between partner companies	C-III	3	International multilateral agreements such as for the ISS can be of help. However, in case any country wants to withdraw they need to replace their capacity both financially and technically.

Table 5-7: Risk Matrix



Consequences

	22	18,19,15,20,16,17	3,4,6,7,9,12,13,14,20,23,	11,27,8,24,25	
Class II			1,2	24,21	
Class III			10,19,26		
Class IV				21,18	
Class V					
	1	2	3	4	5

Likelihood

Consequences

Class II		15,20	14	8	
Class III	22,	4,7,17,2 11,16	1,2,6,9, 23,24,5	25	
Class IV		3,10,18	12,19, 13	21	
Class V					
	1	2	3	4	5

Likelihood

Negligible	Fair	Moderate	Critical	Catastrophic	Less	Med Low	Medium	Med High	Most
Class V	Class IV	Class III	Class II	Class I	1	2	3	4	5
CONSEQUENCES					LIKELIHOOD				
Before Mitigation					After Mitigation				

5.10 Reaching Forward

In this section, after analyzing some of the issues that exist today in the fields of education and outreach, a Mars-X TV Show is recommended to address the shortcomings in space education outreach. It also aims to analyze and discuss some of the main ethical questions that arise in a mission such as Mars-X.

5.10.1 The Gap

The following figure can be interpreted in many ways. Some people may see a hat, some may see an elephant, and some may see a snake that ate an elephant. Any of these interpretations are correct. This image is taken from the children's book The Little Prince and for the purposes of Mars-X it can be interpreted as the course that public interest has taken in regards to space. The far left or lowest point represents pre-space, which includes everything that came before Yuri Gagarin's historical space flight. Following Yuri, NASA and the Apollo Missions to the Moon created a huge leap forward in human spaceflight. This resulted in a huge increase of interest of space and is represented by the rising trunk of the elephant in Figure 5-5. Subsequent to this it appears that there has been a large decline in interest of the general public. As Neil deGrasse Tyson (2012), Director of the Hayden Planetarium, tweeted, "Apollo in 1969. Shuttle in 1981. Nothing in 2011. Our space program would look awesome to anyone living backwards thru time." This is where Mars-X can take the next step. It will be the allegorical small effect at the end of the hat that makes the brim tip upwards. Instead of continuing this downward slope, Mars-X strives to become the next pivotal moment in space; sitting in space history along with landing on the Moon.

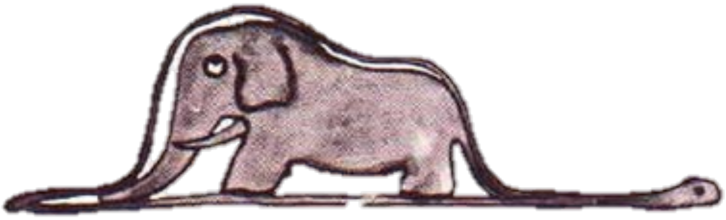


Figure 5-5: Drawing from Le Petit Prince [Sfar, 2010]

"We choose to go to the Moon … not because it is easy but because it is hard." –John F. Kennedy (NASA, 1962)

With these words in 1962, John F. Kennedy (JFK) inspired an entire nation to reach the Moon. Today, Mars-X aims to re-ignite that same passion throughout humanity in an effort to reach Mars. Beyond all the technological advancements, acquired scientific knowledge, and the development of political and legal frameworks; the strongest impact a human mission to Mars will be on humanity and the awakening of further curiosity. In order to mobilize not only a nation but also the world to support space exploration, there is a need to educate the general public as to how further exploration of the Universe will benefit them and the generations to come.

Space education is extremely valuable as it has the potential to excite imaginations and is able to combine a range of fields and disciplines into one, encouraging students to look at a problem from an interdisciplinary perspective. However, space in multifaceted programs needs to be incorporated into the education system to target school students in order to see any change in the general public's mindset towards space and science, technology, engineering and mathematics (STEM) subjects. The International Space University Space Studies Program Report outlined some important aspects of this topic:

> Space brings students to the very frontier of human knowledge, where the deepest and most exciting questions are posed, and where new, innovative, creative, and artistic ways of thinking are required to solve them. Space delivers excellent applications for all the STEM disciplines and it promotes ways of thinking that are currently lacking in today's STEM education. The implementation of space-related materials in STEM education allows students to learn from hands-on activities and stimulate their curiosity and creativity. This is why space should be used as an enabling medium, as it works both as a tool to educate, and to inspire. Historically, space projects and activities have produced a number of humanity's greatest achievements in grand scale exploration projects, scientific discoveries, international cooperation, and technological advancement. Space, therefore, provides an enabling medium to improve STEM education systems the world over. (International Space University Space Studies Program [ISU SSP], 2012, p.2)

The lack of interest in space and STEM based subjects is not unknown to the major space agencies, and in accordance most have implemented educational outreach programs. However, the main problem with maintaining these outreach programs is a lack of funding which ultimately stems from a lack of support from the general public. Most of the general public is not aware of how space directly impacts their daily lives and as a result they see the billions of taxpayers' dollars going towards space as a waste. This STEM issue is further exemplified in the following:

> In some developed countries young people are less interested in STEM education, and we need to find out what kinds of education the new generation of designers, builders, and creators will need to develop life-critical systems such as clear water supply, safe and reliable transportation systems, good and affordable medical assistance, as well as energy control and management. The Cold War energized the space race, and space contributed to STEM education by providing incentives and motivation in research, development, and manufacturing. Tremendous progress in technology has been made between the Second World War and the end of the Twentieth Century. Today's framework is heavily dependent on international cooperation in space business, industry, and research. It is time to think about what we will need in the near future to build new spacecraft, organize new missions, and train people in new fields to explore our Universe. (ISU SSP, 2012, p.vii)

While space agencies such as NASA are now attempting to generate public involvement in missions such as the Curiosity Rover through various social media outlets, there is still a lack of communication with the general public on how exploring space directly affects them. Spin-offs from space cover a wide range of products from smart phones' use of the Global Positioning System (GPS) system, to the most advanced cancer detecting technologies used in hospitals around the world. Implementing a space spin-off identification logo similar to the concept of the 'energy saver' logo currently used on many appliances is one method that can be utilized to increase general awareness of the impact space has on daily life.

The entertainment industry is an important channel for educating the general public and garnering the interest of young people in STEM. Movies and video games, along with other modern media formats highly influence young children and have the potential to draw them into STEM fields. Recently, space has been a recurring theme throughout several children's movies including Wall-E, Despicable Me, Mars Needs Moms, and Zathura among others. The creators of the popular game Angry Birds, Rovio, teamed up with NASA to create Angry Birds Space and following its success released Angry Birds Space: Red Planet, which features NASA's Mars Curiosity Rover. David Weaver, the associate administrator for communications at NASA Headquarters in Washington DC, demonstrated the importance of games for STEM:

> Games are fun and entertaining, but they also can be inspirational and informative. This ongoing collaboration with Rovio and Angry Birds is an exciting way to get people engaged with NASA's missions of exploration and discovery, and get students energized about future careers in science and technology. (Rovio, 2012)

By combining the use of interactive games and creative thinking, new ways of teaching children STEM subjects can be explored. The incorporation of Art education in association with STEM is something that is greatly lacking in school systems today. This is why the concept of STEM to STEAM was generated. The concept art in Figure 5-6 provides an innovative solution to an existing problem. Art is the missing piece in STEM that makes space relatable to people's everyday lives. Examples of Art in STEM are how baking is just applied chemistry in the kitchen, and how math and music go hand-in-hand to understand the scales and rhythm of a piece of music.

Art is an essential part of the innovative design process as can be seen in Figure 5-6. If your product is not relatable to the end user, it will not be successful in the marketplace. Steve Jobs, former CEO of Apple demonstrated this by prioritizing design for the user above all else. Companies around the world are striving to catch-up to Apple by concentrating on innovation and design of their products. This method of thinking needs to be introduced at an early age by bringing STEAM into schools around the world, this will prevent the stifling of creativity in future generations.

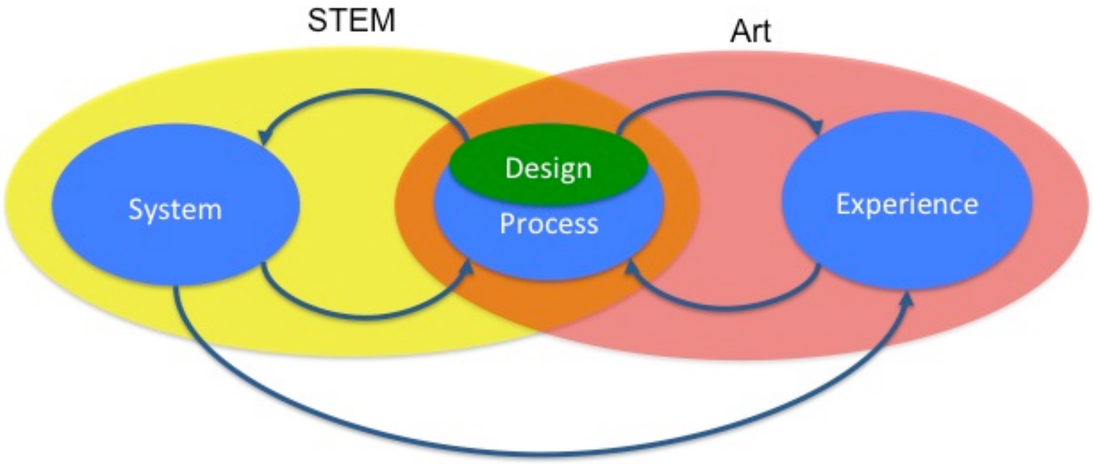


Figure 5-6: STEM to STEAM [ISU SSP, 2012, p.17]

5.10.2 Mars-X - The TV Show

It was demonstrated in Section 5.10.1 that in developed countries, there is a decline in the number of students pursuing education in STEM fields. On the other hand, in developing countries the situation is different, the interest in STEM fields does not decrease although it is seen as uninteresting (Boy, 2013).

The impact space education can have in regards to STEM was previously indicated, however it should be stated that it can also greatly impact other disciplines including law, politics, economics, and business. In order for a rocket to reach the stars, all these disciplines must unite, which is often not realized. The general public has to be educated on how space contributes to their daily life and the significance of space to society. In order to achieve this education, the space sector needs to invest more effort into communication.

