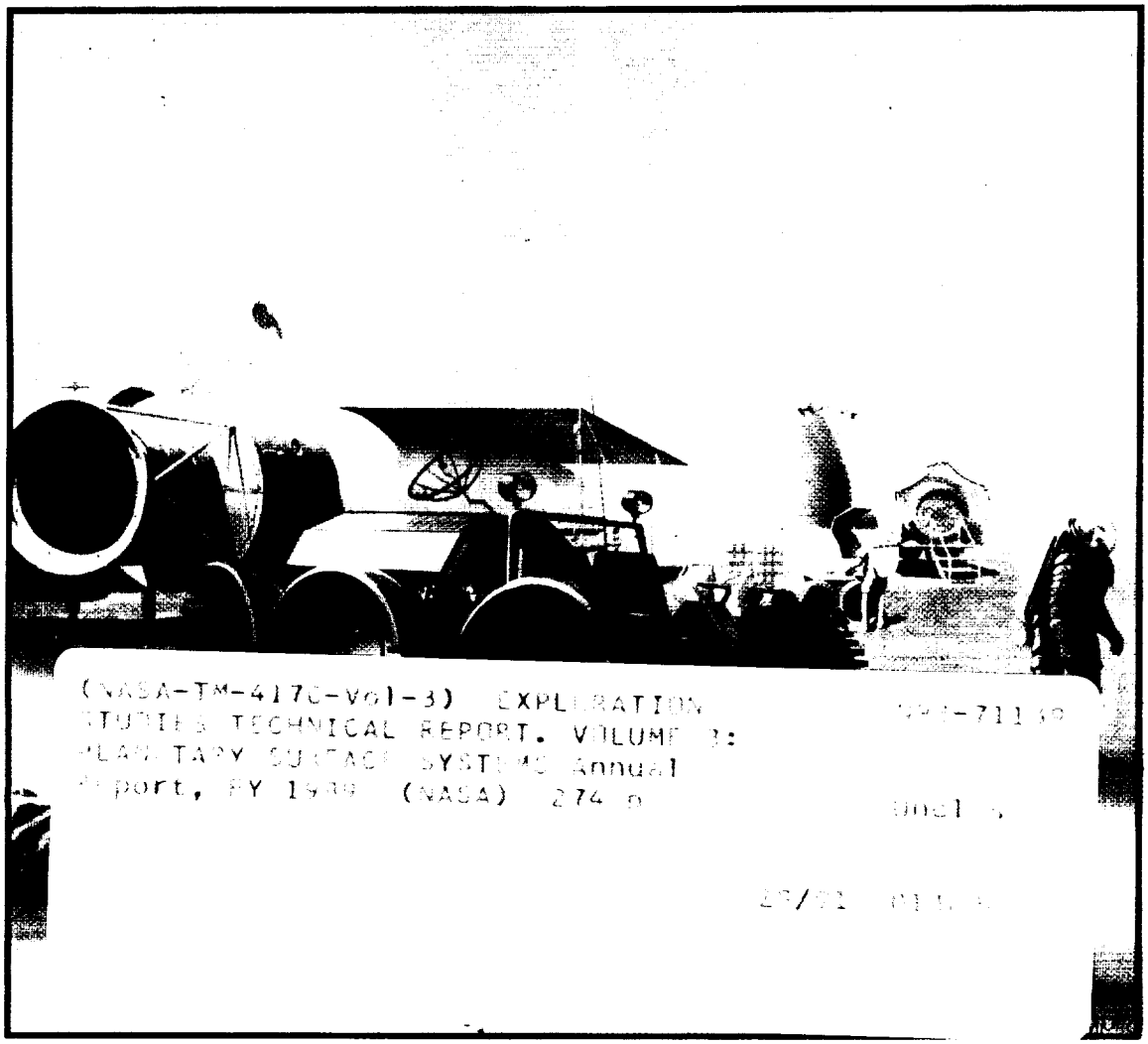
Technical Memorandum 4170

# THE OFFICE OF EXPLORATION

# FY 1989 ANNUAL REPORT




## EXPLORATION STUDIES TECHNICAL REPORT

## Volume III: Planetary Surface Systems

National Aeronautics and
Space Administration

*This publication is one of seven documents describing work performed in fiscal year 1989 under the auspices of the Office of Exploration. Volume 0, titled "Journey Into Tomorrow," provides an overall programmatic view of the goals, opportunities, and challenges of achieving a national goal for human exploration. The technical details and analyses are described in the other six volumes of the series. Volume I is Mission and Integrated Systems; Volume II is Space Transportation Systems; Volume III is Planetary Surface Systems; Volume IV is Nodes and Space Station Freedom Accommodations; Volume V is Technology Assessment; and Volume VI is Special Reports, Studies, and In-Depth Systems Assessment. These seven volumes document the status of Exploration Technical Studies at the conclusion of the FY 1989 study process in August 1989, and, therefore, do not contain any analyses, data, or results from the NASA 90-Day Study on Human Exploration of the Moon and Mars.*

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16. Abstract

The Office of Exploration (OEXP) at NASA Headquarters has been tasked with defining and recommending alternatives for an early 1990's national decision on a focused program of human exploration of the solar system. The Mission Analysis and System Engineering (MASE) group, which is managed by the Exploration Studies Office at the Lyndon B. Johnson Space Center, is responsible for coordinating the technical studies necessary for accomplishing such a task. This technical report, produced by the MASE, describes the process that has been developed in a "case study" approach. The three case studies that were developed in FY 1989 include:
1. Lunar Evolution Case Study, 2. Mars Evolution Case Study, 3. Mars Expedition Case Study. The final outcome of this effort is a set of programmatic and technical conclusions and recommendations for the following year's work.

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# The Office of Exploration FY 1989 Annual Report

# Exploration Studies Technical Report Volume III: Planetary Surface Systems

NASA

## Disclaimer Statement

The Exploration Studies Process, as explained in detail in Section 2 of Volume I, was a requirements driven, iterative, and dynamic process developed for case study analysis. This process consisted of three parts: (1) requirements generation, (2) implementation development, and (3) integrated case study synthesis.

During the final step of the process, an integrated mission was developed for each of the case studies by synthesizing the implementations developed earlier into a coherent and consistent reference mission. These are presented in Section 3 of Volume I of this annual report. Given the iterative and dynamic nature of this process, there are two important items to note:

- **The integrated case studies do not always reflect a mission that has a direct one-to-one correspondence to the requirements specified in the March 3, 1989, *Study Requirements Document.* Many changes were made to these requirements prior to and during the synthesis activities when warranted.**

- **The integrated case studies presented in Volume I represent the results of the synthesis process. Volumes II, III, and IV are the implementation databases from which the integrated case studies were derived. Therefore, the implementations outlined in Volumes II, III, and IV are generally reflected in the integrated case studies, but, in some cases, the implementations were changed in order to be effectively included in the integrated case studies. These modifications are only briefly discussed in Volumes II, III, and IV.**

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# Executive Summary

## GENERAL

The Planet Surface Systems (PSS) office made significant progress last year. The results of the surface systems studies have enhanced the current understanding of exploration problems and have identified the scientific and technical benefits available through human exploration and occupation of extraterrestrial planetary surfaces.

During FY 1989 the PSS office studied systems and architectures for the exploration and utilization of the Moon, Mars, and the martian satellites Phobos and Deimos. The Planet Surface Systems Integration Agent (PSSIA) organized activities into two broad areas. The first area supported the development of integrated exploration case studies identified by Mission Analysis and Systems Engineering (MASE). The second area encompassed distributed studies and workshops that focused on particular systems and technical topics. FY 1989 activities, especially the distributed studies, focused on lunar systems and lunar outpost definitions. More detailed considerations of martian systems are planned for FY 1990.

## FY 1989 CASE STUDIES

The PSS office supported the analysis, synthesis, and integration of three case studies: lunar evolution, Mars evolution, and Mars expedition. These studies identified surface elements, determined facility layouts, and analyzed overall base performance. Furthermore, the PSSIA identified supporting precursor data and technological development needs and produced the associated program schedules.

### Lunar Evolution Case Study

The lunar evolution case study (Section 2) focuses on the gradual development of a permanent base on the Moon. The initial base supports a crew of four for a period of one month to a year. The enhanced base supports a crew of twelve for two-year tours of duty. The base serves as a test bed for human occupation of extraterrestrial planetary surfaces. Beginning in 2003 and extending over a ten-year period, approximately two lunar landings per year deliver an average of 55 t of cargo to the lunar surface to achieve evolutionary development of the base.

Key features of the lunar base's development include:

- Habitation begins with a modified Space Station Freedom (SSF) habitat module that is eventually augmented by a large, spherical, constructible habitat. This initial module is retained to satisfy safe haven, storage, and other requirements.
- Power requirements increase from 50 kW per lunar day and 25 kW per lunar night using a solar photovoltaic and regenerative fuel cell system to 1 MW using a nuclear power system.
- Initial oxygen production begins with a 24 t per year demonstration plant and progresses to a 100 t per year production capacity.
- The life support system initially emplaced on the lunar surface is an SSF-derived system with 95 percent functional closure in air and water loops. The system evolves from an advanced physical-chemical system to a mature system including biological components.

Important findings of the study include:

- More than four crew members are needed in the early phase if a high degree of automation is not attainable.
- Overall resupply mass is significant during early phases, averaging 2.05 t per person per year. Resupply mass drops to 1.07 t during the later phases.
- By itself, life support system closure beyond space station technology may not be the answer to reduced resupply. Full closure may be too costly in terms of energy, effort, and mass.
- Energy storage devices needed for continuous operational capability during the lunar night have high mass requirements. As lunar outpost activity increases and power demand grows, the prudent solution is to replace outpost solar energy with nuclear power.
- Precursor data needs include resource surveys, surface and subsurface engineering properties, and local site details. This information is needed in the early 1990's, but may not be available until after the year 2000.
- Proper understanding of surface systems and operations, such as construction and resource processing, may be more appropriately accomplished in test beds rather than in "paper studies."

Certain enabling and enhancing technology areas, applicable to extraterrestrial development, were identified as critical. The top few include: extravehicular

mobility unit (EMU) development, in situ propellant plant technology, and mobile and surface power.

**Mars Evolution Case Study**

The objective of this case study (Section 3) is the emplacement of a permanent and self-sufficient base on Mars. Parallel with the growth of the base are the requirements for development of science research and propellant production capabilities on the martian moon Phobos.

The Mars evolution development efforts include:

- The first flight to Mars is an unmanned 50 t cargo mission scheduled to arrive in 2006.
- An initial crew of four lands in 2008 with 15 t of cargo to augment the previous cargo mission.
- The initial modular habitat supports up to five crew members for 540 days with 50 kWe of solar-generated power.
- By 2016, the completed constructible habitat houses a crew of seven, over 1 MW of combined solar and nuclear power is available, and over 300 t of materials and equipment are present on Mars and Phobos.

Important findings of the study include:

- The martian atmosphere should significantly reduce requirements for radiation and micrometeoroid protection below lunar requirements.
- The crew member surface suit requires significant development effort.
- The mass of the portable life support system (PLSS) can be a maximum of 53 kg and must support a significant number of surface excursions.
- Photovoltaic/regenerative fuel cell systems offer advantages on Mars. In terms of mass, power for night operations is less costly on Mars than on the Moon due to the shorter martian night.
- Spare parts resupply may be the limiting factor in reducing terrestrial resupply mass.
- Telerobotic operations and monitoring from Earth will be extremely difficult to conduct, if not impossible, due to the time delay caused by the great distance from Earth to Mars and back.
- Thermal control may be less difficult on Mars than on the Moon.
- Similar systems appear appropriate to both lunar and martian outposts; however, due to environmental and operational differences, individual subsystems may be quite different. More substantial precursor data is required to define and design martian equipment.

Technology development needs for the Mars evolution case study include Phobos propellant and food production technologies, plus the technological needs listed for the lunar case study.

**Mars Expedition Case Study**

The Mars expedition case study (Section 4) proposes a single opposition class mission to Mars with an overall round-trip time of 18 months as follows:

- Three crew members land at an equatorial site to perform scientific activities for 20 days.
- Each crew member is assigned five six-hour EVA's during the surface stay time.
- Surface equipment consists of EMU's, an unpressurized manned rover, a remotely controlled unmanned rover, and an assorted science package including one meteorological balloon.

Important findings of the study include:

- The surface suit requires significant development effort.
- The mass of the PLSS can be a maximum of 53 kg and must support at least five surface excursions.

The technological development needs for the Mars expedition case study include:

- Development of a lightweight surface suit.
- Development of a technology for a PLSS that can be refurbished for a minimum of five surface excursions.

## OTHER SURFACE SYSTEMS STUDIES

The PSS office sponsored a number of distributed studies and several workshops. Case study results are based on inputs from these distributed studies, but they

are not identical because of the process of integration and synthesis.

## Distributed Studies

### Constructible Habitat

A constructible spherical habitat (Section 5.1.4) with an inflatable pressure vessel was designed to be partially constructed and assembled on the lunar surface. This spherical habitat has a diameter of 16 meters, provides a volume of 2,145 $m^3$, and has a floor space of 68.8 $m^2$ for a crew of twelve. The mass of this habitat, with outfitting gear, not including airlocks or other attachments, is approximately 41 t.

