LunAres

International Lunar Exploration in Preparation for Mars

Student Team Project Final Report

International Space University

Summer Session Program 2004

The 2004 Summer Session Program of the International Space University was hosted by the University of South Australia, The University of Adelaide and Flinders University in Adelaide, Australia.

The cover image shows the Earth rise over the Moon with an artistic collage of Mars in the background. The picture was one of the first images taken from the lunar surface by the Apollo 11 crew.

Images courtesy of National Aeronautics and Space Administration, USA.

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The authors would like to express their sincere gratitude and appreciation to the individuals who contributed their time, energy, and passion to assist in making this project possible.

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Space Renshi is a linked verse, which was established by a Japanese famous poet, Ooka Makoto, by modernizing Japanese traditional linked verse "Rehka". At the Space and Society course in the Summer Session Program 2004 by the International Space University, held in Adelaide, South Australia, the Space Renshi, "One Earth" is composed by Co-Chairs, faculty, and students, from 27 countries, to study "Why Space for human society?" The "One Earth" is composed sequentially under simple rules: The next verse shall have three (five) lines, if the previous verse has five (three) lines, and shall have the same word, or phrase, which is used in the previous verse, as a link, and the link shall not be repeated. - Tsutomu Yamanaka

"One Earth"

§

The first day or so we all pointed to our countries,
The third or fourth day we were pointing to our continents,
By the fifth day, we were aware of only one Earth
- Al Saud

In One Earth we see fragility
On One Earth we learn connections
For One Earth we inspire humanity
From One Earth we will return to the cosmos
To look back on only One Earth together
- Bob Richards

When we return to the Moon
We shall find there, not just rocks
But a new understanding of ourselves
- Jim Burke

Hunger pain overwhelm my body and mind
Like a black hole out of time,
New dimensions bended by stars of yesterday devoured
No worries mates, traveling in galaxies and in the vastness of space
The restaurant at the far end of universe will be our meeting place
- Luigi Scatteia (Italy)

The fire on the beach. A whisper… A breeze.
Lucky are the stars, privileged the moon
The journey comes to an end. I will find home soon.
- Regina Riegerbauer (Sweden)

Surrounded by the dark and hostile cosmos
A small and lonely star in the martian sky
The Earth - Home to everyone you have ever known
Theater of all wars you have waged
But the future lies in your hands
- Anne Pacros (France)

§

Then let us begin, side by side
And out of the darkness, build a future for all with
The uniting power of a journey shared
- Michael Oelke (United States)

Sharing a tiny umbrella in winter darkness
Listening to penguins under Southern Cross,
"We just borrow ocean from the Universe
You have divided everything, even the water"
Our voyage on Milky Way has started
- Tsutomu Yamanaka (Japan)

Power of evil. A monster in space.
A voyage of nothing…
Be very afraid.
- Christian Kulik (Sweden)

Each day we awaken and celebrate the mystery of life;
Every human, every animal, every plant in its own way.
Space is the new realm in our eternal search for truth;
Somehow, somewhere, some time, new meaning will be found;
The collective mind of Man will grow in wisdom.
- Subhajit Sarkar (United Kingdom)

A journey of discovery through the cosmos,
Isolation from pleasures and pains, merely dreams;
The meaning is our own to make.
- Mindy Gallo (United States)

A failure burning in the blue sky.
Honour these great, by reaching to the Moon and beyond.
Treasure our Earth and gently look upon her knowledge.
A small red dot is roaming closer, accept the greatest challenge of all.
Tread lightly on the bold journey towards the never ending stars.
- Ella Carlsson (Sweden)

Ancient processes and miraculous events have led us to our perch
A vantage point from which to discover or destroy
The treasure of answers will be found within
- Hugo Blomfield (Canada)

The Earth stands at the mouth of an open door,
Cradled beneath the ancient cosmos - Each stargazer
Like islands on an island - can we think as one, as one Earth?
Where should the sun go down,
At the end of each other's common sundown?
- Jamie Doran (Canada)

We are born of Starstuff.
Do the primordial molecules from which we came
know pride that we return to the Cosmos?
- Kerrie Dougherty (Australia)

§

One earth for love and hate, also one earth for peace,
Passions which made our world even better or worst,
Unity, friendship, patience, tolerance, respect,
Are basics Molecules for future space travelers,
Hope will be our light through the Universe's darkness
- Frederique De Dinechin (France)

Climbing up to the highest mountains, traveling to the furthest galaxies…
When you look back to the Earth and feel its eternal peace,
You will learn that the only reason why you wanted to escape is to find your way back
- Enikö Patkós (Hungary)

You and I, traveling the Dreaming. A vessel of clay and hope. An emerald sapphire.
Our mind's cradle grows small; the dreams trickle, ebb and flow. Droplets and sparks.
Beautiful splendor; you are our world, our future, our now.
Can you hear the Earthlight? Glisten to the delicious promise of tomorrow's reality.
We are (but bounded in a nutshell). Together.
- David A. Broniatowski (USA)

We are all filled with dreams of love and peace on this One, OUR, Earth.
Just open your eyes, look around – my heart is in your hands and yours in mine.
Handling this with care, exchanging a warm smile – and our dreams become true!
- Tina Buechner (Germany)

In your eyes, sparkles of excitement for this new adventure
Leading the new Gondwana land in an everlasting unity
With a common strength and capital expenditure
Niles of emotions, wits, vision and audacity
That set us free, and focused towards a brighter future
- Irene Guiamatsia (Cameroon)

§

Stop. those sparkles from wetting your cheeks- not yet!
Enjoy and preserve this moment of wombly intimacy.
The sun's temptation will too soon pierce through our crimson maple
canopy of sustenance.
- Anjali Nayar (Canada)

On the horizon, change was looming
And in the innocence of his youth
He looked up and wondered.
For a fleeting moment of contemplation
He left the meadows and canals behind.
- Thomas Peters (The Netherlands)

The Great Canals and vast meadows breed up me!
Luckily, shared and cared for the beautiful comb gently
We suck the trickle of the blue honey, Earth, together.
- Ping Li (China)

The Universe is enormous, maybe infinite,
It is however by appreciating the small beauties of daily Earthly life,
That we realize how precious our little corner is,
Like "just another day" on a Sunny beach with blue sky, in Vale do Lobo, with life long friends
I think to myself, what a wonderful world
- Rodolfo Condessa (Portugal)

Wander into our star-spangled backyard,
And sow seeds in the garden to expand and beautify our home.
But realize where our home has always been.
- Mark S. Avnet (United States)

Salt waves roil darkly against the rocks,
Drawing down the dusk into the chill, wet sand.
Above, the clouds slowly deliquesce
Revealing cool spangles anchored in an obsidian ocean.
On the beach the stars call to me.
- Chris Welch (Great Britain)

Space is the sea and we live on this island
On the shore of a quiet beach, with a glass of fine wine
We look away on a clear night
- Miia Eskelinen (Finland)
- Andres Galvez (Spain)

What are we in the wideness of the galaxy
Who are we in the brightness of the starry sky
Where are we in the eternity of the universe
Why are we separated by mountains and seas
When are we joined despite boarders to become one
- Gertraud Wisiak (Austria)

"To see what your house looks like,
visit your neighbor and see it from there."
To fully understand the wideness of our earth, we must go to the moon and beyond!
- Ulf Livoff (Denmark)

Beyond the pale white snowy mountain peaks of the Alps
glowing lightly in the transparent moonlight,
the stars are like shimmering jewels
on the velvety black dome of the winter sky.
Why explore when we can admire?
- Urška Demšar (Slovenia)

§

One sun, one earth, nine planets, beautiful jewels in the universe
there will always be problems in the future, however change will endure
and preferred visions are made of the ingredients of heart, soul and brain
- Hubert Gleissner (Germany)

Colours stacked on a street side fruit stand,
Beachside walking, heart in hand,
Noontime Sun in the black lunar sky,
Same starry light wherever you fly,
Shines bright in memories like the southern sun.
- George Dyke (Canada)

O lovely planet earth, floating so fair
Surely we are made special to observe the starry universe
So simple for us, sunrise in the East, sunset in the west.
-John Herrmann (Australia)

We will return
Where the Sun beams warms the East every morning Where
Life is ladled from the crystal goblets
Where there is nothing impossible…
Yes, this is not a lot, but this is not little.
- Andrey Karandaev (Russia)
- Maria Ejova (Russia)

The first week or so we create strong links between us in goblets
The third or fourth week we build an eternal galaxy
By the ninth week we discover our universal identity
- Fabrice Trolio (Belgium)
- Alexandre Nicolas Hachem (Lebanon)
- Kirsten Beyer (United States of America)

In One Earth we will learn to use space to bring peace
On One Earth we will unite and live in harmony
For One Earth we will be more tolerant than we are
From One Earth we will launch ourselves anew
To save all beauties with passion, for the next generation
- Maya Glickman-Reich (Israel)
- Øyvind Sørstrøm (Norway)
- Amal Rakibi (Morocco)
- Lynn Moran (Ireland)
- Selime Gürol (Turkey)
& Wakako Kondo (Japan)

Only one Earth? One Moon? Blue sky! How narrow were we
Before our children left and learned that our small beauties
Paled in the light of their own cosmic lives beyond.
- Jim Dator (Hawaii)

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Signatures


International Lunar Exploration in Preparation for Mars
LunAres
SSP04 - Adelaide

Faculty Preface

The 2004 International Space University (ISU) Summer Session Program (SSP) was hosted during July and August in Adelaide, Australia by the University of South Australia, the University of Adelaide, and Flinders University.

A key component of every SSP is the Team Project, in which students undertake a space project on a topic of international relevance. At the time of writing, new exploration initiatives exist in several parts of the world and are being defined in more detail. In all these initiatives the Moon is proposed as a testbed for human missions to Mars.

Acknowledging this new focus, a team of 47 graduate students and young professionals from 17 countries undertook the LunAres team project. LunAres had the following objectives:

- To identify and critically assess enabling concepts for martian exploration that can be rehearsed in the context of near-term lunar space missions
- To produce a robust and influential report as a contribution to planning for lunar and martian exploration, both robotic and human, and to the international co-operation aspects of such endeavors
- To organize the team and project in a manner that takes full advantage of the intercultural and interdisciplinary nature of the team members and that works effectively under deadline and resources pressure

LunAres was supported by staff, advice, and funding from ESA as well as NASA and the Canadian company Optech. Other space experts from around the world, from inside and outside the ISU community, also provided significant input to the students.

During the project, the students analyzed current lunar activities, developed an independent critical view of them, identified obstacles and new opportunities, and recommended international actions to accelerate progress. This is the report of their work. We, their faculty and teaching associate, have been fortunate to be associated with such a competent, mature, and energetic team. We are pleased to introduce them to the reader and to urge decision-makers to consider seriously their conclusions and recommendations.

Piero Messina
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Student Preface

The LunAres project is one of three completed at the International Space University Summer Session Program of 2004, held at the joint campus of the University of Adelaide and the University of South Australia. The course brought together people from all over the world into an interdisciplinary, intercultural, and international environment to undergo nine weeks of intensive lectures, workshops, site visits, and research.

The main goal of the LunAres project was to identify and critically assess enabling concepts for martian exploration that can be rehearsed in the context of near-term lunar missions. We believed this to be a robust and influential report that can contribute to the planning for lunar and martian exploration, both robotic and human, and to the international co-operation of that endeavor. The LunAres name is an amalgam of the words *Luna* (Latin for the Moon) and *Ares* (Greek for Mars).

The LunAres team was composed of 47 members from 17 different countries. While managing such a large and diverse group was a challenge, working with people from all over the world was a wonderful experience. Each member was able to contribute uniquely through his or her different cultural and academic background. In hindsight, it is clear that this had the effect of enriching not only the project itself, but also the individuals in it.

Australia was a terrific host country. In particular, our team enjoyed many activities made possible by the similarities of the Australian continent to the martian landscape. From the red, dusty, windswept landscapes of Woomera to the ancient geology of Arkaroola, the outback of Australia helped us gain a new appreciation for the martian surface. We have also reveled in the brilliance of the night sky, with the Moon, Milky Way, and billions of stars shining down on us clearly and vibrantly; the Southern Cross became a new guardian for many in the team. We were amazed at the local wildlife, especially the koalas who were getting all the sleep that we were missing out on!

We would like to acknowledge all of the people who helped us make this report a reality. Many thanks are due to the LunAres Co-Chairs and TA group, ISU Faculty and staff, the Mars Society of Australia, and visiting ISU alumni, as they offered facilitation, guidance, and knowledge whenever needed.

The LunAres Student Team

ISU SSP 2004

Abstract

The Aurora program in Europe and The Vision for Space Exploration in the United States represent a shift in space policies worldwide toward the goal of human and robotic exploration. Although some details differ, these plans share a common theme of expanding the human presence across the solar system. In particular, the plans involve near-term exploration of the Moon in preparation for human missions to Mars.

Given the current relevance of the topic and the international nature of lunar and martian exploration as expressed in these policies, a group of post-graduate students and professionals attending the 2004 Summer Session Program (SSP) of the International Space University (ISU) evaluated the uses of the Moon in preparing for an initial international mission to Mars. This LunAres report was commissioned by the European Space Agency (ESA) and sponsored by ESA, the National Aeronautics and Space Administration (NASA), and Optech Inc. in Canada. The resulting report analyzes the critical enabling technologies, human aspects, and operational capabilities needed for Mars exploration. In addition, the report suggests a policy, legal, and social framework for a lunar and martian exploration program.

The report discusses the current gaps and overlaps between existing international public and private Moon and Mars exploration programs. It then provides a list of enabling elements for an initial human mission to Mars. From these enabling elements, the report selects those that can best be tested on the Moon. The report then suggests a set of international robotic and human missions in which those elements can be rehearsed.

The report concludes with a set of 28 recommendations for initiating and implementing the suggested program. Among these recommendations are the formation of a loose-knit international coordinating body and the prioritization of operational and human aspects in lunar rehearsal missions.

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List of Acronyms

A

AAS	American Astronautical Society
ACWF	All-China Women's Federation
AG-Pod	Autonomous Garden Pod
AIAA	American Institute of Aeronautics and Astronautics
AMIE	Asteroid-moon Micro-Imager Experiment
AOCS	Attitude Orbit Control System
APEX	Automated Plant-growth Experiment
Art	Article
AS	Ascent Stage
ATV	Automated Transfer Vehicle
AU	Astronomical Unit

B

BAA	Broad Agency Announcement
BFO	Blood Forming Organs
BIS	British Interplanetary Society
BNTR	Bimodal Nuclear Thermal Rocket
BSC	Babakin Space Center

C

CAST	Chinese Academy of Space Technology
CAV	Crew Ascending Vehicle
CCD	Charged Couple Device
CEV	Crew Exploration Vehicle
CGR	Cosmic Galactic Rays
CMO	Crew Medical Officer
CNSA	China National Space Administration
CNY	ChiNese Yuan
COSPAR	Committee On SPAce Research
CPM	Cargo Preparation Mission
CRV	Crew Return Vehicle
CSA	Canadian Space Agency
CSL	Crew Surface Lander
CTV	Crew Transfer Vehicle

D

DIN	German Institute for Standardization
DFH	Dong Fang Hong communication satellite
DNA	Deoxyribonucleic Acid

E

EAR	Export Administration Regulations
EC	European Commission
ECLSS	Ecological Closed Life Support System
EDLS	Entry, Descent, and Landing System
EGNOS	European Geostationary Navigation Overlay Signal
ELV	Expendable Launch Vehicle
EMS	Environmental Media Services
EP	Electric Propulsion

ESA	European Space Agency
ESC-B	Ariane5 - Cryogenic Upper Stage
ETV	Exploration Transfer Vehicle
EU	European Union
EVA	Extravehicular Activity

F

FMI	Finnish Meteorological Institute

G

GCR	Galactic Cosmic Rays
GDP	Gross Domestic Product
GJU	Galileo Joint Undertaking
GLONASS	GLobal Orbiting Navigation Satellite System
GMS	Ground Monitor System
GNC	Guidance, Navigation & Control
GNP	Gross National Product
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSLV	Geo-synchronous Satellite Launch Vehicle
GTO	Geostationary Transfer Orbit

H

HEND	High Energy Neutron Detector
HEO	Highly Elliptical Orbit
HMM	Human Mars Mission
HSF	Human Space Flight

I

ICT	Interplanetary Crew Transport
IDEM	In-Situ resource Utilization demonstrators
ILEWG	International Lunar Exploration Working Group
ILPG	Inflatable Low-pressure Greenhouse
IPA	International Platinum Association
IS	Injection Stage
ISE	Inflatable Structure Experiment
ISO	International Organization for Standardization
ISS	International Space Station
ISR	*In situ* resource
ISRO	Indian Space Research Organization
ISRU	*In situ* resource utilization
ISTC	International Science and Technology Center
ISU	International Space University
IT	Information Technology
ITAR	International Traffic in Arms Regulations
IVHM	Integrated Vehicle Health Management

J

JAXA	Japan Aerospace eXploration Agency
JSF	Joint Strike Fighter

K

L

LAM	Lunar Ascent Module
LEM	Lunar Exploration Module (Apollo)
LEO	Low Earth Orbit
LIDAR	LIght Detection and Ranging System
LLO	Low Lunar Orbit
LPF	Lunar Precursor Family
LRO	Lunar Reconnaissance Orbiter
LSHLM	Long Stay Human Lunar Mission
LSHS	Lunar Surface Habitation Station
LSLD	Lunar Soft-Lander Demonstrator
LSR	Lunar Sample Return
LSS	Life Support Systems
LTB	Lunar Transfer Bus
LTHV	Lunar Transfer Habitation Vehicle

M

MET	Meteorological Station
METNET	The Next Generation Lander for Martian Atmospheric Science
MIT	Massachusetts Institute of Technology
MML	Mars Meteorological Landers
MOU	Memorandum of Understanding
MSN	MicroSoft Networks
MTCR	Missile Technology Control Regime

N

NASDA	National Space Development Agency of Japan
NASA	National Aeronautics and Space Administration
NCRP	National Council of Radiation Protection and Measurements
NEO	Near-Earth Object
NEP	Nuclear Electric Propulsion
NERVA	Nuclear Thermal Rocket Engine
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPD	National Policy Directive
NPS	Nuclear Power Source
NSF	National Science Foundation
NTEP	Nuclear Thermal and Electric Propulsion
NTP	Nuclear Thermal Propulsion

O

OE	Operational Experience
OIG	Office of the Inspector General
OOSA	Office for Outer Space Affairs
OTSV	Orbit Transfer Service Vehicle

P

PB	Program Board
PC	Program Committee
PLS	Policy, Law and Social
PPP	Private-Public Partnership
PROPU	Propulsion Unit

PSLV	Polar Satellite Launch Vehicle

Q

R

RFP	Request for Proposal
RLM	Robotic Lunar Missions
RSA	Russia Space Agency
RTG	Radioisotope Generators

S

SEC	Space Exploration Council
SEDS	Students for the Exploration and Development of Space
SEF	Space Exploration Forum
SELENE	SELenological and ENgineering Explorer
SETI	Search for Extra-Terrestrial Intelligence
SM	Service Module
SMAD	Space Mission Analysis and Design
SMART-1	Small Missions for Advanced Research in Technology 1
SMU	Surface Mobility Units
SPE	Solar Protons Events
SSHLM	Short Stay Human Lunar Mission
SSP	Summer Session Program

T

TBD	To Be Determined
THM	Transfer Habitation Module
TPA	Thermal Plasma Analyzer
TRL	Technology Readiness Level
TT&C	Telemetry Tracking and Command

U

UA	University of Arizona
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
USB	Universal Serial Bus
USSR	Union of Socialist Soviet Republics
UV	Ultra-Violet

V

VLBI	Very Long Baseline Interferometry
VRAD	VLBI RADio

W

WHO	World Health Organization

Chapter 1

INTRODUCTION

Here men from the planet Earth first set foot upon the Moon
July 1969, A.D.
WE CAME IN PEACE FOR ALL MANKIND.
Apollo 11 plaque on the Moon

It's human nature to stretch, to go, to see, to understand. Exploration is not a choice, really; it's an imperative.

Michael Collins, Gemini and Apollo astronaut

Mission Statement

Select, among the identified key concepts, technologies, and systems that will enable human Mars exploration, those that can best be tested on the Moon, and suggest a framework for international lunar missions that can be carried out to validate them by 2020. Include the enabling policy, legal, societal, and economic aspects.

1.1 Rationales for Human Space Exploration

On May 25, 1961, U.S. President John F. Kennedy announced to a joint session of Congress that the United States should embrace the goal of landing a man on the Moon and returning him safely to the Earth before the end of the decade. This announcement was the result of a complex set of political circumstances (Logsdon 1970; McDougall 1985). Nevertheless, the decision was based essentially on two immediate factors. First, on April 12, 1961, the Soviet Union succeeded in becoming the first country to send a human being into space. Within a week of this event, the Kennedy-supported Bay of Pigs invasion, in which an attempt was made to overthrow Cuban leader Fidel Castro, was aborted. This failure was an embarrassment for the President and the nation (Launius and Ulrich 1998).

In response to these setbacks, Kennedy sent a memo to Vice President Lyndon B. Johnson asking,

> "Do we have a chance of beating the Soviets by putting a laboratory in space, or by a trip around the moon, or by a rocket to land on the moon, or by a rocket to go to the moon and back with a man. Is there any other space program which promises dramatic results in which we could win?" (Kennedy 1961).

Johnson and his advisors concluded that the best way for the United States to compete with the Soviet Union was to land a human being on the Moon. President Kennedy made his decision based on this conclusion, and the space race began (McDougall 1985).

The U.S. decision to go to the Moon was not based on an imperative for exploration. Rather, it was the result of political stimuli coming from outside the space sector. The United States went to the Moon to assert technological superiority over the Soviet Union. On July 20, 1969, the United States achieved the goal with the landing of Apollo 11. However, soon after the race was won, the Apollo program was discontinued. Since 1972, no human has ventured beyond low Earth orbit (LEO).

Without the impetus that existed four decades ago as a result of competition between two world superpowers, humanity now needs a new set of rationales for engaging in space exploration. The Vision for Space Exploration in the United States and the Aurora program in Europe attempt to establish those new rationales. Even though one of the stated motives of the U.S. Vision is "to further U.S. scientific, security, and economic interests," the nation's stated purpose in returning to the Moon is not to demonstrate technological superiority. Rather, the purpose is to establish a permanent presence so that the Moon can be used to prepare for further exploration of Mars and beyond (NASA 2004). Similarly, although Europe is planning a human landing on Mars by 2033, it has decided to pursue the goal through "a stepwise build-up of capabilities and knowledge" that includes robotic precursor missions and preparation on the Moon (Bonnet and Swings 2004). Therefore, Europe's purpose for planning missions to the Moon is to prepare for human exploration of Mars.

Whereas the Apollo program was conceived as a competitive endeavor, current policies are focused on international cooperation (NASA 2004; Bonnet and Swings 2004). As will be discussed later in this report, virtually all major space powers now consider international involvement to be a cornerstone of space exploration.

Space agencies worldwide are moving toward an orientation of lunar exploration, including international missions in preparation for eventual human exploration of Mars. As such, the goal of this report is to identify the enabling elements for an initial human mission to Mars that can be practiced in the context of near-term international lunar missions. The report uses this list of enabling elements to suggest a set of lunar missions leading to an eventual human landing on Mars.

1.1.1 Why Explore Mars?

A detailed discussion of the various arguments in favor of human space exploration is beyond the scope of this report. However, the reasons for sending humans to Mars need to be clearly stated here. These reasons will dictate the activities to be conducted during the first human Mars mission, which, in turn, will determine the path of lunar exploration. In other words, the enabling elements selected to be tested in the context of lunar missions depend critically on the underlying reasons for planning a human Mars mission.

A number of reasons exist for sending human beings to explore Mars. These include:

- **Inspiration**. Human space exploration is an exciting endeavor that has the capacity to engage the human spirit and to motivate youth (NASA 1998).
- **International cooperation**. Space exploration provides an opportunity to bring nations together and to unify humanity (NASA 1998).
- **National prestige**. The capability to send human beings into space and especially to another world can serve as a great source of pride for individual nations.
- **Flexibility and adaptability in science**. Human attributes that cannot be duplicated by robots can aid in the conduct of science on Mars. For example, these attributes may prove critical to the search for evidence of life on the planet.
- **Societal benefits**. Exploration may be able to help society grow "technologically, economically, socially, internationally, and intellectually" (NASA 2004).

- **Education**. "If engaged effectively and creatively, space inspires children to seek careers in math, science, and engineering" (NASA 2004).
- **Opening a commercial market for space exploration**. One of the goals of the U.S. Vision is to involve the private sector in exploration (NASA 2004).
- **Enabling further human exploration across the solar system**. The U.S. Vision, for example, states that the Moon will be the first step in exploration of Mars **and beyond** (NASA 2004).

The main purpose of the initial Mars mission discussed in this report is to be the first step in establishing a sustained human presence. The framework for lunar exploration is designed under the assumption that the primary driver for the first Mars mission will be to establish a base and, perhaps eventually, a permanent settlement on the planet.

1.1.2 Why Go to the Moon to Prepare for Exploration of Mars?

Before identifying concepts to test on the Moon in preparation for Mars, it is helpful to define categories of lunar activities to aid in the selection process. In the report, all lunar activities are placed into one of three categories: technology rehearsal, operational activity, and supplemental activity. **Table 1-1** provides a description of these three categories.

Table 1-1 Types of activities that can be conducted on the Moon.

<table>
<tr><th>Activity Type</th><th colspan="2">Description</th><th>Examples</th></tr>
<tr><td>Technology rehearsal</td><td colspan="2">Use of the Moon as a technology test bed</td><td>Nuclear power
Radiation shielding
Space suits</td></tr>
<tr><td>Operational activity</td><td colspan="2">Lunar activity directly applicable to Mars exploration</td><td>Physiological effects
Psycho-social aspects
Living and working</td></tr>
<tr><td rowspan="2">Supplemental activity</td><td rowspan="2">Lunar activity that does not directly contribute to Mars exploration and that has…</td><td>…indirect applicability to Mars exploration</td><td>Private or academic experimental payloads</td></tr>
<tr><td>…little or no applicability to Mars exploration</td><td>Lunar astronomy</td></tr>
</table>

Despite the many differences between the Moon and Mars, the Moon provides an excellent laboratory in which to validate critical technologies (ie., technology rehearsal) and to develop an understanding of the issues associated with living and working on another planetary surface (ie., operational activity). Furthermore, certain supplemental activity, such as the inclusion of private or academic experimental payloads, will help to involve the public. This involvement will be critical if the program is to retain its funding long enough to realize the goal of landing humans on Mars.

Other supplemental activity that is not useful for future Mars missions will be selected out according to the criteria applied in the report. This type of activity makes the Moon an interesting destination for exploration independent of preparation for Mars, but the reasons for conducting this type of activity are not the focus here. The reader is referred to Spudis (1996) for a discussion of the reasons to go to the Moon and to Mendell (1985) for a treatment of activities to be conducted there.

1.2 Baseline Human Mars Mission

A necessary step in identifying a list of enabling elements for an eventual mission to Mars is to assume a baseline human Mars mission (HMM). The HMM used in this report is based on the 1998 NASA reference mission (Hoffman & Kaplan 1998). The baseline mission is not intended to serve as a suggested design but rather to provide a basis on which to choose the critical capabilities necessary to carry out such a mission.

This report assumes a long-stay, fast-transit (4 to 6 months, see **Figure 1-1**) mission. The crew will spend 18 to 20 months (approximately 600 days) on the surface of Mars, depending on orbital mechanics and the launch date. The mission will employ a fast-transit return to Earth. Using this baseline, the minimum mission time is 26 months and the maximum 32 months (Hoffman & Kaplan 1998).

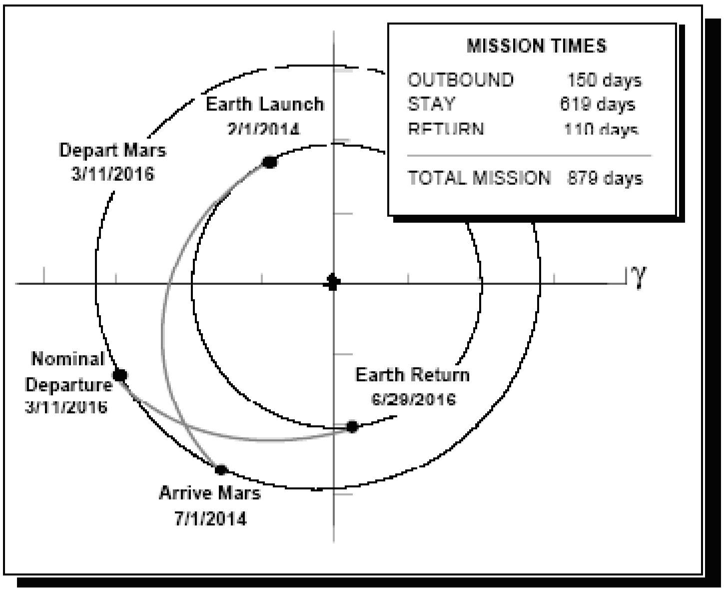

Figure 1-1 Typical fast-transit trajectory
(Hoffman & Kaplan 1998).

The baseline HMM breaks mission elements into pieces that can be launched directly from Earth using Saturn V-class launch vehicles. The design will not require LEO rendezvous or assembly. Instead, the elements will be integrated on the martian surface. This will require precision landing and surface mobility (Hoffman & Kaplan 1998). With this mission strategy, the cargo will be sent to Mars before the crew, which will help to reduce launch mass and to mitigate human risk both in transit and on the martian surface.

The crew of the baseline HMM assumed in this report will consist of four to six members of both genders (NOTE: The NASA reference mission suggests a six-person crew). Exploration activities will be conducted by the human crew as well as by robots (Hoffman & Kaplan 1998).

1.3 Project Scope

With the rationale for Mars exploration identified, the criteria for selecting enabling elements from lunar missions defined, and the baseline Mars mission described, the discussion now turns to the scope of the report. The tasks undertaken within the body of the report are:

- Summarize, review, and assess current plans for exploration of the Moon and Mars.

- Identify critical scientific and technological elements that will enable Mars exploration.
- Among the identified enabling elements, select those that can best be tested and rehearsed through a set of lunar missions.
- Define a legal, policy, and social framework to sustain a program of exploration of the Moon in preparation for Mars.
- Describe a set of international missions to the Moon in which to test the identified enabling elements.
- Define a legal, financial, and policy framework to enable international cooperation.
- Draw conclusions and make recommendations to the space community and to policy-makers

The report analyzes the Moon as a test bed for Mars, but it does not consider other possible "stepping stones" (NASA 2004) to Mars, such as Earth analogues, the International Space Station (ISS), near-Earth objects (NEOs), Lagrange points, and the martian moons. While a complete examination of the reasons to use these locations in preparation for Mars may be important to a broad program of solar system exploration, it is not undertaken in this report. Nevertheless, the International Space Station and various Earth analogues to the space environment are already in use and should play a part in any realistic exploration program. The ways that these sites can be used to support the use of the Moon in preparation for Mars are considered in the report. Only their uses as independent "stepping stones" to Mars are not treated.

1.4 Report Structure

The structure of the LunAres report is as follows:

Chapter 2 provides a description and analysis of the exploration plans of the United States, Europe, China, Japan, Russia, India, and Canada. In addition, it discusses initiatives proposed by the private sector. This analysis identifies gaps and overlaps and combines the plans into a single exploration timeline for the next three decades.

Chapter 3 analyzes the policy, legal, and social implications of a program of exploration of the Moon and Mars. The conclusions of this chapter serve as a set of non-technical "enabling concepts" to be refined later in the report into concrete programmatic recommendations.

Chapter 4 provides an analysis of the science and technology issues relevant to the program. After discussing the similarities and differences between the lunar and martian environments, the chapter discusses the difference between a mission to the Moon and one to Mars. The chapter identifies the enabling elements for an initial Mars mission and uses the definitions of technology rehearsal, operational activity, and supplemental activity to select from the list of identified elements those that best be tested on the Moon.

Chapter 5 integrates the analysis and identified enabling elements of Chapters 3 and 4 into a complete series of missions. The discussion includes a series of human and robotic lunar missions leading to an eventual human mission to Mars. Finally, the chapter considers some contingencies and alternatives to account for the inherent uncertainty involved in designing a long-term mission plan.

Chapter 6 draws some conclusions and makes a concise set of recommendations for implementing the program.

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Chapter 2

CURRENT PLANS FOR LUNAR AND MARTIAN EXPLORATION

From bed I spotted frost on the floor,
It was moonlight that I actually saw.
Looking up I gazed into the moon,
My head hanged, as homesick I became.

Chinese folk song by Li Bai

The above song by Li Bai dates back 1300 years to the Chinese Tang Dynasty. Although far from home, the Moon is a tangible reminder to the traveler of all he has left behind. The Moon is the single constant in his changing surroundings.

2.1 Introduction

This chapter summarizes the exploration plans around the world for the Moon and Mars and identifies gaps and overlaps existing at the program-, mission-, and technology-level. The discussion includes policy, budget, and outreach (where applicable) as well as the scientific and technological goals of the proposed lunar and martian missions.

2.2 Exploration Plans in the United States

2.2.1 Overview

Since its announcement on January 14, 2004, the Vision for Space Exploration has served as the basis for discussion on exploration goals in the United States. The stated objectives of the Vision are to:

- "Implement a sustained and affordable human and robotic program to explore the solar system and beyond;"
- "Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;"
- "Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration;"

- "Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests" (NASA 2004a).

Before the Vision was announced the five-year budget plan for the National Aeronautics and Space Administration (NASA) totaled US$86 billion. After the announcement, NASA requested an increase that amounts to an additional US$1 billion over the next five years (Aldridge et al 2004). However, a subcommittee of the U.S. House Committee on Appropriations has recommended a cut of about US$1.1 billion from the requested budget for the 2005 fiscal year (NASA Headquarters 2004). Therefore, NASA's budget could remain unchanged during the coming year.

2.2.2 Moon Program

NASA's lunar program will be focused on "demonstrating capabilities to conduct sustained research on Mars" and other destinations in the solar system. In addition, the missions will emphasize the conduct of science on the Moon (NASA 2004a).

The first planned lunar mission is "an orbiter to confirm and map lunar resources in detail." This orbiter will be launched in 2008. The orbiter will be followed in 2009 by a lander that will "begin demonstrating capabilities for sustainable exploration of the solar system." After these two missions, NASA plans to send up to one additional mission per year "to demonstrate new capabilities such as robotic networks, reusable planetary landing and launch systems, pre-positioned propellants, and resource extraction" (NASA 2004a).

NASA's first human mission to the Moon within the Vision is planned for launch between 2015 and 2020. Human lunar missions "will be determined by their support to furthering science, developing and testing new approaches, and their applicability to supporting sustained human space exploration to Mars and other destinations" (NASA 2004a).

2.2.3 Mars Program

The goals of NASA's planned Mars missions are (NASA 2004b):

- "Determine if Life ever arose on Mars."
- "Characterize the Climate of Mars."
- "Characterize the Geology of Mars."
- "Prepare for Human Exploration of Mars."

The missions and objectives are:

- **Mars Exploration Rover Mission**. The rovers Spirit and Opportunity are currently investigating how past water activity on Mars has influenced the red planet's environment over time.
- **Mars Reconnaissance Orbiter**. In 2006, NASA will put a probe in orbit around Mars for longer-term, global studies.
- **Mars Phoenix Lander**. In 2008, NASA will send a lander to study the geology of the planet, to search for water, and to seek clues about whether Mars was ever habitable.
- **A Mars mobile lab**. Before 2010, NASA will send a mobile laboratory to the surface of Mars to develop scientific experiments.

- **Mars test beds and scouts**. NASA plans to develop Mars test beds and scouts to demonstrate the technology of aerodynamic entry, Mars orbital rendezvous and docking, resource extraction and utilization, and optical communication.
- **Mars sample return**. NASA plans the first martian sample return mission no earlier than 2014. This will bring samples of martian rocks, soils, and atmosphere back to Earth.
- **Eventual human Mars landing**. The first human mission beyond the Moon will be determined on the basis of available resources, accumulated experience, and technology readiness (NASA 2004b).