An outreach plan or roadmap similar to the principles governing the Global Exploration Roadmap (GER) need to be implemented to achieve a noticeable increase in people's interest in space. The Mars-X mission suggests the introduction of an outreach roadmap in order to generate this increased awareness, especially during preparation stages. Some of the key points are outlined:

- Space agencies during speeches, in their websites, and throughout their public relations departments will include Mars.
- The use of social Media, by space agencies, private companies or space enthusiasts. This will start creating the space atmosphere and uncover feelings ideas, and debates.
- News and public debates about the topic.
- Mars announcements by entrepreneurs such as Elon Musk or Dennis Tito.
- Spread the word throughout associations or organizations that are in communication with both space professionals and the general public. These include: Space Generation Advisory Council (SGAC), Mars Society, and World Space Week (WSW), among others.
- Extension of presentation of the concept through popular entertainment methods such as movies and TV shows. An existing example of this is 'The Big Bang Theory' comedy show. Furthering this, celebrities could present their opinions on the Mars-X mission, which could initiate public debate.

- The raising of awareness through conferences and symposiums such as the Humans to Mars (H2M) conference and the International Astronautical Congress.
- Ultimately the Mars-X Consortium would be in charge of an advertising campaign that would be initiated in the early stages of the mission. This is further explained in the following.

With the introduction of these actions the concept of a human mission to Mars would be a daily life topic of conversation. This could generate the opportunity for the implementation of one solution proposed by Mars-X for a combination of issues; the production of a Mars-X TV show. This TV show would be broadcast all over the planet and could be used by NASA or ESA on their TV channels to help boost viewers. The success of this TV show is dependent on establishing the mindset of 'humans going to Mars' in early stages, which would be significantly greater through advertising.

In the past, Carl Sagan inspired many people with his video documentary "Cosmos", and following this was Bill Nye with his science TV Show "Bill Nye the Science Guy". Both of these helped facilitate interest in science, especially with children (Rockman et al., 1998). There are numerous science and technology documentaries all around the world and many are successful, however there is still a sort of stigmatism towards STEM as some people see it complicated to understand. The incorporation of arts into the field as previously mentioned would help remove these negative connotations and increase interest.

The Mars-X TV show can be a uniting point for the entire mission, an interactive production with the rest of the world. It will be a place where the entire mission can be explained and where all the news, merchandising, media, and spin-offs produced are broadcasted. It will be the platform to educate the general public about the mission, to inspire the next generation of explorers, to increase people's awareness of space activities and uses. In order to maximize the educational potential it is suggested that two TV shows are produced, one focused on children and the other focused on the rest of the general public, whilst maintaining common themes between.

5.10.2.1 TV Show Structure

The suggested structure for the Mars-X TV shows is one weekly show for adults and a daily 30-minute show for children. The concept of the TV shows is to have a mixture of documentaries, competitions, education, interviews, experts' opinions, public polls, public participation, and interaction with astronauts. The idea is to have a harmonized conglomerate of concepts covered by the umbrella of education, ethics, and basic morals. There will be a single presenter for both shows who will go through all the sections and phases of the shows. Therefore they will be required to be an excellent communicator, inspirational, and be capable of facilitating a conversation with both children and space experts.

Such a production could bring additional economic value to the mission. The Mars-X mission is international, interdisciplinary, and intercultural, where more than one nation, culture and discipline will be joining together to reach Phobos and then Mars. Due to this the distribution of the Mars-X TV shows may be difficult as TV shows around the world aren't the same. What works for a western culture may not work for an eastern culture, or vice versa. To account for such a mixed audience it is suggested that all different types of culture are addressed in an international environment. This could be achieved by the TV show to move location. For example every 4 shows, the show and presenter move to different continents, and incorporate parts of the local culture to further identify with the audience (Hjarvard, 2004).

The Mars-X TV show will not be produced for a few years and therefore it is unknown what type or structure of television will be appealing in the future. However, technology is driving media in general to a personalized platform where the user chooses what they want to watch and where to watch it. In order to react to this the Mars-X TV Shows will be structured in sections to allow people to pick and choose which sections they watch if they do not wish to view the entire show (2020 Vision: Future of the Television, 2011).

The language to be used within the shows is a difficult decision as the most spoken language today is Mandarin (1.2 billion people) with the most native speakers, and the second is English with a total of one billion non-native speakers. Following these are Spanish and Hindi (KryssTal, 2010).

English is still the global language for international communication, which will probably not change dramatically within the next five years. There are two main options to address this problem, the first is selecting one language and ensuring there are subtitles for all the other languages, and the second is to dub every episode, so with the viewer's device they have the option to listen to it in the language of their choice (Hjarvard, 2004). It is difficult to predict the exposure that such a production could have, however there are some key factors than can be estimated including:

- The world population in those years
- The internet accessibility of the world population
- The nationality of the crew (or people interested in the mission)

In order to calculate a rough estimation of extent this outreach, some examples of big events are useful to compare to, such as:

- The Moon landing in 1969: around 600 million people watched the Apollo 11 landing live on television (The Telegraph, 2009)
- Princess Diana's funeral in 1997: approximately 2.5 billion people watched Princess Diana funeral (A&E Television Networks, 1997)
- Football World Cup in 2010: was viewed in all countries on Earth. Based on in-home data, over 3.2 billion people watched at least one minute of the World Cup. The highest figure for an individual game, was the final between Spain and the Netherlands in 2010 where maximum viewership reached 909.6 million for at least one minute, and over one billion, taking into account people gathering in streets, public places, and through devices connected to internet (FIFA, 2011)
- London Olympic Games 2012: The opening ceremony was watched by 27 million people live
- The royal wedding between Prince William and Catherine, Duchess of Cambridge reached around 20 million (Indo-Asian News Service, 2012)

It is predicted that there will be four or five peak moments that will generate audiences with orders of magnitude higher than the average daily audience. These include:

- The launch of the crew
- Arrival to Phobos and first images of Extra Vehicular Activity (EVA)
- Departure from Martian orbit
- Landing on Earth
- Broadcasting of major discoveries (if any)

The United Nations predicts that in 2025, the population will be around eight billion people (United Nations, 2011). It would be unrealistic to believe that eight billion people would be aware of the mission, or watching even during peak moments. Therefore to gain a more accurate estimation it is important to consider how many people are predicted to have Internet access. The actual number of people that have Internet access or are Internet users is shown in Figure 5-7.

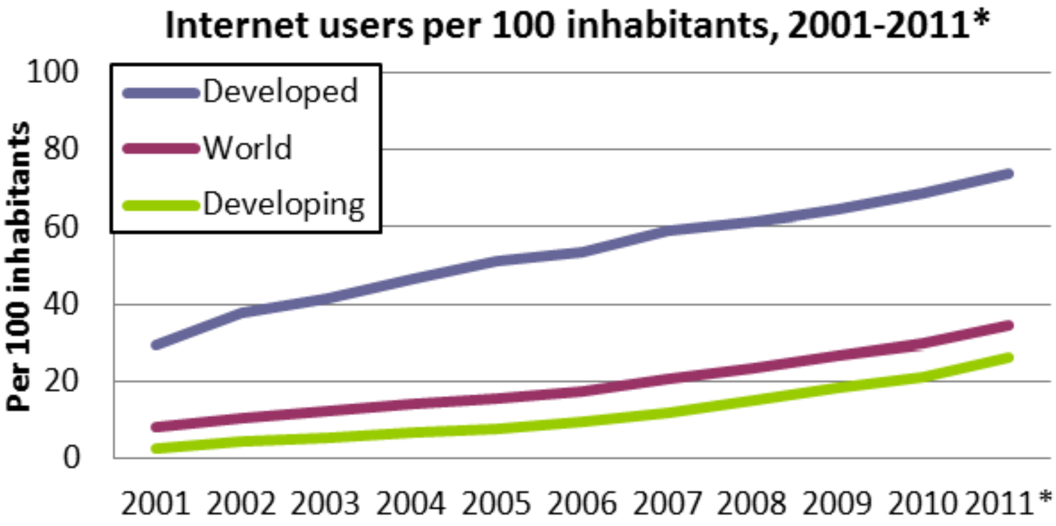


Figure 5-7: Internet Users per 100 Habitants, 2001-2011 [Ogden, 2012b]

Following this tendency, and including the “Other 3 billion” project that will be delivering broadband connectivity within 45 degrees of latitude north and south of the equator (as shown in Figure 5-8), then the percentage of population that would have connectivity by the projected crew launch in 2024 could be around 80-90% (O3b Networks, 2013).

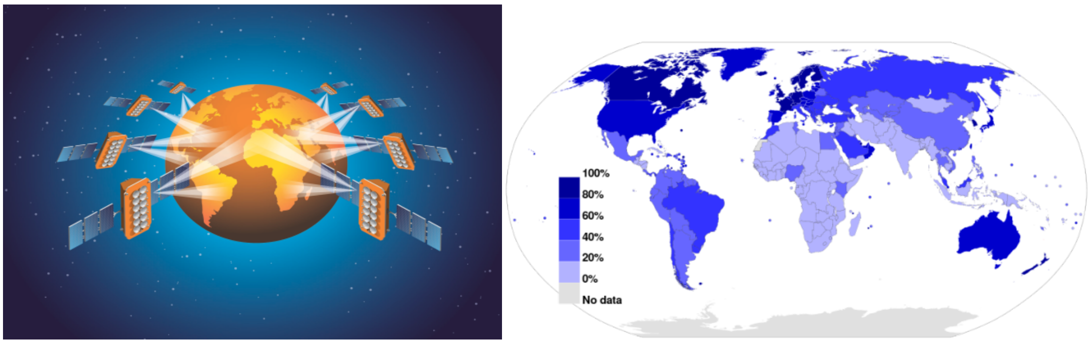


Figure 5-8: O3b Constellation (left) [O3b Networks, 2013], Number of Internet Users as a Percentage of Population (right) [Ogden, 2012a].

The nationality of the crew will also have a bearing on the level of outreach, especially within different countries and cultures. The crew selection should be as objective as possible. However, the location on earth the astronauts are from affects the level of outreach achievable. For example in China the TV is centralized to the Chinese Central Television (CCTV), that has an audience potential of 1.2 billion people. If there is a Chinese astronaut in the crew, a 1.2 billion strong audience is not guaranteed, but it can be assumed that the mission has a potential viewership of that many people. So if for a political decision China is not part of the consortium and the government decides that they are against such a mission, CCTV can make the decision to not broadcast the show (Madden, 2008). This outlines the power that politics can play in outreach.

