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ANALYSIS OF THE SYNTHESIS GROUP'S *MOON TO STAY & MARS EXPLORATION* ARCHITECTURE

January, 1992

NASA

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FOREWORD

The NASA activity to analyze the ***Moon to Stay and Mars Exploration*** architecture as proposed by the Synthesis Group began in October, 1991. An agency-wide team led by the Exploration Programs Office (ExPO) worked through December to implement the strategies suggested by the Synthesis Group. The present document is the result of that study.

Many persons performed analyses and wrote segments of this document. The key points-of-contact on the NASA team in various disciplines included:

Planetary surface systems	JSC/John Connolly
Space transportation systems	MSCF/Phil Sumrall
Earth-to-orbit transportation	MSCF/Phil Sumrall
Robotic, precursor missions	JPL/Richard Wallace
Power and propulsion	LeRC/Bob Cataldo
Orbital nodes	LaRC/Vern Gillespie
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Science	ExPO/Nancy Ann Budden
Human support	ExPO/Brenda Ward
Technology/advanced development	ExPO/Alex Dula
Operations	ExPO/Jerry Bell

Ms. Lisa Guerra and Mr. John Gruener of ExPO contributed immensely to this document both by authoring several sections and by technically reviewing many inputs.

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Lastly, please allow me to express my personal appreciation to the many members of the NASA team across the Centers for their time, effort, and excellent contributions to the analysis of the ***Moon to Stay and Mars Exploration*** architecture.

--David Kaplan

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LIST OF ACRONYMS

AAGRA	Architecture Analysis Ground Rules and Assumptions
ARC	Ames Research Center
ATDRSS	Advanced Tracking and Data Relay Satellite System
CO	Communication Orbiter
COMPLEX	Committee on Planetary and Lunar Exploration
CRV	Crew Return Vehicle
CTV/KS	Cargo Transfer Vehicle/Kickstage
DIPS	Dynamic Isotope Power System
DOE	Department of Energy
DSN	Deep Space Network
ECLSS	Environmental Control and Life Support System
EDO	Extended Duration Orbiter
EMS	Electromagnetic Sounding
EMU	Extravehicular Mobility Unit
ESDB	Element Systems Data Base
ETCC	Exploration Technology Coordinating Committee
ETO	Earth-to-Orbit
EVA	Extravehicular Activities
ExPO	Exploration Programs Office
g	gravity
GPS	Global Positioning System
HLLV	Heavy Lift Launch Vehicle
IMLEO	Initial Mass in Low Earth Orbit
IOC	Initial Operational Capability
IS	Information System
ISP or I_{sp}	Specific Impulse
ISRU	In-Situ Resource Utilization
IVA	Intravehicular Activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
L/D	Lift-to-Drag Ratio
LaRC	Langley Research Center
LEO	Low Earth Orbit
LeRC	Lewis Research Center
LEV	Lunar Excursion Vehicle
LEVPU	Lunar Excursion Vehicle Payload Unloader
LLO	Low Lunar Orbit
LOI	Lunar Orbit Insertion
LORAN	Long Range Navigation System
LOX	Liquid Oxygen
LOX/LH2	Liquid Oxygen/Liquid Hydrogen
LOX/RP	Liquid Oxygen/Rocket Propellant #1
LTS	Lunar Transportation System
LTV	Lunar Transfer Vehicle
MCO	Mars Communication Orbiter
MECO	Main Engine Cut Off
MESUR	Mars Environment Survey
MEV	Mars Transportation Vehicle
MCO	Mars Communications Orbiter
MLT	Mobile Launch Transporter
MOC	Mars Orbit Capture
MRS	Mars Relay Satellite
MRVR	Mars Surface Rovers
MSFC	Marshall Space Flight Center
MSRO	Mars Site Reconnaissance Orbiter
mt	metric tonnes
MTV	Mars Transfer Vehicle
NEP	Nuclear Electric Propulsion
NERVA	Nuclear Engine for Rocket Vehicle Applications
NLS	National Launch System
NOC	Next Operational Capability
NPO	Nuclear Propulsion Office
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket
OMS	Orbital Maneuvering System
P/L	Payload
PBR	Particle Bed Reactor
PI	Principal Investigator
PLSS	Portable Life Support System
PSS	Planetary Surface Systems
PSS-ST	Planetary Surface Systems (JSC) - Space Transportation (MSFC)
PV	Photovoltaic
PVA	Photovoltaic Array
q	dynamic pressure
RCS	Reaction Control System
RF	Radio Frequency
RFC	Regenerative Fuel Cells
RFP	Request for Proposal
RTG	Radioisotope Thermal Generator
SEI	Space Exploration Initiative
SEP	Solar Electric Propulsion
SG	Synthesis Group
SPE	Solar Proton Event
SR	Sample Return
SRO	Site Reconnaissance Orbiters
SSF	Space Station Freedom
ST	Space Transportation Office (MSFC)
STME	Space Transportation Main Engine
STS	Space Transportation System
STV	Surface Transportation Vehicle
TBD	To Be Decided
TEI	Trans-Earth Injection
TLI	Trans-lunar Injection
TPS	Thermal Protection System
TRL	Technology Readiness Level
VAB	Vertical Assembly Building
VIF	Vertical Integration Facility

1.0 INTRODUCTION

The purpose of the Architecture Analysis White Papers is to document the results of the NASA's effort to analyze the architecture recommendations of the Synthesis Group. In *America at the Threshold: America's Space Exploration Initiative*, the Synthesis Group outlined four different possible approaches for carrying out the Space Exploration Initiative (or, alternatively, the Mission From Planet Earth). These approaches are defined as architectures, and they include descriptions of the goal of the particular architecture and a top-level description of an implementation strategy. The goal for each architecture is defined in terms of the objectives to be achieved on the planetary surfaces, with the differences between architectures resulting from the degree to which each of three broad categories are emphasized: science and exploration, human presence, and space resource utilization.

The Exploration Programs Office (ExPO) at the Johnson Space Center has led the architecture analysis effort and was responsible for coordinating and integrating the inputs received from the participating NASA Centers. The four Architecture White Papers contain a first-order assessment of the technical and strategic details required to implement the four Synthesis Group architectures. The purpose of the analysis effort has been to develop a thorough understanding of the implications of pursuing the architecture objectives outlined by the Synthesis Group and to provide complete descriptions of implementations that are consistent with those objectives. The analysis effort was intentionally constrained to examine the unaltered objectives and strategies presented in the Synthesis Group architectures. Thus, the Architecture White Papers present only a possible implementation of one of the Synthesis Group architectures. There has been no attempt to determine or present an optimal implementation, nor does the implementation presented in each White Paper represent a recommended approach on the part of NASA.

The Synthesis Group architecture descriptions contained a number of specific and detailed mission- and system-level recommendations in addition to the higher-level architecture goals and strategies. These recommendations were followed, whenever possible, in conducting the analysis of the architectures in order to be as consistent as possible with the intent of the Synthesis Group. The Architecture Analysis Ground Rules and Assumptions document (AAGRA) Version 2.1, published by ExPO, contains the study assumptions for each architecture and serves as technical guidance for analysis of the Synthesis Group architectures.

There will be four White Papers at the conclusion of the architecture analysis effort; one for each of the four recommended Synthesis Group architectures. This White Paper presents the results of the analysis for the ***Moon to Stay and Mars Exploration*** architecture. However, all the White Papers have a similar format and table of contents. Section 2 of each White Paper outlines the architecture objectives, the key milestones and accomplishments, and the end-to-end mission description. Section 3 provides detailed descriptions of the various systems defined for the architecture implementation, the reasoning behind the selections of the systems employed, and an overview of how the particular system is operated during the various phases of development within an architecture. Section 4 of each White Paper lists possible issues with the Synthesis Group recommendations for the architecture, provides alternative strategies/implementations, and outlines additional analysis that may be needed before any recommendations can be made for a particular area.

In addition to the four White Papers, at the conclusion of the architecture analysis effort, a summary of the results and recommendations across all four architectures will be documented in a volume entitled "Architecture Analysis Summary and Recommendations." The purpose of this document is not to merely compile the various results and recommendations from the analysis of each architecture, but to determine how the results and recommendations for each architecture complement or contradict each other. These results will be used to define features that are common to all architectural goals as well as those features that are specific to particular architectural goals. In addition, these results will provide the foundation from which an Initial Operational Capability (IOC) can be determined for the Space Exploration Initiative (SEI).

Many of the features of the ***Moon to Stay and Mars Exploration*** architecture are similar to the ***Mars Exploration*** architecture. Indeed, all the Mars missions are identical. Throughout the present document, many references are made to the ***Mars Exploration*** architecture. Due to the possibility of confusing ***"Mars Exploration"*** with ***"Moon to Stay and Mars Exploration,"*** the convention will be adopted to refer to the ***Mars Exploration*** architecture as "Architecture 1."

Architecture 1 is described in the document **"ANALYSIS OF THE SYNTHESIS GROUP'S *MARS EXPLORATION* ARCHITECTURE"** (NASA Exploration Programs Office; NASA/Johnson Space Center; Mail Code XE; Document No. XE-91-001; 25 October 1991).

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2.0 ARCHITECTURE REFERENCE DESCRIPTION

2.1 OBJECTIVES

The primary objective of the ***Moon to Stay and Mars Exploration*** architecture is to conduct "long term human habitation and exploration in space and on planetary surfaces." This objective emphasizes the "permanent human presence on the Moon, combined with the exploration of Mars." The thematic approach recommends building life-support self-sufficiency on the Moon in order to enable a permanent human presence. Particular areas of development include gas and water generation from lunar resources, waste management technologies, and food production. Ultimate goals of the lunar establishment involve achieving limited independence from Earth as well as an opportunity for terrestrial spinoffs to improve conditions on Earth. The ***Moon to Stay and Mars Exploration*** architecture also focuses on the initial human missions to Mars, accomplished through a combination of extensive system and human experience on the Moon and a steady-paced schedule. Additional architecture objectives include establishing an impressive scientific capability on the Moon, limiting technical risk by following an extensive test and development strategy, and expanding human presence on Mars.

2.2 STRATEGY

2.2.1 Overview

The ***Moon to Stay and Mars Exploration*** architecture uses a combination of lunar and martian missions to achieve the goal of expanding human presence beyond the boundaries of the Earth. The role of the Moon is to act as a convenient space location for establishing the first human residence outside Earth's orbit. This long lunar base life is reflected in the number of missions and the corresponding schedule -- an average of one cargo and three piloted missions per year from 2006 to 2020. This extensive experience at the lunar base also provides the engineering and operational data to successfully achieve multiple missions to Mars. According to the Synthesis Group Report, "This long duration on the Moon creates an important database on human presence in a reduced gravity environment."

The first and second missions to the Moon, occurring in 2004 and 2005, substantiate a human presence on an extraterrestrial surface. Precursor missions are deemed necessary to successfully select the proper site for a permanent base on the Moon. Recall that the presence on the Moon is intended for development of a self-sufficient community. The third and fourth lunar mission in 2006 extend the crew's size and surface duration, thus expanding the database on humans in a harsh, partial-gravity environment. The follow-on missions, flown from 2007, establish the permanent occupation of the base with a consistent crew of 18 living and working on the Moon. A set of missions flown in 2009 provide the core opportunity for testing martian systems and operations, part of a risk abatement strategy for a successful Mars mission.

During the lunar preparatory phase of this architecture, precursor missions are flown to Mars to gather the data necessary for selecting Mars landing sites. A minimum set of robotic infrastructure is included. Five years after the dress rehearsal, the first human mission to explore Mars is launched in 2014. The successful completion of this initial mission leads to a second Mars exploration mission in 2016 to a different and unique location.

General strategy for the ***Moon to Stay and Mars Exploration*** architecture is summarized by the following points:

- Send site reconnaissance orbiters and a surface robotic rover to the Moon to provide site selection data in preparation for human landings and permanent habitat emplacement.
- Use a crew of six evolving to eighteen for the Moon missions.
- Use a crew of six for the Mars missions.
- Scout the Mars territory with robotics before committing to a human landing site.
- Minimize complex orbital operations by using large Earth-to-orbit transportation capability.
- Mars exploration activities begin once extensive space and lunar surface operations are conducted to provide the necessary life science and engineering data.

Transportation strategy for the ***Moon to Stay and Mars Exploration*** architecture is summarized by the following points:

- Use a heavy lift launch vehicle for low-Earth-orbit transportation.
- Use separate cargo and piloted flights for Moon and Mars missions.
- Deliver the cargo (major support infrastructure) to the surface before the crew arrives for Moon and Mars missions.
- Use current propulsion system technology for lunar missions.

- Use nuclear thermal propulsion as the primary propulsion system for Mars transits.
- Return the crew to Earth's surface using direct entry.
- Use the first Mars cargo mission as the validation flight for the nuclear thermal propulsion system.

Planet surface strategy for the ***Moon to Stay and Mars Exploration*** architecture is summarized by the following points:

- Establish lunar infrastructure with the intent of permanent human presence.
- Build towards life-support self-sufficiency on the Moon.
- Emphasize exploration and scientific observation on the Moon.
- Use the Moon as a testbed (dress rehearsal site) for the first Mars mission.
- Use lunar regolith as radiation protection for the lunar surface habitat.
- Use nuclear surface power on the Moon and Mars.
- Stay up to 100 days on the Mars surface for the first human visit.
- Stay up to 600 days on the Mars surface for the second human visit.

The following quotes extracted from the Synthesis Group report, America at the Threshold, provide the basic strategy for each operational capability.

Lunar Precursors:
"Orbital and surface precursors are used to select a site prior to the establishment of permanent facilities."

Lunar IOC:
"The goal of this Initial Operational Capability is to return safely to the Moon and establish a crew-tended site while conducting survey work for a future permanent habitat."

Lunar NOC-1:
"The objective is to remain on the lunar surface safely through a complete lunar day/night cycle while establishing the infrastructure for the permanent habitat."

Lunar NOC-2:
"The ability to emplace and operate multiple habitats while accumulating life science data and operational experience is demonstrated."

Lunar NOC-3:
"The permanent presence of humans on the Moon is the goal of this phase, featuring regular resupply and crew rotation."

Lunar NOC-4:
"The aim is to perform a complete dress rehearsal for the mission to Mars while acquiring significant life science data." (from Architecture 1)

Mars Precursors:
"The overall approach is to achieve knowledge of Mars from robotic missions and then to follow up with detailed field science by humans." (from Architecture 1)

Mars IOC:
"The goal of the Mars Initial Operational Capability is to arrive at Mars and successfully accomplish scientific exploration of its surface." (from Architecture 1)

Mars NOC:
"The architecture next aims to achieve a long surface stay on Mars to perform extensive field exploration, including addressing difficult and complex scientific problems." (from Architecture 1)

2.2.2 Mission Accomplishments & Methods

2.2.2.1 Human Presence

An emphasis on human presence refers to an approach leading to permanent habitation beyond Earth. Surface infrastructure expands with the intent of accommodating larger crews for longer periods of time, with the ultimate objective of colonization. The general strategy for the ***Moon to Stay and Mars Exploration*** architecture follows such an approach.

The function of the Moon as a future home instigates the growth of surface facilities and thus human expansion. Sufficient and comfortable accommodations are provided as the outpost expands into a base. The crew size increases beyond six in the second operational capability with twelve people staying for 90 days. NOC-3 specifies the first year-long (Earth year) stay on the Moon, with a steadily increasing crew size from six to eighteen. The base population is maintained at eighteen for the duration of the architecture, establishing a constant human presence on the Moon. The crew rotations are on a quarterly basis at six crewmembers per rotation. The lunar missions continue even during the Mars exploration phase of the architecture.

Figure 2.2-1 shows the annual crew days on the lunar surface from 2004 through 2020, and Figure 2.2-2 presents the cumulative crew days on the lunar surface. Note that the lunar crews achieve the cumulative surface experience required for the forthcoming Mars missions by the year 2007. Furthermore, over 50,000 crew-days are accumulated by the time the first Mars crew departs in 2014. The ***Moon to Stay and Mars Exploration*** architecture ensures a wealth of human experience on a planetary surface prior to sending a crew to Mars.

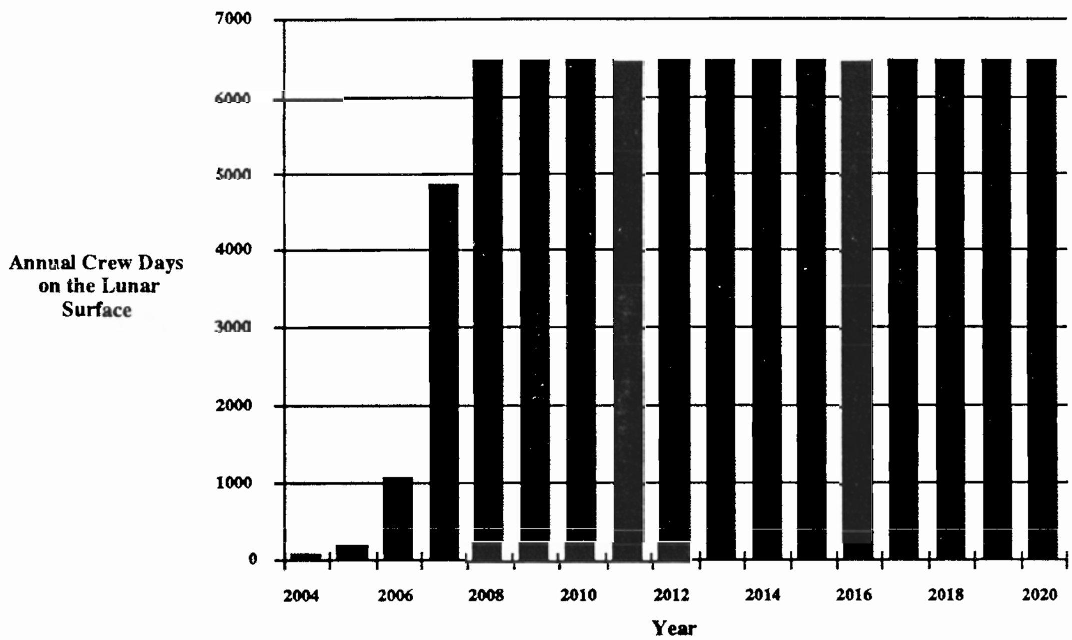


Figure 2.2-1 Annual Crew Days on the Lunar Surface

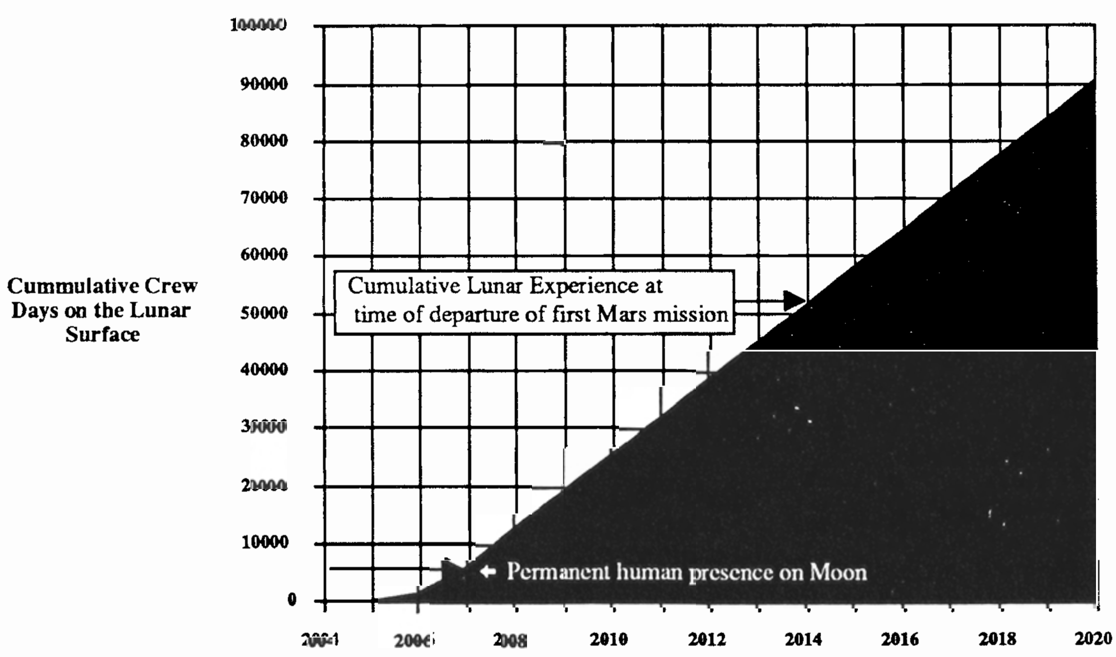


Figure 2.2-2 Cumulative Crew Days on the Lunar Surface

The Mars portion of the ***Moon to Stay and Mars Exploration*** architecture focuses on the initial exploration of the planet by humans. The second piloted mission for a period of 600 days tests the human capability of staying on another planet, other than the Earth's Moon, for more than a year. At that point in the architecture, the total surface time on both the Moon and Mars approaches 95,000 crew-days, more than enough experience to continue sending humans to Mars. The architecture alludes to the human presence intent if follow-on Mars missions prove successful. The exploration phase allows for evaluation of the potential for long-term habitation by proving extended stay capabilities and the feasibility of in situ resource utilization.

Figure 2.2-3 shows the annual crew days on the martian surface from 2014 through 2018, and Figure 2.2-4 gives the cumulative crew days on the martian surface.

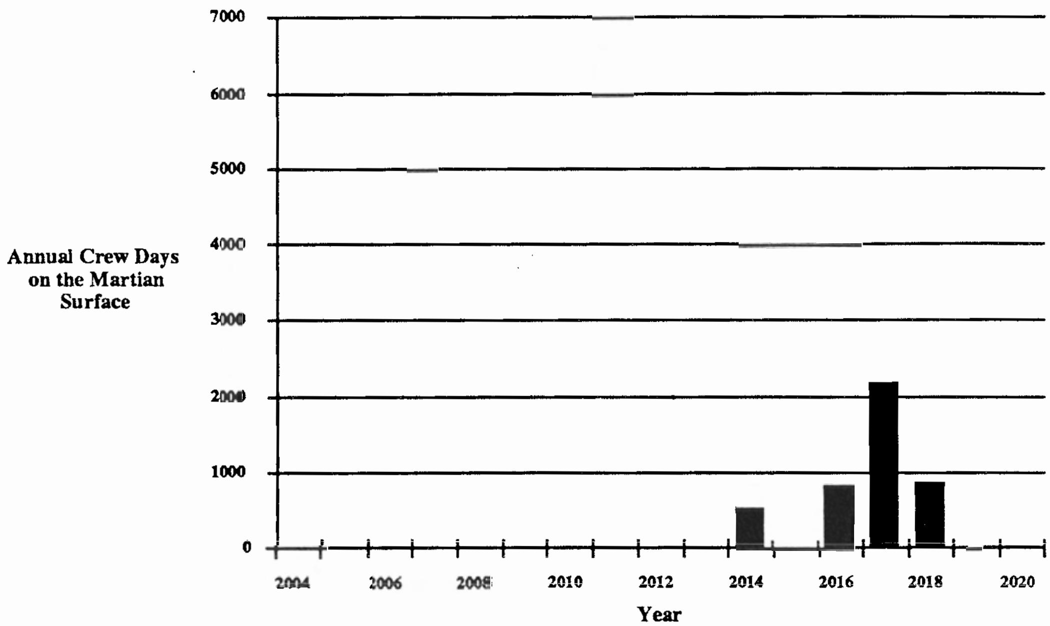


Figure 2.2-3 Annual Crew Days on the Martian Surface

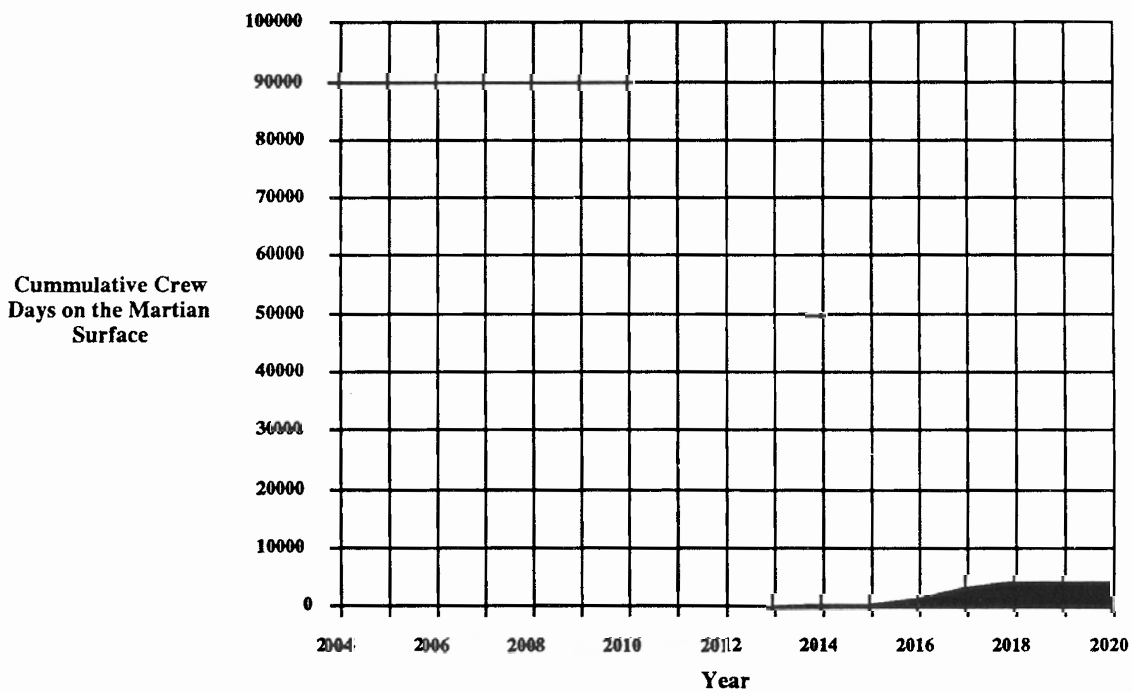


Figure 2.2-4 Cumulative Crew Days on the Martian Surface

2.2.2.2 Exploration & Science

The primary theme of the ***Moon to Stay and Mars Exploration*** architecture is to provide for permanent human presence on the Moon, combined with the exploration of Mars. For both the Moon and Mars, the basic science strategy is to emphasize early build-up of lunar infrastructure and science capability. To accomplish this goal, construction of large astrophysical observatories is conducted in concert with long duration pressurized rover traverses and buildup of analytical laboratory capability, resulting in a progressive increase in overall science capability, and an increasing science return from the Moon in all disciplines. The Mars dress rehearsal and Mars exploration program take place after the lunar infrastructure is established.

In support of the architecture, an early program of planetary reconnaissance orbiters and rovers precedes human explorers and establishes a baseline of data on the global geologic and geochemical heterogeneity. This baseline will be used to select a site for an outpost prior to the establishment of permanent facilities. In particular, the initial plan is to establish a crew-tended site while conducting survey work for a future permanent habitat. The human crew gradually builds stay time and infrastructure capability, both in terms of science, transportation and materials utilization.

Observatories will be deployed on the Moon for astronomy and space physics studies in a gradual build-up to large scale structures. Optical telescopes will gradually build from small, <1-m class operational test instruments to a 16-m single telescope and interferometer arrays. At the same time, radio astronomical facilities will build interferometry arrays for use both as lunar-only instruments and as test telescopes for very long baseline interferometry between the Earth and the Moon. Space physics instruments and monitoring packages that investigate the relationship between the Moon and the Earth's magnetosphere, the lunar atmosphere, the interplanetary particle environment and the variations in the Sun will also be deployed.

The Moon is used as a Mars simulation dress rehearsal to test and operate equipment, systems and exploratory activities to be used on the Mars missions.

On Mars, orbital science will enable the crew to act as operators of instrument platforms, observers of planetary features, and participants in surface exploration with teleoperated robots. Crews will study the surface geology and search for evidence of past life, investigating changes in global climate as preserved in sediment archives, volatiles, and the physical processes responsible for transforming surface and atmospheric systems.

The major science accomplishments in ***Moon to Stay and Mars Exploration*** are distributed throughout the science disciplines. Geoscience activities will allow planet-wide reconnaissances of both the Moon and Mars to be completed; these reconnaissances will then be augmented by detailed studies at a number of locations on both the lunar and martian surface. In addition, deployment of numerous geophysical stations will form a network that will allow a comprehensive picture of the interior of both planets to be determined for the first time.

A significant amount of astronomy is performed at a number of wavelengths and with wide varieties in both technique and resolving power. Space physics will also develop a planet-wide understanding of the lunar particle environment and atmosphere, the variability of solar cycles and the variations in the interaction between the Moon and the Earth.

Lastly, experimental life sciences for human, plant and lower animal research will establish a significant baseline on both humans and animals, both through long-term stays on the moon and Mars, and on the effects of long duration zero-g voyages to Mars.

The science strategy, by phase, is outlined below.

Lunar IOC Initial missions are 14 days in length, and will concentrate on geologic sampling and survey work to establish the future habitat site. Some local, unpressurized rover traverses will be conducted to collect bulk samples from interesting "targets of opportunity." Also, small automated geophysical and space physics stations will be deployed, and a small, robotic operational test telescope will be set up to provide information for the design of future large robotic telescopes.

Lunar NOC-1 The duration of manned stays on the surface increases to 40 days for this operational capability. Activities support primarily the build-up of major science infrastructure, including the deployment of a lunar transit telescope and a 4-m optical telescope. Remote deployment of space physics and geophysics packages, and geologic sampling is also stressed through the conduct of two long, pressurized-rover traverses. Some selection of samples will take place through the use of analytical facilities in the pressurized rover and at the outpost.

Lunar NOC-2 Crew surface stay times increase to 90 days, emphasizing life science data acquisition to support the decisions on Mars mission modes, and on the long-term effects of lunar habitation. Astrophysics is also emphasized through the deployment of an optical interferometer array. Additional pressurized rover traverses are conducted, expanding the geoscience knowledge base through analytical work on samples in expanded laboratory facilities.

Lunar NOC-3 Permanent habitation begins at this operating capability. The astrophysics infrastructure continues to be built up with the aperture of the 4-m telescope increasing to 16-m and the construction of a radio telescope interferometry array. Secondary emphasis is is placed on further expansion of the geoscience knowledge base through additional long, pressurized-rover traverses and additional sample analyses. Expansion of life science laboratory capability emphasizes the need for continued research on biological evaluation of long-term lunar habitation.

Lunar NOC-4 The science strategy for Mars dress rehearsal is as in Architecture 1 — to take advantage of 120 days in orbit for teleoperations on the Moon surface, remote geochemical sensing, life science experiments, astronomy, and discretionary science. In addition to the orbital science, surface crews will conduct "Mars-like" science during the surface phase of the dress rehearsal, also deploying some telescopes as construction simulations.

Mars IOC The Earth-Mars transit affords the opportunity to conduct cruise science, including solar observations, astrophysics, experimental biomedicine, and discretionary science. While in Mars orbit the crew accomplishes investigations similar to those practiced in lunar orbit, including remote sensing, visual observations, and telerobotic exploration. The first human mission to the martian surface focuses on scientific exploration around the landing site with a pressurized rover, a small suite of instruments, and a period of approximately 100 days. A balance is established between local exploration and pressurized excursions. Only basic analyses are possible at the martian outpost; the achievement is twofold: first hand observational science, and the return of substantial samples back to Earth. This phase also allows teleoperations of robotic rovers from the outpost in order to extend access, exploration and discovery to areas beyond the landing site.

Mars NOC Cruise science, en route to Mars and on return to Earth, continues during the second human transit. Orbital investigations similar to those conducted in Mars IOC provide additional data for mapping the martian surface. The second human landing expands the scientific domain by selection of a different site and an extended duration. The access to the martian surface and diversity of martian environments also increases. Anticipated scientific accomplishments are similar to Mars IOC with the additional potential to understand more complex scientific questions.

2.2.2.3 Space Resource Development

"One of the major objectives is to build towards life-support self-sufficiency for breathing gases and food production on the Moon. Waste management technologies are developed to support an extended human presence on the lunar surface."

The ultimate intent of using space resources is to reduce mission dependency on Earth and to augment outpost accommodations. Space resource development ranges from simple applications, such as covering habitation facilities with regolith, to production of propellant, such as liquid oxygen from lunar soil. Various opportunities for using planetary resources exist on both the Moon and Mars.

The Synthesis Group general strategy is to demonstrate the production, storage, and use of lunar resources prior to the Mars dress-rehearsal mission in 2009. The feasibility of lunar resource utilization will be based upon the potential exploration cost reduction and effective base self-sufficiency. The Moon to Stay and Mars Exploration architecture takes a fast but evolutionary approach to attaining the stated goal. As a result, by the time the Mars dress rehearsal occurs in 2009, an outpost inhabited by 18 people with means for supplying all the breathable gas, usable water, and 40% of the food is established.

Extraction, production and use of the resources begins with the simple processes and applications (e.g. covering the habitation facilities with regolith) and incrementally increases in complexity. In addition, and consistent with the architecture objectives, the early resource focus is on oxygen and volatile production due to its high leverage potential for sustaining a permanent presence. The exploitation of the lunar resources is prioritized as shown in the following list:

1. Unprocessed regolith (radiation protection, berms, etc.)
2. Oxygen and Volatiles (vehicle fuel cells, ECLSS, EMUs)
3. Construction materials (cast basalts, ceramics, metals)

Immediate emphasis is placed on processing lunar regolith into oxygen and volatiles. Since the amount required for human support is not significant, an integrated method is recommended. Such a method uses the same regolith to extract the volatiles and feed the oxygen reduction process. The sequence of development is as follows: demonstration units to pilot plants to production plants. Figure 2.2-5 charts the evolutionary development of the resource activities.

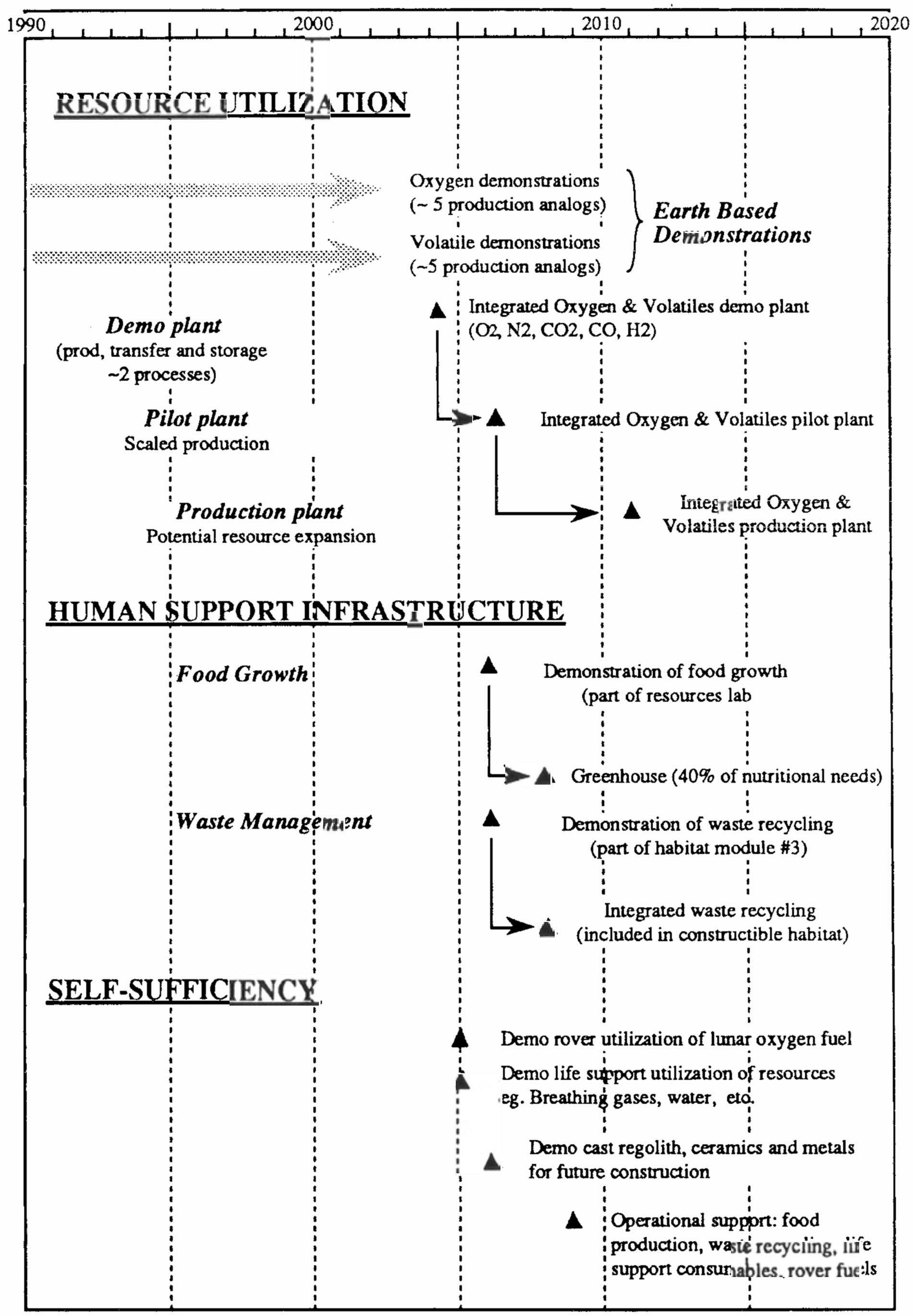


Figure 2.2-5 Lunar Resource Development Milestones

The integrated LLOX/volatiles demonstration unit produces approximately 1 mt/year of hydrogen, 1 mt/year of nitrogen, and 4 mt/year of CO/CO_2. The oxygen production related to this unit could produce up to 33 mt/year; however, such a level would not be required to support the crew. Production of 5 mt/year is recommended for this architecture. Assuming this demonstration proves successful, a pilot plant is introduced to augment base production. The integrated LLOX/volatiles pilot plant makes approximately 5 mt/year of hydrogen, 5 mt/year of nitrogen, and 20 mt/year of CO/CO_2. The oxygen production recommendation is for approximately 10 mt/year, depending on consumption rates.

The following discussion accounts the space resource strategy and accomplishments of each lunar operational capability within the Moon to Stay and Mars Exploration architecture.

Lunar IOC: The first fourteen-day mission contains no substantial resource utilization. Crew activities focus on the preparation of the outpost. The only effective use of resources on the Moon, at this time, is the burial of the habitation facility in order to protect the crew from cosmic and solar radiation.

Lunar NOC-1: The crew continues to settle the outpost for future permanent residency. To begin the steps toward outpost self-sufficiency an in situ gas demonstration unit is installed within 10 km of the habitat. The intention of the unit is to produce breathable gas by extracting oxygen from the lunar regolith.

Lunar NOC-2: Given the successful production of oxygen from the gas unit demonstration, a larger gas production plant is delivered and installed at the lunar outpost. Initial demonstrations of resource utilization continue with additional volatiles extraction. In order to produce water on the Moon, production of hydrogen from the volatile content of the lunar soil must be proved. A resources lab is established during this operational capability.

Additional advancements in supporting the human presence on the Moon include food production and waste recycling. Demonstrations in these areas are started during this operational capability. The use of resources in the food (lunar soil as a planting medium) and waste (disposal sites) disciplines has potential, although other advanced methods could be used. Also supporting the human presence, the NOC-2 crew investigates using indigenous materials for future construction on the Moon.

Lunar NOC-3: A larger, 18-person crew is maintained on the Moon in this operational capability, starting a permanent presence with a rotational crew. The constant crew size of 18 leads the outpost toward achieving self-sufficiency. In particular, food production begins to support the crew's nutritional requirements, and breathing gas and water productions are verified.

Lunar NOC-4: The orbital dress rehearsal scheduled during this phase dominates the activities. Advancements in self-sufficiency continue their course during the dress rehearsal. The end of NOC-4 marks the beginning of continuous outpost operations with a steady crew of 18.

Mars: The major focus of the Mars missions is to explore new territory with humans. The first mission, due to surface duration limitations, affords little opportunity for human performance beyond initial exploration and science. The second mission, given a surface duration of 600 days, allows time for experimentation in addition to exploration. According to the Synthesis Group report, "an in situ resource demonstration unit is included in this mission to test the feasibility of producing fuels at Mars." Such a demonstration provides information for advancing human existence and extending the exploration capability on future Mars visits. Furthermore, the experience gained on the Moon with respect to the use of indigenous resources lends some commonality of techniques that may prove helpful in easing the 600-day logistics problem.

SELF-SUFFICIENCY OF A LUNAR BASE

The major goal of this architecture is to build toward self-sufficiency of a permanent lunar base. This means that the base is able to provide from local resources more and more of the materials and products necessary to sustain its operation, and in the long term, allow it to expand in space and capability.

Self-sufficiency implies that materials produced from local resources can provide an increasing proportion of import requirements, and at some point, most of the high-mass materials required at the base can be produced locally. These high-mass materials which are all initially imported, will be slowly phased over to local production. The effect will be to reduce the supply masses and costs required to keep the base operating or to allow it to expand capability. These materials are listed here in generally increasing levels of complexity, and correspondingly increasing levels of self-sufficiency.

Note that the propellant usage issue for the lunar transportation system is not included here. Although propellant production has the potential for major savings, the intent of this architecture was to focus on resources as applied to establishing a permanent human settlement. The use of lunar-derived flight propellant should be considered in the steady-state mode of this architecture, in the post 2010 time frame.

Level 1: Self-sufficiency of an emplaced lunar base

1. Propellants

- Propellants can be produced for use in local transportation (rovers and ballistic hops in the LEV). As local propellants are produced (hydrogen, oxygen, methane), their use in local transportation systems (rovers, trucks, miners, robotic exploration systems) will greatly increase the capability of the base to perform scientific exploration, resource exploration and assessment, and infrastructure emplacement. The goal is to produce enough propellant to meet the needs of an expanding local transportation system having expanded capability.

2. Life support consumables

- Initially, local materials can be used for makeup of life support system consumables such as water, oxygen, nitrogen, and carbon dioxide for plant growth. Early production of these consumables may greatly decrease the requirement for complete recycling in regenerative life support systems and may therefore decrease the mass, complexity, and cost of such systems. As the capability for producing these consumables increases, the base will acquire significant backup storage for the regenerative life support systems and will acquire the ability to expand in size using even less stringent recycling equipment. For example, locally derived carbon may replace systems required for recycling carbon in solid waste. This increased capability will mean also fewer requirements on imported spare parts for the life support systems and reduced requirements for crew operational and support time for those systems.

3. Food

- Food can be grown in base greenhouses using modified local soils and imported or extracted nutrients. Production of food may start with "salad machine" units which can be expanded to gardens capable of producing a variety of vegetables as well as basic grain crops. Food production integrated with a regenerative life support system will likely be a part of the human support systems design. At some point, as lunar-derived soils and nutrients are produced in abundance, the initial base can become nearly self-sufficient in basic food production, and may acquire the capability for significant growth.

4. Simple construction materials

- Blocks, bricks, beams, and other forms can be made from local regolith and metal byproduct of the oxygen plants by sintering, melting, or casting. These simple construction materials can be used at the initial base for radiation protection, for constructing landing pads and blast shields, and for constructing roads if required. As the base becomes more developed, these simple low-tech construction materials can be used for such purposes as unpressurized shelters for rovers and other surface equipment.

Level 2: Self-sufficiency of an expanding lunar base

This level begins when it becomes possible to increase the actual space and capability of the original emplaced base using mainly local materials. Much of the transported cargo is now equipment and instruments necessary for increasing the capability of the base, as well as some food, medicine, spare parts, and other resupply items. At this level, self-sufficiency now means that high-mass products necessary for base expansion can be produced locally, and only lower mass, more complex products have to be imported. Examples of high mass item which can be produced locally include the basic structures for new buildings. Examples of low-mass items which must continue to be imported includes electronics, airlocks, communications equipment, and the cores for basic utility distribution systems. Specific examples might include:

1. Pressurized buildings for living quarters, shops, laboratories, and food production.

The ability to produce pressurized human-rated buildings from mostly local materials will be a requirement if the base is to expand under ground rules of constant or decreasing support from the earth. This ability will require more complex processes which can fabricate and join together plates, blocks, or other locally produced units, provide reliable pressure seals, as well as basic internal structures such as floors and walls. While the base can approach self-sufficiency without this capability, this capability is necessary before the base can expand to more significant permanent residence.

2. Expandable food production facilities

More complex and expanded food production facilities can be added using local materials to produce additional greenhouses and the necessary soils, watering, ventilation, lighting, and nutrient management systems. Self-sufficiency requires that such facilities be made from local resources. Such facilities can be variations of the pressurized structures necessary for habitat expansion. Additional lighting, air circulation, and nutrient systems will be required, and some of these systems will still have to be imported from earth. However, if the high-mass part of such food production facilities can be made from local resources, the base will have gone a long way toward self-sufficiency of an expanding base.

2.3 ARCHITECTURE DEFINITION

2.3.1 Groundrules

Listed below is a complete set of the *implementation-specific* groundrules taken directly from the Synthesis Group's discussion on the Moon to Stay and Mars Exploration architecture. These groundrules provide a framework for the architecture analyses presented in this paper. Groundrules and assumptions for this architecture are also stated in requirements terminology in the *Architecture Analysis Groundrules and Assumptions* document. The following groundrules are presented according to architecture phase.

Lunar Precursor Missions

"Reconnaissance orbiters are launched in 2000 to gather information on potential landing sites ... A robotic rover is sent to the lunar surface in 2002 to further investigate ... ."

1) Two site reconnaissance orbiters are sent to the Moon to scout the future piloted site and to collect global remote sensing data.
2) One robotic surface rover is sent to the Moon to further investigate and characterize the future piloted site. The rover may also be equipped to certify the site for the installation of the habitat.

Lunar IOC

"The launch of the cargo mission takes place in 2004, followed by a piloted flight with a six-member crew. ... for a 14 Earth-day mission."