2.3 Exploration Plans in Europe

2.3.1 Overview

The exploration plans of the European Space Agency (ESA) are defined by the Aurora program. Aurora's goal is to create and implement a long-term plan for European exploration of the solar system, including initial steps of human exploration beyond low Earth orbit (LEO). The main aims of the program are:

- "To allow European astronauts to reach Mars as part of an international endeavor by the end of the third decade";
- To continue the close cooperation within ESA and with collaborators such as European and Canadian industry and academia;
- To utilize space endeavors to encourage peaceful international cooperation and to build European identity;
- To stimulate the interest of the general public in science and technology and in particular to inspire the young people of Europe;
- To stimulate new technology by encouraging innovation and research with the possible benefit of valuable spin-offs for the Earth; and
- To continue scientific exploration which, although not foreseen as the driver of most of the missions, will nevertheless remain an indispensable tool (ESA 2001a).

To define its strategy, from 2002-04 ESA embarked on an Aurora preparatory phase supported by 10 ESA countries (including Canada) and costing approximately €20 million. At present the period 2004-05 is seen as a bridging phase during which the roadmap for 2006-10 will be finalized with a requested funding of €40-50 million and a final decision due in September 2004 (Spiero, pers. comm.). Approximately €2 million of this will be channeled into education and outreach programs.

The preliminary Aurora roadmap of 2001 has evolved. As a consequence of work done in the preparatory phase, human Moon missions are under consideration as rehearsals for a human Mars mission. The first decade of Aurora is dedicated to development and launch of robotic missions and testing of human technologies. The experience gained from ESA's first robotic missions to the Moon (SMART-1) and Mars (Mars Express) is paving the way for the first steps of Aurora, while experience in human space flight is obtained through the participation in the International Space Station.

2.3.2 Moon Program

SMART-1, the first of ESA's Small Missions for Advanced Research in Technology, was launched as an auxiliary payload onboard an Ariane-5 launch vehicle in September 2003. Currently en route to the Moon, this is the first European spacecraft to travel to and orbit the Moon. The spacecraft is powered by an ion engine and incorporates some subtle operations of the kind needed in distant missions, combining solar-electric propulsion with maneuvers using the gravity of planets and moons. Upon arrival in early 2005, the set of miniaturized scientific instruments aboard will make the first comprehensive inventory of key chemical elements in the lunar surface (ESA 2004a).

2.3.3 Mars Program

Mars Express, launched in June 2003 by the four-stage Soyuz/Fregat launcher, is a scientific orbiter mission (ESA 2004b). The spacecraft encountered Mars in December 2003. Mars Express contains seven scientific experiments intended to:

- image the entire surface at high resolution (10 meters/pixel) and selected areas at super resolution (2 meters/pixel);
- produce a map of the mineral composition of the surface at 100 meter resolution;
- map the composition of the atmosphere and determine its global circulation;
- determine the structure of the sub-surface to a depth of a few kilometers;
- define the effect of the atmosphere on the surface; and
- clarify the interaction of the solar wind with the atmosphere (ESA 2004c).

Aurora incorporates two types of robotic mission. The Arrow class missions are technology demonstration missions. Flagship missions, which are more expensive and more complex, are intended as major missions to advance scientific and technical knowledge in preparation for a human mission (ESA 2004b). Three robotic missions have been approved for studies:

- **EDLS** (Entry, Descent, and Landing System), scheduled for 2009, is a re-entry vehicle demonstrator and the first Arrow class mission of the Aurora program. This mission is considered vital to reduce the risk of a sample return mission by demonstrating that the proposed capsule design and mission conditions fully comply with the planetary protection requirements and maintain the integrity of the sample container (ESA 2003a).
- **EXOMars**, scheduled for 2011, is a Flagship mission combining technology demonstration and scientific goals. Autonomous rendezvous and docking will be validated in preparation for a sample return mission. The spacecraft will transport an orbiter and a large rover carrying 40 kg of astrobiology instruments. The Pasteur exobiology instrument package will be landed on the surface of Mars to perform soil sample analysis and look for signs of past or present life. The instruments package will be carried by a rover and powered by solar arrays (ESA 2003a).
- **Mars Sample Return-1**, scheduled to launch in 2014, is another Flagship class mission. All modules must comply with rigorous conditions for planetary protection. These include verification of container seals, hermetical sealing prior to Earth return, and prevention of external contamination of the container. In addition, some sub-elements need to be designed, such as the sample container, a container transfer system, and a Mars drilling station to drill, handle and collect the samples (ESA 2003c).

METNET

METNET is mission led by the Finnish Meteorological Institute (FMI) with the goal of placing a widespread surface observation network on Mars to investigate atmospheric structure, physics, and meteorology. A precursor mission and a series of missions is expected to start in 2007 and 2009 and extend to 2016. The Babakin Space Center (BSC) in Russia is the system lead, and the FMI and the Space Research Institute in Russia are the payload leads. The network will be composed of a number of new semi-hard landing vehicles called Mars Meteorological Landers (MML). The primary goal of the METNET mission is to measure all key meteorological characteristics at various locations for several years. This includes taking panoramic pictures, recording pressure, temperature, humidity, wind direction and speed, and atmospheric optical depth (Harri et al. 2003).

2.4 Exploration Plans in China

2.4.1 Overview

In October 2003, China launched its first taikonaut into space, making China the 3rd country to do so (after Russia and the United States). China seems poised to become a major space player in the 21st century.

The China National Space Administration (CNSA) issued a White Paper on Space Activities in November 2000. China's policy emphasizes the international nature of space activities (CNSA 2000). In addition, CNSA aims to target a limited number of projects so as to concentrate strength (Ibid). The CNSA divides its future development targets into short-term and long-term targets. Those most relevant to space exploration include the following:

2000-2010

- "To upgrade the overall level and capacity of China's launch vehicles. This will be achieved by … developing the next generation of launch vehicles with non-toxic, non-polluting high-performance … qualities;"
- "To realize manned spaceflight;"
- "To develop space science and explore outer space by developing a scientific research and technological experiment satellite group… and carrying out pre-study for outer space exploration *centering on the exploration of the Moon* ;" (emphasis added)

2010-2020

- "To establish China's own manned spaceflight system and carry out manned spaceflight scientific research and technological experiments on a certain scale"

Future development concepts identified in the White Paper as means to achieving the above-mentioned targets include industrialization, smart management and public outreach (CNSA 2000). Finally, international space cooperation is discussed in the White Paper. China believes that international cooperation should follow the "Declaration on International Cooperation on Exploring and Utilizing Outer Space for the Benefits and Interests of All Countries, Especially in Consideration of Developing Countries' Demands" (OOSA 2004).

There are no official figures for China's civil space budget, but some details have been announced, and others are based on outside assessments. The results are summarized in Table 2-1.

Table 2-1 China's civil space budget and comparison with US civil space budget

Activity	Annual Budget (CNY)	Equivalent (USD 2004)	Source
Chang'e I spacecraft	1.4 billion	170 million	Astronotes 2004a
CNSA's space dedicated budget	18 billion	2.2 billion (~1% of China govt's total budget)	Peeters 2004, pers. comm.; Futron 2003
Comparison with NASA's annual budget	124 billion	15 billion (~1% of US govt's total budget)	Whitehouse 2004

2.4.2 Moon Program

China's Chang'e lunar program consists of three phases: the orbiter phase, the automated soft lander/rover phase and the return spacecraft phase (Astronotes 2004b, Spacetoday 2004).

Phase 1

The orbiter will be based on the design of the Chinese Dong Fang Hong-3 (DFH-3) communications satellite.

Chang'e-1 will be launched December 2006, will orbit the Moon three months later (Astronotes 2004a). The mission, which carries out Scientific objectives, will last for about one year:

- Take three-dimensional images of the surface of the Moon [topographical];
- Analyze the quantity of the useful elements and the distribution of the material types on the surface of the Moon--mainly the quantity and distribution of 14 elements of value, such as titanium (Ti) and iron (Fe) [geological]; and
- Measure the thickness of lunar soil and grasp the age of the surface of the Moon and estimate the quantity of helium 3 (He-3) [geological] (Spacedaily 2003b).

Phase 2

Phase 2 of the Chang'e program is in the proposal stage, so information regarding it is much more sparse. However, China has stepped up its activities in space robotics to address this phase. For example, in 2002, China set up its first space robotics institute. In addition, extensive university research on rovers is being carried out under the High Tech Research and Development Program. Also, a number of models have been proposed for this automated lander/lunar rover and its associated polar lunar orbiter (Senate 2004).

The launch date for the automated soft lander/rover is around 2010-2012. A soft landing is being planned (Spacedaily 2003b, Space 2004).

Phase 3

This last phase will be a spacecraft for the return of samples collected by the rovers. This is expected to happen by 2020.

2.4.3 Mars Program

Feasibility studies on trips to Mars have been conducted (Astronautix 2004). China has no plans for independent exploration of Mars. However, expertise gained during the Chang'e program is meant to put China in a position to be part of international activities on Mars exploration (Space daily 2000).

2.5 Exploration Plans in Japan

2.5.1 Overview

At present, the Japan Aerospace Exploration Agency (JAXA) is focussed on the Moon with no martian exploration program. JAXA considers the Moon to be an optimal base for observation of the solar system as there are no disturbances due to the atmosphere, light, radio waves, and vibrations on the Moon. JAXA is planning to place an astronomical observatory on the Moon in the future which requires some preparatory missions.

Due to a relatively small budget for space development, JAXA does not have an independent human space exploration program; Japanese astronauts work under international cooperation, and JAXA emphasizes the use of robotic technologies.

As a part of JAXA's outreach program, all Japanese spacecraft after launch are given two names. The first is an alphabetical name to show the mission purpose. The second is a term of endearment in Japanese, which is named through a public vote and a naming committee. This name is used to popularise the spacecraft with the general public. (JAXA 2004).

2.5.2 Moon Program

LUNAR-A

Japan's first full-fledged lunar mission, LUNAR-A, is scheduled to launch in 2005 using the M-V launch vehicle. LUNAR-A will directly investigate the interior of the Moon, to provide data on the Moon's origin and evolution. The total development budget, including the launch cost, is about $200 million (23 billion yen).

LUNAR-A consists of a mother ship and penetrators. LUNAR-A will release the two penetrators, which will hit the lunar surface and penetrate to a depth of about two meters. The penetrators are equipped with seismometers and heat-flow probes, and will investigate the lunar interior for about one year. The mother ship will orbit the Moon and gather information sent from the penetrators, while photographing the lunar surface with its camera. This camera will gather geographical information and technical information on optical navigation, which will make future exploration of the Moon much easier (Hiroshi et al., 2002).

SELENE

SELENE (SELenological and ENgineering Explorer) will be launched by the H-IIA launch vehicle in 2006. This mission is the largest lunar mission since the Apollo program. The scientific objectives of SELENE are to understand the Moon's origin and evolution, and to observe the Moon in various ways to enable future utilization. SELENE will investigate the entire Moon to obtain information regarding elemental and mineralogical composition, geography, surface and sub-surface structure, the remnant magnetic field, the lunar gravity field, the existence of a lunar electromagnetic field, and plasma and high-energy particles.

For publicity and educational purposes, High Definition Television cameras are carried to observe the Earth from the Moon's orbit. The total development budget, including the launch cost, is about $370 million (41.4 billion yen).

SELENE consists of a Main Orbiter and two small satellites, Relay and VRAD. The Main Orbiter will reach the vicinity of the Moon in five days. Once at the Moon, it will be placed into a polar orbit at an altitude of 100 km. The Relay Satellite will be placed in an elliptic orbit with a periapsis of 2400 km, and will relay communications between the Main Orbiter and the ground station. The VRAD Satellite will play a significant role in measuring the gravitational field around the Moon. The VRAD Satellite in conjunction with the Relay satellite will enable differential Very Long Baseline Interferometry (VLBI) observations from the ground. The Main Orbiter will be employed for about one year and will observe the entire Moon (Satoru et al. 2002).

SELENE B

SELENE B has been proposed. The scientific objective of the mission is a geological survey of extruded rocks originating from the deep lunar surface. The appropriate destination for this purpose is the central peak of a crater, but this is quite difficult to reach because of the complicated geological features. The technological objectives of the mission are the demonstration of accurate, robust, and reliable lunar landing and the deployment of an autonomous rover including science instrument handling, telecommunication and night survival (Ichiro et al. 2002; Sho et al. 2002).

2.5.3 Mars Program

NOZOMI (PLANET-B)

Japan's first Mars orbiter, NOZOMI, was launched on July 4, 1998 to study the upper atmosphere of Mars and its interaction with the solar wind. Unfortunately, NOZOMI did not arrive at Mars because of a malfunction in a fuel valve (Takafumi et al. 2002; Sho et al. 2002).

2.6 Exploration Plans in Russia

2.6.1 Overview

Russian plans for planetary exploration include a Russian led mission to Phobos, one of Mars' two moons, and contributions to Mars missions led by other countries. Russia's extensive experience in long duration spaceflight in low earth orbit is also relevant to lunar and martian exploration.

2.6.2 Moon Program

At this time, the Russian Space Agency (RSA) has no proposed missions for lunar exploration.

2.6.3 Mars Program

Phobos-Grunt

The Phobos-Grunt mission (Korablev, n.d.) is a sample return mission that is scheduled for launch in 2009. The mission is the only Russian planetary project of this decade and is intended to complement the current American and European Mars and small bodies exploration programs. The spacecraft will orbit Phobos. The scientific objectives of the mission include:

- Study characteristics of Phobos regolith and subsurface layers *in situ* and under laboratory conditions;

- Study the role of asteroid impacts in the formation of terrestrial planets and their evolution;
- Study the origin of the martian satellites and their relation to Mars;
- Search for organic matter and life;
- Study the martian environment (dust, gas, plasma); and
- Monitor the martian atmosphere and climate.

The mission is expected to cost approximately 1.5 billion rubles (US$ 50 million).

Russian Contributions to Mars Missions Led by Other Countries

Russia contributes instruments to missions led by other countries. For example, Russia contributed the High Energy Neutron Detector (HEND) to the gamma-ray spectrometer for NASA's 2001 **Mars Odyssey** mission. Data from the spectrometer is being used to map element abundance and distribution on Mars. In addition, the Babakin Space Center (BSC) in Russia is the system lead for the Finnish Meteorological Institute's **METNET** mission and the Space Research Institute of Russia is collaborating with the Finnish Meteorological Institute as the payload lead for this mission.

2.7 Exploration Plans in India

2.7.1 Overview

India's overall space policy objective remains the utilization of space for national development. However, with China planning to launch a lunar probe, the Indian Space Research Organization (ISRO) is keen not to be left out of the race. ISRO hopes that the Indian lunar mission will serve as a test bed for future missions to other planets in the years ahead.

India's space budget for 2003-4 was $500 million (US), up 9% from the previous year. More than half of this budget was spent on the launcher program, specifically for development of the Geo-synchronous Satellite Launch Vehicle (GSLV) Mk 3. In current dollar terms, the budget increased five-fold in the decade from 1993-1994. Reflecting the level of wages in India, the program is estimated to directly employ some 40,000 people across the country.

India will continue to develop and implement:

- Remote sensing satellites, increasing its interest in high resolution and possibly moving into active sensors;
- Meteorological sensors and satellites; and
- Communications satellite, very likely moving into high bandwidth technology.

Lifting of the US sanctions against India's nuclear program in mid-2004 has opened up new opportunities for international cooperation. The US has two sensors short listed to fly on the Indian lunar orbiter mission, and India has agreed to cooperate with Boeing Satellite Systems of the US to design and build new communications satellites.

2.7.2 Moon Program

India has a main mission to the Moon called Chandrayaan-1. This is the first Indian space exploration mission. The rationale for this mission is national pride and responds to the

Chinese space program. The mission is due to launch by 2007/2008 and will have a duration of two years. It will be launched using a modified version of India's indigenous Polar Satellite Launch Vehicle. The objective of the mission is purely scientific and the total budget of the mission is around 80 million US dollars. The satellite will provide the following features:

- Chemical mapping of the entire lunar surface;
- 3-D atlas of regions of interest (Moon's topography, north and south polar regions, Aitken basin);
- High resolution remote sensing (visible, near-infrared, low and high energy X-ray);
- Better understanding of lunar surface processes; and
- Better modeling of the Moon's gravity.

The Indian government is rethinking its plan to send a human to the Moon by 2015, as the mission would be very expensive and yield very little in return (Srinivasan 2004).

2.7.3 Mars Program

At this time ISRO has no proposed missions for martian exploration. However, it has envisaged other future landing and planetary missions.

2.8 Exploration Plans in Canada

2.8.1 Overview

Canada's Planetary Exploration Program is a science-driven program, managed by the Canadian Space Agency (CSA) and outlined in the Space Exploration White Paper (CSA 2001). The main scientific thrusts of the program include, but are not limited to:

- Solid planetology (planetary geology);
- Planetary atmospheres, magnetospheres, ionospheres;
- Solar system small bodies;
- Exo/astrobiology;
- Life support systems; and
- Terrestrial analogues of space environments.

2.8.2 Moon Program

At this time CSA has no proposed missions for lunar exploration.

2.8.3 Mars Program

The CSA is considering a two-track approach to Mars exploration by contributing instruments or enabling technologies to Mars missions led by other countries and conducting a Canadian-led mission to Mars (CSA 2004a).

Canadian expertise applicable to solar system exploration includes:

- Robotics;

- LIDAR for spacecraft guidance, control, hazard avoidance and high-precision landing systems as well as for scientific instrumentation to study planetary atmospheres;
- Synthetic aperture radar to study geomorphology and search for subsurface water; and
- Biological life support systems.

The CSA is already contributing to the following Mars missions led by other countries:

Phoenix (NASA)

Canada is contributing a complete meteorological station (MET) with a Light Detection and Ranging (LIDAR)-based science instrument to the NASA Phoenix mission, scheduled for launch in 2007 (CSA 2004b).

Aurora (ESA)

The CSA provides financial contributions to ESA to participate in the Aurora program. In 2002, the CSA committed to investing €700 000 over 3 years to the preparatory phase of the Aurora program. In return for this investment, Canadian companies are eligible to compete for technology development contracts from ESA (CSA 2003; CSA website media advisory).

2.9 Non-Government Plans

Several private organizations have proposed missions and scenarios for space exploration.

The Artemis Project is a privately-funded commercial venture that intends to "place the first element of the lunar base on the Moon within the next decade." The purpose of the Project is to demonstrate that "manned space flight is within the reach of private enterprise and create an environment for the growth of private industry in space" (Artemis Society 2001).

LunaCorp has plans for private missions to the Moon. One project, SuperSat, is to provide the first broadband telecommunications link with deep space by 2005. Another project, Icebreaker, is to search for water ice on the Moon two years later (LunaCorp 2004).

TransOrbital, Inc is a US private company planning to perform commercial missions to the Moon with the aim of delivering any kind of item that the customer might want: ashes, business cards, certificates (TransOrbital 2004). TransOrbital is currently studying two missions: Trailblazer and Electra 1.

Besides these private companies, other societies and individuals are pushing for the private exploration of Mars. **The Mars Society** (2004) pursues the settlement of the red planet by an important outreach program and many ground simulations of Mars missions with the aim of advancing our knowledge and facilitating Mars missions. Robert Zubrin is the biggest advocate of the **Mars Direct Manned Mission** (2004) which proposes and "demonstrates" the feasibility of a human Mars mission today, using today's technology and private or mixed capital investments.

2.10 Integration of Plans

This section analyzes the gaps and overlaps existing among the exploration plans discussed above. It also provides some general recommendations on how to initiate an international program of lunar exploration in preparation for Mars. These recommendations will support the analysis of subsequent chapters of the report.

2.10.1 Overlaps in Lunar Plans

The scientific and technological objectives of planned lunar missions (the U.S. Vision, SMART-1, Chang'e-1, LUNAR-A, SELENE, Chandrayaan-1) are similar, but the instruments used and mission details are different. For example, SMART-1 is the only spacecraft using solar-electric propulsion. SELENE will be broadcasting an earthrise (SELENE 2003).

The following overlaps exist among the planned lunar missions:

- X-ray spectrometers and infra-red spectrometers for geological studies. SMART-1 will look for Mg, Al, Si (SSTD 2004), and Chang'e-1 will look for these elements and eleven others.
- Topographical studies using cameras and altimeters will be performed by SMART-1's AMIE camera (ESA 2004e) and Chang'e-1's, SELENE's, and Chandrayaan-1's CCD cameras and laser altimeters.
- Studies of the radiation environment around the Moon will be performed by Chang'e-1 with a high-energy particle detector and two low energy ion detectors and by SELENE with a charged particle spectrometer.

2.10.2 Overlaps in Martian Plans

NASA and ESA programs include a series of missions with the goal of sending humans to Mars. RSA is planning a sample return mission to one of the martian moons. CSA and RSA are planning to contribute instruments to missions that will be carried out by NASA and ESA.

Table 2-2 Scientific objectives of current and planned Mars missions.

	NASA	ESA	RSA
Atmosphere/Climate	Yes (mission to be determined)	Mars Express METNET	Phobos-Grunt
Geology/geography	Spirit and Opportunity Phoenix	Mars Express EXOMars METNET	Phobos-Grunt
Search for Life	Phoenix	EXOMars	Phobos-Grunt
Other science and preparation for human exploration	Mars Mobile Lab	EXOMars	

Table 2-2 summarizes the scientific objectives of current and planned Mars missions. Overlaps exist in the following areas:

- Atmospheric science – observing the climate and characterizing the composition of atmosphere and its interaction with solar wind;
- Geography – recording the topography of Mars by imaging;
- Geology - characterizing and mapping the structure and mineral composition of the surface and sub-surface; and
- Search for life.

2.10.3 Gaps in Lunar and Martian Plans

Some broad programmatic gaps can be identified. Although the United States and Europe plan to use the Moon as a test bed for Mars, neither has determined a transition strategy that would free resources for the Mars program and make optimal use of the lunar infrastructure that will be established. Furthermore, a coordinating body to ensure that nations take advantage of complementarities between their programs does not currently exist.

2.10.4 Recommendations

The discussion of overlaps above is meant to provide the information on science that will be conducted by the various agencies' missions. However, the discussion is not intended to imply that all of these overlaps should be avoided. In many cases, duplicated science is of great value. Nevertheless, it is important that the duplication that does exist serves to advance the goals of the program. Additionally, gaps between programs cannot be avoided, but minimizing those gaps will help to ensure that the program is successful. For these reasons, the following is recommended:

Recommendation 2-1: Establish a multilateral exploration panel to collect and disseminate information related to exploration of the Moon and Mars. This panel, composed of representatives from all space agencies, will promote and coordinate international collaboration on lunar and martian missions.

This panel can be established soon. A model for it already exists. The International Lunar Exploration Working Group (ILEWG) conducts activities similar to those of the panel described here (ESA 2000).

Eventually, the panel might be able to serve as the basis for a broader forum on international exploration activities. The establishment of such a forum will be discussed later in this report.

The primary purpose of the panel will be to optimize the results of the missions being conducted throughout the world. Given the plans of each of the world's space agencies, the following is recommended:

Recommendation 2-2: Augment NASA and ESA human lunar exploration objectives by using robotic capabilities under development in other nations.

In order to facilitate the initial work of the panel, Figure 2-1 provides a timeline of the current and planned missions discussed in this chapter, and Table 2-3 provides a listing of the past, current, and planned missions of the each of the space agencies and the private sector.

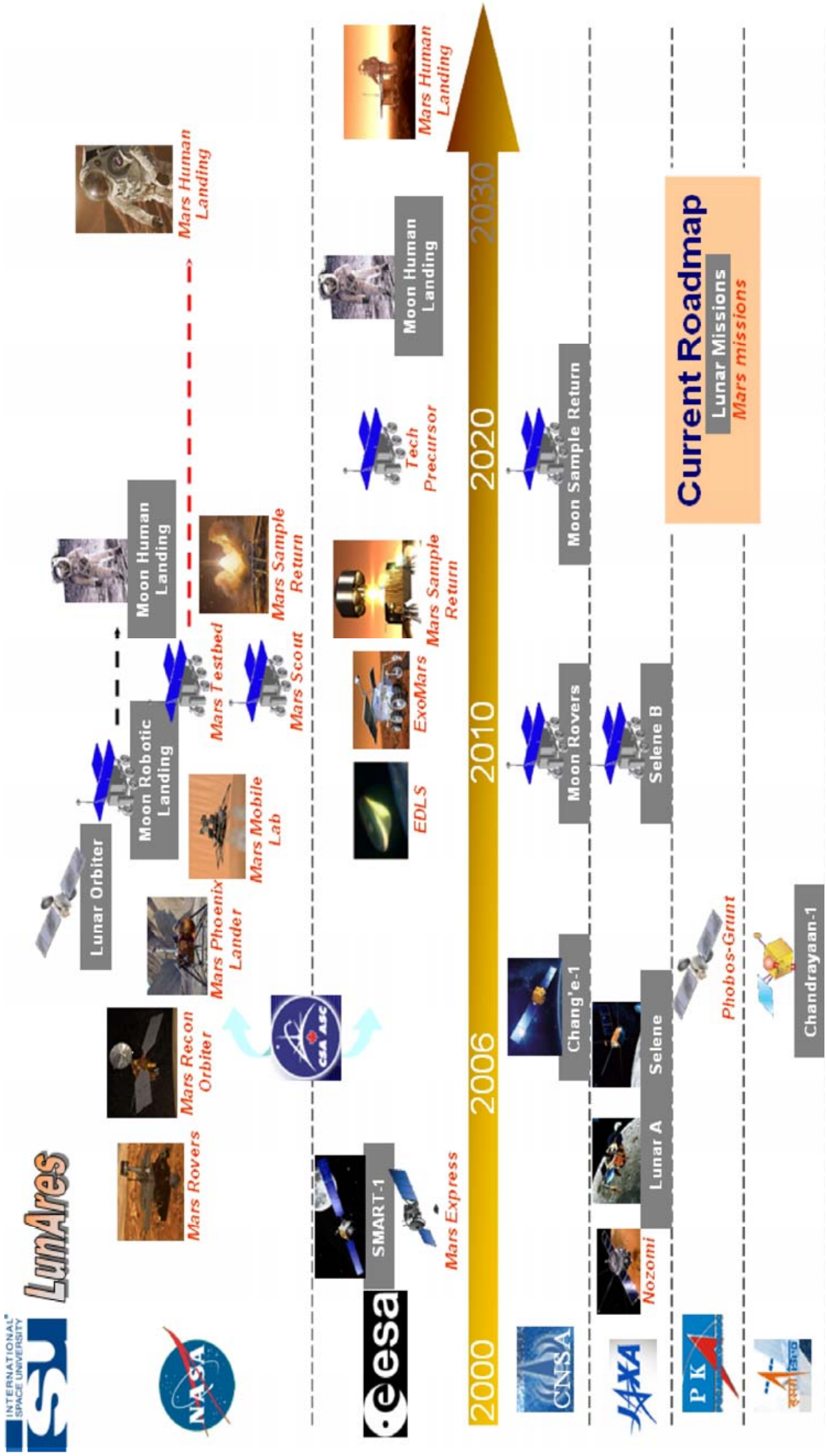

Figure 2-1 Current and planned mission roadmap

Table 2-3 Past, current, and planned missions worldwide

O: past mission
●: current mission
*: mission in development
+: proposed mission
×: no planned

Moon	NASA	ESA	CNSA	JAXA	RSA	ISRO	CSA	Private
Impacter	O: Ranger (1961-65) O: Lunar Prospector (1999)	×	×	O: HITEN (1990) *: LUNAR-A (2005)	O: Luna (1959)	×	×	×
Flyby	×	×	×	×	O: Zond (1965-70)	×	×	×
Orbiter	O: Lunar Orbiter (1966-67) O: Apollo (1968-72) O: Clementine (1994) O: Lunar Prospector (1999)	●: SMART-1 (2004)	*: Chang'e Phase 1 (2006)	O: HAGOROMO (1990) *: LUNAR-A (2005) *: SELENE (2006)	O: Luna (1966-76)	*: Chandrayaan-1 (2007)	×	×
Lander	O: Surveyor (1966-68) O: Apollo (1969-72) +: New Vision (2008)	×	+: Chang'e Phase 2 (201X)	+: SELENE B (201X)	O: Luna (1965-76)	×	×	+: TransOrbital, Inc (?) +: LunaCorp (?)
Rover	O: Apollo (1971-72) +: New Vision (2009)	×	+: Chang'e Phase 2 (201X)	+: SELENE B (201X)	O: Luna (1970, 73)	×	×	+: LunaCorp (?)
Sample Return	O: Apollo (1969-72)	×	+: Chang'e Phase 3 (201X)	×	O: Luna (1970, 72, 76)	×	×	×
Human	O: Apollo (1968-72) +: New Vision (201X)	×	×	×	×	×	×	×

Mars	NASA	ESA	CNSA	JAXA	RSA	ISRO	CSA	Private
Impacter	×	×	×	×	×	×	×	×
Flyby	O: Mariner (1964, 69)	×	×	×	O: Mars (1962, 69)	×	×	×
Orbiter	O: Mariner (1971) O: Viking (1975) O: Mars Observer (1992) O: Mars Global Suervayor (1996) O: Mars Climate Orbiter (1998) O: Mars Odyssey (2001) +: Recon (2007)	●: Mars Express (2004)	×	O: NOZOMI (1998)	O: Mars (1971) O: Phobos (1988) +: Phobos-Grunt (2009)	×	×	×
Lander	O: Viking (1975) O: Mars Polar Lander (1999) +: Phoenix (2009)	O: Mars Express/Beagle 2 (2004) +: EXOMars (2009)	×	×	O: Mars (1973)	×	×	×
Rover	O: Mars Pathfinder (1996) ●: Opporunity (2004) ●: Spirit (2004)	+: EXOMars (2009)	×	×	×	×	×	×
Sample Return	+: New Vision (201X)	+: Mars Sample Return-1 (2011)	×	×	×	×	×	×
Human	+: New Vision (201X)	+: Aurora (203X)	×	×	×	×	×	×

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Chapter 3

POLICY, LAW, AND SOCIAL ANALYSIS

For I dipped into the Future, far as human eye could see; saw the vision of the world, and all the wonder that could be.

Alfred Lord Tennyson

Many lessons are to be learned from the past 40 years of human space flight and some of the greatest lessons concern the policy, legal and social aspects of programs. There have been several space programs in which two or more agencies or governments formed a partnership to meet common goals. Jasentuliyana (1999) states that "the international cooperation on a Mission to Mars is almost as inevitable as the Mission itself, not only to maximize the obvious financial resources but also the substantial technical resources."

This chapter first discusses factors affecting space exploration that cannot be controlled (e.g. changing political environments and fiscal situations), the existing legal treaties and space laws, and then recommends a regulatory changes and a program coordination framework that will facilitate future space exploration. Next, the program management framework used on selected existing international space programs (i.e., Galileo and ISS) will be analyzed to determine what did or did not work well. Based on that analysis, the chapter describes a management framework for our missions to the Moon. The framework includes aspects of social involvement and commercial applications that are important in order for missions to have long-term sustainability. Long-term sustainability is achievable by having an innovative framework that solicits active support from all interested parties: ordinary citizens, non-space commercial companies, the science community, and educational institutions.

This framework of international cooperation, program management, and social involvement will then be the basis for the development of the implementation plans in Chapter 5.

3.1 Management of Change, Legal Considerations, and Impact Scenario Analysis

Decisions to explore space are political in nature. It is therefore necessary, in constructing any type of cooperative program, to recognize that partners' national priorities must be accommodated (Cline, Finarelli, Gibbs & Pryke 2002, p.6). Governments change over time, and the political and policy priorities of partners may then change along with the government. Changing political and policy priorities will naturally flow down to economic considerations affecting partners' contributions to space exploration. Likewise, the methods by which governments allocate money toward space exploration are generally set and not subject to change.

Legal considerations affect partners' relations and should also be recognized and accommodated in partnering arrangements. For instance, the United States has strict strategic export regulations: the International Traffic in Arms Regulations (ITAR) nominally regulates military exports by granting licenses or other approvals under the control of the Secretary of State, and the Export Administration Regulations (EAR) regulate dual-use items and some civilian items. This regulation impacts the ability of partners to share information and data.

In the case of technology and knowledge transfers, space exploration projects have to deal with the international framework, such as the Missile Technology Control Regime (MTCR) or the European Space Agency framework, and also with regulations (such as from the World Trade Organization) that are not directly related to space technologies but that could have an impact on the transfers of technologies.

The legal environment, including the differences between regional and national regulations, under which partners form their relationships will be accommodated within the individual mission cooperating arrangements.

The following paragraphs of this section illustrate conceivable changes that would have major impact on the development of an exploration program. The space systems engineering graduate design class (2004) at MIT has performed a scenario analysis based on various alternatives for the future. A new space race, a launch system failure, the dawn of the nuclear propulsion age, an asteroid strike, the presence of lunar water, the presence of life on Mars, and policy change due to budget cuts were investigated as possible scenarios. Similarly, this analysis addresses some general scenarios.

3.1.1 Technological issues

Dator (pers. comm. 10 August, 2004) identifies a number of emerging technological trends, including artificial intelligence, genetic engineering, nanotechnology, and robotics. These trends are important to consider as they are now at the beginning of their growth curve, indicated in Figure 3-1, and as their maturity increases, they will significantly influence the development of space exploration and society as a whole.

Technological developments responsible for the exponential part of the curve cannot be foreseen at this time, so their ramifications cannot be predicted. Kurzweil (1999) makes an interesting case for the future development of artificial intelligence in combination with nanotechnology and robotics. He focuses mainly on the implications of these developments on terrestrial society, but consequences for space exploration may be extrapolated from his ideas about future development.

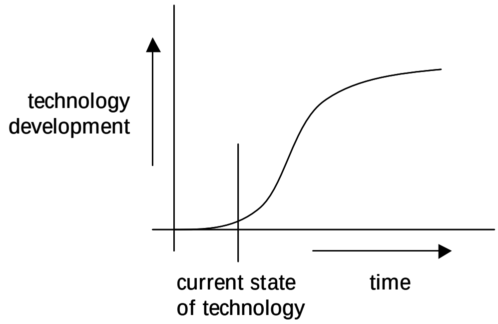


Figure 3-1 Conceptual Model of a Technological Growth Curve.

Possible consequences of an exponential growth stage in some or all of these technologies may lead to very different strategies for space exploration. For example, artificial intelligence could be used to terraform a planet for human life. A non-human intelligence may be adapted to live on other planets instead of sending humans to live there.

Some technologies may be too dangerous to test on Earth. Worden (pers. comm.) suggests that Moon or Mars bases could be used as safe testing laboratories or quarantines for emerging technologies considered too dangerous to be tested on Earth.

Edwards and Westling (2003) discuss the space elevator, another emerging technology that may provide easy access to space. NASA's Breakthrough Propulsion Project (1996-2002) or a similar project might lead to a dramatic advance in space propulsion systems and promote the emergence of small affordable commercial launch vehicles. The impact of the development of this kind of technology on space programs would be dramatic. Easy access to space would facilitate the scaling up of space activities and would allow larger spacecraft to be put in orbit at lower cost. Though the development of the space elevator is not foreseen before 2020, the implications for missions to the Moon or Mars would be enormous.

3.1.2 Social Issues

Buckland (pers. comm.) and Dator (pers. comm.) both touched upon the idea of 50 to 60 year cycles in social economics and technological achievement. There seems to be a cycle in society every 4 generations, where each generation has different characteristics. Members of one generation effectively work on projects for about 15 years, so a full cycle of 4 generations would take about 60 years to complete. For example, the Apollo program was carried out in a time when society was highly motivated to accomplish this goal. Another peak in one such cycle could lead to major global development and an interest in space exploration and colonization.

A shift in economic power can occur due to the fact that older infrastructure and production technologies that an industrialized nation carries inhibit retaining a lead-role. Less developed parties can take advantage and even take over the lead role by developing new production technologies and infrastructure, as argued by Dunne and Pobodnik (1995). For example, economic growth in Asia could lead to a shift of the economic center of gravity.

The launch of the first Chinese taikonaut and subsequent human missions may be a first indication of a new space race. The benefits of a space race are the rapid development of technology at the risk of stagnation afterward. This is illustrated by Mendell's (pers. comm.) statement that U.S. President Nixon almost cancelled the entire human spaceflight program along with the Apollo program. Lobbying in Congress prevented this decision, but the Apollo program was discontinued, as indicated by the National Space Science Data Center (2004). Policy makers must recognize that the space race environment is not sustainable.

Space can be a powerful uniting factor. A present day example of international cooperation is the ISS, seen on HSF International Space Station (2004). Space cooperation can be a powerful political symbol, examples of which can be found in Finney and Lytkin (2003).