### Modular Habitat

An SSF modular habitat (Section 5.1.5) with the interior redesigned to meet planetary surface requirements was studied. This modified SSF modular habitat provides a volume of 200 $m^3$ for a crew of four. The mass of the habitat, with outfitting gear, is estimated to be 14 t.

### Extravehicular Mobility Unit

The EMU study disclosed that the resupply requirements for Apollo-style, open-looped EMU's (Section 5.2) are high, on the order of 8 kg per 8 hours of extravehicular activity (EVA). The mass of an EMU with a regenerable PLSS is greater than the mass of an open-looped EMU; furthermore, the mass of a PLSS based on current technology is above reasonable human carrying capacities.

### Life Support System

A life support system (Section 5.3) derived from SSF technology was studied and proposed for the initial base. Its estimated mass is 2.2 t and requires approximately 4.9 kW to support a crew of eight. The estimated 90 day resupply mass is 1.3 t. An advanced controlled ecological life support system (CELSS) was studied and proposed for the enhanced base. The mass of the CELSS is estimated to be 12 t to support a crew of four. A greenhouse accounts for most of the mass.

### Thermal Control

Thermal control (Section 5.4) studies addressed lunar and martian habitats. On the lunar surface, low temperature heat rejection of 25 kW from an SSF module requires a heat pump system (dual loop with bypasses during twilight and nighttime) to raise the rejection temperature. The mass of this heat pump system is approximately 2 t and requires 14 kW peak power during the lunar day. The mass of a system that removes 65 kW from the constructible spherical habitat on the lunar surface is estimated to be 5 t and requires 36 kW peak power. Thermal control on Mars will be less difficult than on the Moon because of the lower daytime temperatures.

### Radiation Protection

Studies (Section 5.5) were performed to determine the radiation protection required by the crew on the lunar and martian surfaces. Current allowable radiation dose for astronauts is 50 rem/year. The annual dose (galactic cosmic rays plus one large solar particle event) is approximately 15 to 20 rem/year for an SSF-type modular habitat and the same for the constructible habitat with 50 cm (equivalent to 75 $g/cm^2$) of lunar regolith shielding. A variety of uncertainties may result in an error as large as a factor of 2 in this dosage range.

The martian atmosphere provides significant shielding, 16 to 22 $g/cm^2$ directly overhead depending on the local elevation and pressure. An unshielded person will be subjected to doses of 20 to 34 rem/year (galactic cosmic rays and one large solar particle event). This dosage range also has an uncertainty factor of two.

### Electrical Power

Desired power levels, operating times, and life expectancies were determined from case studies (Section 5.6) for particular applications ranging from hundreds of watts (initial outpost) to megawatts (developed base). To satisfy these requirements, many power generation systems and storage devices (solar, chemical, isotopic, and nuclear) were assessed. Studies found that solar power and energy storage devices satisfy initial outpost power requirements. Nuclear power is required to satisfy needs during the later phases.

Power distribution via power conductors versus free space transmission (microwave power transmission or laser power transmission) was also studied.

### Telecommunications, Navigation, and Information Management (TNIM)

TNIM support to the PSSIA by the Office of Space Operations was divided between Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL) (Section 5.7). TNIM architectures and designs were developed by GSFC for the lunar outpost and by JPL for Mars, Phobos, and Deimos activities.

GSFC identified communications circuit requirements by user group and developed an architecture in which local communications are satisfied by an ultra high frequency (UHF) system having an omini-directional antenna atop a 30 meter tower. The radio range coverage includes an area of 10 km in all directions from the antenna. All communications beyond the Moon's surface are satisfied by two relay satellites in halo orbits about libration points 1 (for near side communications) and 2 (for far side communications). The satellites also serve as navigational information sources. Solar powered navigational beacons are installed at the launch and landing facility and other locations as required.

JPL's design considerations for Mars and its moons included frequency selection, data compression and coding needs, transmitter versus antenna size tradeoffs, footprint versus satellite altitude tradeoffs, satellite configuration, Mars-Earth link capacity versus mission range tradeoffs, emergency communications strategy, and link characteristics. Communications beyond Mars and its moons is satisfied by two relay satellites. Ka-band links are used for high-rate data and broadbeam UHF links are used for low-rate data. Broadbeam links via UHF are available between the relay satellites, and the Mars piloted vehicle and science packages on Mars, Phobos, and Deimos. Emergency links are available directly to and from the Earth via X-band. Preliminary analysis of surface-to-surface communications advocates using a 30 meter tower at the Mars outpost to support links up to 20 km. JPL developed a model for mission operations functions used to formulate a basis for information management. Trade studies in this area are scheduled for FY 1990.

### Surface Transportation

A variety of historical planetary surface transportation systems (Section 5.8) provided a basis for conceptual designs of unpressurized rovers, pressurized rovers, and unmanned rovers for the Moon and Mars. Trades favored wheeled designs. Lunar unpressurized rovers are estimated to weigh 1.7 t loaded and require an energy source of approximately 1.9 kW. Pressurized rovers for short ranges averaged 6 t and required an energy source averaging 9 kW. The pressurized rover design incorporates a train concept to extend the range to hundreds or thousands of kilometers. Approximate rules of thumb were used to rescale lunar rovers for martian applications.

### Construction

Although the environmental conditions of the Moon and Mars are different, the same functional needs are required for the development of construction equipment. Construction equipment is required to lift, haul, dig (move soil, trench, scrape), pave, and survive environmental exposure. Thus, lunar and martian construction equipment, like rovers, can be developed from common designs, reducing development time and support infrastructure, e.g., spare parts.

### In Situ Resource Utilization (ISRU)

The ISRU study indicated that lunar propellant production, including hydrogen production, may not be as difficult as previously expected. ISRU studies showed that useful ISRU plants may be feasible early in the base development phase. On the other hand, the Phobos ISRU effort cannot progress without additional data on the moon's composition and other physical characteristics.

### Workshops

The PSSIA sponsored four workshops during FY 1989. These workshops addressed issues and matters concerning automation and robotics and human performance (January 1989), requirements for a planetary environment analog facility (April 1989), extraterrestrial mining and construction (May 1989), and in situ resource utilization (June 1989). Workshops included representatives from government, industry, and academia.

## RECOMMENDATIONS

Four major areas of concern that must be resolved were identified. It is recommended that follow-on study and action to resolve these issues be accomplished during FY 1990. They include:

- Complete a thorough investigation and analysis of the time-critical technology needs cited.
- Conduct a concept evaluation of advanced construction techniques for habitats and operations.
- Establish Earth-based laboratories and facilities to simulate and evaluate logistic operations. Results need to be evaluated and recommended courses of action must be determined and implemented.
- Develop automated systems for control and monitoring of lunar, Mars, and Phobos operations.

Robotic mechanisms, advanced sensors, knowledge-based computer systems, and high capacity TNIM systems are essential for telerobotic operations from Earth and from control centers on the Moon and Mars.

# Section 1

# Introduction

This document is the third volume of the six-volume Office of Exploration (OEXP) Annual Report. It summarizes the activities of the Planetary Surface Systems Integration Agent (PSSIA) at the NASA Johnson Space Center during fiscal year 1989. In conjunction with the space transportation IA and the orbital node IA, the PSSIA is designated to perform detailed technical analyses and conceptual design at the system level. This volume reflects the PSSIA's efforts in particular technical areas plus the PSSIA's response to requirements levied by Mission Analysis and Systems Engineering (MASE).

This volume covers three distinct segments of the PSS IA's activities: responses to the three MASE case studies, conceptual design and analyses in eight functional areas, and operations analyses pertaining to the case studies and functional areas. The sections describing the case study analyses (sections 2 through 4) include the lunar evolution case study, the Mars evolution case study, and the Mars expedition case study. Those sections provide mission statements, base site layouts, functional area systems selection, performance assessments, required mission programmatics, and identification of mission technology and precursor data needs. Case study results are based on inputs from distributed studies. They are not identical to the distributed studies, however, because of the process of integration and synthesis. Section 5 details the efforts in the various technical areas specified by the PSSIA, including descriptions of surface system element options applicable to both lunar and martian scenarios. Section 6 describes operational requirements associated with the human occupation of an extraterrestrial base. A summation of the year's findings is not completely addressed in this volume. Expanded studies and additional products regarding planetary surface systems are provided in volume 6. Lists of acronyms, abbreviations, references, and other data are provided in the appendix.

## 1.1 ORGANIZATION OF PLANETARY SURFACE SYSTEMS OFFICE

The PSSIA has the responsibility for the conceptual design and systems engineering for all systems needed for the human exploration of an extraterrestrial surface. To meet these responsibilities, the PSSIA formed a team comprised of representatives from government, industry, and academia. Figure 1.1-1 describes the planetary surface organization. To assure continuity and cohesiveness, the PSSIA assigns tasks to functional area managers (FAM's). A FAM represents a combination of disciplines necessary to describe a basic area of study related to the overall surface systems. For example, the energy FAM is responsible not only for the traditional conceptual studies of power generation and storage, but also the transmission of electrical energy to habitation facilities or resource processing units. Another manner of describing the work done by the FAM is to regard the FAM as one of the many master craftsmen needed to build a house, each with his own area of expertise.

The following terminology was developed to describe the various facets of planetary surface systems. The term "element" refers to the major hardware items such as rovers, habitat modules, and power plants. The term "subsystem" refers to the major functional systems that perform a specific operation for an element. For example, the subsystems of a habitat module include the life support system and the thermal control system. (Note that the term "system" continues to be used descriptively.) Generally, a variety of elements are required for substantial surface activities. For the sake of organizing the planetary surface systems, elements and activities with related functions and attributes are grouped together and referred to as "functional areas." For the FY '89 studies, eight functional areas were identified, as summarized in table 1.1-I and described further in section 1.2. Finally, the term "architecture" refers to the overall management structure to describe the total occupation of the planetary surface. Thus, architecture includes a set of elements from the various functional areas, their interfaces, organization, and layout.

To some extent, the taxonomy selected to describe PSS architecture corresponds to National Space Transportation System (NSTS) terminology, in which an orbiter is an element and each orbiter component, such as communications, is a subsystem. In NSTS terminology, a "system" is equivalent to the PSS organizational term "functional area."

The various FAM's make their study assignments to the assembled members of their teams. These individuals then follow the assignments to completion. The FAM's report their results to the PSSIA for inclusion in the OEXP study reports. At this time, the PSS office uses its own internal team of experts in systems engineering and integration (SE&I) to combine the inputs of all the FAM's and incorporate them into the MASE focused case studies. Thus, the SE&I team integrates the FAM's results to define the overall surface architecture. These

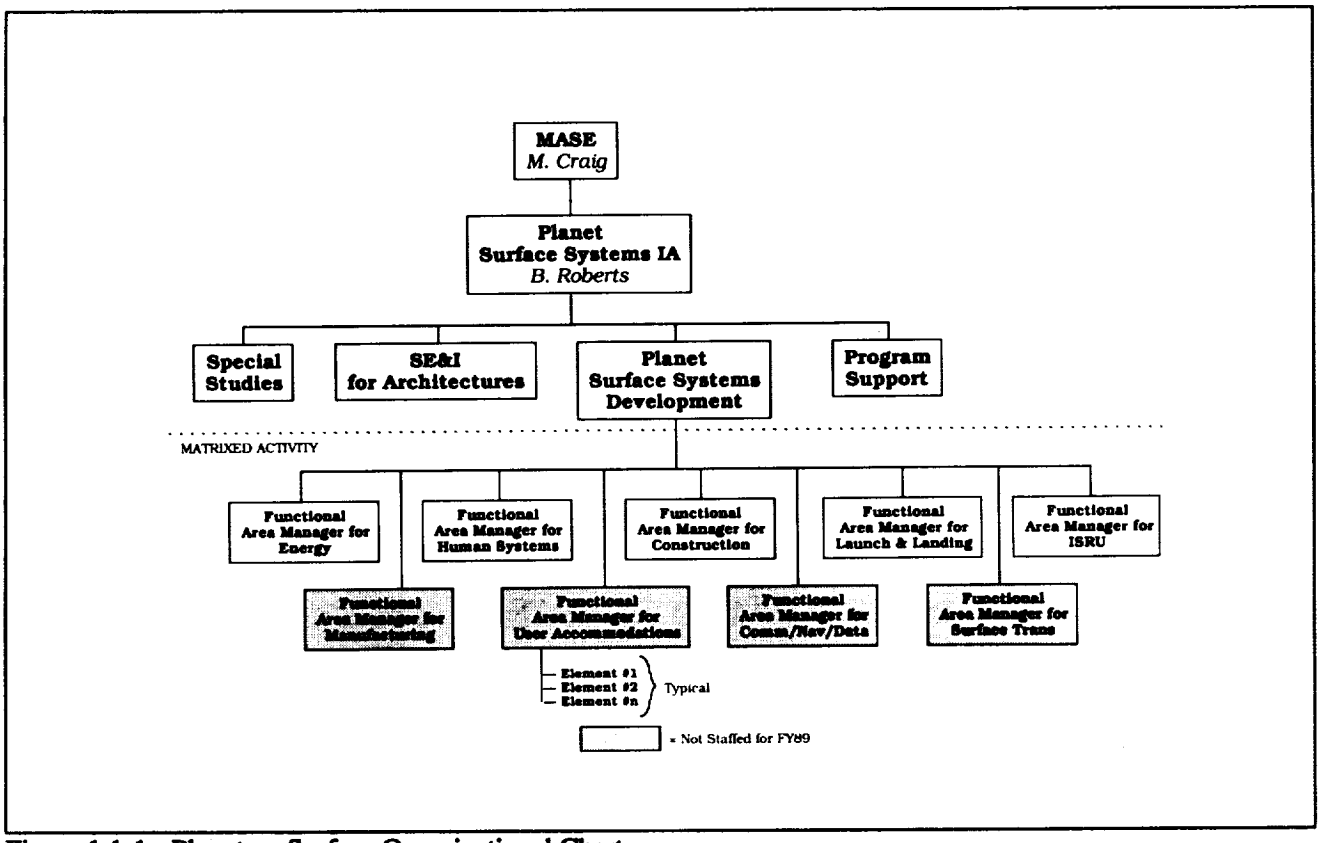



Figure 1.1-1.- Planetary Surface Organizational Chart.