1) A cargo mission precedes the human mission landing on the Moon in 2004.
   The IOC cargo mission contains a habitat with airlock, a nuclear power supply, a backup photovoltaic power supply, cryotank verification test equipment, mining equipment, portable science instruments, an optical test telescope, pressurized rover, a solar flare warning system, and an unloader.
2) The first piloted mission lands on the Moon in 2004.
   Five crew members stay on the surface, while one crew member remains in lunar orbit.
   An unpressurized rover and crew supplies (for 14 days) are delivered with the crew.
   The crew spends 14 Earth days on the lunar surface.
   The crew lives in the lander while setting up the regolith-shielded habitat.
   Nuclear power is used for the initial stay.
   The power system is approximately 1 km away from the habitat.
   A solar flare warning system is installed near the habitat.
   The crew emplaces portable instruments and an optical test telescope within 1 km of the habitat.

Lunar NOC-1

"The Next Operating Capability of this architecture takes place in 2005. A cargo mission brings... Five crew members land and stay on the lunar surface for 40 Earth days."

1) A cargo mission precedes the NOC-1 human mission landing on the Moon in 2005.
   This cargo mission returns to the original landing site in IOC.
   This cargo mission contains a pressurized rover, consumables, and other cargo.
2) The second piloted mission lands on the Moon in 2005.
   The crew spends 40 Earth days on the lunar surface[1].
   The crew performs 2 long traverses up to 100 km from the outpost site.
   Crew activities include: setting up instruments, surveying sites for roads and landing areas, and preparing for telescope emplacement.

Lunar NOC-2

"This Next Operational Capability takes place in 2006 with two piloted missions preceded by one cargo mission."

1) A cargo mission precedes the NOC-2 human mission landing on the Moon in 2006.
   This cargo mission returns to the original landing site in IOC.
   This cargo mission contains a habitat, and a volatile production plant.
2) The third and fourth piloted missions land on the Moon in 2006.
   Two piloted missions occur during NOC-2.
   A total of 12 crew members land on the surface.
   The crew spends 90 Earth days on the lunar surface.
   The first piloted mission delivers an unpressurized rover, a resources lab, waste recycling demonstration, and an optical interferometer.
   The crew conducts five-day exploration sorties and operates the new instrumentation.

Lunar NOC-3

"The third Next Operational Capability is scheduled for 2007 and consists of cargo and piloted missions."

1) A cargo mission precedes the NOC-3 human mission landing on the Moon in 2007.
   This cargo mission returns to the original landing site in IOC.
   This cargo mission contains a third habitat.
2) Three piloted missions are flown to the Moon in 2007.
   Six-member missions are flown on a quarterly basis for the first three quarters, bringing the surface crew total to 18.
   The crew conducts 14-day exploration sorties at a radius of 100 km.
3) Two cargo missions are flown the last quarter in 2008.
   These cargo mission return to the original landing site in IOC.
   These cargo missions contain outpost supplies.
4) Three piloted missions are flown to the Moon in 2008.
   Six-member missions are flown on a quarterly basis for the first three quarters, rotating with the previous 18-person crew.
   The crew conducts 14-day exploration sorties at a radius of 100 km.

Lunar NOC-4

"This capability begins in 2009 and prepares for Mars missions by conducting the Mars dress rehearsal... "

1) A simulation crew lands on the Moon in 2009[2].
   The crew stays in lunar orbit for 120 days performing a Mars transit rehearsal in lunar orbit.
   The crew descends to the Mars rehearsal site for a 30-day Mars simulation.
   The crew activities parallel those planned for the initial Mars mission.

---

1 The Synthesis Group has recommended leaving a single crewmember in lunar orbit for forty days. The changes necessary to the crew module for this one mission would either require a special crew module or inflict a severe mass penalty on all other flights. Also, there are psychological concerns related to leaving a single crewmember isolated in space for that length of time. In as much as all crewmembers will be descending to the lunar surface in the subsequent NOC-2 phase, the implementation chosen herein will accelerate by one year the confidence to leave assets in lunar orbit unattended. Consequently, all six crewmembers will descend to the lunar surface for forty days in NOC-1.

The rehearsal crew carries additional mass to simulate the three-eigths gravity environment of Mars.
The crew returns to Earth, upon completion of their stay on the surface.

2) Three piloted missions are flown to the Moon in 2009.
Six-member missions are flown on a quarterly basis for the first three quarters, rotating with the previous 18-person crew.
These piloted missions land at the original site.
Three of the crew members drive to the Mars rehearsal site in a rover and provide assistance to the Mars rehearsal crew.

Mars Precursors

"Landing sites on Mars are chosen for scientific interest. In order to assure adequate margins of crew safety, each site is certified prior to landing. Site certification involves collation of photographic and other remote sensing data to identify and map hazards." (from Architecture 1)

1) Two site reconnaissance orbiters (SRO) are flown to Mars in 1998.
At least 12 candidate sites are imaged.
SROs obtain high-resolution contiguous imaging of potential landing sites.
The capabilities of a communication orbiter are combined with each SRO.
2) Two site characterization rovers are flown to Mars in 2003 and in 2005.
Rovers are deployed before a piloted mission is launched.
Rovers verify terrain models and certify site safety.

Mars IOC

"The first mission with a crew of six establishes the Mars initial operational capability in 2014 with a surface stay of 30 to 100 days." (from Architecture 1)

1) A cargo mission precedes the human mission landing on Mars.
The IOC cargo mission departs for Mars in 2012.
The cargo flight serves as the validation flight for the nuclear thermal rocket system.
The IOC cargo mission contains a habitat, a pressurized rover, a nuclear power plant, a minimal photovoltaic emergency backup system, an unloader/mover, scientific exploration equipment, and communications equipment.
The cargo is predeployed and remotely operated prior to the crew's arrival.
2) The first piloted mission departs for Mars in 2014.
The first martian crew stays on the surface of Mars up to 100 days.

Mars NOC

"The cargo vehicle departs in 2014 and lands at a different site to maximize science return. The piloted mission, again with a crew of six, launches in 2016." (from Architecture 1)

1) A cargo mission precedes the second human mission to Mars.
The NOC cargo mission departs for Mars in 2014.
The NOC cargo mission lands at a different location than the original site.
Cargo includes an in-situ resource demonstration unit to test the feasibility of producing fuels at Mars, plus Earth-return propellant and a crew excursion vehicle.
The emplaced equipment of the NOC cargo lander is remotely tested to ensure functionality before the second piloted mission is launched.
2) The second piloted mission departs for Mars in 2016.
A conjunction-class mission is used for the piloted flight.
The martian crew stays on the surface of Mars up to 600 days.
The feasibility of producing fuels with in situ resources is demonstrated.

2 The Synthesis Group has recommended that the Mars dress rehearsal site be situated in close proximity to the established lunar site. However, by 2009, the lunar base will have grown to a permanent crew size of 18. Clearly, a preponderance of data will have already been collected about the set-up and operations of predeployed habitats on the Moon. Given this wealth of information, little new data seems to be offered by predeploying yet another habitat at a different site. Furthermore, aside from the dress rehearsal, there is a great demand for HLLV launches with this architecture. Three additional cargo missions (i.e., six HLLV launches) would be required to land a Mars dress rehearsal habitat, pressurized rover, nuclear power plant, unloader/mover, etc., at a new site. Since all these items are already present at the established lunar outpost, the implementation chosen herein will be to locate the Mars dress rehearsal at the lunar outpost and thereby relieve the need for those six additional HLLV launches in 2009.

2.3.2 Lunar Mission

2.3.2.1 Mission Profile

Transportation between the Earth and the Moon is provided by three transportation elements: 1) an Earth-to-Orbit launch vehicle (which may be man rated for crew delivery), 2) a Lunar Transfer Vehicle (LTV) which provides transportation of crew and cargo between Low Earth Orbit (LEO) and Low Lunar Orbit (LLO), and 3) a Lunar Excursion Vehicle (LEV) which provides transportation of crew and cargo between LLO and the lunar surface. Both the LTV and LEV can be flown in a piloted-plus-cargo or cargo-only mode. A pressurized crew module is provided for habitation for the crew for the piloted missions. The crew modules are not included for the cargo-only missions.

As previously mentioned, this architecture makes maximum use of available resources at the Moon to support a permanent human presence. Although not explicitly stated in the Synthesis Group Report, the same resources for human accommodation, mainly oxygen and hydrogen, can be used as propellant. Therefore, the option of expanding the production levels to include propellant usage was investigated in this analysis. Since this architecture carries three piloted missions every year for at least 13 years (for a total of 39 piloted landings), a possible approach is to use lunar-derived propellant and a reusable piloted LEV.

Depending on the amount of propellant supplied at the Moon, various modes of transportation system operations exist. The mode alternatives include expendable, ascent LEV propellants, and all propellants from Earth.

Expendable	In this mode of operation all of the transportation elements are expended. The cargo LTV is expended into the lunar surface, the cargo LEV is expended on the lunar surface. Likewise the piloted LTV is expended in Earth-Moon space (i.e. Earth fly-by), and the piloted LEV is expended into the lunar surface. In this mode of operation the transportation system can deliver 40.8 and 20.8 mt to the lunar surface for the cargo and piloted vehicles respectively.
Ascent LEV Props	In this mode of operation the piloted and/or the cargo LEVs are reusable. Lander reusability is introduced to take advantage of the in situ production of oxygen and hydrogen. For this mode the oxygen and hydrogen required for ascent are provided on the surface. Two versions of this mission mode exist: 1) additional payload (28.5 mt for the piloted vehicle) can be delivered to the lunar surface with no change in IMLEO if the dual HLLV launch strategy is maintained, or 2) a reduction in HLLV flights to 1 can be achieved by reducing the payload capacity (5 mt for the piloted vehicle).
All Props from Earth	In this mode of operation the piloted and/or the cargo LEVs are reusable. Lander reusability is introduced based on an increased flight rate. For this mode, all propellants are supplied at Earth. As a result the payload capacity of the LEVs greatly decreases. Two versions of this mission mode exist: 1) reduction of payload to the lunar surface using the dual HLLV launch strategy, or 2) further reduction of payload to the lunar surface using the single HLLV launch strategy (0.5 mt for the piloted vehicle and 13 mt for the cargo vehicle).

For the analysis period (2004-2009) of the Moon to Stay and Mars Exploration architecture, the selection of all expendable vehicles was made. (See Section 3.4.1 for an explanation.) Reusable vehicles sustained to some degree by lunar-derived propellants may still appear viable in the out years (2010-2020) of this architecture. Table 2.3-1 outlines how the transportation elements are expended. The cargo LTV remains in lunar orbit for a subsequent controlled deorbit to the lunar surface. The impact of this vehicle with the surface can serve as a seismic disturbance for a geophysical network. The cargo Lunar Excursion Vehicle is expended on the surface of the Moon.

A typical cargo mission to the Moon is initiated by the launch of two 150 mt class ETO launch vehicles to a low Earth staging orbit. A 160 n.m., circular Earth orbit was chosen as the optimal location for the vehicle staging point. The two ETO launch elements rendezvous and dock together to complete the lunar transportation system stack. Once the docking operation is complete the vehicle systems are verified prior to Earth departure. The Lunar Transportation System is propulsively captured into a low altitude lunar orbit. Once in lunar orbit the LEV separates from the LTV and descends for a precision landing at the desired landing site.

A typical piloted mission to the Moon is shown in Figure 2.3-1; it is also initiated by the launch of two 150 mt class ETO launch vehicles to LEO. The two ETO launch elements rendezvous and dock together to complete the lunar transportation system stack. Crew transportation to LEO can be accomplished via the Shuttle or on the ETO launch system if man rated. Once the docking operation is complete the vehicle systems are verified prior to Earth departure. The Lunar Transportation System is propulsively captured into a low-altitude lunar orbit. Once in lunar orbit the LEV separates from the LTV and descends for a precision landing near the previously deployed cargo missions. The piloted LTV remains in lunar orbit during the crew surface mission. After the nominal surface mission, the crew is transported in the LEV back to LLO to rendezvous with the LTV. The piloted LEV remains in lunar orbit for a subsequent controlled deorbit to the lunar surface. Prior to arrival to Earth, the crew enters an Earth entry capsule for direct entry for either water or land recovery. The piloted LTV flies by Earth and is expended in Earth-Moon space.

Lunar mission milestones are presented in Figure 2.3-2. This figure provides a general summary for the remainder of the discussion in section 2.3.2.

Element	Mode	Expended in/on
LTV	Piloted Cargo	Earth/Moon system (Earth fly-by) Lunar surface (controlled deorbit)
LEV	Piloted Cargo	Lunar surface (controlled deorbit) Lunar surface

Table 2.3-1 Lunar Transportation System Operational Modes

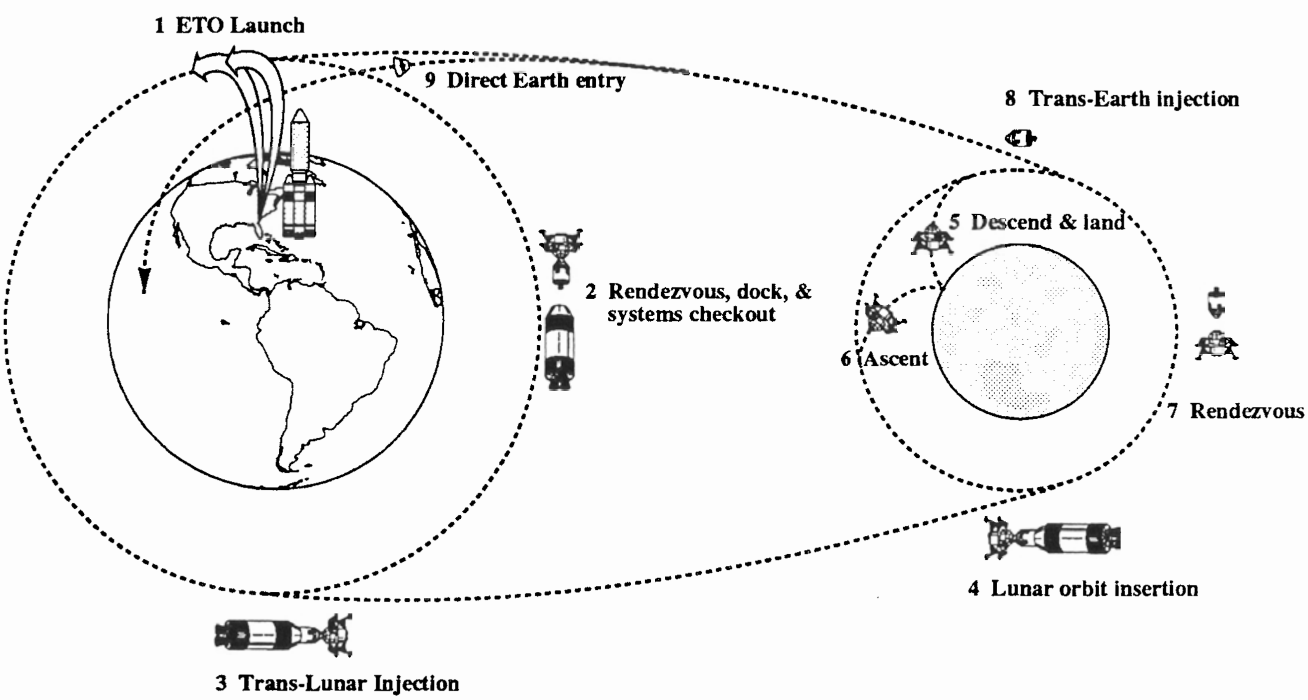


Figure 2.3-1 Typical Lunar Mission Profile

2.3.2.2 Lunar Precursors

The primary focus of the precursors phase of the Moon to Stay and Mars Exploration architecture is to characterize the outpost site. This phase begins in 2000 when two site reconnaissance orbiters are sent into a low lunar orbit to survey the entire surface of the Moon. Through remote sensing techniques, data is gathered to allow the selection of an outpost site based on resource availability and science potential. In 2002 a telerobotically operated rover is landed at the selected site to verify its suitability for the installation of a permanent habitat and resource processing.

2.3.2.3 Lunar Initial Operational Capability

The first launches occur in 2004, and the Initial Operational Capability (IOC) is achieved in 2005. IOC requires two cargo and one piloted missions. Activity begins with the delivery of the first outpost elements to the lunar surface. The initial outpost infrastructure provides the capability to support a crew of 5 for 14 days. The cargo payload includes a surface habitat, airlock, power supply, construction equipment, communication equipment, and solar flare warning equipment.

Two cargo missions (four 150 mt launches) are required to deliver the initial outpost infrastructure in early 2004. The cargo lander performs precision autonomous landing at the desired landing site. Many of the operations associated with the initial outpost emplacement and set-up are conducted remotely from Earth to minimize the initial crew involvement. All operations which can not be performed remotely are conducted by the crew upon arrival.

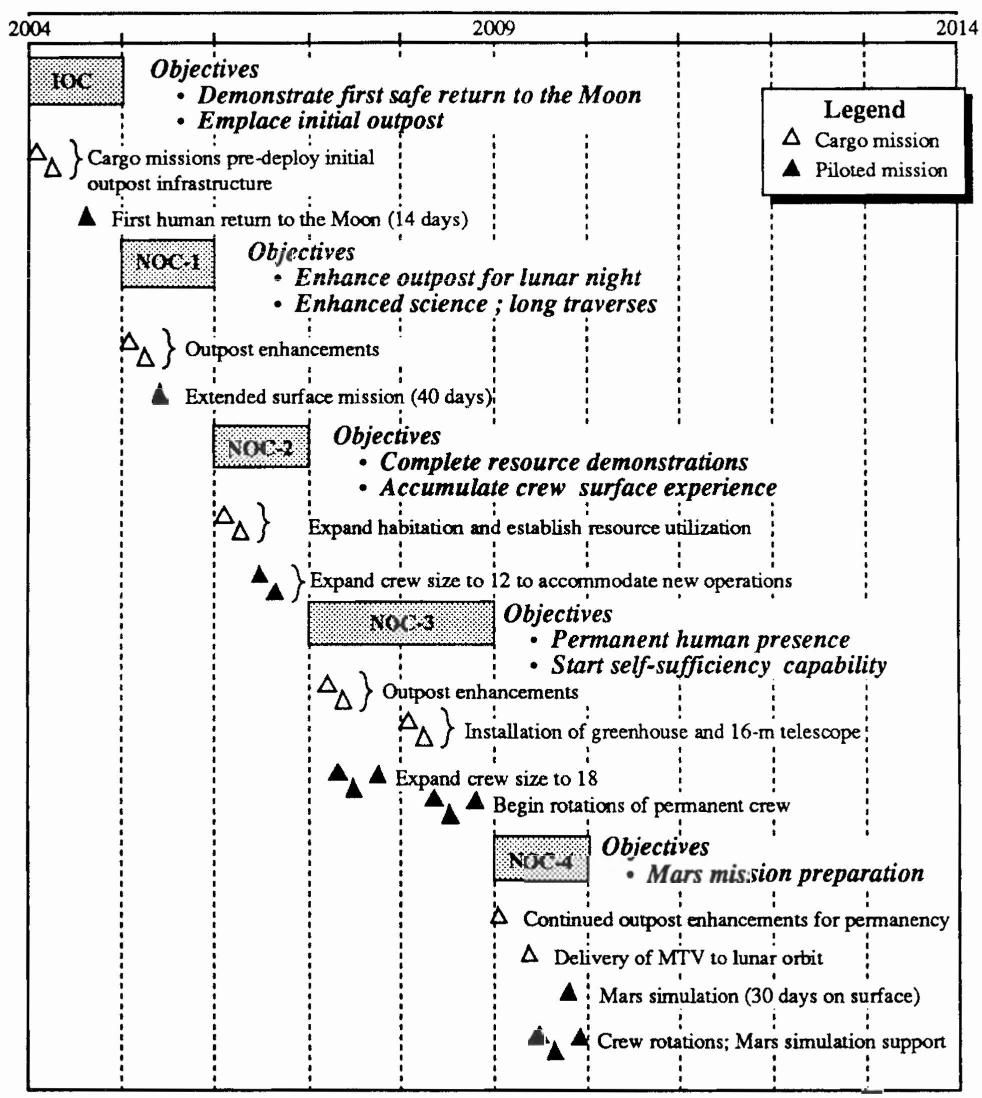


Figure 2.3-2 Lunar Mission Milestones

Crew departure from LEO is not initiated until the lunar outpost systems have been verified remotely from Earth. The objective of the first crew is to demonstrate the safe return to the Moon, and to complete the emplacement of the outpost elements. Six crew depart from LEO in early 2004 with five descending to the lunar surface for 14 days. Initial crew operations are conducted via extravehicular activity (EVA) or intravehicular activity (IVA) from within the LEV. A minimum of three days habitation (two days nominal with one day of contingency) within the LEV is provided for outpost set-up and checkout. Science is limited to activities which support outpost emplacement, with additional science as time allows. Science activities include reconnaissance geology and exploration, sample collection for Earth return, and deployment of small science instruments. The successful completion of this flight constitutes achieving the Initial Operational Capability.

2.3.2.4 Lunar Next Operational Capability - 1

The focus of the next operational capability for the Moon to Stay and Mars Exploration architecture is to demonstrate the human ability to live and work in a nonterrestrial environment for extended periods, as well as to conduct significant science on the Moon. In accomplishing this objective two cargo and one piloted missions to the Moon are required in 2005. The cargo missions contain equipment required for the extended surface mission providing the capability to stay through the first lunar night. In addition, a pressurized rover, with power cart and experiment trailer, is included to expand human access from the outpost. A vehicle depot is established (for cryogenic fuel storage and electrolysis of water for fuel cell usage) to maintain the two pressurized and two unpressurized rovers.

The piloted mission consists of six crew to the lunar surface for up to 40 days (see footnote on page 2-11). The initial crew activities focus on expanding the lunar infrastructure for future additional crew members by emplacing another habitation module and interconnect node. Lunar night activities are enabled with the surface nuclear power source delivered during IOC. Once upgrades of the facilities are complete, activities emphasize science instrument emplacement. With the expanded traverse capability (up to 100 km), the crew makes observations, conducts geoscience experiments, and emplaces additional monitoring instruments. Demonstration units for oxygen and volatile production are also initiated during NOC-1.

2.3.2.5 Lunar Next Operational Capability - 2

The NOC-2 phase of the Moon to Stay and Mars Exploration architecture initiates the resource utilization activities. Equipment, such as an oxygen/volatiles integrated pilot plant and a resources laboratory are delivered by the two cargo flights. Assuming successful demonstrations of oxygen and hydrogen extraction during NOC-1, the outpost is ready to start the production process and proof of usage. The oxygen is intended for breathable gas makeup in the habitats, labs, and pressurized rovers. In addition to gas production, NOC-2 activities involve demonstrations of food production via benchtop experiments in the resources lab. Further measures toward base self-sufficiency include the prototypical waste management unit in the habitat delivered by the second cargo flight. Waste recycling on a small scale is attempted prior to a permanent crew of 18 persons.

The expanded operations at the outpost require a larger crew. Two piloted flights bring a total of 12 crewmembers to stay at the outpost for a period of 90 days. The cargo flights deliver the infrastructure to handle the increased crew occupation. An additional habitation module and nuclear power module (100 kW) are integrated into the previous outpost establishment. In addition to the resource experimentation and the outpost expansion, the crew also performs science tasks, including geophysical instrument deployment and life sciences lab research. Given the two pressurized rovers and three unpressurized rovers, the crew has more than adequate mobility for scientific purposes.

2.3.2.6 Lunar Next Operational Capability - 3

Unlike the preceding three phases that lasted only one year each, this phase spans two years and emphasizes an expansion of capabilities on the Moon for permanent occupation and an increase in self-sufficiency. This phase begins in 2007 with two cargo missions delivering additional systems and equipment to the initial lunar outpost. A constructible habitat, initially capable of housing up to 12 persons, is delivered to accommodate the 18-person crew by the end of 2007. The constructible is deployed, outfitted, and integrated with the existing outpost pressurized volumes over a 6 month period. In order to excavate an adequate foundation, additional construction equipment is delivered on the first cargo flight. By the end of 2007, an 18-person crew (three piloted flights) is located at the outpost intending to stay for 365 days.

The activity during the first half of the year focuses on constructing and outfitting the large habitat, as well as integrating the habitation systems between the previous outpost structures and the new facility. The second half of 2007 concerns scientific activity such as installing new lab facilities, continuing geologic excursions, and installing additional interferometers. Resource utilization activities continue, particularly the application of lunar-derived oxygen to be used in the new habitat as well as power for the surface vehicles' fuel cell systems. The previously installed resource plant maintains the capability to produce usable quantities of volatiles such as hydrogen, helium, nitrogen and carbon dioxide. An LEV servicer is also delivered to the Moon in NOC-3. With the advent of permanency, the LEVs require preventive maintenance (e.g., thermal protection) during their dormant period.

In 2008, another cargo LEV delivers a additional constructible outfitting and the infrastructure for a greenhouse. The greenhouse, intended to reduce the resupply requirements from Earth, provides the capability for food production on the Moon. At a steady crew size of 18 persons, the greenhouse accommodates up to 40% of their nutritional needs on a yearly basis. The carbon dioxide produced with the volatiles plant is used to supplement the greenhouse atmosphere. In addition, the resupply rate is reduced at this point with all of the life support consumables being supplied by the oxygen/volatiles plant. Once the greenhouse is on line, the resupply required to support the crew consists of 60% of their nutritional needs, crew expendables, and life support system expendables.

The second cargo mission in 2008 delivers additional consumables for the permanent crew as well as the final structure for the 16-meter telescope. Activities at this point focus on establishing the food growth process and setting up astronomical operations. The final installation of the 16-meter telescope provides a new and expanded capability for observing from the Moon. The submillimeter array also continues to expand with the inclusion of two new elements. NOC-3 also marks the outpost's preparation for the Mars dress rehearsal. The crew also begins verification of some of the dress rehearsal operations and the isolation of current outpost activities from the dress rehearsal site.

2.3.2.7 Lunar Next Operational Capability - 4

During NOC-4, the aim is to perform a dress rehearsal for the mission to Mars while acquiring significant life science data. The objective is to test systems and operations which are needed for Mars missions. All of the experience and knowledge gained from the lunar surface systems and operations in the earlier phases are put to use in designing and testing prototype equipment for Mars. Current lunar outpost facilities are used to supplement the simulation. Mars practice surface infrastructure basically consists of an unpressurized rover, extravehicluar mobility units, and a suite of scientific experiments. A total of one cargo and one piloted missions are required to accomplish the rehearsal objective of this phase (Figure 2.3-3).

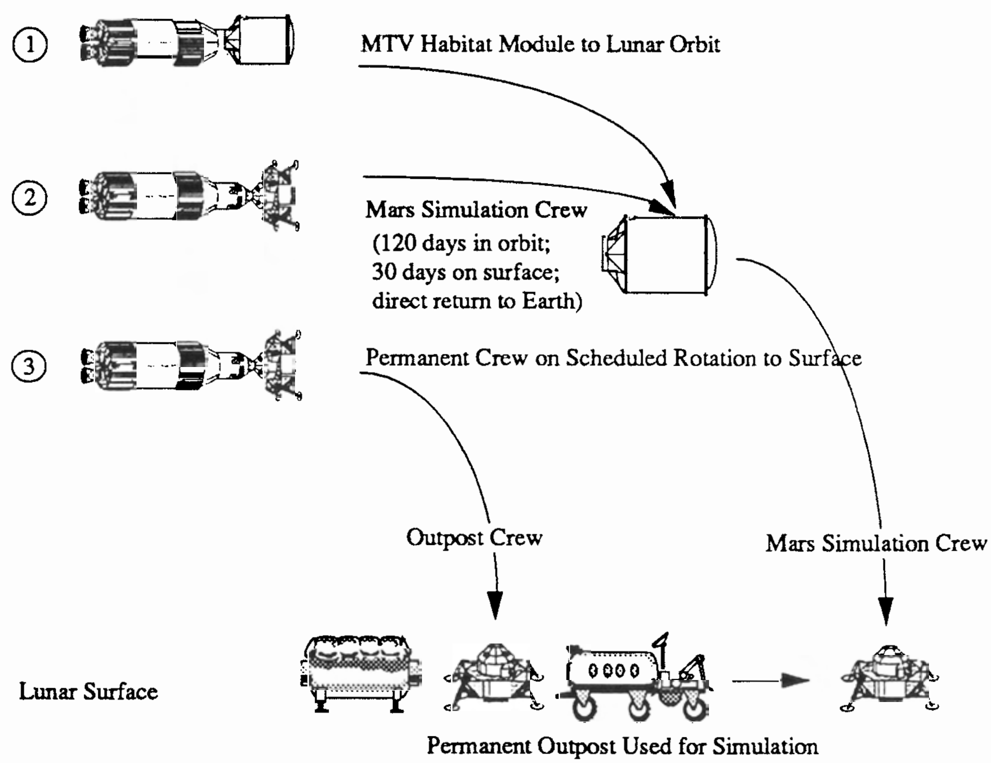


Figure 2.3-3 Mars Dress Rehearsal Flight Sequence

In 2009, a Mars transfer vehicle (MTV) habitat is delivered to lunar orbit by an LTV. Shortly thereafter, the six member Mars dress rehearsal crew and an LEV are sent to lunar orbit on a piloted LTV. They rendezvous with the MTV. The Mars dress rehearsal crew stays in the MTV habitat to simulate the long transfer times to Mars and to test the systems in the habitat. They live in the MTV habitat for 120 days conducting life science research and operating telerobots on the surface of the Moon. After that time, the crew descends to the lunar outpost in their LEV and spends 30 days on the Moon simulating tasks that are planned to occur at Mars. Once the surface portion of the dress rehearsal is completed, the crew ascends to orbit and returns directly to the Earth. This zero gravity/one-sixths gravity simulation will provide vital information regarding the issue of human health and performance after long exposure to zero and partial gravity, and the effectiveness of countermeasures to long-term exposure to zero gravity. In addition, the degree of autonomy required in systems and equipment is better assessed after understanding crew adaptability to a reduced gravity environment.

On the surface, the rehearsal crew members acclimate in facilities on the Moon, performing tasks similar to those required at Mars. They conduct a 30-day science program that simulates EVA activities and instrument deployment and operational techniques that will be used on Mars. Operational concepts are developed to make best use of the systems and crew on the planetary surfaces.

While the Mars simulation flight is in progress, the crew rotations for the permanent lunar outpost continue. Six-member missions are flown on a quarterly basis for the first three quarters, rotating with the previous 18-person crew. When the orbiting dress rehearsal crew lands, the permanent outpost is occupied. The outpost crew provides assistance if necessary to the Mars rehearsal crew after they land.

While the dress rehearsal takes place, the permanent lunar crew remains actively involved in achieving surface self-sufficiency. Activities continue predominantly in the areas of food growth, waste recycling, and gas and water production. Additional science and exploration is also accomplished during this time, with pressurized and unpressurized expeditions.

The successful completion of this phase of lunar operations constitutes the Mars mission dress rehearsal. If redesigns are required that necessitate further testing on the Moon, there are opportunities to fly additional rehearsal missions in 2010 and 2011 prior to launching the Mars cargo mission in 2012.

Several differences must be noted between the lunar and martian missions in order to understand the validity of the simulation. First, the Moon is essentially void of an atmosphere and therefore radiation shielding is required to protect the crew from galactic cosmic radiation and solar flares. This shielding can be accomplished by designing the required protection into the habitation elements or by covering the habitats with a layer of lunar regolith. The lunar regolith option is preferred due to mission mass savings. Conversely, Mars has an atmosphere, although rather tenuous, which will provide moderate protection for lower altitude landing sites. Therefore, unloading and covering the habitats on Mars may not be required as it is on the Moon.

Second, the energy requirements (measured in terms of velocity change required or ΔV) needed for descent and ascent from the surfaces of the Moon and Mars are significantly different. These differences are due to the difference in mass of the two planets and the presence of an atmosphere on Mars as depicted in Table 2.3-2. As noted, the atmosphere of Mars is relatively thin, but can provide significant advantages for descent via drag deceleration.

	ΔV REQUIRED (m/sec)	
PHASE	Moon	Mars
Descent	~2000	~1000
Ascent	~1900	~5000

Table 2.3-2 Transportation System Descent/Ascent ΔV's

Third, the environments between the Moon and Mars are different. The lunar period of rotation is 655 hours long, whereas Mars rotates approximately once every 24 hours. This in day/night cycles greatly accentuates the differences between the surface systems specifically in terms of power, thermal control, fluid conditioning, and thermal cycling.

Due to these variances between the lunar and martian environments, the actual simulations may be limited to sub-systems and operations, rather than complete end-to-end hardware tests, but are conducted where possible.

2.3.3 Mars Mission

(Editor's note: The Mars phase of the ***Moon to Stay and Mars Exploration*** *architecture is identical to that of Architecture 1. Consequently, Section 2.3.3 of the present document is the same as that presented in* "Analysis of the Synthesis Group's **Mars Exploration** Architecture." *The writeup is reproduced here (with only editorial changes) for the convenience of the reader.)*

2.3.3.1 Key Features

The key features of the Mars mission phase of the ***Moon to Stay and Mars Exploration*** architecture, as mandated in the Synthesis Group Report, are:

a. First human landing on Mars in 2014,
b. Expendable transfer and excursion vehicles,
c. Six-member crew,
d. Zero-gravity transfer to Mars and back, and
e. Nuclear thermal propulsion for the interplanetary transits.

2.3.3.2 Mission Profile

The Synthesis Group Report states that "cargo and piloted landers are separate vehicles". In addition, the Report provides a mission schedule that commits to a split mission strategy for the Mars missions. Several different split mission modes are available. The following four modes have been investigated for the ***Moon to Stay and Mars Exploration*** architecture:

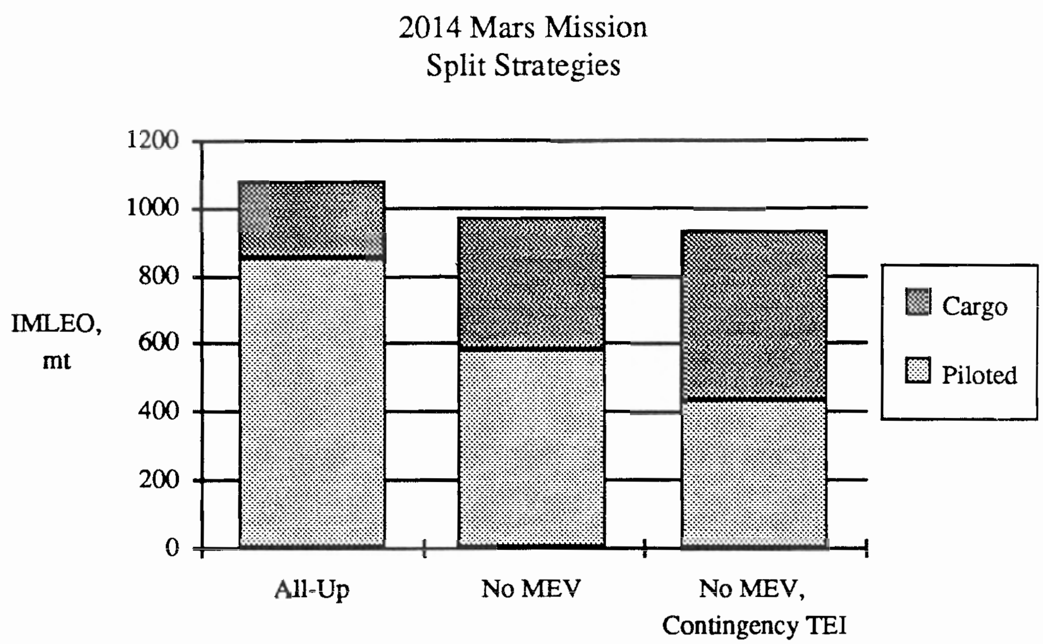
All-up — In this mission mode the piloted transfer vehicle carries a piloted lander and all propellant required for the nominal fast-return mission. The corresponding cargo vehicle only carries a cargo lander outfitted with surface supplies.

No MEV — In this mission mode the piloted transfer vehicle only carries enough propellant for the nominal fast return mission. The corresponding cargo vehicle carries the outfitted cargo lander plus the Mars excursion vehicle (MEV) required by the crew. Thus, a rendezvous in Mars orbit is required between the piloted and cargo transfer vehicles.

No MEV, Contingency TEI — In this mission, the piloted transfer vehicle carries only enough propellant for an energy-efficient, Earth-return. The corresponding cargo vehicle carries the cargo lander, piloted lander, and the additional propellant required for the piloted vehicle fast-return mission. Thus, a rendezvous in Mars orbit is required between the piloted and cargo transfer vehicles.

No MEV, No TEI — In this mission mode, all cargo and Earth-return propellant are pre-deployed at Mars prior to Earth departure. The cargo transfer vehicle thus carries the piloted and cargo landers along with the TEI propellant. The piloted transfer vehicle arrives at Mars empty with no propellant available for return to Earth. They must rendezvous with the cargo vehicle to obtain the return propellant. This mission mode was rejected due to the high level of risk associated with the Mars orbit rendezvous and propellant transfer.

Analyses have shown that the higher degree of splitting, i.e., the more mass the cargo vehicle transports, the better the overall initial mass in LEO (IMLEO), but correspondingly the higher the level of risk and mission complexity. As can be seen in Figure 2.3-4, the difference in the total mission mass in LEO between the various split modes is about 10% (~200 tons). At this level of analysis, this mass differential is insignificant relative to the uncertainty in the numbers themselves. Therefore, the baseline decision for the ***Moon to Stay and Mars Exploration*** architecture is the All-up mode. (A final decision should be made only after further studies and assessments are performed.)



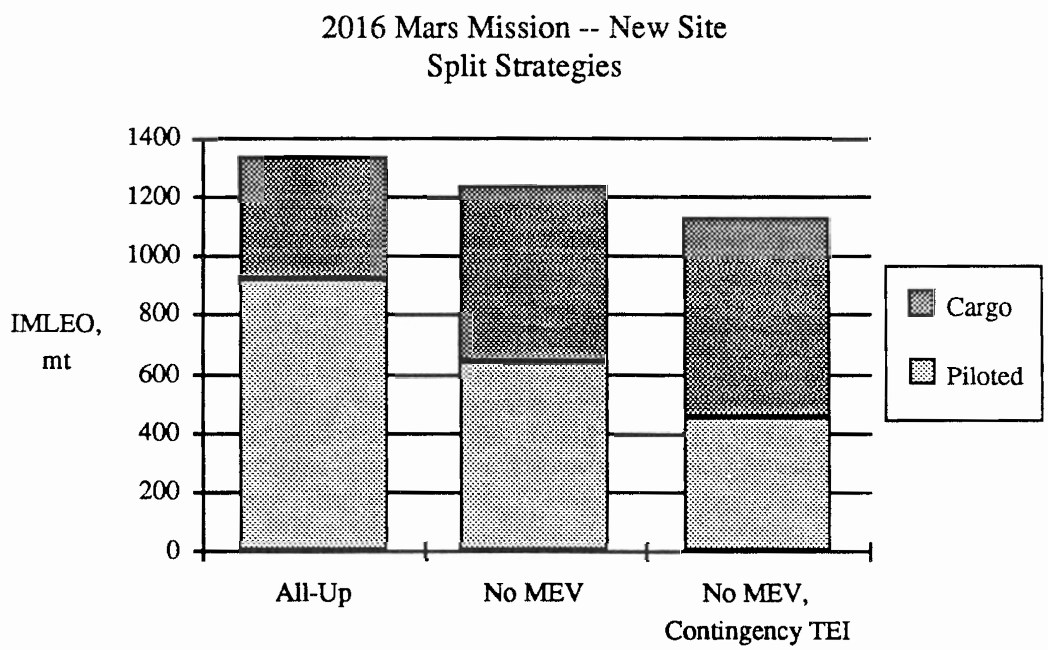


Figure 2.3-4 Mars Split/Sprint IMLEO Comparison

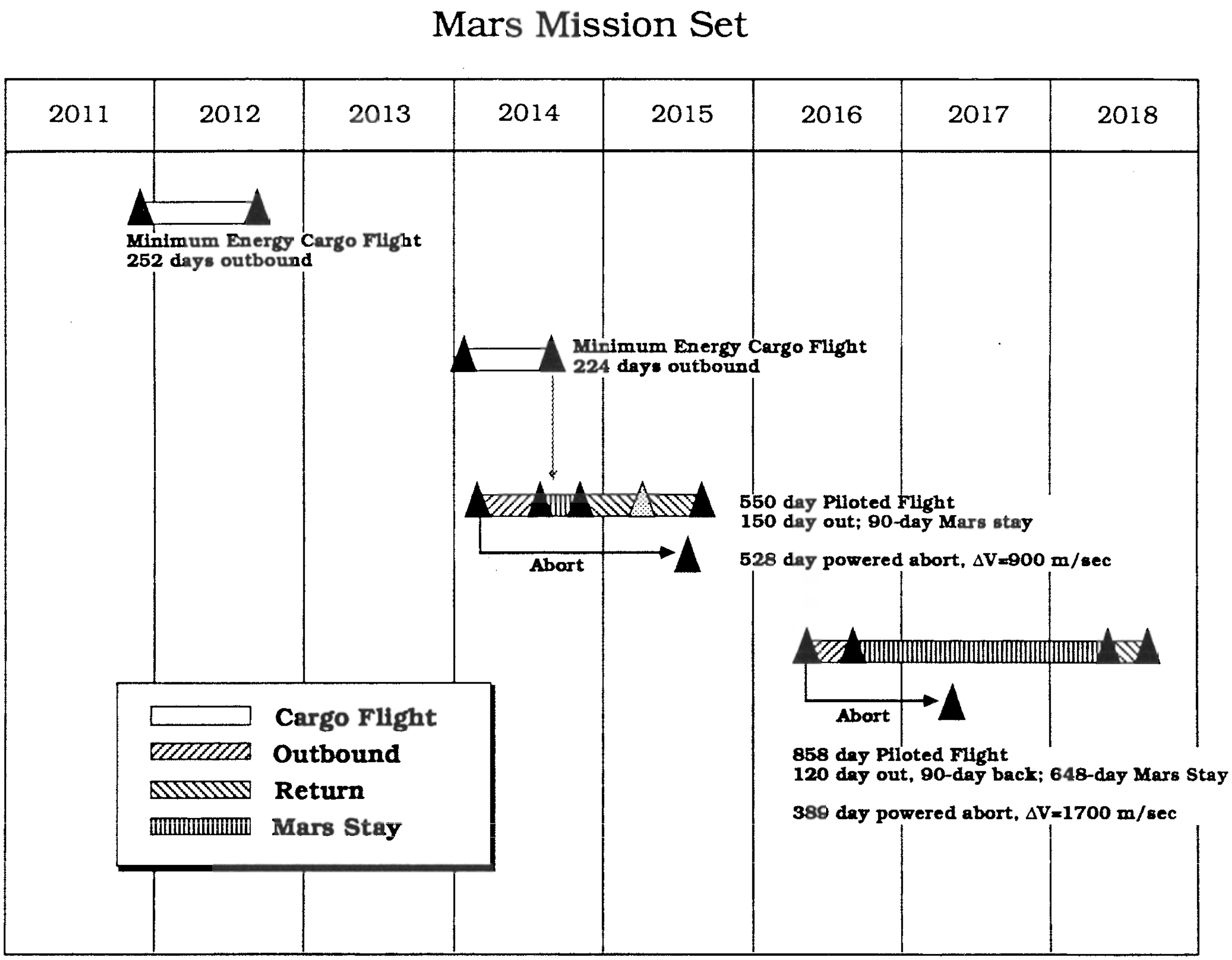


Figure 2.3-5 ***Moon to Stay and Mars Exploration*** Architecture Mission Set

The mission by mission timeline for the Mars mission phase of the ***Moon to Stay and Mars Exploration*** architecture is shown in Figure 2.3-5. Heliocentric trajectory plots and mission ΔV budgets for each flight are provided in Appendix A.

2.3.3.3 Mission Design Strategies

Two different Mars mission classes, generally characterized by the length of time in the Mars system and the total round-trip mission time, are available. The first mission class is typified by long-duration, Mars stay-times (as much as 500 days) and long, total round-trip times (approximately 900 days). This mission class is referred to as a Long-Duration-Stay mission. Long-Duration-Stay missions have long surface stays, but potentially fast one-way transit times. The second mission class consists of short Mars stay-times (typically less than 50 days) and relatively short, round-trip mission time (400-650 days). This mission class is referred to as a Short-Duration-Stay mission. Short-Duration-Stay missions have short surface stays, but generally have one long transit leg.

The outbound trajectories of these two mission types can be roughly matched for four of seven trans-Mars departure windows in the 15-year synodic cycle. This suggests several mission strategies for these opportunities. First, the same Mars transfer vehicle can be designed to accomplish either of the mission classes from a propulsive standpoint, with the excess performance available for the Long-Duration-Stay option utilized by reducing the transit times. This could allow the same vehicle design to perform a Short-Duration-Stay mission for the initial Mars expedition, followed by a series of longer surface stays. Second, if the fast-transit mission, with its associated long Mars stay-time represents the nominal mission, the return leg of the short-duration-stay mission can act as an "early return" abort if the landing must be abandoned after insertion into Mars orbit. (The alternative would be to wait ~600 days in Mars orbit until the fast-transit window opens.)

The nuclear propulsion choice appears to allow the flexibility in mission design that is required to accommodate an integrated mission approach coupled with a realistic abort strategy. For example, the total ΔV for these missions is on the order of 14 km/sec, a regime in which a nuclear thermal propulsion (NTP) vehicle begins to look very attractive. When one considers including an option for a realistic abort strategy, which is discussed next, the NTP vehicle appears to be enabling, assuming realistic values for initial mass in LEO.