Finney and Lytkin (2003) argue that the promotion of space through science fiction and popular scientific works generated enormous interest in space throughout society during the 20th Century. This demonstrates the power present-day outreach could have. A future scenario where broad public support for space activities pervades is highly desirable. This report recommends, for that reason, the creation of a renewed broad interest in space through outreach. A study of the past interest in space and the way it came about could help to define a good general outreach strategy.

Other issues to consider in more detail are the nostalgia driver: 2019 will be the 50th anniversary of the first Apollo landing. It may be interesting to consider the first human rehearsal mission to go to the Moon in that year.

Space tourism is another interesting social trend to consider. The Ansari X-Prize Competition may create a market for space tourism and civilian space travel. This does not seem to impact on the exploration program directly, but cheaper launch solutions developed commercially could help bring down the cost of exploration and speed up the exploration program.

Another scenario would have rich benefactors invest in the space sector. This would represent a financial boost to space activities. An investment in space exploration would be most likely, as the public outreach value of exploration is high. However, it would not be prudent for any space exploration program to factor in or to expect a financial injection by a rich benefactor.

3.1.3 Shortage of Resources

Shortage of rare metals, such as platinum and copper, could drive their prices up and lead to interest in gathering these resources in space. These are two of many examples which should be researched more in depth. The International Platinum Association (IPA) states that platinum availability will be sufficient to meet future demands.

Shortage and unequal distribution of resources will likely lead to global tension, according to an observation made by Dunne and Pobodnik (1995). Mitigating these problems before they escalate will help to keep the space program on-track. For example, today's society is heavily dependent on oil derived products. Greenpeace (2002) goes so far as to speak of an oil addiction. At some point, this resource will run out, resulting in a lower availability of fuels and plastics. Groups like EMS (2003) point out the threat of oil shortage: global economy and space industry would both suffer. Conversely, it could also provide an incentive to create solar power satellites or to perform further research on fusion power and, subsequently, to extract helium 3 from the Moon.

3.1.4 Global Catastrophe

Humanity can mitigate the effects of some types of global catastrophes, but for others the technology does not exist to shield humanity from their effects. Solar flares could disrupt or destroy electrical networks.

A global pandemic could arise through further increases in the AIDS epidemic in Africa or worse, new viral diseases could lead to a global epidemic, according to Health Canada (2003) and WHO (2003). Health Canada (2003) states that a global pandemic can be expected within five to ten years, based on historical data of past pandemics. In case this happens, resources will likely be diverted away from the space program towards mitigation of the disease.

The threat of a Near Earth Object (NEO) hitting the Earth could either paralyze humanity if the object is too close to divert or spur space development to divert the threat. Exploration programs would likely be cancelled to divert resources towards mitigating the threat. Yeomans (2004) shows the risk of a NEO impact to be low. Some resources should be devoted to finding potential threats, but in proportion to the risk.

Rapid climate change would likely create world-wide chaos. Large-scale climactic events may include: collapse of the Antarctic icecaps, nuclear accidents or nuclear holocaust, volcanic eruptions, and large-scale releases of carbon dioxide or methane from trapped ice or ocean floor sources. A rapid climate change would induce governments to invest in mitigating this problem.

An unforeseen event may lead to the breakdown of the Internet or Information Technology (IT) resources in general. Such an event would be catastrophic to modern society, which is becoming increasingly dependent on these resources.

Some of these global catastrophes, such as the pandemic, the NEO threat, rapid climate change and the IT breakdown can be mitigated through thoughtful preparation. Some resources need to be invested in preparing for these worst case scenarios to keep the timeline for the exploration program on-track to the best extent possible.

3.1.5 Loss of Spacecraft

Loss of ISS, another Shuttle loss as reported by NASA (2004), or the loss of a Soyuz vehicle could lead to the general view that human spaceflight is too risky. In addition, a serious risk to be dealt with in the future is space debris. Space debris increases the risk of collisions and the risk of the loss of a crewed vehicle.

Within the context of any exploration program, the failure of the first human mission to the Moon or to Mars would seriously impact on the program. It would increase the debate on the use of human missions. The likelihood of this scenario occurring can be mitigated by testing all mission elements in small steps.

3.2 Analysis of General Existing Legal Frameworks against the Exploration Program Structure

The international regulations for space law established after the Cold War were influenced by the political situation at that time. Several decades have passed since then, and space exploration plans are now significantly different. Therefore, it is necessary to have a closer look at the existing legal regulations of space law and their relevance today and, in particular, to the LunAres program.

The legal framework for space exploration can be found primarily in the five United Nations (UN) space treaties and is also part of customary international law.

3.2.1 UN Regulations

Outer Space Treaty

The UN Outer Space Treaty contains important legal descriptions for space exploration and the basic principles for space activities.

- All space activities shall be conducted for the benefit and in the interest of all mankind, and all states shall have free access to all areas of space. Furthermore, outer space shall be free for exploration without any discrimination on the basis of equality and in accordance with international law (Art I).

- Outer space is not subject to national appropriation by claim of sovereignty (Art II).
- All exploration activities on the Moon and other celestial bodies need to have a peaceful purpose (Art IV).
- State parties of the Treaty are internationally liable for their activities (Art VII).

The Outer Space Treaty is a very general reference for space exploration issues and has been ratified by 98 states. It is therefore considered to be a solid and recognized basis for international space law. Additional space treaties provide further specific information.

Moon Treaty

The provisions of the Moon Treaty are explicitly applicable to the Moon and all other celestial bodies within the solar system except for the Earth. It embodies the following principles:

- Following the principles of the Outer Space Treaty, the Moon Treaty states that the Moon is a common heritage of mankind and is therefore not subject to appropriation by states, organizations, or private persons.
- Freedom of scientific investigation on the Moon is specified without discrimination under the principles of equality and international law and only for peaceful purposes.
- State Parties have the right, in carrying out scientific investigations, to collect and remove samples of minerals and other substances from the Moon.
- It is an obligation for states to take measures to prevent disruption of the environmental balance of the Moon.

The greatest difficulty connected with the Moon Treaty is the lack of agreement among the UN members concerning the provisions and its ratification. The Moon Treaty provides the opportunity for the establishment of an international regime (Art. 11), but no such regulatory authority exists. According to the Office for Outer Space Affairs' website (2004) only 10 nations, none of which has significant space programs, have ratified the Treaty. A state that has not ratified the Treaty has no obligation to follow its regulations unless it is cooperating with a state that has ratified it. In general, because of this lack of acceptance in the international community, the Moon Treaty cannot be seen as a source of legal regulation of space exploration.

Liability Convention

The Liability Convention deals with the liability of a launching state for damage caused by its space object both on the surface of the Earth and elsewhere. It includes procedures for instituting claims of compensation and dispute settlement. One of the main problems with the Liability Convention is that it contains numerous ambiguous terms such as "damage" or "space object." This leaves a great legal gap when interpreting and applying the Convention to possible future liability cases in space exploration programs.

Rescue Convention

The Rescue Convention elaborates on Art. V of the Outer Space Treaty in which astronauts are considered envoys of mankind. It provides guidance on the rescue and return of both astronauts and objects launched into space. If any contractual party receives information regarding an incident, it has the obligation to immediately inform both the launching authority and the Secretary General of the UN. The Rescue Convention imposes a large range of obligations for contracting parties in such cases. It does not include regulations regarding rescue of astronauts from space. Diederiks-Verschoor (1999) considers this contingency as being highly improbable without a stand-by vehicle or another backup system. Technical feasibility of rescue should be considered before initiating exploration programs.

Customary Law

International customs play an important role in the formation of international law and, in particular, international space law. According to Cheng (1998) most of the principles for customary law are stipulated in the Outer Space Treaty and have been expanded by a number of rules of customary law codified in several UN Treaties. These include the non-appropriation rule, freedom for exploration and use, and the general principle of use of outer space. Even if states acceded to the treaties they are obliged to follow these rules of international customary law.

3.2.2 Environmental Law Issues

The space treaties define outer space and the space environment as "the province of all mankind," and specify that exploration and peaceful use should be carried out for the benefit and in the interest of all mankind. The Outer Space Treaty in Art. IX imposes the obligation for States to conduct all exploration without harmful contamination and adverse changes in the environment of the Earth and, if necessary, to take appropriate measures for this purpose. When exploring and using the Moon, the Moon Treaty obliges states to take measures to prevent disruption of the existing balance of the environment of the Moon as well as the environment on Earth through introduction of extraterrestrial matter. In such cases, States have an obligation to the UN to provide certain required information. Because the Moon Treaty lacks broad acceptance, this environmental regulation is irrelevant according to Roberts (1997).

The Committee on Space Research (COSPAR) is a scientific organization concerned with international progress in space exploration. It maintains a planetary protection policy that is expressed in NASA's instruction on planetary protection (NASA Policy Directive NPD 8020.7F 1999).

"The conduct of scientific investigation of possible extraterrestrial life forms, precursors and remnants must not be jeopardized. In addition, the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by a spacecraft returning from another planet. Therefore, for certain space mission target-planet combinations, controls on organic and biological contamination carried by spacecraft shall be imposed in accordance with directives implementing this policy."

This policy is currently applicable to all robotic missions within the solar system and for all sample return missions. However, it might also be appropriate for an exploration mission carrying humans.

One issue requiring consideration from the environment perspective is what should happen to natural resources such as the putative polar ices at both the north and south poles of the Moon. For the use of limited natural resources that may exist on both the Moon and Mars, general regulations regarding methods of recovery, quantity limitations, and permissible uses should to be established.

3.2.3 Legal Status of Possible Extraterrestrial Life

Although the possible existence of life elsewhere in our solar system is still to be determined, it is necessary to analyze the legal status of such life. Outer space, and in particular all celestial bodies, are subject to the "common heritage of mankind" principle, meaning that they belong to all and may be used by all, but cannot be appropriated (Outer Space Treaty 1999, Art. I & II). In other words, no state or private entity can claim sovereignty or property in space and over extraterrestrial forms of life. Therefore, such life forms will be treated the same way as the celestial body on which they were discovered.

3.2.4 Recommended Changes and Modifications

The existing legal framework for space exploration is not adequate for future exploration plans because of lack of agreement and the legal ambiguity that most of the space treaties have in common.

As previously stated, the Moon Treaty cannot serve as a legal role model for regulation of space exploration because it has not been ratified by a sufficient number of states. It is presently a non-binding legal source for all states that have not ratified it. In order to guarantee that exploration follows international law and, in particular, space law, broadly accepted general regulations valid for all participating parties must be established and ratified by the international community. This can be accomplished either by ratification of the existing Moon Treaty or through a possible re-evaluation or amendment of the Treaty. Re-evaluation of the Moon Treaty will not be easily achieved because of political constraints in some countries. Since it cannot be expected that most nations will change their opinion of the existing Moon Treaty, it would be best to establish a new treaty.

One model for a new version of the Moon Treaty and a new legal framework for space exploration on the Moon and other celestial bodies could be the UN Convention on the Law of the Sea (UNCLOS). Part XI of the UNCLOS contains the "common heritage of mankind" principle for the high seas, and also an International Sea-Bed Authority as representative of mankind that organizes and controls all activities. Referring to Jasentuliyana (1999), this could be a model for a possible Moon Authority controlling all activities on the Moon. In addition, the new regulation must include provisions for dealing with liability issues in case of incidents occurring during exploration programs, as well as provisions for environmental issues dealing with the status of nature on Moon or Mars. It should also include provisions for enforcement of these regulations. It would be very beneficial for the exploration of Moon and Mars to provide the same rights and obligations for all participating entities. Therefore, a treaty based on the UNCLOS is recommended. The UNCLOS enjoys greater acknowledgement and acceptance than the Moon Treaty and, therefore, a treaty based on the UNCLOS is more likely to be ratified.

It is important to establish a treaty that is applicable to the Moon, Mars, and all other celestial bodies to define the rights and obligations of entities engaged in space exploration. Adherence to such regulations throughout the international community is the key for the legal realization of space exploration.

3.3 Differences between the LunAres Program and Previous Cooperative Efforts

As detailed in Chapter 2, human space exploration beyond Low Earth Orbit (LEO) is a concept that has been proposed by a number of countries. As a result, there are a number of approaches to space exploration with both parallel and diverging goals. These programs do not consist of the development of a single end product, such as the International Space Station (ISS), Galileo Program, or Joint Strike Fighter (JSF) described below, but are successive steps that result in the building of a suite of capabilities needed in order to move on to the next step of exploration. The following three examples will examine the differences between the LunAres program and previous international space cooperative efforts so as to select successful concepts and methods that could be integrated into the LunAres program.

3.3.1 International Space Station

The International Space Station (ISS) program is one of the largest international cooperation efforts ever attempted and has been a tremendous accomplishment in terms of design, integration, and operation through the involvement of 16 cooperating nations. The framework for cooperation among the ISS partners began with an Intergovernmental Agreement that allowed four Memoranda of Understanding (MOUs) (Cline, Finarelli, Gibbs & Pryke 2002, p.5). These MOUs have led to Implementing Arrangements which can be multilateral or bilateral agreements. The purpose of this international partnering framework was to "establish a long-term international cooperative framework among the partners, on the basis of genuine partnership, for detailed design, development, operation and utilization of a permanently inhabited civil International Space Station for peaceful purposes, in accordance with international law" (ISS Intergovernmental Agreement, Article 1). This agreement identifies the partners and their internal relationships, ownership of equipment and elements, use of Space Station assets, a high-level management structure, and other high-level structural issues. The agreement assigns the lead role for management and coordination to the USA, and generally describes the rights and obligations of each of the partners.

The most important lesson learned from the ISS partnering framework is that partners should be flexible in the developing a future exploration framework to allow adjustments to changing political situations and country needs (ISS Intergovernmental Agreement, Article 1).

Because no country can presently afford human exploration of the Moon and Mars on its own, it is undesirable to structure a one-country-led partnering framework. It is more advantageous to take the positive aspects of the ISS partnerships and incorporate them into a framework that will meet the larger and broader requirements of the LunAres program.

3.3.2 Galileo

Europe has embarked upon the Galileo program, an independent European satellite navigation system. It will be interoperable with other satellite global positioning systems such as the United States' Global Positioning System (GPS) and Russia's GLONASS. Galileo will provide a highly accurate, guaranteed global positioning service under civilian control. It will use a constellation of 30 satellites in medium orbit linked to a network of terrestrial command stations and centers required for the provision of services.

To date Galileo is the biggest and first Public-Private Partnership (PPP) attempted within the European Union. The reason that the Galileo founders (ESA/EU) decided to use this form of cooperation is that the program contains several opportunities for the commercial sector.

The program is divided into the following three parts: development, deployment, and commercialization. The development phase (2001-2006) is mainly conducted by ESA through ESA contracts, using the ESA rules such as the "fair return" principle, which provides geographical return of through contracts to businesses in contributing countries. The development phase is 50-50% funded by ESA and the EU. A special legal entity, called the Galileo Joint Undertaking (GJU) was established to manage the development phase. Both ESA and the EU transfer the money to the GJU, and the GJU is in charge of managing the EU 6th Framework Program Calls, and the ESA procurement, using the specific EU and ESA rules, respectively. Finally, the GJU will choose the consortium that will form a Public-Private Partnership to manage the deployment (2006-2007) and commercial operation (2008) phases. Since Galileo will also provide some public services such as frequency allocation, the EU, through a Galileo Authority, will regulate and supervise some of the activities of the Galileo PPP. The selection process for public procurement of the consortium is about to be completed. The consortium will be the owner of the service warrants and satellites.

The entire Galileo concept of financing, provision of services, and operation is based on the PPP concept where the initial investment is made by the public sector and the private sector (concessionaire) takes over the operational phase.

A private financing approach brings several positive aspects to both the private and public sectors. These positive aspects weigh against the drawbacks for the private sector due to the higher cost of money in the private sector compared to government financing and the longer time it takes to produce a contract.

Advantages for the private sector due to private financing are:

- Unlimited availability of capital in the private sector
- Balancing of early capital expenditure with long-term operational revenue and expenditure

The Galileo management structure and the PPP are good examples of how a supranational organisation (EU), an intergovernmental institution (ESA), and the private sector can work together to complete a mission. This type of cooperation could be used for a future exploration mission if some aspect of the mission or program ignites commercial interest.

3.3.3 Joint Strike Fighter

Although not a space program, the Joint Strike Fighter (JSF) program is described here because it has been suggested in the "Aldridge Commission" report as an alternative structure for international participation in the recently proposed US space exploration program (Aldridge et al 2004).

The goal of the JSF program is to produce an affordable, common family of strike fighter aircraft that is interoperable among the operating countries (Joint Strike Fighter Program Office 2004). The structure of the program is such that partners "buy in" to the program as a Level I, II or III partner, or as a Security Cooperation participant. There is no guarantee to any of the partners or participants of a geographical return for their investment with respect to domestic contracts. The USA prime integrator, Lockheed Martin, selects subcontractors (foreign and domestic) on the basis of technical merit and affordability, with the overarching goal of making the JSF an affordable aircraft. The arrangement between the partners is governed by Memoranda of Understanding between the US government and each of the partners.

Recently, however, Europe refused to participate in this type of cooperation, so it is not considered to be an option for the future. Europe will not participate in a cooperative venture where "fair return" can not be guaranteed, and where the integration leadership belongs to any single private company.

3.4 Program Management Proposals

The previous three examples can be categorized in two major groups: the public-led type of international cooperation (ISS), and the Public-Private Partnership (PPP) type (Galileo and JSF). The following sections examine these two types of cooperative ventures in order to find the most efficient structure for successful international cooperation and sustaining humans on the Moon and on Mars.

3.4.1 Public-Led Exploration Programs

To manage the LunAres program effectively, a highly integrated and cooperative international organization is needed. Two types of public-led organizational structures were evaluated and include an International Space Agency and a Virtual Program framework.

The International Space Station (ISS) experience illustrates that a more international management approach is required to effectively organize, integrate, and execute such a broad exploration program as sustaining humans on the Moon and on Mars. The first framework examined is an international space agency that would combine the efforts of all agencies into one body. One benefit of this concept is that it would be effective at executing the LunAres program and maintaining continuity in the development of the various robotic and human exploration technologies and missions. Such an agency would be able to integrate the best technology, manufacturing capabilities, and skills of member countries into one cohesive exploration program.

An international space agency could incorporate concepts from the European Space Agency (ESA) model that integrates certain space activities of member and cooperating countries through one coherent intergovernmental agency. The intergovernmental nature means that all the member states participate in the decision-making process of the agency through representatives to the decision-making bodies. The highest decision-making body of ESA is the Ministerial Council. The next levels are the Program Boards (PB) followed by the Committee (PC) level. Every ESA program has a Program Board containing the delegates from the participating states (participating states are those that participate in the given program). ESA has four permanent Committees (Science, Administrative, Financial, Industrial Policy) that act as horizontal committees over the ESA programs. ESA programs are divided into two parts: mandatory and optional programs. The mandatory programs (such as Science, Future Studies, and Education) are funded according to a percentage of the Gross National Products (GNPs) of the member states. Participation in the optional programs (via funding) is subject to national decision. All these elements are contained in the Program Declaration. ESA has special rules related to procurement, contractual, financial, and intellectual property rights matters.

Many questions exist about the criteria that would be used to evaluate a state's entrance to an international space agency. These questions include the deposit and allocation of finances, and how to accommodate individual state needs (political, financial, technological, social). As a consequence, the timing is not right for the creation of an international space agency in the vein of ESA because of issues of national security and technology transfer, funding, and political needs would prevent agreement. Further, nations' current lack of a multi-country integrated vision of an exploration program also contributes to making this a difficult task.

A more realistic scenario is to build up a more flexible system. The Working Group on "International Cooperation in the Context of a Space Exploration Vision" at the 7th AIAA Workshop on International Space Cooperation held May 3-6, 2004 suggested the concept of "A Virtual Program of Programs" for structuring international cooperation in the exploration program. This paper suggests integrating the various national exploration programs into a Virtual Program through the formation of an International Coordination Council (hereafter the "Council") for the purpose of facilitating coordination of the exploration program. This Virtual Program, "rather than trying to develop a cooperative concept for exploration as a whole, would be comprised of a coordinated set of individual activities, each activity employing the most sensible international arrangement as determined by the specific parties involved." Not all partners would be involved in all activities, and not all activities would necessarily be cooperative. This framework would incorporate the lessons learned from the ISS experience along with aspects that would be beneficial from the International Space Agency concept. The results of Council deliberations would guide progress and would promote sustainability and continuity of the Exploration Program in the face of changing commitments over the span of the program. The Council, though it would have no directing or funding authority, would have the ability to bring together the best aspects of space programs from around the world on a mission basis. This, then, allows countries to participate and finance in which they have interest, and allows them to develop new technologies of greatest interest to them.

3.4.2 Comparison of Public vs. PPP

The basic difference between the two cooperation types concerns the partners. The public-led program can be applied if there is no private interest in the program management or the services offered by a program implementation scheme. Where there are commercial opportunities in a mission, the involvement of private companies may be realistic.

From a legal point of view, the two types of activities differ in the formulating and implementing documents, because monetary commitment and transfer, liability, and management must be different.

At present, it cannot be determined whether a public-led, PPP type, or an efficient combination of the two would be preferable. However, the determination of the mission structure should not be made prior to identification of participating partners and mission objectives.

3.4.3 Public-Private Partnerships

Based on the experiences with Galileo and the Joint Strike Fighter, Public-Private Partnerships (PPP) can be used if the partners can identify clear commercial interest in a mission. This identification may come from the private sector itself, so it is not necessary that the space agencies supply the commercial plan—in fact, such an approach would likely fail. Agencies are responsible for the announcement and request of commercialisation plans, and then the private sector can submit their commercial plans.

If a commercial interest can be identified, and if the public sector and the program management find it acceptable, a component of a mission can be structured as a PPP, combining public and private funding in that mission part. This structure requires solid legal solutions, since public and private funding are incorporated, and both would require specific legal treatment.

3.5 Social Involvement & Commercial Applications

3.5.1 Gap Analysis

The total funding necessary to accomplish a human Mars mission will be several times larger than that of the US Apollo project, because the program has two destinations, the Moon and Mars, and travel between Earth and Mars takes on the order of 100 days, necessitating new space vehicles, new technology and new research efforts.

Current governmental budgets for the space sector are fixed in the USA, Europe, Russia, and Japan relative to each country's Gross Domestic Products (GDPs). In these countries, under current economic conditions, the growth rates of the GDPs are forecast to be around a few percentage points. (Krishnan 2004).

One possible solution for the gap between the demand side and the supply side is to extend the timeframe of a human landing on Mars. In the current US Space Exploration Vision, the timeframe for landing on Mars is 2030, with only a small increase to the budget planned for the first five years. Another solution is to fund the LunAres program through international cooperation. The USA, Europe, and Japan have started information exchanges to understand the possibilities and opportunities for future space exploration in the realm of international cooperation (Malik 2004); nevertheless, a large gap still exists.

Who can secure 30 years of governmental expenditure from taxes? How can ordinary people be engaged to such an extent as to provide active support to sustain a 30 year program? That these questions are not answered illustrates that there is no current cohesive solution to the issues surrounding an exploration program on this scale. The exploration program must be sustained over decades. Possible solutions for this gap are set forth below. The objective is to get active support from all members of society to support the expenditure of tax dollars for this effort.

3.5.2 Enabling Concepts

To secure long-term sustainability, the program must engage all members of society, including ordinary people, media companies, commercial companies (including those not operating in the space sector), communities, and societies.

The current outreach program, focusing on the promotion of science, should be maintained and enhanced. The recommendation is to provide students in school with educational tools that simulate lunar rovers and greenhouses on the Moon. These tools are commercially available. Such an educational program is necessary but not sufficient as a basis for large Moon and Mars ventures.

It is also recommended that a new concepts be introduced to provide all members of society with opportunities of direct participation in an exploration program. The following concept has been researched in Japan, and has been found to be a commercially viable opportunity in which society can contribute to an exploration program. The Moon/Mars programs will have a strong influence on human society as a gateway to civilization on the Moon, and a gateway to new understanding of human beings in the space age. To enable this fundamental concept, two missions classes are envisioned.

One is the "Civilization Mission," which would build monuments on the surface of the Moon bearing ordinary people's messages for civilization in space. This could attract media companies, ordinary commercial companies, and communities interested in future businesses on the Moon, for example, Lunar cities, Moon Mining, and Lunar Tourism.

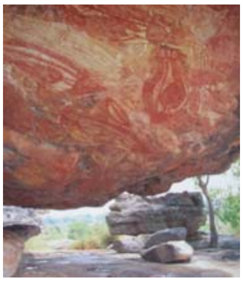
Another is "Humanity Mission," which would place ordinary people's messages on the surface of the Moon. This type of mission could also attract media companies, ordinary commercial companies, and communities interested in the promotion of their social responsibilities.

These missions could be implemented as piggyback payloads of lunar landers. Implementation plans are discussed in Chapter 5. The purpose of these missions is to obtain support from all members of society who have not previously been interested in space activities. Those who will participate in the LunAres program in this manner will remember the LunAres program whenever they see the Moon.

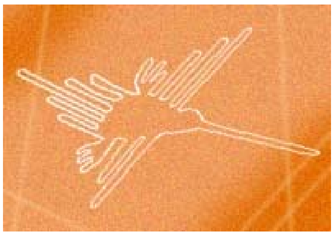
The next three sections expand on the outreach, civilization, and humanity mission concepts.

3.5.3 Civilization Missions

Rationales: Throughout the ages, humanity has left monuments of its collective imagining, ushering society toward the future, under the creedo "The Dream will come true". The oldest paintings, recently found in a cave at Twin Rivers, near Lusaka, Zambia, are believed to be between 350,000 and 400,000 years old. Since then, human beings have built many historical monuments, and these monuments opened new stages of civilizations. For example, aboriginal rock arts on Ubirr Rock (Figure 3-2a) and ground drawings in Peru (Figure 3-2b), were built, and encourage people to realize new vistas, as public symbols. Looking forward to the future, many civilization concepts on the Moon and Mars including settlements, hotels, cities, power plants and mining facilities, are studied and proposed. Building the first brick as a monument to civilization on the surface of the Moon and Mars will help to engage members of society. This value shall be used to assist the long-term sustainability of the LunAres programs.



a)



b)

Figure 3-2 Ancient Monuments

Enabling Concepts: Historical monuments, containing messages from all members in society, shall be constructed on the surface of the Moon and Mars through the LunAres program, to obtain active support from all members of society.

3.5.4 Humanity Missions

Rationales: Human beings have felt that space is a special place to think naturally about human society and the Earth and send messages of encouragement or warning toward human society. Arthur C. Clarke (1968) symbolized this special value of space as the "Monolith" in "Space Odyssey 2001." These values are also found in cosmonauts' and astronauts' messages transmitted from space. During the Cold War, Russian cosmonaut Yuri Gagarin sent the message, "The Earth is blue." This message can be interpreted to suggest that even the USSR could not make him speak communistic propaganda. Over conflicts in the Middle East, the first Saudi Arabian astronaut, Al Saud, sent this message: "The first day or so we all pointed to our countries, the third or fourth day we were pointing to our continents, by the fifth day, we were aware of only one Earth." These messages have strong effects on human society to develop the concept of star ship Earth. From 2001 to 2003, the Japanese Space Agency, NASDA (now JAXA), and the Japanese Space Industry, IHI Aerospace, demonstrated that ordinary people could also make this kind of message through compositions of Space Renshi, linked verse under the sponsorship of the Japanese media company FM Tokyo, and the commercial companies SOGO and SEIBU (department stores).

Enabling Concepts: Messages from humanity should be composed and installed on the surface of the Moon and transmitted to human society, to obtain active support from all members of society.

3.6 Conclusions

Providing a framework for cooperative space exploration is a complex subject. Various factors such as the legal structure, program and mission plans, and public participation and ownership must be considered and accommodated in order to successfully carry out space exploration efforts on a cooperative basis. Certain factors such as the political and economic motivations for engaging in space exploration change over time and cannot be prevented from changing. Therefore, the model selected for implementing space exploration among multiple entities, and the participants themselves, must recognize and accommodate such circumstances.

The legal regulation surrounding the exploration effort badly needs clarification. The Moon Treaty binds only the few states that have ratified it. It is a source of guidance only. In order to enable an exploration program, legal regulation concerning participants' obligations respecting exploration of celestial bodies must be proposed, clarified and ratified. It is suggested that the UN Convention on the Law of the Sea might be used at the basis for regulation of the use of the Moon and other celestial bodies. In addition, the new regulation must include provisions for dealing with liability and environmental issues related to exploration and conditions on the Moon or Mars. The regulatory scheme should also include provisions for enforcement.

The ISS, Galileo, and JSF programs provide concepts that may be applied to cooperative missions in the context of an exploration program. However, a strong framework must be provided at the exploration program level. The conclusion is that, because of the global and political climate surrounding the exploration efforts proposed by multiple countries, creation of an exploration forum is necessary for two primary reasons. First, to avoid duplication of effort and, second, to ensure that when participants commit funds toward exploration missions, such funds are committed with the knowledge of what is occurring in other countries and projects. Membership of this council should consist of countries interested in lunar and martian exploration. It is based on modifications to the Virtual Program concept that take advantage of high-level design concepts (such as evolutionary design and public-private partnerships). This exploration forum would coordinate the LunAres program, consisting of a coordinated set of individual activities employing the most sensible international arrangement as determined by the partners. The exploration forum would play no role in guiding the decisions, nor in the arrangement of individual partnering agreements for missions.

With respect to social and commercial issues, the analysis indicates a need for sustained long-term funding. The proposal is to provide social outreach programs to actively engage stakeholders (taxpayers) in the programs and projects. Such projects include, in addition to scientific activities, aspects related to the welfare of humanity.

The recommendations of this chapter are:

Recommendation 3-1: Revise or rewrite the Moon Treaty, possibly using the Part XI Agreement of the U.N. Convention on the Law of the Sea as a basis. Incorporate language that addresses liability and environmental concerns. Consider implications of the treaty for Mars exploration.

Recommendation 3-2: Enhance public outreach programs through educational simulations and social missions.

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Chapter 4

TECHNOLOGY AND SCIENCE ANALYSIS

Any sufficiently advanced technology is indistinguishable from magic.
Arthur C. Clarke

The purpose of this chapter is to identify key technical and scientific enabling elements for human exploration of Mars that are best evaluated on the Moon. In Section 4.1, a comparison of the lunar and martian environments is given. In Section 4.2, the main phases for future lunar and martian space human and robotic missions are identified and compared. In Section 4.3, enabling categories and those enabling elements for human and robotic lunar and martian space missions are identified. Finally, in Section 4.4, those enabling elements for a human Mars mission (HMM) suitable for evaluation on the Moon are identified, along with their rationale for selection.

4.1 Moon and Mars Environment Comparison

The following section gives an overview of the general properties of the Moon, Mars, and the Earth.

4.1.1 Size, Mass, Gravity, and Orbital Parameters

Table 4-1 gives a brief overview of the general properties of Mars, the Moon, and the Earth.

Table 4-1 General properties of Moon, Mars, and the Earth.

Property	Moon	Mars	Earth
Mass [kg]	0.073 $\times 10^{24}$	0.642 $\times 10^{24}$	5.970 $\times 10^{24}$
Diameter [km]	3475	6794	12104
Density [kg/m^3]	3340	3933	5515
Gravity [%g], [m/s^2]	16.5, 1.6	37.9, 3.7	100, 9.8
Escape velocity [km/s]	2.4	5.0	11.2
Length of Day [hours]	708.7 (29.53 days)	24.7	24.0
Solar flux [W/m^2]	1368	589	1368
Orbital eccentricity	0.055	0.094	0.017
Orbital inclination [deg]	5.1	1.9	0.0
Orbital period [days]	27.3 Around Earth	687.0 Around Sun	365.2 Around Sun
Perihelion [km]	0.363 $\times 10^6$	206.6 $\times 10^6$	147.1 $\times 10^6$
Aphelion [km]	0.406 $\times 10^6$	249.2 $\times 10^6$	152.1 $\times 10^6$
Axial tilt [deg]	6.7	25.2	23.5
Min distance from Earth [km]	0.363 $\times 10^6$	55.7 $\times 10^6$	0
Max distance from Earth [km]	0.406 $\times 10^6$	401.3 $\times 10^6$	0

(Williams 2003)

4.1.2 Structure & Composition

Topography

The martian landscape has a rich variety of different features such as valleys, knobs, sand dunes, mountains, gullies, craters and plains. Mars has the highest mountain in the Solar System, Olympus Mons, 25 km high. Valles Marineris is a grand valley that is 5000 km long with canyon floors that reach down to a depth of 7 km (Boyce 2002). The martian highlands are located in the southern hemisphere, 1-4 km above the datum[1]. The vast plains are located in the northern hemisphere, 1-2 km below the datum (Smith et al. 1999).

Like the highlands of Mars, the Moon is covered with craters. The craters found in the lunar highlands are up to 40-50 km in diameter. The ones on the nearside of the Moon have depths of 2-4 km below the datum. The far side of the Moon has a large basin depression 8 km below the average elevation. The lunar highlands are dominant on the far side (Smith et al. 1997). The lunar surface may possibly have lava tubes and rilles, which could aid in building lunar habitats (Doyle et al. 1978).

Polar Caps & Water

The seasonal polar caps of Mars reside above 80 degrees latitude and consist mainly of frozen CO_2 and frozen water (Richardson 2003). The northern cap is 1,000 km across while the

[1] On Earth, the normal reference datum is sea level. On other planets, such as the Moon or Mars, the datum is the average radius of the planet

southern cap is 350 km across (Boyce 2002). The northern cap is 2.7 km thick, while the southern cap is 3.1 km thick. These dimensions vary widely with seasons (Hartmann 2003, p. 401). The martian gullies are believed to be created by liquid aquifers that lie in the subsurface.

The Moon does not have any polar caps on the surface. The possible water on the Moon is frozen in the lunar soil and located at both poles. The amount of water appears to be larger at the North pole, buried 40 cm under the dry regolith. Ice could also be found at the surface in shadowed craters at the poles (Feldman 1998).

Surface Composition

The surface of Mars consists of basalts, hematite, and a variety of other minerals. Table 4-2 shows the composition of rocks and soil on the martian surface measured by Pathfinder at the site Ares Vallis. Minor trace elements such as chromium, manganese, nickel, and phosphorus can also be found in the martian regolith (Rieder et al. 1997). Due to the high oxidation state of the martian soil, hexavalent chromium might occur on the surface. These amounts are probably small but would be toxic to the crew. The presence of sulfur and chlorine could imply that the soil and airborne dust is acidic, which could also be dangerous both for equipment and crew (National Research Council 2002).

The dark areas on the Moon have been found to be Mare basalts, which are crystalline materials that are more abundant on the nearside. The lighter highland areas consist largely of anorthosites. The Moon is also rich in silicon and oxygen as seen in Table 4-2 (Heiken et al. 1991, p.261). Minor trace elements such as phosphorus, scandium, gallium, strontium, vanadium, chromium, and manganese can also be found on the lunar surface.

Table 4-2 Composition by Weight of Rocks and Soil of the Martian and Lunar Surfaces.

	Mars	**Moon**
Oxides	**Concentration (wt.%)**	**Concentration (wt.%)**
SiO_2	51.6	45.2
FeO (Fe_2O_3)	13.4 (20)	22.1
Al_2O_3	9.1	8.6
CaO	7.3	9.8
MgO	7.1	10.3
SO_3	5.3	none
Na_2O	2.0	0.31
TiO_2	1.1	2.4
K_2O	0.5	0.04
MnO	none	0.3
Cr_2O_3	none	0.68
Cl (chlorine)	0.7	none

Abrasion

Grains of minerals and rocks on the martian surface are usually 0.06-2 mm in size. These fragments can be carried to other places or rolled on the ground by the wind, making them rounder due to erosion (Phillips 1998). The average particle size on the Moon is 70 µm. The shape of the particles varies between spherical and extremely angular. Lunar dust is extremely abrasive since its components do not weather chemically or by erosion (Heiken et al. 1991, p.478).

4.1.3 Atmosphere & Climate

Atmospheric composition

The Apollo program showed that the space just above the lunar surface is not a total vacuum, but the Moon's atmosphere is essentially negligible for base design.

Mars has a much more abundant atmosphere. Table 4-3 compares the atmosphere of Mars with that of the Earth. The pressure on Earth is much larger (~160 times) than that on Mars.