TABLE 1.1-I.- FUNCTIONAL AREAS LISTING

Human Systems
- Habitation facilities
- Extravehicular activity systems
- Life support systems
- Thermal control systems
- Radiation protection

Energy
- Generation
- Conversion
- Storage
- Transmission

Telecommunications, Navigation, and Information Management
- Communications
- Navigation and tracking
- Data systems

Surface Transportation
- Local
- Long-range
- Unpressurized
- Pressurized

In Situ Resource Utilization
- Mining
- Materials transport
- Beneficiation
- Processing
- Storage and distribution

Assembly and Construction
- Base and science systems
- Utilities
- Roads and landing pads

Launch and Landing Operations
- Ascent and descent operations
- Payload integration and deintegration
- Servicing and fueling
- Environmental protection

User Accommodations
- Astronomy
- Planetary science
- Life sciences
- Other science

relationships and interactions are further illustrated graphically in figure 1.1-2.

## 1.2 FUNCTIONAL AREA DESCRIPTIONS

Human systems encompass those areas relating directly to the crew, either by providing for their well being or by enabling crew operations. Human systems include life support systems, habitation facilities, extravehicular activity (EVA) systems, habitat thermal control systems, and radiation protection. Life support systems are defined in terms of functional closure, i.e. the percentage of closure with respect to the atmospheric and water system cycles. An evolutionary approach to life support is studied with the intent of increasing system closure (90 to 100 percent) given the proper conditions in time. Habitation studies involve definition of pressurized volume for crew living accommodations. Habitats under consideration span the range from prefabricated, modular structures to constructible, multi-leveled facilities. EVA systems include extravehicular mobility units (EMU), portable life support systems (PLSS), and mobility aids such as a manned maneuvering unit. Important parameters for EVA analysis involve levels of suit pressure, EMU and PLSS mass constraints in various gravitational environments, and the nature of the consumables. The thermal control systems concern the heat transfer problems associated with pressurized inhabited volumes. Design concerns for thermal systems include radiator sizes and orientations plus system masses and capacities for different habitat heat loads. Radiation protection pertains to methods of shielding crew members against solar particle events and galactic cosmic rays. A promising protection option uses innate planetary regolith as a shielding material according to the environmental factors.

Energy comprises the areas of generation, conversion, storage, management, and distribution of power for surface systems. Major energy needs, as applied to fixed or mobile applications, are typically mechanical, electrical, or thermal. This functional area includes thermal management with respect to the waste heat generated by energy production or use. Power generation sources range from photovoltaic with regenerative fuel cells to various nuclear plants. Power systems support habitation facilities, surface transportation, resource utilization plants, construction operations, and science activities.

Telecommunications, navigation, and information management (TNIM) support both internal and external communications interfaces required for surface opera-

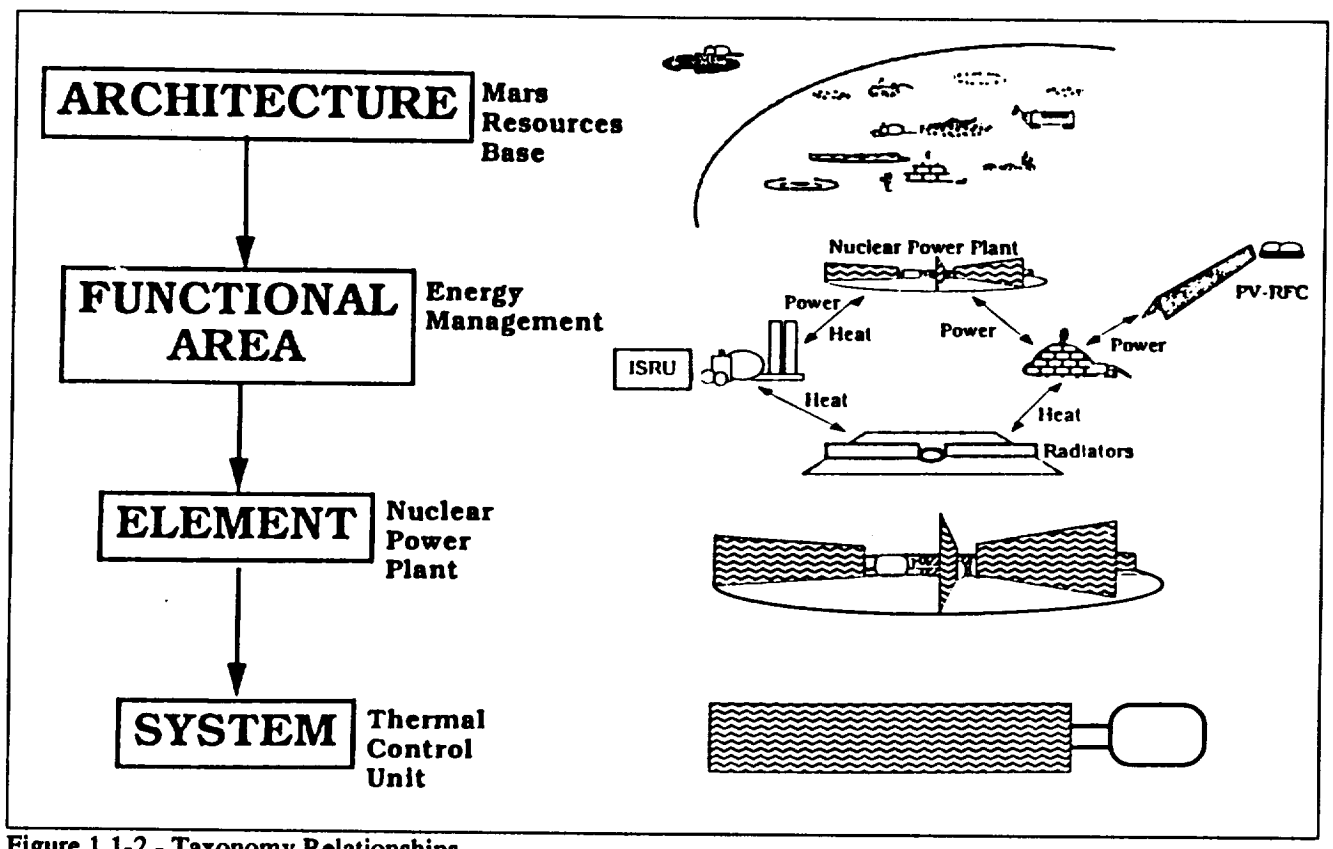



Figure 1.1-2.- Taxonomy Relationships.

tions. Internal communications are processed completely by planetary surface systems (ground station, radio tower), whereas external communications involve some processing by non-surface systems (satellites). (The PSSIA is not responsible for these non-surface systems, but may be responsible for interfaces with them.) Surface-to-surface communications refers to links with various elements like EVA crew, rovers, base facilities, and science users.

Surface transportation is classified in terms of distance capacity, including local, mid-range, and long-range vehicles. Local transportation provides general capabilities for moving crew, equipment, and materials unpressurized in the vicinity of the landers and the base at distances less than 10 km. Parameters of interest for a short-range, unpressurized rover include power source for locomotion, extent of sortie, maximum traverse grade, payload capacity, mass, and type of chassis. Long-range manned vehicle options require pressurized facilities with EVA access. Extended traverse vehicles need additional power supplies, an expanded thermal control system, payload transport outfitting, and accommodations for scientific interests.

In situ resource utilization (ISRU) refers to those operations involved in the processing of native planetary materials to produce a useful commodity. Utilization of native resources spans a broad range, such as propellant production, cast basalt, and sintered blocks. Production of oxygen is the predominant ISRU operation currently addressed. Oxygen production methods involve mining to extract raw feedstock, beneficiation for refinement of input materials, processing for conversion to refined output, and storage for maintaining distribution supplies. With respect to Mars, ISRU also applies to the planet's predominantly carbon dioxide atmosphere, a prime source for extracting oxygen.

The functional area of assembly and construction applies to establishing base systems, routing utilities, and improving surfaces. Base systems are categorized as pressurized facilities (habitats) and their dedicated subsystems (radiators). Utilities include systems for communication, power distribution, and sewage disposal. Surface improvements concern enhancements to the natural planetary surface, such as roads and landing pads, and may vary from basic clearing to paving. The studies of the construction area focus on conceptual techniques and equipment for construction and deployment of surface and user elements. Equipment options range from single dedicated machines, such as a crane, to multipurpose machines similar to a prime mover with multiple attachments. Equipment functions are characterized as grading, drilling, trenching, and digging. Assembly and construction also deals with operational issues including site preparation, excavations, foundations, anchoring, backfilling, and off-loading equipment. Operations involving minimal processing of native materials (e.g. bagged regolith) are also considered part of construction.

The launch and landing functional area encompasses those facilities and activities associated with landers. These include payload integration, servicing, and propellant loading. Detailed steps regarding flight vehicle turnaround are defined in order to provide adequate system support. Surface equipment, such as auxiliary power and thermal control, is necessary to support launch and landing operations.

User accommodations refer primarily to the scientific experiments to be conducted on the surface of the planetary body in question and the support required for them. As such, the base itself acts as a service support system available to accommodate the science user's needs. The user is classified according to the primary science divisions of astronomy, planetary science, and life science. User base support is described in terms of needed resources and facilities, such as crew or energy and pressurized laboratories or surface transportation units.

## 1.3 PLANETARY SURFACE SYSTEMS FY '89 ACTIVITIES AND PRODUCTS

The office of the PSSIA generated a variety of products during fiscal year 1989. A key product was the Planetary Surface System Requirements Document (PSSRD), which directed the study efforts of the PSS team. Other products during this study period included workshops, an assessment of technology needs, the elements data base, distributed studies, performance analyses of PSS operations, and data produced for working group weeks. Table 1.3-I lists the pertinent internal products of the PSS office.

The PSSRD, distributed in March 1989, serves as an instructional guideline for the FAM's. The document outlines the PSS taxonomy, product requirements, MASE case study descriptions, PSS alternative case architectures, and system design information. The top-level functional requirements and baseline assumptions are included in the context of the MASE case studies. The alternative architectures, such as the Mars resource base, were designed to provide specific responses to planetary surface system issues and are not reported in this volume. The PSSRD is an internal product used as a directional aid throughout the year and is not intended as part of the annual report.

TABLE 1.3-I.- INTERNAL PRODUCTS OF THE PLANETARY SURFACE SYSTEMS OFFICE

| Document | | Number or Date |
|---|---|---|
| Planetary Surface System Requirements Document | | Z-89-2.4-002 |
| Technology Needs for Human Exploration Missions (Section 5) | | Z-89-1.2-001 |
| Elements Data Base | | Ongoing |
| Workshops: | Automation and Robotics/Human Performance | January 1989 |
| | Planetary Environment Analog Facility | April 1989 |
| | Extraterrestrial Mining and Construction | May 1989 |
| | In Situ Resource Utilization | June 1989 |
| Presentation Material: | Working Group Week #1 | December 1988 |
| | Working Group Week #2 | February 1989 |
| | Working Group Week #3 | April 1989 |
| | Working Group Week #4 | June 1989 |

An assessment of technology requirements for PSS activities was performed. These technology needs include 37 unique areas, such as equipment shelter, habitats, controlled ecological life support systems, ISRU, power, assembly and construction, and launch and landing services. The PSS assessment, organized according to functional areas, was included as section 5 of a larger technology study which eventually evolved into the technology needs data base. The information provided concerns descriptions of particular needs. For example, in the area of surface transportation, dust contamination control is identified as a critical technology need to ensure efficient system performance. Specific PSS technology needs are recognized in the sections of this volume concerning the focused MASE case studies.

The element data base is a compilation of detailed descriptions of elements required for surface system activities. The data base lists elements from current conceptual studies as well as elements from previous design efforts. Element data forms, as specified in the PSSRD for inclusion in the database, contain specific characteristics of pertinent elements as determined by the FAM's in the course of the year. Requested element parameters include summary descriptions, dimensions, external support requirements, subsystems, references, illustrations, and other miscellaneous details. The element data base is not included in the annual report. Instead, it is maintained at the PSS office as an internal reference.

Four workshops were sponsored by the PSSIA during FY '89. The automation and robotics/human performance workshop, conducted in January 1989, included representatives from government, industry, and academia. This workshop addressed issues related to the potential for automation and robotics and the expected capabilities of humans. Several specific extraterrestrial scenarios were considered. These included lunar mining, initial deployment of a martian habitat, and exploration of Phobos. The second workshop focused on the requirements for a planetary environment analog facility, basically a large-scale simulation of a lunar base. This workshop, held in April 1989, identified the issues and problems associated with such a facility and defined representative facility concepts. The extraterrestrial mining and construction workshop, held in May 1989, addressed the issues concerning mining and construction in an extraterrestrial environment. Specific topics of this workshop included adapting terrestrial experience to planetary environments, determining the nature of the lunar base facilities, and identifying synergies between mining and construction equipment. Finally, the in situ resource utilization workshop, conducted in June 1989, included discussions of precursor data needed for obtaining in situ resources, comparisons of oxygen production processes, identifications of volatile and metals extraction, and production of advanced materials from native resources.