In the table below (Table 5-8) there is a rough calculation of the outreach peak (in billion people) that these TV shows would have (meaning total viewers, not necessarily at the same time), as a function of the nationality of the astronauts. For example, if all the astronauts are from North America, the outreach would be four billion people; if they are from the European Union China, then the estimated audience would be 4.7 billion. There is also information about the total if there are more than two countries, for example if the crew is European, North American and Chinese then the outreach would be 4.9 billion. These numbers are calculated firstly by the population in 2024, then by how many people would have internet access in 2024, and then how many of these people that would have internet access would be interested in one of the main events. One conclusion is that, if a nation goes by themselves, the outreach would still be four billion, which would be half of the population in 2024, and these numbers are reasonable in comparison to the main events shown before; the second conclusion is that the solutions with higher numbers include Asian (Chinese or Indian or Japanese or other) astronauts.

Table 5-8: Number of People (in billions) that Mars-X would Reach, as a Function of Astronaut Nationality.

	EU	North America	China	South America	Africa	Russia	Asia/Oceania	India
EU	4	4.3	4.7	4.3	4.4	4.2	4.7	4.4
North America		4	4.5	4.2	4.3	4.1	4.6	4.3
China			4.3	4.5	4.6	4.3	4.9	4.6
South America				4	4.3	4	4.6	4.3
Africa					4	4	4.7	4.4
Russia						4	4.5	4.1
Asia/ Oceania							4.5	4.7
India								4

5.10.2.2 TV Show Sections

Basic rules, morals and culture – Ethical television

The Mars-X TV shows will have rules of conduct, basic behavior and ethics. The basis of morals, are very similar, if not the same, around the world and therefore this production has the potential to emphasis such principles. These TV shows will be produced with a respect to all cultures and without violating any basic ethical questions. It is a unique occasion to educate about culture, and the differences in the world. Intercultural relations and reduction of xenophobia are other aspects which could be taught through this medium.

Space education

Mars-X can be used to excite people about education. It will involve real examples of dreams and inspiration. Space has inspired generation after generation, and has been present in many human aspects including religion, myths, stories, and navigation

The show for children will be designed to foster creativity, curiosity and critical thinking with questions, challenges, and hands on activities. It is intended to make children think and wonder about all the disciplines that are involved in space missions, and where new space technologies come from and how they work. These same principles will be involved in the show for adults but at a higher level in order to break the barrier between the space sector and the general public.

Arts

The intention is also to increase outreach to the maximum, and therefore the Mars-X TV shows will also be the nuclei for other productions. For example, there will be a call for singers, where the ones with Mars or Mars-X songs, will play live. Another idea is to implement music concerts such as the successful concert Tomorrowland. This would be transformed into the organization of concerts or large parties for the launches, with some of the most popular DJ's in the world, who would use the vibration and sound of the launches to make a song. This would be included as part of the show. This concept can be extended to competitions such as short movies, poems, and paintings. Art is a source of feelings, and when feelings are transmitted, other people can be reached.

Linking Schools and Media

Media and social media have increasingly become part of daily life. This can be harnessed to link education centers and the media. For example, these TV shows would set a series of activities, projects or questions at the end of the program, and those would be adopted as work during some school hours encouraging competition to produce the best answer. This does not mean that Mars-X would decide parts of the curriculum; it means that Mars-X would comply with the curriculum whilst bringing creativity and innovation.

Competitions

Competitions produce a unique opportunity to make people participate and feel like an active part of the mission. There can be many different global competitions, two of which are presented here:

"Decide the first sentence to be said when we get to Mars" - With this competition, the winning sentence will be chosen by the audience and will be said when the crew gets to Phobos.

"Send your robot to Mars" – This competition will run between students from all around the globe for months before launch of Mars-X. The winning group will get a spot on the spacecraft to send the software or hardware they designed for a scientific rover. The astronauts would run this with some feedback from the students back on Earth.

Experts

Discussions with experts are envisioned to be a TED talk style of presentation by the experts followed by a short informal discussion. The language used will be basic so that the general public can understand and the discussions will be informal to prevent separation between audience and presenter. There will be a main topic of the week (such as Engineering, Science, Law, Policy, etc.), which will be addressed in detail and also related to the whole mission. This will show topics that are not typically revealed or related to space activities, making them identifiable to the general public.

Astronauts' interaction

In every episode, there will be a section with the astronauts onboard the mission. Both children and adults will have the chance to address the astronauts and ask questions. Due to time delay in communication during the mission, the astronauts will answer these questions either later in the episode or on the next episode. It is important for the general public and for the astronauts, to still feel some connection with the planet. The astronauts will have to run experiments and other sorts of competitions which will also be shown in those episodes.

Mars-X is an excellent opportunity to bridge the gap between the space industry and the general public. The inspiration of the mission can be harnessed to educate the public, increase space awareness, and to raise funds. The Mars-X TV shows will be difficult to implement, especially due to cultural differences. However, if presented in the right places and contexts it has the potential to make a significant impact in space awareness both for children and for adults around the world.