Table 4-3 Comparison between Martian and Earth Atmospheres

Property	Mars	Earth
Atm. surface pressure [mbar]	6.36	1014
Atm. surface density [kg/m³]	0.02	1.217
Atm. scale height [km]	11.1	8.5
Major components [volume %]		
Carbon dioxide CO_2	95.32	0.036
Nitrogen N_2	2.7	78
Argon Ar	1.6	0.9
Oxygen O_2	0.13	21
Carbon monoxide CO	0.08	traces

The martian atmosphere is sparse, cold, and dry. Due to the low temperature and pressure, water merely sublimates to the gas state and back. During winter at the poles, the carbon dioxide in the atmosphere condenses and forms a dense ice layer, extending the polar caps, or precipitates as snow. However, geological evidence suggests that water once existed in liquid form.

Temperature, weather, and climate

The temperature profile on Mars, as shown in Table 4-4, is primarily influenced by the planet's orbital mechanics and its thin atmosphere.

Table 4-4 Comparison between Temperatures on the Moon, Mars, and Earth

Property	Moon	Mars	Earth
Average temperature [°C]	-23	-55	15
Maximum temperature [°C]	127	27	58
Minimum temperature [°C]	-147	-133	-89

(Kieffer 1992)

The most important orbital parameters are the obliquity of the planet (25 deg) which creates the seasons, and the eccentricity of its orbit (0.094), resulting in a variable distance from the Sun. Due to the eccentricity, the southern summer is shorter, but more intense, while the northern summer is longer but less intense.

Since the martian atmosphere is very thin, and there are no oceans on the planet, its thermal inertia is very small (i.e., surface temperatures change rapidly if the intensity of radiation changes). Therefore, on Mars, only two days are required to reach thermal equilibrium (Earth: 25 days) (Goodman 1997), resulting in a day-to-night temperature change of 80 °C.

Martian weather is heavily affected by dust storms caused by strong winds (up to 30 m/s). Apart from these huge dust storms, which can become completely global, minor "dust devils" of about 2 km width have been observed.

4.1.4 Space Environment

The space environment is harmful for both human beings and equipment because of galactic cosmic rays and solar particle events. Galactic cosmic rays have a significant cumulative effect whereas solar particle events and coronal mass ejections have mainly transient effects. Any mission must include a risk assessment and a balance of these two factors (Jokipii 1991).

On the surface of the Earth, humans are relatively protected from these space hazards because the magnetosphere carves out a hollow in the solar wind, creating an efficient natural protective shell. This natural protection exists in planets with a magnetic field but not on Mars or the Moon. Furthermore, an atmosphere provides additional protection against radiation and cosmic rays. However, the atmosphere is rarefied on Mars (less than 10 mbar) and negligible (~10^{-15} bar) on the Moon. As a result, martian atmospheric protection is only ~20 g/cm^2 of CO_2, and since there is no effective ozone layer, no special protection is provided from ultraviolet radiation (Simonsen and Nealy 1991).

The magnetosphere of the Earth is not symmetrical due to the distortion induced by the solar wind; it extends from <10 Earth radii in the compressed region to >50 Earth radii in the magnetotail. This situation creates a strong radiation environment asymmetry as the Moon periodically enters and leaves the magnetosphere.

Another important concern in the space environment is the presence of meteoroids and debris in the inner Solar System. Near Earth Objects (NEO) are significant threats for space travel. Furthermore, they represent a serious hazard not only for interplanetary space but also on the surface of the Moon and Mars, because atmospheric density is not high enough to prevent such objects from striking the surface. Several small meteoritic impacts have been reported, mainly on the Moon (Yanagisawa and Kisaichi 2002), but also on Mars (Christou and Beurle 1999).

4.2 Moon and Mars Mission Differences

4.2.1 Definition of the Mission Phases

Mission phases for a general human or robotic Mars mission are summarized in Table 4-5. These phases will be used in subsequent analyses conducted in this chapter and in Chapter 5. The mission phases are applicable to both human and robotic missions. For the robotic missions, Phases from IX to XIV may not be necessary, except for a sample return mission.

Table 4-5 General Phases for a Mars Mission

Phase	Description	Comments
I	Earth ground operations	Mission preparation, crew training
II	Launch to Earth orbit	Launch vehicle
III	Near-Earth operations	Rendezvous & docking, assembly in Low Earth Orbit (LEO), L points, orbital maneuvers
IV	Interplanetary travel	Trans- Lunar/Mars Injection, trajectory, transfer duration, propulsion, navigation, life support, communication
V	Moon/Mars orbit operations	Orbital insertion (impulsive, aerocapture, aerobraking), rendezvous & docking, orbital maneuvering
VI	Entry, descent	Deorbit, entry/descent vehicle, atmospheric deceleration
VII	Landing	Autonomous landing, shock absorption (retro rockets, airbag)
VIII	On-Planet operations (Moon or Mars)	Habitat, stay duration, mobility (rover, suits), power generation, *in situ* resource utilization, science, communication
IX	Ascent from Moon/Mars surface	Ascent vehicle (propulsion/propellant choice)
X	Moon/Mars orbit operations	Rendezvous & docking, orbit maneuvers
XI	Interplanetary travel to Earth	Trans-Earth injection, trajectory, transfer duration, propulsion, navigation, life support, communication
XII	Earth orbit operations	Orbit insertion, rendezvous & docking, orbit maneuvering
XIII	Entry, descent and landing on Earth	Entry capsule, recovery
XIV	Post-landing ground operations (Earth)	Planetary protection, quarantine, reusable vehicles

4.2.2 Differences between Moon and Mars Missions

Phase I – Earth Ground Operations

These operations are similar for both types of missions concerning spacecraft integration, launch site preparation, and mission support operations. Differences for human operations are crew selection and training. Also, due to the more isolated human mission to Mars (i.e., farther away from Earth with no possibility for rapid abort), a more robust psychological evaluation and training must be provided for the crew.

Phase II – Launch to Earth Orbit

The launch vehicle could be the same in each case since a heavy lift vehicle may be required for both missions. There is a possible variance in launch mass and the total number of launches. A Mars mission is likely to require much more mass in orbit at departure. The required launch capability is determined by the largest structure intended to be put on the planet's surface. If the launch capability is not available (due to cost or technology constraints), an assembly in near Earth orbit may be required (see Phase III).

Phase III – Near Earth Operations

Maneuvers, rendezvous, and docking may be needed for both types of missions. The final assembly of the interplanetary transfer vehicle for a mission to Mars is likely to be done in Earth orbit, since more equipment will be needed for the long-duration transfer. The mass at departure from low Earth orbit to the Moon is estimated to be about 100 tonnes for a 4-person crew in a short duration mission (Apollo type). The mass is estimated to be 550 tonnes for a lunar outpost and 750 tonnes for a mission to Mars (Craig 1989).

Phase IV – Interplanetary Travel

Due to the different destination and required trajectory, the amount of required ΔV is different. The required ΔV for a trans-lunar injection from a low Earth orbit is 3,050 m/s. For a trans-martian injection, it differs from 3,530 m/s (for a conjunction-class trajectory in 2018) to 13,053 m/s (for an opposition-class trajectory in 2011) (Larson 1999). For a whole roundtrip (Earth orbit – Moon/Mars – Earth orbit), the numbers are, on average, 8,120 m/s for a Moon mission and 11,200 m/s for a Mars mission.

The launch opportunity to get to Mars is available roughly every 26 months for a suitable trajectory. To the Moon, the opportunity arises almost every day. This interplanetary trajectory window influences the previous phases as well.

As used on the Apollo missions, a free return trajectory to travel to the Moon is preferred. There is no free return for a long-duration Mars mission. For a Moon mission, there could be several separate flights to the Moon with equipment and one quick trip with a small crew exploration vehicle. Due to the very short transfer duration, the relatively predictable nature of space weather, and the possibility of transfer conducted in the wake of the Earth's magnetosphere, there may be no need to provide specific radiation shielding, but it will be required for the long duration transfer to Mars.

A typical Moon mission has a translunar transfer that lasts for about 3 to 5 days. A Mars mission has an interplanetary travel duration from 120 days (fast-transit trajectory) to 330 days (opposition-class trajectory with Venus flyby or deep-space maneuver). This difference in duration has a direct effect on the resource consumables that have to be carried along. The main consequences, however, are the physiological and psychological effects. An interplanetary voyage that lasts for such a long time has never been directly studied before.

If relying upon solar power generation, the distance from the Sun is critical. For a Moon mission, the solar flux averages to that 1 AU (as on Earth orbit, i.e., 1368 W/m²). When traveling to Mars the solar flux decreases as $\sim 1/d^2$ to a value of 589 W/m² in the vicinity of Mars, where d is the distance between the spacecraft and the Sun.

The distance also influences the communication capability. For Mars missions, the communication system has to be more powerful or the data rate will decrease. For interplanetary communication, a larger antenna, more electrical power, and better pointing accuracy is needed.

Phase V – Moon/Mars Orbit Operations

There are differences due to the mass of the central body that affect orbital maneuvers. Also, the atmosphere at Mars, in contrast to the Moon, enables aerocapture and aerobraking, reducing propellant demands.

Phase VI – Entry, Descent

The atmosphere of Mars enables aerodynamic deceleration with entry capsules and parachutes. For a Moon descent retrorockets are needed.

Phase VII – Landing

Differences in the two mission types are due to geographic features, soil properties, and the presence of an atmosphere, wind, and dust storms in the case of Mars.

Phase VIII – On-Planet Operations

The ground operations of Moon and Mars missions differ due to large variances in the surface environment. This not only alters the design and operation of habitats, vehicles, and spacesuits but also the science and purpose of the mission.

Many aspects of the martian surface are unknown. For example, the presence of organics, acids, and other toxins (including carcinogens) are all possible in the martian soil and airborne dust. This will dictate higher levels of hardware ruggedness. In addition, tighter controls than during Moon missions will be necessary to minimize surface materials from entering the habitat, both for crew safety and equipment degradation issues.

Communication with Earth is more complex from the surface of Mars than from the Moon. This is due to the greater distance between Mars and the Earth and because Mars rotates with respect to the Earth, unlike the Moon which is tidally locked. Constant communications from Mars, therefore, require more complex infrastructure, such as orbiting relay elements. In addition, new communication protocols will need to be developed for responding to one-way transit signals that may take from 10 to 25 minutes to travel between the Earth and Mars, as compared with roughly 1.2 seconds from the Moon. These communications between Mars and Earth must be done in batches, rather than the more normal discourse possible between Earth and the Moon.

Solar generation is also affected by differences in diurnal duration (especially in equatorial regions) and dust storms. Solar power generation on Mars is much less capable than at lunar stations. Solar cells on Mars are protected from particulate radiation by the atmosphere sufficiently well such that normal lunar coverglass shielding is not required (Landis 1998).

Phase IX – Ascent from Moon/Mars Surface

Differences in the two mission types are due to gravity, atmospheric pressure, atmospheric friction, and mass of the vehicle.

Phase X - Moon/Mars Orbit Operations

This phase is the same as Phase V.

Phase XI - Interplanetary Travel to Earth

This phase is the same as Phase IV.

Phase XII - Earth Orbit Operations

The insertion into Earth orbit for both mission types is similar due to the similar magnitude of arrival velocity of about 11 to 12 km/s.

Phase XIII - Entry, Descent, and Landing on Earth

Both mission types are very similar. Differences could be due to possible mass and trajectory variations. Landing on the Earth's surface may be determined by different international agreements for both Moon and Mars missions, with consideration of facilities, mission involvement, and trajectory possibilities.

Phase XIV - Post Landing Ground Operations

There will be likely quarantine precautions for Mars astronauts and mission elements, as determined by international agreements.

4.2.3 Summary Table: Human Missions to Moon and Mars

Table 4-6 provides a summary comparison of the Moon and Mars environments for human exploration missions based on the previous analysis.

Table 4-6 Comparison Between Human Missions to the Moon and Mars.

Areas	Elements	Effect on mission to	
		Moon	Mars
Mission preparation	Complexity (technical, mission)	Same	Same
Crew training	Mission duration Distance from Earth	Short transfer No special training	Long transfer Psychological testing and training Emergency medical training
Launch vehicle	Largest structure to put on surface	Same	Same
Rendezvous & Docking	Total mass in LEO at departure	Up to 550 tonnes	Up to 750 tonnes
Assembly in space	Total mass in LEO at departure and need of integrated transfer vehicle	Can split up in several single transfers	Need more mass to sustain long duration transfer
Orbit maneuvers	Gravitation	Less	More
Trans- Lunar/Mars Injection	Needed ΔV	3050 m/s (Apollo type)	5600 m/s (for minimal energy Hohmann)
Trajectory	Orbit mechanics	Free return possible	Trade off between transfer duration and propellant mass
Transfer duration	Distance	3 – 5 days	150 – 300 days
Life support	Mission duration Possibility to resupply	Same Is possible (fast response)	Same No
Communication	Distance	Low gain ~2.5 s round trip time	High gain, power, accuracy ~20 up to 50 min round trip time
Orbit insertion	ΔV required Other possibilities	920 m/s (Larson 1999)	2000 – 2800 m/s (Larson 1999) Aerocapture
Entry/Descent vehicle	Atmosphere	No atmosphere requires greater impulsive maneuvers	Entry capsule, parachute
Habitat	Stay duration Radiation Environment	Same Sometimes shielded from Earth's magnetosphere	Same Interplanetary space, some shielding from atmosphere
Mobility	Soil properties Pressure Gravity	Same Same 1/6 g	Same Same 3/8 g

Areas	Elements	Effect on mission to	
		Moon	Mars
Power generation	Solar Flux Day/Night cycle	1368 W/m² 27.3 days (except at poles)	589 W/m² 24.66 hours
In-situ resource utilization	Soil composition Atmosphere Water	Yes No atmosphere Maybe	Yes Yes Maybe
Earth entry capsule and recovery	Arrival velocity	11 km/s (direct) 7.6 km/s (from LEO)	12.3 km/s (direct) 7.6 km/s (from LEO)
Quarantine	Alien lifeforms	Not necessary	Maybe yes

(Larson 1999; Landis 1998)

4.3 Mars Mission Enabling Elements

This section identifies those enabling elements required for a human or robotic mission to Mars. The definition of an enabling element is a technology or concept necessary to achieve a human mission to Mars.

4.3.1 Description of the Main Categories

Communication

During interplanetary travel, communication between Earth and Mars needs to be maintained at all times. One problem arises when Mars is in conjunction with the Sun. Relay satellites at one of the Earth-Sun Lagrange points or martian orbit (Thangavelu 2000) could overcome this situation. Transmission at higher frequencies is also a possible option (Morabito 2001). Both these technologies need further investigation. By setting the lunar facilities themselves on the Moon beyond Earth line of sight, useful experience can be gained in handling indirect communication methods.

Major improvements have been made since the first probe was sent on an interplanetary trajectory. Systems, such as the Deep Space Network, used by NASA, will be key components for future human missions. Robotic missions provide an efficient and safe way of further developing and improving communication technologies. Ground communication on Mars, as well as Earth-Mars communication, are critical because the crew will explore and perform activities away from their main habitat. Local infrastructures on the planet and in Mars orbit need to be implemented together with data handling, network, and sensor technologies (ESA 2001). For more effective communication, high data rate communication could be developed using optical links.

Mars communication technologies can be tested on the Moon, as they are an integral part of every mission. Other critical phases such as aerobraking, entry, and landing also affect communication. Laboratory testing and simulations would be important to insure that these systems can survive in the martian environment.

Crew Comfort and Welfare

Privacy is a key consideration for maintaining a healthy crew. A mission to Mars could take more than six months, and in a cramped space, it would be essential that the astronauts have their own small quarters where they could have privacy.

Equally important are such simple things as staying in touch with family and friends back on Earth. Although the International Space Station (ISS) and Space Shuttle crews have regular broadcasts back to the Earth, the distance between the spacecraft and Earth during a mission to Mars and the resulting time delay experienced may not make regular contact practical; pre-recorded messages and broadcasts can be transmitted.

There could also be an onboard database loaded with music, movies, or other hobby material for the astronauts to enjoy while enduring the long space flight.

The crew should also have different kinds of physical countermeasures to strengthen their muscles and bones. Many different countermeasures are being evaluated and tested on the ISS which could be adapted for long duration space flights.

Crew Rescue, Safety, and Survivability

For all human spaceflights, the main concern is to keep the crew safe during every phase of the mission. The actual requirement on the reliability for crew survival is 0.9999 (Kelly 1999).

For near-Earth or lunar orbit phases, available technology such as crew escape towers, crew return vehicles, and space station vehicles can be used. For a HMM, many options are not readily available, because of orbital mechanics, so redundancy is a key aspect in the design of the mission. Extra supplies can be shipped before the arrival of the crew, with a crew return vehicle, similar to the Mars Direct approach (Zubrin & Wagner 1996). A space station in Mars orbit could provide an escape option for the crew. The martian moons could also be used as natural space stations and can also serve as escape destinations from the martian surface, if needed.

A structure built on Mars can be used as a safe haven location. Other options include taking advantage of the martian surface features such as regolith or caves to provide a safe haven (Hoffman & Kaplan 1997). To test these options, development of training and construction methods in the lunar environment are of prime importance.

Although automatic piloting will be an important aspect of a HMM, human piloting skills could be necessary in case of an emergency.

During a Mars mission, return options are not possible when the crew is on an interplanetary trajectory. Therefore, emergency and medical training will be even more important.

Environmental Shielding

As an analogy to the natural protection we have on Earth from the magnetosphere, magnetic/electrostatic shields have been proposed as a way to protect the spacecraft. The magnetoelectric field can be created by a set of three charged spheres, one positive in between two negative ones (Malik 2004). It is possible to protect the spacecraft against a solar particle event, but demonstration and investigation still need to be done for effective protection against galactic cosmic rays (Townsend 1992). We also need to better understand the effects of magnetic and electric fields on humans. This option is not suitable for ground operations on Mars, as the electrostatic field would react with the martian atmosphere.

Another efficient method of shielding against radiation is by using specific types of materials in the design of vehicles. However, it is important to look at the scattering effect of particles striking the spacecraft in the choice of material. Secondary radiation can be even more dangerous for life than primary radiation. For this reason, heavy materials such as aluminum cannot be considered. The materials chosen need to have a high hydrogen component. If liquid hydrogen is needed for propulsion, it is already part of the mission and therefore can be used as a shielding method (Malik 2004). The geometry of the vehicle would then need to be designed to protect the crew from the hydrogen. Methods in handling liquid hydrogen also need to be further investigated in order for the crew to be safe at all times.

On the surface of Mars, the atmosphere provides partial protection against radiation but shielding is still necessary. Construction materials, either imported or *in situ*, such as composite materials with a high hydrogen component, or regolith, are promising technologies, both for radiation and micrometeoroid shielding. Studies and tests have being performed using polyethylene/carbon fiber composite and Kevlar in the design of spacesuits, construction of habitats, and inflatable structures (Malik 2004; Marcy 2004). The disadvantage is the extra weight and cost if construction materials are brought from Earth. However, this can be overcome by using *in situ* resources in the fabrication of such materials. The process of making bricks or cement out of regolith has already been tested. Shielding could also be made from regolith only. A thickness of about five meters is estimated to provide enough shielding (Aulesa 2000). Handling, drilling, and covering methods would need to be tested and developed. Land features such as caves or lava tubes (Billings 2000), if they exist, could be effective natural shields.

Finally, shielding using food and water has already been used in the ISS against radiation for a human stay in space.

Extravehicular Activity

A human mission to Mars will require extravehicular activity (EVA) to perform effective exploration, technical, and scientific duties outside the main habitat. An EVA suit and life support system for sustained human Mars exploration will need to be greatly advanced over anything currently in use (Harris 2001). Unlike previous U.S. and Russian spacesuits designed for the Moon or microgravity, a number of significant new factors must be considered.

Overall capability for performing EVAs should be improved. For a martian encounter, an EVA capability will not only be required for the surface of Mars, but also for the cruise to and from Mars. With a total mission duration on the order of 1,000 days, the EVA system will require the use of robust and efficient technologies for numerous cycles. Consumables will be severely limited due to mass considerations, so regenerative systems must be developed. Advanced concepts, such as venting metal hybrid/hollow fiber membranes, and CO_2 and water vapor scrubbers may need to be employed, as they have low overboard loss of oxygen, no moving parts, and a long operating life (Harris 2001). This EVA capability will also require the use of a greatly improved data and communication system to respond to both planned and unplanned tasks. Such a system could be comprised of a computer network, transceivers, cameras, helmet-mounted displays, navigation equipment, and databases. Efficient airlock depressurization designs (both in space and terrestrially) will be required while collecting airlock gases for re-use.

Surface operations on Mars will require a flexible, reliable EVA system for a long-term stay of approximately 500 days and will require that the EVA spacesuit be resistant to soil, rock abrasion, tearing, and repeated use by astronauts. For effective scientific and technical activity, advances must be made in improving the flexibility of the suit (walking, bending, and gloved-hand manipulation). This will require advances in gas-pressurization techniques, mechanical counter pressure garments, or mechanical actuator systems (Clapp 1984, Sorenson 1997). Furthermore, “zero pre-breathe” spacesuit techniques must be developed in order to reduce the EVA timeline overhead for frequent EVAs (Harris 2001). Decontamination due to exposure to toxic chemicals (either from environment or by accident) will be required along with the requirement for soil/regolith containment from being introduced into the habitable environment. It may also be necessary to minimize human and biological contamination of the surface, driving a reduction in suit leakage rates and life support system operation (Harris 2001). Important consideration must be given for a light-weight design for the suit, life support system, and tools.

Finally, a number of improved and new external interfaces must also be considered. New EVA-friendly tools and equipment will need to be identified and provided. EVA strategies and ergonomic solutions will need to be developed in order to maximize rover use and end-effectors (e.g., rock collection without EVA) while minimizing suit usage for EVA exploration. Unlike previous programs, pressurized rovers will be required and will include a habitat, airlocks, decontamination station, glovebox, end-effectors/robotic augmentation, chassis, propulsion, docking mechanism (to primary habitat), and environment control & life support system (ECLSS).

Ground Facilities (on Earth)

Considerable ground infrastructure is required to enable a HMM. Such ground facilities are required for preparation and support throughout all phases of the mission. In the first instance, the flight crew must be thoroughly trained in many disciplines to prepare for the mission. This will occur at many locations to enable focused training and practice on such aspects as flight hardware, isolation issues, space medicine, and translation/surface procedures. Mission control will then be needed for management and communication with the spacecraft and crew. For these communications, a ground-based network of deep space antennas will be required to provide near-constant contact throughout the Earth's rotation. A data processing facility will be required to handle received data. Several other facilities are required for mission support. A surface analog must be created and populated with identical equipment to that used on the mission to replicate and troubleshoot hardware and operational problems. The surface analog would be complemented by virtual reality computing, a neutral buoyancy laboratory, and 3/8g parabolic flight simulator. The greatest challenge for the Mars analog is producing extended periods of 3/8g to fully replicate the surface conditions. This may be accomplished by a centrifuge in Earth orbit or perhaps on the lunar surface.

Guidance, Navigation, and Control

The Guidance, Navigation, and Control system (GNC) is important in all phases of the mission. Mars exploration will not be possible without the ability to perform surface navigation and localization. As similar exploration activities will take place on the Moon, useful experience can be gathered in this area.

For planetary operations, automated rendezvous is one of the key technologies of a HMM. In particular, technology improvement is needed for rendezvous in non-circular orbits, relative navigation for long and medium range rendezvous, and GNC sensors (ESA 2001). Lunar orbit activities could provide an opportunity to test these technologies.

Entry and precision landing technologies differ for robotic and human missions. Areas such as hypersonic and atmospheric flight technologies and aerocapture guidance and control need to be further investigated to ensure safety during the entry phase at Mars. In terms of landing, hazard-avoidance, autonomous and vision-based piloting and navigation, precision landing, and abort strategies all must be tested (ESA 2001). Lunar testing is possible, especially for landing methods. As the Moon has no atmosphere, some technologies involving entry and atmospheric dynamics can be best tested in Earth's atmosphere and with simulations.

Two of the most important stages using GNC are descent and landing. The assessment of these procedures must include all the requirements for a soft and safe landing, namely atmospheric hazard avoidance and proper site identification. The recommended solution is the utilization of an optimized 3D imaging LIDAR system, including heritage from laser altimetry. The accuracy and spatial resolution of this system matches the requirements for a safe landing. So far, the identified solutions, namely using radar, do not have enough accuracy and cannot be used close to the surface. This new solution can be used not only to identify surface features and ground hazards with large accuracy but also to monitor atmospheric hazards, such as dust storms and dust devils. Furthermore, this concept is suitable to operate close to the surface for altitude less than one meter. This technology can be partially tested on the Moon despite the lack of atmosphere prevents fully validation of the system. Thus, the validation must best assured with lunar and ground based tests.

Integrated Vehicle Health Management

In order to guarantee maximum crew and vehicle safety, and to reduce systems health processing time, human transport vehicles to Mars will need an advanced Integrated Vehicle

Health Management (IVHM) system. Autonomous spaceflight and the ability of real-time decision making for the crew is a prerequisite for a long-duration HMM. On a Mars mission there is a ~40-minute time delay to send and receive a message. Therefore, future vehicles will require more autonomous capabilities. The necessary technology for that could be ready around 2010 (Guerra 2003).

Mars Habitat

The crew will live, work, and spend most of their time in the Mars habitat. For a long-term mission, aspects such as human perception, psychology, and socio-cultural factors will become as important as engineering and safety aspects of habitat design.

Some enabling technologies for the habitat can be derived from or based on existing systems such as the ISS. For example, airlock tunnels (equipment lock, crew lock and EVA dust-off porch) and pressurization systems (joints) have been used for a long time for space station hardware. However, the feasibility of more advanced techniques is still to be proved. The systems or technologies that fit within this category are modular and mobile (wheeled) habitats that would be assembled on the surface, microgravity and/or martian gravity inflatable structures (greenhouses, safety area around the habitat), or advanced construction materials. On-surface habitat module assembly is required in some mission scenarios to allow base expansion. Whether the habitat will be used for the outbound and return trip by the crew is an important issue, as it must be designed to be both microgravity and 3/8g gravity compatible. So far, many studies have been carried out without hardware testing (The Mars Society 2001). The Mars analog sites mainly involved architecture, operations, and human factors, regardless of technology. A huge effort needs to be undertaken to improve knowledge for this crucial concept.

In Situ Resource Utilization

Currently, no technology is available for utilizing any form of extraterrestrial resources, except for solar photovoltaics. Martian resource utilization shares some common elements with lunar resource utilization: need for resource localization and determination of extractability, need for a resource cache to store products, propellant production is the same, plant growth experiments in regolith are operationally similar, regolith preprocessing is operationally similar, water extraction from lunar and martian soil are analogous processes, and *in situ* resource utilization (ISRU) plant for regolith processing is comparable in both Moon-based plants and Mars-based plants, especially for water extraction, but also for processing the regolith itself.

Several processes can be tried out on the Moon. McKay et al. (1992) and Mendell (1985) give extensive lists of processes and techniques that could be tested for the extraction of lunar resources. Haskin (1985) takes a pragmatic approach and suggests minimal processing to keep the cost low. The list shown in table 4-7 provides brief descriptions of common ISRU processes and the materials produced. The "site" heading is intended to emphasize the primary process location. Sites in parentheses indicate that the process is adaptable to other environments; others are not site specific.

Table 4-7 *In Situ* Resource Utilization Processes of Lunar and Martian Regoliths

	Description	Products	Site	Reference
Unprocessed Regolith				
Construction, Construction materials	road construction, soil grading for construction prep, aggregate material	rock flour', glassy agglutinates, clay sized to boulder-sized materials,	Moon (Mars)	Haskin 1985, McKay 1992
Passive Shielding	material for burying facilities or base compartments as protection from heat and radiation	unprocessed or crushed regolith	Mars or Moon	Haskin 1985, McKay 1992
Simple Processes				
Water Extraction	gentle heating used to liberate frozen water in liquid or gaseous state	water	Mars or Moon	Guterl 1998, Haskin 1985, McKay 1992, Mendell 1985
Magnetic Extraction	passive collection of magnetic elements and conglomerates using (magnetic/electromagnetic) soil probes	iron, nickel, cobalt, magnetic agglutinates	Moon (Mars)	Haskin 1985
Electrostatic Processing	separation or fractionation of monomineralic soil components	purified anorthosites, dunites, ilmenites	Moon (Mars)	Haskin 1985
Melting	high temperature liquification unprocessed regolith	casts, blocks, drawn materials for construction	Moon (Mars)	Guterl 1998, Haskin 1985
Helium-3 Collection	gentle heating used to liberate trapped gases, primarily helium-3	helium-3 for nuclear fusion reactions	Moon	Guterl 1998
Advanced Processes				
Thermal Release of Gases	controlled heating of regolith to liberate trapped gases	hydrogen, helium (helium-3), nitrogen, carbon (50 - 100 ppm), lower levels of sulfur, chlorine, argon, water, hydrogen sulfide, carbon monoxide, carbon dioxide, ammonia, hydrogen cyanide	Moon (Mars)	Guterl 1998, Haskin 1985, Sanders et al. 2001
Hydrogen Reduction of Ilmenites	hydrogen produced from the electrolysis of water used to reduce metal oxides of ilmenites	oxygen, pure metals, mixed oxides	Moon (Mars)	Haskin 1985, McKay 1992
Carbo Thermal Reduction	carbonaceous wastes used to reduce metal oxides of ilmenites in smelting system	oxygen, pure metals, mixed oxides	Moon (Mars)	Culter and Krag 1985, Le Van et al. 2002
Carbonyl Processing	high pressure carbon dioxide with hydrogen sulfide catalyst used to liberate pure metals	highly pure iron, potential use for cobalt and other heavy metals, pure silicates as byproducts	Moon (Mars)	Haskin 1985, McKay 1992
Electrolysis of Water	electrical separation of oxygen and hydrogen from water	oxygen and hydrogen	Moon/Mars	Guterl 1998, Haskin 1985
Electrolysis of Molten Silicate	electrical separation of oxygen from metal silicates	oxygen, iron alloys with magnesium, chromium. titanium, silicon	Moon (Mars)	Haskin 1985
Dual Electrolysis	combined electrolysis of water and carbon dioxide	oxygen (free of water vapor)	Moon/Mars	Finn et al. 2001, Finn et al. 2000
Destructive Distillation	high temperature separation of silicates and oxides	calcium aluminate, calcium oxide, alkaline oxides, gases	Moon (Mars)	Haskin 1985
Carbon Dioxide Acquisition Membrane	collection of carbon dioxide from atmospheres, Martian atm., crew compartments, other regolithic extraction processes	carbon dioxide (with argon and nitrogen byproducts)	Mars (Moon)	Mason 2004, Finn et al. 2000
Reverse Water Gas Shift Process	reduction of carbon dioxide to produce methanol	methanol, water and oxygen	Mars (Moon)	Whitlow and Parish 2003
Micro-chemical/Thermal System	processing of carbon dioxide to generate methane	oxygen and methane	Mars (Moon)	Sanders et al. 2001
Benzene Production from Carbon Dioxide	reduction of carbon dioxide to produce methane, further processing of methane to produce aromatics	methane, benzene, aromatics for fuel and chemical syntheses	Mars (Moon)	Muscatello et al. 2004

Life Support Systems

A long-duration mission to Mars requires a closed loop life support system since precious resources such as oxygen, carbon dioxide, water, and nutrients must be recycled. The tasks of a life support system are air management, water management, waste management, food production and storage, and crew safety (Eckart 1996). Air, water, and waste management can be accomplished by the use of physico-chemical life support systems. For food production, bio-regenerative systems are required. There are many on-going studies on the performance of plants in different environments, including reduced and microgravity, low atmospheric pressure, low temperature, and low light level. There is a trend towards research on low-pressure Mars greenhouses as a reduction of the pressure difference between the inside and the outside of the greenhouse leads to structural mass savings and reduced leakage (Fowler et al. 2000).

The disadvantage of operating a greenhouse on Mars is that the break-even point of *in situ* produced food compared to food resupplied from Earth is generally in the order of a few years. Thus, it is not feasible to rely on 100% *in situ* produced food for a Mars mission with a surface stay of only 1.5 years. Small plant growth chambers have been studied extensively on Earth and on the ISS. An on-board plant growth chamber producing fresh vegetables would offer significant psychological benefits to the crew, as the fresh crop enhances the diet of mostly freeze-dried food. This concept is often called a "salad machine", as the crops considered for the on-board plant growth chamber are comprised of vegetables that require almost no processing such as lettuce, onion, and tomato (Kliss et al. 2000). The on-board salad machine would produce vegetables during the complete Mars mission duration of 2.5 years. The operation of this salad machine should be tested on a long duration Moon mission.

Medical Issues and Human Physiological Research

Isolation drives a number of enabling elements. Unlike in LEO, there is no option for terrestrial evacuation in the event of a medical emergency during a HMM. Also, due to the communications delay, flight surgeon advice and remote telemedicine procedures will have limited applicability (Watanabe 2000). There must therefore be a totally self-sufficient medical system (Kozlovskaya & Egorov 2003), including: a physician with broad capabilities, diagnostic and therapeutic equipment, and sufficient supplies for managing all levels of medical events from ambulatory to critical care; training systems to maintain medical skills (Doerr 2003); and back-ups, such as a second trained crewmember and a computerized expert system (Gardner et al. 1989). Procedures must be developed specifically for total isolation and will be distinct from those appropriate for the ISS. These include how to manage crew death, sexual issues (Sturgeon 1992) including contraception and pregnancy (Sullivan 1996), and critical care allocation (e.g., how many crew to ventilate and for how long). Pre-flight prophylactic measures might be necessary such as appendectomy, cholecystectomy (Ball & Evans 2001), or sterilization. The crew must not have any chronic medical conditions.

Galactic cosmic rays produce a chronic radiation exposure, both in transit and on the martian surface, and must be shielded so that the biological dose received over the entire mission does not exceed an agreed safe limit. Career dose limits for NASA astronauts are based on an increased risk of fatal cancer of 3% (Cucinotta et al. 2001) and may be an acceptable standard to adopt for a Mars mission. The limit is higher with age; thus, it may be preferable to select an older crew. Solar particle events can result in acute exposure with acute radiation syndromes. The spacecraft must protect the crew from this massive exposure, possibly by the use of a heavily shielded storm shelter (Townsend et al. 1992). Other crucial aspects of radiation management are dose monitoring and radiation treatment.

The nature of physiological deterioration (e.g., bone demineralization, cardiovascular deconditioning, wound healing) in 1/6g and 3/8g is largely unknown. Research must be conducted to both investigate this deterioration and to produce effective countermeasures that must then be implemented during the surface stay. There is already much experience in LEO with zero-g countermeasures; however, improved countermeasures should be developed for the Earth-Mars transit. Certain diagnostic and treatment procedures are affected by reduced gravity such as ultrasound (Melton et al. 2001), cardiopulmonary resuscitation (Sarkar 2004), blood containment in surgery (Kirkpatrick et al. 1997), and fracture management; alternatives must be developed for both 0g and 3/8g.

Operations

Experience in operations can be gained in all activities associated with a mission to another planetary body. Optimization along a learning curve is a well-known phenomenon when dealing with novel complex systems or processes. Improvements over the course of the Apollo missions may serve as an example (Jones 2003). When undertaking a venture as challenging as a HMM, it is desirable to anticipate as much as possible of this learning process in a lower risk, lower cost environment. Lunar missions provide such an environment. Operational experience will, in large part, be inherent to lunar missions, but can also be augmented by taking additional measures to simulate aspects of martian operations not required in a traditional lunar mission. Examples include ground operations, extraterrestrial construction, housekeeping, planetary science, running a lunar mission on a martian day cycle, introducing an artificial time delay into radio communication with Earth, or implementing planetary protection and decontamination procedures.

Determining the required duration of certain operations, what strain they place on the crew, and how they are best performed can help develop optimal procedures and realistic, sustainable work schedules. Lunar missions could provide the opportunity to rehearse and optimize strategies for handling various contingencies both in staged and real situations. Extended lunar operations will also help in determining how to maintain crew qualification for tasks not performed regularly, how to qualify crewmembers for unforeseen tasks, and what pre-flight skills training crews require. This knowledge is vital prior to a mission as long and versatile as a HMM being performed by a small crew. Concepts to be developed from this could be refresher training schedules, simulation tools, and tele/e-learning methods. Performing both robotic and human tasks routinely will yield information about how work can best be distributed among robots and humans and how they can perform most efficiently together.

The only experience in traveling to and operating on the surface of another planetary body available today is from the Apollo missions. Although these missions are well documented, some information on operations is lost or outdated. Also, personnel actively involved in the program will not be active in a future human lunar or martian mission, so much of the knowledge available is theoretical. Moreover, the nature of Apollo excludes any operational experience unique to extended missions. The LEO operations part of a HMM can draw on substantial experience in operating and assembling complex vehicles gained from Skylab, Salyut, Mir and ISS. This knowledge is available and will likely be expanded through the ISS program.