Periodic technical results and design data from the PSS team were assembled and presented at four OEXP working group week events for the purpose of integrating information with other integration agents, MASE, and headquarters. The four presentations represent delivered products in the course of the study period, with some of the information included in this volume.

Working group weeks were intended as communication sessions to review, comment, and amend technical analyses. PSS presentations typically contained functional implementation plans for the case studies, supporting program needs, and exploration study team interfaces. Presentation material from these sessions are maintained on file at the PSS office.

# Section 2

# Lunar Evolution Case Study

The lunar evolution case study, as defined by the Mission Analysis and System Engineering (MASE) team, focuses on the establishment of a permanently manned lunar base. The term evolution implies the gradual development of the base into a test bed for human occupation of an extraterrestrial environment with the intent for further human exploration of the solar system. In this case study, the lunar base grows in time with respect to expanded support capabilities, including manpower, surface transportation, habitation, and power generation. Increased levels of support satisfy the base's main objectives: aggressive science activities and usage of local resources. Figure 2-1 illustrates a portion of the base as depicted by a scale model.

In response to the MASE case study definition, the Planet Surface System (PSS) office characterized the lunar base in terms of the system elements, the site layout, and the base performance. In addition, precursor data needs and technology needs were identified and the surface systems schedules were developed. The process of system element selection was dictated by the requirements outlined in the Study Requirements Document (SRD) and the MASE case study definition. Case study results are based on inputs from distributed studies. They are not identical, however, because of the process of integration and synthesis.

## 2.1 MISSION STATEMENT

The principal feature of the lunar evolution case study is the emplacement of a human-tended facility that evolves into a permanently occupied base capable of supporting up to twelve persons. The establishment of an evolutionary lunar base is accomplished according to three phases of development--emplacement phase, consolidation phase, and utilization phase. The emplacement phase is characterized by the establishment of initial habitat facilities capable of sustaining a crew of four for six months to one year. Extending from 2003 to 2006, this phase depends significantly upon Earth support for crew logistic supplies, construction teleoperation, and operations monitoring.

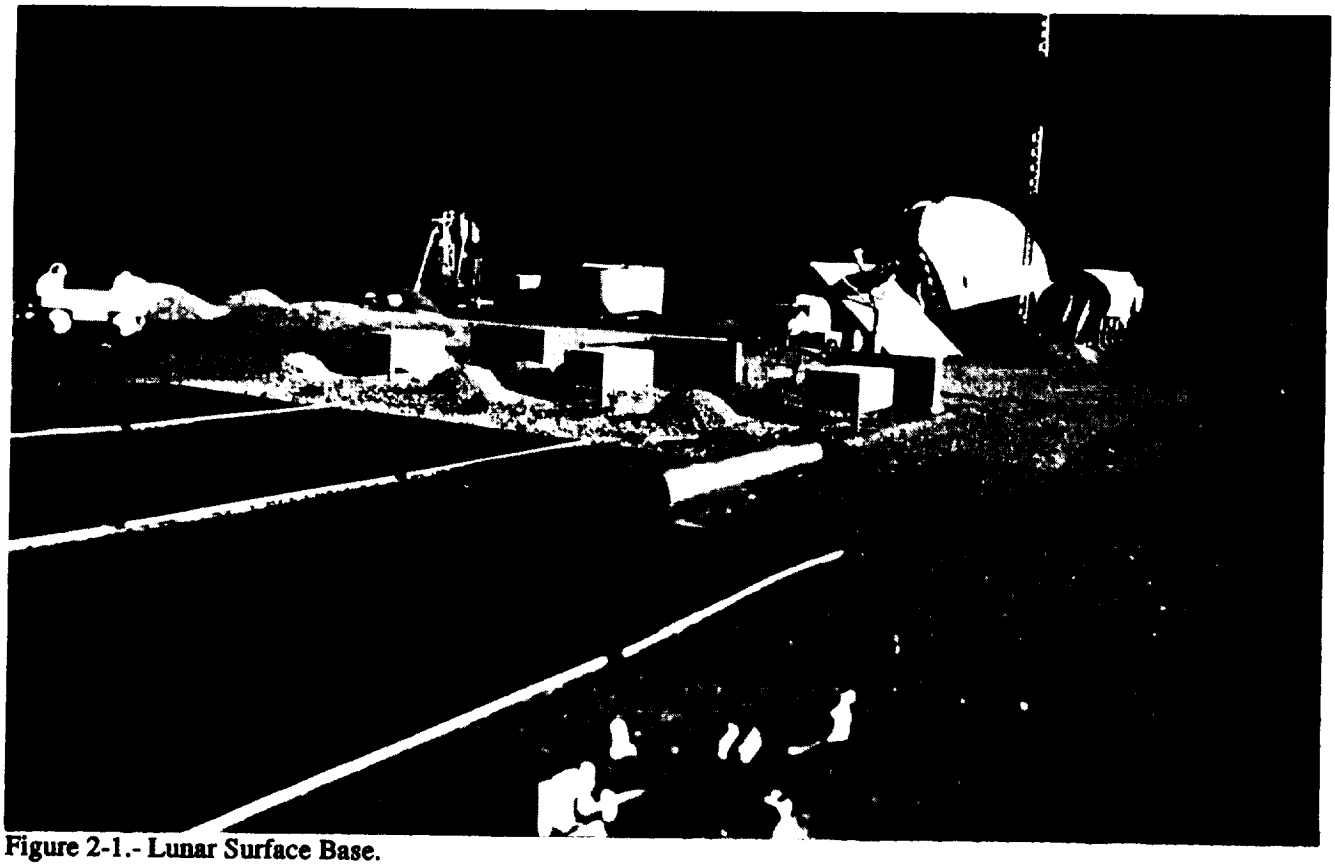


Figure 2-1.- Lunar Surface Base.

Substantial enhancements to the habitation architecture and capabilities are achieved in the consolidation phase, enabling eight crew members to live on the lunar surface for a one year period. The consolidation phase, from 2006 to 2012, enables the base inhabitants to perform an increased level of activity with less Earth dependence. Additional activities include advanced construction, exploration science, laboratory operations, and landing vehicle maintenance and servicing.

The utilization phase is marked by the utilization of lunar resources, specifically for the production of oxygen for lander and ballistic vehicle propellant. Initiating in 2012, this final phase curtails development of the base and Earth support, while focusing on maintaining a crew of twelve for two year tours of duty.

From the planetary surface systems perspective, the three lunar base phases address distinct and evolving objectives. The emplacement phase acts as a test bed for learning the techniques for set-up and operation of a non-terrestrial outpost. During the consolidation phase the base architecture strengthens and extends its boundaries, while the lunar activities merge into specific scientific and operational objectives. Accomplishments include learning to construct pre-fabricated habitats and learning to utilize local resources. The utilization phase is instrumental in proving the usefulness of local resources and the viability of base self-sufficiency. As the surface support systems progress along the mission timeline, the scientific opportunities also follow the pace. Beginning with local geophysical experiments, the science activities grow to include extensive laboratory research, two-week exploration missions, and finally global access via ballistic vehicle missions.

### 2.1.1 Mission Manifest

Automated emplacement of the initial habitation facility occurs in 2003 prior to human presence on the lunar surface. During the period from 2003 through 2005, three piloted missions and two unmanned cargo missions are flown to the Moon. The first crew, who stays on the Moon for thirty days, is responsible for deploying and operating the initial support systems for the base. This early mission is followed by a six month period of unmanned testing and verification of the surface facilities. By mid-2004, permanent habitation of the lunar base begins with four astronauts on a six month tour-of-duty. Crew rotations are increased to one year in 2005 and to two years in 2008. Figure 2.1.1-1 shows the lunar evolution crew manifest including tours-of-duty, dates of base occupation, and crew size. With the crew up to 12 persons in 2012, the base achieves steady-state operations, i.e. completed significant construction operations, continuous oxygen production, a lander flight rate of twice per year, and yearly global explorations.

The manifest for the lunar evolution case study, as defined by the PSSIA and Mission Analysis and System Engineering (MASE), is outlined in table 2.1.1-I, showing the delivery date and quantity of each surface support and science element. The manifest reflects the sequencing of payloads in order to achieve the aggressive and evolutionary base schedule. Certain surface support elements are dependent upon other elements. For example, construction equipment is delivered in 2003 for use throughout base development, the 825 kW nuclear power source is emplaced (2009) before continuous oxygen production begins, and the landing pad instruments (markers and beacons) are manifested in 2004 prior to multiple, yearly landings. The manifest for science users emphasizes early delivery of equipment, particularly astronomy and laboratories, in order to accelerate data acquisition as well as spend the utilization phase on remote sorties.

The manifest is represented in a different format in figure 2.1.1-2. This chart marks the emplacement of specific cargo packages according to delivery. Each filled square represents a flight to the lunar surface, categorized by mission phase. The arrows designated below the figure indicate the achievement of benchmarks within the lunar case study. These benchmarks are time sequential and provide reference points of base progress. The eight milestones, a subset of those originally cited in the Study Requirements Document (SRD), include:

a. First occupation of the base for a lunar night
b. First six month tour-of-duty
c. Availability of life science research facility
d. First 100 km surface sortie
e. First 1,000 km surface sortie
f. Utilization of non-terrestrial resources for life support system
g. Utilization of non-terrestrial propellants
h. Establishment of a farside observatory

### 2.1.2 Mission Requirements and PSS Responses

While the time sequencing of the surface elements is devised by MASE in the form of a mission manifest, the particular elements delivered in the course of the case study are determined by the Planet Surface Systems (PSS) group. Each element is a response to systems requirements, phase definitions, and timeline constraints. Specific system requirements are levied in the SRD, the original source for focused case study specifications. These requirements form the basis for systematic selection of the appropriate elements (equipment and materials) to support a particular activity. Table 2.1.2-I lists

## TABLE 2.1.1-I.- PAYLOAD ELEMENT MANIFEST FOR LUNAR EVOLUTION BASE

| Surface Systems | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Support Element Name** | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Habitation Module | 1 | | | | | | | | | | | | |
| Airlock | | 1 | | | | | | | | | | | |
| Node | | 1 | | | | | | | | | | | |
| Thermal Control System | 1 | | | | | | | | | | | | |
| PVA/RFC (50 kw/25 kw) | 1 | 1 | | | | | | | | | | | |
| PVA (100 kw) | | | 1 | | | | | | | | | | |
| Crane | 1 | | | | | | | | | | | | |
| Digger | 1 | | | | | | | | | | | | |
| Truck | 1 | | | | | | | | | | | | |
| Fuel Cell Power Carts | | 1 | 1 | | | | | | | | | | |
| Thermal Control Carts | | 1 | 1 | | | | | | | | | | |
| Liquefaction Plant/Tanks | | 1 | 1 | | | | | | | | | | |
| Tents | | | 1 | | | | | | | | | | |
| Pressurized Tunnel Ramp | | | 1 | | | | | | | | | | |
| Pressurized Utility Vehicle | | | 1 | | 1 | | | | | | | | |
| Unmanned Local Rover | | 1 | 1 | | | | | | | | | | |
| Laboratory Trailer | | | 1 | | | | | | | | | | |
| Power Trailer (14 kw) | | | 1 | | | | | | | | | | |
| Power Trailer (25 kw) | | | | | 1 | | | | | | | | |
| Ground Station | | | 1 | | | | | | | | | | |
| Communications Equipment | | 1 | 1 | | | | | | | | | | |
| Communications Tower | | | | | | 1 | | | | | | | |
| Cable (1.3 km) | | 1 | | | | | | | | | | | |
| Pad Markers | | 9 | | | | | | | | | | | |
| Navigation Beacons | | 1 | | | | | | | | | | | |
| Construction Hand Tools | | 1 | | | | | | | | | | | |
| EVA Equipment | | 1 | | | | | | | | | | | |
| LLOX Demonstration Plant | | 1 | | | | | | | | | | | |
| SP-100 Power Module | | | | 1 | | | | | | | | | |
| Nuclear Power Plant (825 kw) | | | | | | | 1 | | | | | | |
| Constructible Habitat | | | | 1 | | | | | | | | | |
| Constructible Thermal Control | | | | | 1 | | | | | | | | |
| Constructible Regenerative LSS | | | | | 1 | | | | | | | | |
| Constructible Outfitting | | | | | 1 | | | | | | | | |
| PMAD & Cable (3 km) | | | | 1 | | | | | | | | | |
| Lander Facility Upgrades | | | | | | 1 | | | | | | | |
| LLOX Plant | | | | | | | | 1 | | 3 | | | |
| PMAD for Plant | | | | | | | 3 | 1 | | | | | |
| Plant Beneficiation Equipment | | | | | | | | 1 | | 3 | | | |
| Mining Equipment | | | | | | | | 1 | | | | | |
| Propellant Refill Vehicle | | | | | | | | | 1 | | | | |
| **Science Element Name** | | | | | | | | | | | | | |
| Geologic Exploration Equipment | | 1 | | | | | | | | 1 | | | |
| Geophysical Station | | 1 | | | | | | | | 1 | | | |
| Laser Reflectometer | | 1 | | | | | | | | | | | |
| Portable Geophysical Package | | 1 | | | | | | | | 1 | | | |
| Particles and Fields Instruments | | | 1 | | | | | | | | | | |
| Geologic Exploration Instruments | | | | 1 | | | | | | | | | |
| Solar Observatory | | 1 | | | | | | | | | | | |
| Monitoring Telescope | | | 2 | | | | | | | 1 | | | |
| Optical Telescope | | | 1 | | 1 | 1 | | | | | | | |
| Ultraviolet Telescope | | | | 1 | | | | | | | | | |
| Infrared Telescope | | | | 1 | | | | | | | | | |
| Moon-Earth Radio Interferometer | | | 1 | | | | | | | | | | |
| Earth Observing Instruments | | | 1 | | | | | | | | | | |
| X-ray Telescope | | | | | | | | | 1 | | | | |
| Gamma Ray Telescope | | | | | | | | 1 | | | | | |
| Low Frequency Radio Array | | | | | | | | | | | 1 | | |
| Biomedical Laboratory Instruments | | | 1 | | | | | | | | | | |
| Analytical Science Laboratory | | | 1 | | | | | | | | | | |
| Plant/Animal/Microbe Lab | | | | | | | | | 1 | | | | |
| Teleoperated Instrumented Rover | | | 1 | | | | | | | | | | |
| Science Expedition Package | | | | | | | | | | | | 1 | 1 |