5.10.3 Ethics

Ethics are an important part of the Mars-X mission; however it is extremely difficult to provide a formal definition of ethics and to formulate answers to the questions that are generated. Ethics could be defined by a philosophical discipline dealing with morals. For the purpose of Mars-X, ethics is a set of rules which determines the types and extent of activities that can be carried out in space exploration.

In the case of exploring Mars from Martian orbit, the astronauts, the ground support teams and the rest of the world will experience something that nobody has faced before. If something deemed "unethical" occurs and is not covered by law, there is no Martian tribunal to judge what should happen and there is also not any terrestrial tribunal that covers this jurisdiction. These types of issues and general ethical questions from different viewpoints will be discussed in the following section. The questions that engineers, scientists, businessmen and life science physicists need to address should be considered. It is important to investigate ethical problems, how to manage them and to prepare for their consequences.

5.10.3.1 Icarus' Heritage

In Chapter 2, the importance of exploring Mars from Martian orbit was uncovered and the benefits for science and also humankind were described. From an ethical point of view, the myth of Icarus is used to illustrate both the pleasure and the inspiration that arises in the exploration of something new.

The book "Icarus' Second Chance" by Jacques Arnould (2011) discusses the basics and different perspectives of space ethics through the Icarus myth. Icarus is a character of

Greek mythology that perished because he wished to fly so close to the Sun, ignoring advice provided by his father Daedalus. Pioneers of aeronautics and astronautics are familiar with this situation. They are led by ambitious ideas and work actively to make them tangible. Technical progress provides more and more solutions for any challenges. Considering the large amount of possibilities offered it is now very important to determine whether or not humanity is destined to explore the cosmos. The first question should be: is it natural to dream about Mars? People are delighted to see a child talking about space, astronauts and Mars with stars in their eyes. Amazingly, there are also many adults, well considered by society such as scientists, engineers or artists who are seriously hoping to go to Mars. Is it reasonable to think about it? In other words, was Icarus right to try to fly so high in the sky, so close to the Sun? Icarus is usually portrayed as an arrogant young man. Daedalus warned his son but Icarus was escaping from a prison and was enjoying liberty for the first time. Icarus had no possibility to know where the borderline was. Comparing this scenario with our case: is it arrogant to go to Mars?

The reasons why Icarus wanted to escape from the labyrinth are identifiable to many. However, he was compelled by an internal force to fly as high as possible in the sky. This same strong and irresistible force led some explorations to disaster, such as Franklin's expedition in 1845. This crew was looking for the Northwest Passage in the Arctic when the ships became stuck in ice and there were no survivors. It was impossible to predict this fatality. The McClure Arctic Expedition looking for the Franklin expedition around 1853 discovered the passage. This passage is now strategic for connecting the Atlantic and the Pacific oceans. Icarus and Franklin tried and failed but this failure was an important step for future successes. If these examples are transposed to the Mars-X case, is it ethical not to try to go to Mars?

5.10.3.2 Are We Space Invaders?

Planetary protection is an important aspect of exploration ethics, which must be addressed. It aims to prevent contamination on Earth from elements coming from space but also to prevent celestial bodies from contamination from Earth. An important aim of planetary protection is to prevent alterations to the natural evolution of the planet by protecting from human-caused microbial pollution. Implementation of this contamination prevention is extremely difficult as exploring another planet is not a neutral or easily reversible action.

Rovers will perform many actions and experiments including: drilling of the surface, collecting samples, and executing tests. It is unknown what could be found. There is still the possibility of finding life or evidence of life. From the perspective of an alien, who are we? In the book “The War of the Worlds" Herbert George Wells (1898) describes the conflict between humankind and Martians. In this scenario Martians invade Earth with big machines called ‘Tripods’. The Martians easily defeat humankind but finally the Martian invaders die because of terrestrial diseases. In case of the Mars-X mission, humankind is exploring Mars with machines called rovers. Rovers will modify the surface of the planet and they also could carry with them bacteria from Earth. This could have devastating effects for life on Mars.

In the past, most of the time human invaders were not kind and respectful regarding natives. But sometimes, the invader can act differently. In 1788, the Britannic Admiral Arthur Phillip established several settlements in Australia. He adopted a protective policy towards the Aboriginal people, who lived around Sydney Harbor. Killing an Aboriginal was punishable by death. The line of conduct adopted by the Admiral was very strict. Any action, which had not been approved by an authority, was punished. Later, Phillip became friends with Bennelong, an Eora Aboriginal. Thanks to their collaboration the peace was maintained for a few years between the Eora and the British people. Is it possible to apply this kind of rule for Mars exploration? Could we be friendly space invaders?

Additionally, an important question must be asked. What should we do in the case where the formal evidence of Martian life becomes obvious? It is possible to find fossilized evidence of life, living bacteria and perhaps intelligent life. There is no agreement on the correct procedure in such an event and there are many differing opinions on the topic. Although there is no evidence of intelligent life on Mars to date, there are still many unknowns and the ethical issues involved cannot be disregarded. The only thing that appears obvious currently is that an answer needs to be found. The roles of Mars and potential Martians have differing places in different cultures. This demonstrates different interpretations on what is considered to be ethical or not. The astrogeophysicist Dr. Chris McKay suggests that only experiments and actions that are reversible be performed in order to preserve Mars (McKay, 2013). We have different options to react in case of such discovery:

- Destroy it.
- Neglect it.
- Co-existence with minimal interference on Mars.
- Absolutely no interference (humans leave Mars forever).
- Protect it (but not foster it).
- Foster it (i.e. help it evolve).
- Use it (i.e. financial benefits)

Space explorers should not take advantage of alien life in an intrusive way. They should reach a compromise: respect this precious life whilst using this opportunity to understanding more about Life.