Planetary Protection

Planetary protection is mandatory and refers to the practice of protecting Solar System bodies from contamination by Earth life and protecting Earth from possible life forms that may be returned from other Solar System bodies. Technical aspects of planetary protection are developed internationally through deliberations by the Committee on Space Research (COSPAR). Each mission is categorized (from I to V, see Table 4-8), according to the type of encounter it will have (e.g., flyby, orbiter, or lander) and its destination (e.g., a planet, Moon, comet, or asteroid).

If the target body has the potential to provide clues about life or prebiotic chemical evolution, a spacecraft going there must meet a higher level of cleanliness, and some operating restrictions will be imposed. Spacecraft going to target bodies with the potential to support Earth life must undergo stringent cleaning and sterilization processes and greater operating restrictions (Rummel 2004). For example, a mission to the Moon is classified as Category I and does not require planetary protection whereas a Mars sample return mission is classified as the highest Category V. For a human mission to Mars, the requirements will be more stringent and perhaps more difficult to fulfill, as astronauts will be involved. Planetary protection requirements need to be taken into account at the beginning of a mission design.

Table 4-8 Planetary Protection Categories

Category	Mission Type	Planetary Body
I	Flyby, Orbiter, Lander	Venus; Moon; Undifferentiated, metamorphosed asteroids; others TBD
II	Flyby, Orbiter, Lander	Comets; Carbonaceous Chondrite Asteroids; Jupiter; Saturn; Uranus; Neptune; Pluto/Charon; Kuiper-Belt Objects; others TBD
III	Flyby, Orbiter	Mars; Europa; others TBD
IV	Lander	Mars; Europa; others TBD
V	Earth Return	"Restricted Earth return": Mars; Europa; others TBD; "Unrestricted Earth return": Moon; others TBD

Power Generation and Storage

Human Mars exploration in a scenario requiring more than 50kW of electrical power is difficult to accomplish with the photovoltaic technology developed for Earth orbit and terrestrial applications. These systems suffer from low efficiency and attenuation of sunlight on the martian surface owing to dust. The Sun's energy decreases according to an inverse square law, such that if the distance from the Sun is doubled, the amount of available energy decreases by a factor of four. Mars lies, on average, 1.5 times further from the Sun than Earth, reducing the average solar flux available to a spacecraft in Mars orbit to ~45% of that in Earth orbit. Furthermore, Mars's orbit is more eccentric than the Earth's, so the solar flux varies considerably according to the time of year. On descending to the surface of Mars, the available solar energy must penetrate Mars's thin atmosphere, which is loaded with fine dust particles. It can be assumed that a best case year-round average of 300W/m^2 is available on the Mars surface, or 22% of that in Earth orbit. In the event of a global martian dust storm, this would diminish to 100W/m^2 (7.5% Earth orbit) or even less, depending on the severity and duration of the storm. This would imply a very large area for a solar photovoltaic array and very low reliability.

Extensive nuclear reactor technology development, including flight tests of a number of different reactor designs, power conversion, and waste heat rejection technologies has been carried out in numerous countries since the early 1950s. This technology fits well to the specific requirements of a HMM, and it is available to enable a human mission.

Propulsion

Nuclear propulsion always comes to the foreground as a power and propulsion source for a HMM. One system that holds promise is a concept for a Bimodal Nuclear Thermal Rocket (BNTR), a mission design that uses nuclear reactors to produce thrust and electricity for a human mission to Mars. Nuclear power can potentially get human missions to the Moon, Mars, and elsewhere in the Solar System faster, safer, and cheaper than any other alternative. It is the next evolutionary step after chemical propulsion, and it has twice the specific impulse of the chemical rockets that we currently use (Marcus 2001). The advantage of Nuclear Thermal Propulsion (NTP) is its high specific impulse obtained at the cost of lower propellant mass ratio. NTP can provide a greater specific impulse (Isp 925s) and reduce the trip time for HMMs to about 200 days. In the 1960s and 1970s, the NERVA program investigated the solid-core solution (uranium-zirconium carbide fuel). Current NASA research (Prometheus) focuses on Nuclear Electric Propulsion (NEP) and power conversion technology, high temperature fuels, and advanced thermal propulsion, as well as nuclear reactor test facility and support equipment (Newhouse 2003).

Potential improvement in terms of specific impulse for chemical propulsion is relatively limited. To enhance performance of existing stages, research on advanced chemical fuels will be needed (e.g., high performance monopropellant or recombination energy fuels like metallic hydrogen).

Because of its high ΔV capability, electric propulsion (electrothermal, electrostatic and electromagnetic propulsion) and thrusters (Hall effect thrusters or gridded ion engines) could be used for precursor interplanetary exploration. Very high power applications like Magneto Plasma Dynamic thruster in combination with a nuclear reactor (Nuclear Electric Propulsion) could be candidates for HMMs (ESA 2001).

Psycho-Social Factors

Key drivers for enabling elements in the psycho-social area are total isolation (with no chance of rescue, unlike in LEO, or on the Earth), confinement, and altered gravity (0g or 3/8g). These factors may all affect both individuals and the group as a whole. Little is known about large group interactions under reduced gravity (Bishop 2004); thus, research must be conducted to examine this, so that appropriate selection, training, hierarchy structures and countermeasures can be implemented. Conflict resolution, crisis management strategies, and provision of adequate privacy and personal space are also elements that must be developed for an isolated and confined crew. The optimal crew work schedule and workload must be determined and may be different in 0g and 3/8g.

Psychological countermeasures and treatments must be developed and applied to help the crew deal with isolation and confinement and to maintain performance; these include addressing entertainment needs, emotional health, sleep patterns, and mood changes (Sandal 2001). Ultimately, the selected crew must be able to function effectively as a team and fulfill mission objectives. Criteria must, therefore, be applied to select individuals who are best suited for functioning in a group under isolated and confined conditions (Morphew 2001). Additional crucial selection requirements will be other psychological "select-in" and "select-out" criteria, the lack of any previous psychiatric disease, gender mix (Rosnet et al. 2004), nationality mix (Kealy 2004), age, and the selection of multi-skilled individuals to provide redundancy in expertise (Hoffman & Kaplan 1997).

Robotics

Robotics is essential in the context of a human mission to Mars. Its rationale as an enabling element is based on precursor robotic missions, as well as a human support system.

Many operations will need to be carried out autonomously on Mars. Current technology does not allow such operations to be performed efficiently. A sustainable research and development program has to be performed with a particular effort in perception and cognition capabilities. Experience in on-orbit assembly is essentially based on a human support system. In the framework of a human mission to Mars, such operations need to be performed without human intervention. For example, some Mars base elements may be assembled on the surface a long time before the crew's arrival. In addition to adapting artificial intelligence, the different gravity environment means that kinematics has to be adapted. Surface rovers benefit from the success of the Mars Exploration Rovers (180 kg) and Pathfinder (12 kg) missions, but are limited to these mini-rover categories. Carrying out science on Mars may involve big rovers (500 kg class) as well as micro-rovers or nano-rovers that are far from being space qualified. Unmanned Aerial Vehicles are also a category of robots for which the technology is mature on Earth but, due to the low martian atmospheric pressure, needs to be further investigated prior to use on Mars. In terms of risk management, robotics provides a safe (no humans losses) and economic (less redundancy) system available in a relatively short timeframe compared to human missions.

Science

There are some scientific activities related to research and development of new technologies or specifically to provide information concerning ISRU. However, other actions are driven by planetary sciences and are presented below. Many scientific instruments can be used to study the lunar and martian environments, namely the chemical and mineralogical composition of the surface, atmosphere, plasma interaction, and the search for extinct or extant life.

Subsurface water and ice detection is optimized utilizing related capabilities of several instruments. Water and ice have unique strong dielectric signatures at low frequencies, which allow their identification among other materials in the regoliths of both bodies (Heggy et al. 2001; Trautner and Simoes 2002; Picardi et al. 2004). Therefore, in the frame of HMM, the suggested method to detect water is to use simultaneous capabilities of quadrupolar probes, ground penetrating radar, and orbital sounding radar to cover the range 10Hz-20MHz, which allow the detection of water/ice with high accuracy from the surface down to several kilometers. With this new method it is possible to measure not only water and ice contents but also subsurface interfaces and inhomogeneities in the medium, because measurements performed with the quadrupolar probe can be used to calibrate the ground penetrating radar, which provides valuable results for the calibration of the orbital sounding radar signals.

Robotic lunar missions could be used to test deployable and inflatable greenhouse structures. Validation of environmental control technologies and the adaptation of chambers, fans, pumps, and artificial lights to low-g environments and solar radiation would be possible. In addition, studies of ISRU for water supply, plant growth media, nutrient source, or greenhouse shielding would build upon the results of physical analysis of such materials (Campbell and Moore 1994). Greenhouses operated at low pressure can also be tested on the Moon, as the Moon's atmospheric pressure is zero. Lunar greenhouses would require artificial lighting during the lunar night and shutters during the lunar day, since plants require diurnal variation every 24 hours (Schwartzkopf 1990). Setting up a greenhouse at the lunar pole offers a constant source of light. Validation of power supplies, such as photovoltaic cells or batteries, would be required to ensure adequate light intensity, temperature control, air, and solution circulation. Large-scale hydroponics systems would only be tested during long-term human stays.

Once reliable lunar growth facilities are developed, subsequent experiments would concentrate on full life cycle trials, optimization of photosynthesis and transpiration, adaptation of plant growth to the lunar or martian day, and extraction of useful or dangerous elements or compounds from lunar soils using phytoremediation. In all cases, species selection is of prime importance, and experimentation will be required. Further studies may consider transgenic species designed for lower levels of light, pressure, temperature, and gravity.

Thermal Management

The HMMs will require advanced thermal control for all system elements of the mission. Advanced thermal control includes the latest temperature & humidity control technologies, such as advanced heat pipes, phase-change fluid loops, refrigerants, heat exchangers, radiators and thermo-electric devices (Larson & Linda 1999). However, a big difference between Mars and Moon missions is the environment on the surface. Because of the atmosphere on Mars, there is convective heat transport on the surface. This leads to different requirements for the thermal management system. For instance, it can use natural convection or heat exchangers with fans. Therefore, testing a thermal control management system on the Moon in preparation for Mars is not useful. The martian environment can be simulated on the Earth, rather than going to the Moon.

Transportation

If a HMM uses classical chemical propulsion with an upgraded version of existing launch vehicles, at least five or six 20 tonnes launches will be necessary. An option would be to design a heavy lift launch vehicle that could deliver payloads of 100 tonnes into LEO, assuming only one or two launches and a reliable system to carry crewmembers into LEO is necessary. A crew transfer/interplanetary module has to deliver the crew into Mars orbit, then a Mars descent vehicle ensuring a soft landing has to deliver them onto the surface, and an ascent vehicle has to lift them off. The Mars habitat, as the descent or ascent vehicle, could be an option. These vehicles might be Apollo-based designs. There is no doubt, however, that the size, mass, and flexibility of these vehicles compared to the Lunar Exploration Module (LEM) and the Command and Service Module are totally different, and the whole design has to be revised. To get into Mars orbit, aerobraking and aerocapture insertion are investigated as enabling elements for a HMM (NASA 1989). The first concept, aerobraking, is quite reliable for robotic missions but has no human trial background. The second, aerocapture, remains to be tested even for robotics missions. To avoid using different vehicles for each journey to Mars, cyclers (McConaghy 2002) have been proposed. The "cycler" spacecraft would constantly ferry people and materials between the two planets and would be necessary for a sustainable effort. On the surface, two transportation systems approaches are available: non-pressurized and pressurized rovers. Non-pressurized rovers can benefit from the Apollo lunar rover vehicle experience, while pressurized rovers have to be developed.

4.4 Selection of Elements

In this section, those enabling elements for a HMM suitable for evaluation on the Moon, are identified. Then, those elements are ranked in terms of priority order.

4.4.1 Selection Criteria

This section identifies the criteria used to select the enabling elements to be rehearsed on human Moon missions. In order to narrow the enabling elements list the following selection process was used.

For each element, the question "Where can this element best be tested before the Mars mission?" was asked. The possible answers were Earth, LEO, in space outside the radiation protection from the Van Allen belt, on the Moon, or only on Mars. The results are presented in Table 4-9, Table 4-10 and Table 4-11.

Table 4-9 Where can this element best be tested before the Mars mission? (part 1 of 3)

Categories	Enabling Elements	On Earth	LEO	Space outside Van Allen belt	Moon	Mars
Crew Comfort & Welfare	Surface stay				X	
	Interplanetary travel		X			
Crew Rescue, Safety & Survivability	Crew escape tower	X				
	Contingency rescue scenarios	X				
	Emergency training				X	
	Ergonomics	X				
	Safe Haven				X	
Communication	Earth Mars relay satellite(s)				X	
	Martian ground communication system	X				
	High data rate communication system	X				
Environmental shielding	Magnetoelectrostatic shield (radiation)			X		
	Liquid hydrogen shielding (radiation)			X		
	Regolith, caves (radiation)				X	
	Lightweight material shielding (radiation, micrometeroid)			X		
	Food/water supply shielding (radiation)		X			
Extravehicular Activity	Advanced interplanetary suit capability			X		
	Advanced planetary suit capability				X	
	Integrated data handling	X				
	Decontamination				X	
Ground Facility (Earth)	Data Processing	X				
	Mission Support	X				
	Training	X				
	Ground Analog & testing	X				
	Design & Simulation	X				
Guidance, Navigation and Control	Advanced deep space network					X
	Automated rendezvous		X			
	Entry navigation, guidance and control					X
	Precision landing				X	
	Surface navigation & localization				X	
Habitation (Mars Surface)	Airlocks				X	
	Living, working area, greenhouses				X	
	Advanced construction materials				X	
	Inflatable structures				X	
	Modular & mobile concepts	X				
	Pre-deployed habitat				X	
Integrated Vehicle Health Management	Fire detection & suppression		X			
	Biohazard detection & control	X				
	Fault detection, isolation and recovery	X				
	Data processing	X				
	Command & Control	X				
***In situ* resource utilization**	Construction from local materials (cave, regolith)				X	
	Water extraction from surface				X	
	Propellant production technologies from local ressources				X	

Table 4-10 Where can this element best be tested before the Mars mission? (part 2 of 3)

Categories	Enabling Elements	On Earth	LEO	Space outside Van Allen belt	Moon	Mars
Life Support Systems	Atmosphere management	X				
	Water management	X				
	Food production & storage				X	
	Waste management	X				
	Low Pressure Greenhouse				X	
	On-board salad machine				X	
Medical issues & Human Physiology research	Microgravity countermeasures		X			
	Surface stay countermeasures				X	
	Crew member medical selection	X				
	Self-sufficient medical system (including crew and equipment)	X				
	Isolation-related medical strategies (critical care requirements, pregnancy, death)				X	
	Telemedicine and medical communications		X			
	3/8g medical procedures (including diagnostics and treatments)				X	
	0g medical procedures (including diagnostics and treatments)		X			
	Radiation management				X	
	Prophylactic medical and surgical measures				X	
	Sexual management strategy				X	
Operations	Maintenance and repair				X	
	Skills training				X	
	Mission control aspects				X	
	Contingency training				X	
	Construction				X	
Planetary Protection	Containment				X	
	Life/biohazard detection	X				
	Sterilization				X	
	Earth ground facilities	X				
	Guidelines for human missions (procedures)				X	
Power Generation and Storage	Radioisotope Thermal Generators			X		
	Stirling Radioisotope Generators			X		
	Nuclear Reactor				X	
	Advanced Solar Photovoltaic	X				
	Power Transmission	X				
	Fuel Cells	X				
Propulsion	Nuclear thermal propulsion				X	
	Advanced chemical propulsion				X	
	Solar sail			X		
	Electric propulsion			X		
	Tripropellant			X		
Psycho-social Factors	Crew selection (non-medical aspects)	X				
	Conflict Resolution				X	
	Crisis management	X				
	Group structure and interactions				X	
	Privacy & personal space	X				
	Crew workload & spare time				X	
	Psychological countermeasures and treatments				X	

Table 4-11 Where can this element best be tested before the Mars mission? (part 3 of 3)

Categories	Enabling Elements		On Earth	LEO	Space outside Van Allen belt	Moon	Mars
Robotics	Autonomous operations			X			
	On-orbit assembly (Docking, rendez-vous, long-arms)			X			
	Surface rovers		X				
	Kinematics on Mars						X
	Unmanned Aerial Vehicles (UAV)						X
	Digging & drilling robot		X				
	Surface reconnaissance & targeting		X				
	Tele-presence operations		X				
Science	Environmental reconnaisance (climate, atmosphere)						X
	Planetary science (geology, astrobiology)					X	
	Life sciences (human physiology, plants growth)					X	
Thermal Management	Heat pipe			X			
	Phase change processes			X			
	Advanced radiators			X			
	Thermo-electric devices			X			
	Condensing heat exchanger			X			
	Advanced refrigerant			X			
Transportation	Heavy lift capability			X			
	Human transport (e.g., CEV)					X	
	Assembly capability in space			X			
	Entry and descent system						X
	Mars ascent vehicle						X
	Aerobraking						X
	Aerocapture						X
	Soft Landing					X	
	Cycler						X
	Pressurized rover with robotic end-effectors		X				
	Non-pressurized rover with robotic end-effectors		X				

The elements found to be best tested on the Moon were retained, and a ranking process with a grade from 1 to 3 was then applied, taking into account the criteria presented in Table 4-12. One criterion is the technology readiness level (TRL) as explained in Figure 4-2.

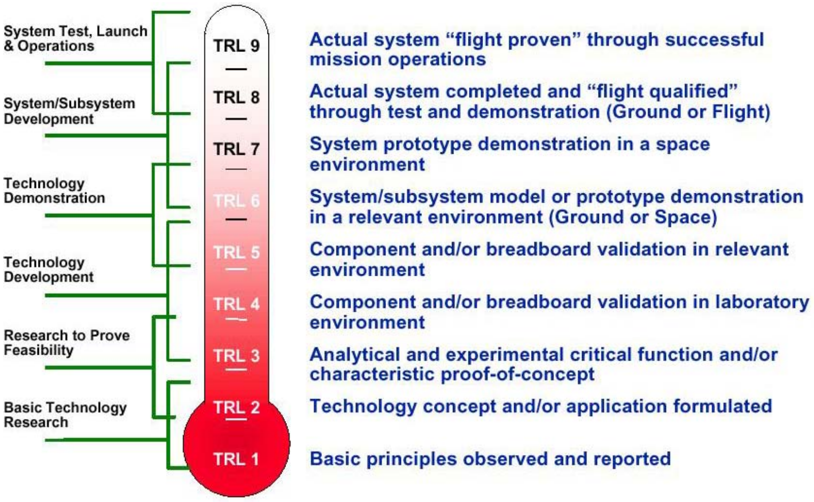

Figure 4-2 Technology Readiness Levels (NASA)

Table 4-12 Ranking Criteria

Criterion	Grade 1	Grade 2	Grade 3
Performance	Low efficiency	Medium efficiency	High efficiency
Safety	Less important	Medium	Most important
Technology Readiness Level	TRL 1 to 3 Basic to feasibility	TRL 4 to 6 Development	TRL 7 to 9 Space
Cost	High	Medium	Low
Policy	Debatable	-	Acceptable
Sustainability	No	-	Yes
Scientific value	Low	Medium	High

The weight of each criterion was determined by comparing each criterion in rows with one another with the following rules:

- If the criterion X (in one row) is more important than the criterion Y (in one column), then X gets a grade 2 and Y a grade 0.
- If both criteria are as important, or, if they are not comparable, they both get a grade 1.

The weight for each criterion was then computed by adding the grades in each row as presented in Table 4-13.

Table 4-13 Weight of Each Criterion

Criterion	Performance	Safety	TRL	Cost	Policy	Sustainability	Scientific value	Weight
Performance	1	0	1	0	1	0	2	**5**
Safety	2	1	2	2	2	1	1	**11**
TRL	1	0	1	1	1	1	2	**7**
Cost	2	0	1	1	0	1	2	**7**
Policy	1	0	1	2	1	0	1	**6**
Sustainability	2	1	1	1	2	1	1	**9**
Scientific value	0	1	0	0	1	1	1	**4**

4.4.2 Results and Justification: Weighting Matrix

This section describes the selected enabling elements as presented in Table 4-14 that should be tested on human Moon missions, as well as the justification for their choice.

Table 4-14 Enabling Elements to be Rehearsed on the Moon by Order of Priority

Rank	Categories	Enabling Elements	Performance	Safety	TRL	Cost	Policy	Sustainability	Scientific value	Score
1	**Psycho-social Factors**	Conflict Resolution	2	3	3	3	3	3	1	134
2	**Extravehicular Activity (EVA)**	Advanced planetary suit capability	3	3	1	3	3	3	2	129
3	**Guidance, Navigation and Control**	Precision landing	3	3	2	2	3	3	2	129
4	**Transportation**	Soft Landing	3	3	2	2	3	3	2	129
5	**Medical issues & Human Physiology research**	Isolation-related medical strategies (critical care requirements, pregnancy, death)	2	3	2	2	3	3	3	128
6	**Medical issues & Human Physiology research**	Radiation management	2	3	2	2	3	3	3	128
7	**Psycho-social Factors**	Crew workload & spare time	3	2	3	3	3	3	1	128
8	**Psycho-social Factors**	Psychological countermeasures and treatments	2	3	2	2	3	3	3	128
9	**Psycho-social Factors**	Group structure and interactions	2	3	2	3	3	3	1	127
10	**Habitation (Mars Surface)**	Airlocks	3	3	2	2	3	3	1	125
11	**Guidance, Navigation and Control**	Surface navigation & localization	3	3	2	1	3	3	2	122
12	**Medical issues & Human Physiology research**	Surface stay countermeasures	2	3	1	2	3	3	3	121
13	**Environmental shielding**	Regolith, caves (radiation)	2	3	1	3	3	3	1	120
14	**Medical issues & Human Physiology research**	Prophylactic medical and surgical measures	3	3	2	3	1	3	1	120
15	**Operations**	Maintenance and repair	2	3	2	2	3	3	1	120
16	**Crew Rescue, Safety & Survivability**	Emergency training	2	3	2	3	3	2	1	118
17	**Crew Rescue, Safety & Survivability**	Safe Haven	3	3	1	2	3	3	1	118
18	**Science**	Planetary science (geology, astrobiology)	3	1	3	2	3	3	3	118
19	**Transportation**	Human transport (e.g. CEV)	3	3	2	1	3	3	1	118
20	**Communication**	Earth Mars relay satellite(s)	2	2	2	2	3	3	3	117
21	**Extravehicular Activity (EVA)**	Decontamination	3	3	1	2	3	2	3	117
22	**Medical issues & Human Physiology research**	3/8g medical procedures (including diagnostics and treatments)	2	3	1	2	3	3	2	117
23	**Planetary Protection**	Containment	3	3	1	2	3	2	3	117
24	**Planetary Protection**	Sterilization	3	3	1	2	3	2	3	117
25	**Planetary Protection**	Guidelines for human missions (procedures)	3	3	1	2	3	2	3	117
26	**Habitation (Mars Surface)**	Pre-deployed habitat	2	3	1	2	3	3	1	113
27	***In situ* resource utilization (ISRU)**	Water extraction from surface	3	2	1	2	3	3	2	111
28	**Operations**	Construction	3	3	1	1	3	3	1	111
29	**Science**	Life sciences (human physiology, plants growth)	3	1	2	2	3	3	3	111
30	**Power Generation and Storage**	Nuclear Reactor	3	3	2	1	1	3	2	110
31	**Operations**	Contingency training	3	3	1	2	3	2	1	109
32	**Medical issues & Human Physiology research**	Sexual management strategy	2	3	1	3	1	3	1	108
33	**Operations**	Skills training	2	3	1	2	3	2	2	108
34	**Habitation (Mars Surface)**	Advanced construction materials	3	2	1	2	3	3	1	107
35	**Life Support Systems (LSS)**	On-board salad machine	2	1	3	3	3	2	2	107
36	**Operations**	Mission control aspects	2	2	3	2	3	2	1	107
37	**Life Support Systems (LSS)**	Food production & storage	2	2	1	2	3	3	2	106
38	**Habitation (Mars Surface)**	Inflatable structures	3	2	1	3	3	2	1	105
39	**Crew Comfort & Welfare**	Surface stay	3	1	2	2	3	3	1	103
40	**Propulsion**	Nuclear thermal propulsion	3	3	1	1	1	3	2	103
41	***In situ* resource utilization (ISRU)**	Propellant production technologies from local ressources	2	2	1	2	3	3	1	102
42	**Habitation (Mars Surface)**	Living, working area, greenhouses	3	1	1	2	3	3	2	100
43	**Life Support Systems (LSS)**	Low Pressure Greenhouse	2	2	1	1	3	3	2	99
44	***In situ* resource utilization (ISRU)**	Construction from local materials (cave, regolith)	2	1	1	3	3	3	1	98
45	**Propulsion**	Advanced chemical propulsion	2	3	1	2	3	1	1	95

Psycho-social Factors

Several psycho-social factors that will have an impact on the success of a long-duration human mission to Mars can be best examined on the Moon. The Moon is a better analog than LEO or terrestrial facilities since it includes the two crucial stressors of complete isolation and reduced gravity. **Group interactions, hierarchy structures and conflict resolution** must be studied under such conditions. The results obtained can then be used for a HMM for better crewmember and group selection, as well as for training. **Crew workload and spare time provision** will be affected by the combination of isolation, confinement and reduced gravity. **Psychological countermeasures and treatments** developed for long-stay lunar missions will be distinct from those for LEO or Earth analogs, and may be transferable to a HMM.

Extravehicular Activity

As summarized earlier, an **EVA suit and life support system** for human Mars exploration must be greatly advanced with respect to overall capability, terrestrial considerations, and external interfaces. Most, if not all, of these capabilities require a rehearsal design on the Moon.

Guidance, Navigation, and Control

Setting up a human base on Mars requires the development of GNC technologies for **precision landing**. This type of landing is difficult on another planet mainly due to the lack of navigation precision by standard means (Deep Space Network or Inertial Systems). Therefore other techniques will have to be investigated and tested on a lunar mission (for example vision based navigation): after a voyage of about 400,000 km, Apollo 12 astronauts navigated to a landing 170 meters from Surveyor 3.

Once on the surface of Mars, rovers and humans will have to have **surface localization and navigation systems** to be able to explore the environment around the base. The use of vision-based navigation is also an option. Another option would be deployment of a GPS-like satellite system.

Transportation

One of the great technological challenges of interplanetary human travel is transportation. **Human transport capabilities** have to be developed for carrying a relatively large crew (6-8 people) on a long trip to Mars. Even if the same vehicles would not be required to go to the Moon, the Mars vehicles will have to be tested prior to a Mars mission.

Upon arrival at Mars, human crews have to perform **soft landing** and **precision landing.** The first is obviously required for safety reasons, the second is required if previously sent equipment is to be used (avoiding long surface movement). Both of these technologies are not yet mature and will have to be developed and tested on the surface of the Moon.

Medical Issues and Human Physiology Research

By conducting human, animal, and cell biology research on the Moon, data on physiological deterioration and its prevention in 1/6g will be obtained. When combined with data from 0g, the situation for 3/8g may be extrapolated. This can then be used to help provide appropriate **surface-stay countermeasures** for a Mars mission. The Moon is more suitable than planned centrifuge experiments in LEO or parabolic flights, in that long-duration and human-scale experiments can be conducted. For similar reasons, the Moon offers the best scenario to research, develop and validate **medical procedures that will be affected by reduced surface gravity** and/or associated physiological changes, such as cardiopulmonary resuscitation and the management of hemorrhage. In contrast, research and development into better microgravity countermeasures, and medical procedures adapted for use in 0g, are best conducted in LEO facilities such as the ISS.

The management of **medical issues particularly related to total isolation** (e.g., critical care resources, crew member death), as well the management of **sexual relations** (including contraception and pregnancy) will generally be applicable for a long-duration, isolated Moon mission as well as a Mars mission. These issues might however be handled very differently in LEO or Earth analog facilities. **Prophylactic, pre-flight medical or surgical procedures** are much more likely to be considered for a crew preparing for a long-stay Moon mission, than for LEO or Earth analogs, where evacuation is a much more ready option; the Moon also offers the ability to follow-up the effectiveness of such procedures after exposure to reduced gravity. Other aspects of a self-sufficient medical system and crew medical selection criteria can be developed on the Earth. The Moon does not have particular advantages over LEO or terrestrial facilities for the development of telemedicine and medical communications applications for Mars, which will be primarily affected by time delays.

Of all the environments humans are likely to visit prior to a HMM, the Moon offers the best analog for researching and developing **radiation management**. When the Moon passes outside the Earth's magnetosphere, the lunar surface is exposed to a radiation environment that resembles, better than LEO, the environment in interplanetary space in terms of the fluxes of galactic cosmic rays and solar particle events. Therefore, data regarding the effectiveness of shielding materials in reducing biological dose during lunar missions, may be applicable for radiation protection during a HMM. Other requirements for a HMM such as establishing acceptable dose limits, dose monitoring, and treatment of acute radiation exposure will also be developed for long-stay lunar missions.

Habitation (Mars Surface)

Living and working on the surface of Mars will require the development of habitats facing challenging constraints. **Airlocks** will be required to separate the habitat's breathable atmosphere from the CO_2 atmosphere outside. **Living and working areas**, as well as **greenhouses** will have to be developed to accommodate the crew and provide food.

The constructions of these habitat systems will have to be performed using the lightest materials possible. Therefore, testing of new construction options will have to be done on a lunar mission: **advanced construction materials, inflatable structures, pre-deployed habitat**.

Environmental Shielding

Without a magnetic field to protect it from Solar and galactic radiation, Mars is a dangerous environment for humans. One possible way to protect the crew against radiation is the use of **regolith** or **natural caves**. The regolith can be used to cover an existing inflatable (or rigid) habitat. This shielding principle should be tested on the surface of the Moon, since the radiation environment is similar.

Operations

The main focus of the lunar missions should be the test of procedures and operations that will be necessary for a HMM. These operations have to be tested on Moon missions, since they cannot be tested in orbit or on the Earth.

The crew will have to perform **maintenance, repair, and construction** operations that will be necessary on the habitat, rovers and other equipment. The astronauts will also have to **train in various skills** to perform activities in a reduced gravity-environment, including performing **science** experiments. In case of emergency, they will have to be trained to react appropriately.

Finally, from the point of view of the ground, there are **mission control aspects** that will have to be tested (communications with the crew with a long delay, uploading procedures, and emergency procedures).

Crew Rescue, Safety and Survivability

Unlike Space Station astronauts, the crew leaving on a Mars mission cannot be brought back to Earth if a major problem arises. Therefore, innovative procedures and plans have to be developed to cope with all kinds of emergency issues. These procedures can only be tested on a similar type of mission in space and on the surface of the Moon.

In particular, the astronauts will have to receive **emergency training**, to be able to react if something goes wrong, without the support of a mission control center on Earth (communication delay problem). This kind of training can be performed on the Moon and monitored from Earth.

A second important factor for crew safety and survivability is the establishment of a **safe haven**, where the astronauts can go in case of an increase of radiation (solar storm, galactic radiation increase) or in case of a major system failure (depressurization of living quarters for example). This safe haven should be equipped to withstand extreme scenarios (high radiation protection) and be able to protect the crew while awaiting a rescue mission (in case of system failure) or for the return of nominal environmental conditions (end of storm). Food, drinks and oxygen should be provided in this haven. The safe haven can be the return module to ensure that the crew can escape in case of a serious problem. This could lead to a heavy return module (due to radiation shielding mass), so other options should be investigated (regolith covered habitat, natural caves).

Science

Even if the martian and lunar environments are not the same, scientific procedures and tests will have to be tested for **planetary science** and **life sciences**.

Communication

In the case of a human mission to Mars, **relay communication satellites** should be used to ensure a permanent link with mission control. These satellites will be used when the Mars base is facing away from the Earth or in periods of solar conjunction. These satellites could be tested on a Moon mission by placing the crew beyond Earth line of sight and using these relay satellites to communicate with the Earth.

Planetary Protection

The procedures required for planetary protection can be tested on lunar missions. **Containment** is required on the Mars habitats, to avoid life forms, if they exist, from coming into the habitat after a crew excursion on the surface. Also, containment is required for any samples, vehicles or crew coming back to Earth. **Sterilization** procedures are required for all objects (including humans) sent to Mars to avoid sending biological forms from Earth. In general, **guidelines for human missions (procedures**) are necessary. All these procedures can be tested on lunar missions.

In Situ Resource Utilization

The long duration of Mars missions will require the progressive transition between using Earth resources and the use of Mars resources. Therefore, ISRU is an important technology that will have to be tested on lunar missions. Even if the atmospheric and soil compositions are not the same between the Moon and Mars, methods and techniques will have to be tested, including astronaut training. Three main ISRU principles to be used on Mars can be tested on the Moon: construction from local materials (cave, regolith), water extraction from surface and propellant production technologies from local resources.

Power Generation and Storage

For long duration missions, the only practical technological solution is the use of nuclear reactors. Even though nuclear reactors have already been tested in space, this technology has never been tested in a remote planetary surface environment so this testing will be necessary before it is used on a human mission to Mars.

Life Support Systems (LSS)

Long-duration Mars missions require bioregenerative life support systems in addition to physico-chemical systems, as they offer self-sufficiency and possibly cost reduction. **Food**

production and storage procedures and methods will have to be tested on the surface of the Moon, where food can be sent from Earth as a backup in case of a problem. Plant growth in **low pressure greenhouses** leads to structural mass savings and reduced leakage. Testing an **on-board salad machine** for food production during transit and during the surface stay combines gaining operational experience with testing the psychological benefits.

Crew Comfort and Welfare

Because astronaut well-being has a major effect on the success of the mission, crew comfort is a key element to be tested. Important work has been performed on this subject for zero-gravity environments (for the ISS) and, therefore, the interplanetary travel phase could be tested on LEO missions. However, crew comfort during the **surface stay** can only be tested on another planetary surface with similar gravitational characteristics.

A lot of different elements can be included in the crew comfort category, all of which will have to be designed for long-term missions: privacy, food preparation, diets, sleep quarters, sanitary facilities (showers, toilets), spare-time activities, and communication with Earth (family, friends).

Propulsion

The large amounts of energy required for a Mars mission and the high masses required for long-duration human missions lead to unrealistic amounts of propellant if chemical propulsion is used. Therefore other types of propulsion need to be developed.

Nuclear thermal propulsion is likely to be the best choice, offering considerably higher specific impulses. This type of propulsion should be tested in a human Moon mission, since it would considerably reduce the propellant mass required for this mission.

Advanced chemical propulsion will also be required for lifting off from Mars surface. These propulsion systems will ultimately have to use ISRU-made propellants from the surface and be robust enough with the best possible performance.

4.5 Conclusions

Chapter 4 has highlighted the major environmental and mission architectural conditions that both govern and differentiate lunar and martian missions. Within this context, major enabling elements for a human mission to Mars have been identified, discussed and rated in terms of their suitability for rehearsal during a lunar mission. The elements that can best be rehearsed on the Moon have been rated by performance, relevance to safety, technology readiness level, cost, political acceptability, sustainability, and scientific value. The resulting list of elements is thus ranked by the priority of rehearsing them during a lunar mission prior to their martian application. This list forms the baseline of elements to be integrated in the mission design performed in Chapter 5.

Elements that can be tested well on Earth, in LEO, or elsewhere than the Moon are not included, because they do not justify a lunar rehearsal mission. Nevertheless, some of these elements will be inherent to such a mission. The elements of a martian mission to be rehearsed on the Moon will have to be reevaluated and revised constantly, in order to reflect novel technological, social, or political developments, as well as the evolution of human Mars mission designs. In some cases, more detailed investigation will be necessary to determine which hardware is similar enough in both a lunar and a martian mission to warrant rehearsal. With regard to human driven elements it is safe to say that they will certainly benefit greatly from lunar rehearsal.

Chapter 4 recommends the followings:

Recommendation 4-1: Test on the Moon those elements of a human Mars mission identified as best suited to lunar rehearsal.

Recommendation 4-2: Investigate further potential for lunar rehearsal of human Mars mission elements as mission designs and technologies progress and as new information on the martian and lunar sites becomes available.

Recommendation 4-3: Emphasize human-driven elements, including psycho-social issues, medical factors, and operations.