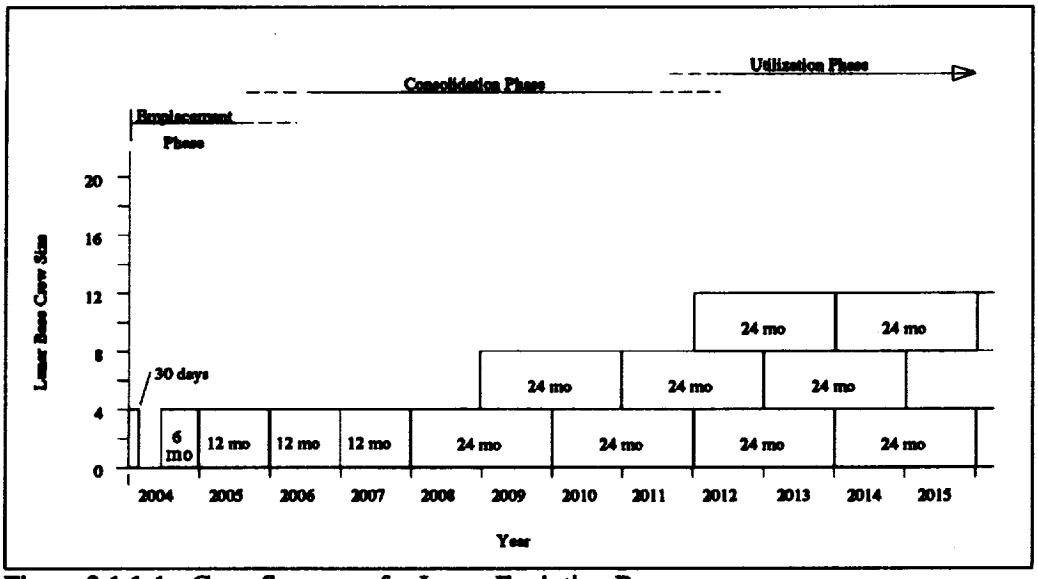



Figure 2.1.1-1.- Crew Summary for Lunar Evolution Base.

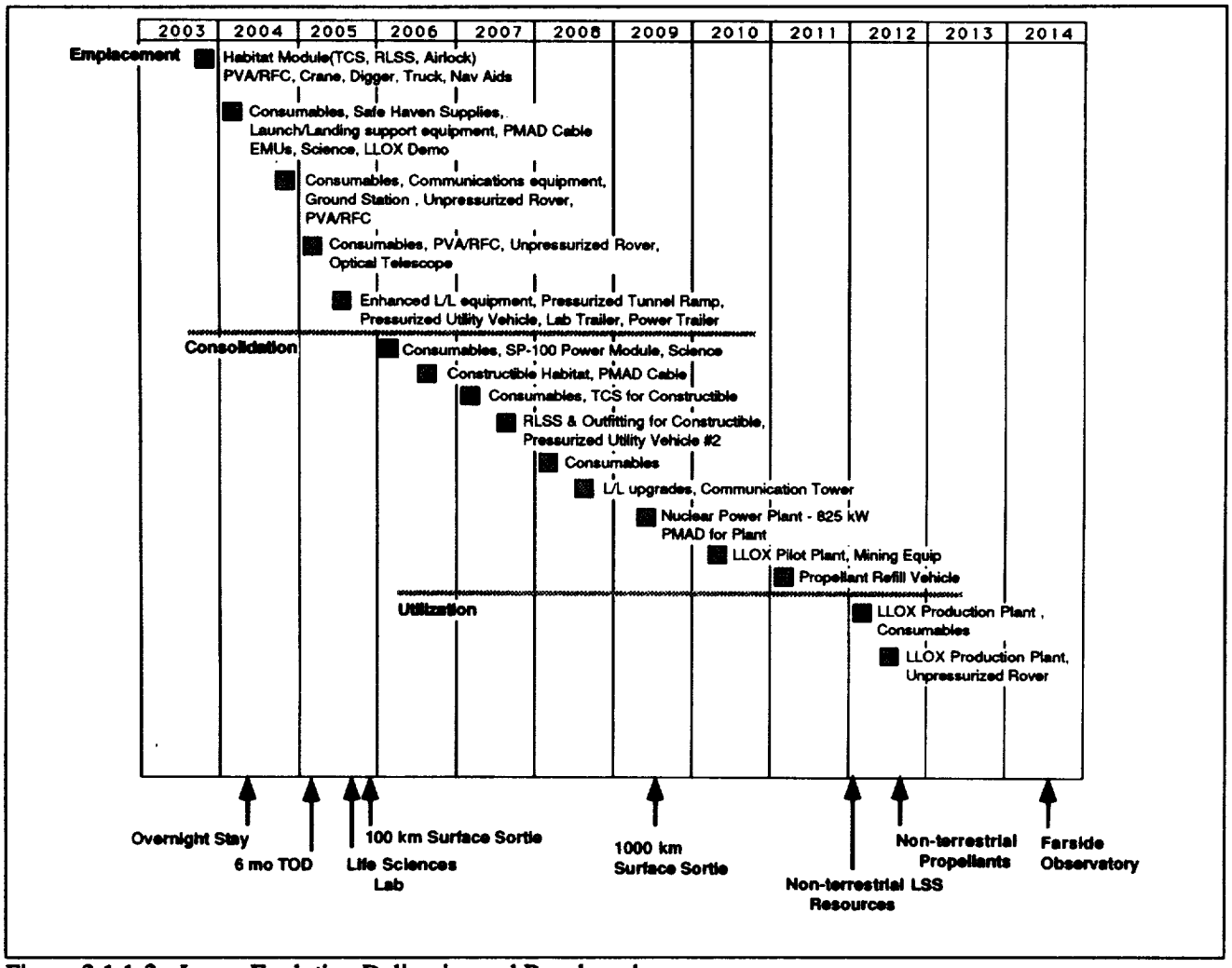



Figure 2.1.1-2.- Lunar Evolution Deliveries and Benchmarks.

## TABLE 2.1.2-I.- SURFACE SYSTEMS REQUIREMENTS COMPLIANCE

| Requirement | Response |
|---|---|
| EMPLACEMENT PHASE | |
| Human Systems | |
| • Establish habitable facility with the capability to support a crew of four up to 12 months. | • Habitat module, airlock, consumables, PVA/RFC, cable |
| • Provide radiation shielding by using local resources. | • Digger, truck |
| • Provide EVA capability of 8 hours per person per day. | • Airlock, EVA equipment, unpressurized rover |
| Construction | |
| • Provide, to the extent possible, automated placement of the initial habitat. | • TBD |
| Surface Transportation | |
| • Transport crew and cargo locally in support of science activities. | • Unpressurized rover, pressurized utility vehicle |
| In Situ Resource Utilization | |
| • Demonstrate the feasibility of producing lunar-derived liquid oxygen. | • Oxygen process demonstration plant |
| Launch and Landing Operations | |
| • Support launch and landing vehicle operations on the surface. | • Pad markers, navigation beacons, pressurized tunnel ramp |
| • Provide the capability to service, maintain, and store landers. | • Fuel cell power cart, thermal control cart, liquefaction system, tents |
| User Accommodations | |
| • Emplace a capable suite of science instruments. | • Geophysical and geological equipment, particles and fields instruments, telescopes (solar, monitoring, optical, MERI, Earth-observing), laboratories (biomedical, analytical science), teleoperated instrumented rover |
| Energy | |
| • Provide support of initial habitat and related surface activities. | • PVA/RFC (50 kW/25kW), PVA (100 kW) |
| TNIM | |
| • Provide surface communications capability (voice, data, and video). | • Ground station, communications |
| CONSOLIDATION PHASE | |
| Human Systems | |
| • Support a crew of 4 for 12 months, expanding to a crew of eight for 24 months by the end of the phase. | • Constructible habitat with thermal control system and interior outfitting |
| • Initiate a life support system that minimizes Earth resupply for consumables. | • Regenerative life support system for constructible |
| Construction | |
| • Provide capability to unload, assemble, construct, and check out lunar base system elements and user payloads. | • Crane, digger, truck, unpressurized rover, pressurized utility vehicle, enhanced off-loader, construction hand tools |
| • Provide capability to assemble and outfit constructible habitat. | • Crane, digger, truck, enhanced off-loader, construction hand tools |
| Surface Transportation | |
| • Provide mobile systems for exploration and base operations. | • Pressurized utility vehicle, power trailer, laboratory trailer |

TABLE 2.1.2-I.- SURFACE SYSTEMS REQUIREMENTS COMPLIANCE (CONTINUED)

| Requirement | Response |
|---|---|
| In Situ Resource Utilization | |
| • Establish liquid oxygen production to provide oxidizer for one lander round trip per year to retrieve 20 t payload. | • Oxygen production plant, plant beneficiation equipment, mining equipment, power distribution system |
| Launch and Landing Operations | |
| • Facilitate the storage, management, and transfer of lunar-produced liquid oxygen. | • Propellant refill vehicle, lander facility upgrades |
| User Accommodations | |
| • Emplace a capable suite of science instruments. | • Geological equipment, telescopes (UV, IR, optical, gamma ray, X-ray), microbial lab |
| Energy | |
| • Provide power to constructible habitat and increased base operations. | • SP-100 power module, nuclear power plant (825 kW) |
| TNIM | |
| • Extend surface communications capability for navigation purposes. | • Communications tower |
| UTILIZATION PHASE | |
| Human Systems | |
| • Support a crew of 8 for 24 months, expanding to a crew of 12 for 24 months. | • Constructible habitat with thermal control system and interior outfitting |
| • Increase closure of life support system (95% air and water closure) using indigenous resources. | • Regenerative life support system for constructible, lunar oxygen production |
| Construction | |
| • Provide capability to unload, assemble, construct, and check out a farside observatory. | • Unpressurized rover, construction hand tools |
| Surface Transportation | |
| • Provide capabilities for long distance surface sorties. | • Pressurized utility vehicle, extended power trailer, laboratory trailer |
| • Provide global access using suborbital means. | • Ballistic vehicle |
| • Provide local crew transport at farside observatory. | • Unpressurized rover |
| In Situ Resource Utilization | |
| • Mine lunar regolith for production process. | • Mining equipment |
| • Expand oxygen production to support landers. | |
| Launch and Landing Operations | |
| • Provide vehicle accommodations for suborbital exploration systems. | • Pad markers, navigation beacons, pressurized tunnel ramp, fuel cell power cart, thermal control cart, liquefaction system, tents, propellant refill vehicle |
| • Provide launch and landing capability at farside observatory. | • Pad markers, navigation beacons |
| User Accommodations | |
| • Expand science activities to perform exploration and experimentation beyond the base (at farside observatory and globally). | • Low frequency radio array, science expedition packages |
| Energy | |
| • Increase power and thermal management in support of advanced oxygen production facilities | • Extended power distribution system |

the requirements as referenced to the SRD and the PSS response. The requirements and matching responses are organized according to base phase and functional area. Further detail on these elements and their selection for the lunar case study appear in section 2.2.

## 2.2 LUNAR SURFACE SYSTEMS SELECTION

As previously noted, the lunar surface system elements are selected in response to the requirements specified in the Mission Analysis and System Engineering (MASE) Study Requirements Document (SRD) and the integrated mission manifest. Elements are categorized according to the functional areas devised by the Planet Surface Systems Integration Agent (PSSIA).

Table 2.2-I summarizes the major elements selected for the lunar evolution case study with an accompanying brief functional description and estimates for mass, power required, and volume. The science equipment manifested for the base is not selected by the PSS office, since it is not considered surface systems support. To provide a complete picture of the elements located at the base, table 2.2-II lists the major science users with corresponding mass, power required, and volume values.