In general, it is thought that for the challenging Mars mission, free-return aborts are not sufficient to provide for safe crew-return in the event of a propulsion system failure. A flawless injection onto the free-return trajectory is required. In addition, the abort capability is lost when the terminal Mars orbit targeting takes place. Therefore, this abort mode offers protection only during the ballistic trans-Mars coast. It is also difficult to justify an abort scenario in which protecting against mechanical failures necessitates placing the crew in a high-risk environment (i.e., longer exposure to radiation and zero-g). Finally, a low-probability event like an abort substantially drives vehicle designs with no gain in mission productivity, thus increasing the cost and complexity of the nominal mission. Because of these limitations, the recommended approach is to require redundant Mars transfer vehicle main propulsion capability (probably in the form of multiple engines, tanks, and propellant lines) along with a powered abort strategy which allows a faster return of the crew using the degraded propulsion capability.

2.3.3.4 Transportation System Strategies

The Mars transportation system is designed to accommodate both Short-Duration-Stay missions (opposition-class trajectories) and Long-Duration-Stay missions (conjunction-class trajectories). The excess propulsive performance available for this latter class is used to shorten the interplanetary transit times. An all-propulsive mission profile using nuclear thermal propulsion is assumed for both piloted and cargo missions.

The Mars excursion vehicle (MEV) is sized to allow the descent stage to function in either a piloted and cargo mode. Due to the uncertainties in the long-duration storage of cryogenic propellants, storable propellants are selected for use on both the ascent and descent stages of the MEV.

2.3.3.5 Planetary Surface Strategies

Habitats: The habitat, or pressurized volume, strategy employs pre-fabricated, space station type modules. Associated systems such as airlocks and connecting nodes are also based on space station hardware. (However, all habitable elements and their subsystems are designed for a reduced gravity environment, rather than zero-gravity.)

Power: Nuclear surface power (SP-100 class) is used from the start of surface activities. A backup photovoltaic power system is provided.

Surface Mobility: Extravehicular mobility units (EMUs) are provided for each crew member. The same suit is used for both the Moon and Mars, however, the portable life support systems are different. Unpressurized rovers are brought to the martian surfaces with the crews on the piloted landers. Pressurized rovers are also used in this architecture. To expand the exploration capability, a power cart and experiment/sample trailer are used with the pressurized rover. All rovers are powered by fuel cells. Finally, teleoperated vehicles are used for unloading, construction, and mining purposes.

2.3.3.6 Mars Precursors

A minimum set of robotic precursors are flown to gather the data necessary for selecting Mars landing sites. The precursor missions for the ***Moon to Stay and Mars Exploration*** architecture are characterized as follows:

- Site Reconnaissance orbiters image at least 12 candidate landing sites in sufficient detail to "certify" the safety of the site and to provide strategic science data and resource data to aid in site discrimination and selection.

- Robotic rovers are sent to the prime and backup landing sites for the human crews. Rovers provide imagery of the surface and subsurface, make in situ chemical and mineral measurements, identify sites of interest for humans to investigate in the pressurized rover, and test for toxicity.

Two site reconnaissance orbiters are launched to Mars in December, 1998. The Synthesis Group Report has stated that the capability of a communications orbiter is to be combined with each reconnaissance orbiter, if feasible. The feasibility of this combination is discussed in Section 3.1 with the detailed implementation of the spacecraft. A minimum energy trajectory profile was selected for these flights launching in December 1998; arrival at Mars occurs 287 days after launch. Upon arrival at Mars the reconnaissance spacecraft are placed into 300 km altitude, sun-synchronous orbits to begin the mapping phase of their mission. The nominal duration for this phase is 20 months. Due to spacecraft lifetime issues, (the first piloted flight arrives at Mars 16 years later) and communications rate limitations, separate, more capable communications orbiters are required to support the piloted phase of the Mars exploration. The implementation of these orbiters is also presented in Section 3.1.

Allowing sufficient time to reduce the data from this mapping phase overlaps with the next launch opportunity (2001). Therefore, the site characterization rovers are launched to Mars the following two opportunities (2003 and 2005). The spacecraft fly minimum energy trajectories, launching in June, 2003 and August, 2005, respectively. Upon arrival at Mars, the spacecraft are placed into a low altitude orbit, from which the rovers are de-orbited. The nominal lifetime for each rover mission on the surface is two years.

A summary of the operations strategy for the Mars precursor missions, as well as for Mars IOC and NOC, is presented in Table 2.3-3.

2.3.3.7 Initial Operational Capability

Four missions comprise the Mars IOC phase. The first three missions are cargo missions launched in late 2011. These missions pre-deploy the surface systems required to support the first Mars crew which launches in 2014. The payload for these cargo missions consists of a habitat, a pressurized rover, a nuclear power plant, a minimal photovoltaic emergency backup power system, an unloader/mover, scientific exploration equipment, and communications equipment. In addition to pre-deploying the Mars surface systems, these first cargo flights also serve as a demonstration of the NTR system intended for use on the piloted Mars flight.

Three cargo landers are needed to deliver the required mass to the martian surface. A fully integrated cargo lander and its propulsion (TMI/MOC) stage can be launched intact on one 250 mt ETO flight, thereby eliminating the need for on-orbit-assembly. Thus, three separate cargo flights are launched independently to Mars (as opposed to three cargo landers all on one cargo vehicle). The cargo flights are launched during the 40-day window beginning in November, 2011 by the NTR system. Upon arrival at Mars, the NTR propulsively breaks the entire vehicle into an elliptic orbit from which the cargo MEV de-orbits. The MEV uses aeromaneuvering to reach the martian surface, and uses storable propellants for the final breaking maneuver.

Upon reaching the surface the cargo is autonomously deployed and set-up, and remotely tested to ensure the equipment is functional prior to the first piloted mission launch.

The first piloted flight launches during the next opportunity in 2014. This flight sends a crew of 6 to Mars for a nominal 90-day stay in the Mars system. The mission profile selected for this flight is of the Short-Duration-Stay class, having a 90-day stay-time, with an overall mission duration of 550 days and a "fast"outbound transit of 150 days. This mission scenario has a flyby abort with a flight time of slightly over 500 days as part of its features.

After reaching the surface, all six crew members live out of the lander for up to three days during the check out of the surface equipment sent on the previous cargo flight. The crew members then carry out scientific objectives, both laboratory science and local exploration of the outpost vicinity.

2.3.3.8 Next Operational Capability

Five missions comprise the NOC of the Mars phase of the ***Moon to Stay and Mars Exploration*** architecture. Using the split

	MARS SITE RECONNAISSANCE	FIRST MARS MISSION	FIELD EXPLORATION
	PRECURSOR	IOC	NOC
Overview	Earth-based operations control emphasized Primarily automated operations **Earth-based operations preparation and analysis necessary for unpiloted mission**	Distributed and in situ element control stressed Primarily automated and teleoperated control Crew-intensive contingency/recovery operations Distributed operations preparation for crew autonomy and flexibility	In situ control stressed Automated and telepresence operations modes facilitate long planetary surface stay Crew-intensive contingency and recovery operations In situ and distributed operations preparation allow flexible and autonomous crew operations
Mission Elements	Earth-based automated control of nominal operations Mission operator intensive control of contingency operations Mission data analyzed on Earth Elements deployed fully assembled in Mars orbit	Distributed control of remote operations Balance between telepresence and automated operations **Crew performs realtime and interim analysis of data to maximize "closed" operations**	In situ and distributed for control and monitor activities Balanced telepresence and automated operation modes during extensive field operations Crew performs real-time and interim data analysis to close operations during long stay
Science Elements	Earth-based control in early/middle operation Automated control of in-transit operations Telerobotic control of planetary operations Automated/human-tended monitoring for surface operations	Telerobotic and human-tended operations to maximize exploration on planetary surface Distributed control of Planetary Operations In situ operations analysis to facilitate discretionary PI science	In situ operations preparation conducted Telerobotic and human-tended control of operations to maximize field exploration Operations analysis primarily controlled in situ to allow crew science exploration flexibility
Support Infra-structure	Earth-based and automated control of all operations	Distributed control and automated/telepresence operations emphasized as crew focus on exploration	Distributed control evolving to Earth-based Teleoperated and automated operations modes used as crew focus on scientific exploration

Note: Bold type indicates architecture-unique operations

Table 2.3-3 Operations Strategy -- Mars Operational Capabilities

mission strategy, the cargo missions (paired with the NOC piloted flight in 2016) launch the previous opportunity in 2014. These flights arrive after the first Mars crew is on the surface. If an emergency occurs during piloted mission 1, the assets of the cargo missions are available to this crew.

The second crew carries out an approximately 600-day surface stay at a different site than the initial outpost. Since the crew cannot use the existing surface assets from the IOC, the payload for this cargo mission also consists of a habitat, a pressurized rover, a nuclear power plant, a minimal photovoltaic emergency backup power system, an unloader/mover, scientific exploration equipment, and communications equipment. In addition, a two-year surface stay requires considerable supplies; thus, four cargo landers are required to deliver the necessary payload to the surface. The cargo landers are launched to Mars as separate flights as in the IOC.

The NOC six-member crew launches in 2016. The mission profile selected for this flight is of the Long-Duration-Stay class having a 120-day outbound transit, a 648-day stay, and a 90-day return transit, giving an overall total mission duration of 858 days. This mission scenario has a flyby abort that returns to Earth in slightly over one-year as part of its features.

After reaching the surface, all six crew members live out of the lander for up to three days during the check out of the surface equipment sent on the previous cargo flight. The crew members then carry out scientific objectives, both laboratory science and surface exploration. The long surface stay time enables extensive surface exploration in the vicinity of the outpost including geologic field work to interesting sites. A demonstration unit is delivered to conduct experiments in local resource utilization.

2.4 MISSION OPTIONS

The ***Moon to Stay and Mars Exploration*** architecture is designed for certain mission options. During the lunar portion of the architecture, options exist for continued research and expanded presence. Depending on the level of success toward base self-sufficiency, the crew size could increase or decrease (from 18). If an increase occurred, additional habitation facilities, as well as resource/food production, would be required to accommodate the growth. The change in base size is anticipated in NOC-3. NOC-3 also offers further options by allowing additional missions pass the 2020 scheduled timeframe. The dress rehearsal period in NOC-4 provides the option to "fly" the Mars vehicles in the lunar vicinity, if practical. According to the Synthesis Group Report, "the lunar lander could be the Mars lander. The use of this vehicle allows for realistic mission-critical evaluations of the performance of the systems and the crew with a high degree of operational fidelity."

For the Mars portion of the architecture, options exist for infrastructure reconfiguration, abort strategies, and schedule flexibility. The precursor mission strategy calls for site reconnaissance orbiters which could be reconfigured as communications orbiters, depending on the orbital constraints. During the first human mission, an emergency option exists, that is to land the second cargo mission (departed in 2016) at the initial outpost site. The assets available in this cargo mission could be used to supplement the first crew if a longer stay is required. If an emergency situation does not exist, the second cargo mission may still land at the initial outpost site. Returning to the first site allows the next crew to use previous infrastructure, thus expanding the mission facilities or requiring less cargo in the 2016 opportunity.

Schedule flexibility is contained throughout the Mars portion of the ***Moon to Stay and Mars Exploration*** architecture. Following NOC, additional flights are available in 2018 and 2020. These mission opportunities include long stay times and are, consequently, dependent upon the success of the second piloted mission launched in 2016. Finally, the option always exists in this architecture to accelerate the program. The initial Mars mission, scheduled in 2014, could be earlier if the lunar testbed phase proceeds exceptionally well. Note that appropriate experience on the Moon, measured in cumulative crew days on the surface (see Figure 2.2-2), occurs in 2007 - seven years prior to the first human Mars mission.

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3.0 IMPLEMENTATIONS

Section 3 describes specific **implementations** developed in response to the strategies described in the Synthesis Group Report Generally, several implementation options were available to satisfy those strategies. The implementations which were chosen represent, it is hoped, a thoughtful, intelligent approach to satisfying the ***Moon to Stay and Mars Exploration*** theme, strategies, and groundrules, as described in Section 2 - "Architecture Reference Description." However, the implementations presented herein do not necessarily achieve an optimal solution.

Additionally, where the Synthesis Group Report stated a specific implementation (such as the type and number of robotic, precursor missions), that implementation has been followed.

An implementation falls within a functional area and logically follows from the strategy employed within that functional area. Implementations are the very specific method (or tool) selected to accomplish a particular job within a functional area. Implementations lie at the bottom of the hierarchical chain, but are not necessarily restricted to systems or hardware.

Each of the implementations presented below in the functional areas include an overview, a system description, and an operational description. The overview states the reasons why the particular implementation was selected and how the implementation abides by the architecture reference strategy. The system description provides details of the elements supporting the lunar and martian segments of the implementation. The operational description provides a succinct description of the operational characteristics relating to the systems described.

The functional areas included in Section 3 are precursor/robotic missions; science; planetary surface systems; space transportation systems; Earth-to-orbit transportation systems; and telecommunications, information systems and navigation.

3.1 PRECURSORS / ROBOTIC MISSIONS

3.1.1 Overview

With an emphasis on early and substantial human presence on the moon, the Synthesis Group outlined a two part strategy for selecting a site to be used for a permanent outpost. This strategy relies first on data from past missions and future specialized robotic missions to provide data from which a single site can be identified and selected. In the second step, a rover will be sent to this site to certify decisions based on orbital data and to explore the region surrounding the site. For the initial exploration of Mars, current knowledge is "considered inadequate" for identifying and certifying safe and scientifically interesting sites. A two-part strategy was suggested by the Synthesis Group to address the lack of sufficient data to characterize the martian surface and identify landing sites. This strategy also relies on data in hand from previous missions and new data obtained from both orbiters (the first step in the strategy) and surface rovers (the second step in the strategy). The role of robotic missions in each of these strategies is discussed in the following paragraphs, with additional detail regarding implementations and operations discussed in later sections.

Because of the emphasis placed on lunar habitation in this Architecture, early robotic missions will be used to gather data so that a sound judgement can be made when selecting a location for the Lunar Outpost. Data gathered from Earth-based observations, Lunar Orbiter missions, and Apollo missions can be used effectively to screen some of the potential sites. However, this is not a complete data set for making a final decision of this magnitude: selecting the site for a permanent and significant human presence. Additional data necessary to make such a decision includes surface composition data to identify and characterize potentially usable resources, terrain adequate for the construction of anticipated facilities (e.g., habitation, power generation, landing sites, observatory-class science instruments, etc.) and a locale of sufficient scientific interest to support extended duration traverses (by humans and robots) over a period of many years. Additional robotic missions will be needed to collect the necessary information. From orbit, compositional mapping allied with imagery at appropriate scales can provide the foundation for site selection to develop lunar resources. Photogeologic interpretation of compositional and morphological data will result in a suite of candidate sites for outpost location. Detailed mapping of these sites from orbit will narrow the field to one or perhaps several. The key to narrowing the field is data that provides the best estimate of the viability of the site to meet the various criteria discussed above. This data may be obtained from orbit by x-ray and gammaray detection, spectral studies of mineralogy and regolith maturity indices, laser altimetry to develop topographical maps and locate key tie points for controlled maps, and other techniques all used to support interpretation of candidate sites as driven by critical engineering requirements.

Once the outpost site has been selected, a rover will be used to validate or refute judgements made from orbital information and provide the data for final certification of site suitability and site selection. First, the rover will gather data from which decision-makers can certify that the site meets fundamental requirements for a safe landing by human crews and their equipment landers as well as the needs of the lunar outpost habitat and ancillary components. Second, the rover will gather data from which decision-makers can determine whether or not the judgements made, based on orbital data concerning properties of the regolith, will support the kind of resource utilization activities planned for the outpost. The rover plays the role of the mining geologist who surveys a site as a last step before commitment to proceed. Three dimensional characterization of the regolith, therefore, is cost effective and is a critical role for the rover in addition to its role in certifying characteristics essential to construction of outpost components. Three dimensional characterization is possible using active seismic or electromagnetic sounder techniques and, perhaps, drilling. Samples representative of various depths may be obtainable from crater ejecta and could be important in minimizing the need for core samples collected by drilling. Once these initial activities have been completed, the rover is available for exploration of the region surrounding the site. The suite of instruments used by the rover for site certification will also be valuable for the scientific investigation of this region, providing valuable reconnaissance data that can be used to plan later missions by humans and more capable rovers.

For initial Mars exploration, the Synthesis Group outlined a strategy that applies to all four of their architectures. The first part of the strategy is to identify and image in detail at least 12 sites from orbit in order to identify hazards that are of approximately one meter in size and to help better understand the terrain types and general surface conditions found on Mars. Additional data types would also be obtained for each of these sites to help discriminate which are of highest scientific interest. From this set of candidate sites, a primary and backup site will be selected based on the dual criteria of scientific interest and availability of a safe location to land and establish a surface base. The second phase of this strategy is to deploy a vehicle to the surface at the primary and backup site. This vehicle would then perform a number of tasks and gather data that will be used in making a number of key decisions. The first of these tasks is to verify that the site selected based on orbital data does in fact satisfy the criteria for a safe landing and surface base location. The next task is to check the local environment for potential hazards, such as the presence of potentially toxic materials. The third task is to survey the immediate vicinity of the landing site to provide the necessary data to plan for the construction and setup of the surface base. Finally, this surface vehicle will support initial scientific investigations, such as general field work and sample analysis, to assist in planning for the tasks that will be performed by the human crews to follow. Mobility is an obvious necessity of this surface vehicle.

To meet these needs, the Synthesis Group Report proposes the following set of robotic precursor missions for the Space Resource Utilization architecture:

Lunar Missions: Site Reconnaissance Orbiters (2)
- both 2000 launch

Surface Rover (1)
- 2002 launch

Mars Missions: Site Reconnaissance Orbiters (2)
- both 1998 launch

Surface Rovers (2)
- 2003 & 2005 launches

The following sections provide a description of candidate spacecraft and their operations which are capable of fulfilling these strategies.

3.1.2 System Description

3.1.2.1 Lunar Site Reconnaissance Orbiter (LSRO)

The dual objectives of the LSRO are primarily to identify sites suitably safe for landing and construction of habitation facilities and secondarily to locate potentially useful raw material concentrations. Data products are intended to provide an understanding of surface objects at a 1-m scale resolution, and topography at the 10s of meters scale for specific candidate sites measuring approximately 10 x 10 kilometers, while mineralogical and elemental distributions will be understood to the kilometer level globally. The basis for the candidate LSRO configuration is the Mars Observer spacecraft bus, an existing design that would allow early deployment of the LSRO, with a mission-optimized payload. The spacecraft will carry an instrument complement capable of mapping the surface in a number of spectral bands to characterize its chemical and mineralogical makeup as well as providing visible-band imagery from which landing sites can be identified. The vehicle will have a launch mass of approximately 1800 kilograms when fully loaded with propellants. The Atlas IIA/Centaur launch vehicle/upper stage has been tentatively selected as capable of delivering this vehicle to its trans-lunar injection point.

3.1.2.2 Lunar Surface Rover (LRVR)

The objectives of the rover mission are to certify a safe human landing site and construction site for a permanent habitat as well as to collect, analyze, and verify the sources of raw materials identified remotely. As needed, the rover will also emplace infrastructure elements, such as navigation aids, for human missions. The reliance on cargo vehicles to make relatively frequent deliveries of high value cargo increases the importance of these infrastructure elements.

The basis for a candidate LRVR configuration is a six-wheeled, single-bodied vehicle using a series of passive levers to allow the vehicle to climb over one meter obstacles and climb up 30-degree slopes. The rover will be teleoperated from the Earth. This assumes that control will be at a supervisory level and that the rover can automatically execute low-level traverse and sampling functions in response to moderately high level goals provided by human operators. Two 6-degree-of-freedom manipulator arms will have a set of interchangeable tools to acquire surface samples. The baseline concept provides for subsurface mapping, using an electromagnetic sounder, and for shallow regolith sampling, but not for deep coring. This configuration is estimated to have a mass of approximately 600 kilograms. With the inclusion of a landing system, this vehicle will have a launch mass of less than 1500 kilograms. At this mass level, the Atlas IIA/Centaur launch vehicle/upper stage is capable of delivering the vehicle to its trans-lunar injection point.

3.1.2.3 Mars Site Reconnaissance Orbiter/Communications Orbiter (MSRO/MCO):

The basic objective of the MSRO is to locate a safe and scientifically interesting site on the Martian surface. The basis for a candidate MSRO configuration is the Mars Observer spacecraft bus, allowing early development, with a payload focused on the site selection objective. The basic payload will consist of a high-resolution imaging system (capable of resolving objects of approximately one meter scale), a multi-spectral mapping instrument for locating and characterizing useful resources on the surface, and an electromagnetic sounding instrument to characterize the subsurface structure. This payload will be designed to provide an understanding of surface objects at approximately a 1-m scale resolution, while mineralogical and elemental distributions will be understood to the kilometer level. This configuration is estimated to have a mass of approximately 2900 kilograms at launch.

All data acquired by each of the MSRO's are transmitted to the Earth in a manner similar to that used by Mars Observer, wherein data acquisition in a nadir pointing orientation is alternated with data return in an Earth pointing orientation. The MSRO spacecraft are placed in low altitude, sun synchronous orbits with a low sun angle. As stated in the Synthesis Group Report, it would be preferable to include communications capability within the MSRO's so that they could provide relay support for the later Mars Rover missions. To include this function, a nominal 10 year life is projected for these spacecraft to cover the MSRO and MRVR missions.

Because of the lengthy time between the MSRO and MRVR missions, and since the orbit requirements for the MSRO and MCO functions are different, separate MCO's launched in conjunction with the MRVR missions may be prudent. If the relay communications functions are not incorporated in the MSRO's and separate MCO's are required, they would be launched in conjunction with the first MRVR mission, which is 5 years after the MSRO missions. This would provide higher probability of successful support to the MRVR missions both because the support would occur earlier in the MCO life and more time would be available to implement technology (e.g., Ka band). The separate MCO's could be placed in areostationary orbits for continuous, dedicated rover support, or lower altitude, inclined repeating orbits for global coverage, with multiple rover relay link opportunities per day at shorter range. Each MCO is estimated to have a mass of approximately 2300 kg.

3.1.2.4 Mars Surface Rovers (MRVR):

The objectives of the Mars rover missions are to certify human landing sites, collect and analyze a diverse suite of rock samples, and possibly cache samples for collection by later human missions. The rover missions are designed to refine the understanding of proposed sites for human activities to the submeter level, characterize resource availability to more detailed resolution, and determine suitability for human habitation. In addition, the rovers will contribute further to the resolution of crew health (i.e. possible toxic agents), forward-contamination and back-contamination issues and will emplace infrastructure elements such as navigation aids for human and cargo missions. The basis for a candidate MRVR is the same as the LRVR with suitable design changes to allow operations in the martian environment. The configuration is a six-wheeled, single-bodied vehicle using a series of passive levers to allow the vehicle to climb over one meter obstacles and climb up 30-degree slopes. The assumed level of control will be minimal and that the rover can automatically execute extended traverses of approximately 10 kilometers distance and sampling functions in response to high level goals provided by human operators. Two 6-degree-of-freedom manipulator arms will have a set of interchangeable tools to acquire surface samples. The baseline concept provides for shallow regolith sampling, but not for deep coring. This configuration is estimated to have a mass of approximately 600 kilograms. This vehicle is assumed to use aerocapture to place the rover and its entry/landing system in orbit at Mars. The aerocapture system will vary in mass depending on the opportunity used. Given this variability, the complete system at launch is estimated to have a mass in the 4000 to 4500 kilogram range. A launch vehicle with a capability comparable to a Titan IV/Centaur will be required.

3.1.3 Operational Description

3.1.3.1 Lunar Site Reconnaissance Orbiter (LSRO)

The LSRO is targeted for a low altitude (approximately 100 kilometers altitude) mapping orbit. After the flight system has been operationally verified in orbit, the LSRO will proceed with its primary mission which lasts approximately 20 months. During this phase the two LSRO systems will acquire high resolution maps and other pertinent data for several candidate outpost sites. The communications function for the LSRO is handled with its own systems, sending data directly to Earth.

3.1.3.2 Lunar Surface Rover (LRVR)

The primary surface mission for the LRVR is projected to last two years. During the first year, a fairly autonomous rover initially surveys a 10 x 10-km area for surface trafficability, sub-surface obstacles, and elemental and mineral compositions for resources. The site survey is conducted by traversing over the terrain, imaging the surface with stereo cameras and other instruments, sounding the subsurface with electromagnetic sounding (EMS) or radar, and physically probing the surface to about 2 meter with a drive tube to conduct soil tests and validate the EMS data. Within this area, the rover will intensively survey candidate locations for a power plant, a habitat, and a landing site for human and cargo missions. There is also time for sample selection, collection, and caching. During the second year, the rover could be used to explore regionally outside the 10 x 10-km area for useful resources and to collect and cache more samples. The rover could be either more or less autonomous in this phase, depending on how much interaction is desired.

An extended mission could last an additional two years, considering the rover's probable lifetime if it has survived the primary mission phase. At this time, the first of the human and cargo missions will be landing and the outpost construction and expansion will be starting. Resources to support the outpost will become a more important factor. The necessary observations could be made during an extended use of the rover, complemented by astronaut field work in the first four years of outpost operation. Similar judgements could be made concerning other uses of lunar resources or lunar properties. These data will form the basis for strategic decisions for exploitation if it is warranted.

3.1.3.3 Mars Site Reconnaissance Orbiter/Communications

The MSRO's are targeted for operational mapping orbits that are sun-synchronous at about 4:00 p.m. local time near the equator with a near-polar inclination. This type orbit is characterized by a one-day repeat cycle and an altitude of 299 kilometers. After the flight system has been operationally verified in orbit and due consideration given the martian dust storm season, the MSRO will proceed with its primary mission. During this phase, which lasts up to 4 years, up to 50% of the martian surface will be mapped in the panchromatic, multispectral, and electromagnetic sounding modes at low to moderate spatial resolutions. Of major importance during this period, the two MSRO systems will acquire high resolution maps (scale about 1 meter) of at least 12 candidate landing sites for the planning of piloted missions. The MSRO alternately acquires data with the body-fixed instruments in a nadir orientation and returns data with a body-fixed high-gain antenna in an Earth-pointing orientation.

If relay communications capability is included in the MSRO's, these spacecraft will be designed with sufficient life expectancy to provide relay support for the MRVR missions. The MRSO repeat orbit will be phased to provide numerous passes over the rover for burst communications. If it is elected to provide the relay communications function with separate MCO's, they would be launched in conjunction with the first MRVR mission.

3.1.3.4 Mars Surface Rovers (MRVR):

The two MRVR missions will be supported either by the MSRO's, if equipped with relay capabilities, or by MCO's launched during the same opportunity as the first MRVR mission. The first MRVR mission is a single flight system which is launched in June 2003 using a Titan/Centaur launch vehicle.

The primary surface mission is to locate specific sites on the surface for major infrastructure elements to be used by the human crews and is projected to last approximately two years. During the first year, a fairly autonomous rover initially surveys a 10 x 10-km area for surface trafficability, sub-surface obstacles, and elemental and mineral composition. The site survey is conducted by traversing over the terrain, imaging the surface with stereo cameras and other instruments, sounding the subsurface with electromagnetic sounding (EMS) or radar, and physically probing the surface to about 2 meters with a drive tube to conduct soil tests and validate the EMS data. Within this 10 x 10-km area, the rover more intensively surveys approximately nine 100 x 100-m sites for selection of locations for a power plant, a habitat, and a landing site for human missions. There is also time for sample selection, collection, and caching. During the second year, the rover could be used to explore regionally outside the 10 x 10-km area for useful resources and to collect and cache more samples.

An extended mission could last nearly two years, considering the rover's probable lifetime if it has survived the primary mission phase. During this period, the rover would continue to explore regionally. The rover would probably be used in a more autonomous mode in this phase to minimize interaction while the next rover is being supported in its primary mission.

This same pattern would be repeated for the second rover in the next launch opportunity (August 2005) landed at the selected back-up site.

3.2 SCIENCE

3.2.1 Science Overview

The rationale driving the following implementation follows the Synthesis Group theme which indicates that the mission will provide for a permanent human presence on the moon, combined with the exploration of Mars. Accordingly, we assume a science and exploration program which is aggressively implemented, and accomplishes an extensive buildup of science infrastructure on the moon, while acquiring surface operations experience and life science data to support the planned missions to Mars.

3.2.2 Key Science Features Common to Architectures

Orbital Science: Scientific observations conducted in orbit are considered important in the Synthesis Group Report, but they are not baselined for each architecture. These activities are considered important enough that they are routinely included as an integral element of the science program. Orbital science is conducted during the Mars dress rehearsal, which orbits crew around Moon for up to 120 days. During the Mars mission, orbital science is kept to a minimum unless there is a situation that does not allow the crew to land on the surface.

Orbital science includes using humans as operators of instrument platforms, e.g. instrument cycling, repair, and manual contingency operation. In addition, humans as observers in orbit can provide direct visual observations of physical features occurring on the planet's surface. Further, humans in orbit can teleoperate instruments and rovers on the planet surface without the delay times incurred from teleoperations from Earth. In addition, a wide variety of remote sensing of the Earth, Moon, and Mars can be done from orbit.

Orbital science is particularly applicable to this architecture because it provides additional large-scale chemical, topographic, and even some subsurface mapping opportunities from orbit before deploying humans to the lunar or Martian surface.

Common Lunar Science Studies: The Synthesis Report summarizes four areas of lunar science that will be accomplished to some degree by each architecture. The Moon is to be used as a target of study, i.e. for geosciences and tenuous atmosphere. Additionally, the Moon will be used as an observatory platform from which telescopes and sensors can measure and record astronomical phenomena and particle fluxes. The regolith will be studied for its historical archive of solar and geologic information and for its resource and energy potential. Finally, excursions on the Moon will be used as a simulant for Mars terrains for geosciences field work and experience in traversing and operating on a planetary surface.

Common Mars Science Studies: Surface Science: 30-100 days The Synthesis Group report specifies that as surface capabilities are enhanced, the Mars surface will be characterized at progressively greater distances from the landing site and in increasing detail. During the 30-100 day missions, the site is characterized at 2, 50 and finally a maximum of 100 kilometers. Field studies are conducted by a combination of humans and robots. A pressurized rover capability enables more distant access for humans, increasing to 50 - 100 km. During the longer pressurized traverses, a crew of 2-3 people explores key geologic sites, collects samples, deploys instruments, and does field work.

Surface Science: 600 days With the advent of longer Mars stay-times, the crew is able to conduct more thorough field work and revisit sites of scientific interest if necessary. A modest geochemical laboratory enables some rock/exobiology sample analyses including bulk examination, chemistry, mineralogy, and volatile concentrations.

Meteorological and environmental measurements are made, studying such parameters as seasonal climate variations and dust storms.

Long-term studies of complex scientific studies are initiated, such as the search for life, the study of ancient climates and past physical processes which formed and molded the planet.

Exploratory observations are enhanced by robots deployed at diverse locations which are then controlled from the Mars landing site or Mars orbit. There, rovers can do field work, deploy instruments, and take / deliver high grade samples for Earth return.

Scientific investigations build on data and advances that were catalyzed by previous Mars missions.

3.2.3 Suggested Science Implementation and Payloads

Lunar IOC: The first 14-day missions of Lunar IOC in 2004 will establish a man-tended outpost, and will concentrate on detailed geologic sampling and survey work to support establishment of the future habitat site. Some local, unpressurized rover traverses will be conducted to collect bulk samples from interesting "targets of opportunity." Also, small automated geophysical and space physics stations will be deployed, and a small, robotic operational test telescope will be set up to provide information for the design of future large robotic telescopes.

Science payloads and delivery schedule for this and other lunar IOC/NOC phases are listed in Figure 3.2-1. Two tables showing 1) science payload mass vs. mission phases and 2) science instruments delivered vs. mission phase are included in Figures 3.2-2 and 3.2-3. The science instrument icon key is included as Figure 3.2-6. Detailed mass volume, power and data parameters for lunar science payloads are listed in Appendix B.

Lunar NOC-1: The second series of missions beginning in 2005 are dedicated to developing the outpost infrastructure and extending the length of human presence on the moon. The duration of manned stays on the surface increase to 40 days for this operating capability. Activities support primarily the build-up of major science infrastructure, including the deployment of a lunar transit telescope and a 4-m optical telescope. Remote deployment of space physics and geophysics packages, and geologic sampling is also stressed through the conduct of 2 long pressurized rover traverses. With the use of the pressurized rover, the radius of geologic investigations and deployemtn of geophysical instrument packages will increase to 100 km. A typical pressurized excursion is described:

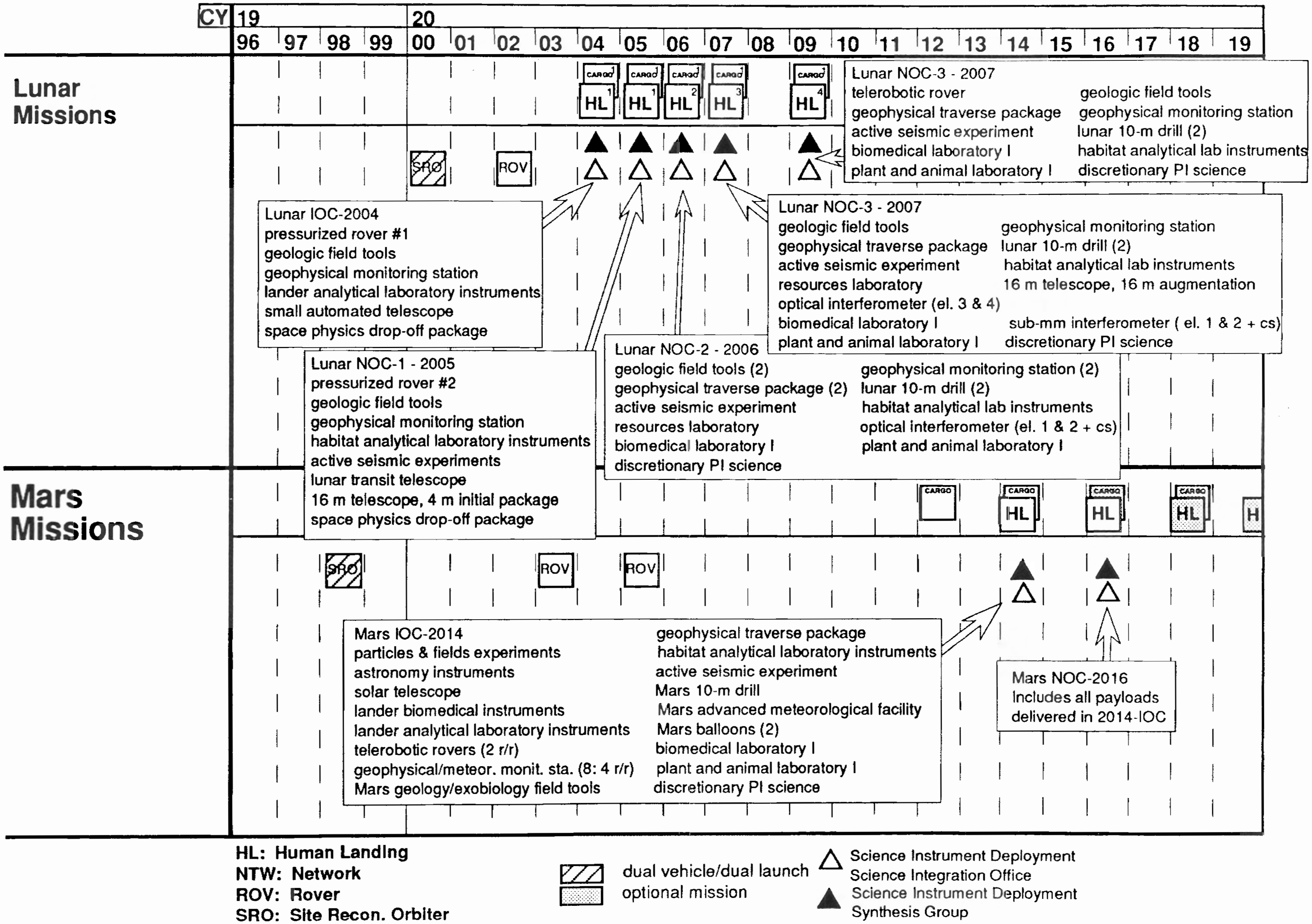

Figure 3.2-1 Science payloads and delivery schedule

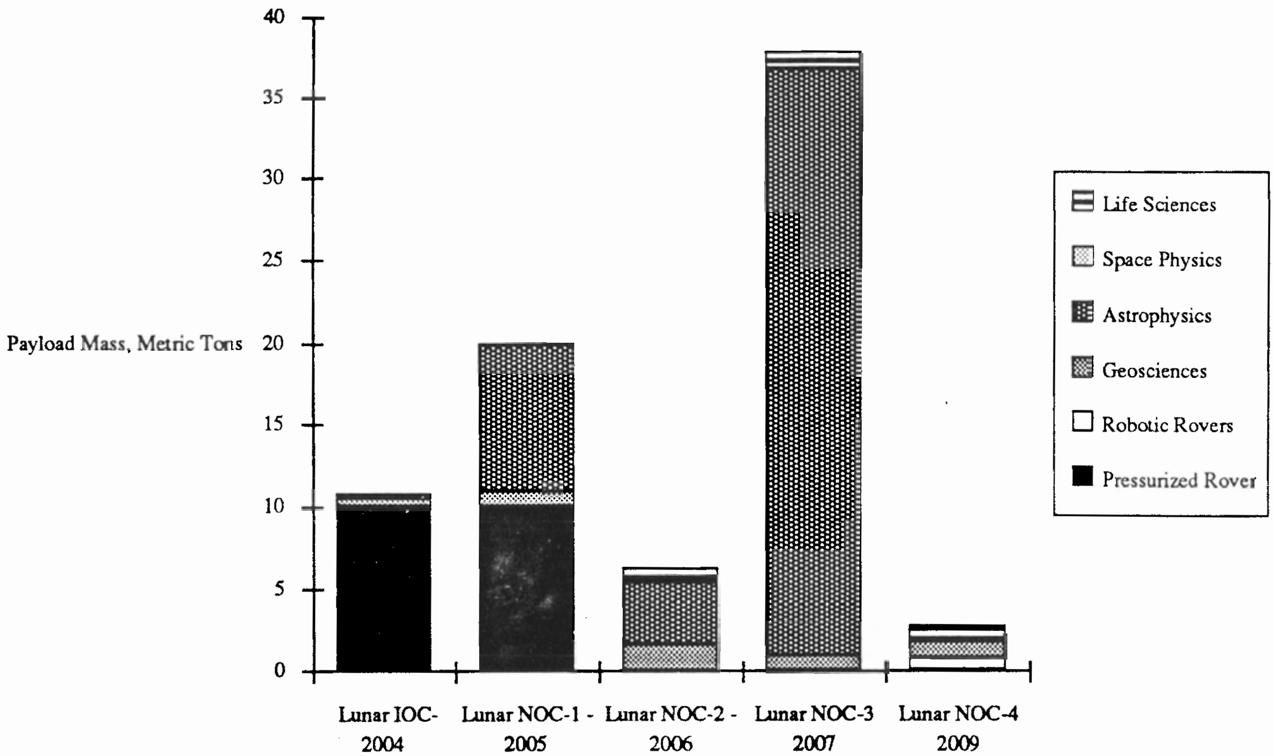

Figure 3.2-2 Science payload mass versus lunar mission phase

—Loop from outpost back to outpost;
—Operate geophysical instruments while underway (traverse geophysics)
—Stop for EVA activities
-reconnaissance geology and comprehensive sampling of large areas
-detailed field work and documented sampling of targeted areas
-deploy instruments/conduct experiments/active seismic tests/drill
-teleoperate a rover for additional exploration and resource evaluation.
—Return to rover
-sleep, eat
-examine samples
-proceed next site/traverse geophysics

Meanwhile, back at the outpost in continuing support of science development, some basic sample analyses are done to high grade samples collected thus far. Some experimental biomedical experiments are conducted on crew members as stay time on the surface increases.

Lunar NOC-2: NOC-2 begins in 2006, with crew surface stay times increase to 90 days, emphasizing life science data acquisition to support the decisions on Mars mission modes, and on the long-term effects of lunar habitation. Astrophysics is emphasized through the deployment of an optical interferometer array. Additional pressurized rover traverses are conducted, expanding the geoscience knowledge base through analytical work on samples in expanded laboratory facilities. Pressurized rover traverses emphasize careful sampling, drilling, active seismic surveying and traverse geophysics. Robust build-up of observatories and labs will occur at the outpost, increasing the infrastructure and research capability. The elements to be include the first elements of the optical interferometer, and augmented geoscience, biomedical, and plant and animal laboratories

Lunar NOC-3: Lunar NOC-3 marks the start of permanent habitation, beginning in 2007. The astrophysics infrastructure continues to be built up with the aperture of the 4-m telescope increasing to 16-m and the construction of a radio telescope interferometry array. Secondary emphasis is is placed on further expansion of the geoscience knowledge base through

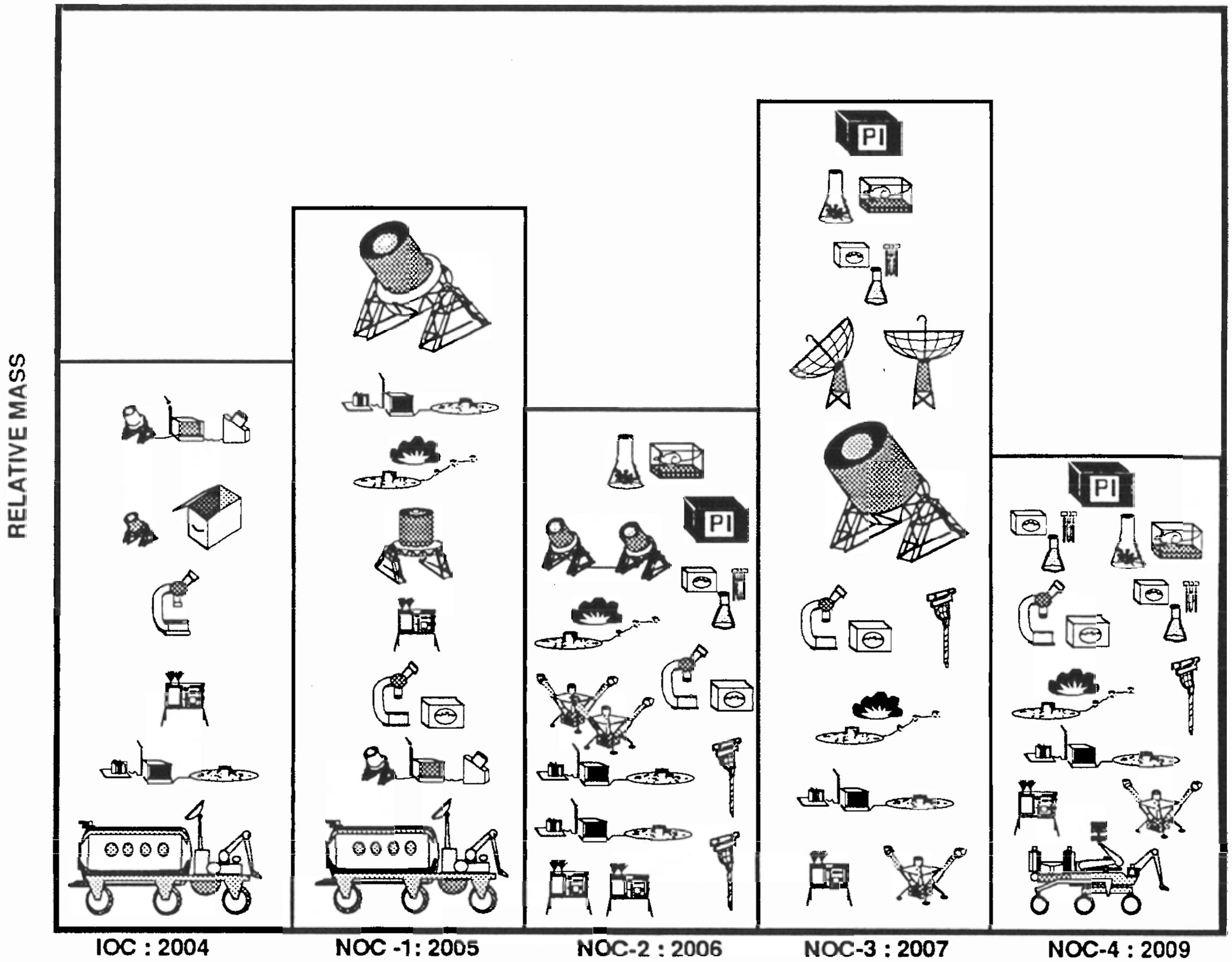

Figure 3.2-3 Lunar science instruments delivered versus mission phase

additional long pressurized rover traverses and additional sample analysis. Expansion of life science laboratory capability emphasizes the need for continued research on biological evaluation of long-term lunar habitation.

Lunar NOC-4: Lunar NOC-4 marks the conduct of the Mars dress rehearsal, beginning in 2009. During the Mars dress rehearsal, the crew spends 200 days in orbit, deploys to the established lunar site at the Mars prototype habitat for 40 days, and then returns to orbit for 260 days. While in orbit, the crew acquires additional life sciences data and enhances teleoperation of surface systems in remote locations. Remote sensing and imaging of the earth and moon are accomplished with appropriate sensors attached on the LTV. Astrophysics and space physics can also be done. Sensing the lunar surface augments an already expanding data base of geochemical and topographic maps and provides more detailed science and resource data at sites of particular interest.

In order to conduct an authentic Mars simulation, a teleoperated rover capability is required on the lunar surface. To maximize access, it is suggested that two rovers be deployed to sites that are geologically interesting and closely simulate Mars environments (for example areas with complex geology). This provides crew experience in teleoperations while collecting real surface geologic and geophysical data that would be otherwise unattainable. Delivery options for the rovers are to soft land them at specific sites or to deliver them to the outpost. Later, these rovers can be teleoperated from the landing site.

During the 40-day surface stay, activities are executed that closely approximate what the crew would do at Mars, focusing on science and exploration. An attempt is made to choose sites, strategic approaches and investigations that are relevant (at least operationally) to those to be done on Mars. The crew, equipped with a pressurized rover and exploration equipment, conducts pressurized and unpressurized traverses and deploys instruments as before. They collect samples, do traverse science, conduct active seismic experiments, and do a 10-meter drilling test. At the outpost, the crew conducts local traverses, deploys instruments, performs basic sample analyses, and conducts plant/animal/human biomedical experiments in the small laboratory.