Recommendation 4-4: Rehearse planetary protection procedures and technologies.

Recommendation 4-5: Demonstrate both operational and technical implementation of *in situ* resource utilization on the Moon while paying special attention to the aspects that are transferable to Mars and favoring approaches that support a sustained presence on the Moon.

Recommendation 4-6: Conduct lunar science that yields knowledge useful to preparation for a human Mars mission, contributes to sustainability by attracting public support, or promises significant scientific return at a relatively small additional cost.

Recommendation 4-7: Demonstrate during lunar missions the utility of quadrupolar probes, ground penetrating radar, and orbital sounding radar instruments for examining the water content of the martian subsurface.

Recommendation 4-8: Develop an optimized 3-D imaging LIDAR system for descent and landing procedures. To the extent possible, demonstrate the applicable capabilities of this technology on the Moon.

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Chapter 5

REHEARSAL MISSIONS TO THE MOON

Enfin, me plaçant sur un plateau de fer,
Prendre un morceau d'aimant et le lancer en l'air!
Ça, c'est un bon moyen le fer se précipite,
Aussitôt que l'aimant s'envole, à sa poursuite;
On relance l'aimant bien vite, et cadedis!
On peut monter ainsi indéfiniment.

[***Translation:***

Sitting on an iron platform—thence
To throw a magnet in the air. This is
A method well conceived—the magnet flown,
Infallibly the iron will pursue:
Then quick! relaunch your magnet, and you thus
Can mount and mount unmeasured distances!]

From Edmond Rostand's "Cyrano de Bergerac" - 1897
(Act 3, Scene 13: How to travel to the Moon)

The previous chapters describe the current international plans for the future exploration of Mars, identifying the critical technical, political, social, and legal concepts needed. This chapter describes the LunAres Program, which recommends a way to test and verify on the Moon these critical elements for future Mars missions. This chapter is divided into four sections. The first section describes the assumed situation and rationale for verification missions. A section describing the policy, legal and social framework recommended for space exploration missions follows. This framework will be refined during Moon missions before a Mars mission is carried out. The third section outlines the logical steps of the recommended lunar mission sequence in relation to existing national space programs, and gives a more detailed description of the recommended missions.

5.1 Assumptions

The rehearsal missions described in this chapter are built on the following assumptions:

5.1.1 General Assumptions

All missions will be performed within a framework of international cooperation. An important aspect of the recommended missions, beside their technical and operational focus, is therefore to build international cooperation between agencies and private partners.

The current space infrastructures (including the ISS and launchers such as Ariane 5, Atlas V, and Titan IV) will remain available. In addition, the national space agencies will successfully fulfill the ongoing and funded missions of their current space programs; in particular, the future launchers and space infrastructures (such as ATV, Ariane 5 ESC-B, Crew Exploration Vehicle - CEV) will be developed as planned.

Finally, no technological revolution will be necessary for the recommended sequence of missions to be possible.

5.1.2 Mission Objectives Assumptions

The final goal of the lunar rehearsal missions will be a long-term stay in a lunar surface base, comparable to a Mars mission profile and operations. To accomplish this objective, mission duration and complexity will progressively increase throughout the program. This report assumes that robotic missions will be needed as precursors to re-establish the capability to send humans to the Moon in a sustainable manner. Section 5.3.1 shows the recommended incremental steps in this mission sequence.

5.2 Selection of a Program Management Framework

The following suggested framework is aimed at ensuring that interested nations minimize duplication of effort while accomplishing their space exploration activities. In doing so, it is intended to lay the groundwork for future, closer international cooperation on a global scale.

5.2.1 Exploration Program Management Structure -- The Space Exploration Forum

We recommend that the Virtual Program concept (Cline & Finarelli et al 2002), be implemented with modifications that take advantage of high-level design concepts (such as evolutionary design and public-private partnerships), discussed in Chapter 3. The proposed structure for the LunAres Program is to implement a loose coordinating body called the Space Exploration Forum (SEF).

Initially, the primary role of the Space Exploration Forum will be to maintain a database in which participating nations will register their lunar and martian exploration activities. Nations wishing to participate in exploration activities can register those activities with the Forum to limit duplication of effort and allow for synergies among countries. Such a structure will allow nations to coordinate their space exploration activities while still maintaining a national space identity.

Forum membership will be open to any nation willing to participate in long-term human and robotic lunar and martian exploration and to develop capabilities and technologies within a framework of international cooperation. Implementation of the Forum's information-sharing program will be based upon the maintenance of a registry of space exploration activities. This registry will be part of the public domain and will store five critical types of knowledge: high-level (non-sensitive) technical information, all scientific information, the location of exploitable resources, operational and procedural routines, and catalogues of human experience (Crawley 2004). As suggested in Chapter 3, the Forum will allow for adaptability to a changing political environment over the long-term by "providing its members a forum for communication, consultation and coordination, leading ideally to an alignment of national exploration programs" (Cline & Finarelli et al 2002).

Management of individual missions is accomplished by the agency or partnership and is facilitated by the Forum. The Forum will not have the authority to manage the missions; however, agencies are encouraged to follow the Forum's recommendations. The space agencies are responsible for implementing a management structure that will meet the goals of the mission. For example, a specific mission may be managed through a Public-Private Partnership (PPP) if the private sector has a specific interest in the mission or some aspect of it.

Forum Substructure

It is recommended that three Advisory Boards be established under the aegis of the Forum: one for legal and ethical issues, one for societal outreach, and one for technical issues which will make recommendations to the Forum on standardization, technology harmonization, and overall mission operations coordination. These recommendations are not binding given the structure of the Space Exploration Forum; however, if space exploration is to be implemented in a sustainable manner, space-faring nations should make maximum use of pre-existing equipment, data, and capabilities. Forum recommendations will facilitate this endeavor.

Role of the Technical Advisory Board

Standardization, a major responsibility of the Forum's Technical Advisory Board, will involve implementation of an evolutionary design process through interoperability and compatibility of technical components (e.g., technical interfaces, data formats) (Cline & Finarelli et al 2002). To facilitate cooperation on a technological level, a common family of technical interfaces should be established for connecting space system elements. These technical interfaces would specify the way in which spacecraft or space systems physically interact with each other. An international organization may establish these common interfaces.

Definite economic advantages of standardization exist for agencies and industry, as indicated by a general study performed by the German Institute for Standardization (DIN) (2000), with a summary provided by Business Link (2001). Standardization has served as a cost-reducing mechanism for other industries, as indicated by the DIN (2000), and could be an enabling element in the reduction of mission cost and the modularity of space systems as suggested by the Air University (1994). Standardization promotes sustainable access to space through easy replacement of system elements, assistance of one spacecraft to another spacecraft or rescue of spacecraft. Benefits for cooperation and international subcontracting between international space industries and agencies is an aspect deserving further study. This study should include the effect of standardization on space commercialization and competition between companies: some companies may be able to develop a competitive edge by focusing on certain space hardware. For example a company might focus on manufacturing space tugs, space tankers or resource utilization plants.

A space standardization organization could start up as an offshoot of the International Organization for Standardization (ISO). This strategy has definite advantages. Industry which has both a space branch and a terrestrial branch for operation may already be affiliated with the ISO. Within the ISO both an organizational structure and expertise already exist. Some start-up funding may be available in ISO and the ISO affiliation will add credibility to the organization. Starting up as a separate entity has the advantage that solutions can be tailored specifically for space applications. Structure of bodies like ISO can be studied, adapted and improved; however, starting up as a separate entity may lead to difficulty in deciding on a structure and would take much more time. An intermediate solution would be to start up as a separate entity loosely affiliated with ISO or to establish an alliance between the ISO and the space standardization organization.

In summary it is recommended that a spacecraft standardization organization be formed and that this body starts up through or is closely affiliated with the ISO. The Technical Advisory Board would be responsible for the implementation of this recommendation.

Role of the Social Outreach Advisory Board

The Social Outreach Advisory Board's role is to inspire the public and to enable their sustained participation in, and support for, Moon and Mars exploration missions. In doing so, it will provide to the Forum recommendations that are aimed at highlighting the human element. As suggested in Chapter 3, the Social Outreach Advisory Board will promote programs that foster a sense of ownership of, and participation in, Moon/Mars exploration activities by the public. The "Humanity Missions" suggested in Chapter 3 provide a method for exploration plans to incorporate a human element (such as a personal message) without interfering with the mission objectives.

The Social Outreach Advisory Board will also serve as a source of Moon-Mars information to the media and to the public, thereby helping to keep the public well-informed of LunAres exploration activities. The implementation of a space exploration mission registry that is part of the public domain serves as an example of such an information source. Since the Forum is an international organization, any person around the world will be able to take part in the Social Outreach Advisory Board's activities.

The Advisory Board will also play a role in the inspiration of children throughout the world, including those in developing countries. For example, the large-scale international implementation of programs such as The Planetary Society's "Red Rover, Red Rover" program (2004), would be an ideal outreach activity for children. This program allows children to build toy rovers and operate others' rovers tele-robotically through the internet.

Finally, it will be one of the Social Outreach Advisory Board's roles to coordinate with existing space advocacy groups, such as the American Astronautical Society (AAS), the British Interplanetary Society (BIS), The Planetary Society, and the Students for the Exploration and Development of Space (SEDS) to provide outreach activities for their own constituents.

Role of the Legal Advisory Board

Since the legal aspects of individual lunar and martian missions and their management structures will have to be defined individually by participating states, there will be more than one international agreement to define the legal basis for the whole program. The legal structure of individual missions will depend on the participants' needs and desires for that mission (for example, whether or not industry is directly involved through a PPP). It will be the role of the Legal Advisory Board to facilitate the creation of legal agreements between countries that wish to cooperate on a joint mission.

The Legal Advisory Board will define recommendations for the individual missions' legal documents and their basic legal structure. In particular, some basic rules related to the methods of retaining commitment and the Intellectual Property Rights will have to be defined by this Advisory Board. In general, the three Advisory Boards will submit their findings in the form of a proposal to the Forum. Upon approving a proposal, the Forum will submit these findings as mission recommendations.

Timeline

Membership in the Forum will be voluntary. Lawyers coming from the signatory states, agencies, or other organizations that express an interest in participation in the Forum will define the rules that the Forum will approve at its first meeting. Representatives from industry and societal organizations (e.g., space advocacy groups such as the Planetary Society) will be welcome as observers.

At its first meeting, the Forum will accept its rules of procedure defining detailed member voting rights. After approval of the rules of procedure, the Forum will have to approve a document which establishes the three Advisory Boards, including their own rules of procedures and funding.

Given the current political scene, in which the future of space exploration is still uncertain within most governments and agencies, establishment of a commitment by most space-faring nations to the Space Exploration Forum as described herein is premature. In the near-term it is recommended that regular meetings should occur between space agencies at the administrator level so as to encourage future coordination. These meetings should become progressively more formal, culminating in the eventual formation of the Space Exploration Forum. The Forum, with all three Advisory Boards, should be fully-formed as described above by the time preliminary conceptual designs for the first human lunar mission are being carried out. The first highly-publicized act of the Forum should therefore be the first international human mission to the Moon.

Exit and Transition Strategies for Lunar Engagement

If a lunar engagement is primarily intended to serve the purpose of rehearsing a Human Mars Mission (HMM), it must be insured that it does not at the same time bog down humanity on the Moon by consuming all available resources. Depending on the available budget, conceivable scenarios range from abandoning the Moon completely, followed by a period of financial recovery, to funding both a Moon and a Mars program in parallel. Since the latter seems unlikely, any lunar engagement with the ultimate goal of reaching Mars should incorporate an exit strategy (Mendell, pers. comm. August 2004) or transition strategy, enabling a smooth shift of resources towards the martian goal, once the Moon has yielded the desired experience.

Such a strategy need not terminate all support of lunar activity, but must free up sufficient resources. As shown in Chapter 2 this issue constitutes a substantial gap in all current exploration road maps. The strategy chosen to address this deficiency will ultimately depend on the total available resources as well as on the desired timeframe and the policy concerning long-term lunar objectives. Several major conceivable strategies are characterized in Table 5-1.

Such a strategy would also contribute to achieving a firm commitment to an exploration program by participating parties. Having a strategy and timeline in place that clearly define how and when participants in a program can terminate, change or reevaluate their contribution, will make such a commitment more attractive than an open-ended program with non-defined total commitment.

Table 5-1 Exit and transition strategies for lunar engagement on the way to Mars.

Strategy	Description	Pro	Con
Minimum engagement strategy	Mission and hardware are designed solely around martian rehearsal objectives; only semi-permanent infrastructure is deployed; Moon is completely abandoned once desired experience is gained	Cheapest in the short run; fastest route to Mars	No long run benefit to lunar development; if martian program fails investment is lost; danger of losing operational experience (OE) if transition is not made quickly
Privatization strategy	Pass on/sell infrastructure to private entity	Lunar development without expending government resources	A lunar engagement must be commercially attractive by this time; could be hard to maintain ethical standards
Self-sustaining presence strategy	Lunar presence is built up to the stage where it becomes economically self-sustaining and no or only little public support is required; e.g. through mining, energy production, manufacturing of space hardware, tourism, He3 export	Sustainability; OE is maintained	HMM is delayed almost indefinitely; huge investment; no proven approach to achieve economic self-sufficiency
Inheritance strategy	Lunar infrastructure tailored to long term presence is built up and exploited for martian rehearsal; once martian program is scaled up the infrastructure is passed on/sold to second generation space powers; gradual transition possible	Possibility for second generation powers to "earn their wings"; gradual transition possible; OE maintained	Questionable whether politically attractive; assumes that not all nations are fully involved in martian effort
Staging point strategy	Moon is actively used in the launch of a HMM; most likely propellant production by lunar ISRU; launch of complete mission from lunar surface unlikely	Possibly cheaper for a long term martian effort; OE is maintained	Large investment; long lead time
Parallel strategy	Both a martian and a lunar program are supported at full scale; resource demand is likely prohibitive in the foreseeable future	Both lunar and martian development; OE is maintained	Likely prohibitively expensive
Mothball strategy	Lunar infrastructure is designed for long term use and for unattended survival in dormant state over years; once Mars program is scaled up lunar base is temporarily abandoned or only sporadically used until eventually new funds become available;	Compromise between minimum engagement and more sustainable approach	Challenging in terms of creating autonomous survivability

The strategy chosen will have implications for most aspects of program design, ranging from lifetime of hardware to political framework. Therefore, making a decision on how to proceed in a lunar engagement once its primary objective has been achieved should take place at an early stage of the program.

5.3 Recommended Rehearsal Missions

The missions required to test the different technical and science options are described in the following section.

5.3.1 Mission Selection and Roadmap

Mission Categories

In order to select rehearsal missions for the enabling elements listed in Chapter 4, it was first found useful to define four categories of missions in order of complexity:

- Type I: Robotic missions: Remote sensing and resource mapping, technology testing, automated science experiments.
- Type II: Preparation missions: Essential technology demonstrations to prepare specifically for a human mission; cargo missions for the pre-deployment of infrastructure for human missions.
- Type III: Human short-stay missions: Human expeditions of a few days duration.
- Type IV: Human long-stay missions: Human missions where up to three years are spent on the Lunar surface.

The recommended lunar program should therefore be composed of these four categories of missions successively. The process used to come up with rehearsal missions to the Moon is described in Figure 5-1.

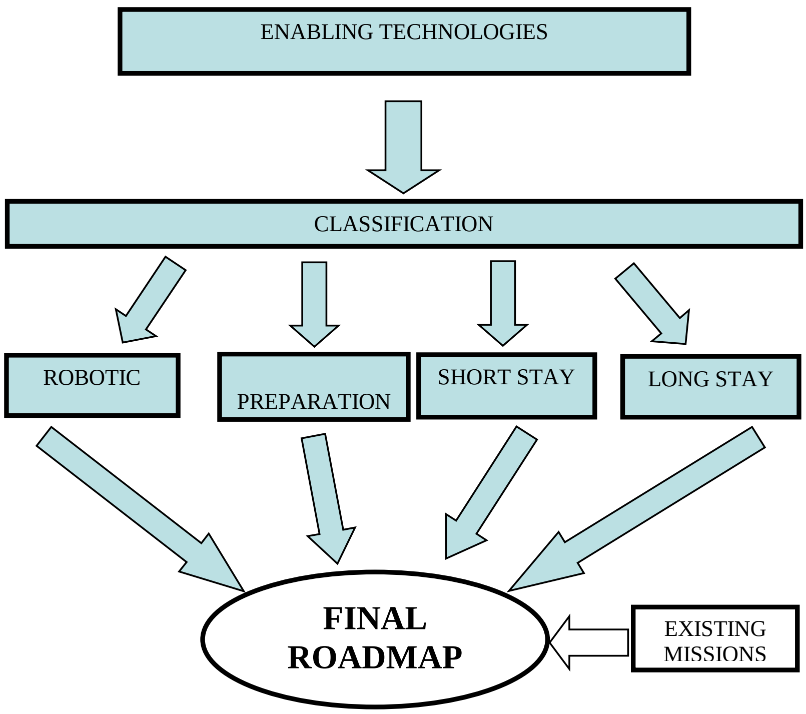

Figure 5-1 Missions Definition Process

First, the selected enabling elements to be rehearsed on the Moon (see Chapter 4.4) were divided among the four mission types depending on their level of complexity. Whenever deemed possible, technologies that can be accurately tested on robotic missions were removed from the human missions. The resulting breakdown can be found in Table 5-2.

Table 5-2 Classification of the Selected Enabling Elements.

ENABLING ELEMENTS CATEGORY	I Robotic Missions	II Preparation Missions	III Short Stay Human Mission	IV Long Stay Human Mission
Crew comfort			Surface stay	
Crew Rescue, Safety and Survivability		Safe haven	Safe haven	Emergency training
Communication	Relay satellite(s)			
Environmental shielding				Regolith, caves (radiation)
Extravehicular Activity (EVA)			Advanced planetary suit capability, decontamination	
Guidance, Navigation and Control	Precision landing, surface navigation			
Habitation (Mars Surface)		Living area, greenhouses, inflatable structures, pre-deployed habitat	Airlocks	Inflatable structures, advanced construction materials
In-situ resource utilization (ISRU)	Water extraction, propellant production			Construction from local materials
Life Support Systems (LSS)		Low pressure greenhouse		Food production & storage, On-board salad machine

Then, several missions were defined in each category to address the enabling elements listed above. These missions are listed in the subsection entitled "Roadmap – Mission operations" and a more detailed description is provided in 5.3.2, 5.3.3, 5.3.4, and 5.3.5.

Finally, compatibility with existing lunar missions was checked. The various lunar missions envisaged currently or in the near future by the different space agencies are listed below.

- SMART 1 – (2003) from ESA

  Solar electric propulsion – lunar mapping

- Lunar A – (2005) from Japan

Penetrators

- Selene – (2006) from Japan

  Remote sensing and resource mapping (entire lunar surface)

- Lunar Reconnaissance Orbiter (LRO) – (2009) from NASA

  Remote sensing and resource mapping emphasizing South pole

- Chang'e (2006-2010) from China

  Remote sensing and resource mapping, Possible 2nd phase – rover (not funded yet)

- Chandrayaan-1 (2008) from India

  Stereographic coverage (5m), Moon gravitational field

To avoid duplication of efforts, there is no overlap between the existing missions and the ones resulting from the analysis conducted in this report.

Roadmap - Mission operations

The resulting roadmap is composed of existing missions and future complementary missions.

A roadmap starting from present up to the first human Mars mission is shown in Chapter 2. This roadmap includes the existing and currently planned missions of all agencies. The specific LunAres Program roadmap with the recommended lunar missions that serve as enabling missions for Mars is shown in

Figure **5-2**.

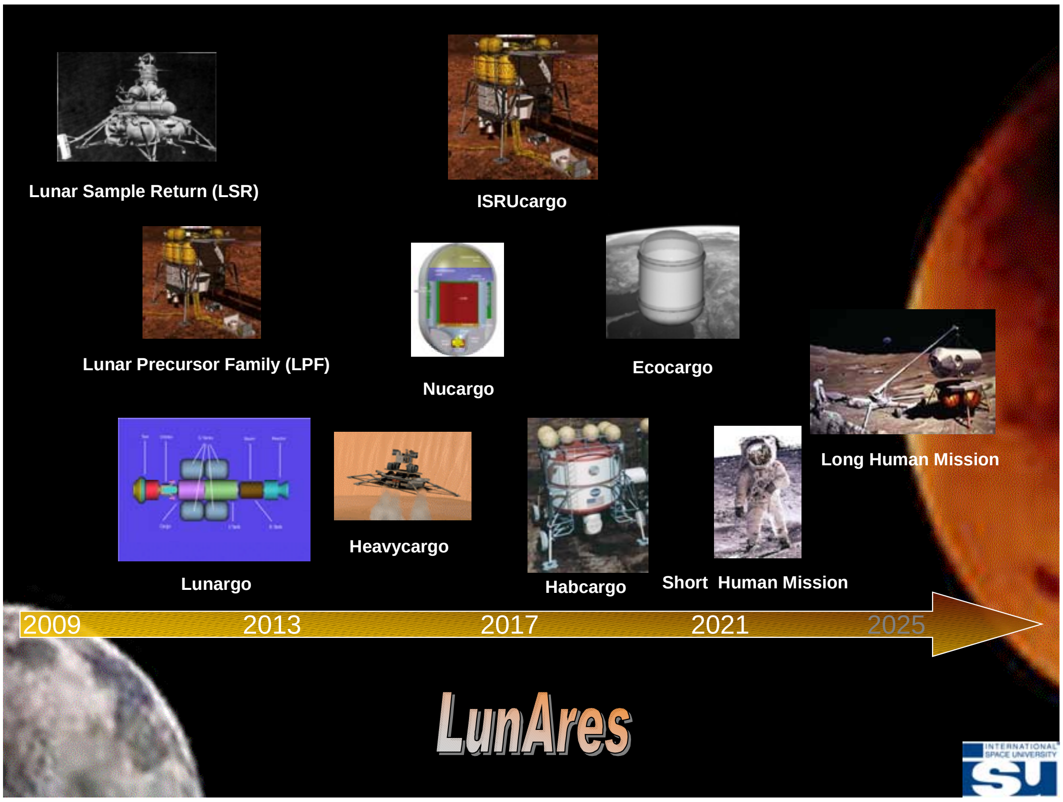

Figure 5-2 Roadmap for LunAres Program

All of the missions recommended in this roadmap are also geared towards rehearsing operational activities in preparation for Mars.

The recommended missions will involve a lot of international cooperation. Therefore, common standards need to be defined, as explained in the next subsection.

Standardization

Several different levels of standardization of space systems may be distinguished, namely the space system level, the spacecraft level and the subsystem level. Interface specifications need to allow room for future development, meaning that a new interface within the same field needs to be compatible with the older one, e.g. USB 2.0 is compatible with USB 1.0.

On the space system level, some form of standardization is already taking place. The telecommunication protocols for Mars missions will be standardized. Some common standards exist today for spectrum allocation to geostationary telecommunication satellites, as indicated by Pelton (2003). A further standardization of communication and encryption protocols would allow more spacecraft to interact meaningfully with each other. This also was one of the findings of NASA OIG (1998).

The interface on the spacecraft level is hardware-based. The common hardware interface should be thought of as a way to connect different spacecraft during close operations. Such operations would include docking, berthing or using moveable robotic arms on orbit or assembling a base or other facility on a planetary surface. The variety in spacecraft mission objectives means that different hardware interface classes have to be considered. For orbiting spacecraft separate classes can be considered for small spacecraft, large spacecraft, robotics to structures, human vehicles, and cargo vehicles. The interfaces would determine how these craft interact with each other for example during rendezvous and docking. On planetary surfaces the following standard interfaces could be considered: modules, i.e. cargo/habitation/crewed vehicles, airlocks, cooperative robotic operations, spacesuits, ISRU equipment, specifically back-end product collection interfaces or resource caches such as oxygen valves, tanks and connectors.

Common hardware interfaces on the spacecraft level may be considered for transferring the following goods: propellant, electrical power, data (wired/wireless), humans, cargo, consumables, plant growth and ISRU resources. Boeing has done some studies on standard docking interface definitions for serviceable spacecraft (Gottselig n.d.). The two spacecraft in this system would be able to exchange propellant, electrical power and pressurized gas. Standardization on the spacecraft level would promote interaction between different types of spacecraft and the interchangeability of different spacecraft having more or less the same functions.

On the subsystem level interface standardization manifests itself in the creation of standard buses and subsystems with common mass, volume, structural, component interface and bus communication characteristics. For data relay, several standards either exist already or are under development, for example the MIL STD 1553 bus. The Electronic Warfare and Radar Systems Engineering Handbook (1999) discusses the advantages of standardizing data buses. A family of spacecraft sharing the majority of their design would employ standardization on the subsystem level. The introduction of mission families increases the reliability of the entire system, reduces cost through the learning effect, enables incremental increase in know-how through application of lessons learned in spacecraft design and operation. The Lunar and Planetary Institute (2004) gives a description of the Surveyor mission family. Modular design of spacecraft with standard subsystems would facilitate repairing spacecraft on orbit through replacement of worn-out or damaged subsystems.

It is recommended that standardization of space systems be studied further.

5.3.2 Robotic missions

The first of the recommended missions are robotic missions that take the missions already planned and proposed by agencies around the world into account. This paragraph introduces a lunar Sample Return Mission, a family of precursor lunar missions for technology demonstration, a recommendation for a scientific instrument that can be included in any of the robotic missions and a suggestion for piggy back missions serving a societal outreach function. Figure 5-3 shows a typical scenario for all robotic missions:

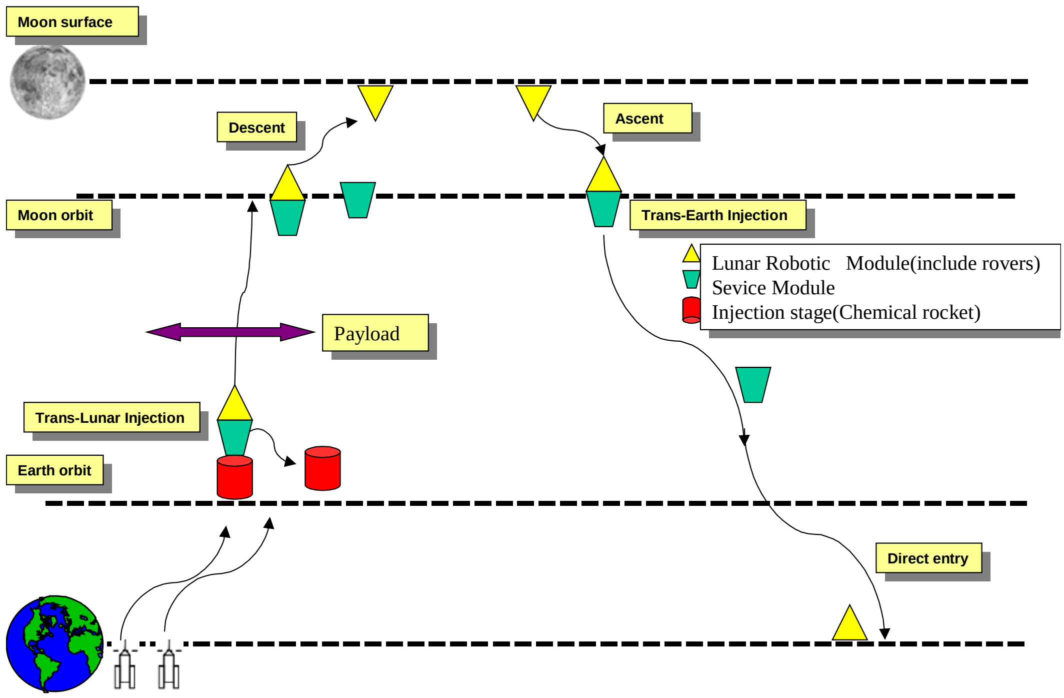

Figure 5-3 Robotic lunar mission scenario

Lunar Sample Return Mission (LSR)

Mission objectives:

- Demonstrate soft and precision landing.
- Demonstrate surface Guidance, Navigation and Control (GNC) capabilities.
- Demonstrate automatic sample return.
- Test technologies for probe sterilization, power transmission and radiation measurement.

This mission proposal is based upon NASA's concept for the Moonrise mission that, if selected, will be launched in 2009. It is a lunar sample return mission that drops two identical robotic landers into the south pole Aitken Basin of the Moon and returns samples to Earth. Over two kilograms of lunar materials from a region of the Moon's surface believed to harbor materials from the Moon's mantle shall be brought back to Earth.

In addition to the proposed technologies, power transmission capabilities could be tested on this mission in preparation for the arrival of a nuclear power plant. Power transmission via microwaves is a possible option for transmitting the power from the power plant to the respective habitat modules, rovers and other elements.

Another possible instrument on this and other robotic missions is a sensor to measure the radiation level experienced by the vehicle for the entire mission duration.

Lunar Precursor Family (LPF)

A family of robotic missions shall be developed to allow for consistency among robotic precursor missions that carry payloads for technology demonstrations. The interfaces for the robotic missions will be standardized. The recommended technology demonstrators are:

- Lunar Soft-Lander Demonstrator (LSLD)
- ISRU demonstrators I-IV (IDEM)
- Inflatable Structure Experiment (ISE)
- Automated Plant Growth Experiment (APEX)
- Construction Rover

SMART-1 bus technology could be used. The hardware shall be a new design, but it will take certain subsystems from SMART-1 such as the autonomous navigation system and the electric propulsion system. New elements in the design are a solid rocket motor and a descent imager, as suggested by Burke (2004, pers. comm. August).

The mission shall be designed within an extremely short timeframe. Transfer time to the Moon shall be shorter than one year, possibly by including two Electric Propulsion (EP) units. Cost shall be minimized by using space-qualified and demonstrated hardware.

The technology demonstrator family shall be designed as an auxiliary payload mini-satellite spacecraft weighing up to 500 kg. It shall be designed such that it can either be launched by the Ariane 5 as auxiliary payload into Geostationary Transfer Orbit (GTO) or by the Delta II in a dual launch into GTO. Deno (2004, pers. comm. August) suggests that the Falcon V could be a cheap alternative to the Delta II. Space Exploration Technologies Corporation (2004) indicates that the Falcon V has similar capabilities to the Delta II.

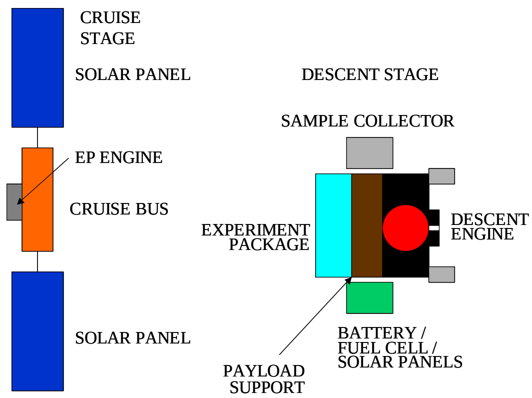

Figure 5-4 LSL family configuration elements

Figure 5-4 shows the configuration elements of both the cruise stage and the lander. The cruise stage shall contain the EP and navigation subsystems. The lander shall contain the experiment payload and a solid rocket motor descent stage.

The cruise and descent stage need to be developed and built by either a single company or by two companies with the capability to set up production serial lines for the standard buses. The learning curve effect (as described in Wertz & Larson 1992, paragraph 20.4.4) will serve to reduce cost of the mission family. The mission family concept introduces reliability to the system: if one mission fails, another mission with an identical experiment can be sent to replace it.

Table 5-3 Spacecraft mass allocation

Cruise Stage: ΔV 3.8 [km/s] @ I_{sp} 1600 [s][1]	
Propellant (Xe) mass	106 kg
Descent Stage: ΔV 2.2 [km/s] @ I_{sp} 250 [s]	
Propellant (solid) mass	87 kg
Mass Allocation	
Dry lander mass	60 kg
Wet lander mass LLO	147 kg
Dry cruise stage mass	180 kg
Dry cruise stage mass + wet lander mass	387 kg
Wet mass GTO	493 kg

[1] Based on characteristics and delta-V requirements of the SMART-1 propulsion system.

Table 5-3 shows a preliminary mass breakdown based on delta-V requirements. A quick overview of the preliminary mass breakdown shows that only 180 kg is available for cruise stage subsystems and 60 kg for the Lander to keep the total mass below 500 kg. The Swedish Space corporation (2004) indicates the target mass for SMART-1 was 350 kg, of which 70 kg is reserved for xenon propellant, leaving a dry mass of 280 kg. The mass of subsystems needs to be decreased in comparison to the SMART-1. This makes complete re-use of all SMART-1 subsystems uncertain. Further miniaturization of subsystems would probably be required. An alternative would be to further shrink down the Lander stage.

The mission sequence for the lunar precursor family shall be as follows: The spacecraft shall be launched as an auxiliary payload into GTO. After initial systems checkout, the lunar precursor family shall use electric propulsion to transfer to the Moon. Upon arrival at the Moon the orbit shall be circularized and preparations for landing shall commence. Before descent to the lunar surface, command shall be handed over to the descent stage. The solar panels and the electric propulsion system shall be jettisoned. The Lander shall then descend to the surface using a solid rocket motor stage. After landing, the Lander shall commence its intended surface operations.

Table 5-4 Mission specific characteristics of the lunar precursor family

LUNAR LANDER FAMILY OVERVIEW					
	experiment	**purpose**	**landing site**	**power**	**mission number**
LSLD	water ice extraction, electrolysis	H2O, O2, H2	South Pole crater	batteries / fuel cells	1
IDEM I	electrolysis of molten silicate	O2, iron alloys	peak of eternal light	solar electric + collector	2
IDEM II	hydrogen reduction of ilmenite	O2, pure metals	peak of eternal light, maria	solar electric	4
IDEM III	carbo-thermal reduction	O2, pure metals	peak of eternal light	solar electric + collector	6
IDEM IV	carbonyl processing	highly pure iron	peak of eternal light, maria	solar electric	7
ISE	inflatable structure	technology validation	peak of eternal light	solar electric	3
APEX I	automated plant growth	technology validation	peak of eternal light	solar electric + mirror	5

Table 5-4 shows the mission specific characteristics of the lunar precursor family members. The differences in experiment payload and power source lead to different configurations, as shown in Table 5-4. A landing site near the lunar south pole at a permanently lighted location requires solar panels which rotate about the vertical axis, as shown in the ISE, IDEM and APEX recommended missions (Burke 1978; Burke 1985; Bussey, Spudis & Robinson 1999). The IDEM lander shown here includes a solar collector and radiator panels on the same vertically rotating platform to provide heat for the experiment payload as required.

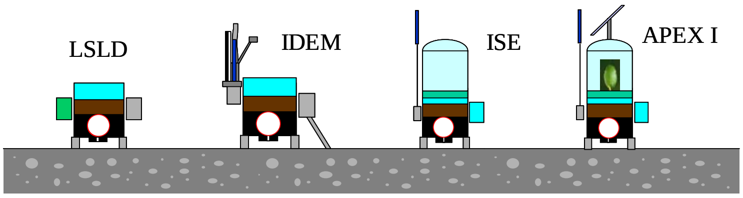

Figure 5-5 lunar precursor family - deployed configurations

Lunar Soft-Lander Demonstrator (LSLD)

Mission objectives:

- Demonstrate precision and soft landing capability on the Moon;
- Identify water in lunar south pole craters if present, determine its extractability, and perform electrolysis experiments.

The LSLD shall be the parent of a family of missions, so it will serve as a validation of the landing technologies and the mission concept. The LSLD shall be deployed in a lunar south pole crater, so no solar energy will be available. This means that the mission shall be of short duration, as energy will need to be provided either by batteries or by on-board fuel cells.

ISRU demonstrators I-IV (IDEM)

Mission objective:

- Demonstrate the practicality of different ISRU processes

The ISRU demonstrator mission family will consist of up to five separate spacecraft, all with the same type of bus. Each mission shall assess a different method of resource processing for practicality, efficiency and potential commercial application. Where possible, the sample collection equipment shall be similar. The experiment package shall be about the size of a box of cereal and shall process about 1 to 2 kg of material. The generic measurement setup for the experiment shall measure the input power, the amount of input sample material, the amount of output resource material and the quality of the output material. Where possible, the experiment shall be repeated over an extended period of time to assess robustness and degradation over time. The experiment packages shall be designed by different international research groups who shall be supplied with the interface definitions. Specific missions could be partially funded by industry interested in exploiting a certain resource. Possible experiments are suggested in Table 4-7 (In-Situ Resource Utilization Processes of Lunar and Martian Regolith).