### 2.2.1 Habitation

During the emplacement phase of the lunar base, a Space Station Freedom-derived common module (4.5 m x 13.7 m) is selected for the initial habitat. The single module provides shelter for crews of four persons for durations of 30 days to one year. The module interior is adapted to the constraints of the 1/6 gravity environment with specifications for sleeping berths, galley, health maintenance facility, and storage space. Volume limitations restrict the amount of space for science users to approximately one rack. Residence in the module is highlighted by the predominance of construction operations.

The initial module is designed as a self-contained structure, including the life support system, thermal control system, and logistics supplies. Only the primary power source is located external to the habitat. This prefabricated, all-in-one approach is necessary in order to allow crews to focus on base establishment and surface science activities. The module is delivered to the Moon on a cargo lander and placed on the surface (perhaps robotically), such that the first crew need only to connect the power supply and certify the module for pressurized occupation.

As the base grows, the requirements for pressurized volume for crew accommodations, lab equipment, workspace, and storage increase substantially. A spherical constructible habitat 16 meters in diameter is defined for the second generation of base habitation, as opposed to a multiple common module configuration. A direct comparison between the constructible and modular approaches is presented in figure 2.2.1-1. Note that the 16 meter diameter habitat provides the volume equivalent to 11 common modules, with a structural mass slightly greater than two modules. Even if the base expanded through the use of multiple linked modules, at some time a single large volume would be desired instead of corridor-like living spaces.

The reference concept provides living accommodations for 16 persons, although the lunar evolution case study configuration calls for twelve. The habitat requires roughly one year to construct, due to the frequency of cargo deliveries. Construction tasks include excavating the site, inflating the structure, installing the life support and thermal control systems, outfitting the interior, connecting utilities, and emplacing radiation protection. The inflatable sphere is also selected from a variety of constructible options due to mature design definition and extensive study.

### 2.2.2 Extravehicular Activity (EVA) Systems

Development of the lunar base requires frequent EVA's for purposes of base construction, operation, maintenance, and scientific exploration. An extravehicular mobility unit (EMU), consisting of a pressure suit and portable life support system (PLSS) developed specifically for the lunar environment, is central to the EVA system. EVA systems are further enhanced with Shuttle-type hand tools and unpressurized rovers for local area access.

Requirements for non-orbital EMU's include minimum weight and volume, long-term durability and reliability, and efficient servicing and maintenance. The PLSS design is driven by the case study emphasis on reduction of resupply logistics, thus leading to the choice of a regenerative system. The human carrying capacity on the Moon limits the PLSS mass to 121 kg, compared to the Space Station Freedom (SSF) regenerable PLSS of 195 kg mass. In order to use SSF technology, additional options are employed on the Moon, such as changeable ice packs for thermal cooling and umbilical connections from the rover. Factors affecting the design further include suit versus habitat pressure levels, currently baselined at 57.2 kPa and 101.3 kPa (8.3 psi and 14.7 psi) respectively, and the duration of the EVA, set at eight hours for the lunar case study.

The airlock design facilitates EVA operations. Lunar dust contamination in the pressurized facilities is a major concern. A dust porch with brushes and grates is located outside of the airlock for overgarment removal. Further-

## TABLE 2.2-I.- SELECTED LUNAR SURFACE ELEMENTS

| Element | Mass (t) | Volume ($m^3$) | Power Req. (kW) | Functional Description |
|---|---|---|---|---|
| Habitat Module | 13.7 | 200 | 40 | Provides safe accommodations for a crew of four for 30 days to 12 months. |
| Photovoltaic Array/ | 0.97 | - - | N/A | Provides power for base day and night operations with |
| Regenerative Fuel Cells | 9.1 | | | increments of 50/25 kWe. |
| Crane | 1.9 | 273 | 5 | Unloads payloads up to 20 t. Self-propelled to transport payloads. Provides access for construction activities via telescopic boom. |
| Digger | 1.9 | 94.5 | 5 | Trenches in mining operations. Displaces regolith for radiation protection. Prepares sites and road with angle dozer. |
| Truck | 1.9 | 43.8 | 5 | Hauls regolith in mining operations. Provides means for short scientific traverses. Provides means for transporting payloads up to 2.5 t. Provides support of local base operations. |
| Telerobotic Rover | 3.0 | 15.0 | S/C | Provides scientific access to remote sites. |
| Fuel Cell Power Cart | 6.8 | 7.3 | N/A | Provides supplemental power at site removed from main power source. |
| Thermal Control Cart | 1.2 | | N/A | Provides a means of heat rejection at remote sites such as launch and landing areas. |
| Airlock | 3.7 | 25 | 5 | Provides ingress and egress capability to pressurized facilities. Provides a safe means for donning and doffing EVA equipment. Provides a reliable means for dust contamination control. |
| Cable | 1 | 1.3* | N/A | Provides utilities interface between source and systems. |
| Pad Marker | 0.01 | 0.03 | N/A | Provides in-flight sightings of landing pads. |
| Navigation Beacons | 0.1 | | N/A | Provides in-flight navigational assistance. |
| Construction Hand Tools | 0.5 | | N/A | Provides a means of effecting small construction and repair tasks. |
| Lunar EMU | 0.16 | 1 | | Enables EVA activities on surface. |
| Lunar Oxygen Demonstration | 0.2 | 1 | 2.9 | Demonstrates feasibility of ilmenite reduction process to produce liquid oxygen. |
| Lunar Oxygen Pilot Plant | 25 | 390 | 146 | Continues to demonstrate lunar oxygen production with capability of 24 t/yr. |
| Lunar Oxygen Production Plant | 75 | 1,170 | 438 | Provides full production capability of lunar oxygen with 100 t/yr benchmark (3 units and pilot). |
| Propellant Refill Vehicle | 14 | 16.8 | N/A | Provides a means of refueling lunar landers from lunar oxygen supply. |
| Interconnect Node | 4.7 | | 5 | Provides means of circulation between two or more habitable volumes. |
| Communication Tower | 0.1 | | 0.3 | Enables VHF communications of base. |
| Ground Station | 1 | | 1 | Provides a "dedicated" central facility to regulate base communication traffic. |
| Unpressurized Rover | 0.7 | 15 | 2.3 | Provides a means of local transportation in base area (10 km). |
| Pressurized Tunnel Ramp | 2.8 | 63 | 1 | Provides pressurized access between lunar landers and surface vehicles. |
| Pressurized Utility Vehicle | 5.6 | 144 | 12 | Provides a means for carrying crew, tools, and materials to construction, repair, and remote science sites (100 km). |
| Laboratory Trailer | 5.6 | 144 | 12 | Provides required pressurized laboratory volume for early science requirements. Provides pressurized laboratory for remote sites. |
| Power Trailer | 5.2 | - - | 6 | Provides a power source for remote operations. Provides auxiliary power for base operations. |
| SP-100 Power Module | 5 | | N/A | Provides required energy up to 100 kWe for mining and processing operations. |
| Nuclear Power Plant | 14.9 | 291 | N/A | Provides energy up to 825 kWe for base activities. |
| Constructible Habitat | 18.5 | 2,145 | 80 | Provides larger habitable volume for increased crew size and increased laboratory requirements. |
| Constructible Hab. TCS | 5.3 | 13.6 | 36 | Provides rejection of waste heat from constructible habitat. |
| Constructible Hab. ECLSS | 16.8 | 49.3 | 8.5 | Provides necessary life support and environmental control for constructible habitat. |
| Constructible Hab. Outfitting | 27.7 | | N/A | Includes interior furnishings to carry out base activities. |

Notes:
*indicates length in kilometers.

TABLE 2.2-II.- LUNAR SCIENCE USER ELEMENTS

| User Element | Launch Mass (kg) | Power Required (kW) | Pressurized Volume ($m^3$) |
|---|---|---|---|
| Geologic Field Equipment | 80 | -- | -- |
| Preliminary Petrology Analysis Lab | 1,200 | 10.7 | 6.5 |
| Portable Geo. Exper. Package--shallow | 1,220 | 0.1 | -- |
| Portable Geo. Exper. Package--deep | 50 | 0.1 | -- |
| Traverse Exploration Package | 110 | 0.3 | -- |
| Field Geology and Equipment | 90 | -- | -- |
| Penetrators and Sieves | 100 | 0.2 | -- |
| Geophysical Stations | 111 | -- | -- |
| Physics Instrumentation | 100 | -- | -- |
| Optical Telescope (1 m) | 870 | 4.0 | -- |
| Initial Low Frequency Array | 100 | -- | -- |
| Radio Interferometer | 2,100 | 0.7 | -- |
| Gamma Ray Telescope | 3,820 | 0.3 | -- |
| X-ray Telescope | 2,850 | 1.0 | -- |
| Ultraviolet Telescope | 730 | 4.0 | -- |
| Infrared Telescope | 5,700 | 1.2 | -- |
| Solar Observatory | 2,300 | 3.0 | -- |
| Earth Observatory | 2,100 | 3.0 | -- |
| Initial Monitoring Telescope | 100 | 0.4 | -- |
| Monitoring Telescope | 10 | -- | -- |
| Higher Animal Lab | 8,600 | 4.0 | 45.9 |
| Microbial Animal Lab | 400 | 1.9 | 4.5 |
| Higher Plant Lab | 3,700 | 3.2 | 13.2 |
| Microbial Plant Lab | 400 | 2.4 | 2.4 |
| Advanced CELSS Lab | 5,800 | 4.5 | 22.3 |
| Biomedical Lab | 3,700 | 4.2 | 14.5 |

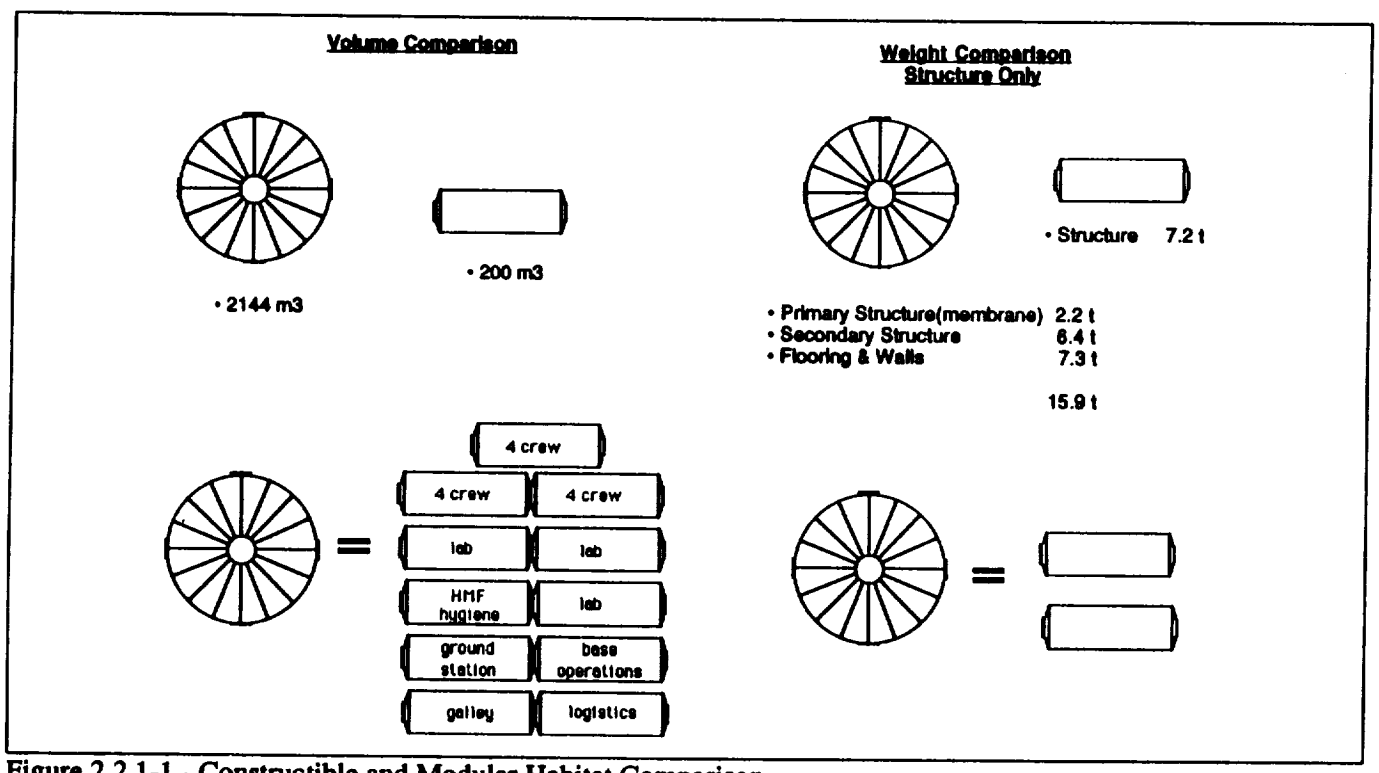



Figure 2.2.1-1.- Constructible and Modular Habitat Comparison.

more, a dual airlock layout, with a crew lock and an equipment lock, keeps any remaining dust in the outer lock. Two airlocks are manifested to support EVA activities from both the construction shack and the constructible habitat. Figure 2.2.2-1 shows EMU servicing in the equipment lock.