Mars IOC: The Synthesis Group Report indicates that crewmembers will arrive at Mars and accomplish scientific exploration of the surface. Science activities are categorized in three phases: cruise science, orbital science, and surface science.

Cruise science is done during each human mission, and consists of experiments that will be carried out en route during the prolonged transit to and from Mars. The science payloads are confined to the MTV and are never deployed to the Mars surface. For this reason they are listed as a separate mass total (see Appendix B). Cruise science experiments include solar, particle and astrophysics, human biomedical research, sample analyses (return trip) and Principle Invesigator (PI) experiments.

Orbital science is conducted from Mars orbit primarily if the mission is aborted before landing. Activities include telerobotic science, remote sensing, and human observations. To maximize the scientific return of such a failed mission would require the contingency measure of a teleoperatable rover that could be soft landed to the surface and operated from orbit.

Once on the Mars surface, the crew has 30 to 100 days to do outpost science and exploration. Activities are balanced between local exploration and 2-3 pressurized traverses. A geophysical monitoring station is deployed near the outpost which is also equipped to monitor meteorological phenomena. EVA's, both local to the outpost and during pressurized excursions, do reconnaisance geology , traverse geophysics, sampling, and search for traces of past life. Special attention is given to understanding the Mars geomorphology, erosional features, fate of past water systems, and depositional environments responsible for sedimentary patterns.

Active seismic experiments are conducted to unravel the subsurface structure and composition, and, for the first, time a drill spirals into the martian strata.

A modest analytical laboratory allows for examination and chemical analyses of sediments and rock samples. Sediments are likewise tested for organic content and volatiles.

A biomedical laboratory allows for experimental research on human response and performance on low gravity planetary surfaces.

Later in the mission, a collection of more advanced dedicated meteorological instruments are deployed in a facility that will include launching of weather balloons to test the chemistry, physics and structure of the martian atmosphere.

Additional basic research is accomplished through discretionary science experiments which are deployed and operated on the surface.

Science payloads for Mars IOC/NOC are also shown in Figure 3.2-1. Two tables showing (1) science payload mass versus mission phase, and (2) science instruments delivered versus mission phase are presented in Figures 3.2-4 and 3.2-5, respectively. (The science instrument icon key for Figure 3.2-5 is given in Figure 3.2-6.) Detailed mass, volume, power, and data parameters for Mars science instruments are provided in Appendix B.

Mars NOC: Research conducted during Mars NOC is an elaboration and refinement of Mars IOC, and builds on the science framework of discoveries and hypotheses established as a result of the previous Mars IOC. The most complex scientific puzzles can now be tackled and pieced together. Elusive phenomena requiring long-term observing are monitored. Cruise science in-transit and orbital science are conducted as before.

On Mars, increased surface access combined with longer stay-time greatly enhances the science return. A diversity of environments can be visited and observed. More time is available for detailed geologic observations, real-time contemplation, experiential analogs and additional discoveries in the field. Very important return visits to strategic sites are now possible.

The past two years (that is, Earth years) of meteorological monitoring data provides a reliable base for further observations, and human crews will now experience and record first-hand the seasonal changes of another two-year weather cycle.

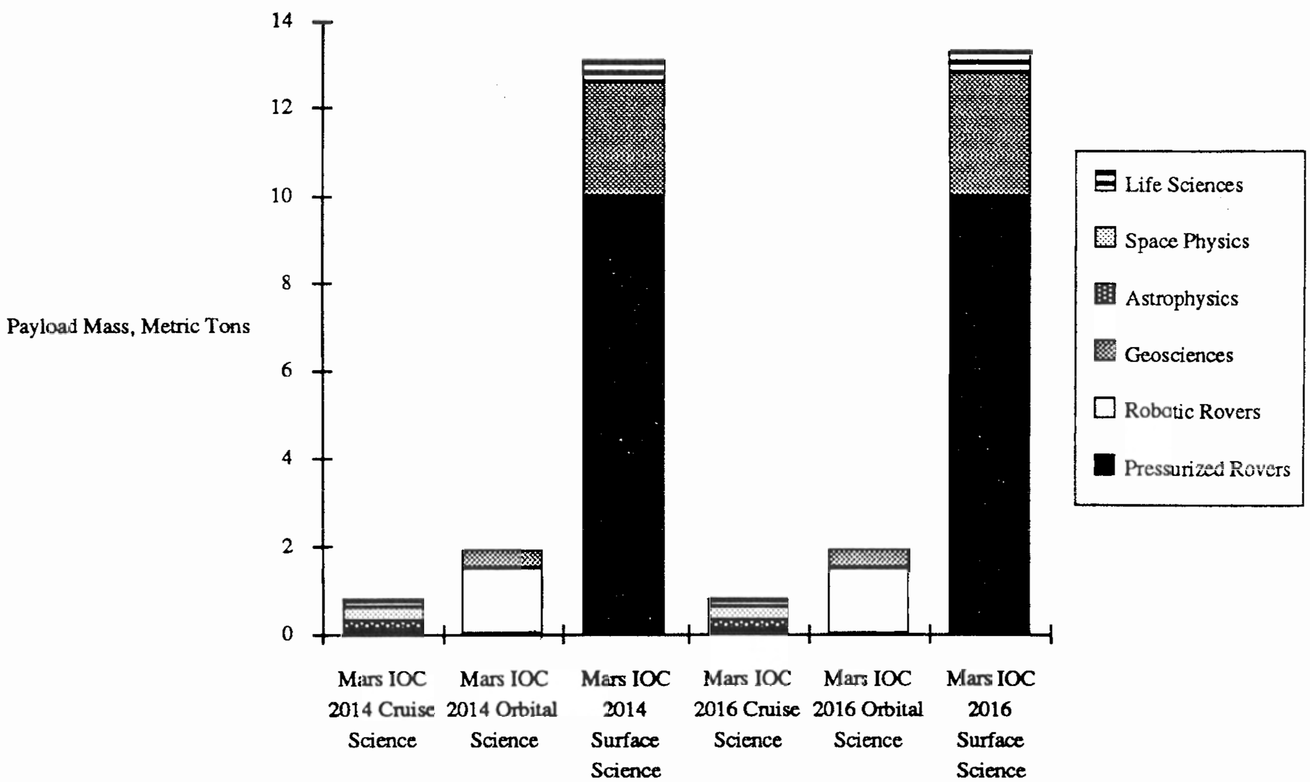

Figure 3.2-4 Science payload mass versus Mars mission phase

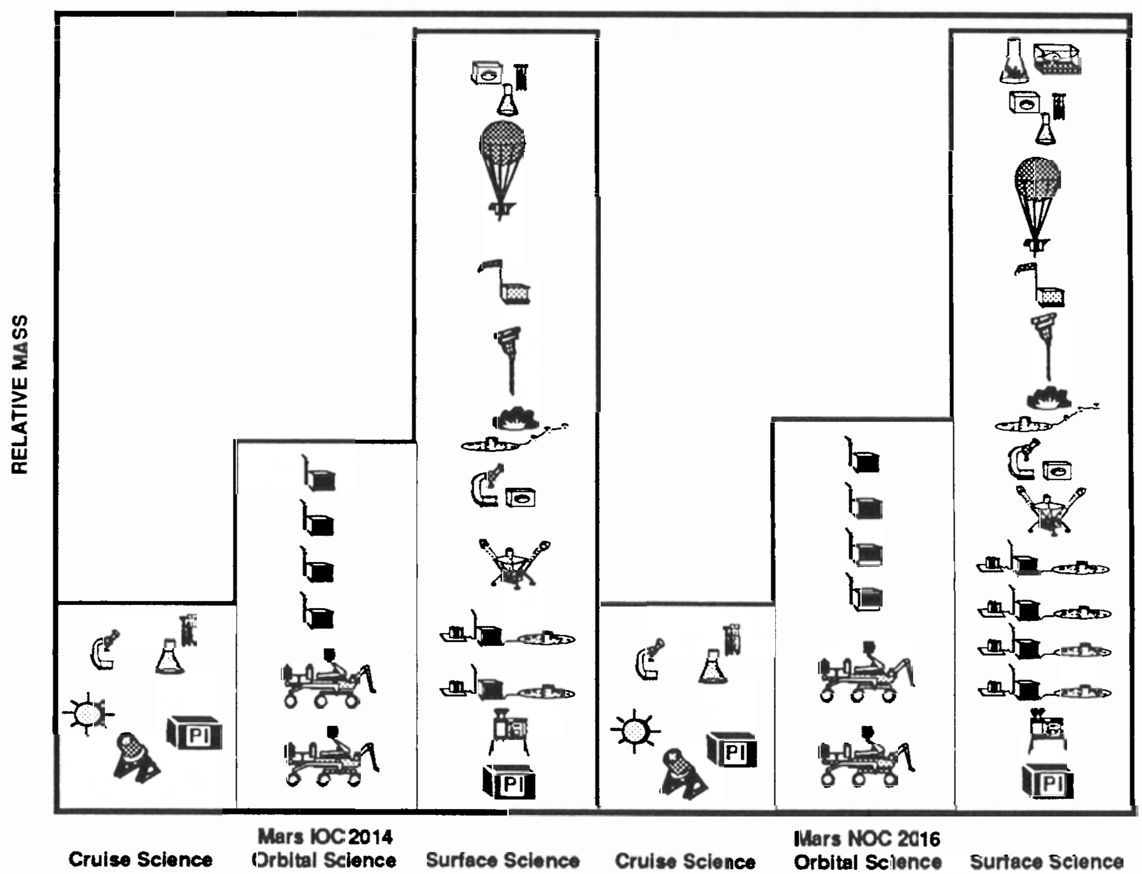

Figure 3.2-5 Mars science instruments delivered versus mission phase

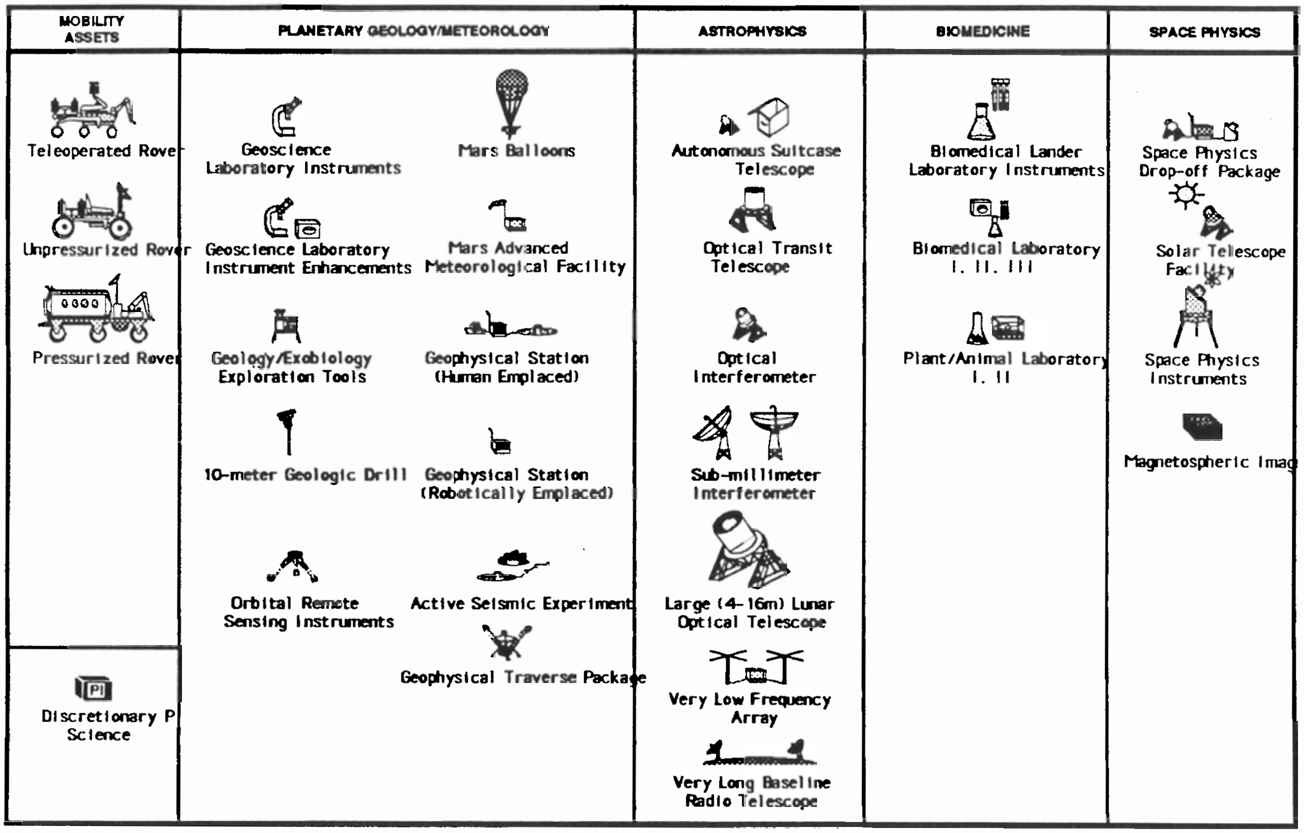

Figure 3.2-6 Science instrument icon key

Multiple robots deployed at diverse locations can be controlled from the Mars landing site (and/or orbit) to conduct reconnaisance geology, collect and/or analyze samples, deploy simple instruments, and do traverse geophysics.

The Synthesis Group Report suggests a different landing site may be chosen for the Mars NOC outpost. This would additionally enhance the science return as a result of increased local exploratory opportunities in the vicinity of a different Mars environment.

3.3 PLANETARY SURFACE SYSTEMS

3.3.1 Overview

The ***Moon to Stay and Mars Exploration*** architecture focuses on developing the capability to support a permanent presence on the Moon. A substantial infrastructure is emplaced on the lunar surface which allows for a permanent crew of 18 people. The Moon's resources are used, but only to the degree necessary to produce breathing gases and water for the crew's habitat and fuels for surface transportation systems such as rovers and construction vehicles. Closing the life support system of the lunar outpost and growing food at the Moon are emphasized to help the outpost become more self sufficient and reduce the required logistics from Earth. Finally, a simulation of a Mars mission is carried out on the Moon.

Two separate outposts are also emplaced at Mars. The first outpost supports a 90-day crew stay to conduct scientific exploration of the martian surface. A second, long duration mission explores a different site on Mars and uses commonality of resource utilization techniques and equipment tested at the Moon to ease the logistics problems for a 600 day stay.

3.3.2 System Description

Following is a phase-by-phase description of the systems emplaced on the surfaces of the Moon and Mars, together with a discussion of what capability is provided and some of the reasoning behind the choices made. Further information on the surface elements can be found in the Element/Systems Data Base (ESDB), Release 91.1; JSC Document Number JSC-45107.

3.3.2.1 Lunar IOC

Overview: Lunar IOC establishes the basic infrastructure to support 5 crew on the surface during the lunar day. Also, detailed surveys of the site for the large permanent habitat and surface science exploration are conducted. A schematic drawing of the lunar IOC outpost is shown in Figure 3.3-1.

Habitation: A single, integrated habitat which can support 5 crew for 14 days is provided. The habitat is a Space Station Freedom-derived cylindrical module, with an airlock attached to one end and a docking adapter on the other end. The module is 8.2 m long and 4.5 m in diameter. The pressure shell is essentially identical to that of a SSF module, with leveling legs and deployable regolith shielding retention devices. Internal systems of the habitat include life support, thermal control, power management and distribution, crew accommodations, limited health care equipment, science accommodations, and utilities distribution. The life support system is an advanced SSF regenerative system, with greater than 98% oxygen and water recovery, hygiene water processor, and non-expendable water polisher/bacteria barrier. Thermal control is provided by coatings, heat pumps, and composite reflux radiators with a 2-phase non-toxic working fluid.

The airlock is a SSF-derived system which enables egress/ingress and also provides EVA suit storage, checkout, and recharge. The airlock system is composed of an equipment lock, a crew lock, an EVA dust-off porch, and adjustable legs for leveling. The airlock's life support and thermal control systems are tied into the habitat. The airlock also has a docking adapter for later use by a pressurized rover. Ideally, the airlock is delivered pre-attached to the habitat, in order to avoid the difficult operation of connecting the two in-situ.

Power: A nuclear system for primary power, and a photovoltaic array (PVA) power system for backup, are employed during IOC. The PV array consists of 150 m² of sun-tracking panels. The cells are of amorphous silicon. The PVA system can provide 25 kW during the lunar day. The nuclear system consists of a thermoelectric SP-100 reactor, providing 100 kW of electrical power continuously. It is designed for easy deployment, with little or no human intervention required. Limited shielding is provided on the reactor to enable short-duration proximity operations by humans. Additional shielding is provided by placing the reactor in a pre-excavated hole. The system is fully autonomous and employs fault detection, isolation, and recovery systems which result in a reliable, long-lived (nominal 15 year lifetime) unit.

Extravehicular Activity: Extravehicular Mobility Units (EMU) are provided for each crew member on the lunar surface. An EMU consists of a pressure suit, a Portable Life Support System (PLSS), and communications subsystem. The suits are a back-entry, hybrid (fabric and hard components), 5.85 psi design. The PLSS is a regenerable system which provides for 8 hours of EVA. EMU accessories include helmet-mounted video cameras and lighting systems.

Surface Transportation: A six wheeled, unpressurized rover is provided. The rover can seat four suited astronauts, or can carry two astronauts and a removable, self contained extended life support package. The segmented chassis is composed of a light weight tube framework, with independent drive on each wheel. Power is provided by fuel cells, which will be recharged from a centralized regeneration system at the outpost (delivered in the next phase). Thermal control is provided by a heat pump with metallic reflux radiators, enabling the rover to operate anytime. The range of the rover is 50 km from the outpost, or 150 km total traverse.

A pressurized rover system is delivered for use in this and subsequent phases. The pressurized rover has a limited capability on the order of 50 km from the outpost. The rover has twin manipulator arms for geologic sample collection and IVA access to surface equipment. Power is provided by fuel cells, thermal control is provided by coatings and a 2-phase heat pump. The life support system is partially closed with storage of wastes for return to the outpost.

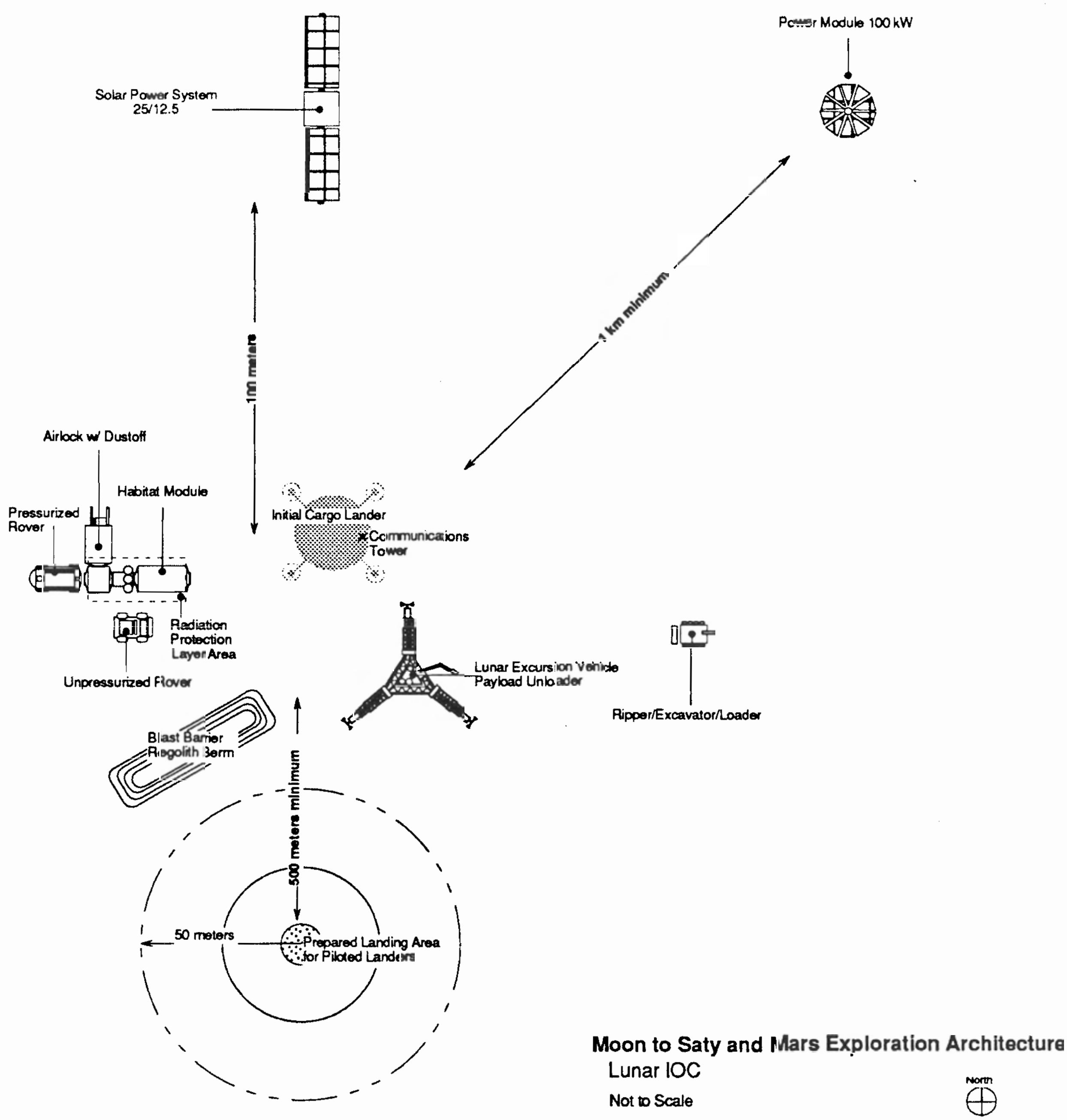

Figure 3.3-1 Lunar IOC Outpost schematic

A multipurpose construction vehicle is also provided. The Lunar Excursion Vehicle Payload Unloader (LEVPU) is a three-strut, cone-wheeled, teleoperated gantry crane. It is capable of unloading cargo from the excursion vehicle, transporting cargo (up to and including an integrated habitat), and emplacing elements on the lunar surface. A set of implements and attachments designed for its 3-joint manipulator arm enable the LEVPU to perform various other tasks, including light excavation (e.g. boulder clearing, regolith smoothing, and/or trenching), and precision surface element alignment and attachment. The choice of a LEVPU plus attachments avoids the need to deliver several specialized construction vehicles. The LEVPU's primary structure consists of open web, aluminum alloy members with telescoping struts, and independently driven and controlled wheel assemblies. The power and thermal control subsystems are similar to those on the unpressurized rover.

A regolith ripper/excavator/loader (REL), a multi-purpose mining vehicle, is provided to acquire and transport loose regolith for use as radiation shielding for the habitat. It utilizes many of the same subsystems as the unpressurized rover, but its 5 mt load capacity requires heavier construction. The REL can operate autonomously or by teleoperation.

Communications: Radio frequency equipment and associated electronics are integrated into the habitat. A deployable tower and dish antenna are located near the habitat (they might remain on an expended lander). The system provides UHF communications to and from the tower, satellite communications (Ka band) to Earth, S-band communications to the landers, a LORAN-type means for navigation of surface rovers and landers (within 12 km of the outpost), and internal habitat communications.

Launch and Landing: A small verification unit for demonstrating the storage of cryogenic liquids on the lunar surface is attached to an excursion vehicle and operated at the initial outpost. It operates autonomously with monitoring from Earth, and conducts tests of systems to control cryogen boiloff by the use of thermodynamic vents, vapor cooled shields, low conductivity supports, and refrigeration and/or reliquefaction equipment.

An expended cargo LEV's cryogenic propellant tanks in conjunction with a limited amount of dedicated test hardware ($\approx$ 200 kg) will be required. After landing on the lunar surface, the LEV's propellant tanks will contain both hydrogen and oxygen propellants consisting of the residuals and contingency flight performance reserves. The vehicle and propellant tanks will be instrumented to establish the lunar thermal environment and the tank boil-off rates will be measured to determine the insulation system performance. Approximately two to three months of cryogenic liquid storage system capability data will be available before the tanks are emptied. Simultaneously with the thermal control system evaluation, the oxygen tank boiloff will be routed to a liquefier which will provide liquid oxygen to a dedicated experimental test tank for storage. Interfaces will be required for electrical power to operate the liquefier and with a coolant loop for waste heat rejection (the test article could include its own power source and radiator if necessary). The storage tank test article will be equipped with a quick disconnect and transfer line to allow liquid oxygen supply to a user such as the unpressurized rover.

Science Accommodations: Limited crew time, power, and habitat volume is available for science activities. However, the LEVPU can deploy scientific instruments on the lunar surface, and the unpressurized rover can be used for geological traverses.

Other: In addition to the systems described above, a warning system for solar flares is also emplaced near the habitat. It consists of an autonomously controlled system for monitoring the particle and electromagnetic output of the sun. Threshold alarms are included which alert the crew when the incident solar radiation exceeds a predetermined value, so that they may take shelter until the flare subsides. This system is a backup to solar monitoring stations on the Earth and in space.

Consumables pallets are delivered on each crew flight. Consumables include food, life support expendables, clothing, hygiene supplies, and housekeeping items. The pallets provide pressurization and thermal control where required for the consumables.

3.3.2.2 Lunar NOC 1

Overview: Lunar NOC 1 extends the surface infrastructure in order to support a 5 person crew for 40 days. Surface transportation range and functions are expanded. The capacity to produce small quantities of locally derived breathing gases and water is developed.

Habitation: During this phase, a second habitation module is emplaced. This habitat is delivered with an interconnect node (similar to the SSF design) attached to one end, and a docking adapter on the other; see Figure 3.3-2. It is externally identical

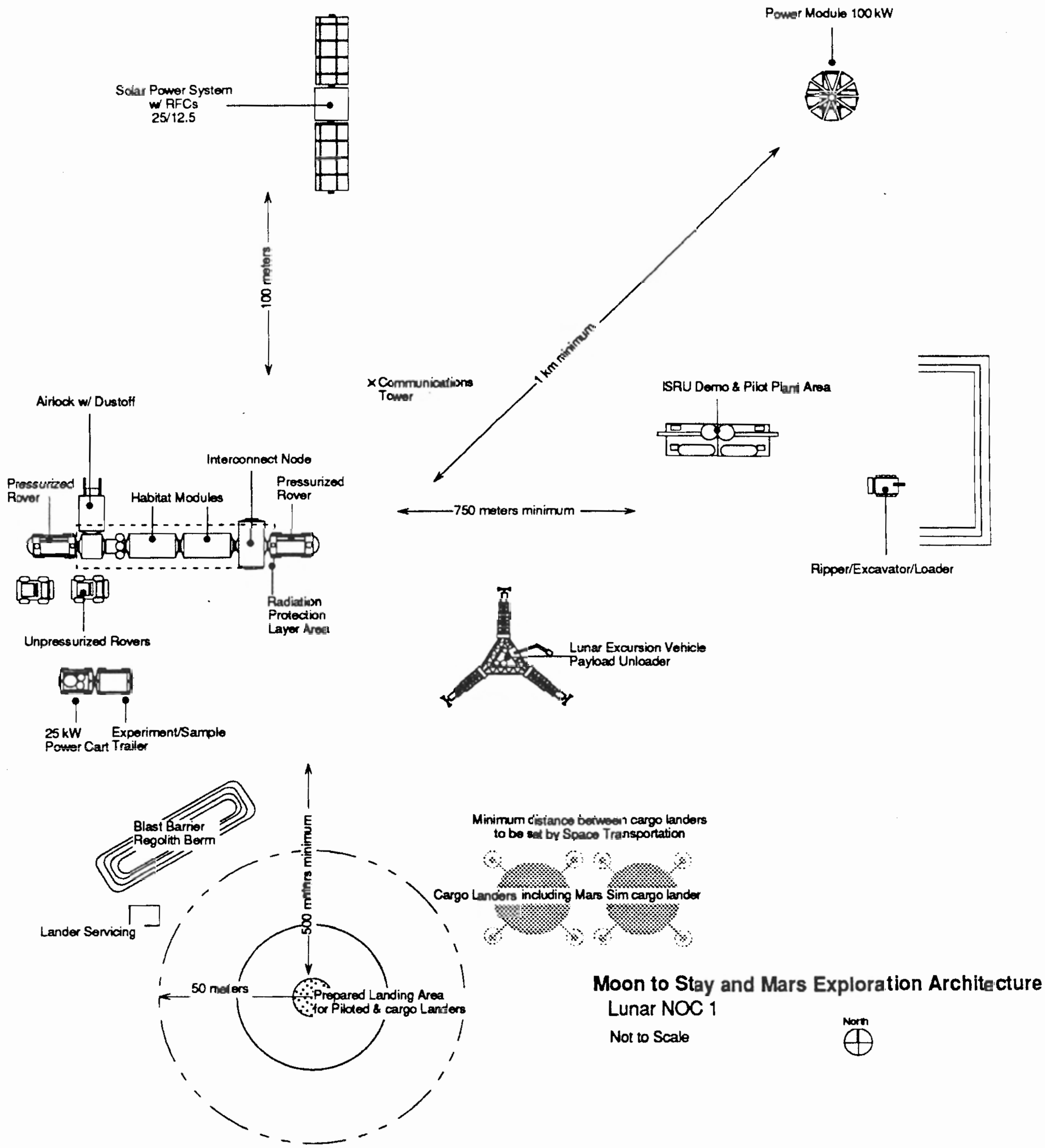

Figure 3.3-2 Lunar NOC-1 Outpost schematic

to the initial habitation module and is connected to the existing lunar outpost. Its critical internal systems can operate independently of the initial habitat, providing separate pressurized volumes in case of difficulty in either habitation module. It differs only in its internal outfitting: crew quarters, galley, etc are located in the initial habitat, while the second habitat contains an expanded crew health care facility, scientific/workshop accommodations, and storage space for the consumables required during long term (45-90 day) missions. With the addition of this second habitation module, and the emplacement of the requisite regolith shielding, the outpost can support 6 person crews for up to 90 days.

Power: The power capability of the outpost is upgraded by the emplacement of a regenerative fuel cell (RFC) system that will be used in conjunction with the PVA backup power system. During this phase, the first manned stay through a lunar night occurs, and the RFC system is needed to provide redundant power at night if the SP-100 should fail. The system is delivered in one package and gross assembly is performed by teleoperation of the LEVPU. Final connections and checkout are performed by EVA. System health is monitored from the habitat.

Surface Transportation: A second unpressurized rover is delivered with the crew providing another vehicle for local mobility and exploration. Also, a second pressurized rover system is delivered with an auxiliary power cart and an experiment/sample trailer. These auxiliary systems extend the range of the rover to 100 km from the outpost, for 2 crew members for up to 6 days.

During this phase, equipment is delivered to the outpost that will enable the regeneration of liquid oxygen and liquid hydrogen from the water produced in the fuel cells of rover and construction vehicles. The system includes electrolysis equipment, storage tanks, and refrigeration equipment. The storage tanks will be scavenged propellant tanks from expended cargo LEVs. This system will provide a central reservoir of cryogens and water for general outpost use.

ISRU: An integrated ISRU demonstration package is emplaced and operated in NOC 1. The unit tests processes for extracting volatiles (H_2, CO/CO_2, N_2, etc.) and oxygen for use as breathing gases and water in the outpost's life support system. It is also possible to use the lunar-derived water in the regeneration equipment to produce fuel for the surface vehicles. The demonstration is self contained, needing only power from the outpost and regolith feedstock (provided by the payload unloader and ripper/excavator/loader). The knowledge gained is used in the design and construction of a larger subsequent pilot plant. The O_2/Volatiles demonstration should produce annually approximately 1 mt of H_2, 1 mt of N_2, 4 mt of CO/CO_2, and 5 mt of O_2. It will require the mining of 3000 kg of regolith per hour. Thise requirement is satisfied by the payload unloader and ripper/excavator/loader mentioned above. The demonstration package runs at 90% process duty cycle.

Science Accommodations: Expanded science accommodations are available in the second habitation module. The pressurized rover extends the range of surface exploration.

3.3.2.3 Lunar NOC 2

Overview: During lunar NOC 2, the ability to accommodate a large crew on the Moon while accumulating life science data and operational experience is demonstrated. Also, food production and waste management experiments are begun while continuing to build up the capability to produce useable amounts of lunar volatiles and oxygen for breathing gases and water.

Habitation:

The outpost habitat increases in both size (pressurized volume) and capability, with a third habitation module, a resources laboratory module and a second airlock being added to the existing outpost during this phase. The habitation module and most of its subsystems are similar to the lunar habitation modules already at the outpost, however, the life support system is a regenerative system, evolved from the outpost's life support system, which incorporates waste processing to reduce consumables usage. With the addition of this module, the outpost has the capability to support 12 people at a time. The resources laboratory module's critical systems are also identical to those of the other modules. Its internal outfitting consists of storage, science racks, a workshop area for servicing and repair of outpost machinery, and a small area to test food production techniques on the Moon. Both modules are attached to the interconnect node, and the new airlock is attached to the laboratory. The layout of lunar NOC-2 is given in Figure 3.3-3.

Surface Transportation: A third unpressurized rover is delivered to the outpost, completing the pool of surface transportation vehicles for use by the crew for general tasks around the outpost and surface exploration.

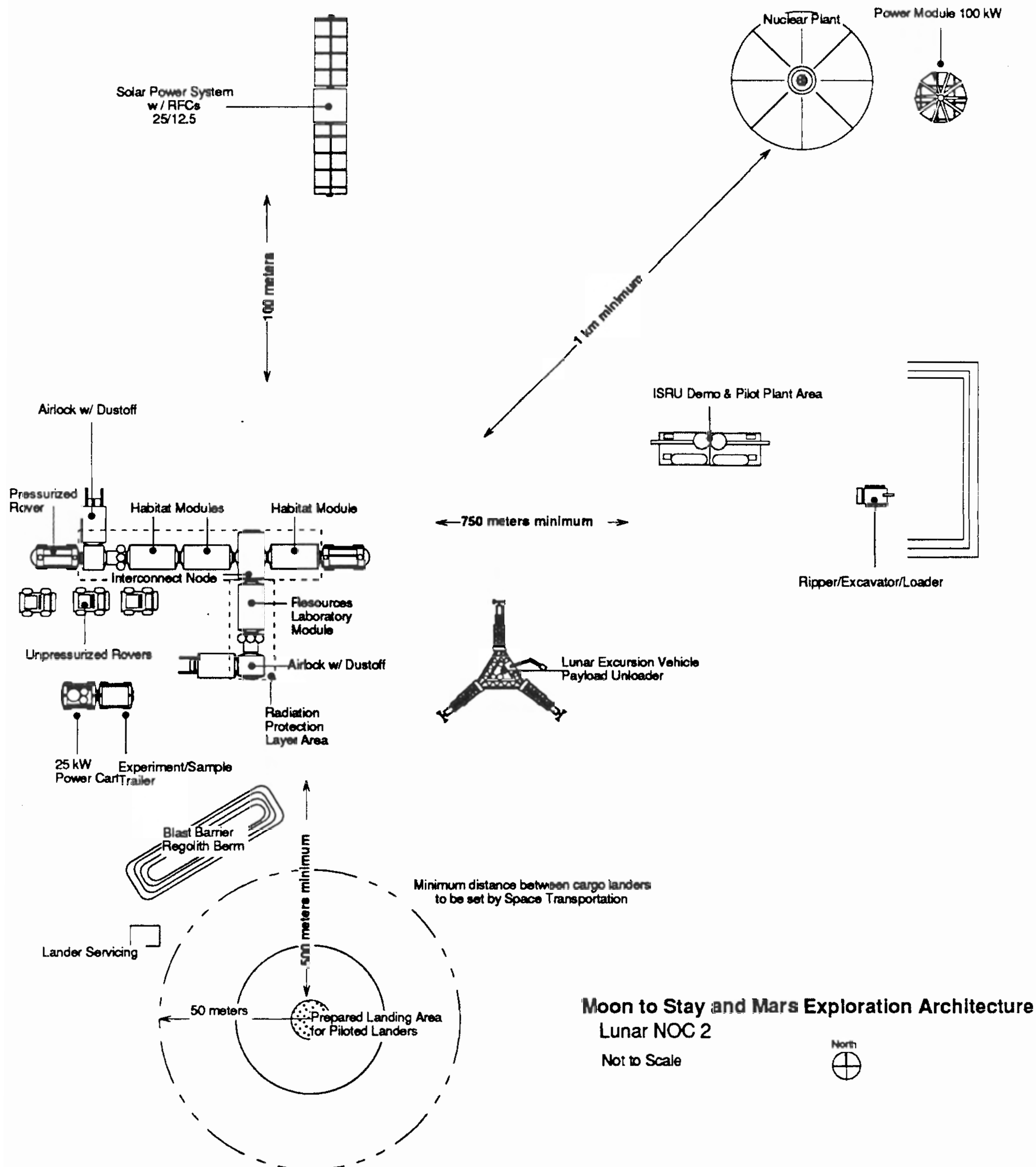

Figure 3.3-3 Lunar NOC-2 Outpost schematic

Power: The outpost power system is augmented by a 550 kW nuclear power plant. This plant is similar to the 100 kW system deployed in IOC. It employs an SP-100 type reactor placed into an excavation, with 8 Stirling engines arranged on the surface around the excavation. The Stirling engines operate at a higher temperature than on the 100 kW system (1300°K versus 1050°K). The system is delivered in several packages, and gross assembly is performed by teleoperation of the LEVPU. Final connections and checkout are performed by EVA. System health is monitored from the habitat. Power management and distribution equipment is also delivered to support this larger power network.

ISRU: One year after the O_2/Volatiles demonstration is emplaced, an O_2/Volatiles pilot plant is delivered with the capability to annually produce 5 mt of H_2, 5 mt of N_2, 20 mt of CO/CO_2, and 10 mt of O_2. The H_2 produced can be used to make water for the crew or for plant growth. The O_2 and N_2 is used in the atmosphere of the habitats and in plant growth demonstrations. The CO/CO_2 can also be used in the food growth demonstrations. As mentioned earlier, the H_2 and O_2 could also be used as reactants for the fuel cells of the surface rovers and construction vehicles.

When the O_2/Volatiles pilot plant is operating at full capacity, the mining requirement increases to approximately 15 mt per hour. However, the pilot plant is only assembled and tested in this phase, so the mining requirement is much less and can be satisfied with the existing construction equipment.

Launch and Landing: During this phase, the piloted LEVs remain on the lunar surface for 90 days, requiring support from the outpost to keep the vehicle in a healthy condition. This support for the landers is provided by an excursion vehicle servicer. These surface units provide power, thermal control, and reliquefaction and/or refrigeration of the vehicles' cryogens. Heat rejection is provided by a heat pump with composite radiators, and reliquefaction is accomplished by Heyland cycle machinery. A tent structure is provided for covering a excursion vehicle which provides micrometeoroid protection and reduces the heating and cooling loads.

3.3.2.4 Lunar NOC 3

Overview: The permanent presence of humans on the Moon is the goal of this phase. To accomodate this, the oupost's habitat is expanded so that it can support 18 crew members year round. Also, food growth, waste mangement, and the production of breathing gases and water are done at the scale necessary to reduce the amounts of Earth-supplied logistics required to support the large crew.

Habitation: Up to this point, the outpost's habitat has been based on Space Station Freedom derived modules. In this phase, a second generation of lunar habitats is delivered that consists of inflatable structures that are constructed on the lunar surface. The primary structure is an inflatable sphere 16 meters in diameter. It provides space for crew, laboratory, and base operations and provides approximately 2150 cubic meters of open volume. Its envelope consists of high strength multi-ply fabric with hard top and bottom caps, an impermeable inner layer and a thermal coated outside. After inflation, internal support is provided by installation of aluminum framing. The life support system includes an integrated oxidation process for water and waste management. The constructible sphere is connected to the existing outpost by an inflatable tunnel; see Figure 3.3-4.

Across the interconnect node from the resources laboratory, a greenhouse is constructed. The greenhouse structure is an inflatable design similar in concept to the 16 meter constructible habitat. Access is restricted/controlled by hatches in the node, since the greenhouse will operate at elevated CO_2 levels. The greenhouse is sized so that it produces up to 40 percent of the food required by the 18 crew members*.

Surface Transportation: Two regolith ripper/excavator/loaders are delivered to the outpost to augment the mining capabilities already at the Moon. This enables the O_2/Volatiles pilot plant to operate at full capacity.

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* A 16 metric tonne agriculture facility (i.e., greenhouse) can provide a maximum of 40% of the recommended daily allowance (RDA) crew diet for 18 crewmembers *if there are no crop failures.* To depend on 40% RDA, 1,930 kg of emergency crew food must be on hand for the period of 100 days that may be required to re-establish crop production. Agriculture facility operations will average 5 person-hours per day. Power requirement will be approximately 170 kW.

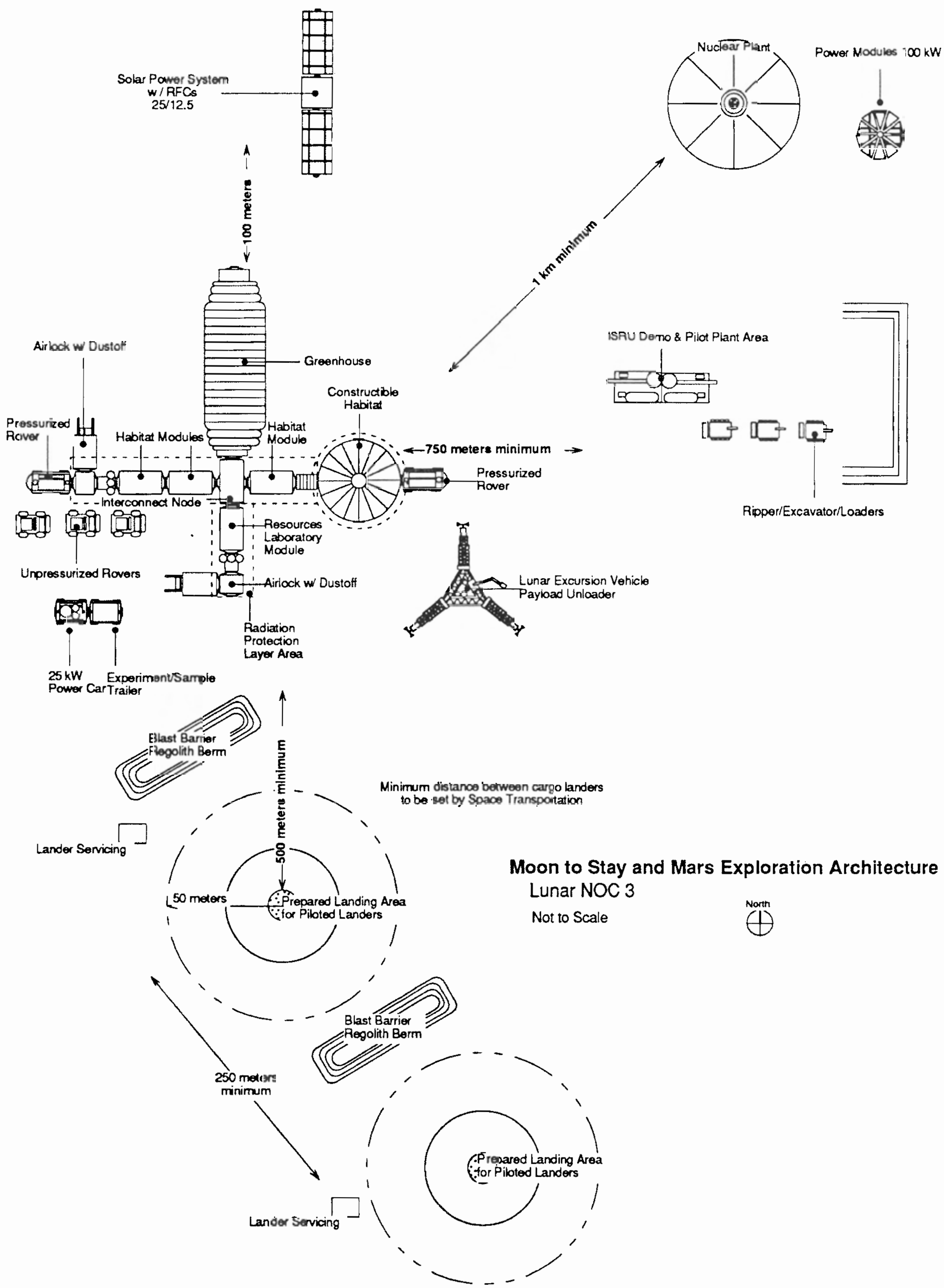


Figure 3.3-4 Lunar NOC-3 Outpost schematic

Launch and Landing: An additional LEV servicer package is delivered to the outpost to accommodate the requirement to support 3 piloted LEVs on the lunar surface.

3.3.2.5 Lunar NOC 4

Overview: During lunar NOC 4, a Mars dress rehearsal is supported by the lunar outpost. The Mars dress rehearsal crew will occupy a portion of the lunar outpost separate from the lunar crew. The lunar crew will support the rehearsal crew in addition to their other activities.

Habitation: The Mars simulation will take place in existing facilities, so no new habitation infrastructure is necessary.

Surface Transportation: The Mars simulation crew brings an unpressurized rover like the one planned for use on Mars. This rover is similar to the unpressurized rovers used on the Moon. The Mars simulation crew will also use the pressurized rover already at the lunar outpost.

3.3.2.6 Mars IOC

Overview: Mars IOC establishes the infrastructure to support 6 crew on the martian surface for 90 days.

Habitation: The need to support 6 crew for 90 days, together with the down-mass capability of the Mars landers, dictates that the martian habitat be delivered in two pieces. As in the lunar case, a single habitat capable of fulfilling the mission requirements would weigh approximately 40 metric tons, but this is divided into packages of 23 and 25 tons to accommodate the capabilities of the lander.