For future ISRU missions the cost per kilogram of resource produced needs to be established. If the cost per kilogram is low enough, a private company may come forward to privately fund the next generation of ISRU facilities of the Moon, selling the resources produced there to interested parties on a commercial basis. The total cost of the resource production mission needs to be lower than the cost of bringing the resource from Earth.

Inflatable Structure Experiment (ISE)

Mission objectives:

- Demonstrate the usability of inflatable structures on the lunar surface
- Demonstrate precision landing

The Inflatable Structure Experiment (ISE) shall serve as a precursor to a plant growth experiment. The ISE shall assess the viability of an inflatable structure for plant growth and shall measure the pressure, temperature, particle and ultra-violet (UV) radiation environment and gas composition inside the structure. It shall also asses the integrity of the inflatable structure and its degradation over time. The internal environment shall be controlled to keep pressure and temperature within acceptable limits for plant growth.

An offshoot of this mission may be an inflatable work of art landed on the Moon, as suggested by Burke and Dokbua (2004). Small deployable cameras should be included to record the inflation. This mission could be partially funded through funds for space art.

Automated Plant-Growth Experiment (APEX)

Mission objective:

- Demonstrate automated plant growth in the lunar polar environment

The APEX shall be a small-size inflatable low-pressure greenhouse (ILPG), adapted to fit onto the LSL standard bus, to be tested on the way to Moon and on the surface of Moon. The plant growth test chamber will be similar to the Autonomous Garden Pod (AG-Pod) described by Clawson, Hoehn, Stodiek and Todd (1999). As the ILPG consists of a collapsible cylindrical structure (shown in Figure 5-6, it can be stored in a small volume during launch and deployed in orbit or on the surface of Moon. The mass of the ILPG is minimized by using inflatable technologies and by growing the plants at a reduced pressure of 25% atm (Fowler, Wheeler, Bucklin & Corey 2000). The ILPG's diameter of 0.9 m is sized based upon the Extra-Vehicular Activity (EVA) airlock of the Moon transit vehicle/Moon habitat, which is expected to be the same size as the International Space Station (ISS) EVA airlock. The bottom end cap contains the data handling, thermal control system and interfaces to carbon dioxide and water storage, whereas the transparent top cap provides plant lighting either through direct solar light or an external light collection system, e.g. the Himawari design (UA Controlled environment agriculture center 2002; Cuello 1998). If solar lighting is used at the lunar pole, mirrors are installed on top of the ILPG to reflect the photosynthetically active radiation vertically onto the plants. Radiation requirements are usually lower for plants than for humans as plants are less sensitive (Eckart 1996). Radiation effects on sensitive plant species are reduced by flushing water in between the double layered UV-stabilized transparent polycarbonate cap. Additionally, the transparent cap is coated to maintain proper thermal/optical properties. An artificial dark-period for plant photo-respiration is achieved by periodically covering the ILPG with an opaque insulation layer simulating the Earth 24-hour day/night cycle.

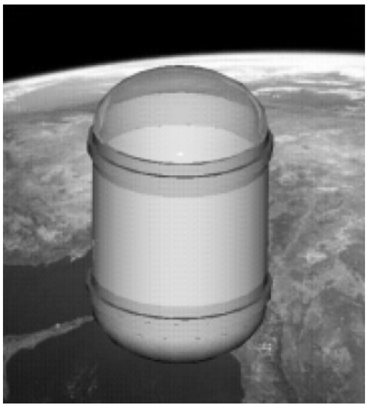

Figure 5-6 ILPG

Figure 5-6 shows an ILPG, that incorporates a simple, collapsible cylindrical structure with rigid end caps similar to the AG-Pod concept (Clawson, Hoehn, Stodiek & Todd 1999).

Sources of water, nutrients and carbon dioxide, and an oxygen removal mechanism are needed for growing plants in the ILPG. As long as the ILPG is attached to the transfer vehicle or the surface habitat the resources are provided through an interface. If the ILPG is separated from the transfer vehicle or surface infrastructure the resources have to be stored in a separate module. The ILPG will be used as a "salad machine" (see Chapter 4.2.2) producing fresh salad crops including lettuce, onion and tomato. The greenhouse provides a combined root/shoot height of 50 cm for the crop. The mass of the ILPG is approximately 125 kg based on the design masses of the TransHAB inflatable material (Kennedy 1999; Clawson, Hoehn, Stodiek & Todd 1999). The crop growth area is 0.5 m2. The ILPG inputs and outputs are summarized in Table 5-5 (Eckart 1996; Hanford 2002). The power required for the ILPG plant growth system (mechanics, fluid pumps, etc.) is 130 W. Additionally, 520 W (80% of total power requirement) of solar or artificial lighting and thermal control are needed.

Table 5-5 ILPG inputs and outputs

ILPG Input		ILPG Output	
CO_2	20-150 g/day	CO_2	20-150 g/day
Water	2.5-5 kg/day	Water	2.5-5 kg/day
Minerals	5-50 mg/day	Minerals	5-50 mg/day
Lighting Power	100-520 W	Lighting Power	100-520 W

Construction Rover

Mission objective:

- Investigate the use of unprocessed lunar regolith

A company could be asked to look into designing a simple lunar rover to do experiments with lunar regolith. The main mission objectives would include: dirt-moving, burying radiometers, clearing terrain, testing lunar regolith mechanical properties and possibly some microwave heating to create a hardened floor.

Subsurface water and ice detection (scientific instrument)

Mission objective:

- Investigate the use of unprocessed lunar regolith

As an additional instrument on one of the other payloads, a water and ice detector shall be sent to the Moon to fulfill some of the identified scientific goals presented in Chapter 4.3.2. Subsurface water and ice detection is optimized utilizing overlapping capabilities of several instruments best fitted for different frequency ranges. Water and ice have unique strong dielectric signatures in low frequency, which allow their identification among the other materials in the regolith of both bodies. Therefore, the recommended method to detect soil/water mixtures includes the maximum sensitivity range of quadrupolar probes, ground penetrating radar, and orbital sounding radar. This method, which uses multi position with a number of different low frequency radio waves, is able to measure and determine not only the water content but also subsurface interfaces and inhomogeneities. The suggested instrument can be tested on the Moon in preparation for a Mars mission. Moreover, the measurements performed by the quadrupolar probe can be used to calibrate the ground penetrating radar, which, in turn, provides results for the calibration of the orbital sounding radar.

Societal Piggyback Payloads

To enable the long-term sustainability of the recommended exploration program, implementation of societal piggyback payloads to robotic missions is recommended as described in Chapter 3. One suggestion for a societal piggyback payload is to send a small robot as illustrated in Figure 5-7 that builds monuments using lunar regolith and water. Another idea is to mount memory devices, which contain messages from members of the public about the celebration of the new beginning of civilizations on the Moon. The public's messages of new understandings of the human race in the space age could be printed on the lunar surface by using installed stamping devices in the lunar rovers wheels.

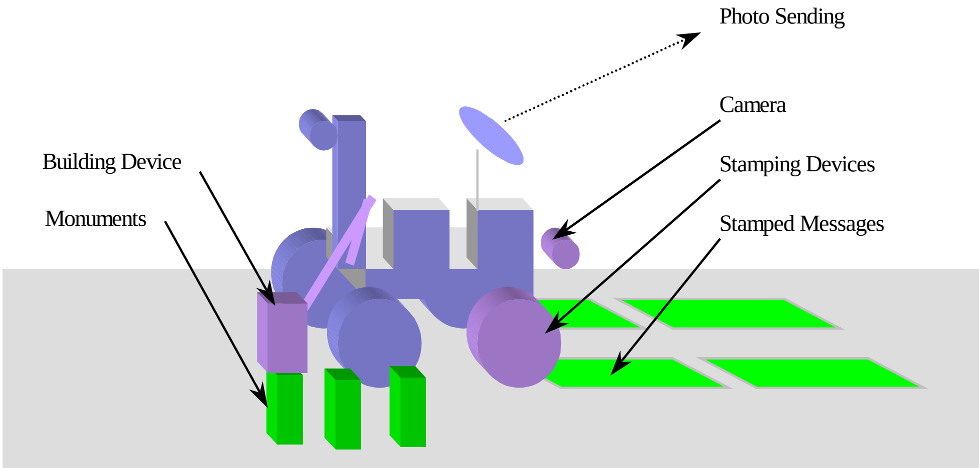

Figure 5-7 Social Piggyback Payloads

Missions to the Moon and Mars have a great potential to excite students and get them involved in space activities. This section describes ideas that teachers can implement in their own way to supplement the current curriculum.

One suggested classroom activity includes a project where students build a lunar rover using a modeling kit and running a mission in their classroom. Commercially available modeling kits (see Figure 5-8) for schools include programmable computer chips and parts to build robots. Programming capabilities include a feature for incorporating timing delays to be more representative of commanding a robotic rover on the Moon. The students can also build a simulation of a lunar habitat. These kits contain all the materials and instructions for teachers. If the teacher wishes to go further, he or she can build a mockup of the lunar surface so the rover can execute its mission in a more realistic environment (The Planetary Society's Red Rover Project).

Figure 5-8 Model Robot

Using simple, inexpensive parts from a hardware or home improvement store, students can also construct mockups of a lunar greenhouse. The greenhouse is an enclosed environment containing sensors that measure the inside temperature, illumination, and humidity (see Figure 3-2). The students control the environmental conditions by using heaters, fans, and artificial light. The exterior of the greenhouse should be a variable temperature environment like the 24 hours 37 minutes martian day/night cycle. During the day, artificial light would be shining on the greenhouse. At night, the greenhouse could be located near an open window to lower the temperature.

Figure 5-9 Greenhouse, Rock Wool Plugs, and Hydroponics Greenhouse Components (TCS Hydroponics 2004 and Future Garden 2004)

To demonstrate different principles of growing plants in an enclosed environment, a hydroponics system can be used instead of using the rock wool plugs. A hydroponics system constructed from a piece of square Styrofoam holding a small cup with holes in the bottom and floating in a tray of water demonstrates this concept. A small pump circulates the water and an optional air pump aerates the water and decreases the growth of algae and root fungus. Seeds that have been previously germinated prior to putting them in the hydroponics system grow best. Seeds may be germinated inside moist cotton balls. Lettuce, green beans, and radish are plants that are easy to grow, have short growth cycles, and are recommended for student experiments.

5.3.3 Cargo preparation missions

After a first series of robotic missions, a series of preparation missions should start in order to test all the capabilities and the technologies needed for heavy landing. This will simulate a possible sequence of martian cargo missions.

The first capabilities that these missions will demonstrate are heavy, soft and precise landing. Next, inflatable structures, a nuclear reactor, an ISRU reactor, a habitation module and a green house will be tested.

Cargo can be designed so that these different missions could be incorporated into a standard spacecraft as payload. Two options are conceivable for this cargo spacecraft: a standard spaceship built 4-5 times to reduce the cost per craft, or just one cycler spacecraft travelling on an Earth-centred orbit that would receive a capsule with the payload directly from Earth and bring it to the Moon.

These two options have already been studied by NASA, ESA and other research institutes, the second option seems less feasible, but as the same concept could be rehearsed for Mars testing also a fast-docking procedure on a Moon-Earth system, examples for Mars can be the Aldrin cycler (Aldrin 1985).

The Cargo spacecraft, travelling on an Earth centric orbit that encounters Earth and Moon, has to be designed. At a given encounter with the Earth, a small probe (called Taxi) joins the Cargo spacecraft. Once the Cargo reaches the Moon, the Taxi lands on the lunar surface and carries supplies to the Moon base. The payload may include inflatable structures, a nuclear reactor, an ISRU reactor, a habitation module or a greenhouse. As this load could be a life-form, it must be stored in a controlled environment (variables to be controlled include pressure, temperature, and radiation).

The Cargo is a big structure containing all the life support and the orbit maintenance systems (engine, power supply system, attitude control, Telemetry, Tracking & Command). The Taxi is a service module that contains the payload. It assures the safe transport of the goods by controlling the radiation dose, the thermal and pressure gradient and the general stability of the environment on board. After a first Cargo assembly phase around Earth, the heavy Cargo always travels on the Earth centric orbit chosen. The advantage of this configuration is in the light structure of the Taxi probe, so that the payload mass is maximized.

Cycling spacecraft take advantage of planetary gravity-assist swingbys to continuously repeat voyages between at least two worlds with minimal use of rocket propellant. The cislunar cyclers contain the heaviest equipment needed for economical and safe cislunar transport - closed-loop life support systems and radiation shielding for protecting the crew and passengers from solar flares and cosmic rays - plus a propellant farm for taxis leaving the cycler for Earth or for the Moon. The cycler could encounter the Moon three times every two months. The three types of paths possible are:

- Earth-Moon transfer orbit requiring 9 days or 14 days to complete
- "BackFlip" high-inclination transfer lasting 14 days
- Low-inclination 28-day holding orbit matching the Moon's orbit but inclined to the Moon's orbital plane.

Electric (ion) rockets are used for almost all routine manoeuvres once the cycle is established. As Nuclear Thermal Propulsion (NTP) capabilities have already been established by the recommended robotic missions by that time, NTP engine will be employed, and operations will occur as follows:

- At the beginning of its career, the cycler departs its low-Earth orbit assembly point for the Moon on a trip lasting 4.5 to 7 days
- The cycler flies past the Moon. The capsule containing the payload detaches from the cycler to land at the Moon base or enter lunar orbit. The cycler, with no payload on board, performs a gravity-assist that takes it into an orbit matching that of the Moon, but inclined at least 25 degrees to the Moon's orbit (Uphoff and Crouch use a 46-degree inclination). They dub this transfer orbit the "BackFlip"
- The spacecraft remains within 318,000 kilometers of the Moon (78 percent of the Earth-Moon distance of 397,000 kilometers) throughout the BackFlip, experiencing gravitational perturbations to its orbit, which must be corrected. Fourteen days later it re-encounters the Moon on the opposite side of the Moon's orbit. By applying a modest amount of rocket thrust during the BackFlip, the cycler can be targeted to either enter a 14-day or 9-day Earth-Moon transfer orbit or a 28-day holding orbit (Figure 5-10).

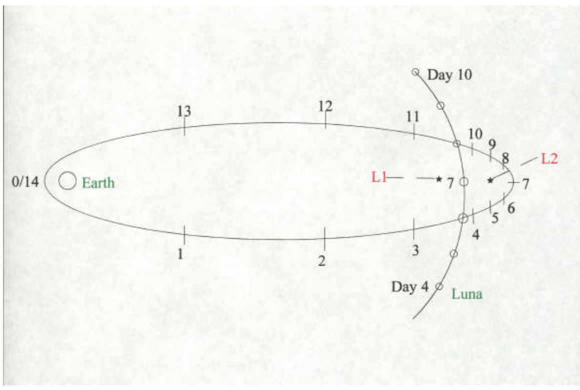

Figure 5-10 Orbit chosen for the Cycler
(Dietzel)

The following is a typical description of a proposed robotic lunar rehearsal mission after assembly of the Cargo around Earth (Figure 5-11):

1. Each Taxi module will be launched individually into LEO or highly elliptical orbit (HEO)
2. The launcher upper stage will inject the Taxi in the Cargo orbit
3. The Cargo docks with the Taxi and travels to reach the Moon
4. The Taxi capsule undocks during the Moon fly-by
5. Lunar orbit insertion of the Taxi
6. Entry, descent and landing on Moon for the Taxi
7. The Cargo travels back to Earth

The launcher Ariane V ESC-B will be adopted. As the capability of this launcher is limited, missions requiring more that 10 tonnes will be split into 10 tonne modules and assembled on the lunar surface.

A first assembly of the cycler, called **Lunargo**, occurs prior to any other cargo mission. Then five main Taxi missions are foreseen to test enabling elements for Mars mission.

The payload of these five missions will be:

- Heavy robotic and structures landing- **Heavycargo**
- Nuclear Reactor - **Nucargo**
- ISRU Unit - **ISRUcargo**
- Habitation modules - **Habcargo**
- Low pressure greenhouse modules - **Ecocargo**

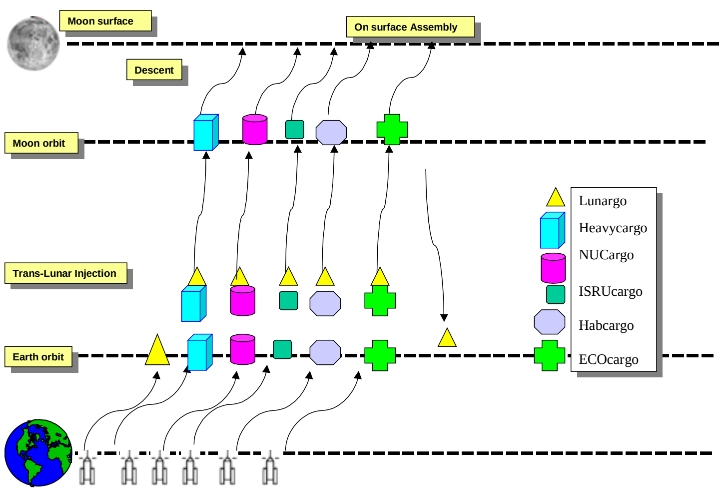

Figure 5-11 Cargo Preparation Mission

Heavycargo

Heavy landing missions will include robotic units and inflatable structures. The mass budget of these missions is shown in Table 5-6. Construction material and other cargo needed on the surface will be brought prior to human arrival. Tele-operated and automatic robots will first be sent to the Moon to do as much mining and construction as is possible. Structures needed by the first and the long human missions will also be sent in advance. Technologies and capabilities to be demonstrated by this mission include:

- In orbit spacecraft assembly capabilities
- Heavy landing capability (10-15 metric tonnes)
- Inflatable structures deployment.

As the capabilities of the cargo are not totally defined yet this mission could be divided, however, the first mission should assess the heavy, precise, and soft landing capabilities. On Mars, most inflatable deployment strategies make use of atmospheric gases such as CO_2. On the Moon such an approach cannot be considered because of the absence of an atmosphere.

Table 5-6 Mass budget for Heavycargo

Surface vehicle	800 kg	Rover vehicle
	8,000 kg	Pressurized rover vehicle
Robotic capabilities	2,000 kg	Digging robot
Inflatable structures	9,000 kg	
TOTAL	**20,000 kg**	

Inflatable devices and gases necessary for carrying out the inflation have to be brought to the Moon. Large inflatable structures can be folded into compact packages for launch. They are usually made ridgid after deployment so that internal pressure is not required to maintain structural stiffness and shape. In terms of mass and deployment capability, inflatable truss elements are the most efficient. They self-rigidize to enable inflatable structures with integral radiation shielding, impact shielding, thermal management, and equipment to keep tabs of their overall health.

As soon as the lunar habitat is completed, inflatable structures are released. First, the truss (composite beams) will be deployed automatically and will give the structure its final shape. Then, all the sides are inflated. Eventually, airlocks will balance the pressure in the inflatable compartment at the desired pressure.

If the mission involves regolith radiation shielding, the last phase would be to cover the habitat and the inflatable structures with regolith. One example of how this could be accomplished is through the use of an assembly vehicle, which would have to be designed for this purpose.

NUCargo

The second mission will have the nuclear reactor as main payload as foreseen in Chapter 4, its mass budget is 7,000 kg.

As the technology for soft, precise, and heavy landing will already be assessed, the main target of this mission will be the demonstration of the deployment of the radiators of the reactor and the reactor's start-up.

The kind of reactor that can be brought on the lunar surface is the same as the one on the martian surface; options for the surface reactor are in

Table 5-7.

The reactor would require the establishment of a shield by a robot already present on the Moon surface, deployment of all the radiators, and a first heat of the secondary system. A few operations will occur prior to the real reactor ignition: the primary cycle should be pressurize, the radiators should be deployed and the core should be heated, power conversion systems have to be tested (including turbine, compressor, alternator, radiator, recuperator, and conditioning) together with tankage, start/re-start reactor and battery, refrigeration, communications and reaction control.

Table 5-7 Reactor Under Study

	SP-100	SURE-G	SURE-W	JIMO
Country	US	ESA	ESA	US
Dates	1992	2003	2003	2002
kWt	2000	2144	2144	?
kWe	100	100	100	100
Converter	Thermoelectric	Thermoelectric	Rankine	Brayton/ Heat pipes
Fuel	UN	UO_2	UO_2	UN
Reactor Mass [kg]	5422	3000	4000	?
Neutron Spectrum	fast	thermal	thermal	fast
Control	Be	Be	Sliding slices	Be
Coolant	Li	He	H_2O	NaK
Max. Core Temp. [°C]	1377	812	345	1900

ISRUcargo

The third mission will have the ISRU system as a main payload. Its mass budget is 7,200 kg. At the time this mission will be executed, at least one precursor for this system will have already been sent to the Moon. Therefore, the main target of this mission will be the installation phase of the entire system that will be used on Mars and the demonstration of the processes that can be used on the Moon.

Based on experience gained in the ISRU demonstrator missions, a scaled-up ISRU plant can be erected at the lunar south pole. In-situ resource utilization of the possible lunar water ice would require the establishment of a mining system to mine dust-contaminated water ice, an ice intake with some buffer capacity, a plant with a liquefier, filter, heat radiators, electrolysis equipment, gas dryers and gas liquefiers, a resource cache, namely storage tanks for water, oxygen and hydrogen, and a power plant. The inputs for the plant are dust contaminated water ice and power, and the outputs are liquid oxygen, liquid hydrogen, water and dust. It is recommended that supporting elements, such as the interface for oxygen, hydrogen and water collection be standardized.

Other ISRU experiments may lead to other practical resource utilization processes. Both Mendell (1985) and McKay, McKay and Duke (1992) provide extensive examples of large scale ISRU facilities near the lunar south pole. Possible ISRU processes are suggested in Chapter 4. In case of oxygen production, there is a need for a gas liquefier, heat rejection and liquid oxygen storage, similar to oxygen production through the electrolysis of water.

HABcargo

The fourth mission will have the habitation module as the main payload. Its mass budget is shown in Table 5-8.

Table 5-8 Mass budget for HABcargo

Lander's Elements and Systems for Cargo Missions)	Approximate Mass (kg)	Further Characteristics of the Elements and Systems
Habitation structure	33,000	Cylindrical module, made of Aluminum, rack Structures
Crew accommodations	10,600	Accommodations facilities, waste collection, maintenance, Crew Health Care
ECLSS	1,000	LiOH, life support system
Thermal control	16,500	
Communication equipment	1,500	On-Board Data Handling, Telemetry
Airlock	2,000	Separate airlock
EVA equipment	2,800	suits, portable life support systems
Science equipment	2,200	Includes instruments and tools
Total	70,000	

The total habitation mass would be between 65 and 75 tonnes for a long-term mars mission for a 6 members crew. In order to rehearse the technology for Mars missions on the Moon, the same model of habitat should be used. The launcher has the capability to put 10 tonnes into the lunar transfer trajectory in order to lock the habitat onto the cycler. Based on these assumptions, we come to the conclusion that the habitat has to be modular.

All the modules of the habitat have to be landed around the same area with a maximum distance between two modules of a few hundred meters compatible with a precision landing. This requires the use of an assembly wheeled-vehicle on the surface. Each module should be of rectangular shape to simplify the assembly, and is of the single-floor type.

The assembly of the modules can be realized with inflatable pipes if the precision landing tolerance would be 10-15 m, otherwise an assembly vehicle should be envisaged.

This assembly vehicle should have a 10 tonne lifting capability. To optimize the assembly trajectory and maneuvers, this vehicle must wait for each module to land. This will take 70 days prior to the start of its mission given the masses previously assumed. The vehicle will gather the modules together on the best scientific and most flat site. Each module includes two airlocks to connect the other modules.

Prior to the human arrival on the site, inflatable structures and the life support system should be installed, thus making sure that human arrival is safe.

All the habitation systems have to be tested. The first crew has to comment on the general design of the habitat and make recommendations about living areas. Is there room enough for crew comfort in the low gravity environment? Is the modular concept a good concept? What are the kinematics of the habitat components in reduced gravity environment (bed deployments)? Different light systems and different pressure level inside the habitat will be tested. Radiation measurements inside the habitat and the greenhouse will help in improving shielding for a Mars mission, especially if regolith is the shield. Airlocks are the most important habitat components to test both in terms of safety and operations. Procedures inside the habitat for EVA must be defined. Isolation from Earth communications must be tested by simulating a delay from 15 minutes to 40 minutes.

ECOcargo

The fifth mission will have an inflatable low-pressure greenhouse as the main payload. Its mass budget is 22,300 kg. It will provide 55% of the food required for a crew of 6 astronauts. If more than 50% of the required food is produced locally, both the water and the air required for the crew can be regenerated completely (Drysdale & Hanford 1999). The inflatable greenhouse structure is similar to the TransHAB shell concept: Gas retention is achieved by a redundant bladder assembly, whereas structural restraint is achieved by Kevlar webbings. The greenhouse is covered with a multi-layer insulation and radiation protection. The greenhouse provides a growth area of 215 m^2, the power required for the electric growth lights is 680 kW (Hublitz 2000).

Conclusion

A general rule for any transportation scheme is to accelerate the smallest amount of mass possible. Consequently, full cyclic systems may possibly provide the energetically cheapest method of sustaining a transportation system between Earth and Mars. However, cyclers are not always the best alternative. Systems incorporating parking orbits become more efficient as the approach velocity at planetary encounters decrease, i.e. as less mass is accelerated. Moreover, as the midcourse corrections to sustain a full cyclic trajectory increase, cycling systems become a less attractive alternative. The relative effect of this added cost is dependent on the scenario, but a cycling system will still require the least propellant for large ΔV. There are several factors besides propellant cost to consider when examining the best method of transporting mass between Earth and Mars. For example, cyclers often provide the cheapest propulsion alternative, but are also the most complicated in terms of rendezvous, require the most precision in encounter dates and optimal control of the spacecraft in the re-entry phase.

The first recommendation to realize this kind of mission is the development of heavy lift launchers. As with currently planned launchers the number of launches required is almost twenty. A heavy lift launcher could enable these missions with 4-5 launches.

The other recommendation to enable these missions is the development of reliable automated docking capabilities on eccentric orbits, in order to allow future hyperbolic dockings required for Mars cargos.

The use of low thrust propulsion could be very interesting for the cycler concept. The recommendation is to use Nuclear Electric Propulsion (NEP) for the Mars cycler.

5.3.4 Short-Stay Human Lunar Mission

Mission Design

Human presence on the Moon will start with a **short-stay mission** to the **lunar south pole**. The duration of this mission depends on the risk level allowed. The assumed time for the first mission in this report is **14 days**. The decision for an approach in several steps is based on the following rationale:

- **Loss of Experience:** The United States of America was able to land astronauts on the surface of the Moon and send them back safely several times, this knowledge and experience is rarely available nowadays.
- **Risk Reduction:** The short-stay mission was selected to test main elements (airlocks, decontamination and sterilization, and advanced planetary suit) for a long stay mission on the Moon. This will reduce the risk of mission failure for following human missions.

The short-stay mission is intended to test all space elements for a long-stay human mission to the Moon as described in Section 5.3.5. This mission is also required to test mission critical elements. To accomplish this task a set of enabling elements were selected to be tested during this mission.

Based on the mission selection from Chapter 5.3.1, Figure 5-12 shows a sequence of activities during the 14 days of the short-stay on lunar surface.

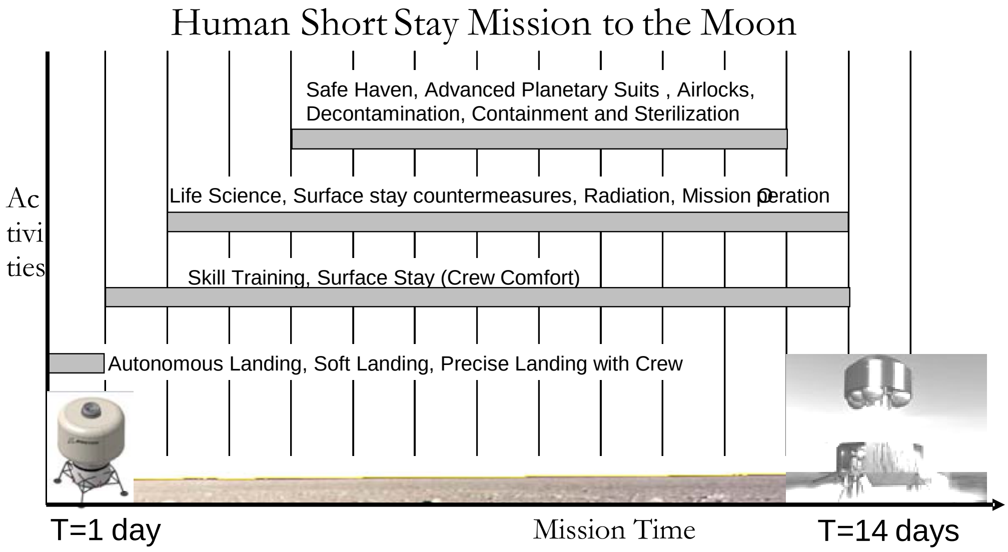

Figure 5-12 Overview of crew activities during short-stay mission to the Moon[2]

Final qualification of precise autonomous soft landing capabilities for human missions will occur at the beginning of the mission.

The habitability of the module design, equipment and some of the procedures needed for a long stay on the surface will be tested and verified during the short-stay mission on the lunar surface. Some of these procedures will be emergency procedures including the use of safe haven. As the emergency procedures can help to avoid or reduce life-threatening situation during the long stay (injuries during EVA's for constructing habitation elements like greenhouse), these activities will be tested during this mission.

Investigating the lunar gravity effects on the human body and the effectiveness of countermeasures will be a major activity during the stay. The results are required to extrapolate the effects of 1/6 gravity on the human body for a 450 day stay. During the mission total radiation dose will be controlled and measured to verify the effectiveness and efficiency of implemented shielding.

All EVA equipment and procedures for lunar surface activities will be tested and verified during this short-stay mission. Any problems identified during this stay can then be solved for future long-stay missions.

The experience gained during the short stay will provide useful data about the strengths and weaknesses for aspects of the long-stay mission. This will result in a more reliable 450 day stay mission on the Moon.

The number of astronauts to be sent on this mission and landed on the lunar surface needs to be determined. Six humans should be sent to the lunar surface to provide the most realistic test environment; however it is also reasonable to keep a part of the crew in the habitation module in a Low Lunar Orbit (LLO). These crewmembers could perform life science experiences for comparison with data from the lunar surface.

[2] Figure composed out of images from The Boeing Company, NASA, and ESA

Assuming a daily schedule similar to the ISS, sending six humans on a 14-day mission would result in approximately 14 days x 6 humans x 8 hrs/(day human) = 672 hrs of work (see Table 5-9). Combining the rationale of risk with the available time and activities planned for a short-stay mission, landing only four humans on the lunar surface without leaving two humans in LLO seems to be reasonable. Two humans would be an Apollo-like approach but would not provide enough manpower for some activities like emergency procedures during EVAs.

Table 5-9 Astronaut's Average Work Day on ISS

Activity	Duration per Day
Sleep	8 h
Pre-/post-sleep activities	4 h
Physical exercise	2-3 h
Work on experiments	8 h
Daily Planning Conferences (DPCs), Public Affairs (PAOs), work preparation, and other miscellaneous activities	1-2 h
Total	24 h

A detailed discussion of all elements for a human Moon mission can be found in Section 5.3.5 describing a long stay lunar mission strategy as a follow up to the short mission. The medical elements are described in Section 5.3.6.

5.3.5 Long-Stay Human Lunar Mission

Mission Objectives

The main purpose of the Human Long Stay Mission to the Moon is to demonstrate technologies for a mission to Mars including long duration habitation technologies. The main concept behind the long-stay lunar mission is to reproduce most of the phases of a Mars mission together with the main issues that astronauts are likely to experience on Mars. As a consequence the operational aspect is being emphasized.

In preparation for missions to Mars it is important to gain experience with large crews size. Therefore the mission will have a crew of **six people**.

Mission objectives

- Landing a human crew on the Moon around 2020, for a mission duration typical to long stay Mars mission scenario (**450 days**) and return them safely afterwards, ensuring planetary protection for both Earth and Moon
- Demonstrate enabling elements needed to support a human presence on Mars
- Continuation of the construction of a lunar base (after short-stay mission)
- Testing of the vehicle building-blocks that will be used in a Mars mission

The basic assumptions of the missions are as follows:

- Based on the mission overview from Section 5.3.1, Lunar Surface Habitation Station (LSHS), ISRU plant, power plant, and other necessary instruments will have been transferred to the lunar location using cargo missions. During the short-stay mission a basic lunar base will have been built.

- During previous robotic and short-stay human missions low-gravity and radiation countermeasures will have been developed by the time the long-duration mission will be performed.

Mission Phases and Analysis

The mission phases of the rehearsal missions are as follows:

a) **Launch:** Each of the components will be individually launched into LEO:

- Interplanetary Crew Transport (ICT)
- Crew Surface Lander and Crew Ascending Vehicle (CSL/CAV)
- Power Module and
- Propulsion Module.

Note: These individual launches are required based on the currently available launchers. A heavy-lift launcher (Saturn size) would substantially reduce the number of launches and largely facilitate a Mars human mission.

b) **Assembly:** Assembly in orbit of all these components. It is assumed that this assembly can be done automatically, as it was done on the assembly of the first ISS modules. Astronauts would later finish performing the necessary assembly connections.

c) **Crew Transfer:** A Crew Transfer Vehicle (CTV) with astronauts on board will be launched into LEO. It will dock with assembled spacecraft ICT+ CLS/CAV + Power + Propulsion. Astronauts will transfer from CAV to ICT during traveling into Low Lunar Orbit (LLO).

d) **Trans-Lunar Injection:** The Propulsion module will provide a necessary impulse to insert the assembled vehicle into a trans-lunar trajectory.

e) **Low Lunar Orbit Insertion:** Upon arrival to the vicinity of the Moon, the Propulsion module will slow down the spacecraft for Lunar capture and insertion into a LLO.

f) **Descent to Lunar Surface:** Astronauts will transfer into the CSL/CAV for descent to the surface. The CSL/CAV undocks from the larger vehicle, leaving ICT, Power, and Propulsion modules in LLO for the duration of the surface mission. Descent and landing on the Moon of the crew using autonomous, precise and soft landing capabilities.

g) **Arrival on Surface:** Astronauts will transfer from CSL/CAV to LSHS. The crew will use this LSHS as living quarters for the duration of the mission.

h) **Lunar Surface Stay:** During the mission, many activities will be performed to test operations, scientific procedures and other activities to be later performed on the Mars mission.

i) **Ascent from Lunar Surface:** At the end of the surface stay, the astronauts will launch from the lunar surface using the CAV into LLO. The CAV will phase orbit and dock with the ICT. Astronauts will transfer from LAM into ICT for the return trip.

j) **Return Flight to Earth:** Using the Propulsion module, the ICT will perform the trans-Earth injection reaching LEO. A LEO insertion maneuver will take place upon arrival to the Earth's vicinity.

k) **Return to Earth Surface:** Using the CTV, all astronauts will undock from ICT, leaving the latter for the following lunar missions. The CTV will reenter the atmosphere and will perform a autonomous soft landing on Earth.

Figure 5-13 shows the mission sequences for the short-stay and long-stay human mission.