5.10.3.3 Interplanetary Species

Travelling into space is a great challenge for humanity. The entire Mars-X mission will be an experiment on the crew. The journey to Phobos is long, risky and has never been achieved before. Appropriate management of risk and interpretation of responsibilities is essential for the mission.

During a space journey to the Martian orbit, astronauts will endure many physiological and psychological changes. Some of these changes could be irreversible, but there is extreme risk to human health. The human body has developed for living on Earth and therefore the effects of such long-term spaceflight are unknown. Undergoing microgravity for 900 days will lead the human body to adapt into something new. Is it destiny to turn human into an interplanetary species? Human bodies are shaped to live on the ground but amazingly there are people living in many different environments. Humans have populated deserts, pack ices, forests, tundra, and small islands. Those humans remarkably adapted to all these different situations. Humans are also capable of travelling for many months over seas and oceans. Humans have endured these environments for centuries. Bodies and minds can survive in extreme environments through evolution or humans transform the environment to make it more comfortable and therefore survivable. Due to the extreme environment of space astronauts returning from Phobos could be physically and psychologically very different from the people initially leaving Earth.

Another question that must be addressed is the level of risk to which the astronauts will be exposed. The crew and the spacecraft will be exposed to many dangers ranging from life support system failure to spacecraft damage caused by debris. Moreover, the exposure to radiation that an astronaut will receive during the trip is 1000 times more than that of a person staying on Earth. This radiation exposure could affect astronaut health many years after their return to earth, especially in regards to cancer. The chosen propulsion method for the spacecraft is nuclear. The danger of nuclear energy was exemplified on 11 March 2011, when Japan experienced the terrible Fukushima nuclear power plant disaster that created pollution for several decades. Space launch related risks are loss of plutonium during mission preparation, operators' exposition during the integration, and pollution after a launch accident. Nuclear propulsion is the only technology that is currently feasible and capable of sending humans to Martian orbit, and therefore it is a risk that must be managed, but could strike questions about ethics. The mission duration could increase which could jeopardize its success and another risk that the crew and ground support have to manage.

Before the commencement of the mission, the crew will be fully aware and accepting of the potential danger and irreversible damages that will result from the Mars-X mission. However, every effort will be made to mitigate risk and it is important to question at what point risk is unethical even if the crew has accepted it. Returning the astronauts safely back to Earth is the most important parameter of the Mars-X mission as demonstrated in the mission statement. The term 'safely' could be open to interpretation if not formally defined. However, a formal definition is difficult to produce due to the large number of unknowns in regards to the mission. In the Mars-X spaceflight to Phobos, five astronauts will be onboard, ground control will be present and a huge amount of money will be invested, therefore who decides in the event of an incident that the mission proceeds or is aborted? The ethical questions that have been demonstrated along with many others must be answered before commencement of the Mars-X mission.

There are many aspects of this mission that will strain the relationships between the crew members. There are 5 international astronauts who are confined together for more than 900 days. Conflicts, sexual dimensions, boredom and depression may appear. Although the crews are astronauts and space pioneers they are still human and must be able to exercise their free will. However, the limits of their free will must be identified. Astronauts must understand all the risks and challenges before committing to the Mars-X. The role and power of ground support should be determined and approved by the crew before the launch. Astronauts are not machines, their lives cannot be fully controlled for 900 days by procedures and schedules dictated by the ground support.

5.10.3.4 Money, Business and Mars

In 1967, the Outer Space Treaty was the result of the policy of space leaders to commit their countries to sign and ratify set of laws, to support the notion of freedom for exploring the cosmos with the addition of aspects such as the non-appropriation, the cooperation and the prohibition of some activities (Arnould, 2011, p.121).

There are many aspects of space law, which are not fully defined and become questions for ethical consideration. First, is it allowable to commercialize Martian resources and data? In the case of the Curiosity rover, the publication of experimental results belongs to NASA and the US government because they are the mission operator. They express major results to the general audience for free and for the benefit of all mankind. The crew of Mars-X will collect a large amount of data and samples. The case of sample return from Mars is different from the Curiosity rover, as it has not yet been performed. However, there was a similar example in the return of Moon samples during the Apollo missions. Distribution of the samples to laboratories or museums was common and it is expected a similar process will be implemented for Martian samples. An interesting problem is the distribution of samples. Who decides who receives a sample? It is suggested that a committee be in charge of the selection process. Scientists, artists, businessmen, and students should all be given a chance to use the return samples.