The habitats and airlocks are similar to those described in lunar NOC 1. A different thermal control system is used on Mars due to the different thermal environment, in particular, the cooler daytime temperatures.

Current information indicates that radiation shielding, beyond that provided by the martian atmosphere, will not be required.

Power: A 100 kW nuclear system is used for primary power, with a 25 kW PV/RFC system as backup. The nuclear system is similar to the lunar system, but has a slightly different thermal control system. The PV/RFC system has a much larger photovoltaic array, due to the reduced solar flux at Mars, but also has a much smaller fuel cell system, because of the significantly shorter martian night.

Extravehicular Activity: EMUs are provided for each crew member. The martian EMU differs from the lunar model only in the PLSS. Due to the greater gravity of Mars, it may be necessary to use a mid-EVA, 4 hour recharge to reduce the mass of the PLSS.

Communications: The communications system is also similar to that employed on the Moon, but depends on an orbital relay network for continuous communications with Earth.

Surface Transportation: One pressurized and one unpressurized rover similar to the lunar models are used. A power cart and sample trailer are also delivered as in the lunar case, to extend the range of the pressurized rover.

Since the Mars lander design delivers the payloads closer to the surface than does the lunar lander, a downsized payload unloader is used. It is a four-legged gantry crane with systems otherwise similar to the LEVPU, but this smaller (shorter) device accommodates payloads delivered by the lander to within one meter of the surface. Like the LEVPU, it is delivered with a set of attachments which allow it to perform simple site improvements and manipulation tasks.

Other: A flare warning system identical to that used on the Moon is also provided at the Mars outpost.

The Mars IOC outpost layout is shown in Figure 3.3-5.

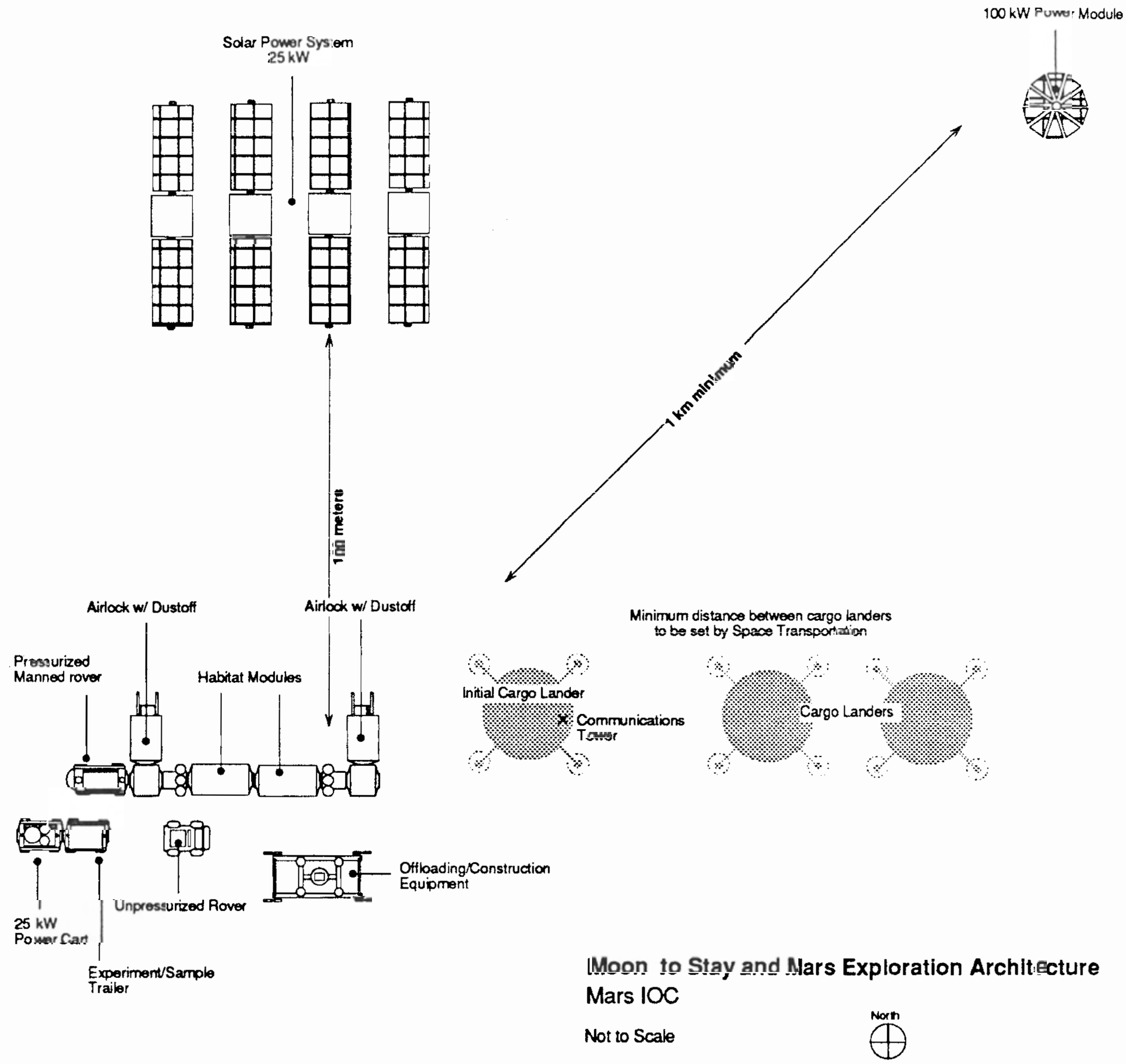


Figure3.3-5 Mars IOC Outpost schematic

3.3.2.7 Mars NOC

Overview: The objective of this mission is to carry out a 600 day crew stay on the Mars surface, *at a different site than the initial outpost.*

Habitation: Since 1) the crew cannot use the existing surface infrastructure, and 2) the habitation and consumables storage requirements of a nearly 2-year mission are considerable, an additional hab/lab/storage module is required, beyond the two module system used in IOC. This module contains expanded crew habitation, science racks, and consumables storage. In this case, the three modules are connected in-line, with airlocks at both ends; see Figure 3.3-6.

Power, Extravehicular Activity, Communications, and Surface Transportation: Power, EVA, communications, and surface transportation systems are identical to those used at the first Mars landing site.

Other: A Mars ISRU demonstration package is emplaced and operated. It combines demonstrations of technologies for extracting water from the martian atmosphere and regolith, and producing oxygen and methane from the atmosphere.

3.3.3 Mission Profile

A detailed manifest for each mission flight can be found in Appendix C.

Lunar Flights 1 & 2 (Cargo), 2004

A cargo lander delivers the payload unloader, unloader attachments, a 100 kW nuclear power supply, a PVA backup power system, the necessary power management equipment with distribution system, , communication equipment, cryotank verification unit, and a regolith ripper/excavator/loader (REL). A second cargo lander delivers the integrated habitat/airlock, the solar flare warning system, and an initial suite of science equipment (mainly geologic exploration equipment). Delivering all of these systems on a single cargo lander would be preferable, but the total would exceed the capability of the current lander design. The unloader operates under supervised autonomy (autonomously, with supervision and intervention as needed from Earth). It self deploys from its lander. The ripper/excavator/loader is then unloaded. These two vehicles, utilizing various attachments, clear and level areas for the habitat, the PVA power supply, and any corridor necessary for the power distribution network. Other surface preparations include the excavation of a hole for the nuclear power supply, and piling of a 1.5 m high regolith berm between the the habitation area and the pre-selected crew landing site (in order to protect base elements from most of the blast ejecta from the landers).

By straddling the second lander the unloader removes the habitat/airlock, transports it to the prepared site, and lowers it to the surface. Next, the nuclear power supply and the backup solar power system are moved to their respective sites, with the sites for each already prepared. After the nuclear power supply is placed into an excavation, its radiator panels self-deploy. Then the necessary connections are made by the unloader between the power supplies and the habitat. The unloader then removes the cryotank verification unit and solar flare warning system and position them on the surface. At the completion of this period of unmanned lunar operations, all systems are in their final positions and their integrity is verified from Earth to the extent possible.

Lunar Flight 3 (Piloted), 2004

A crew of five lands near the outpost at the beginning of a lunar day, bringing with them EMU's and the required consumables. They also bring two surface vehicles to support their operations - an unpressurized rover and a pressurized rover. The crew lives out of the lander for 2 - 3 days, performing EVA's to verify the proper deployment and connection of the photovoltaic array and the nuclear power supply to the habitat and the other support equipment delivered on flight 1. The flare warning system and cryotank verification unit are inspected and adjusted if necessary. After activating and verifying the habitat's internal systems, they occupy the habitat for the remainder of the 14 day stay.

Local geological exploration is carried out near the outpost via the unpressurized rover, and, as time permits using the pressurized rover. A geophysical monitoring station is deployed within walking distance of the outpost.

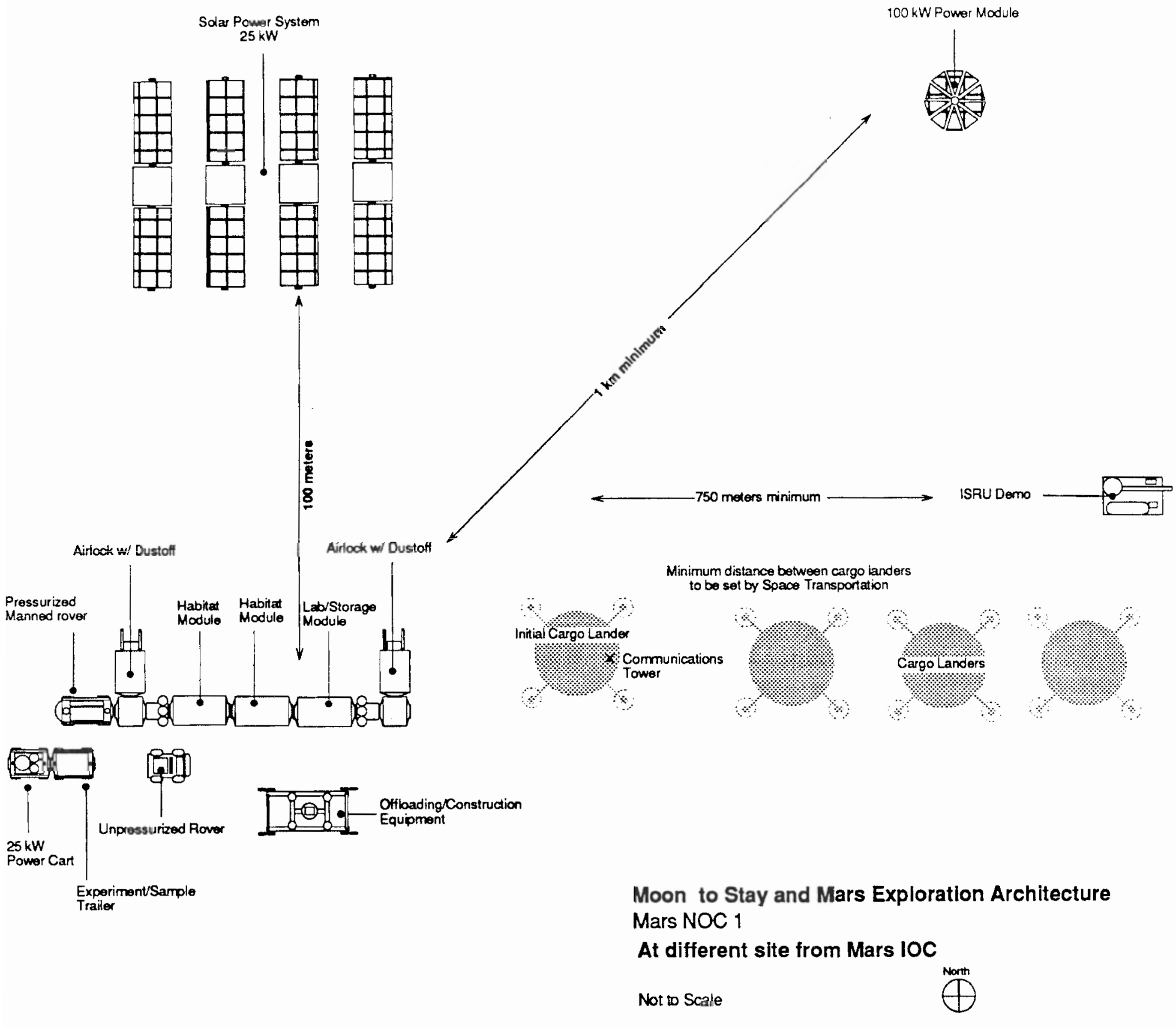


Figure 3.3-6 Mars NOC Outpost schematic

At the completion of the 14 day stay IOC is attained, the crew powers down the habitat, placing it in standby mode until the next mission, and departs in the lander.

Lunar Flights 4 & 5 (Cargo), 2005

A cargo lander delivers the second habitat unit accompanied by an interconnect node. This flight also delivers the Oxygen/ Volatiles integrated demonstration unit. The unloader transports the habitat and node (which are already docked together) from the lander and places them in the proper orientation to the existing habitat. The mating of the two is carried out under supervision from Earth. The unloader then removes the demonstration unit and transports it to the an area removed a safe distance from the habitat. Finally, the unloader uses various implements to emplace the regolith shielding layer over the habitats.

Another lander delivers a second pressurized rover with rover support elements (a power cart and sample trailer), regenerative fuel cells to be added to the existing solar power system, and equipment for surface vehicle support. On command from ground control, the payload unloader moves the fuel cells to the solar power supply area and the surface vehicle liquid oxygen and hydrogen regeneration system to a location removed from the immediate habitat area. The unloader also lowers the pressurized rover and it's power cart with trailer from the lander to the lunar surface. Teleoperated from Earth, the rover train moves to the vicinity of the outpost.

Lunar Flight 6 (Piloted), 2005

A crew of five arrives with science equipment, consumables for a 40 day stay, and spares and needed replacement parts for base systems. They also bring another unpressurized rover. They verify the outpost systems and move into the habitat. Using the REL, the crew prepares sites for a 4 m telescope and a transit telescope which were part of the science equipment brought with the crew.

Science operations are carried out via the pressurized and unpressurized rovers, as maintenance and contingency requirements permit. Locally produced oxygen and hydrogen can be used to replenish the fuel cells of the rovers, if needed.

After 40 days the crew powers down the habitat, placing it in standby mode until the next mission, and departs in the lander. With this mission NOC-1 is attained on the lunar surface.

Lunar Flight 7 & 8 (Cargo), 2006

A cargo lander delivers a Resources Laboratory Module, another 2-person airlock, two lunar excursion vehicle servicers, power management and distribution equipment, and spares needed for base systems in place. On command from ground control, the payload unloader removes the laboratory module and airlock from the lander to the existing habitation area and performs the mating operation. The unloader then proceeds to unload and deliver the excursion vehicle servicers to the landing pad area. Finally, the unloader, using attachments for excavation, prepares a site for another nuclear power source adjacent to the power module delivered on flight 1.

Another cargo lander brings a habitat module, and a 550 kW power supply. The unloader, as previously described, moves the habitat module from the lander to the existing habitat area and integrates it into the existing module configuration. Now with all additional habitation elements in place from flights 7 and 8, the unloader then proceeds to emplace the regolith shielding over the new elements. On command from ground control, the payload unloader then moves the nuclear power plant pieces from the lander to the prepared site. After placing the reactor into the excavation, the other major subsystems are arranged in position.

Lunar Flight 9 (Piloted), 2006

A crew of six arrives with science equipment, EMU's, consumables for a 90 day stay, an unpressurized rover, spares, and needed replacement parts for base systems.

The crew, in combination with the unloader, utilizes one of the LEV servicers to safe the lander. After occupying the base, they use the pressurized rover and perform the necessary EVA to complete the installation of the nuclear power plant. The crew uses the pressurized rover to explore outside of the vicinity of the base and carry on any necessary maintenance of emplaced systems. IVA science activities are carried out in the habitats. EVA science, together with routine maintenance and contingency repairs, are carried on foot and via the rovers. With the augmented power system fully integrated into base systems users, the crew powers down the habitat, placing it in standby mode until the next mission, and departs in the lander.

Lunar Flight 10 (Piloted), 2006

A crew of six arrives with EMU's, an oxygen/volatiles integrated pilot plant, IVA science equipment, and consumables for a 90 day stay. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. After occupying the base, they perform the necessary EVA to verify the proper installation and operation of the integrated pilot plant. The crew, using the unloader and REL, also assists in the preparation necessary for the constructible habitat to be delivered on the next cargo flight.

The remainder of the stay time is spent performing needed base maintenance operations and science investigations. After a stay of 90 days, the crew places the base in standby mode and departs. This flight signifies the accomplishment of NOC-2.

Lunar Flight 11 (Cargo), 2007

A cargo lander delivers two additional regolith ripper/excavator/loaders, a constructible habitat with partial outfitting, and spares for base systems. The unloader transports the constructible with inflatable bladder to the base and mates it in-line with the three existing habitat modules. Installation of this enlarged habitable volume brings the base's crew volume capacity to 18.

Lunar Flight 12 (Cargo), 2007

A cargo lander delivers additional outfitting for the constructible habitat, a third excursion vehicle servicer, consumables, science equipment, and spares for base systems. The unloader transports the excursion vehicle servicer to the launch and landing area. The remaining payloads stay on the lander until the crew arrives the following month to supervise.

Lunar Flight 13 (Piloted), 2007

A crew of six arrives with EMU's and consumables that enable a 365 day surface stay. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. The remaining payloads delivered on the previous cargo flight are removed. The constructible outfitting is installed with the assistance of the unloader and attachments. IVA science equipment is also installed and calibrated.

Lunar Flight 14 (Piloted), 2007

Six crew arrive at the base 3 months after the previous crew. They bring EMUs and consumables. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. This brings to 12 the total number of crew on the surface.

Lunar Flight 15 (Piloted), 2007

A crew of six arrives with EMU's and consumables that help enable their 365 day surface stay. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. This brings to 18 the total number of crew on the surface.

Lunar Flights 16 & 17 (Cargo), 2008

A cargo lander delivers additional outfitting for the constructible already in place, a greenhouse structure with necessary outfitting, and spares for existing base systems. The unloader, with crew supervision, installs the outfitting into the constructible habitat. Their next major activity is the construction of the greenhouse. The unloader is used to deliver the greenhouse components adjacent to the interconnect node. A double-walled bladder package is mated to the node. The bladder is partially inflated and regolith is delivered to the growth chamber floor. The crew then completes the internal outfitting of the greenhouse, completes inflation of the pressurized interior, and initiates the internal subsystems.

Another cargo lander delivers consumables for the base crew, spares for the systems in place, and science equipment - mainly a 16 meter telescope. After the unloader has prepared the site, the telescope is unloaded and assembled at this site. This is accomplished by the unloader and crew.

Lunar Flight 18 (Piloted), 2008

Six crew arrive with EMUs and consumables. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. The initial crew which arrived in 2007 leaves the base.

Lunar Flight 19 (Piloted), 2008

Six crew arrive with EMUs and consumables. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. The second 6 member crew that arrived in 2007 leaves the base. One of the activities during this timeframe are 14 day traverses using the pressurized rover train.

Lunar Flight 20 (Piloted), 2008

Six crew arrive with EMUs and consumables. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. The third 6 member crew that arrived in 2007 leaves the base.

Lunar Flight 21 (Cargo), 2009

A cargo lander delivers power management and distribution equipment to service new power users, an additional 16 meter telescope, and resupply spares for existing base systems. This flight inaugurates the start of NOC-4.

Lunar Flight 22 (Cargo), 2009

Delivery of MTV systems to lunar orbit, not to lunar surface.

Lunar Flight 23 (Piloted), 2009

Six crew arrive with EMUs and consumables. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. After the unloader has prepared the site, the telescope is unloaded and assembled at this site. This is accomplished by the unloader and crew. The initial two crews which arrived in 2008 leaves the base.

Lunar Flight 24 (Piloted), 2009

After a stay in lunar orbit (to simulate the Mars transit), the Mars simulation crew of six arrives with EMU's, an unpressurized rover, a suite of science equipment and experiments, and consumables for a 40 day surface stay. They check out then occupy the Mars simulation portion of the base. While on the surface, they demonstrate as many of the operations to be performed at Mars as is practical. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. They move into the habitat modules and airlock that were initially delivered and carry on a Mars mission simulation. The other 12 crewmembers on the surface support this rehearsal crew if necessary and carry on ongoing base operations which include maintenance of emplaced systems, science operations, and exploration.

Lunar Flight 25 (Piloted), 2009

Six crew arrive for a 365 day stay, bringing EMUs and necessary consumables with them. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander.

Lunar Flight 26 (Piloted), 2009

Six crew arrive for a 365 day stay, bringing EMUs and necessary consumables with them. The crew, in combination with the unloader, utilizes an LEV servicer to safe the lander. Another six member crew, which has been on the surface for one year, leaves the base.

Mars Lander Flights 1, 2, & 3 (Cargo), 2012

Three cargo landers are needed to deliver the required systems to Mars. Lander 1 carries the unloader, nuclear power supply, pressurized rover train, flare warning system, and field science equipment. Lander 2 carries a habitat/airlock unit, communications equipment, and IVA science equipment. Lander 3 carries the other habitat unit and the backup power supply.

The unloader prepares the outpost site, then emplaces all systems. This requires that the unloader operate with a high degree of autonomy, due to the round-trip communication delays between the Earth and Mars. Once all systems are located in their final positions, Earth ground control verifies their integrity to the degree possible, before committing a Mars crew to trans-Mars injection. The systems are monitored throughout the crew Mars transit, and if needed, contingency operations are planned for the crew to execute on arrival.

Mars Lander Flight 4 (Piloted), 2014

The 6 Mars crew members land near the outpost, bringing with them their EMU's, an unpressurized rover, and the consumables required to support a 90 day surface stay. They live out of the lander while finalizing base set up and checkout. They carry out scientific objectives, including IVA (laboratory) science, local exploration of the outpost vicinity on foot or via the rovers, and deployment and operation of science payloads.

At the end of the surface stay, the crew places the outpost systems in low-power standby mode, then departs. Completion of this first human mission to Mars marks the achievement of Mars Initial Operating Capability.

Mars Lander Flights 5, 6, 7, & 8 (Cargo), 2014

Four cargo landers are needed to deliver the required systems to a second Mars site. Three of these carry nearly the same payloads as the three cargo flights in Mars IOC. A fourth carries a laboratory/storage module and airlock. The second airlock is delivered with the laboratory/storage module rather that with the second habitat module as was done in IOC. An ISRU demonstration unit is delivered with the second habitat module. All systems are deployed in the same manner as at the original outpost. The addition of a third habitation module makes two-module mating operations necessary.

The ISRU demonstration unit is also deployed by the unloader. It operates autonomously with supervision from Earth.

Mars Lander Flight 9 (Piloted), 2016

Operations for the six crew members are the same as in IOC, with the exception of thesignificantly longer total mission duration (600 days). The crew analyzes the products of the ISRU demo, and uses the apparatus to perform further experiments. The additional lab volume enables extensive scientific investigations to be carried out. The long stay time allows the crew to thoroughly explore the vicinity of the outpost, revisiting interesting geological sites to collect additional data or test hypotheses.

At the end of the 600 days, this outpost is also placed on low-power standby, and the crew departs Mars. The completion of a long-duration Mars surface stay marks the achievement of Mars NOC.

3.4 SPACE TRANSPORTATION SYSTEMS

3.4.1 Lunar Transportation System

3.4.1.1 Overview

The transportation systems for the Moon are designed to accomplish the principal objectives of (1) conducting long term human habitation and exploration on the Moon, and (2) using the Moon as a testbed for Mars. The Lunar Transportation System (LTS) employs a lunar orbit rendezvous mission mode, similar to Apollo, thereby requiring both lunar transfer elements and lunar lander elements. Crew size is 6 for all missions; however, the first two piloted missions land 5 crew on the surface (where they can live out of the lander for up to three days) while the sixth crewman remains in low-lunar orbit (LLO). Subsequent flights land all 6 crew members on the surface. There are separate landers for cargo and piloted missions. The cargo landers travel to the surface where they are expended, while the piloted landers are sized to return the crew and a minimal cargo to lunar orbit for rendezvous with the transfer vehicle. After crew and cargo transfer is completed, the piloted lander is expended in lunar orbit. The vehicle is checked out and returns to Earth. Crew recovery is via the ballistic Lunar Transfer Vehicle (LTV) crew module. Each mission, cargo and piloted, requires two two launches of a 150 mt Heavy Lift Launch Vehicle (HLLV) vehicle with a rendezvous and dock maneuver performed in LEO.

The option of evolving to a reusable Lunar Transportation System which would utilize lunar-produced cryogenic propellants was considered. This reusable option was rejected and expendible vehicles were used throughout this architecture. Appendix D captures the rationale for this decision.

(Editor's note: Inasmuch as the vehicles of the LTS are expendible, their designs are identical to those presented in Architecture 1. Consequently, the remainded of Sections 3.4.1.1 through 3.4.1.4 of the present document are the same as those presented in "Analysis of the Synthesis Group's **Mars Exploration** Architecture." *The writeup is reproduced here (with only editorial changes) for the convenience of the reader.)*

Lunar Cargo Capabilities: Figure 3.4-1 shows that the cargo capabilities range from approximately 21 mt on a piloted mission to 41 mt on a cargo-only mission.

Lunar Mission Initial Mass in Low Earth Orbit (IMLEO): The IMLEO's of the reference vehicle correspond to the cargo capabilities given. The IMLEO's for each HLLV launch are presented in Figure 3.4-2. For both cargo and piloted missions, the trans-lunar injection (TLI) stage is launched on the first HLLV, and the rest of the lunar vehicle is on the second HLLV launch. The TLI stage requires the full 150 mt capability of the launch vehicle; however, the remainder of the lunar vehicle, for both piloted and cargo missions, utilizes approximately 120 mt of the 150 mt launch capability of the second launch.

3.4.1.2 Vehicle Configurations & Mass Properties

The Lunar Transportation System (LTS) is comprised of Lunar Transfer Vehicle (LTV) elements and Lunar Excursion Vehicle (LEV) elements. The LTV utilizes a large, Trans-Lunar Injection (TLI) stage with high thrust capability and a Lunar Orbit Insertion/Trans-Earth Injection (LOI/TEI) stage. The LTV elements include the TLI and LOI/TEI stages with vehicle subsystems and the crew module. The LEV is a single-stage design. LEV elements include the single stage lander with vehicle subsystems and the crew module. All stages utilize liquid oxygen/liquid hydrogen propulsion and are expended after use.

The TLI stage requires five RL10 derivative engines, makes use of an advanced integral cryogenic reaction control system for attitude control and stabilization, and utilizes aluminum-lithium and graphite-epoxy materials for the structures and tankage. The thermal control system is designed to provide boiloff management for up to 60 days in LEO. Advanced, man-rated, redundant avionics and communications capabilities are provided. Electrical power is supplied by batteries and fuel cells.

The LOI/TEI stage requires three RL10 derivative engines and utilizes common hardware and software design elements with the TLI stage to the extent practical.

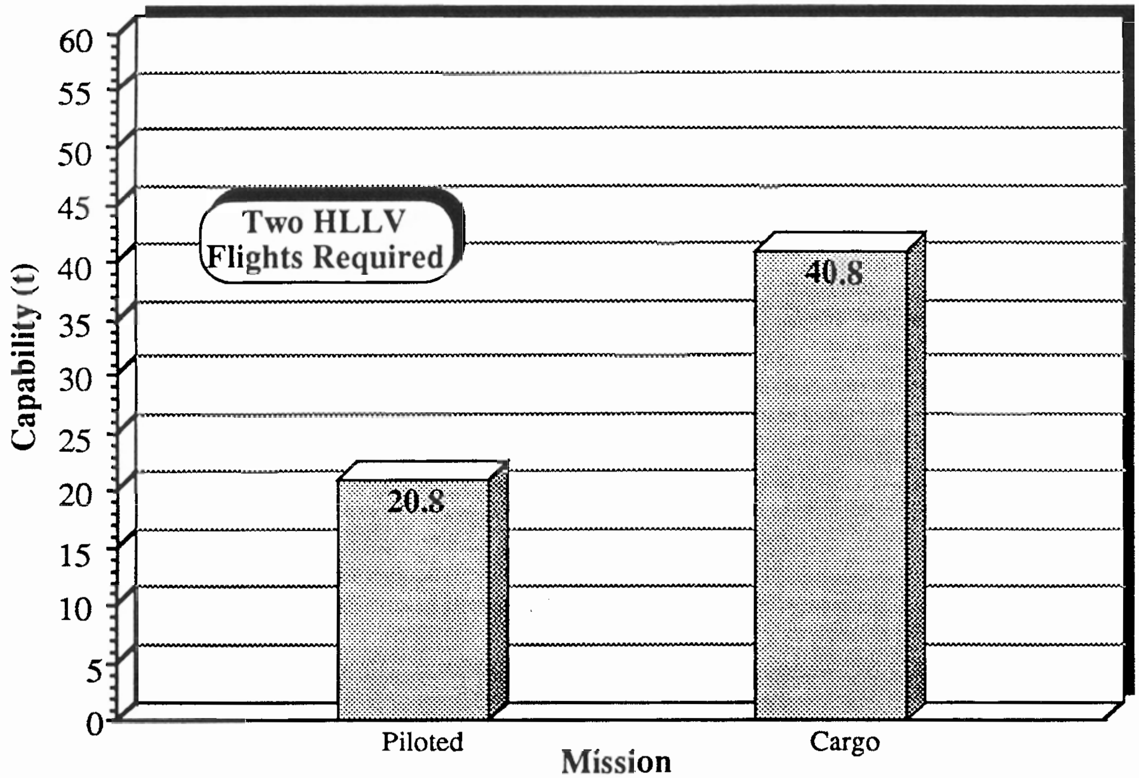


Figure 3.4-1. Lunar Cargo Capabilities

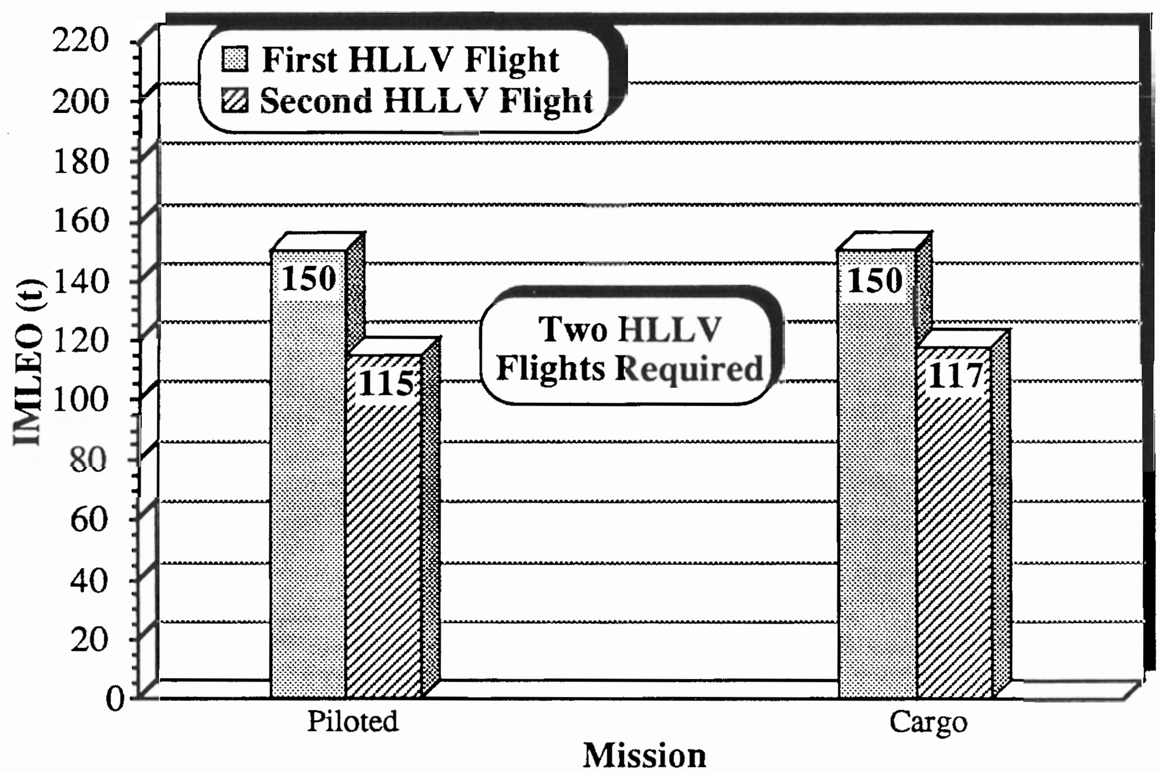
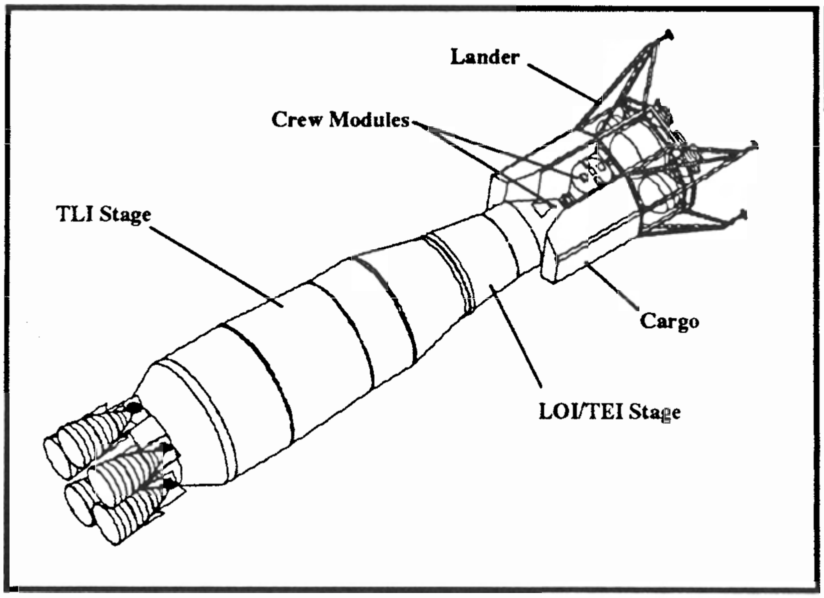


Figure 3.4-2. Lunar Mission IMLEO

The LEV requires five throttleable, RL10 derivative engines with an integral cryogenic RCS for control and stabilization. The structure and tankage makes use of Al-Li and Gr-Ep materials. The LEV and the LTV share common system designs for some elements, including the main engines, RCS thrusters, avionics, and communications. Four advanced fuel cells provide the electrical power for short duration missions. Landing legs and pads are provided for surface clearance and landing in unimproved areas. The thermal control system, utilizing a partial thermal tent, maintains the propellants during short mission stays on the lunar surface. For long durations on the lunar surface, surface system power and thermal conditioning are required.

Several key technologies for the LTS are inherent in this architecture, including cryo-fluid management, automated rendezvous & docking, advanced structural materials, throttable cryogenic engine, and automated precision landing.

Two ETO launches are required to perform each of the missions (cargo and piloted). The TLI stage is launched first, followed 30 days later by the launch of the rest of the LTS. The HLLV incorporates an integral kickstage that is used to circularize the HLLV payloads. In considering these long stays (30 days) in LEO, several operational implications need to be addressed. Orbital maintenance and station keeping, boiloff of cryogenic propellants, man-made orbital debris and micro-meteoroids impacts are the major concerns. With orbit maintenance and station keeping, concerns of propellant utilization become dependant on stay duration and the total number of maneuvers needed during stay. Boiloff of the cryogenic propellants is a factor in determining the size of the tanks and the thermal protection system used or the amount of propellant that must be transferred for resupply. Man-made orbital debris is a by-product of long duration stay in orbit, and proper effective ways

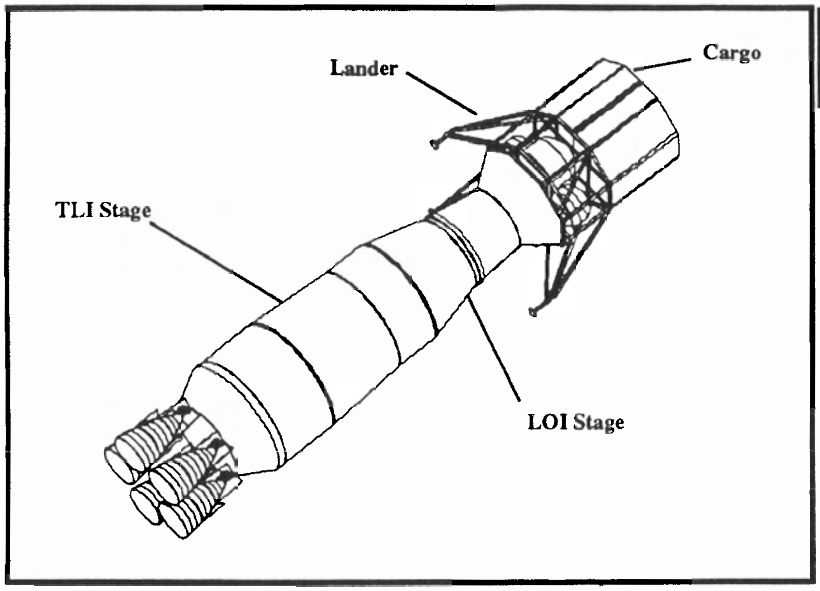


Surface Payload Mass:	20.8 t
Departure Orbit:	300 km
IMLEO:	265 t
Engine Out:	2
Crew Size:	6
TLI Stage	
Stage Inert Mass:	14.1 t
Usable Prop Mass:	135.5 t
Propellant Type:	LOX/LH2
Engine Type	RL10 Derivative
Isp/#:	468/5
Length/Diameter:	15.7m/8.4m
LTV/LOI/TEI Stage	
CM Mass:	10.8 t
Stage Inert Mass:	6.3 t
Usable Prop Mass:	33.0 t
Propellant Type:	LOX/LH2
Eng Type	RL10 Derivative
Isp/#:	468/3
Length/Diameter:	13.3m/7.6m
Lander	
CM Mass:	2.8 t
Stage Inert Mass:	8.4 t
Usable Prop Mass:	31.1 t
Prop Type (Des/Asc):	LOX/LH2
Engines (Descent/Asc):	RL10 Derivative
Isp (Desc/Asc)/#:	450/5
Length/Diameter:	9.2m/7.0m

Propellant Tanks

#/Tank	Fluid(s)	Tank Size (Dia/Length)	Dry Mass (ea)	Prop Mass (ea)	Total Mass
1-TLI	LOX	7.62m/5.38m	0.9t	117.9t	118.8t
1-TLI	LH2	8.38m/6.99m	1.73t	19.7t	21.4t
1-LOI/TEI	LOX	4.26m/3.02m	0.12t	28.7t	28.8t
1-LOI/TEI	LH2	5.48m/4.14m	0.9t	4.8t	5.7t
2-Lander	LOX	2.44m/3.28m	0.13t	14.4t	29.1t
2-Lander	LH2	3.05m/5.35m	0.27t	2.4t	5.3t

Figure 3.4-3. Vehicle Configurations & Mass Properties (Pilot)



Surface Payload Mass:	40.8 t
Departure Orbit:	300 km
IMLEO:	267 t
Engine Out:	2
Crew Size:	n/a
TLI Stage	
Stage Inert Mass:	14.1 t
Usable Prop Mass:	135.5 t
Propellant Type:	LOX/LH2
Engine Type	RL10 Derivative
Isp/#:	468/5
Length/Diameter:	15.7m/8.4m
LTV/LOI/TEI Stage	
Stage Inert Mass:	6.3 t
Usable Prop Mass:	30.5 t
Propellant Type:	LOX/LH2
Eng Type	RL10 Derivative
Isp/#:	468/3
Length/Diameter:	10.3m/7.6m
Lander	
Stage Inert Mass:	8.4 t
Usable Prop Mass:	31.1 t
Prop Type (Des/Asc):	LOX/LH2
Engines (Descent/Asc):	RL10 Derivative
Isp (Desc/Asc)/#:	450/5
Length/Diameter:	6.3m/7.0m

Propellant Tanks

#/Tank	Fluid(s)	Tank Size (Dia/Length)	Dry Mass (ea)	Prop Mass (ea)	Total Mass
1-TLI	LOX	7.62m/6.38m	0.9t	117.9t	118.8t
1-TLI	LH2	8.38m/6.99m	1.73t	19.7t	21.4t
1-LOI/TEI	LOX	4.26m/3.02m	0.12t	26.6t	26.7t
1-LOI/TEI	LH2	5.48m/4.14m	0.9t	4.4t	5.3t
2-Lander	LOX	2.44m/3.28m	0.13t	13.5t	27.3t
2-Lander	LH2	3.05m/5.35m	0.27t	2.3t	5.1t

Figure 3.4-4. Vehicle Configurations & Mass Properties (Cargo)

to dispose of or deal with it must be considered. The longer the stay in orbit, the more exposure the vehicle and the crew undergo to such things as radiation and micro-meteoroids. The effects of these conditions must be accounted for in all aspects of the vehicle design and mission operations.

3.4.1.3 Lunar Piloted Mission Scenario

Figure 3.4-5 displays schematically the lunar piloted mission scenario. After ground processing and integration of the cargo and crew modules onto the relevant vehicles has been completed, the LTS elements are integrated with launch vehicles to prepare for the launch. Following the Earth-to-orbit transfer, the elements are assembled and integrated into a vehicle (via the rendezvous and docking process) and checked out prior to the mission flyout. The bulk of the lunar transportation system must detach from the cargo and lander and redock in order for the loads on the cargo and lander to remain in the same direction during Earth and lunar launches as well as lunar landings. The two HLLV flights are separated by approximately 30 days. Approximately 90 days will separate missions occuring in the same year. After the three day "free return" transfer to the Moon is complete, the vehicle enters LLO and the lander then separates and initiates the lunar descent. The lander is designed to support a crew of six and itself on the lunar surface for up to three days. When the surface mission is complete, the vehicle carrying the crew and minimal cargo is prepared for ascent to LLO. Once in LLO, the lander docks with the crew cab and LOI/TEI stage and the crew transfer is performed. After crew transfer and systems checkout, the LOI/TEI initiates the return to Earth. Finally, the Crew Return Vehicle (CRV) executes a ballistic reentry at Earth.