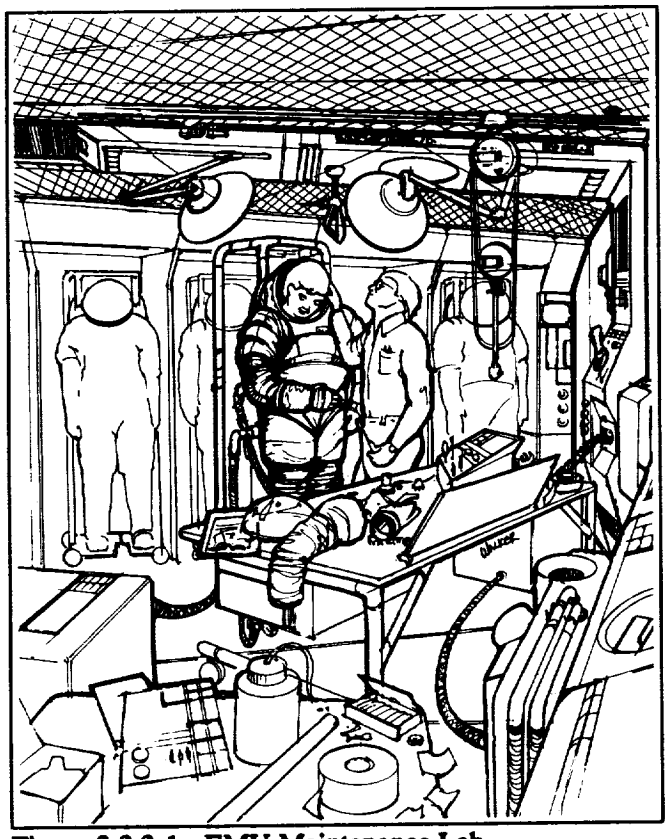


Figure 2.2.2-1.- EMU Maintenance Lab.

### 2.2.3 Life Support Systems

The life support system selected for the evolutionary lunar base is a regenenerable physical-chemical system. This system evolves in two phases, initial and advanced, as the base expands to include larger crews. The initial life support system (ILSS), a derivation of the SSF system, is integrated into the construction shack servicing a crew of four. The ILSS is required to provide a functional closure level of 96 percent; i.e. 96 percent of water and air fluids are recovered through the system. Resupplies for ILSS include nitrogen, food, and system and crew expendables.

With the construction of the inflatable habitat, an advanced life support system (ALSS) is installed to service crews up to twelve persons. The ALSS marks improvements over the ILSS by advancing the recovery of materials from solid wastes and reducing resupply of system expendables. The ALSS also uses lunar-derived oxygen in the regenerable system, thus achieving a functional closure level of approximately 99 percent. Resupplies are still required for nitrogen, food, and crew expendables.

Although not defined in the lunar evolution case study, the next phase of life support includes food production. The mature life support system (MLSS) integrates the physical-chemical systems with a bioregenerative approach as an attempt to increase base self-sufficiency. In addition to providing air and water loop closure, the MLSS starts to close the food loop. Initiating this approach demands a more advanced base with larger crews and extensive pressurized facilities.

### 2.2.4 Thermal Control System

Thermal control systems (TCS) for the initial module and constructible habitat require an active system. The internal TCS selected is similar to the SSF definition--two single-phase water loops operating at 2°C and 21°C for the acquisition of metabolic and equipment heat loads. The total heat load for water loop collection is 25 kW for the initial module and 65 kW for the constructible habitat.

The final step of the active TCS is the rejection of the waste heat to the lunar environment. The design of the radiator system is dependent upon the daily thermal characteristics at the base location, for this case the radiators must function in the temperature extremes of the near-side equatorial region. The selected TCS transports the internal waste heat to the rejection system via a two-phase pumped freon-12 loop operating at -3°C. The rejection system includes a two-stage vapor cycle system, which is basically a heat pump system that raises the radiator rejection temperature, connected to vertically mounted radiators oriented parallel to the plane of the solar ecliptic. The construction shack requires a radiator area of 70 $m^2$ and the constructible habitat requires a radiator of 175 $m^2$.

### 2.2.5 Radiation Protection

Lunar crews require protection from the constant galactic cosmic ray (GCR) background and infrequent, but harmful solar particle events. Recent studies indicate that for crew stay times of less than one year, GCR protection is not required (Nachtway, 1989). In light of the short crew stay times during the emplacement phase, GCR protection with respect to the initial module is not provided. Solar particle event protection constitutes a heavily shielded area at one end of the module. As base capabilities permit, the module is eventually covered with regolith and treated as a safe haven.

Longer durations on the lunar surface necessitate GCR protection at some level. Crews reside in the constructible habitat for up to two years, so a 0.5 meter regolith layer is positioned over the exposed structure. This selected thickness yields a dosage of on the order of 15-20 rem per year based on an annual GCR dose and a time-integrated dose for individual particle events. (The limit for astronauts is currently set at 50 rem per year for the blood-forming organs.) The method of layering the regolith over the constructible includes a variety of options--loose piling, regolith bags, continuous coil bags, and retaining walls or forms. Simple piling involves extensive regolith moving due to the low slump angle, while other methods represent a mass penalty for additional structure (bags, panels, etc.). A particular method has not been selected for this case study. This matter is recommended for study during FY 1990.

### 2.2.6 Power

The expanding nature of the lunar base dictates an evolutionary approach to the power generation system. During the emplacement phase, a solar power system is selected as the major stationary power source. This initial system is a combination of photovoltaic arrays (PVA) for daytime energy needs and regenerative fuel cells (RFC), charged from the PVA, for power during the long lunar night. Due to extensive PVA/RFC space experience, the lunar application provides a very safe and highly reliable surface power supply for early base operations. Note that the loss of any number of individual photovoltaic cells does not prevent the remaining undamaged cells from generating power.

Due to the lack of solar collection during the 14-day night, the storage requirements for the RFC are massive. The first delivered PVA/RFC system provides 50 kW during the day and 25 kW during the night, with the PVA weighing 970 kg versus 9.1 t for the RFC. Higher levels of power at night require more fuel cells (much more mass), so base nighttime activities are maintained at a reduced level. The initial 50/25 kW system is doubled in the second year, followed by a 100 kW array (no additional storage) for increased day power.

As night power demands grow, solar systems become unwieldy. Above 100-200 kW, nuclear power offers reduced system mass compared to fuel cells. During the consolidation phase, the constructible habitat requires a significant power supply around the clock. As a result, an SP-100 nuclear reactor, adapted for planetary surfaces and providing 100 kW continuously, is selected for delivery before completion of the habitat.

The utilization phase is characterized by full-scale lunar oxygen production requiring power supplies in the megawatt range. Round-the-clock plant operation requires a round-the-clock nuclear power generation system. The higher specific power for nuclear systems leads to the selection of an 825 kW nuclear power system for base stationary power. The nuclear system design, based on SP-100 technology, uses Sterling engines for power conversion. This selection of power source is more efficient than multiple SP-100 units: 20 t for 825 kW as opposed to 40 t for eight SP-100's. The larger nuclear sources are buried below grade for safety reasons.

### 2.2.7 Assembly and Construction

The characterization of the lunar base as a permanent facility implies the need for assembly and construction capabilities for long-term structures. Such capabilities include lifting of massive payloads, carrying payloads to the emplacement site, and regolith moving and excavating for site preparation. Selected assembly and construction equipment also share common functions with machinery for resource mining and lander payload unloading.

The analysis performed for this year's case studies in the area of assembly and construction does not address specific equipment design, rather the focus is placed on defining the requirements for base construction. Therefore, the equipment selected to support construction operations is estimated from previous studies while detailed design concepts are under consideration. The equipment manifested in the first cargo flight, 2003, includes a crane to manage off-loading payloads, a digger for surface preparation, and a truck for payload surface transport. Each of these pieces weighs approximately 2 t and supports the construction and assembly during the emplacement and consolidation phases. Under the heading of lander facility upgrades, enhanced off-loading equipment is delivered in 2008 to assist construction and placement of the nuclear plant and oxygen production facilities.

An alternative to using individual pieces of machinery for particular tasks is to employ a prime mover or mobile platform outfitted with a number of removable and replaceable implements. The range of implements for multipurpose functions include reverse clam-shell digger, robotic arm, drill assembly, and grader blade. Further characterization of the equipment in terms of mass, power and productivity is required before an element selection can be performed. Section 6.2 provides an in-depth discussion regarding construction operations for the lunar evolution case study. Operations analyses are based on particular tasks, productivity levels, and assumed equipment functions.

### 2.2.8 Surface Transportation

Surface transportation of varying degrees is required throughout base development for the transport of both crew and cargo. With the delivery of the first crew in 2004, an unpressurized, manned rover is included. The four-wheeled vehicle selected resembles the Apollo rover. The vehicle satisfies local crew transport, within 10 km of the base, for EVA surface activities and carrying equipment in the vicinity. The rover's payload capacity includes two suited crew and 500 kg of payload or four suited crew with minimal payload. Further characteristics include a 100 km range (total sortie distance), a 10 km/hr speed, a 20 degree maximum climbing grade, and a 10 hour maximum sortie time. Two of these unpressurized rovers are delivered in the first two years, with a third added in 2012.

A pressurized utility vehicle (PUV) arrives in 2005 to support base establishment efforts. The four-wheeled mobile module selected for the lunar case study transports crews of four with a mid-range of approximately 100 km. The pressurized rover, equipped with an airlock, provides the following capabilities: 72 hours maximum sortie time, support for a 1 t payload, support for one two-person EVA per day, and a 10 km/hr speed. The pressurized utility vehicle satisfies the transportation needs for mid-range scientific excursions, taxi trips to and from the base and landing pad, and EVA reduction work for construction and maintenance operations. A small 14 kW power trailer (fuel cell energy storage) and a pressurized laboratory unit are manifested early in the base development, extending the science excursion capabilities. A second PUV is delivered in 2007, outfitted with a larger 25 kW power trailer. The power extension increases the vehicle's capabilities to 1,000 km and expedition times up to 14 days. The PUV also has the capability to dock directly to the habitats, providing pressurized transfer of crew between rover and habitat. Combined with the tunnel ramp (delivered in 2005), a crew is able to transfer from the PUV to the lander without having to incur the overhead of EVA.

During the utilization phase, scientific excursions to remote locations on the Moon (far side and poles) are scheduled. Due to the danger and demands inherent in long-duration excursions away from the base, rovers are unsuitable for such long traverses. One ballistic vehicle is manifested in 2012 to accomplish these remote reconnaissance missions. The ballistic vehicle is simply a variation on the lunar excursion vehicles that support the lunar orbit to surface route. Although not considered a surface element, the ballistic vehicle uses locally produced oxygen to satisfy its large fuel requirement, approximately 37 t liquid oxygen and 7.3 t liquid hydrogen.

### 2.2.9 In Situ Resource Utilization

The lunar evolution case study recognizes the potentially substantial savings and enhancements obtained through the use of lunar-derived products, provided that they are of sufficiently high value to justify the overhead of the production facilities. The product selected for inclusion in this case study is liquid oxygen extracted from the lunar soil. The oxygen product is utilized as a base resource to supply oxidizer to the landers and gaseous makeup for the life support system.

Several competing concept processes exist for lunar oxygen production. Hydrogen reduction of ilmenite is the selected process, characterized as less difficult chemically and technologically, and requiring less power than most other candidates. Subject to the most analysis in recent years, the hydrogen reduction process offers a reasonable point of departure for further analysis of a total oxygen producing base architecture. Figure 2.2.9-1 shows a 100 t/year hydrogen reduction of ilmenite plant. The ilmenite content of some lunar soil is 8 percent by weight and 5 percent by volume, with a corresponding availability of oxygen in ilmenite of 10.5 percent. The

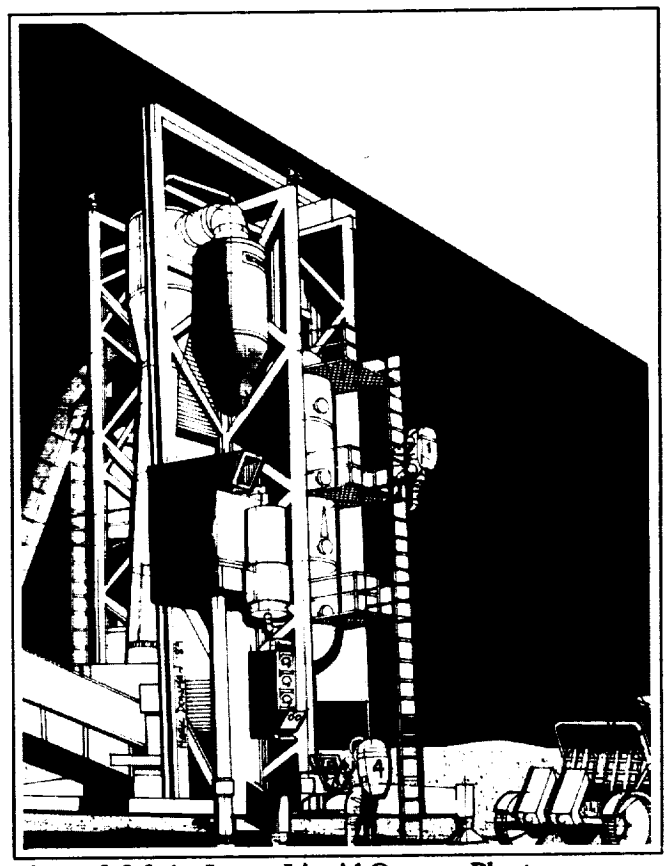


Figure 2.2.9-1.- Lunar Liquid Oxygen Plant.

process includes three basic steps: 1) the separation of ilmenite from lunar soil, 2) the reaction of hydrogen with ilmenite to form steam, and 3) the electrolyzing of water to form hydrogen (recycled) and oxygen. Associated with the chosen process are extensive mining operations. The low natural ilmenite concentration demands the excavation of approximately 300 t of raw soil to produce 1 t of oxygen. In addition to the mining equipment and chemical processing plant, further support is required, including beneficiation equipment, an oxygen liquefier, storage tanks, and thermal control system.