Going to Martian orbit is extremely costly. The budget of Mars-X is estimated at 20 billion USD, it represents 0.12% of the European Union Gross Domestic Product (GDP) , and 0.13% of the US GDP (Eurostat, 2012; Trading Economics, 2012). This is one of the major challenges for mission funding: it is very difficult to convince investors and the general public. The most basic argument is 'why fund a mission to Mars when there are so many problems on Earth?' In 1492, the Catholic Monarchs funded the expedition of Christopher Columbus in order to profit from his discoveries. In 1960, the United State Navy funded the expedition of Jacques Piccard for exploring the ocean bed. Using the bathyscaphe USS Trieste, he reached the floor of the Pacific Ocean. This mission had a high scientific interest for discovering life in the deep ocean but there was no financial benefit. This discovery of life deterred the army from storing nuclear waste in this location. What is the value of this mission today?

The exploration of Mars from the Martian orbit and the landing on Phobos will have consequences on the crew, Mars and all humankind. It will have an influence on culture, policy, sciences, technology and economies. Due to past experience, the explorers of the 21st century are perfectly aware of challenges and ethical problems they face in such an endeavor. Although they are concerned about the impact of their actions they believe in the benefit for all humankind.

6 ASSESSMENT AND RECOMMENDATIONS

It has been illustrated throughout this report that reaching Mars is an important step in humanity's ambition to expand into the solar system. To achieve this, a series of preparatory missions and feasibility tests have to be conducted. While the Global Exploration Roadmap proposes their implementation on an asteroid or the Moon, Mars-X suggests testing the required systems in the Martian system itself. Such a mission will capture humanity's interest for space exploration once again. Herein we aspire to answer:

Is such a preparatory mission feasible?

Yes, with current technological capabilities, assuming moderate progress in the near future.

Is such a mission affordable?

Yes, but only with worldwide cooperation, and also creating opportunities for the private sector. Outreach has an important role to play in order to convince governments, companies and the public to invest in space, by promoting the certain advantages that will arise.

Is such a mission recommended?

Yes, if a major step towards reaching Mars is to be achieved. Other proposals, such as Dennis Tito's fly-by mission, can fulfill some of the goals of Mars-X, like raising public awareness. In terms of scientific research the potential offered by Mars-X is unrivaled. Of course the benefits are accompanied by a significant financial cost; this is, however, considered necessary.

In general, is it worth exploring Mars with humans from orbit before landing?

Yes, if we intend to bring risk levels down to an acceptable level for humans to land. As Apollo 10 was an indispensable stepping stone for the Moon program, Mars-X is a proposal that will require resources, yet is well justified to ensure a safe and fruitful Mars landing.

After dealing with all aspects relevant to designing a human mission to Phobos, the Mars-X team would like to offer the following recommendations:

- More political coordination is needed, based on initiatives such as ISECG. A timeline should be agreed upon, not merely stepping stones.
- There should be more planning to include the private sector. Providing potential return on investment through an interplanetary economy could prove crucial.
- Enhanced outreach is essential, as it is lacking in general. Even in the areas that outreach is performed, it is not very well coordinated.
- Current legislation should be reviewed soon and at an international level.
- More research is needed into advanced space propulsion systems, mainly for high efficiency nuclear engines, cryogenic storability and life support systems.
- Better cost estimation and control is required in order not to have unexpected and overwhelming mission cost over-runs.
- Continued research into Martian environmental conditions, including radiation, is encouraged, together with possible in situ resource investigation to determine potential future landing sites on Mars.

7 NIHIL DIFFICILE VOLENTI

Mars has been an inspiration for centuries; now it is time for dreams to come true. There is a common consensus that Mars is the next goal in solar system exploration. Landing on a moon of Mars will create synergies both in politics, education and science while fueling economic vitality in engineering. Becoming an interplanetary race will elevate the people of Earth to a new level of thought. Mars-X will be a monumental turning point for humanity, and will put fresh wind in the sails of discovery.

By targeting Phobos as humanity's next stepping stone to Mars, this project will unify both the Asteroid-Next and the Moon-Next communities by proving that the technologies needed for landing humans on Mars can be demonstrated on a single mission to its moon, Phobos.

Mars-X has defined an aggressive yet realistic timeline. In 2023 the LEO assembly process will begin and by 2024 the spaceship will be ready to set sail to Phobos. Nuclear engines with cryogenically stored propellant will be used to quickly lead us towards our future home. Artificial gravity will gently prepare the astronauts for the destination, and the ideals of public engagement will inspire those watching from Earth.

Humans will take advantage of this endeavor to study Mars locally, paving the way for future Mars landing missions. This will focus on several key areas of research; the radiation environment, atmospheric conditions, Martian geology, volcanism, in situ resource investigation and life on Mars. The astronauts will take advantage of near-real time telerobotics to impose their presence on the surface of Mars, the rovers will scrape its surface using powerful drills and collect samples to bring back to our nest, Earth.

Mars-X proposes an alternative to the standard multi-national approach. The Mars-X Consortium is ready to revolutionize international collaboration for the benefit of mankind. Nations and private entities together as coequals will start a true international collaboration and they will establish a framework of political initiatives that will offer governments and corporations a platform for cooperation.

'One doesn't discover new lands without consenting to lose sight, for a very long time, of the shore'

André Gide (1869-1951), 1925

This report has come to an end, but Mars-X has just hatched and is about to spread its wings and fly towards our destiny. History teaches that by pushing ourselves towards limits it is possible to overcome them. Humanity has the willpower to always go beyond the boundaries of possibility. Mars is there, waiting for us. We just need to go, because "nihil difficile volenti": nothing is impossible for those who want it.

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Mars, why not?