The piloted missions all carry six crew members; however, the 2004 (i.e., IOC) and 2005 (i.e., NOC-1) missions leave one person in orbit while the other five descend to the lunar surface. (Note, in particular, that the NOC-1 mission has a forty day duration at the Moon.) This scenario requires two crew modules and increases the size, power and consumables required for each module since they are both inhabited. The lander will maintain itself for the first two weeks on the surface. After that, it is assumed that surface power and cryo refrigeration units will maintain the lander for the rest of the surface stay time. The

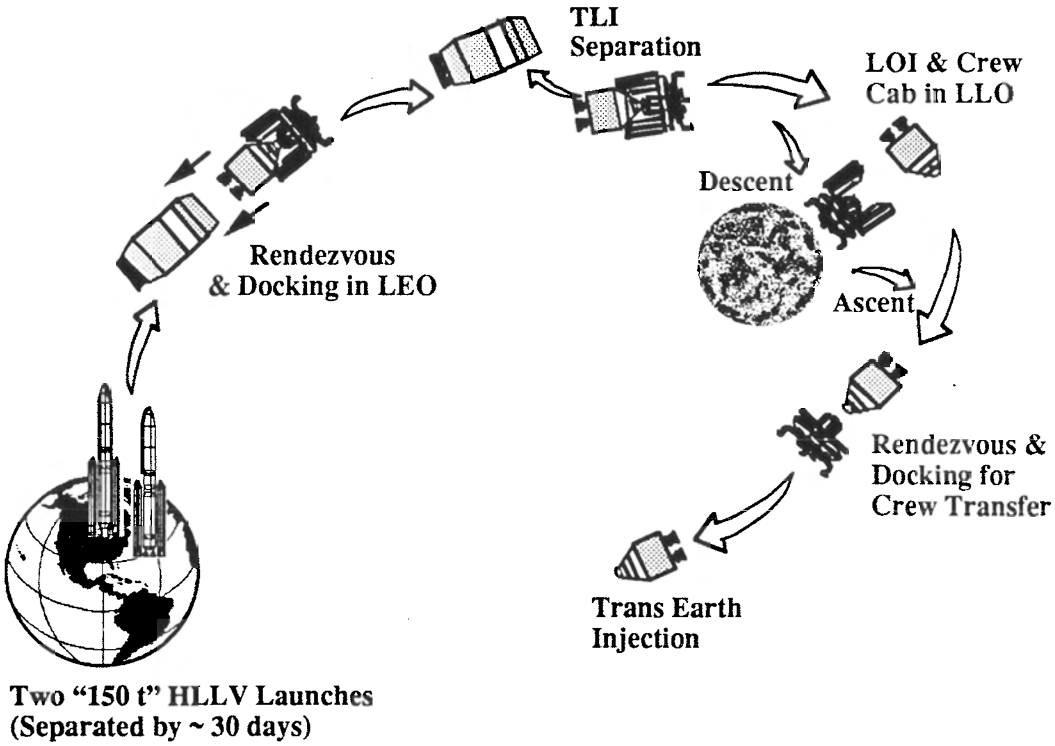


Figure 3.4-5. Lunar Piloted Mission Scenario

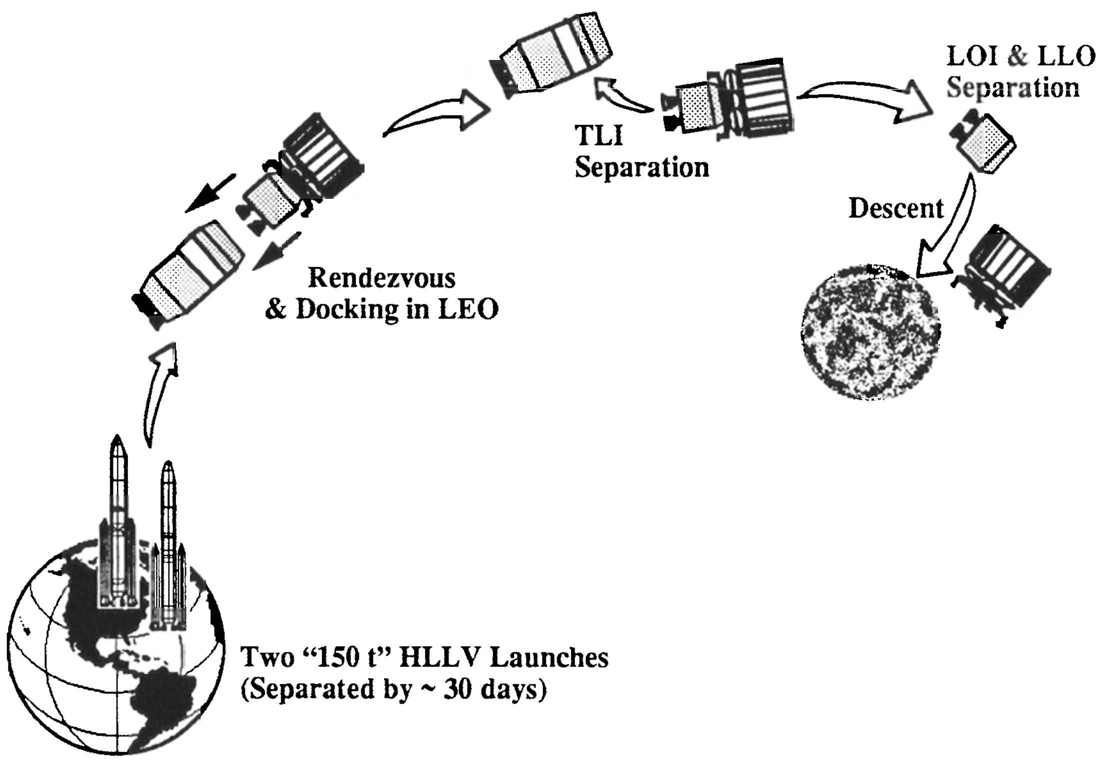


Figure 3.4-6. Lunar Cargo Mission Scenario

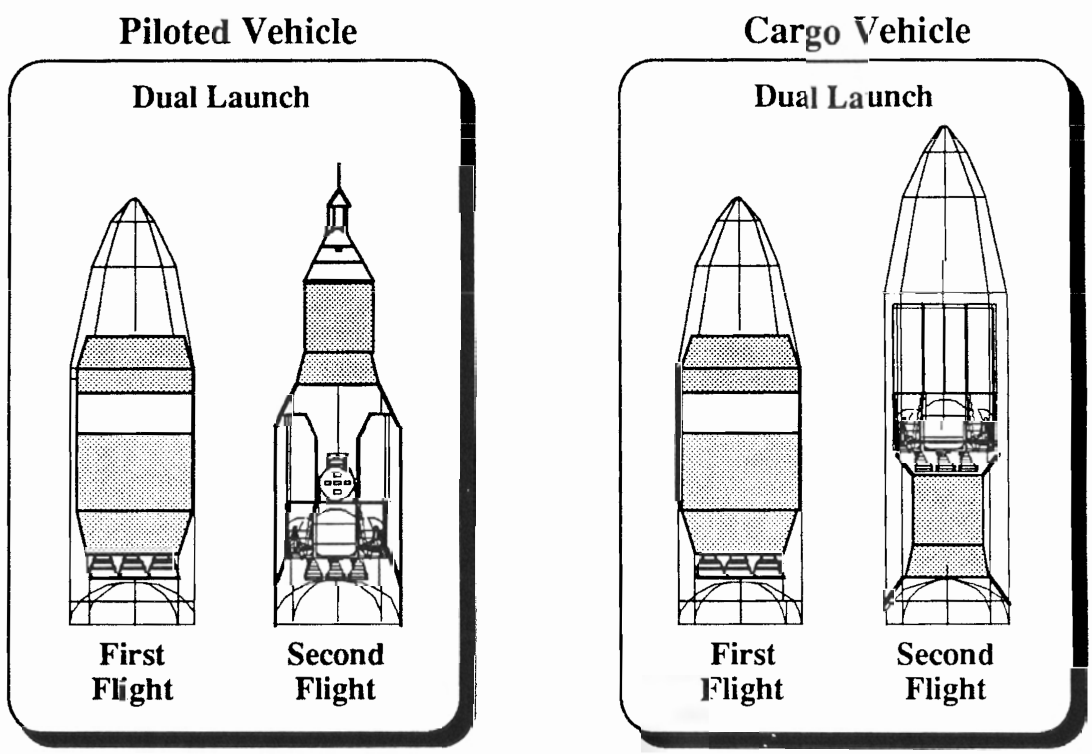
longer stay times for the later missions will have some effect on the LOI/TEI stage since it is not sized for up to 90 days of boiloff; however, it can be assumed that enough about cryofluid management will have been learned that the LOI/TEI tanks can be easily modified, probably by changing the thermal protection system, to accommodate these missions.

3.4.1.4 Lunar Cargo Mission Scenario

Figure 3.4-6 shows the lunar cargo mission scenario. After ground processing and integration of the cargo onto the relevant vehicles has been completed, the LTS elements are integrated with launch vehicles to prepare for the launch. Following the Earth to orbit transfer, the elements are assembled and integrated into a vehicle (via the rendezvous and docking process) and checked out prior to the mission flyout. The two HLLV flights are separated by approximately 30 days. Approximately 90 days will separate missions flown in the same year. After the three day "free return" transfer to the Moon is complete, the vehicle enters LLO and the lander then separates, initiates the lunar descent, and is expended on the lunar surface.

3.4.1.5 Lunar Launch Manifest Summary

The manifesting of the lunar vehicles is shown in Figure 3.4-7 for launches of the piloted and the cargo missions. The second launch of the cargo mission uses the ETO lunar shroud (25 feet x 60 feet, usable). Since the pictures are to scale relative to one another, it may be seen that this shroud could be used for all but the piloted launch. Figure 3.4-7 also gives a summary of the ***Moon to Stay and Mars Exploration*** architecture in terms of the time span, the number of lunar missions, and the number of HLLV flights required.



Architecture	Lunar Missions	Total HLLV Flights	Years	Average HLLV Flts/Year	Maximum HLLV Flts/Year
III	26	51	2004-2009	8 - 9	11

Note: The second flight of the cargo vehicle uses the 25' x 60' (usable) Lunar ETO Vehicle Shroud

Figure 3.4-7. Lunar Launch Manifest Summary

3.4.2 Mars Transportation System

(Editor's note: The Mars phase of the ***Moon to Stay and Mars Exploration architecture*** *is identical to that of Architecture 1. Consequently, Section 3.4.2 of the present document is the same as that presented in* "Analysis of the Synthesis Group's **Mars Exploration** Architecture." *The writeup is reproduced here (with only editorial changes) for the convenience of the reader.)*

3.4.2.1 Overview

The main objective of this architecture is the exploration of Mars and the scientific returns associated with Mars exploration. The transportation elements described herein are designed to accomplish this objective. The mission concept for this architecture is a split-sprint type where the cargo is transported on a separate flight from the manned vehicles. The main groundrules and assumptions which are key drivers in the design of the Mars Transportation Vehicle (MTV) are:

1) Nuclear Thermal Propulsion (NTP) for both cargo and piloted vehicles

2) Crew size of six

3) Piloted lander transported on piloted MTV

4) Earth-to-Orbit (ETO) capability of 250 metric tonnes; shroud size of 14m x 30m

5) Zero gravity vehicles

6) Expendable MTV with ballistic crew return

7) Storable propellents used on descent and ascent stages of landers

8) Cargo vehicles integrally launched with no on-orbit assembly operations required

9) MEV's capable of landing a nominal maximum payload of 45 metric tonnes on the surface

3.4.2.2 Mars Transportation System Description

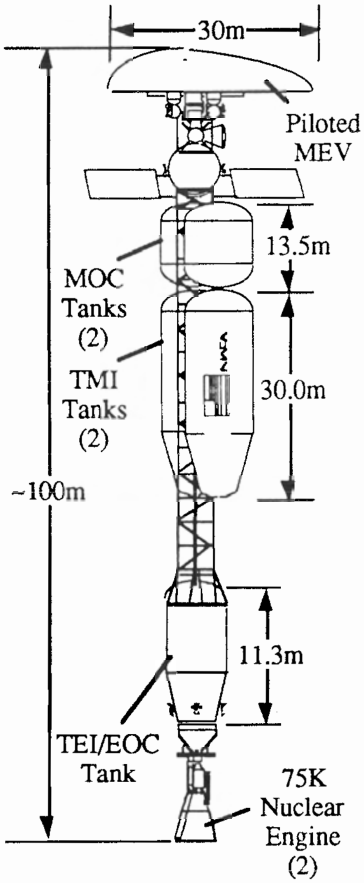
The Mars Transportation System includes two vehicle configurations: Mars piloted vehicle and Mars cargo vehicle.

The Mars piloted vehicle is shown in Figure 3.4-8. It uses nuclear thermal propulsion for all major maneuvers. The core configuration includes two NTP engines at 75,000 lb thrust each, a radiation shadow shield, an aft tank assembly, an interstage structure that includes expendable tank attachment and connect provisions, the Mars transfer crew habitat, power, thermal control, attitude control and communications utility services, and the Mars excursion vehicle. The core configuration is launched in two 30-meter-length sections on the 250 mt nominal payload capability HLLV. Additional hydrogen propellant is provided by expendable hydrogen tanks launched separately and berthed to the core vehicle in low Earth orbit.

The Mars cargo vehicle is shown in Figure 3.4-9; it uses the same nuclear engine as the piloted vehicle, with one per vehicle since engine-out is not required. Each cargo vehicle consists of a nuclear stage which delivers the cargo MEV to Mars orbit and one cargo MEV. This arrangement permits each cargo vehicle launch to be all-up with no Earth orbit operations required. The cargo vehicle is derived from the piloted vehicle, applying subsystems as needed.

The Mars Transportation System for both piloted and cargo configurations is comprised of a Mars Transfer Vehicle (MTV) and a Mars Excursion Vehicle (MEV). The MTV and MEV are described below for the piloted vehicle configuration. The MTV and MEV for the cargo vehicle configuration would be similar, but not include the transfer habitat or crew module.

Mars Transfer Vehicle Description - The nuclear engines characteristics used in this implementation are a thrust-to-weight ratio of ten or greater. Isp is baselined as 925 seconds. Liquid hydrogen propellant is provided by vehicle tanks; warm hydrogen gas is routed from the engines to the tanks for pressurization during burns. Vehicle tanks are thermally insulated



Element Mass (kg)	2014	2016
MEV	81100	81100
CRV	5808	5808
MTV crew habitat system	58000	58000
Truss strongback, struts & RCS	5521	5521
Reactor/engine mass	6804	6804
Radiation shadow shield mass	5598	5598
EOC propellant	0	0
TEI propellant	49067	51930
TEI/EOC common tank (1)	10307	10714
Aft tank total mass	59374	62644
MOC propellant	108930	130360
MOC tanks (2)	20094	21896
MOC tankset total mass	175620	152256
TMI propellant	317220	375930
TMI tanks (2)	49375	57382
TMI tankset total mass	366595	433312
IMLEO	**764420**	**811043**

Figure 3.4-8 2014 Opposition & 2016 Conjunction Piloted Mars Transfer Vehicles
2014 - 440 d transfer time, 100 d stay 2016 - 210 d transfer, 600 day stay

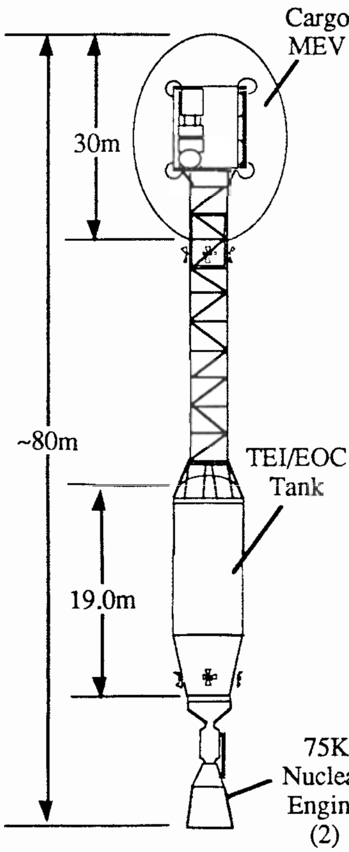
with multilayer insulation and vapor-cooled shields; active refrigeration is not used. Both engines are operated for all maneuvers unless one is inoperable. Mission rules provide for return-to-Earth abort in the event an engine fails.

Attitude control propulsion is provided by mechanically compressed hydrogen gas obtained from main tank boiloff. Hydrogen gas accumulators provide sufficient storage for any one auxiliary propulsion maneuver; the accumulator capacity is sized by Earth-Mars leg midcourse correction requirements. Accumulators are recharged during coast periods. Nuclear engines have low-rate gimbal capability for center of gravity tracking; the attitude control propulsion system provides attitude damping during thrust periods.

Propellant tanks are aluminum-lithium alloy. Intertank and other main structures employ advanced composites for reduced mass. The interstage uses a simple telescoping arrangement to reduce vehicle length during launch. The extended length of this structure is sufficient to allow for attachment of the expendable hydrogen tanks. The transfer habitat is a composite-reinforced aluminum pressure vessel with metallic interior secondary structures.

Thermal control is provided for the transfer habitat and externally-mounted utility services. Cryogens are insulated as noted above. Nuclear engines provide their own thermal control except after-heat removal which is provided by hydrogen bleed flow from the main propellant system.

All electrical power is provided by a solar array/advanced battery system rated at 27 kW average power. Batteries provide



Element Mass (kg)	2012	2014
MEV	81100	81100
CRV	0	0
MTV crew habitat system	0	0
Truss strongback, struts & RCS	5521	5521
Reactor/engine mass	3400	3400
Radiation shadow shield mass	0	0
Navigation pack mass	2000	2000
EOC propellant	0	0
TEI propellant	0	0
MOC propellant	18698	22925
TMI propellant	71910	79236
TMI/MOC common tank (1)	16157	17797
Aft tank total mass	106765	119958
IMLEO	**198786**	**211979**
	x 3	**x 4**
	596358	**847916**

Figure 3.4-9 2012 & 2014 One Way Cargo Mars Transfer Vehicles

power during propulsive maneuvers and solar occultations. The system is operated at a de-rated level while parked in LEO so that LEO operations do not dictate power system capacity.

The avionics system is located in the transfer habitat, except for MEV and CRV avionics, RF power amplifiers for the high-gain antennas, and distributed data acquisition and controllers. The avionics system is multi-string and includes vehicle health management functions as well as crew controls and displays. Commonality across avionics systems is maintained to the extent practical, but each vehicle has special functions such as approach ranging for the interplanetary vehicle and landing radar for the MEV.

The environmental control and life support system for the transfer habitat is a physical-chemical two-gas system closed on oxygen and water. Food is supplied in shelf-stable and frozen forms. A greenhouse is provided for modest fresh vegetable supply but its products are not required for crew health/survival. The ECLSS is redundant as is the pressurized volume of the habitat so that a depressurization only affects half the pressurized volume; recovery and repressurization means are provided. The ECLSS systems for the MEV and CRV are open-loop in view of the short mission duration for these vehicles. The MEV is capable of supporting its crew for up to 5 days while the surface base is checked out and during ascent to Mars orbit at the end of the mission.

The transfer habitat provides full-service crew systems with private quarters, a galley/ wardroom, command and control area, health maintenance, exercise and recreational equipment and space. Dedicated radiation shielding is not provided; radiation dose calculations indicate that the shielding provided by the transfer habitat structure, systems and consumables may be adequate to protect the crew from galactic cosmic rays and solar proton events (SPEs) assuming the crew uses the galley as a storm shelter during severe SPEs. However, further analysis is required to firmly establish shieldiquirements. Radiation analyses indicate the MEV and CRV do not require radiation shielding; this assumes a warning system capable of forcasting approximately 24-hour SPE "safe" periods for MEV ascent. Crew system provisions in the MEV and CRV are similar to those provided by the Apollo command module.

<u>Mars Excursion Vehicle Description</u> - The MEV performs the descent and ascent maneuvers for the piloted Mars missions, and the descent cargo delivery for cargo-only missions. For the cargo-only missions, the MEV does not have an ascent stage. Descent from Mars parking orbit is performed using an aerobrake to slow down from entry speed to about 600 m/sec; final deceleration and descent use rocket propulsion. Descent and ascent propulsion systems are separate, using storable propellants. The same engine design is used for descent and ascent. The MEV cargo delivery capability is 45 mt in the all-cargo mode and 11.5 mt in the crew mode.

The propulsion characteristics of the MEV are:

Propellant type:	Earth storables, N204 + MMH
Rated thrust:	133 kN (30,000 lb.)
Number of descent engines:	5
Number of ascent engines:	3
Type of engines:	Pump-fed gas generator, regeneratively cooled
Vacuum Isp:	340 sec.

The MEV is designed with a deployable aerobrake with L/D < 0.5. The aerobrake is used during the descent maneuver to decelerate the vehicle and to lessen the propulsive requirements. By using a deployable aerobrake concept, the aerobrake does not require orbital assembly, thus allowing the cargo missions to be integrally launched with a single ETO launch.

Propulsion - The ascent and descent main propulsion systems use pump-fed gas generator storable propellant engines. The descent propulsion system has engines distributed around the periphery of the descent stage to permit cargo to be close to the surface of Mars after landing. This leads to a limited engine-out capability; if an engine fails, a balancing engine must also be shut down. The presumed mission rule will be that unless all engines start successfully for the initial deorbit burn, a landing will not be attempted. If an engine fails during or after landing engine restart, an abort to orbit is possible with the ascent stage.

The ascent propulsion system uses the same type of engines, but clustered beneath the ascent stage center of gravity for full engine-out capability.

RCS/Auxiliary Propulsion - Each stage of the MEV has its own RCS/auxiliary propulsion system; these consist of self-contained pressure-fed storable propellant/thruster modules.

Aerobrake - The aerobrake is a multi-petal folding rigid design. Advanced composite materials are used for minimum mass. The heat shield/outer shell is titanium-aluminide with a zirconia overspray. The relatively mild heating environment for deorbit/descent requires only modest thermal protection; the brake is designed with enough thermal mass and structural redundancy to survive worst-case boundary layer leakage through petal seams. The aerobrake is deployed in Earth orbit after launch and remains deployed throughout the mission. During Mars descent, after the entry heat and aerodynamic pressure pulse, doors in the brake open and descent engines are started. As the MEV slows down under rocket thrust and as aerodynamic pressure continues to decline, the aerobrake is jettisoned. Landing occurs on rocket thrust.

A lightweight deployable wake-heating fairing protects the cargo and/or ascent stage during descent. This fairing is deployed just before the deorbit burn and jettisoned on descent after the aerobrake.

Thermal control - Thermal control of the crew module is provided by a simple single-loop system with body-mounted radiators. The system has limited water-boiler heat-sink capabilities for the descent period when the wake heating fairing is in place. MLI and electrical heaters are used to maintain storable propellants in the desired temperature range.

Structures - Propellant tanks are aluminum; the advantages of advanced tank materials are very limited for this small vehicle. Dry structures use advanced composites for minimum mass. The descent stage structure is designed around the cargo-version payload envelope (8 meters diameter x 11 meters length) and the aerobrake, with a removable section at one end, such that the payload can be lowered onto a transporter and moved from under the MEV. The ascent stage structure is a simple truss arrangement that interconnects the propellant tanks, propulsion system, and crew module.

Electrical Power - Electrical power for active periods (descent and ascent) is provided by advanced primary batteries. During dormant, powered-down periods on Mars, health maintenance power is provided by a small solar array/battery system.

Avionics - All avionics except descent-unique functions and distributed sensors, effectors and data multiplex/control units, is contained in the crew module. The avionics system is multi-string and includes vehicle health management functions as well as crew controls and displays. RF communications links with the MTV and surface base are provided; a backup voice-only and low-rate telemetry link direct to Earth is also provided.

ECLSS - The ECLSS system is a simple two-gas open-loop system with LiOH CO_2 absorption. Food is provided in ready-to-eat form. Hygiene is Apollo-style. The crew wear EVA suits during descent and ascent; these provide backup for accidental cabin depressurization. All cabin systems (except the obvious ECLSS functions) are designed to operate normally in vacuum. The entire cabin can be depressurized for egress and ingress; if an IVA crew transport module is available on Mars for later missions, a hatch connection for it can be added to the MEV.

Crew Systems - Interior crew systems consist of seats, windows for descent piloting, and flight controls and displays. The ascent stage crew module is used for descent to enable descent abort to orbit. An ingress-egress hatch at the top of the crew module includes a berthing adaptor for IVA transfer to/from the MTV crew habitat; a similar hatch and stairway in the side of the module near the planet surface provide for on-surface ingress and egress. No solar flare shielding is provided. Since the ascent and rendezvous sequence can require up to 36 hours, a limited capability to predict flare-safe periods is assumed.

3.4.2.3 Mars Transportation System Operational Description - Piloted Mission

The operational scenario for the piloted Mars Transportation System (MTS) is initiated with the ETO launch of the MTS elements. The elements of the MTS are launched to a 220 nmi circular orbit using a 250 metric tonne class ETO capability. The shroud size(s) used is 14m × 30m.

The part of the vehicle launched first includes teleoperation arms for berthing the following vehicle elements. These are equipped with automated rendezvous and proximity operations packages to fly to within reach range of the arms. Vehicle assembly occurs autonomously, assisted by ground-based teleoperation as needed. Debris shields are launched attached to collision-sensitive parts of the vehicle such as propellant tanks, and removed before TMI by a cargo transfer vehicle (CTV).

About one month before the TMI window opens, a test crew will board the vehicle for final tests and pre-orbital-launch checkout. One week before the window opens the mission crew will board; after a tie-in period the test crew will return to Earth on the shuttle that delivered the mission crew.

Trans-Mars injection occurs in three burns of the NTP system. The first burn places the vehicle in a 72-hour elliptic orbit with apogee about halfway to the Moon's orbit. The second burn occurs at apogee and makes the plane change required to access the trans-Mars velocity vector; orbit period is not changed by this burn. The third burn starts just before perigee and increases the vehicle velocity to that required for TMI. The crew spends the time during the first and third burns in the galley area to reduce radiation dose from van Allen belt passage.

Trans-Mars injection tanks are retained during the coast to Mars for their radiation shielding value. Midcourse corrections during trans-Mars are divided into three maneuvers to reduce total delta V, improve targeting, and also reduce the amount of hydrogen that must be stored in the attitude control propulsion system accumulators.

A few days before Mars arrival, terminal navigation and maneuvering begin. Navigation can use satellites in Mars orbit or radar ranging of Mars itself for approach state vector update. A test of the nuclear engines assures that both are ready for operation; if a failure is detected, or if other mission/equipment anomalies dictate, the approach path is retargeted by the attitude control system for a Mars flyby abort.

The Mars phase of the mission begins with a single-burn orbit insertion into an elliptic orbit. The state vector is updated by Earth track, and descent preparations begin, including orbital high-resolution imagery and viewing of the planned landing site. The MEV is checked out. Separation and de-orbit of the MEV occurs near apoapsis of the parking orbit. Atmosphere entry occurs 6 to 12 hours later, depending on the parking orbit period, and atmosphere braking begins. The MEV maneuvers towards the landing site and acquires one of the landing beacons delivered with the surface cargo mission. At about 10 km altitude, landing engines are started and the aerobrake is jettisoned. Terminal maneuvering to the landing site is done on rocket propulsion. The final approach is on a 15° descent "glide" slope so that the landing site is visible to the crew on approach. Touchdown occurs within one km of the base.

During the descent, the crew occupies the crew module of the ascent stage to enable abort. Abort is possible during the terminal phase of the aero descent or after descent engines start; the ascent stage can start engines, separate and return to Mars orbit.

After landing the crew performs an ascent stage checkout, powers down and secures the MEV and initiates the surface mission. The MEV health management system remains active during the surface stay to alert the crew of any problem that might call for an abort to Mars orbit.

Upon completion of the surface mission, the crew returns to the MEV, boards the ascent stage, and prepares for ascent. Ascent windows occur at least twice per Mars day, whenever the surface base is in the parking orbit plane. At the first opportunity, ascent is initiated. The MEV ascent stage flies to a 100 km circular phasing orbit coplanar with the parking orbit. Upon arrival at periapsis, burn to a transfer ellipse (apoapsis coincident with the parking orbit) occurs. At apoapsis the final phasing burn occurs followed by rendezvous and docking with the interplanetary vehicle. The crew transfers and the MEV ascent stage is jettisoned. This nominal ascent occurs about 10 days before the return-to-Earth window closes to allow contingency time.

Trans-Earth injection occurs on a single burn. The coast to Earth is similar to the coast to Mars, with multiple midcourse corrections. Terminal navigation for Earth return is provided by the Deep Space Network (DSN).

About 16 hours before Earth arrival, the crew enters the CRV with the Earth return science. At entry minus 12 hours the CRV separates from the rest of the vehicle. Since the interplanetary vehicle is not on an Earth atmosphere intercept path, the CRV makes a burn of about 20 m/sec to place it on its entry path. The interplanetary vehicle passes by Earth and is abandoned. Earth gravity assist and final attitude control propulsion maneuvers place the vehicle on a trajectory which avoids a later Earth impact. The CRV enters Earth's atmosphere, decelerates, deploys parachutes, and makes a water landing to complete the mission.

Figure 3.4-10 gives a schematic representation of the piloted mission profile (as well as the cargo mission profile).

3.4.2.4 Mars Transportation System Operational Description - Cargo Mission

The cargo missions supporting the manned Mars missions are integrally launched using at 250 metric tonne class ETO vehicle. By integrally launching the cargo vehicle, the complexities of orbital assembly are eliminated. The basic vehicle configuration consists of four major pieces: 1) the cargo MEV; 2) the common TMI/MOC propellent tank; 3) a single nuclear engine; and 4) a truss strongback (retractable design). The MEV utilizes a descent aerobrake which is designed to be deployable in order to fit within the 14 m payload shroud. The initial piloted mission is supported by three cargo vehicles. The subsequent piloted mission requires four cargo vehicles to support a landing at an alternate site.

The ETO scenario for the Mars cargo missions includes the manifesting of the four major vehicle elements along with any secondary elements onto one 250 metric tonne class ETO vehicle with a shroud size of 14 m diameter by 30 m length. In order for the vehicle to fit within this shroud size, the aerobrake is a deployable type and the truss strongback is designed to be collapsable for greater packing efficiency. Once the vehicle has reached its final orbit of 220 n.m., the truss strongback is extended and autonomously berthed with the cargo MEV (which has deployed its aerobrake). The cargo MTV then performs a TMI maneuver which sends the MTV towards Mars on a low-energy, conjunction-class outbound trajectory. Once in the vicinity of Mars, the MTV performs a capture maneuver in Mars orbit. When orbit phasing allows descent to the selected landing site, the MEV de-orbits, jettisons its low L/D aerobrake at about 10 km altitude and lands on the Martian surface. Once on the surface, the landed cargo is translated to within 1.0 m of the surface where it is transferred to a planetary surface system transporter for final relocation and positioning. The cargo lander telemeters its status to Earth to verify a successful touchdown and safes itself until further required.

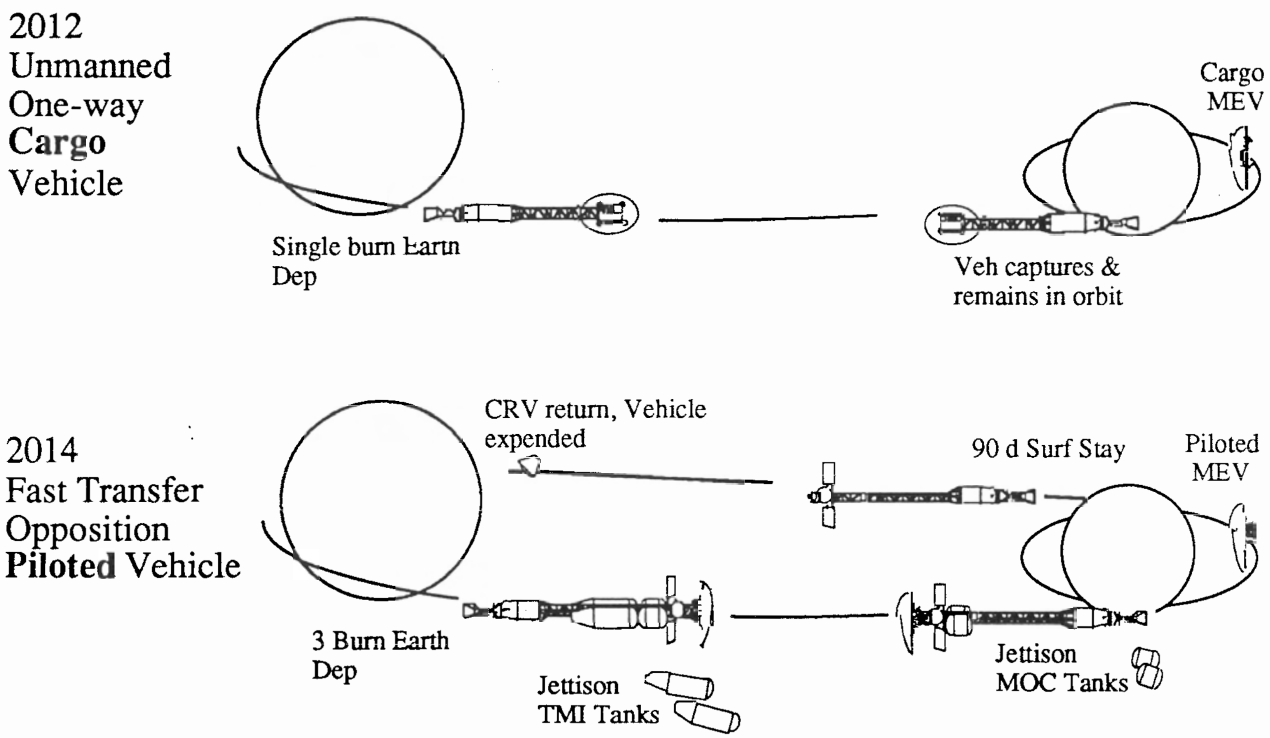


Figure 3.4-10 *Moon to Stay and Mars Exploration* Architecture
Split Sprint Mission Profile -- 2012/2014 First Mars Mission

3.4.2.5 Payload Manifesting-Piloted Vehicle

The chart in Figure 3.4-11 represents the payload manifesting for the piloted vehicle for the ***Moon to Stay and Mars Exploration*** architecture. The masses used in this manifest represent the 2016 piloted mission which is the more difficult opportunity, resulting in the more demanding requirement on ETO capability. The 250 mt class ETO vehicle used for this manifesting has an actual payload capability delivering 233 mt to 220 n.m.-circular orbit. The cargo vehicle for the 2014 mission is launched in 2012 and uses a single launch of the nominal 250 metric tonne launch vehicle. As can be seen from the chart, the piloted vehicle can be delivered to LEO (220 n.m.) with four 250 metric tonne ETO launches.

Flight Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
ETO Capability	**250**	**250**	**250**	**250**				
MTV Crew HAB	**58.0**							
MTV Struct	**5.5**							
Reactor/Eng	**12.4**							
Aft Tank	**62.6**							
CRV	**5.8**							
	144.3							
MOC Tanks (2)		**152.2**						
MEV(1)		**81.1**						
		233.3						
TMI Tank (1)			**216.6**					
TMI Tank (1)				**216.6**				

Figure 3.4-11 Payload Manifesting-Piloted Vehicle

3.5 EARTH-TO-ORBIT TRANSPORTATION SYSTEM

(Editor's note: The Earth-To-Orbit transportation system is the same as that presented in Architecture 1. Consequently, Sections 3.5.1 through 3.5.5 of the present document are the same as those presented in "Analysis of the Synthesis Group's **Mars Exploration** Architecture." *The writeup is reproduced here (with only editorial changes) for the convenience of the reader. Section 3.5.6, however, is specific to the* ***Moon to Stay and Mars Exploration*** *architecture.)*

3.5.1 Overview

The overall methodology behind the design of the Earth-To-Orbit (ETO) transportation system was to minimize on-orbit operations for both lunar and Mars missions. The payload classes desired were 250 mt (550 klb) delivered to 407 km-circular for Mars missions and 150 mt (330 klb) delivered to 296 km-circular for lunar missions (orbital altitudes defined in conjunction with lunar and Mars transportation systems requirements). Another goal was to maximize commonality between the ETO systems for these two mission types. The system chosen to meet these requirements was a core derived from existing STS elements (i.e., tankage) using the Space Transportation Main Engine (STME) for main propulsion (i.e., current National Launch System (NLS) reference). This core then utilizes some existing program infrastructure while continuing to advance propulsion technology. The boosters are essentially an entirely new development, with the exception of the use of the F-1 derivative engine for main propulsion. This allows for a minimum number of engines while reducing engine development since it is based on an already proven design (i.e., Saturn V, S-IC stage). The circularization stage (i.e., kickstage) utilizes STS OMS engines and was sized for the Mars class of payload. Common elements between the lunar and Mars ETO systems are then the core, boosters, and kickstage. Different combinations of boosters and shroud sizes (since lunar and Mars payload volumes differ significantly) are then used to meet both mission goals. Aluminum-lithium materials were used where appropriate in the design of these vehicles. This results in a 10% weight savings in these areas (approximate) and is consistent with the use of advanced, lightweight materials in other elements of the lunar and Mars transportation systems. Finally, all of the above implementation recommendations are consistent with Synthesis Group Recommendation 5 which states that "The Space Exploration Initiative launch requirement is a minimum of 150 metric tons of lift, with designed growth to 250 metric tons. Using Apollo Saturn V F-1s for booster engines, coupled with liquid oxygen-hydrogen upper stage engines (upgraded Saturn J-2s or space transportation main engines), could result in establishing a heavy lift launch capability by 1998."[1] The Synthesis Group also stated that "The need for a new heavy lift launch vehicle has paved the way for an infusion of launch vehicle technology through the joint NASA-Department of Defense National Launch System Program. Many improved production and processing techniques have been identified. These improvements should be incorporated in the contemplated heavy lift launch vehicle."[2]

3.5.2 Vehicle Configuration

3.5.2.1 Lunar Launch Vehicle

The lunar launch vehicle system is shown in Figure 3.5-1 and is comprised of a LOX/LH2 core with two LOX/RP boosters. The primary elements of the lunar launch system have been designed with maximum Mars vehicle commonality. Aluminum-lithium materials were used where appropriate throughout the vehicle.

The core is based on the STS external tank (i.e., 8.4 m diameter) which is stretched 1.52 m (i.e., current National Launch System program reference) and enhanced structurally to support a 250 mt payload with a 15.2 x 30.5 m shroud (i.e., Mars class). The ogival LOX tank of the ET has been replaced with a standard dome/cylindrical section. The propulsion module

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1 *"America at the Threshold,"* Report of the Synthesis Group on America's Space Exploration Initiative, May,1991, page 8.

2 *"America at the Threshold,"* Report of the Synthesis Group on America's Space Exploration Initiative, May,1991, page 31.

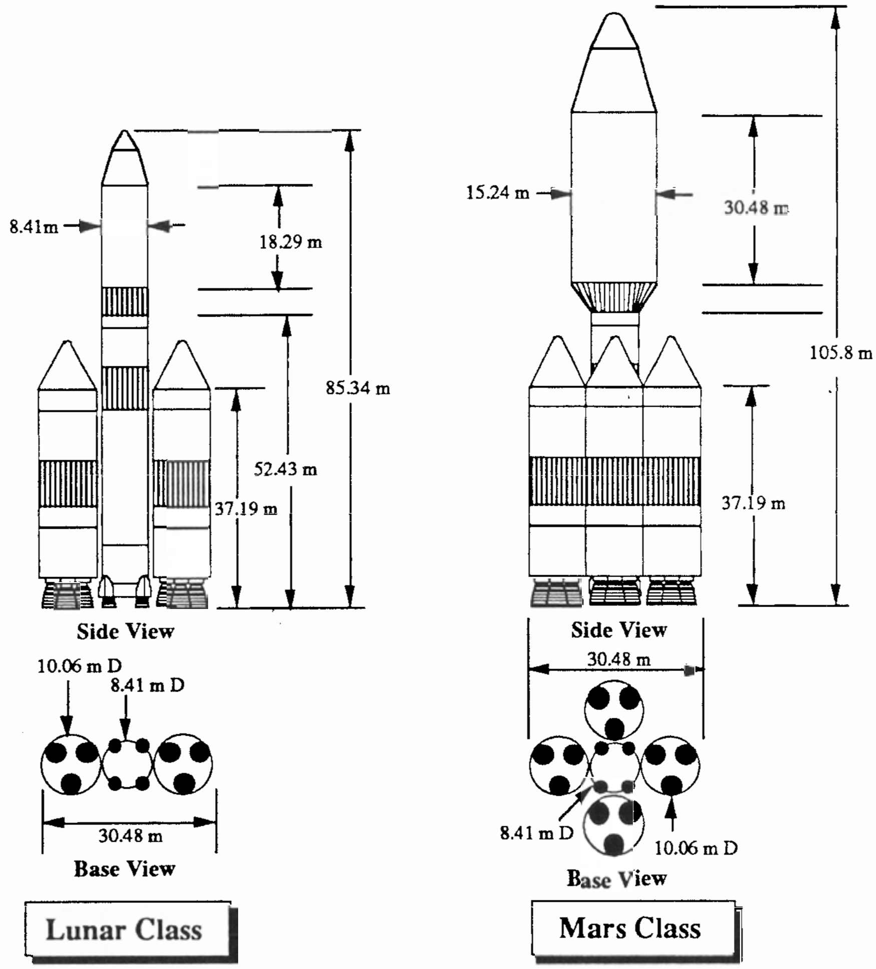


Figure 3.5-1 Vehicle Configurations

is comprised of four STME engines mounted in-line with the propellant tanks (i.e., NLS reference). An 8.4 x 18.3 m (cylindrical section) payload shroud is used to protect the lunar payloads during ascent.

Each 10.1 m diameter booster contains a propulsion module comprised of three F-1A engines. Primary core/booster attachment is accomplished via a thrust beam between the forward adapter of the booster and the core intertank.

3.5.2.2 Mars Launch Vehicle

The Mars launch system is also shown in Figure 3.5-1. It is comprised of the lunar vehicle core (LOX/LH2) with four lunar vehicle boosters (LOX/RP). In addition, a 15.2 x 30.5 m (cylindrical section) shroud and transition section were added to meet Mars payload requirements. As in the lunar system, aluminum-lithium materials were used where appropriate throughout the vehicle.

3.5.3 Vehicle Specifications

The core, boosters, and kickstage are common elements between the lunar and Mars systems. Stretching the STS external tank 1.52 m for the core results in a propellant capacity increase from 725.7 mt to 766.6 mt. The current STME program engine was utilized on the core. Each booster has a propellant capacity of 1633 mt. An uprated F-1 engine, the F-1A (higher thrust, Isp, and throttleable), was utilized for booster propulsion. The kickstage was sized for a propulsion system Isp(vac) of 313 sec (i.e., STS OMS engine) which requires propellant capacity of 9.98 mt (i.e., Mars class payload). The lunar shroud has a *usable cylindrical volume of 7.6 x 18.3 m.* The Mars payload shroud has a *usable cylindrical volume of 14 x 30.5 m.* In addition, neither shroud was designed for structurally supporting the payload during ascent (loads transmitted through payload base).

The tables in Figure 3.5-2 provide detailed specifications for the lunar and Mars vehicles.

3.5.4 Mission Profile

A typical mission profile (for both lunar and Mars systems) is depicted in Figure 3.5-3 and consists of the following: After liftoff, the boosters separate from the core when their usable propellant has been exhausted. When the vehicle attains an altitude of 122 km, the payload shroud is jettisoned. After injection into a 35 x 296 km orbit (lunar) or 31 x 407 km orbit (Mars), the core main engines are cut off (MECO). During the previous sequence, throttling of the engines was performed where required (for a maximum gravity (g) of 4.0 and maximum dynamic pressure (q) of 4310 N/m^2). After MECO, the core separates from the kickstage/payload. The remaining elements coast to the apogee of their orbit, where the kickstage circularizes the payload. The kickstage then deorbits itself as well as any airborne support equipment required (assumed 10%

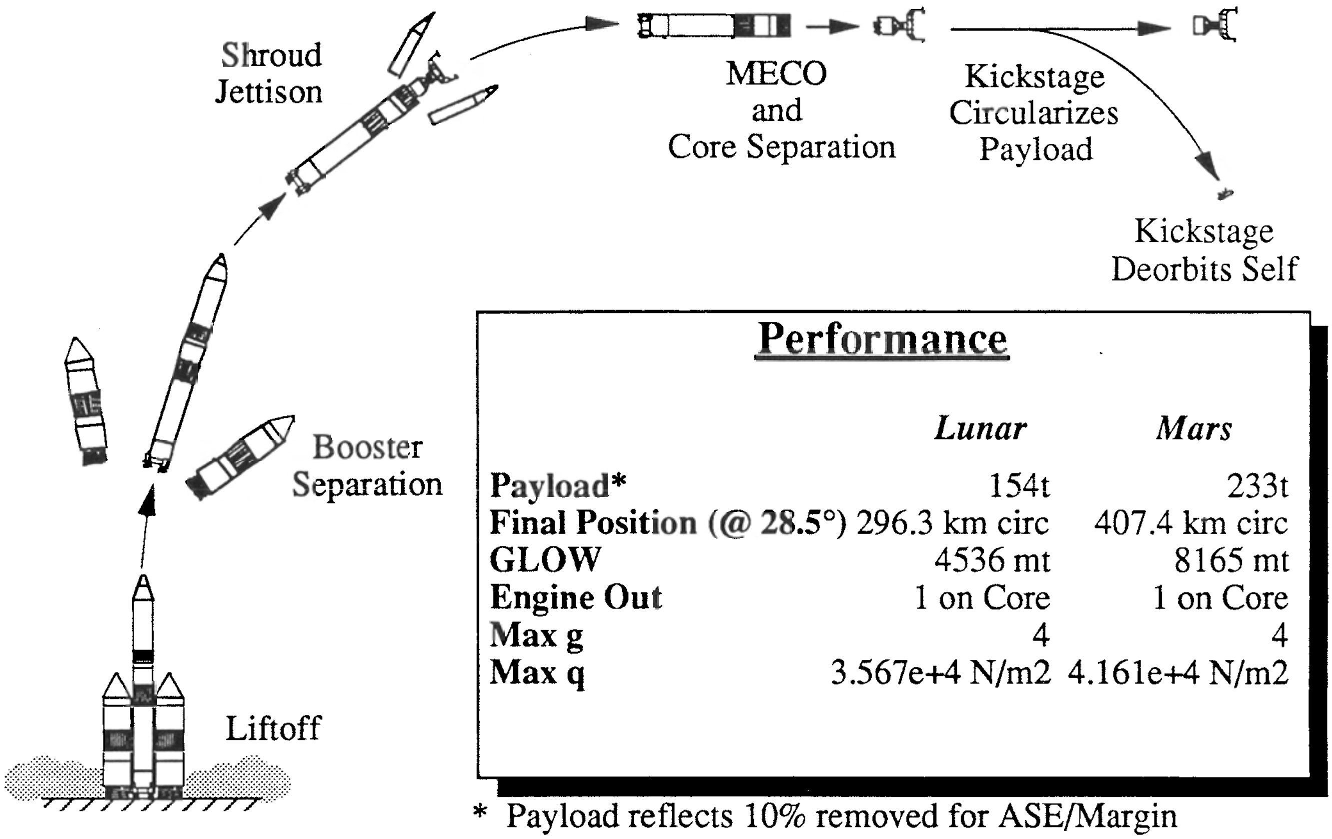
Lunar Class

CORE: (Scarred for Mars)	
Inert Mass:	80.20 t
Propellant Mass:	766.6 t
Propellant Type:	LOX/LH2
Engine Type/#:	STME/4
Vac Thrust (Ea):	264.4 t
Vac ISP:	430.5 s
Engine Exit Dia:	230.8 cm
Length:	52.43 m
Diameter:	8.41 m
Reusability:	None
BOOSTER:	
Number/Type:	2/New
Inert Mass:	114.3 t
Propellant Mass:	1633.0 t
Propellant Type:	LOX/RP
Engine Type/#:	F-1A/3
Vac Thrust (Ea):	916.3 t
Vac ISP:	304.2 s
Engine Exit Dia:	363.2 cm
Length:	37.19 m
Diameter:	10.06 m
Reusability:	None
KICKSTAGE:	
Inert Mass:	2.5 t
Propellant Mass:	6.65 t
Propellant Type:	NTO/MMH
Engine Type/#:	STS OMS/2
Vac Thrust (Ea):	2.7 t
Vac ISP:	313 s
Engine Exit Dia:	54.61 cm
Structure:	Al-Li
Shroud - Usable Volume:	7.62 x 18.29 m
Mass:	8.95 t

Mars Class

CORE:	
Inert Mass:	80.20 t
Propellant Mass:	766.6 t
Propellant Type:	LOX/LH2
Engine Type/#:	STME/4
Vac Thrust (Ea):	264.4 t
Vac ISP:	430.5 s
Engine Exit Dia:	230.8 cm
Length:	52.43 m
Diameter:	8.41 m
Reusability:	None
BOOSTER:	
Number/Type:	4/New
Inert Mass:	114.3 t
Propellant Mass:	1633.0 t
Propellant Type:	LOX/RP
Engine Type/#:	F-1A/3
Vac Thrust (Ea):	916.3 t
Vac ISP:	304.2 s
Engine Exit Dia:	363.2 cm
Length:	37.19 m
Diameter:	10.06 m
Reusability:	None
KICKSTAGE:	
Inert Mass:	2.5 t
Propellant Mass:	9.98 t
Propellant Type:	NTO/MMH
Engine Type/#:	STS OMS/2
Vac Thrust (Ea):	2.7 t
Vac ISP:	313 s
Engine Exit Dia:	54.61 cm
Structure:	Al-Li
Shroud - Usable Volume:	14.02 x 30.48 m
Mass:	46.96 t

Figure 3.5-2 Vehicle Specifications



Performance

	Lunar	*Mars*
Payload*	154t	233t
Final Position (@ 28.5°)	296.3 km circ	407.4 km circ
GLOW	4536 mt	8165 mt
Engine Out	1 on Core	1 on Core
Max g	4	4
Max q	3.567e+4 N/m2	4.161e+4 N/m2

* Payload reflects 10% removed for ASE/Margin

Figure 3.5-3 Typical Mission Profile

of payload in this study).