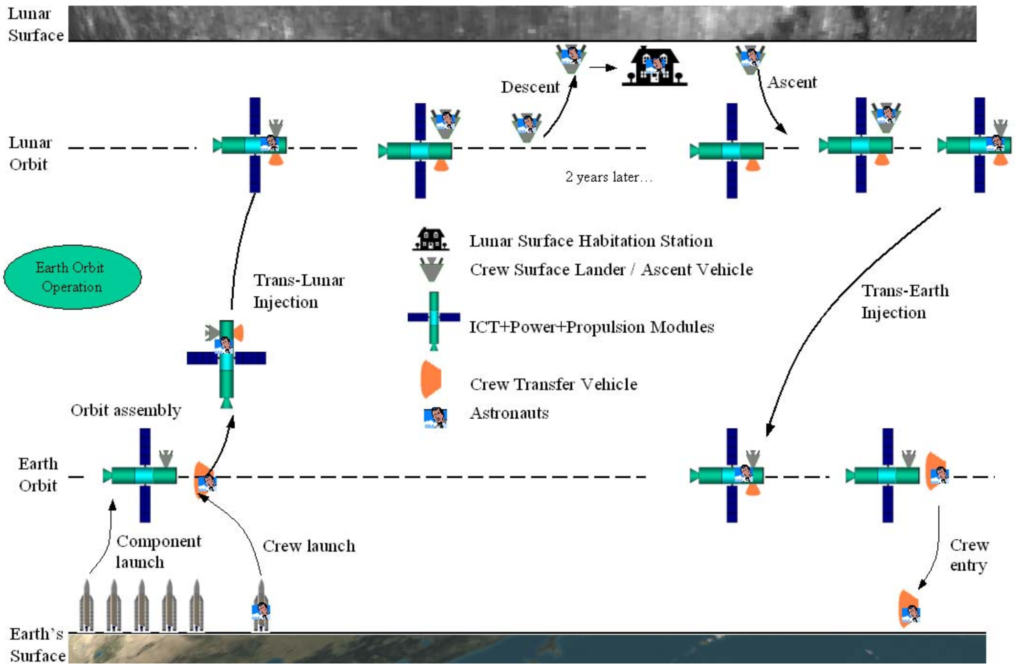

Figure 5-13 Short-Stay Human Lunar Missions (SSHLM 14 days) and Long-Stay Human Lunar Missions (LSHLM 2 years)

Mission Alternatives

A possible mission scenario alternative would be to use a proven vehicle (Soyuz capsule) to perform the ascent and descent between Earth and LEO. In this scenario the Soyuz vehicle would de-orbit into Earth orbit while the modules are transferred into Trans-Lunar orbit. A second Soyuz capsule would be launched at to return the crew to Earth. As Soyuz is designed to transport only three crew members, four Soyuz spacecraft would be needed for each mission.

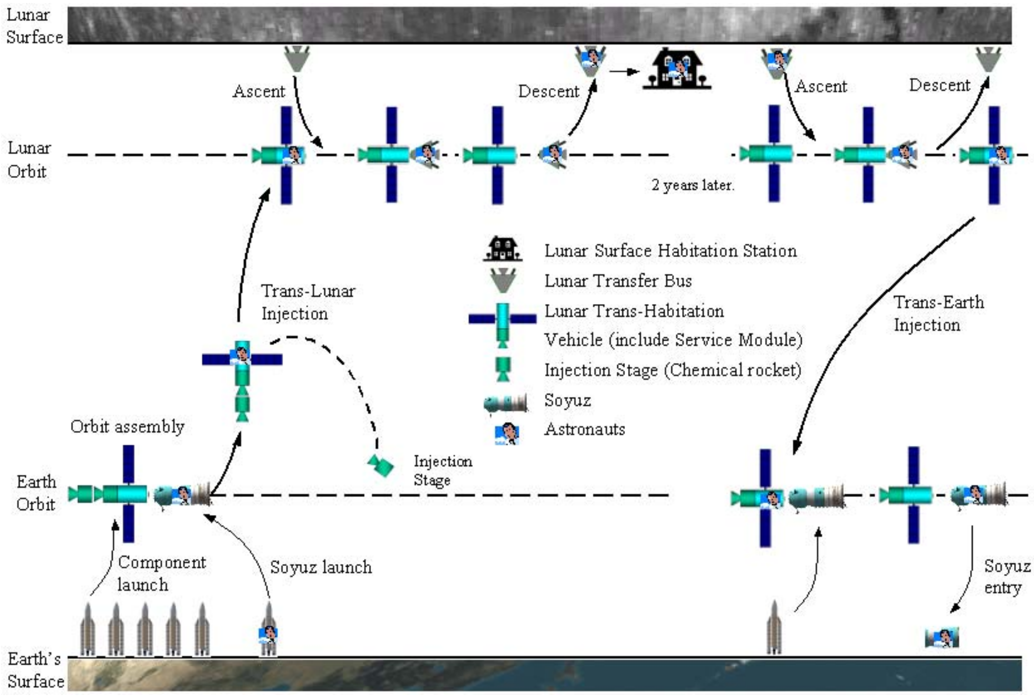

Figure 5-14 Alternative for LSHLM (2 years) using Soyuz

Also, a permanent Lunar Transfer Bus (LTB) could be parked on the surface of the Moon, with the purpose of performing the transfers between the lunar surface and lunar orbit.

Another suggested alternative is the use of Nuclear Thermal Propulsion. The advantages of NTP are mitigated by numerous material compatibility issues. The heated hydrogen tends to erode the reactor fuel core, and as with any nuclear reactor there is a high level of high-energy radiation emitted, which severely constrains the design and configuration of the overall vehicle. Although the higher specific impulse does offer the capability to carry more payload or less fuel, the improvement in overall performance as compared with chemical propellants is not as great as might be suggested from consideration of the improved specific impulse. Because of the weight of the reactor and associated structure, the thrust-to-weight ratio of an NTP system will be substantially poorer than for a chemical system, nullifying part of the presumed payload advantage. Even with these reservations, the potential of NTP as a tool in the exploration of the solar system is enormous, and it has been recognized as such for decades. If these obstacles are overcome, NTP should be used for the lunar mission, to reduce the overall mass budget. In any case, this technology will be necessary for a human mission to Mars.

Exploration Transfer Vehicle

The Exploration Transfer Vehicle (ETV) is a manned spacecraft based on the concept of modularity and it is considered the key element for future human exploration of the Moon and Mars. Its modularity allows it to be used flexibly for different missions and destinations. Depending on the destination and the requirements of the mission it can be upgraded adding different elements.

The short and long human missions to the Moon will be performed using the ETV model presented in Figure 5-15.

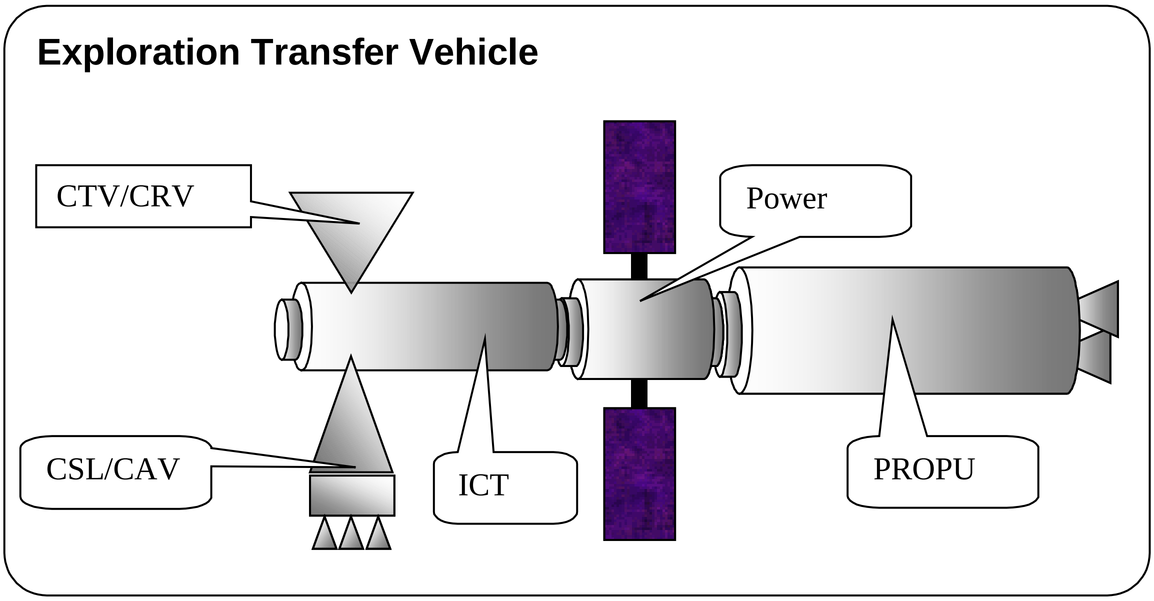

Figure 5-15 Exploration Transfer Vehicle Configuration

It will consist of the following modules:

- **Crew Transport/Return Vehicle (CTV/CRV):** This module is used to transport the crew from the Earth surface into LEO assembly orbit and to return the crew safely after interplanetary flights to the Moon.
- **Interplanetary Crew Transport Vehicle (ICT):** This module provides the necessary living area and required LSS capabilities during interplanetary flight to the Moon. It is sized for the transportation of six humans. Its modularity allows for a

smaller version for a short stay on the Moon with a smaller crew, or the possibility of using two elements for longer trips.

- **Crew Surface Lander/Crew Ascending Vehicle (CLS/CAV):** This module provides the necessary capability to land on the Moon and ascend from it. The descent stage will be left on the Moon's surface. The same concept can be adopted for a Mars mission, with a different descending stage for shielding and parachutes for the martian atmosphere.
- **Propulsion Unit (PROPU):** The PROPU module provides the required propulsion system to transfer the ETV to the Moon and eventually to Mars. The module will consists out of two major elements, a tank and the engine section. Both elements should be designed for reuse.
- **Power Unit:** The power unit provides all required power on board necessary for the ETV. Advanced triple junction solar cells or fuel cells can be considered as power sources.

According to the mission phases described above the following mass budget has been calculated both for a NTP engine and for a chemical engine considering a ISP=900s for the NTP and a ISP=320s for the chemical propulsion system. In addition the following assumptions (**Table 5-10**) have been employed for the mass budget calculation according to using empirical equation based on historical data (Larson and Pranke 1999).

Table 5-10 Assumed Parameters for System Analysis.

Parameter			Reference
Mission			
Crew Size	6	**Human**	
Average Crew Mass	100	**kg / Human**	
Transfer Time Outbound	6	**days**	
Transfer Time Inbound	6	**days**	
Surface Stay	450	**days**	
Volumes			
Volume Capsular	3,35	**m^3/Human**	Apollo Lander
Volume Transfer Module	10	**m^3/Human**	
Volume Habitation Module	50	**m^3/Human**	
Mass Panelties			
Pressurized Transit	153,00	**kg/m^3**	see table to right
Pressurized Surface	160,00	**kg/m^3**	
Unpressureized Transit	75,00	**kg/m^3**	
LSS Structure Mass	31,10	**kg / Human**	Apollo Lander
LSS Resupply	6,22	**kg / Human / day**	Apollo Lander
Propulsion System	Isp		
Chemical	320,00	**sec**	MMH / NTO
Nuclear Reactor	900,00	**sec**	
Solar Cells	**Efficiency**	**Weight (kg/m^2)**	
Advanced Triple-Junction (ATJ)	27,50%	0,84	EMCORE (Cell Producer; space qualified)
≅v			
LEO -> LLO	4,10	**km/sec**	Human Space Flight, p. 276
LLO -> LS	1,88	**km/sec**	Human Space Flight, p. 276
LS -> LLO	1,83	**km/sec**	Human Space Flight, p. 319
LLO -> LEO (Aerocapture)	1,01	**km/sec**	Human Space Flight, p. 277
LLO -> LEO (Propulsive)	4,11	**km/sec**	Human Space Flight, p. 277
LLO -> Earth Direct Entry	0,93	**km/sec**	Human Space Flight
Margin			
Volume Margin:	0%		
Mass Margin:	15%		
LSS Margin:	0%		
Constant			
Gravity Constant	9,80	**kg*m/s^2**	
Solar Constant S_0	1.350,00	**W / m^2**	

Human Space Flight, p. 257		
US-Lab	126,44	**kg/m^3**
US-Hab	184,33	**kg/m^3**
JEM-Lab	121,96	**kg/m^3**
COF	181,82	**kg/m^3**
	153,64	**kg/m^3**

Element	Mass
CTV/CRV	8000 kg
ICT	11000 kg
CLS/CAV	32000 kg
POWER	6500 kg
PROPU	54000 kg
Total Mass	**110000 kg**

Table 5-11: Mass Budget, NTP

Element	Mass
CTV/CRV	8000 kg
ICT	11000 kg
CLS/CAV	32000 kg
POWER	6500 kg
PROPU	230000 kg
Total Mass	**290000 kg**

Table 5-12: Mass Budget, Chemical Propulsion

The mass budget in Table 5-11 and **Error! Reference source not found.**, which consider a 15% margin, shows clearly the advantages of the NTP solution. Although both cases imply very high masses compared to the current launching capability and a high precision and reliable autonomous rendezvous and docking system, the solution with chemical propulsion would require a higher number of launches, mostly of propellant tanks, which results in an additional overall risk.

Lunar Surface Operations and Testing

The long-duration human mission to the Moon will closely emulate a long-duration mission to Mars. Medical topics, operational procedures as well as numerous technologies will be tested and verified including but not limited to

- surface stay countermeasures,
- social activities,
- inflatable structures,
- building construction using regoliths, and
- food production and storage using the greenhouse.

These issues are described in detail in Chapter 4 , Chapters 5.3.2 and 5.3.3. For the long-duration mission general assumptions on martian day cycle, artificial communication time delay or planetary protection and decontamination procedures as given in Chapter 4.3 have been taken into account.

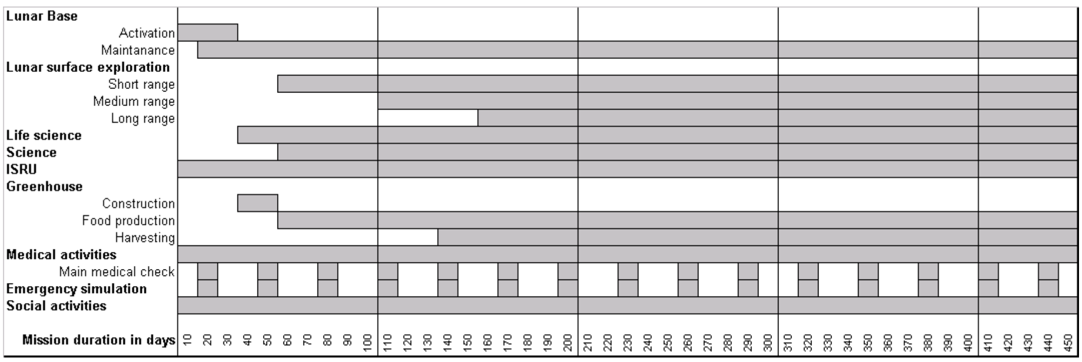

Figure 5-16 Long Duration Lunar Mission, Lunar Surface Operations Timeline.

The identified main activities on the lunar surface throughout the 450 day mission duration are given in the timeline in Figure 5-16. It is assumed that a preparation mission would have already set-up ISRU equipment and this equipment would be up and running by the time of crew arrives.

One of the first crew tasks will be to activate and maintain the base. This activity will include moving the different habitation modules and connecting them as required. A check-out of the base will be necessary before moving in. After activating the lunar base, all modules and elements have to be maintained during the overall mission. The modules and elements should be designed in such a way that their maintenance time will be minimized.

On the lunar surface, the crew will have to perform emergency training specific to surface exploration activities. This training has to be repeated periodically. These activities and procedures will be tested already during the short-stay human mission.

After activation of the main base, life science experiments can be started. Parallel to this the greenhouse can be constructed and activated. The greenhouse will provide fresh fruits and vegetables for the daily diet. Fresh fruits and vegetables grown on the Moon can supplement the diet brought from Earth, as the mass penalties for growing crops like peanuts or wheat will be to high. The maximum reasonable percentage provided by the greenhouse is between 50%-70% depending on the selected diet (Schiffner 1999).

To gain and build up experience in the field of surface exploration short-, medium- and later in the mission long range expeditions will be undertaken. These surface activities will be started after the base is operational and the crew was able to adopt to the new environment. In particular medium and long range expeditions will require surface mobility units (SMU). These SMU must provide pressurized habitation capabilities for traveling several days.

The science activities will be conducted not only within the base area but also during exploration expeditions on the lunar surface. These science activities will be used to gain operational capabilities for later exploration of Mars. This can include geological and biological experiments.

Among all the previously described elements, the social component is one of the most important. The crew should have access to the following:

- regular contact with family and friends
- sports
- social crew activities

Social Aspects

One possible societal mission is to assemble monuments, previously built in robotic missions, as a symbol for the beginning of new civilizations on the Moon. Another possible societal mission is one that stamp messages from human visitors, expressing new understandings of us in space age, on the surface of the Moon, completing the sequence of messages, already stamped in robotic missions prior to the human missions. Some examples are shown in Figure 5-17.

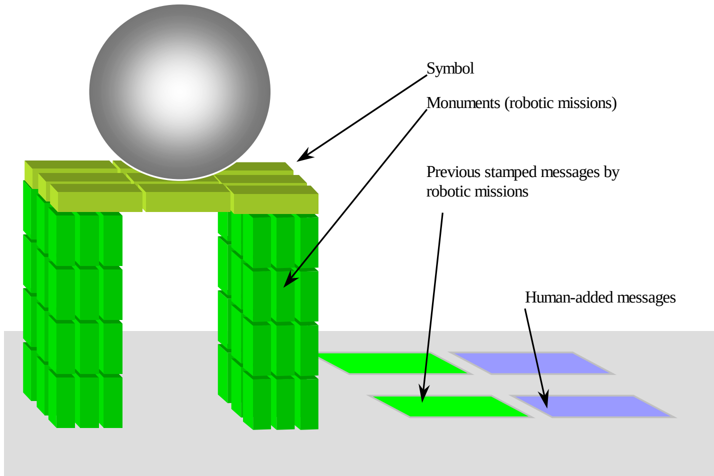

Figure 5-17 Social Mission

5.3.6 Medical and Psychological Aspects of Rehearsal Lunar Missions

Medical and psychological issues are of the highest priority to enable human missions to the Moon and Mars. Although many inferences can be made from our experiences in low Earth orbit, interplanetary exploration adds novel challenges because of its duration, the inability to retreat to the Earth, and exposure to new gravitational and radiation environments. Microgravity research will contribute to these advances, however this section will focus on aspects that can be best tested on the Moon in preparation for a mission to Mars.

Radiation

Acute and chronic radiation exposure outside of the Earth's magnetosphere is a possible showstopper for any long duration mission (Charles 2003). The astronauts on a mission to a lunar base will be unavoidably exposed to ionizing radiation as they pass through the Earth's proton belt and the outer electron belt. This exposure is however brief, and the major problem will be exposure to the constant isotropic flux of galactic cosmic rays (GCR) and the potentially lethal radiation of a Solar Particle Event (SPE).

To avoid acute exposure, warnings of an imminent SPE must be obtained through solar weather monitoring, and the crew will need a "storm shelter" to inhabit for the duration of the event. Chronic low dose radiation exposure due to GCR increases oxidative stress and DNA mutation rates leading to an elevated incidence of cancer and lenticular cataracts as well as germ-line mutations (Jones 1999). The uncertainties listed by the National Council of Radiation Protection and Measurements (NCRP) for incidence of cancer on exploratory class missions may be as high as a factor of four (NCRP Report 1989). In this context, in order to meet the "as low as reasonably achievable" NASA criterion, shielding technologies need to be improved or greater risks accepted.

The crew on an initial lunar expedition will have to establish a safe haven and initiate radiation monitoring in different lunar locations. Phantom torso experiments should be repeated on the lunar surface to obtain organ specific measurements in various shielding environments (Badwhar 2002), and other experiments to measure radiation and biological dosage should be performed early on. These data can be used to produce more accurate shield requirements for future missions.

Acute radiation exposure may have immediate dramatic consequences on the mission. To date, most of our medical capabilities have focused on prevention and symptomatic treatment. The severity of symptoms increases proportionally with radiation dose. Preventative medications have been suggested to enhance cellular protective mechanisms. Two approaches are suggested:

1) Regular intake of medications to minimize the impact of chronic radiation exposure, however this method is associated with possible medication side effects.
2) Event dependant intake to try to minimize the damage of an SPE used in association with maximal shielding understanding the limited additional benefits. However, these medications are most effective when initiated well before the radiation exposure occurs, again requiring early warning of an SPE.

The most appropriate cocktail of medications and the pharmacological action of those drugs in space remains to be shown (Jones 1999). Once acute exposure has occurred, the treatment will be symptomatic (Mettler 2002).

Surface Stay Countermeasures

More then 40 years of research in low Earth orbit has generated much insight into physiological adaptation to microgravity and its implications for long-term missions. The need for adequate countermeasures is clearly established, but major shortcomings are highlighted by the most recent data of crewmembers on the ISS (Kozlovskaya 2004) and the scarcity of information on reduced gravitational environments such as the Moon (1/6 g) and Mars (3/8 g) in contrast to 0g.

Kozlovskaya's study reveals that bone demineralization is still a major concern for prolonged microgravity exposure. Among the eight Russian cosmonauts studied, an average rate of 1%/month decrease in bone density was documented with current countermeasures. This will increase the risk of fractures once exposed to the gravity of the planetary surface and a more physical workload. Experiments on rats in the ISS with intermittent centrifugation showed bone mass conservation (Rubin 2001). This advocates for research on human bone density variation following intermittent short arm centrifugation in both microgravity and lunar gravity (1/6 g).

Compliance with exercise countermeasures needs to be addressed for long-duration missions. None of the Russian cosmonauts studied on the ISS achieved the challenge of exercising twice a day for one hour. Three of the eight cosmonauts fulfilled no more then 50% of the suggested training program (Kozlovskaya 2004). These observations stress the importance of adapting training requirements to include psychological motivators to improve compliance. Examples include interactive games requiring cycling or running, and possibly adding a competitive factor, to appeal to the ambitious nature of astronauts.

Lunar surface-stay studies monitoring the status of the crewmember's condition, including muscle atrophy, endurance and bone density, as well as other biological experiments, can be used to improve lunar surface countermeasures and training programs. Data from 0 g, 1/6 g and future centrifugation experiments, may allow better understanding of the degree of physiological deterioration and what the best countermeasure regime would be for a surface stay on Mars.

Crew Physician Training

Considering the prolonged isolation of the crew and unavoidable communication delays with Earth, it is essential that the Crew Medical Officer (CMO) be a cross-trained physician with surgical skills. Contingency plans should include another crewmember knowledgeable in medicine and a medical expert computerized system. Despite the demands of astronaut training, the schedule of the crew physician (CMO) should include regular exposure to clinical medicine before departure and virtual practice of skills during the mission. Updated medical database and self-evaluation resources should be provided.

Medical Infrastructures and Procedures

Self-sufficient medical infrastructures and procedures must be adapted for ambulatory and critical care provision in reduced gravity environment. The medical infrastructure requirements should be based on the level of health risk accepted by the mission, considering the number of crewmembers that can receive care at once and the duration of pre-determined treatment protocols.

Physiological and clinical experiments could be conducted on the Moon to evaluate diagnostic and treatment procedures. For example testing how ultrasound diagnosis is affected or how to perform CPR in low gravity could be investigated in preparation for a Mars mission. Also the physiological responses to pathological insults such as hemorrhage may be altered in 1/6 g and should be investigated to provide better treatment protocols.

Particular attention to triage scenarios in the context of mass casualties is relevant to long-term missions rehearsal. Trauma is possible considering the nature of the work required of astronauts once on the lunar surface for a prolonged period of time. Animal research conducted in the reduced gravity environment should be used to investigate fracture and wound healing. If medical therapies fail to work, surgery should then be considered where appropriate. How to perform surgery in reduced gravity, including blood containment methods can be rehearsed on the Moon through animal surgery.

Preventative medicine should be emphasized. The need for regular medical and psychological evaluation is paramount to mission success and research in human adaptation to long-duration missions. Surgical prophylaxis such as appendectomy or wisdom teeth removal should be considered prior to flight.

Palliative Care, Euthanasia and Death

Standards must be determined for withdrawal of care and institution of palliation and pain management. A discussion of the very controversial topic of euthanasia could be addressed in the context of prolonged suffering and limited resources (Wilson 2000; Singer 1990). As their will be no abort option on a mission to Mars, the mission and survival of the crew should have higher priority than the life of an individual crewmember, leading to difficult ethical decisions. If death occurs, the body must be disposed from the spacecraft. Due attention to psychological and emotional effects of death on the rest of the crew must be considered.

Sexuality and Birth Control

Sexual health of astronauts is one of the most unexplored territories of human adaptation to space, yet it is one of the fundamental aspects of human interactions. Sex will inevitably happen in space, as crews live for years in close contact. The physical and psychological implications of sexuality during long-duration missions must be examined and an adequate environment for healthy sexual interaction of astronauts provided (Sturgeon 1992).

Human reproduction in space is a very poorly studied field but with serious consequences for the fetus, the mother and the mission. No data exists regarding the development of a human fetus or neonate exposed to reduced gravity or space radiation, but based on animal data in LEO, development may be seriously affected. During a long-term mission, any pregnancy would jeopardize the integrity of the mission, limit or even threaten the life of the mother, and require unplanned resources. Thus, birth control measures must be considered. Hormone-based contraception has never been formally tested in space and is dependant upon human reliability. Sub-dermal contraceptive implants, such as levonorgestrel, could alleviate the issue of human reliability providing 5 years of effective contraception on Earth. However, its efficacy in space has never been assessed. Barrier methods have variable effectiveness but are also flawed by their dependence upon human reliability. Intrauterine devices (IUD) have not been formally studied and concerns about infections and increased rate of ectopic pregnancies are significant. The most reliable and definitive option may be surgical sterilization, which could be considered until further studies are conducted on other contraceptive methods in microgravity.

Psycho-social Stressors, Crew Selection, and Interaction

Analogue studies on the Earth and ISS are used to assist in speculating about long-term exploration missions (Table 5-13). Only five Russian astronauts have lived in space more then a year with a maximal length of stay of 438 days. Prolonged isolation and limited communication with Earth, a small crew, lack of privacy and high level of autonomy without return options are significant stressors that will be assessed on the Moon.

Table 5-13 Comparison of psychological relevant factors for different missions

Comparison of psychologically relevant features of orbital space missions, exploratory missions to Mars and winter-over in Antarctica

	Orbital ISS Missions	Mars Mission*	Winter-over in Antarctica
Duration (in months)	4–6	36	10–14
Distance to Earth (km)	300–400	60–400 million	—
Transfer times to/from destination	1–2 days	200–300 days	2–3 days
Crew size	3–6	6	15–100
Degree of isolation and social monotony	Low to high	Extremely high	Medium to high
Crew autonomy	Low	Extremely high	High
Evacuation in case of emergency	Yes	No	No
Availability of mission support measures:			
• ground-based monitoring	Yes	Very restricted	Yes
• 2-way communication	Yes	Very restricted	Yes
• E-mail up-/downlink	Yes	Yes	Yes
• Internet access	Yes	No	Yes
• Onboard entertainment	Yes	Yes	Yes
• Re-supply flights	Yes	No	No
• Visiting crews	Yes	No	No
Visual link to Earth	Yes	No	Yes

*Based on features of the 1000-day reference missions defined by NASA and ESA [2,3].

Very limited data exist on the most resilient human traits best suited for such conditions. Furthermore, individual crewmember characteristics can only be selected in relation to group dynamics, including particular concerns for age, gender distribution, and cultural belief (Ursin 1992). Essential coping strategies will need to be established individually and collectively ahead of time due to communication restraints with Earth. For example, training on how to deal with the death of a crewmember and the necessary mourning strategies could be implemented. Some astronauts should be cross-trained in clinical psychology to support group interactions and therapy.

The high level of autonomy and isolation are predisposing factors to the development of "groupthink" (Janis 1982). This phenomenon is characterized by idealization of the team and devaluation of ground control. Associated with high group pressure towards uniformity, this can seriously impair the quality of decision-making, and lead the group to disregard essential information. Alleviating strategies could be rehearsed on the Moon to avoid this issue.

The location of a south pole lunar base could be selected to minimize visual contact with Earth and study the impact of a speculated "Earth-out-of view phenomenon." Losing visual contact with Earth may increase the feeling of isolation and may lead to maladaptive responses, which cannot be predicted unless tested on the Moon or on the first mission to Mars (Manzey 2004).

Psychological countermeasures and Performance

Psychological countermeasures presently include monitoring and support. The mental health of astronauts is carefully evaluated on the ISS by regular private psychological conferences. The Russians studied voice intonation as an indicator of the psychological state of astronauts (Johannes 2000). Regular communication with family, crew visits and delivery of gifts from Earth is routinely used to alleviate the monotony, boredom and social isolation of long missions. However, most of those strategies cannot apply to a Mars mission. Thus, Mars-specific countermeasures will need to be tested on the Moon. E-mail may be the best medium for communication on long-term exploration missions (Gushin 1997). Sensory stimulation (i.e. interesting food and music), the architecture of the spacecraft and lunar base (i.e. private and quiet individual quarters), and balanced work and rest schedules with planned recreational activities are essential to the psychological well being of astronauts. The mental health of the crew directly affects the astronauts' performance, their compliance to the training program, and the integrity of the entire mission.

Psychiatric Emergencies

Despite rigorous selection criteria of astronauts for adaptive traits and against psychiatric pathologies, the impact of prolonged isolation and constant exposure to multiple stressors may trigger maladaptive psychological responses. Training, medication and restraints should be provided to face psychiatric emergencies such as mood disturbances, adjustment disorders and psychotic events. Other concerns threatening the mission include suicidal attempts (Krug 1998) or possible homicide, as well as sedation misuse affecting crewmember performance.

5.3.7 Cost Analysis Aspects

A fundamental cost analysis is of great importance for decision-making parties for complex, multi-national programs such as the ISS or the described LunAres Program.

Past experiences have shown that poor or misused cost estimates as well as the improper use of cost and budgetary data can cause serious problems for projects, the involved parties, and consequently to the taxpayers. In the context of this report a number of important points shall be raised to take into account a more detailed analysis.

It goes without saying that the composition of countries for such a mission is the major driver. The choice of companies will also influence the final price to be paid by the undertaking agencies or organizations. Technological capabilities, industrial strength, political and economic stability, overhead and labor costs are different for diverse countries and companies. Therefore costs for a specific system can easily vary by a factor of 10. It will be one of the first steps to clearly identify which company in which country can provide which element of the missions.

To achieve the best value-for-money ratio, an independent group should be set up to perform an unbiased life cycle costing exercise from the very beginning of the program. In continuation to this a cost development monitoring process should be implemented where in an optimal scenario all participating parties cooperate. Surely cost and money are delicate fields but they are clearly a driver for an optimized most advantageous iterative mission design processes.

5.4 Recommendations

In conclusion, the following is recommended, based upon the analysis presented in this chapter.

Recommendation 5-1: Establish an international coordinating body, the Space Exploration Forum, composed of a Legal Advisory Board, a Technical Advisory Board, and a Social Outreach Advisory Board, whose roles are to:

(a) facilitate non-binding legal agreements between cooperating nations.

(b) create and administer a database that the SEF will use to make recommendations regarding the alignment of lunar and martian exploration activities.

(c) maintain an international standard for technical interfaces.

(d) coordinate public inspiration and outreach activities to be conducted as an important component of lunar and martian missions.

(e) maintain contacts among space agencies, industry, the media, and advocacy groups.

Recommendation 5-2: Choose one or more potential transition or exit strategies to be implemented upon the completion of the lunar rehearsal program. These strategies should be designed to ensure the availability of resources for Mars exploration while supporting, to the greatest extent practical, a sustained presence on the Moon.

Recommendation 5-3: Define clear conditions and timeframes under which stakeholders can terminate, change, or reevaluate their contributions to an exploration program.

Recommendation 5-4: Design the lunar rehearsal program with four mission types: robotic missions, preparation missions, short-stay human missions, and long-stay human missions.

Recommendation 5-5: Prioritize operational issues in the lunar rehearsal program.

Recommendation 5-6: Design robotic technologies with common interfaces so that they can be adapted for use in multiple missions.

Recommendation 5-7: Rehearse only one innovative technology during each mission, and assign each mission according to the particular capability that it is demonstrating.

Recommendation 5-8: Pursue the development of automated docking capabilities for use in highly elliptical orbit.

Recommendation 5-9: Pursue the development of a new heavy lift capability (at least 100 tonnes) to LEO.

Recommendation 5-10: Pursue the development of nuclear thermal propulsion.

Recommendation 5-11: Implement modularity in mission design.

Recommendation 5-12: Develop radiation shielding as well as methods to monitor its efficiency. Improve methods of prevention and treatment procedures for the effects of radiation.

Recommendation 5-13: Conduct studies on the Moon to determine the effects of reduced gravity on human physiology. Validate potential countermeasures on the Moon.

Recommendation 5-14: Conduct studies to help ascertain psycho-social effects of isolation on the lunar surface. Develop countermeasures for these effects, and design management strategies for handling psychiatric emergencies.

Recommendation 5-15: Validate reduced-gravity medical procedures on the Moon.

Recommendation 5-16: Undertake an independent, unbiased life-cycle costing exercise from the beginning of the program. Implement a continuous independent cost-development monitoring process to achieve a best value-for-money ratio.

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Chapter 6

CONCLUSION AND RECOMMENDATIONS

Destiny is not a matter of chance. It is a matter of choice. It's not a thing to be waited for – it is a thing to be achieved.

William Jennings Bryan

6.1 Conclusion

Space activities are inherently complex enterprises from a technical, political, legal, social, and international perspective. This is especially true for an international program of lunar rehearsals in preparation for Mars. Careful planning is essential for the success of such a program. The goal of this report has been to serve this need for planning by recommending a framework in which to implement the program. This framework includes:

- a list of enabling concepts for human Mars exploration that can be rehearsed in the context of near-term lunar missions;
- a series of robotic and human lunar missions in which to carry out those rehearsals;
- and the relevant policy, legal, and social issues that must be considered for the program.

This information alone does not provide policy-makers with concrete actions to be taken to implement the program in a sustainable way. Therefore, the report has provided a series of recommendations at the end of each chapter that are meant to aid in the decision-making process.

The baseline human Mars mission (HMM) used in this report to determine the enabling elements for the initial mission was selected under the assumption that this mission will serve as the beginning of a sustained presence on the planet. Because political will is subject to change over time, the purpose for the first human mission to Mars may have changed by the time the mission is actually conducted. If this leads to the need for a different baseline HMM, the enabling elements could change as well.

The recommendations outlined below include measures to handle uncertainties. They are intended to serve as a basis for consideration in the design of a flexible program. With a coordinated stepwise approach, the international community will be able to ensure humanity's expansion to the Moon and eventually to Mars.

6.2 Recommendations

Each chapter of the report has provided a concise set of recommendations based on the analysis of that chapter. This section provides a listing of all of the report's 28 recommendations in a way that allows cross-referencing with the associated chapters. The recommendations are:

Recommendation 2-1: Establish a multilateral exploration panel to collect and disseminate information related to exploration of the Moon and Mars. This panel, composed of representatives from all space agencies, will promote and coordinate international collaboration on lunar and martian missions.

Recommendation 2-2: Augment NASA and ESA human lunar exploration objectives by utilizing robotic capabilities under development in other nations.

Recommendation 3-1: Revise or rewrite the Moon Treaty, possibly using the Part XI Agreement of the U.N. Convention on the Law of the Sea (UNCLOS) as a basis. Incorporate language that addresses liability and environmental concerns. Consider implications of the treaty for Mars exploration.

Recommendation 3-2: Enhance public outreach programs through educational simulations and societal missions.

Recommendation 4-1: Test on the Moon those elements of a human Mars mission identified as best suited to lunar rehearsal.

Recommendation 4-2: Investigate further potential for lunar rehearsal of human Mars mission elements as mission designs and technologies progress and as new information on the martian and lunar sites becomes available.

Recommendation 4-3: Emphasize human-driven mission elements, including psycho-social issues, medical factors, and operations.

Recommendation 4-4: Rehearse planetary protection procedures and technologies.

Recommendation 4-5: Demonstrate both operational and technical implementation of *in situ* resource utilization (ISRU) on the Moon while paying special attention to the aspects that are transferable to Mars and favoring approaches that support a sustained presence on the Moon.

Recommendation 4-6: Conduct lunar science that yields knowledge useful to preparation for a human Mars mission, contributes to sustainability by attracting public support, or promises significant scientific return at a relatively small additional cost.

Recommendation 4-7: Evaluate during lunar missions the utility of quadrupolar probes, ground penetrating radar, and orbital sounding radar instruments for examining the water content of the martian subsurface.

Recommendation 4-8: Develop an optimized 3-D imaging LIDAR system for descent and landing procedures. To the extent possible, demonstrate the applicable capabilities of this technology on the Moon.

Recommendation 5-1: Establish an international coordinating body, the Space Exploration Forum (SEF), composed of a Legal Advisory Board, a Technical Advisory Board, and a Social Outreach Advisory Board, whose roles are to:

(a) facilitate non-binding legal agreements between cooperating nations.

(b) create and administer a database that the SEF will use to make recommendations regarding the alignment of lunar and martian exploration activities.

(c) maintain an international standard for technical interfaces.

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Recommendation 5-15: Validate reduced-gravity medical procedures on the Moon.

Recommendation 5-16: Undertake an independent, unbiased life-cycle costing exercise from the beginning of the missions. Implement a continued independent cost development monitoring process in order to achieve a best value-for-money ratio.