The net payload delivered to orbit is then 154 mt (340 klb) for the lunar missions and 233 mt (513 klb) for the Mars missions. Max g and q requirements were met in both cases. In addition, this assumes an engine-out on the core at liftoff and no booster engine-out.

3.5.5 Ground Processing

Ground facilities at Kennedy Space Center (KSC) will be impacted in order to support lunar and Mars operations; see Figure 3.5-4. The lunar system can utilize many existing or planned (i.e., NLS) facilities, but the Mars (because of timeframe and size) will require several additions.

To support the lunar missions, the following facilities are needed: A new booster processing facility would be required since the NLS core facility cannot support a LOX/RP booster. In addition, this new booster processing facility could be used for core processing. Lunar payloads will require a new processing facility, but the NLS encapsulation facility could support these requirements. Also, the kickstage could be supported in the NLS Cargo Transfer Vehicle/Kickstage (CTV/KS) processing facility. A new Advanced Solid Rocket Motor (ASRM) stacking facility would offload the Vertical Assembly Building (VAB), and VAB high bay 4 could be modified to accommodate this vehicle. A new Mobile Launch Transporter (MLT) would then transport the assembled vehicle to the launch pad. The existing STS launch complex (i.e., 39 A/B) might accommodate a lunar class vehicle, but more analysis would be required. Finally, for both lunar and Mars systems, a new operations support facility would be necessary.

To support the Mars missions, the following facilities are needed: The same core/booster processing facility used for lunar systems would be used for the Mars system. The lunar payload processing facility may accommodate Mars payloads (with

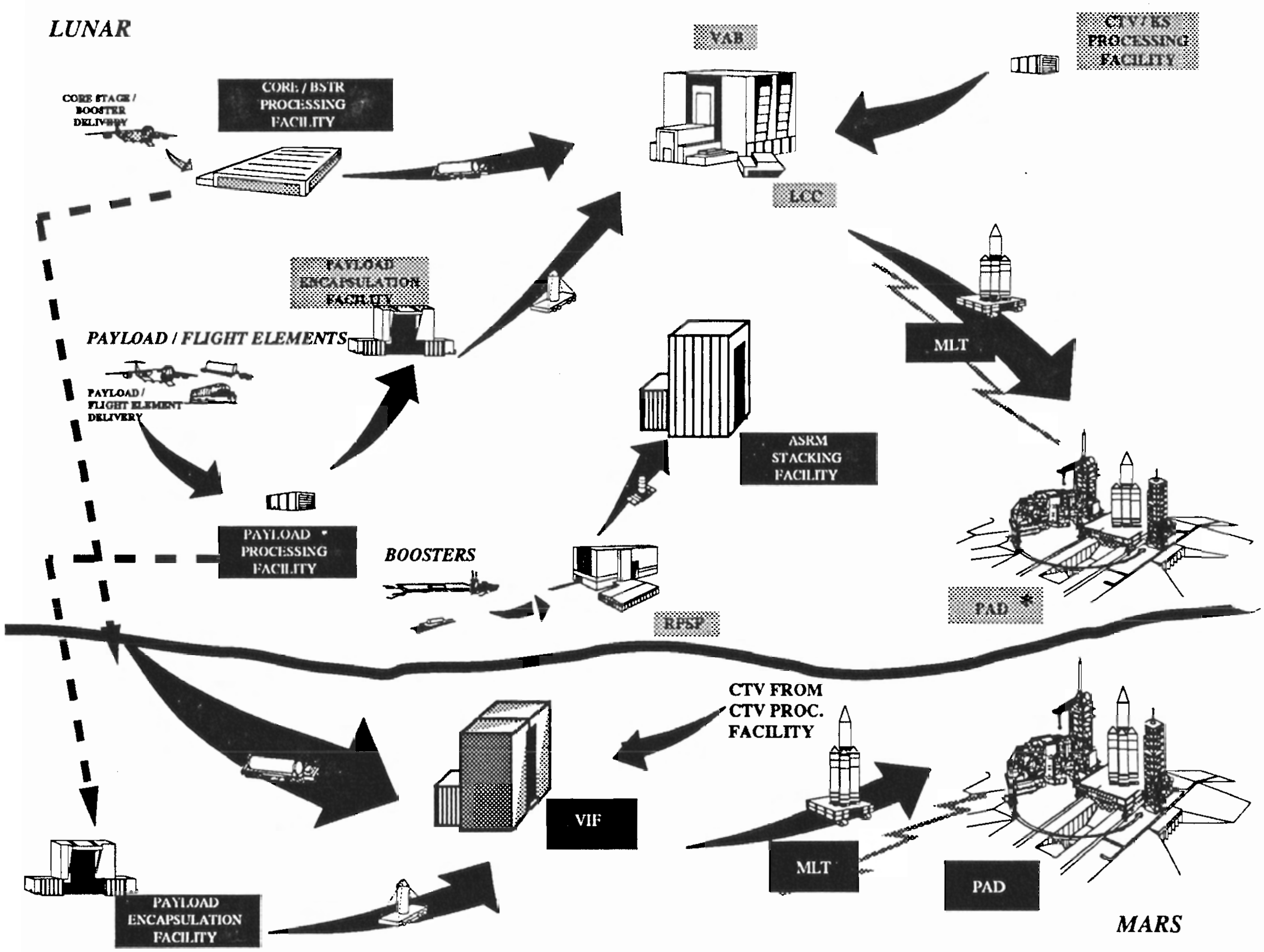


Figure 3.5-4 Ground Processing

modifications), but more analysis would be required. However, a new payload encapsulation facility would be required (size constraint). The NLS CTV/KS processing facility can also support this option. Because of the launch vehicle's size, a new Vertical Integration Facility (VIF) would be required for assembly. A new Mobile Launch Transporter (MLT) would then transport the assembled vehicle to the launch pad. A new launch complex would also be required.

3.5.6 *Moon to Stay and Mars Exploration* Launch Schedule

Lunar mission requirements between 2004 and 2009 utilizetwenty-two 150 mt ETO launches to support the *cargo* flights; one launch to deliver the MTV crew hab into lunar orbit (as part of the Mars Dress Rehearsal); and twenty-eight launches for the *piloted* missions. Multiple launches during one year will be made at 30 day intervals; see Figure 3.5-5.

Mars mission requirements between 2012 and 2016 utilize seven 250 mt ETO launches to support the *cargo* flights; eight 250 mt ETO launches are required for the *piloted* flights. Multiple launches during one year will be made at 90 day intervals; see Figure 3.5-5.

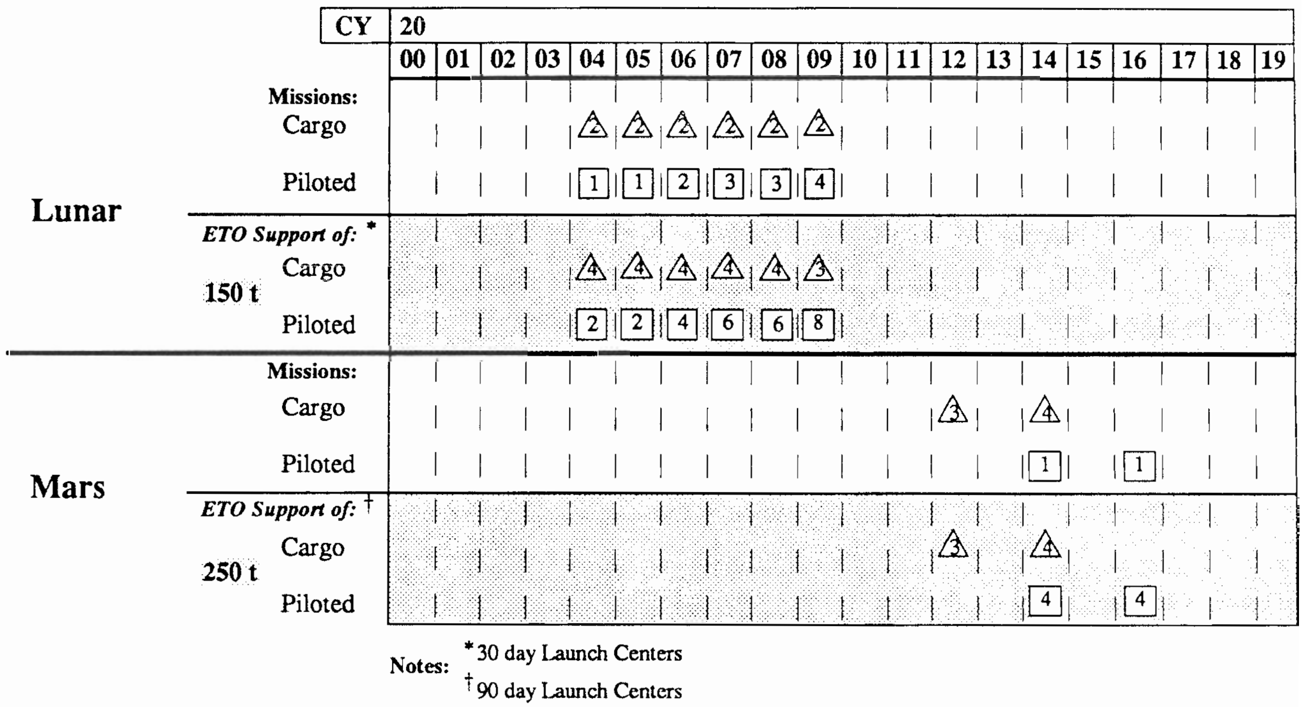


Figure 3.5-5 *Moon to Stay and Mars Exploration* Launch Schedule

3.6 TELECOMMUNICATIONS, INFORMATION SYSTEMS, AND NAVIGATION

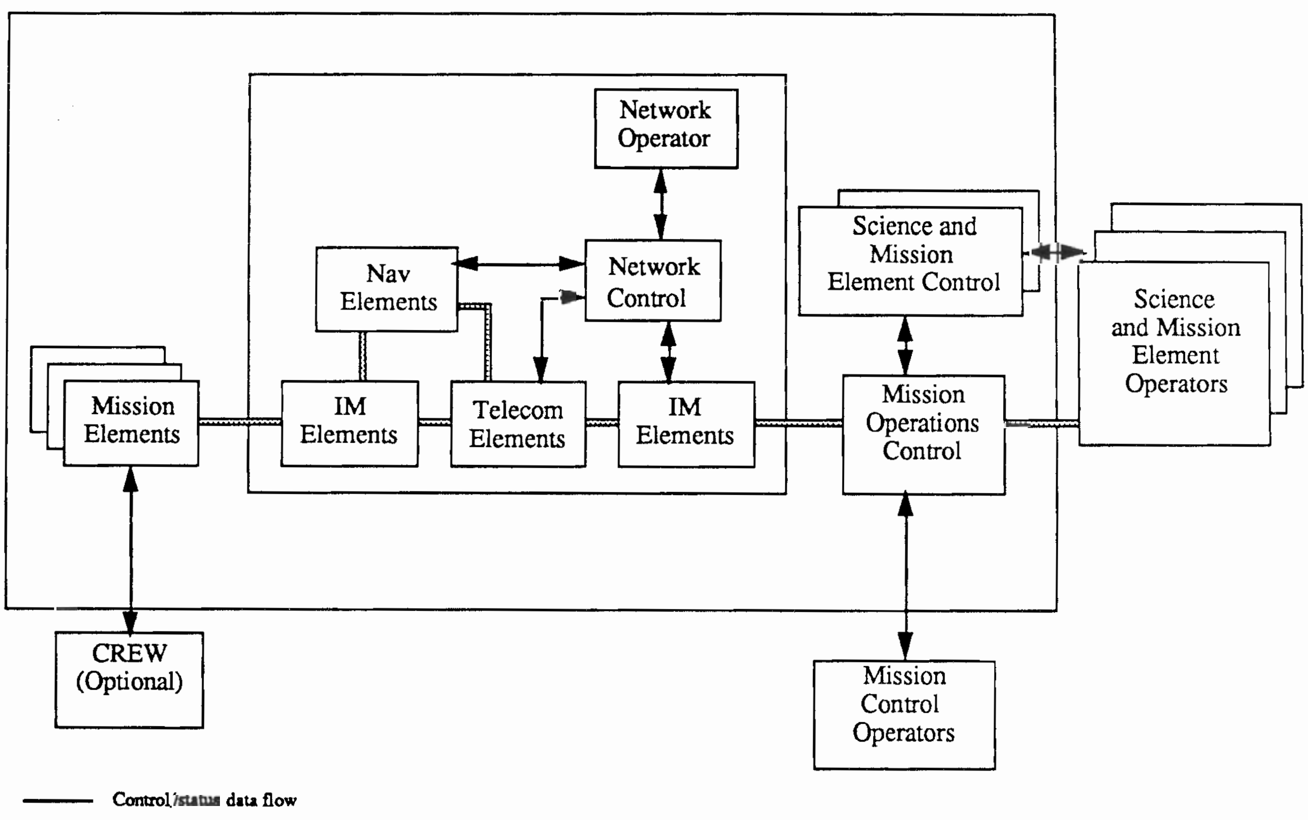
(Editor's note: The telecommunications, information systems, and navigation systems for the ***Moon to Stay*** *and* ***Mars Exploration*** *architecture are identical to those presented in Architecture 1. Consequently, Section 3.6 of the present document is the same as that presented in* "Analysis of the Synthesis Group's **Mars Exploration** Architecture." *The writeup is reproduced here (with only editorial changes) for the convenience of the reader.)*

3.6.1 Overview

The telecommunications, information systems, and navigation infrastructure comprise an integrated set of capabilities that facilitate mission operations and data flow among elements throughout the SEI program. These systems are intended to provide transparent service to the distributed science and mission elements. The end-to-end architecture includes all telecommunications, information systems, and navigation systems within the mission elements, mission operations control systems, as well as the support infrastructure; see Figure 3.6-1. The support infrastructure consists of the deep space network (DSN), the advanced tracking and data relay satellite system (ATDRSS), the global positioning system (GPS) and Mars relay satellites (MRS). The three functional areas are: communications, information systems, and navigation. Communications functions include exchange of science, engineering, health and safety, video, voice, and commands. Information system (IS) functions include control of the communications systems and other supporting infrastructure, controlling mission elements, and analyzing and compiling of data. Navigation functions include determination of vehicle position and orientation with respect to the Earth, Moon, Mars, Sun, and/or another vehicle. These three functions will evolve as the program matures from support of the precursor missions, through lunar initial operational capability, to following mission phases including Mars operational capability. These functions must support all missions phases.

Current manned-mission operations involving telecommunications, navigation, and information system functions are

Figure 3.6-1 End-to-End telecommunications, information systems, and navigation Architecture



highly operator-intensive. The complexity of lunar and Mars local mission operations, if forced to operate using current attended monitor and control techniques, will be nearly intractable, risky, and probably unaffordable. In-situ decision making must be provided and links provided among in-situ data systems to distribute information rapidly among elements and allow nearly autonomous operations.

3.6.2 Implementation

Communications

The mission and science elements of the SEI will have compatible communications equipment to ensure that each element can interface with the others. The Synthesis Group Report specifies using the DSN for SEI earth support. The report does not specify any lunar/Mars polar or lunar farside activities; therefore, it is concluded that no lunar relay satellites or martian polar relay satellites are necessary. Figure 3.6-2 provides an overview of the communications infrastructure.

Communications service between the Earth surface and geosynchronous orbit will be provided by the ATDRSS. Current plans call for the ATDRSS to consist of four operational relay satellites and two independent ground terminals. The ATDRSS will be a shared resource with many programs using its capabilities.

An upgraded DSN will support lunar and Mars missions beyond Earth orbit. For support of the precursor missions, one 34 m antenna is required to be added at each DSN complex. For the lunar manned missions, two 34 m and two 4 m antennae are required to be added at each of the three DSN complexes. For the Mars manned missions, four 34 m antennae are required to be added to each complex.

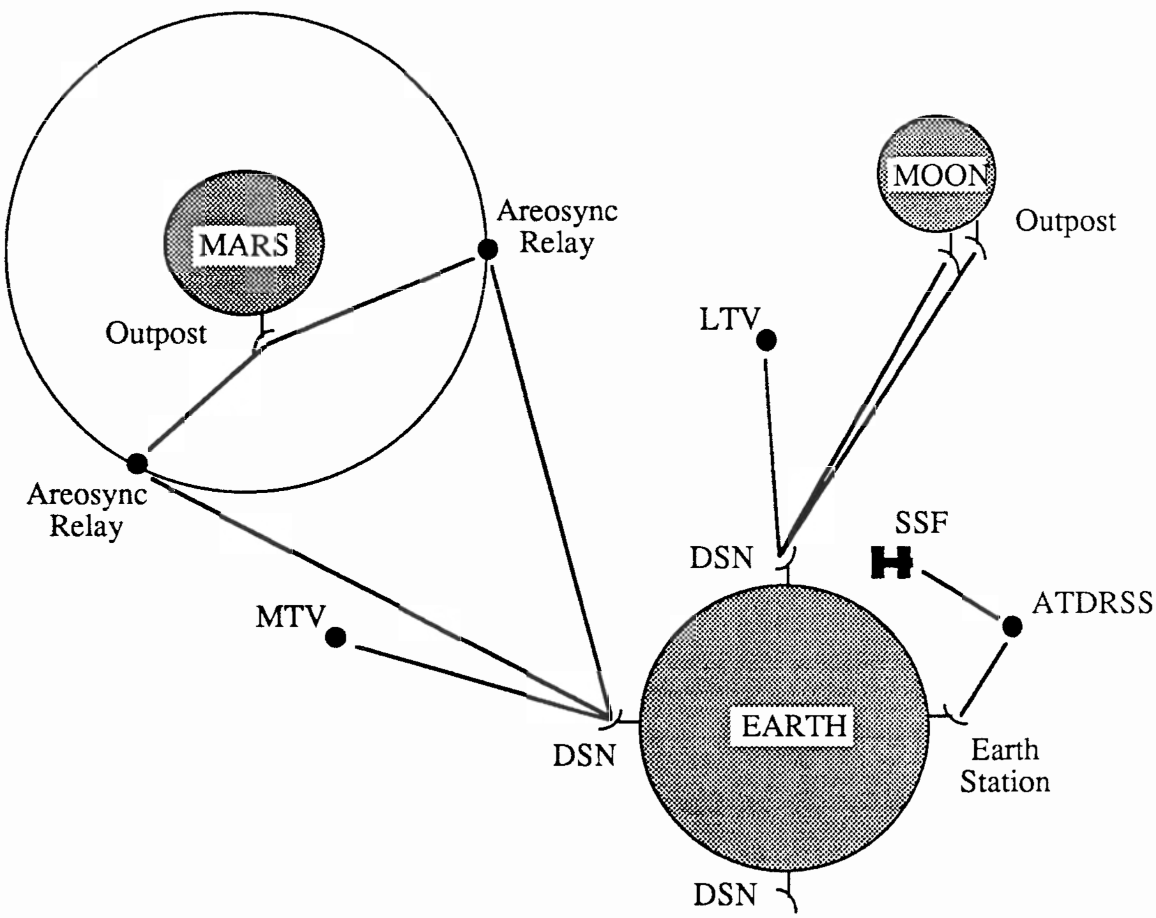


Figure 3.6-2. Communications Infrastructure

The communications equipment at both outposts will support communications to the Earth and to the surface elements within RF line-of-sight of the outpost communications center. Because no lunar relay satellites are employed, only lunar nearside operations will be supported.

Relay satellites will be needed in Mars orbit to achieve Mars/Earth connectivity of greater than 50% for the human missions. The first relay capability may be incorporated in the site reconnaissance orbiters launched in 1998, as suggested by the Synthesis Group Report, or it may be elected to launch separate Mars Communications Orbiters to provide the relay support needed for the precursor rover missions. Due to lifetime constraints, this relay communications capability will only support the precursor missions. The Mars relay network for the manned phases will consist of two satellites in areostationary orbits. The relay satellites will provide dual coverage for activities in the vicinity (≤100 km) of the outpost. Nominally, all intra-Mars communications farther than RF line-of-sight from the outpost are accomplished via relay through one of these satellites. These relay satellites will enable greater than 90% connectivity from Mars habitat and mission in-situ vehicles to Earth and to other in-situ mission terminals.

Information Systems

The information system is represented in Figure 3.6-3 in terms of nodes, interfaces, and data flows. Each of the nodes illustrated will contain a portion of the distributed information system. Some nodes, such as those on the vehicles, at the outposts, and those at ground control, will provide centralized support to their area with powerful computer systems to provide the IS services, while other nodes, such as the relay satellites, will contain embedded IS functions appropriate for their own needs. The centralized ground IS communications support systems will provide telemetry data processing necessary for transmission and delivery.

Earth-based systems will plan and schedule the tracking and data acquisition networks. Space-based control systems

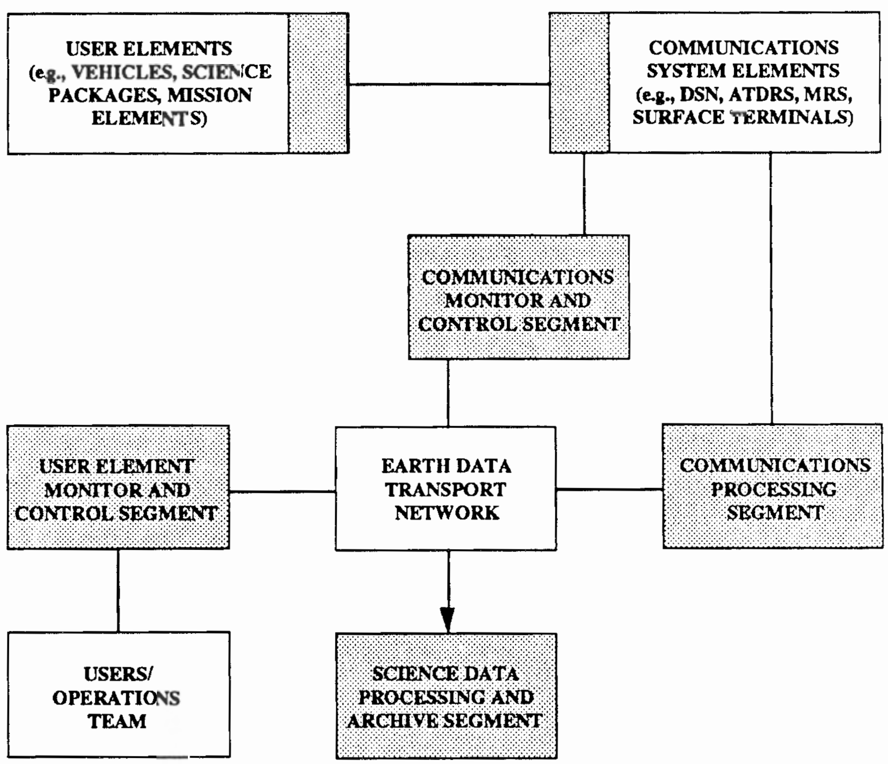


Figure 3.6-3. Representative Information System Overview (Shaded areas indicate information system segments. Additional segments are also possible.)

will monitor and control local nodes based on the network schedule requirements. A centralized control system will be located on the Earth to monitor the network and provide backup control. This centralized information systems control may be co-located and closely integrated with the telecommunications network control.

Initially, the information systems operations will be operator attended. An unattended operations testbed will be deployed on the Moon and will be used for automated operations demonstrations. As unattended operations techniques mature, they will be incorporated into the infrastructure to support Mars operations. The systems will progress from Earth-based operations to largely autonomous. Pre-mission planning support will be provided to the program in order to determine the availability of appropriate communications and information services.

Mars mission elements will require more capable on board systems than the lunar mission elements due to the long communication time delays to Mars. Depending on element requirements, the Mars elements could require very sophisticated management, control, storage, and navigation capabilities that may not be required for the lunar elements.

<u>*Navigation*</u>

There are three segments of the navigation system: (1) an Earth-based segment, (2) an onboard vehicle segment, and (3) a Mars-based segment. The Earth-based segment constitutes those existing space tracking infrastructures which possess capabilities to support one or more mission phases. The vehicle segment will need to be customized for each vehicle type. All flight vehicles will, however, possess an onboard, autonomous attitude determination and control system and piloted vehicles will possess the requisite level of redundancy and failure tolerance to ensure crew safety. The Mars segment is required for time-critical flight operations near Mars as the comparatively long communication time delay between Earth and Mars precludes dependence upon the Earth-based segment. The Mars-based segment supports independent crew operation for critical phases of operation near the planet by enabling precise, real-time position determination onboard the flight vehicle.

The Apollo program demonstrated that lunar missions require only the Earth-based and onboard vehicle segments. However, the Mars dress rehearsal at Lunar NOC-4 should simulate, to the extent possible, the operations of the Mars segment.

The navigation suite for flight and surface vehicles and the Mars-based segment will be defined from the candidates shown in Figure 3.6-4. The flight vehicles process the onboard navigation data with a space-qualified navigation computer and timing information is provided with a precise onboard clock.

3.6.3 Operations

For the Mars precursor missions, the Mars-based segment will not have been constructed and the vehicles must rely upon onboard navigation and the DSN radiometric tracking capability. Precursor missions will emplace transponder or repeater beacons to aid low planetary orbit determination, surface position determination, and descent guidance for the later manned mission phases.

For piloted vehicles, the segments and individual components within the segments will be operated with primary and monitor/backup configurations. For mission critical flight phases, the components will be additionally configured such that the navigation system will continue operation (possibly with degraded accuracy) after the first failure and enter a safe and repairable state after the second failure. For piloted Mars missions, the onboard navigation suite contains navigation aiding devices which make use of the Mars-based segment to perform the primary navigation for time- and safety-critical operations such as Mars descent and landing.

The ATDRSS and DSN will support all pre-launch service planning and testing. Pre-mission support will include determination of interface requirements, applicable network procedures, and development of test plans. Prior to launch, trajectory determination and analysis will be performed for all phases and contingencies of the mission. Data obtained from precursor missions will be used to develop more accurate models and algorithms for spacecraft orbit determination, and surface position for both the manned lunar and Mars missions.

Communications to ground and information systems functions for vehicles during launch, in LEO, and landing will be provided by the ATDRSS system. The ATDRSS and the GPS will support navigation of flight elements. The Earth-based navigation infrastructure will provide the primary navigation for LEO operations. Navigation operations for staging support will include tracking and orbit determination for all elements.

All spacecraft in transit to or from planetary orbit will maintain a direct link to the Earth when line-of-sight to the Earth is achievable. For the information systems, lunar transportation vehicle operations will have Earth-based control systems with on-board systems as backup. The Earth-based navigation infrastructure will provide the primary navigation for trans-lunar injection, trans-Mars injection, and inter-planetary cruise. The Mars transportation vehicle operations will need to be controlled on board due to the long time delays (up to 40 min.) to Earth.

All vehicles in lunar orbit will have a link to the Earth when within line-of-sight on the nearside of the Moon. All vehicles in Mars orbit will have links to the outpost or to the Earth support network via the relay satellites when line-of-sight permits. The link to the surface will only be possible after the surface communications system is emplaced. A communications link between co-orbiting vehicles will be established prior to rendezvous and docking.

For links between elements on the surface, a local communications system is employed which supports a TBD range (outpost zone). Fixed users and mobile users within the outpost zone will communicate with Earth through the outpost communication systems. Nearside lunar users beyond the outpost zone will communicate directly to the Earth support network. Mars elements beyond the outpost but within range of a relay satellite (relay zone) will use the satellite to maintain communications to the Earth and/or the outpost. Mars elements beyond the relay zone will communicate directly to the Earth.

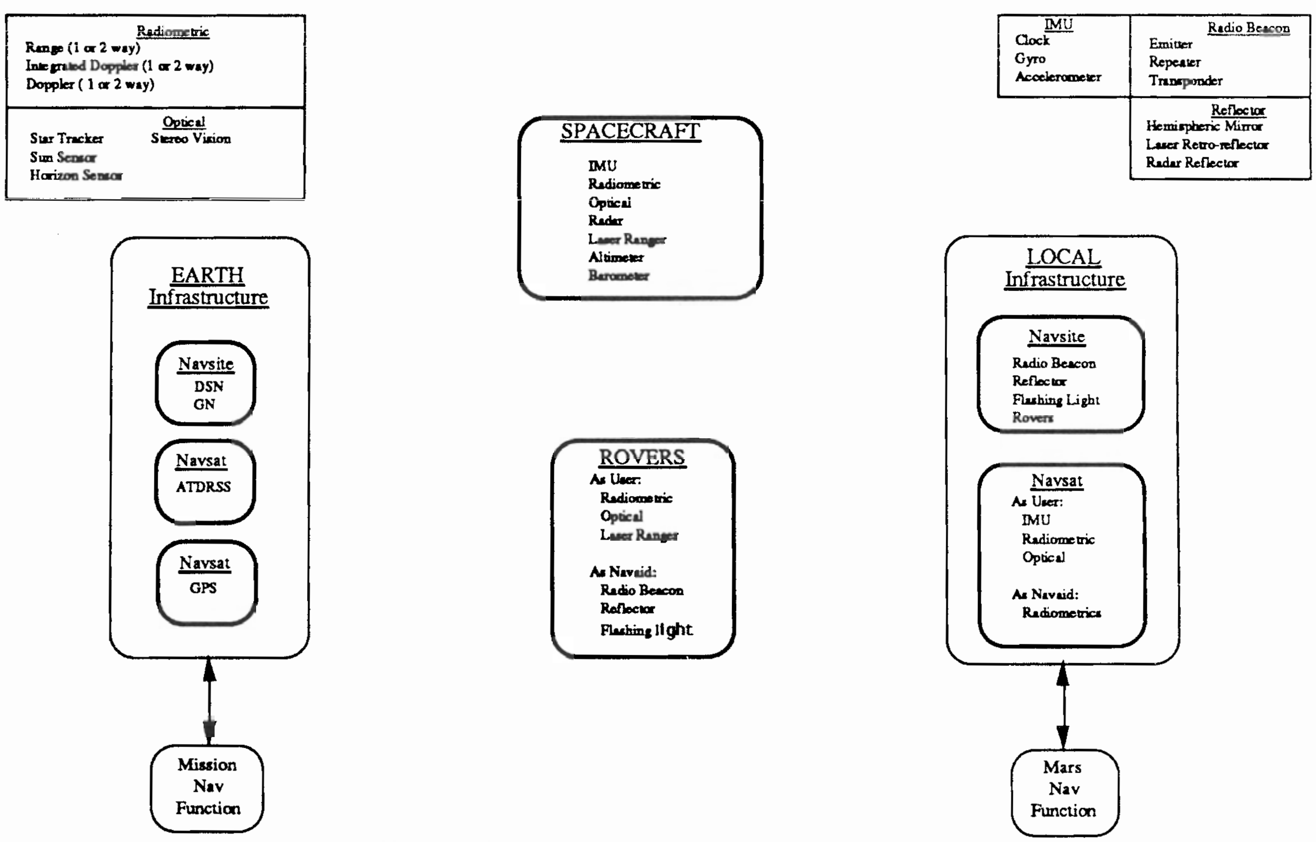


Figure 3.6-4. Navigation Infrastructure Concepts

4.0 ISSUES/ALTERNATIVES/STUDIES

The Synthesis Group Report specifies particular strategies, and to some extent specific implementations, for satisfying the goals and objectives of the ***Moon to Stay and Mars Exploration*** architecture. The members of the NASA analysis team were requested by ExPO to suggest alternative approaches to those Synthesis Group strategies and implementations that might enhance the soundness of this architecture. In order to reduce duplication and thereby improve clarity, only those issues that are *specific* to the ***Moon to Stay and Mars Exploration*** architecture have been accepted. In other words, generic concerns previously expressed in the Architecture 1 document (**"ANALYSIS OF THE SYNTHESIS GROUP'S *MARS EXPLORATION* ARCHITECTURE"**) are not reproduced in the present section. Only those issues above and beyond what has previously been printed and which are *specific* to the ***Moon to Stay and Mars Exploration*** architecture have been accepted. What follows in the remainder of Section 4 is a list of those issues. The issues are presented as they were submitted and without rigorous critique from ExPO.

It is the responsibility of ExPO to evaluate the merits of each of these issues, to integrate similar issues in different functional areas, to prioritize the set of issues, and to recommend requisite studies and trades. The results of this ExPO integration activity will be published in the document *Architecture Analysis Summary and Recommendations*, which will be completed soon after the analysis of the four Synthesis Group architectures has been concluded.

The presence of an issue, alternative, or concern in the below materials does not reflect an acceptance by ExPO, either explicitly or implicitly, of the validity or significance of the issue. Nor does publication in this section imply ExPO concurrence or support for the funding of studies related to that issue. Synthesized recommendations will be presented in the *Architecture Analysis Summary and Recommendations* document.

The format for each of the below issues is comprised of an issue number, a concise statement of the issue, alternative approaches, and recommended focused studies. The **issue number** is ordered, unless otherwise specified, starting from the highest priority and progressing to the lowest according to the contributor's perspective. No attempt has been made to prioritize issues amongst contributors in each functional area. The **issue** discussion provides a succinct description of the specific strategy or implementation under scrutiny and the particular issue at hand. Issues pertain to the strategy and implementation of the Synthesis Group architecture reference description, not to the theme. The **alternative approaches** contain options to the Synthesis Group architecture. Each option states how the alternative strategy or implementation deviates from the Synthesis Group Report. In addition, any implications that may occur to the mission or other systems are identified. Finally, the **recommended focused studies** are discussed as a way to solve an issue or decide on a particular approach. Note that not all issues require future studies. To understand the recommendation, a short description of the focus or purpose of the study and the expected set of analyses are also included.

The identified issues fall into the following functional areas: mission; technology/advanced development; human support; precursor/robotic missions; science; planetary surface systems; space transportation systems; nodes; Earth-to-orbit transportation systems; telecommunications, information systems, and navigation; and operations.

4.1 MISSION

No additional issues/alternatives/studies were submitted in this discipline.

4.2 TECHNOLOGY/ADVANCED DEVELOPMENT

No additional issues/alternatives/studies were submitted in this discipline.

4.3 HUMAN SUPPORT

No additional issues/alternatives/studies were submitted in this discipline.

4.4 PRECURSOR/ROBOTIC MISSIONS

No additional issues/alternatives/studies were submitted in this discipline.

4.5 SCIENCE

No additional issues/alternatives/studies were submitted in this discipline.

4.6 PLANETARY SURFACE SYSTEMS

The following Planetary Surface issues were provided by the Planetary Surface Systems Office at Johnson Space Center.

Issue Number: 1

Issue: Fixed Site Commitment

The approach is to pick a single site and then develop it into a significant outpost for science and local resource use. All lunar facilities are emplaced in the locale of this single site. The site is identified from remote sensing and verified via a remote robotic mission. For many scientific purposes and local resource uses, limitation to a fixed site is individually not too constraining. However, there are conflicts between site needs for science. Furthermore, resources will be limited to those at a site that is chosen before substantial research is done.

Alternative Approaches:
Perform several missions to various sites before committing to full scale development. Each mission can emplace the start of an embryo outpost or campsite. The final architecture could take the form of a central base with distributed satellite camps or facilities.

Recommended Focussed Studies:
Identify site dependent needs for various lunar missions. Trade the various options between lunar development: single site, multiple sites, postponed major site.

Issue Number: 2

Issue: Initial Outpost Emplacement Contingencies

The crew does not depart Earth until the outpost is remotely verified. This indicates that all contingencies must be handled remotely and that the crew mission will not have the capability to handle contingencies. There can be no significant failures in the robotic setup. The crew will not be available to fix them since they won't come until they are fixed.

Alternative Approaches:
Provide a capability for the crew to handle contingencies during the initial emplacement.

Recommended Focussed Studies:
Identify potential failure modes for initial emplacement and identify initial crew mission capability required to counter recoverable failures. If the capability for likely contingencies is too much, then the all-up operational philosophy should be rethought.

Issue Number: 3

Issue: Global Access

The implementation restricts access to the vicinity of a single site. In NOC-1, the pressurized rover extends access to 100 km traverses.

Alternative Approaches:
Provide capability for global access.

Recommended Focussed Studies:
Identify requirements for access to different sites on the lunar surface. Address impact to transportation system and to outpost.

4.7 SPACE TRANSPORTATION SYSTEMS

The following additional Space Transportation issue was provided by the SEI Space Transportation Office at Marshall Space Flight Center.

Issue Number: 1

Issue: Leaving one crewmember in orbit for forty days during lunar NOC-1.

The changes necessary to the crew module for this one mission would either require a special crew module or inflict a severe mass penalty on all other flights. Also, there are concerns relating to leaving a crew-member isolated for that length of time.

Alternative Approaches:

Send all crewmembers to the surface. If this is not possible consider leaving two crewmembers in orbit.

Recommended Focused Studies:

Crew module mass, volume, and subsystem requirements as a function crew size and mission duration. Psychological effects of leaving one crewmember in orbit for an extended period of time.

4.8 NODES

No additional issues/alternatives/studies were submitted in this discipline.

4.9 EARTH-TO-ORBIT (ETO) TRANSPORTATION SYSTEMS

The following additional ETO transportation systems issue was provided by the SEI Space Transportation Office at Marshall Space Flight Center.

Issue Number: 1

Issue: High Flight Rate for Lunar Missions

Alternative Approaches:

1. For expendable vehicles, removal of the kickstage from both launches of a cargo flight and from the first launch of a piloted flight generates increased performance. The TLI stage and LOI/TEI stage of a cargo flight perform a suborbital burn to circularize the stage(s) in LEO. This would allow the cargo on a piloted flight to increase from 20.8 mt to 32.5 mt, and from 40.8 mt to 53.6 mt on a cargo-only flight. This could either eliminate a cargo flight or allow it to become a single launch mission.

2. Develop a reusable ground or space-based system instead of evolving to one.

3. Accelerate the availability of the Mars-class 250 mt HLLV for use with lunar missions.

Recommended Focused Studies:

Perform a trade to determine the most cost effective approach to the high launch rate and design the vehicles, both launch and space, accordingly. Evolving to reusable or space-based vehicles often result in neither approach being optimal.

Also, consider the impact of having a 250 mt launch vehicle available to conduct lunar missions; such a vehicle would certainly reduce the launch rates per year.

4.10 TELECOMMUNICATIONS, INFORMATION SYSTEMS, AND NAVIGATION

No additional issues/alternatives/studies were submitted in this discipline.

4.11 OPERATIONS

No additional issues/alternatives/studies were submitted in this discipline.

APPENDIX A: MISSION TRAJECTORY DATA

This Appendix provides the detailed descriptions of the Earth-Mars trajectories used in constructing the Mars missions described in this document. There are four tables that present the trajectory parameters and four orbit plots that visually describe the missions. The first two tables list the key mission event dates and associated ΔV, and the mission flight times for each trajectory. Mission ΔV calculations were based upon a 407 km circular orbit at Earth and a 500 km circular orbit at Mars. In the third table, instead of ΔV, the V-infinity magnitude is given so that the mission analyst can calculate the appropriate ΔV for any given orbit size at both Earth and Mars. Finally, the last table summarizes the ΔV budgets for the human exploration flights (both cargo and piloted) for both a 500 km circular orbit and a 250 km by 1 sol elliptical orbit at Mars for comparative purposes.

The trajectories were generated using the MULIMP[1] interplanetary trajectory generation tool, and represent impulsive, 0-day launch window, coplanar burns. That is, the solutions shown assume optimal orbital alignments on the given date, and the numbers do not take into account any kind of margin for gravity losses, mission flexibility (launch windows), system margins, performance reserves, nor minor mid-course trims.

The final two pages of this Appendix present a heliocentric orbit plot of each of the human exploration trajectories. The view is from the north pole of the celestial sphere looking down onto a projection of the trajectory onto the ecliptic plane. The first point of Aries, designated by γ (small sigma), is shown for inertial reference.

Mars Precursors
Mars Trajectories

Mission Type	Launch Date	TMI ΔV	Outbound (days)	MOI ΔV	Mars Stay-Time (days)	TEI ΔV	Return (days)	Return V Inf	Mission Duration (days)	Total ΔV
Orbiter(s)	12/16/98	3637	287	2456	---	---	---	---	287	6093
Rover	06/08/03	3574	203	2095	---	---	---	---	203	5669
Rover	08/20/05	3967	217	2034	---	---	---	---	217	6001

All velocities in meters/second.
• Powered abort maneuver = (xxxx)
ΔV's based upon 407 km circ. orbit at Earth; 500 km circ. orbit at Mars

Mars Exploration
Mars Trajectories

Mission Type	Launch Date	TMI ΔV	Outbound (days)	MOI ΔV	Mars Stay-Time (days)	TEI ΔV	Return (days)	Return V Inf	Mission Duration (days)	Total ΔV
Cargo 1	11/28/11	3672	252	2532	---	---	---	---	252	6204
Cargo 2	01/17/14	3832	224	2794	---	---	---	---	224	6626
Piloted 1	02/01/14	4254	150	5261	90	4369	310	4724	550	13884
Abort Option	02/01/14	4254	150	---	Flyby	(913)•	378	5364	528	5167
Piloted 2	04/11/16	4973	120	4672	648	4217	90	9371	858	13863
Abort Option	04/11/16	4973	120	---	Flyby	(1711)•	269	7415	389	6697

All velocities in meters/second.
• Powered abort maneuver = (xxxx)
ΔV's based upon 407 km circ. orbit at Earth; 500 km circ. orbit at Mars

1 Multi-Impulse Trajectory Optimization Program, SAIC, 1975.

Mars Exploration
Mars Trajectories w/Vinf

Mission Type	Launch Date	Launch V inf	Outbound (days)	Arrive V inf	Mars Stay-Time (days)	Depart V inf	Return (days)	Return V inf	Mission Duration (days)	Total ΔV **
Cargo 1	11/28/11	3322	252	3494	---	---	---	---	252	6204
Cargo 2	01/17/14	3831	224	3917	---	---	---	---	224	6626
Piloted 1	02/01/14	4956	150	7181	90	6089	310	4724	550	13884
Abort Option	02/01/14	4956	150	---	Flyby	(913)*	378	5364	528	5167
Piloted 2	04/11/16	6498	120	6466	648	5896	90	9371	858	13863
Abort Option	04/11/16	6498	120	---	Flyby	(1711)*	269	7415	389	6697

All velocities in meters/second.
* Powered abort maneuver = (xxxx)
** ΔV based upon 407 km circ. orbit at Earth; 500 km circ. orbit at Mars

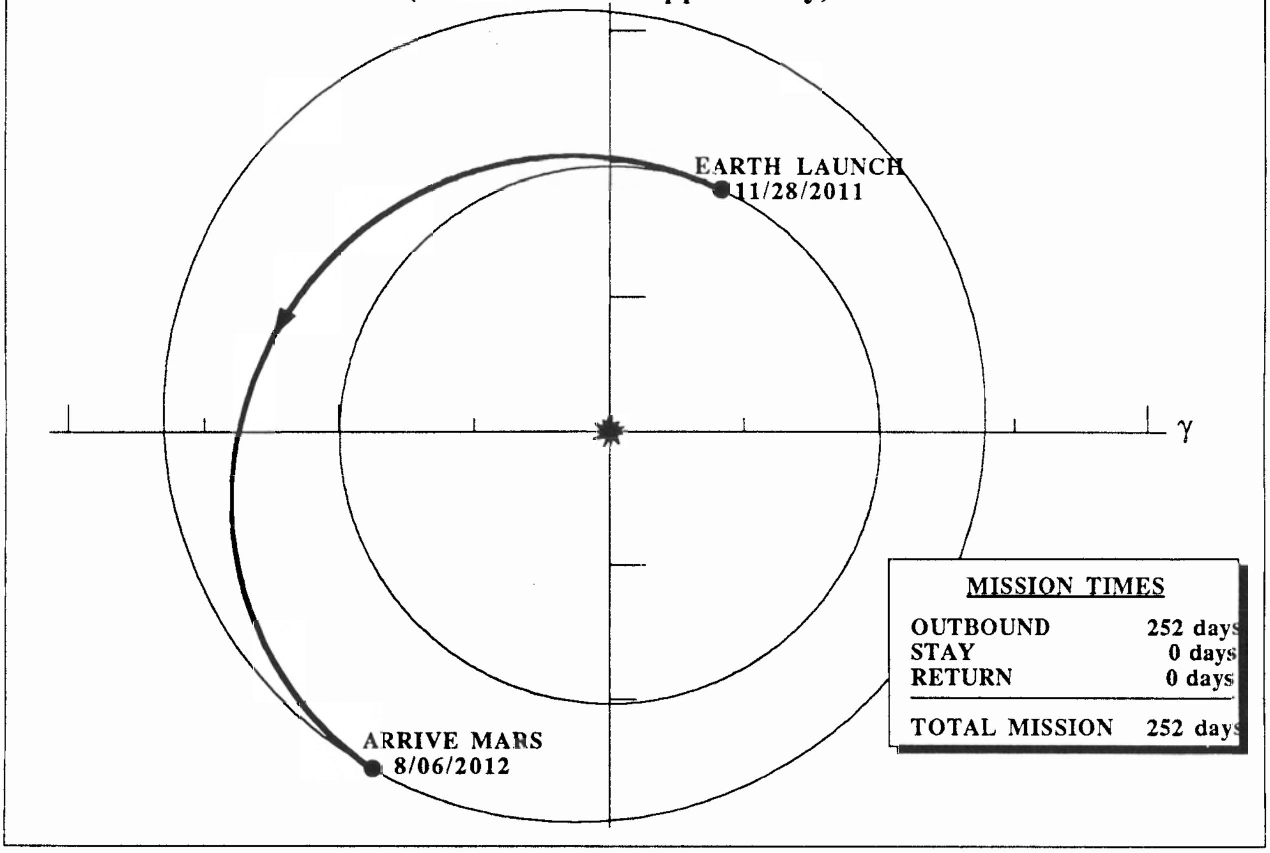
Mars Trajectories
ΔV Budgets

Mars Exploration	Mission Type	Launch Date	TMI ΔV	MOI ΔV	TEI ΔV	Total ΔV
	Cargo 1	2011	3672	2532 (1349)	---	6204 (5021)
	Cargo 2	2014	3832	2794 (1606)	---	6626 (5438)
	Piloted 1	2014	4254	5261 (4038)	4369 (3157)	13884 (11449)
	Piloted 2	2016	4973	4672 (3455)	4217 (3007)	13863 (11435)

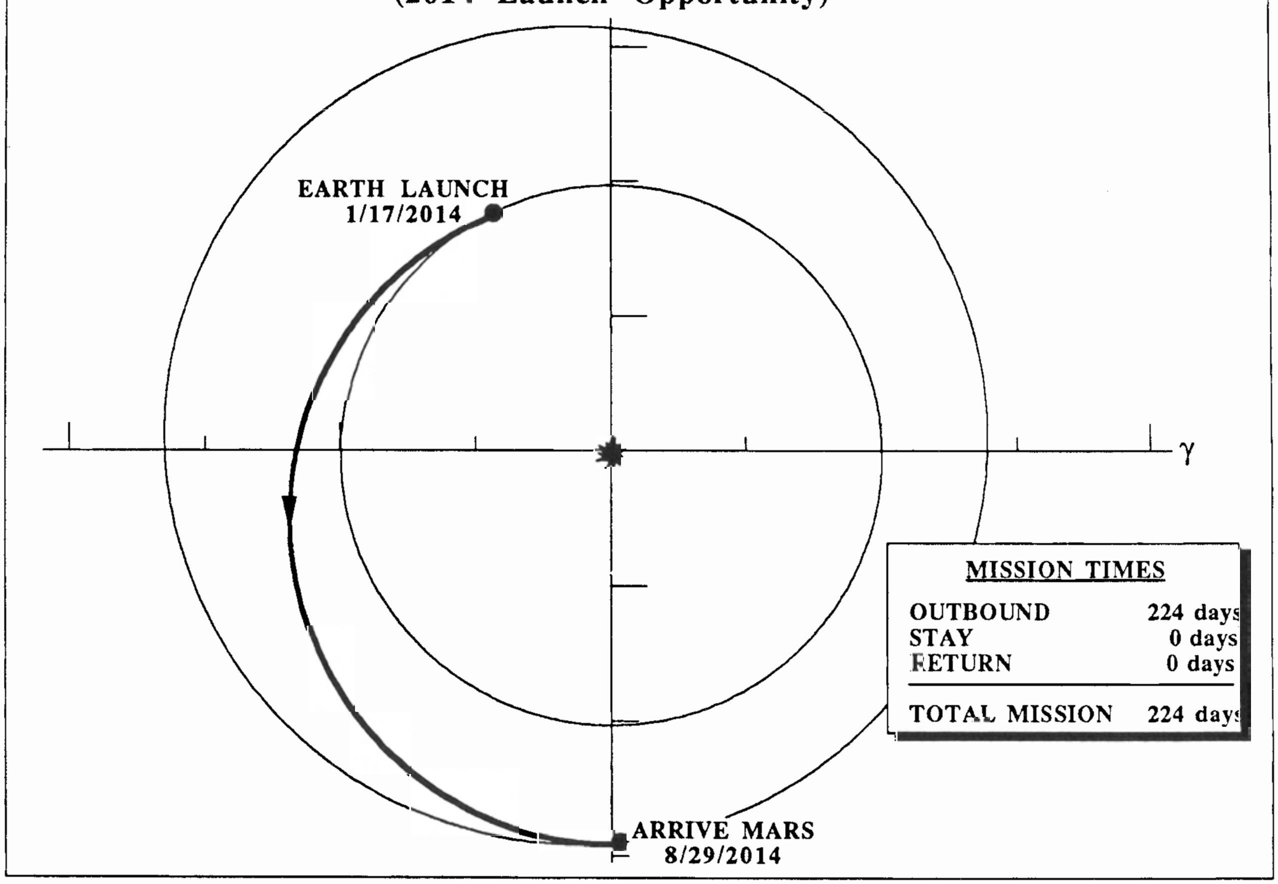
All velocities in meters/second.
ΔV's based upon 407 km circ. orbit at Earth and 500 km circ. orbit at Mars — except (XXXX) = 250 x 1sol orbit at Mars

ONE-WAY CARGO MISSIONS

(2011 Launch Opportunity)

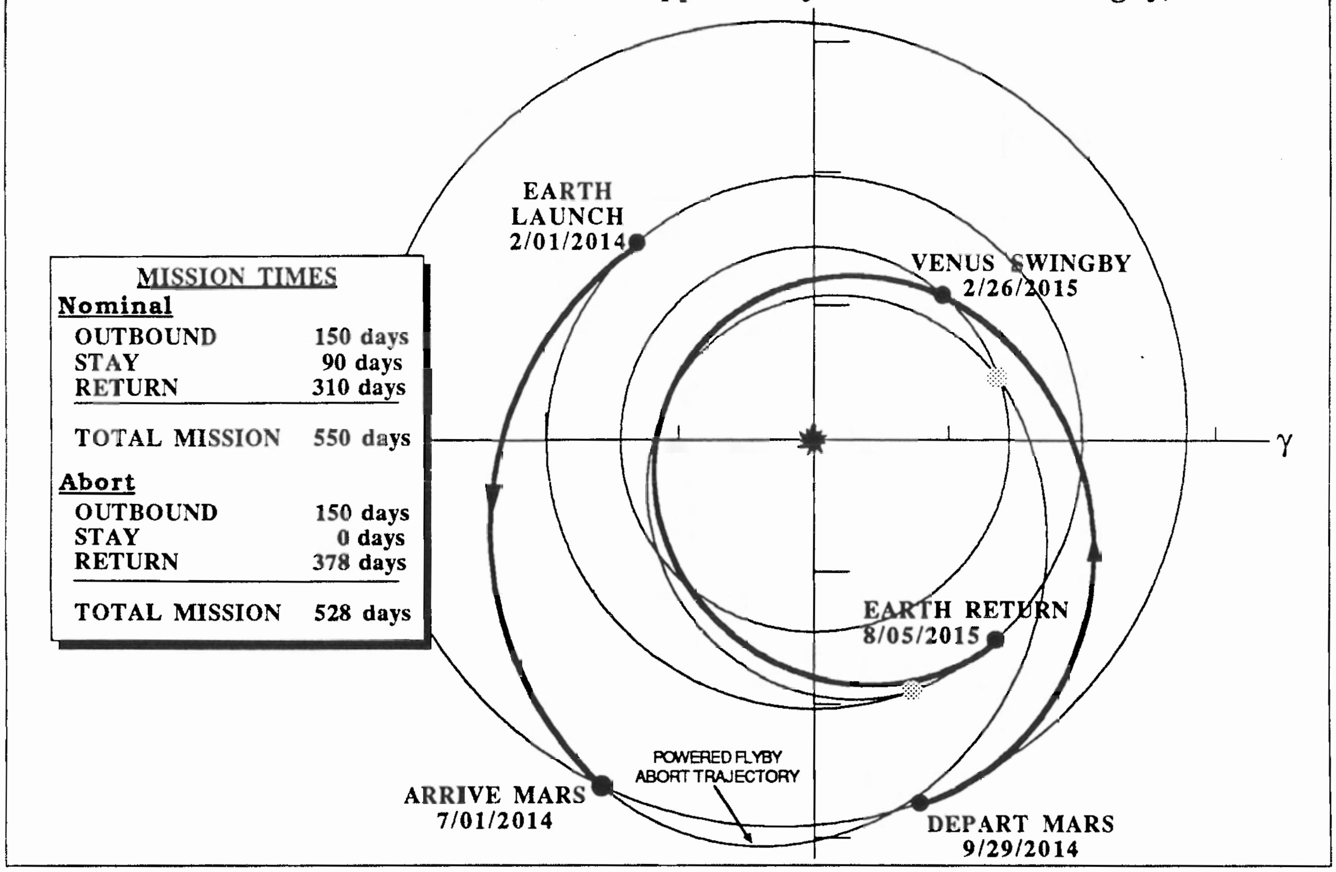


(2014 Launch Opportunity)

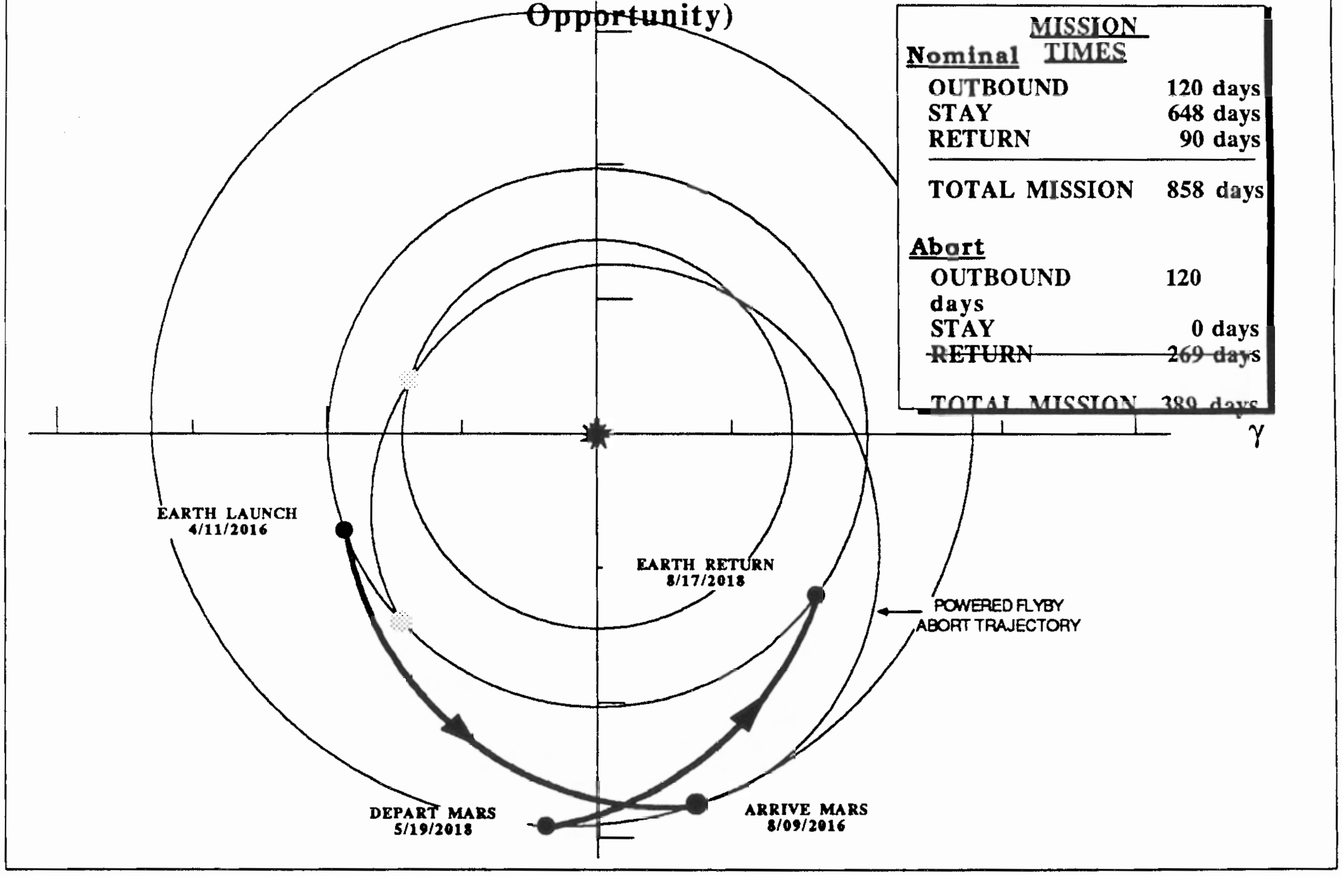


PILOTED MISSIONS

SHORT-DURATION -- (2014 Opportunity with Venus Swingby)



LONG-DURATION -- (2016 Launch Opportunity)



APPENDIX B: STRAWMAN SCIENCE PAYLOAD DATA

The Payloads listed have been chosen from a list of possible science payloads that could be deployed on planetary surfaces as part of the SEI. Most of the physical data comes from the JPL publication JPL D-7955, Rev. A, *FY91 Final SEI Science Payloads: Descriptions and Delivery Options*, which was prepared by the JPL Science Engineering Analysis team. These data represent estimated physical parameters for the proposed instruments, but are only high-level estimates.

B.1 LUNAR SCIENCE PAYLOADS

Payloads	Mass (kg)	Vol. (m^3)	Power (W)	Data
Lunar IOC				
2004 *Pressurized Rover #1	10,000			
Geologic field tools	350	0.6	—	—
Geophysical monitoring station	120	0.1	100	100 kbps
Lander analytical lab instruments	50	0.1		100 kbps
*Small automated telescope	200	2.5	500	100 kbps
Space physics drop-off package	100	0.1	100	150 kbps
Subtotal	**10,820**	**3.4**		
Lunar NOC-1				
2005 *Pressurized Rover #2	10,000			
Geologic field tools	350	0.6	—	—
Geophysical monitoring station	120	0.1	100	100 kbps
Habitat analytical lab instruments	100	2.0	180	100 kbps
Active seismic experiment	300	0.1	10	1Mbps/shot
Lunar Transit Telescope	1,000	2.0		30 Mbps
*16 m telescope, 4 m increment	8,000	40.0	1500	400 kbps
Space physics drop-off package	100	0.1	100	150 kbps
Subtotal	**19,970**	**44.9**		
Lunar NOC-2				
2006 Geologic field tools (2)	700	0.6	—	—
Geophysical monitoring station (2)	240	0.1	100	100 kbps
Geophysical traverse package (2)	240	0.2	100	
Lunar 10-meter drill (2)	30	0.2	430	1.2 kbps
Active seismic experiment	300	0.1	10	1 Mbps/shot
Habitat analytical lab instruments	100	2.0	180	100 kbps
†*Resources Laboratory	*			
†Optical Interferometer (elements #1, #2 and Central Station)	3725	99.0	1,770	20 Mbps
Experimental Biomedical lab I	500	10.0	3,500	
Plant and animal lab I	500	10.0		
Discretionary P.I. science	300	3.0		
Sub-Total	**6,635**	**125.2**		

* No mass figures as yet; bookkeeping purposes only

† Synthesis Group payload

Payloads	Mass (kg)	Vol. (m^3)	Power (W)	Data
Lunar NOC-3				
2007 Geologic field tools	350	0.6	—	—
Geophysical monitoring station	120	0.1	100	100 kbps
Geophysical traverse package	120	0.2	100	
Active seismic experiment	300	0.1	10	1 Mbps/shot
Lunar 10-meter drill	15	0.2	430	1.2 kbps
*16 m telescope, full 16 m augmentation	33,000	175	6,000	2.5 Mbps
Optical interferometer (elements #3 & #4)	430	38	1,770	
Sub-millimeter interferometer (elements #1 & #2)	2,340	200	3,150	500 kbps
Habitat analytical lab instruments	100	2.0	180	100 kbps
Biomedical II	500	10.0	3,500	
Plant and animal lab II	500	10.0		
Discretionary P.I.	300	3.0		
Sub-Total	**38,075**	**439.2**		
Lunar NOC-4				
2009 *Telerobotic rover (cargo flight)	750	16.0	475	1 Mbps
Geologic field tools	350	0.6	—	—
Geophysical monitoring station	120	0.1	100	100 kbps
Geophysical traverse package	120	0.2	100	
Active seismic experiment	300	0.1	10	1 Mbps/shot
Lunar 10-meter drill	15	0.2	430	1.2 kbps
Habitat analytical lab instruments	100	2.0	180	100 kbps
Biomedical I	500	10.0	3,500	
Plant and animal lab I	500	10.0		
Discretionary P.I.	300	3.0		
Sub-Total	**3,055**	**42.2**	**4,795**	
Total	**78,555**	**654.9**		

*Synthesis Group payload

B.2 MARS SCIENCE PAYLOADS

Payloads	Mass (kg)	Vol. (m^3)	Power (W)	Data
Mars IOC				
2014 Cruise Science				
Particles and fields	100	0.2	88	300 kbps
Astronomy instruments	200	2.5		
Solar telescope	200	9.4	500	100 kbps
Lander biomedical instruments	200	1.0		
Lander analytical lab instruments (return trip)	50	2.0		100 kbps
Discretionary P.I. science	300	3.0		
Orbital Science				
Telerobotic rovers (2)	1,500	32.0	950	1 Mbps
Geophysical/meteorological stations (4)	400	0.4	400	100 kbps
Sub-Total	**2,950**	**50.5**	**1,938**	
Mars IOC				
2014 Surface Science				
Mars geology/exobiology equipment	560	0.7	—	—
Geophysical/meteorological monitoring stations (2)	200	0.6	200	
Geophysical traverse package	120	0.2	100	
Habitat analytical lab instruments	150	0.4	180	100 kbps
Active seismic experiment	300	0.1	10	1 Mbps/shot
Mars 10-meter drill	15	0.1	500	0.2 kbps
Mars advanced meteorological facility	1,000	2.0		
Mars balloons	200	14.1	5	15 kbps
Biomedical laboratory I	500	10.0	3,500	
Discretionary P.I. science	300	3.0		
Sub-Total	**3,345**	**31.2**	**4,495**	
Total	**6,295**	**81.7**	**6,433**	

Payloads	Mass (kg)	Vol. (m^3)	Power (W)	Data
Mars NOC				
2016 Cruise Science				
Particles and fields	100	0.2	88	300 kbps
Astronomy instruments	200	2.5		
Solar telescope	200	9.4	500	100 kbps
Lander biomedical instruments	200	1.0		
Lander analytical lab instruments (return trip)	50	2.0		100 kbps
Discretionary P.I. science	300	3.0		
Orbital Science				
Telerobotic rovers (2)	1,500	32.0	425	1 Mbps
Geophysical monitoring stations (4)	400	0.4		100 kbps
Sub-Total	**2,950**	**50.5**	**1,013**	
Mars NOC				
2016 Surface Science				
Mars geology/exobiology equipment	560	0.7	—	—
Geophysical/meteorological stations (4)	400	1.2	100	100 kbps
Geophysical traverse package	120	0.2	100	
Habitat analytical lab instruments	150	0.4	180	
Active seismic experiment	300	0.1	10	1 Mbps
Mars 10-meter drill	15	0.1	500	0.2 kbps
Mars advanced meteorological facility	1,000	2.0		
Mars balloons	200	14.1	5	15 kbps
Biomedical laboratory I	500	10.0	3,500	
Plant and animal laboratory I	500	10.0		
Discretionary P.I. science	300	3.0		
Sub-Total	**4,045**	**41.8**	**4,395**	
Total	**6,995**	**92.3**	**5,408**	

APPENDIX C: MISSION MANIFEST

C.1 LUNAR FLIGHTS

Flight 1 - Cargo Flight 1 (2004,1)

Initial outpost supplies.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation System			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Payload Unloader	11.50		
Unloader Attachments	6.30		
Regolith Ripper/Excavator/Loader	2.90		
Nuclear Power Module (100 kW)	6.50		
Power Management and Distribution	2.50		
Communication Equipment	0.94		
Cryotank Verification Unit	0.50		
Backup Photovoltaic Power Supply	0.29		
Spares	1.00		
	=====	=====	=====
Sub Total	**32.43**	**32.43**	**32.43**
Mission Margin	**8.37**	**8.37**	**8.37**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 2 - Cargo Flight 2 (2004,6)

Initial outpost habitation.

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
LEV-C *(Expended on Lunar Surface)*		8.4	8.4	8.4
LEV-C Fuel			31.1	31.1
LTV-C *(Expended into Lunar Surface)*				20.4
LTV-C Fuel				166.0
		=====	=====	=====
	Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload				
Habitation Module		22.91		
Airlock (2 Person)		5.50		
Solar Flare Warning System		0.23		
Science Equipment:				
Space Physics Drop-off Package		0.10		
Geologic Field Tools		0.35		
Geophysical Monitoring Station		0.12		
Lander Analytical Laboratory Instruments		0.05		
Small Automated Telescope		0.20		
Spares		1.00		
		=====	=====	=====
	Sub Total	**30.46**	**30.46**	**30.46**
	Mission Margin	**10.34**	**10.34**	**10.34**
		=====	=====	=====
	Flight Totals	**49.20**	**80.30**	**266.70**

Flight 3 - Piloted Flight 1 (2004,9)

First return to the Moon. Crew sets up initial outpost & performs science.

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**

LEV-P Payload			
5 crew to the lunar surface for 14 days			
5 EMUs	0.90		
Unpressurized Rover	0.70		
Pressurized Rover	6.50		
Consumables	0.73		
Spares	0.68		
	=====	=====	=====
Sub Total	**9.51**	**9.51**	**9.51**
Mission Margin	**11.29**	**11.29**	**11.29**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 4 - Cargo Flight 3 (2005,1)

Outpost enhancements.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Habitation Module	21.98		
Interconnect Node	4.50		
Oxygen/Volatiles Integrated Demonstration	5.00		
Science Equipment:			
Geologic Field Tools	0.35		
Geophysical Monitoring Station	0.12		
Active Seismic Experiment	0.30		
Habitat Analytical Laboratory Instruments	0.10		
Spares	1.00		
	=====	=====	=====
Sub Total	**33.35**	**33.35**	**33.35**
Mission Margin	**7.45**	**7.45**	**7.45**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 5 - Cargo Flight 4 (2005,6)

Outpost Enhancements.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Pressurized Rover	6.50		
Pressurized Rover Power Cart	6.00		
Pressurized Rover Experiment/Sample Trailer	3.45		
Regenerative Fuel Cells for Backup Power	8.84		
Regeneration Equipment for Surface Vehicles	5.00		
Spares	1.00		
	=====	=====	=====
Sub Total	**30.79**	**30.79**	**30.79**
Mission Margin	**10.01**	**10.01**	**10.01**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 6 - Piloted Flight 2 (2005,9)

First lunar night stay.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
6 crew to lunar orbit			
LEV-P *(Expended into Lunar Surafce)*	11.2	11.2	11.2
LEV-P Fuel		31.1	31.1
LTV-P *(Expended in Earth Orbit)*			31.2
LTV-P Fuel			168.5
	=====	=====	=====
Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload			
5 crew to the lunar surface for 40 days			
5 EMUs	0.90		
Unpressurized Rover	0.70		
Consumables	2.08		
Science Equipment:			
Space Physics Drop-off Package	0.10		
Lunar Transit Telescope	1.00		
4 Meter Telescope	8.00		
Spares	2.00		
	=====	=====	=====
Sub Total	**14.78**	**14.78**	**14.78**
Mission Margin	**6.02**	**6.02**	**6.02**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 7 - Cargo Flight 5 (2006,1)

Delivery of Resource Utilization Equipment.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Resources Laboratory	18.96		
Airlock (2 Person)	5.50		
2 Lunar Excursion Vehicle Servicers	4.14		
Power Management and Distribution	2.50		
Spares	3.00		
	=====	=====	=====
Sub Total	**34.10**	**34.10**	**34.10**
Mission Margin	**6.70**	**6.70**	**6.70**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 8 - Cargo Flight 6 (2006,4)

Oupost Enhancements.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Habitation Module	22.91		
Nuclear Plant (550 kW)	9.50		
Spares	3.00		
	=====	=====	=====
Sub Total	**35.41**	**32.41**	**32.41**
Mission Margin	**5.39**	**8.39**	**8.39**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 9 - Piloted Flight 3 (2006,8)

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
6 crew to lunar orbit			
LEV-P *(Expended into Lunar Surface)*	11.2	11.2	11.2
LEV-P Fuel		31.1	31.1
LTV-P *(Expended in Earth Orbit)*			31.2
LTV-P Fuel			168.5
	=====	=====	=====
Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload			
6 crew to the lunar surface for 90 days			
6 EMUs	1.08		
Unpressurized Rover	0.70		
Consumables and Pallet	5.84		
Science Equipment:			
Geologic Field Tools	0.70		
2 Geophysical Monitoring Stations	0.24		
2 Geophysical Traverse Packages	0.24		
2 10 Meter Drills	0.03		
Active Seismic Experiment	0.30		
Habitat Analytical Laboratory Instruments	0.10		
2 Optical Interferometer Elements & Central Station	3.73		
Spares	1.00		
	=====	=====	=====
Sub Total	**13.96**	**13.96**	**13.96**
Mission Margin	**6.84**	**6.84**	**6.84**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 10 - Piloted Flight 4 (2006,8)

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 90 days				
6 EMUs		1.08		
Oxygen/Volatiles Integrated Pilot Plant		8.00		
Consumables and Pallet		5.84		
Science Equipment:				
Experimental Biomedical Laboratory		0.50		
Plant and Animal Laboratory		0.50		
Discretionary P.I. Science		0.30		
Spares		1.00		
		=====	=====	=====
	Sub Total	**17.22**	**17.22**	**17.22**
	Mission Margin	**3.58**	**3.58**	**3.58**
		=====	=====	=====
	Flight Totals	**32.00**	**63.10**	**262.80**

Flight 11 - Cargo Flight 7 (2007,1)

Oupost Enhancements.

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
LEV-C *(Expended on Lunar Surface)*		8.4	8.4	8.4
LEV-C Fuel			31.1	31.1
LTV-C *(Expended into Lunar Surface)*				20.4
LTV-C Fuel				166.0
		=====	=====	=====
	Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload				
2 Regolith Ripper/Excavator/Loaders		5.80		
Lunar Constructible and Outfitting		22.42		
Spares		5.00		
		=====	=====	=====
	Sub Total	**33.22**	**33.22**	**33.22**
	Mission Margin	**7.58**	**7.58**	**7.58**
		=====	=====	=====
	Flight Totals	**49.20**	**80.30**	**266.70**

Flight 12 - Cargo Flight 8 (2007,3)

Oupost Enhancements.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Lunar Constructible Outfitting	15.00		
Consumables and Pallet	10.00		
Lunar Excursion Vehicle Servicer	2.07		
Science Equipment:			
Geologic Field Tools	0.35		
Geophysical Monitoring Station	0.12		
Geophysical Traverse Package	0.12		
Active Seismic Experiment	0.30		
10 Meter Drill	0.02		
2 Optical Interferometer Elements	0.43		
Habitat Analytical Laboratory Instruments	0.10		
Discretionary P.I. Science	0.30		
Spares	5.00		
	=====	=====	=====
Sub Total	**33.81**	**33.81**	**33.81**
Mission Margin	**6.99**	**6.99**	**6.99**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 13 - Piloted Flight 5 (2007,4)

Permanent occupation of the outpost begins.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
6 crew to lunar orbit			
LEV-P *(Expended into Lunar Surface)*	11.2	11.2	11.2
LEV-P Fuel		31.1	31.1
LTV-P *(Expended in Earth Orbit)*			31.2
LTV-P Fuel			168.5
	=====	=====	=====
Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload			
6 crew to the lunar surface for 365 days			
6 EMUs	1.08		
Consumables and Pallet	12.60		
Spares	1.00		
	=====	=====	=====
Sub Total	**14.68**	**14.68**	**14.68**
Mission Margin	**6.12**	**6.12**	**6.12**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 14 - Piloted Flight 6 (2007,7)

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
6 crew to lunar orbit			
LEV-P *(Expended into Lunar Surface)*	11.2	11.2	11.2
LEV-P Fuel		31.1	31.1
LTV-P *(Expended in Earth Orbit)*			31.2
LTV-P Fuel			168.5
	=====	=====	=====
Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload			
6 crew to the lunar surface for 365 days			
6 EMUs	1.08		
Consumables and Pallet	12.60		
Spares	1.00		
	=====	=====	=====
Sub Total	**14.68**	**14.68**	**14.68**
Mission Margin	**6.12**	**6.12**	**6.12**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 15 - Piloted Flight 7 (2007,10)

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
6 crew to lunar orbit			
LEV-P *(Expended into Lunar Surface)*	11.2	11.2	11.2
LEV-P Fuel		31.1	31.1
LTV-P *(Expended in Earth Orbit)*			31.2
LTV-P Fuel			168.5
	=====	=====	=====
Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload			
6 crew to the lunar surface for 365 days			
6 EMUs	1.08		
Consumables and Pallet	12.60		
Spares	1.00		
	=====	=====	=====
Sub Total	**14.68**	**14.68**	**14.68**
Mission Margin	**6.12**	**6.12**	**6.12**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 16 - Cargo Flight 9 (2008,1)

Oupost Enhancements.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Lunar Constructible Outfitting	12.31		
Greenhouse and Outfitting	16.00		
Spares	5.00		
	=====	=====	=====
Sub Total	**33.31**	**33.31**	**33.31**
Mission Margin	**7.49**	**7.49**	**7.49**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 17 - Cargo Flight 10 (2008,3)

Oupost Enhancements.

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Consumables and Pallet	10.00		
Science Equipment:			
16 Meter Telescope Equipment	16.50		
2 Submillimeter Interferometer Elements	2.34		
Contingency Crew Rations	1.93		
Spares	5.00		
	=====	=====	=====
Sub Total	**35.77**	**35.77**	**35.77**
Mission Margin	**5.03**	**5.03**	**5.03**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 18 - Piloted Flight 8 (2008,4)

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
6 crew to lunar orbit			
LEV-P *(Expended into Lunar Surface)*	11.2	11.2	11.2
LEV-P Fuel		31.1	31.1
LTV-P *(Expended in Earth Orbit)*			31.2
LTV-P Fuel			168.5
	=====	=====	=====
Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload			
6 crew to the lunar surface for 365 days			
6 EMUs	1.08		
Consumables and Pallet	12.60		
Spares	1.00		
	=====	=====	=====
Sub Total	**14.68**	**14.68**	**14.68**
Mission Margin	**6.12**	**6.12**	**6.12**
	=====	=====	=====
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 19 - Piloted Flight 9 (2008,7)

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 365 days				
6 EMUs		1.08		
Consumables and Pallet		12.60		
Spares		1.00		
		=====	=====	=====
	Sub Total	**14.68**	**14.68**	**14.68**
	Mission Margin	**6.12**	**6.12**	**6.12**
		=====	=====	=====
	Flight Totals	**32.00**	**63.10**	**262.80**

Flight 20 - Piloted Flight 10 (2008,10)

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 365 days				
6 EMUs		1.08		
Consumables and Pallet		12.60		
Spares		1.00		
		=====	=====	=====
	Sub Total	**14.68**	**14.68**	**14.68**
	Mission Margin	**6.12**	**6.12**	**6.12**
		=====	=====	=====

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Flight Totals	**32.00**	**63.10**	**262.80**

Flight 21 - Cargo Flight 11 (2009,1)

Final *Oupost Enhancements.*

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LEV-C *(Expended on Lunar Surface)*	8.4	8.4	8.4
LEV-C Fuel		31.1	31.1
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			166.0
	=====	=====	=====
Sub Total	**8.4**	**39.5**	**225.9**
LEV-C Payload			
Power Management and Distribution	2.50		
Science Equipment:			
16 Meter Telescope Equipment	16.60		
Spares	7.00		
	=====	=====	=====
Sub Total	**26.10**	**26.10**	**26.10**
Mission Margin	**14.70**	**14.70**	**14.70**
	=====	=====	=====
Flight Totals	**49.20**	**80.30**	**266.70**

Flight 22 - Cargo Flight 12 (2009,3)

Delivery of MTV systems to lunar orbit

	LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems			
LTV-C *(Expended into Lunar Surface)*			20.4
LTV-C Fuel			165.4
MTV Habitat		55.0	55.0
MTV Consumables (6 crew for 460 days)		13.8	13.8
	=====	=====	=====
Sub Total	**0.0**	**68.8**	**254.6**
Mission Margin	**0.0**	**12.2**	**12.2**
	=====	=====	=====
Flight Totals	**0.0**	**81.0**	**266.8**

Flight 23 - Piloted Flight 11 (2009,4)

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 365 days				
6 EMUs		1.08		
Consumables and Pallet		10.51		
Spares		3.40		
		=====	=====	=====
	Sub Total	**14.99**	**14.99**	**14.99**
	Mission Margin	**5.81**	**5.81**	**5.81**
		=====	=====	=====
	Flight Totals	**32.00**	**63.10**	**262.80**

Flight 24 - Piloted Flight 12 (2009,6)

Mars dress rehearsal crew

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit for 200/260 days				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 40 days				
6 EMUs		1.08		
Unpressurized rover		0.70		
Consumables and Pallet		2.69		
Science equipment:				
Telerobotic rover		0.75		
Geologic field tools		0.35		
Geophysical monitoring station		0.12		
Geophysical traverse package		0.12		
Active seismic experiment		0.30		
10-meter drill		0.02		
Plant and Animal Laboratory		0.50		
Spares		5.61		
		=====	=====	=====
	Sub Total	**12.24**	**12.24**	**12.24**
	Mission Margin	**8.56**	**8.56**	**8.56**
		=====	=====	=====
	Flight Totals	**32.00**	**63.10**	**262.80**

Flight 25 - Piloted Flight 13 (2009,7)

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 365 days				
6 EMUs		1.08		
Consumables and Pallet		10.51		
Spares		3.40		
		=====	=====	=====
	Sub Total	**14.99**	**14.99**	**14.99**
	Mission Margin	**5.81**	**5.81**	**5.81**
		=====	=====	=====
	Flight Totals	**32.00**	**63.10**	**262.80**

Flight 26 - Piloted Flight 14 (2009,10)

		LUNAR SURFACE	LOW LUNAR ORBIT	LOW EARTH ORBIT
Transportation Systems				
6 crew to lunar orbit				
LEV-P *(Expended into Lunar Surface)*		11.2	11.2	11.2
LEV-P Fuel			31.1	31.1
LTV-P *(Expended in Earth Orbit)*				31.2
LTV-P Fuel				168.5
		=====	=====	=====
	Sub Total	**11.2**	**42.3**	**242.0**
LEV-P Payload				
6 crew to the lunar surface for 365 days				
6 EMUs		1.08		
Consumables and Pallet		10.51		
Spares		3.40		
		=====	=====	=====
	Sub Total	**14.99**	**14.99**	**14.99**
	Mission Margin	**5.81**	**5.81**	**5.81**
		=====	=====	=====
	Flight Totals	**32.00**	**63.10**	**262.80**

C.2 MARS FLIGHTS

MARS IOC

Initial cargo flight

Flight 1 Jun-12 C 35.41 t

#	*ID*	*Name*	**Flight Mass**
1	cxg	Equipment: Offloading/Construction	5.75
1	upm100	Power: Martian Module (100 kW)	5.98
1	udlpdm*	Power Management & Distribution	2.50
1	rpm6	Rover: Pressurized Mars	6.50
1	rpmcart*	25 kW Power Cart	6.00
1	rpmtrlr*	Experiment/Sample Trailer	3.45
1	utlflare	Flare Warning System	0.23
1	*zgm-01*	*Mars Geology/Exobiology Equipment*	*0.56*
1	*zgm-02*	*Geo/Meteorological Monitoring Station*	*0.10*
1	*zgm-04*	*Geophysical Traverse Package*	*0.12*
1	*zgm-03*	*Active Seismic Experiment*	*0.30*
1	*zgm-05*	*Mars 10-meter Drill*	*0.02*
1	*zmm-01*	*Mars Advanced Meteorological Facility*	*1.00*
1	*zmm-02*	*Mars Balloons*	*0.20*
27	xs	Spares	2.70

2nd cargo flight

Flight 2 Jun-12 C 35.44 t

#	*ID*	*Name*	**Flight Mass**
1	hmm1*	Habitat Module 1 (Martian)	23.85
1	hxmalk2	Airlock: 2 Person, Martian	5.50
1	utm	Communication Equipment, Martian	0.94
1	*zlm-02*	*Habitat Analytical Lab Instruments*	*0.15*
1	*zlm-03*	*Biomedical Lab I*	*0.50*
1	*zxm-01*	*Discretionary PI Science*	*0.30*
42	xs	Spares	4.20

3rd cargo flight

Flight 3 Jun-12 C 35.35 t

#	*ID*	*Name*	**Flight Mass**
1	hmm2*	Habitat Module 2 (Martian)	25.50
1	hxmalk2	Airlock: 2 Person, Martian	5.50
1	upm25	Power: Mars PVA/RFC System (25 kW)	2.65
17	xs	Spares	1.70

Crew checks out and occupies base

Flight 4		Jun-14	P (90d)	9.15 t
#	*ID*	*Name*	Flight Mass	
6	eem*	EMU: Martian	0.67	
2	eemsp*	EMU Spares	0.22	
1	rum*	Unpressurized Rover (RFCs)	0.70	
1	hsm6-3*	Consumables & Pallet (6 crew, 90 days)	5.86	
17	xs	Spares	1.70	

MARS NOC

1st cargo to new site

Flight 5		Jun-14	C	38.11 t
#	*ID*	*Name*	Flight Mass	
1	cxg	Equipment: Offloading/Construction	5.75	
1	upm100	Power: Martian Module (100 kW)	5.98	
1	udlpdm*	Power Management & Distribution	2.50	
1	rpm6	Rover: Pressurized Mars	6.50	
1	rpmcart*	25 kW Power Cart	6.00	
1	rpmtrlr*	Experiment/Sample Trailer	3.45	
1	utlflare	Flare Warning System	0.23	
1	*zgm-01*	*Mars Geology/Exobiology Equipment*	*0.56*	
1	*zgm-02*	*Geo/Meteorological Monitoring Station*	*0.10*	
1	*zgm-04*	*Geophysical Traverse Package*	*0.12*	
		-continued-		

Flight 5		-continued-		
1	*zgm-03*	*Active Seismic Experiment*	*0.30*	
1	*zgm-05*	*Mars 10-meter Drill*	*0.02*	
1	*zmm-01*	*Mars Advanced Meteorological Facility*	*1.00*	
1	*zmm-02*	*Mars Balloons*	*0.20*	
54	xs	Spares	5.40	

2nd cargo to new site

Flight 6		Jun-14	C	38.14 t
#	*ID*	*Name*	Flight Mass	
1	hmm1*	Habitat Module 1 (Martian)	23.85	
1	hxmalk2	Airlock: 2 Person, Martian	5.50	
1	utm	Communication Equipment, Martian	0.94	
1	*zlm-02*	*Habitat Analytical Lab Instruments*	*0.15*	
1	*zxm-01*	*Discretionary PI Science*	*0.30*	
74	xs	Spares	7.40	

3rd cargo to new site

Flight 7		Jun-14	C		38.15 t
#	ID	Name		Flight Mass	
1	hmm2*	Habitat Module 2 (Martian)		25.50	
1	upm25	Power: Mars FVA/RFC System (25 kW)		2.65	
1	ismdemo*	Mars ISRU Demo		2.30	
58	hsl	Consumables		5.80	
19	xs	Spares		1.90	

4th cargo to new site

Flight 8		Jun-14	C		38.20 t
#	ID	Name		Flight Mass	
1	hmm23/ext*	Lab/Storage Module		14.60	
1	hxmalk2	Airlock: 2 Person, Martian		5.50	
1	*zlm-03*	*Biomedical Lab I*		*0.50*	
1	*zlm-04*	*Plant & Animal Laboratory I*		*0.50*	
160	hsl	Consumables		16.00	
11	xs	Spares		1.10	

Long-duration Crew

Flight 9		Jun-16	P (600d)		9.69 t
#	ID	Name		Flight Mass	
6	eem*	EMU: Martian		0.67	
2	eemsp*	EMU Spares		0.22	
1	rum*	Unpressurized Rover (RFCs)		0.70	
80	hsl	Consumables		8.00	
1	xs	Spares		0.10	

APPENDIX D: LUNAR TRANSPORTATION VEHICLES – OPERATING MODES ANALYSIS

The lunar transportation system reference design is a moderate and balanced transportation approach. The transportation system consists of two types of vehicles. The lunar transfer vehicle (LTV) which transfers crew and/or cargo between Earth orbit and lunar orbit, and the lunar excursion vehicle (LEV) which transfers crew and/or cargo between lunar orbit and the lunar surface. When a piloted mission is flown, crew cabs and cargo are attached to the LTV and LEV. When an unmanned cargo mission is flown, only cargo is attached to the LTV or LEV.

The baseline vehicles are designed to be expendable, and are briefly described below.

Lunar Transfer Vehicle
- Cryogenic propulsion
- All-propulsive direct earth entry
- 6 crew to/from lunar orbit
- 1 crew in orbit for 14 days

- Common propulsive stage (piloted/cargo)
- Max. payload to lunar orbit
  - Cargo ~ 80.3 mt
  - Piloted ~ 63.1 mt

Lunar Excursion Vehicle
- Cryogenic propulsion
- Single stage
- 6 crew to/from lunar surface
- 6 crew live in lander for up to 2 days

- Common propulsive stage (piloted/cargo)
- Max. payload to lunar surface
  - Cargo ~ 40.8 mt
  - Piloted ~ 20.8 mt

Several different operating modes were considered for the transportation system. These modes ranged from all expendable vehicles to reusable LEVs based and serviced at the Moon. As in the analysis of the other Synthesis Group architectures, there was no question that the transportation system would begin in an expendable mode where all vehicles are expended after fulfilling their primary mission. However, with the large crews and sustained flight rates in the later phases of the lunar outpost, the viability of reusable LEVs for this architecture needed to be addressed.

The primary driver in the analysis process was to see what were the logistics requirements (consumables and spare parts) for the steady state operation of the lunar outpost. An initial analysis showed that approximately 42 mt of logistics were required to supply an outpost with a permanent crew of 18 people. Also, it only makes sense to reuse and base vehicles on the Moon if an overall gain in delivery efficiency (i.e., mass in Earth orbit and heavy lift launch vehicle (HLLV) rates) is achieved. At the first level of analysis, this gain is measured in a savings of an integer number HLLV flights.

In the expendable mode of operation, it takes two HLLV flights (using an HLLV capability of 150 mt to Earth orbit) to support either a piloted or cargo mission to the Moon. The Synthesis Group called for a steady-state flight rate of three piloted flights and one cargo flight, which results in approximately 103 mt of payload delivery capability to the lunar surface. This is clearly well above the 42 mt requirement mentioned above. Thus, in an expendable mode, only the three piloted missions to the Moon are required to satisfy the steady-state outpost's logistics requirements. This results in approximately 62 mt of payload delivered to the lunar surface and six HLLV flights.

In any reusable mode, partial or full, the goal is to support a mission to the Moon with only one HLLV, thus creating an overall gain in delivery efficiency. Table D-1 outlines the options, compares the payload capacity of each vehicle, and shows the lunar propellant needs. In a partially reusable mode, the transfer vehicle delivers LEV propellant and LEV payload to lunar orbit for a LEV that has ascended from the lunar surface. The LEV propellant must be used for both descent and ascent. In this mode, one HLLV can deliver a LTV and enough LEV propellant to deliver 13 mt of payload to the lunar surface in a cargo mode, but only 0.5 mt of payload in a piloted mode. Thus, a steady state flight rate of three piloted flights and one cargo flight only results in 14.5 mt of payload delivered to the lunar outpost, well short of the 42 mt needed.

Transportation System Options	Payload to Moon per Flight (mt)	Total Payload to Moon (mt)	Lunar LOX Required (mt)	Lunar LH2 Required (mt)
1. All Props from Earth				
Cargo Flight (expendable)	40.8	40.8	0	0
Piloted Flight (expendable)	20.8	62.4	0	0
2. All Props from Earth				
Cargo Flight (reusable)	13	13	0	0
Piloted Flight (reusable)	0.5	1.5	0	0
3. Descent Props from Earth				
Cargo Flight (reusable)	18	18	4.3	0.7
Piloted Flight (reusable)	5	15	17.1	2.9
4. Descent Props from Earth				
Cargo Flight (expendable)	40.8	40.8	0	0
Piloted Flight (reusable)	5	15	17.1	2.9

Table D-1 Payload and Propellant Trends for Transportation Options

Another possibility for a partially reusable mode would be to supply the required LEV ascent propellant with lunar derived propellants, while still relying on Earth supplied propellants for the LEV descent. In this mode, one HLLV can deliver a LTV and enough LEV descent propellant to deliver 18 mt of payload to the lunar surface in a cargo mode , and 5 mt of payload in a piloted mode. Thus, a steady state flight rate of three piloted flights and one cargo flight only results in 33 mt of payload delivered to the lunar outpost, still short of the 42 mt needed.

A final possibility for a partially reusable mode would be to combine an expendable cargo mission with three piloted missons where the piloted LEVs use lunar-derived ascent propellants and Earth supplied descent propellants. Thus, a steady-state flight rate of three piloted flights and one cargo flight results in approximately 56 mt of payload delivered to the lunar outpost, which does satisfy the outpost's steady-state logistics requirement. The number of annual HLLV flights needed to support this mode is five, thus saving one HLLV flight per year over that needed for the expendable mode with three piloted missions per year. However, to support this mode of operation, approximately 17 mt of lunar produced oxygen and 3 mt of lunar produced hydrogen would be needed. This production rate would require approximately 25 mt of resource processing equipment and a large nuclear energy source at the Moon.

To operate in a fully reusable mode, where the LEVs use lunar produced propellants for both ascent and descent, would require an order of magnitude greater production capability on the Moon and is not compatible with this architecture's theme and emphasis.

Through the analysis presented above, it was decided that it was not cost effective to develop all the necessary propellant production capability on the Moon to support partial reusability for a savings of only one HLLV flight per year. Thus, the expendable mode of operation was continued into the steady-state phase of the lunar outpost, with three piloted missions supporting the outpost each year.