The capability to produce oxygen is developed gradually in the case study. One of the early base objectives is the successful operation of a small ilmenite process certification apparatus. Lessons learned from this test bed guide the design of a pilot plant producing 24 t of liquid oxygen per year. By 2012, three additional modular plants are emplaced, thus increasing the production capacity to roughly 100 t per year. With the utilization phase underway, the lunar-derived oxygen supply replenishes all of the landers, one ballistic vehicle per year, and the life support system.

### 2.2.10 Launch and Landing Systems

Beginning in 2005, landers (cargo and personnel) are designed as reusable vehicles. A major requirement associated with the lunar evolution case study is to maintain and service the landers at the base. Accordingly, launch and landing systems are manifested to provide flight vehicle turnaround on the lunar surface. A minimum required turnaround time is estimated to be 55 hours, 15 minutes, exclusive of flight and surface systems maintenance, which remains a variable. The launch and landing systems service a flight rate of two flights per year from 2005 to 2015 and two flights per year from 2013 to 2015.

A suite of surface support equipment is selected to support launch and landing operations. A thermal control cart is required to dissipate heat generated by flight vehicle systems while the lander is sitting on the lunar surface for long time periods. A reliquefaction facility is provided in the vicinity of the pads in order to reclaim cryogenic propellant boil-off from vehicle tanks. When lunar-derived oxygen becomes available, an oxygen boil-off vent line is necessary to route residual boil-off to the lunar vacuum. Light-weight thermal blankets are used to shield the landers from direct solar thermal radiation and micrometeorites. Additional elements selected to service the launch and landing facility include navigational aids, an electrical grounding system, a range safety system, an engine handling fixture, and blast protection. Finally, a propellant refill vehicle with boil-off control is provided to transfer propellants between the landers, base storage facilities, and the oxygen production plants.

A viable balance between vehicle complexity and reliability and surface systems complexity and capability needs to be established. Vehicle servicing in the harsh lunar environment may eventually prove impractical. Extensive lander accommodations, particularly a pressurized maintenance area, are under consideration but not included in the reference case study manifest.

### 2.2.11 User Accommodations

Table 2.2-II, as previously listed, describes the variety of science equipment to be emplaced on the lunar surface. The specific science elements are defined by MASE as part of the case study objectives. Therefore, the PSS office is not responsible for selecting science equipment like other surface systems. Rather, the function of the user accommodations area is to ensure that user elements receive the required support from the established base systems. Support for user activities comes in the form of pressurized volume, power, communications, surface transportation, and crew. Results of user accommodations at the lunar base are discussed in section 2.4, Performance Assessments.

After consideration of the science requirements specified by MASE, the PSS office has one recommendation to make for accommodation of user science. The recommendation concerns the farside radio observatory manifested in 2013 and emplaced in 2014. Designs of such observatories often consist primarily of an array of dozens, perhaps hundreds, of tiny receivers arranged on the surface in a precise geometric pattern, forming a large low-frequency radio telescope. The reference manifest specifies a manned deployment of the array using a single ballistic vehicle flight for transport to the far side. Basically, deployment of a large array over a considerable area most likely requires several visits to complete, given reasonable assumptions about the capabilities of the manned vehicle and EVA limitations.

A design study was conducted to evaluate and characterize an unmanned system for this task. The automated system consists of a small (2.8 t loaded), semi-autonomous rover delivered in a single expendable vehicle. The rover deploys an initial array of 300 elements in a 17 km spiral. Once completed, a second package is retrieved from the lander for deployment of an additional 300 elements. The study concluded that such an automated deployment sequence accomplishes the job at a lower cost and reduced risk than a manned deployment. Human far side visits could thus be focused on exploration and geology, rather than mundane "drop-rove-

drop" traverses constrained by the need to follow a set course.

### 2.2.12 Telecommunications, Navigation, and Information Management

Various navigation and communication functions are provided by base support systems. The exact requirements depend on the space communication network capability between the Earth and Moon as well as locally on the lunar surface. A single geosynchronous relay satellite (GRS) provides the primary relay for all communications between the Moon and Earth by linking a US-based ground terminal with the nearside lunar base terminal. Base elements are supported by the nearside terminal and by a lunar relay satellite (LRS) in a halo orbit about the L1 libration point. The lunar ground terminal consists of one 4-meter diameter antenna for direct link to the GRS, one 3-meter diameter antenna for links to the LRS, and a 30-meter ultra high frequency (UHF) antenna mast for 10 km line-of-sight communication to surface elements. Additional communications instrumentation is located in the base operations area of the constructible habitat. To assist in high data rate transmission within 10 km of the ground station, hardwire interfaces (coaxial cables) are installed. Farside lunar communications include one 1.5-meter diameter antenna for link to the farside LRS and cable interfaces for surface support. Individual surface elements, such as science instruments and rovers, are equipped with dedicated antennas in the Ka-band.

## 2.3 BASE SITE AND LAYOUT

The following sections describe the base site and layout and the transportation linkages between the various parts of the base.

### 2.3.1 Site Specifications

The lunar evolution base site is located on the near side at the equator just north of the crater Moltke in the southern region of Mare Tranquillitatis, approximately 0 degrees latitude and 24 degrees longitude. This site offers three operational advantages. First, the equatorial location of the base ensures daily access to the low lunar parking orbit. Second, the site is about 25 km from the Apollo 11 landing site and 50 km from the Surveyor V landing site, thus environmental data is available. Figure 2.3.1-1 is a photograph of the lunar near side with the primary base, Apollo 11, and Surveyor V sites marked. Third, the mare designation contains a high concentration of ilmenite basalts, the key in situ resource for producing oxygen via the hydrogen reduction of ilmenite technique. The low frequency array observatory is located on the lunar far side at 0 degrees latitude and 141 degrees east longitude, an excellent astronomical site for avoiding Earth radio interference.

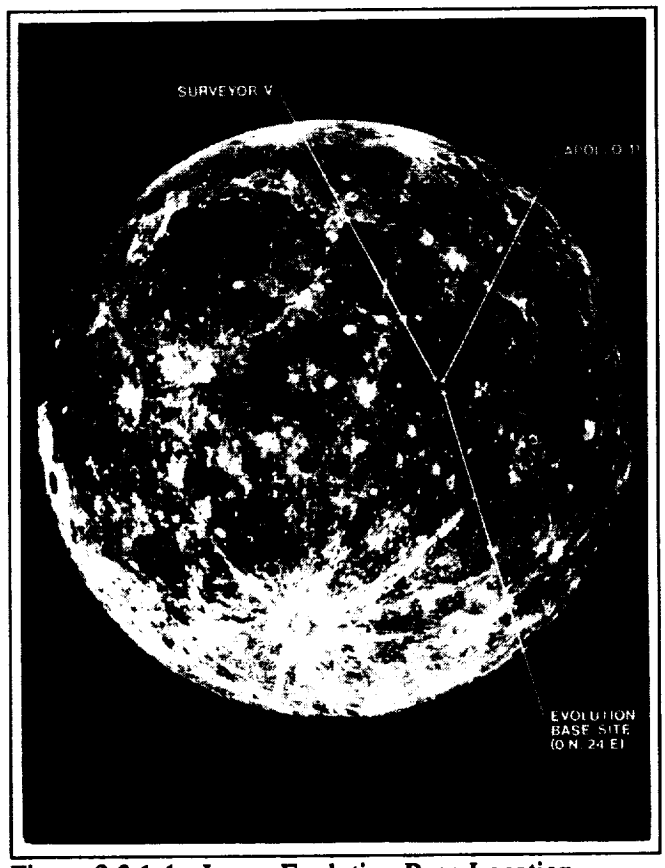


Figure 2.3.1-1.- Lunar Evolution Base Location.

The Planet Surface Systems analyses rely on site-specific environmental data in order to conduct viable design efforts. Data of interest include surface features, temperature fluctuations, diurnal cycle, and radiation levels. Of considerable importance to the construction and mining areas are the surface properties affecting decisions for habitat foundation design and excavation equipment. Subsurface properties determine potential insulation qualities of lunar regolith and effects of mining activities on surrounding areas.

The Mare Tranquillitatis site is characterized by the terrain type referred to as maria. The maria regions of the Moon are vast plains composed of basaltic lava flows that erupted after the highlands and the impact basins formed. The basalt may be several kilometers thick, but is still only a small part of the crust that is approximately 60 km thick. Lunar environmental characteristics are summarized in table 2.3.1-I.

The surface of the Moon is primarily brecciated, or fragmented. The upper portion, the regolith, is composed of shocked fragments of rocks, minerals, and glass debris formed by meteorite impacts. The depth of the

TABLE 2.3.1-I.- LUNAR ENVIRONMENTAL SUMMARY

| Characteristic | Value |
|---|---|
| Circumference | 3,476 km |
| Gravity | 0.165 g |
| Day Cycle | 14.75 days of sunlight |
| Night Cycle | 14.75 days of darkness |
| Temperature Range | 384°K (day), 102°K (night) |
| Regolith Angle of Repose | 30-50 degrees |
| Atmospheric Density | $2x10^5$ molecules/$cm^3$ |
| Soil Density | |
| surface | 1 g/$cm^3$ |
| 10-20 cm depth | 1.5-2 g/$cm^3$ |
| Cohesion | 0.03 to 0.3 N/$cm^2$ |
| Albedo | |
| Oceanus Procellarum | 0.051 |
| Floor of Aristarchus | 0.176 |

regolith varies greatly and depends on the age of the underlying bedrock as well as the proximity to nearby craters and their ejecta blankets. The maria are usually covered by 3 to 16 m of regolith. Slope distributions have been derived from photogrammetric analysis and bistatic radar. In bistatic radar, a spot on the lunar surface is illuminated by a radar signal transmitted from an orbiter. The scattered signal is received on Earth. The maria slopes show typical standard deviations of approximately 3.7 degrees while the highlands are 4.5 to 6 degrees and higher.

The Apollo science experiment packages measured very little seismic activity. The Apollo lunar seismic experiments found the background noise level on the Moon to be extremely low. Apollo 11 and 12 experience suggests that the absence of an atmosphere, oceans, and cultural activities results in a background noise level on the Moon much lower than that on the Earth. An unexpected discovery of long duration L signals by the passive seismic experiment during the Apollo 12 lunar module ascent stage impact test is the result of a propagation effect.

With the lunar cycle extending each lunar day and night to 14.75 terrestrial days, the thermal environment includes extreme temperatures. At the equatorial base site, the temperature ranges from -171°C at night to 111°C during the day. The peak temperature occurs on day seven; there is about an eight-day period with temperatures over 77°C.

The Moon does not at present possess a global dipole magnetic field. However, surface remnant magnetic fields of varying direction and amplitude have been detected and mapped. Strength of surface fields is in the range of 6 to 313 gammas. The strongest fields are associated with the ancient highland areas. The charged particle flux on the lunar surface is higher than that on Earth since the Moon's magnetic field is not strong enough to prevent the direct bombardment of charged particles on the surface. There are two major sources of radiation particles, solar proton events and galactic cosmic rays originating from outside our solar system. The GCR flux is inversely proportional to the eleven year solar cycle due to interplanetary magnetic field variations. The yearly flux ranges from $1.3 \times 10^8$ protons/$cm^2$ during solar minimum to $7 \times 10^7$ protons/$cm^2$ during solar maximum. An average annual dose on the lunar surface is roughly 12 rem.

Meteorite craters have scarred the entire surface of the Moon. The process of creating these craters has taken billions of years. Meteorites of mass on the order of one microgram ($10^{-6}$ g) produce impact craters of approximately 0.1 mm diameter. In a two year period, it is estimated that one square meter of surface on the Moon will be impacted at least three times by particles with mass of one microgram or greater. Consequently, the hazard posed to astronauts on the lunar surface by meteoroid bombardment is minimal.

### 2.3.2 Base Layout

The PSS-defined lunar base layout is an assemblage of elements selected to meet the lunar evolution mission objectives. The elements are grouped in particular physical areas referred to as zones, with each zone identified by a function or activity. Placement of zones is based on optimizing surface operations and functional linkages between systems. The lunar base is divided into five major zones: zone 1, habitation; zone 2, science users; zone 3, in situ resource utilization (ISRU); zone 4, launch and landing; and zone 5, power generation and distribution. The establishment and evolution of zones is governed by the three base phases. The overall lunar evolution base layout is illustrated in figure 2.3.2-1, showing zone locations and orientations.

Zone 1--Habitation exists as the central hub of all crew activities, as depicted in figure 2.3.2-2. The pressurized facilities are the focus of this zone: the construction module for initial crew shelter, the twelve-person constructible for extended living and laboratory space, two airlocks for EVA capability, and docked utility vehicles to minimize EVA exposure. The placement of the habitation facilities is dictated by two rationales. The primary rationale concerns crew safety and specifies the isolation of the habitats from hazardous activities, such as cryogenic storage. The habitat must be at least 4 km from any established launch and landing pad in order to

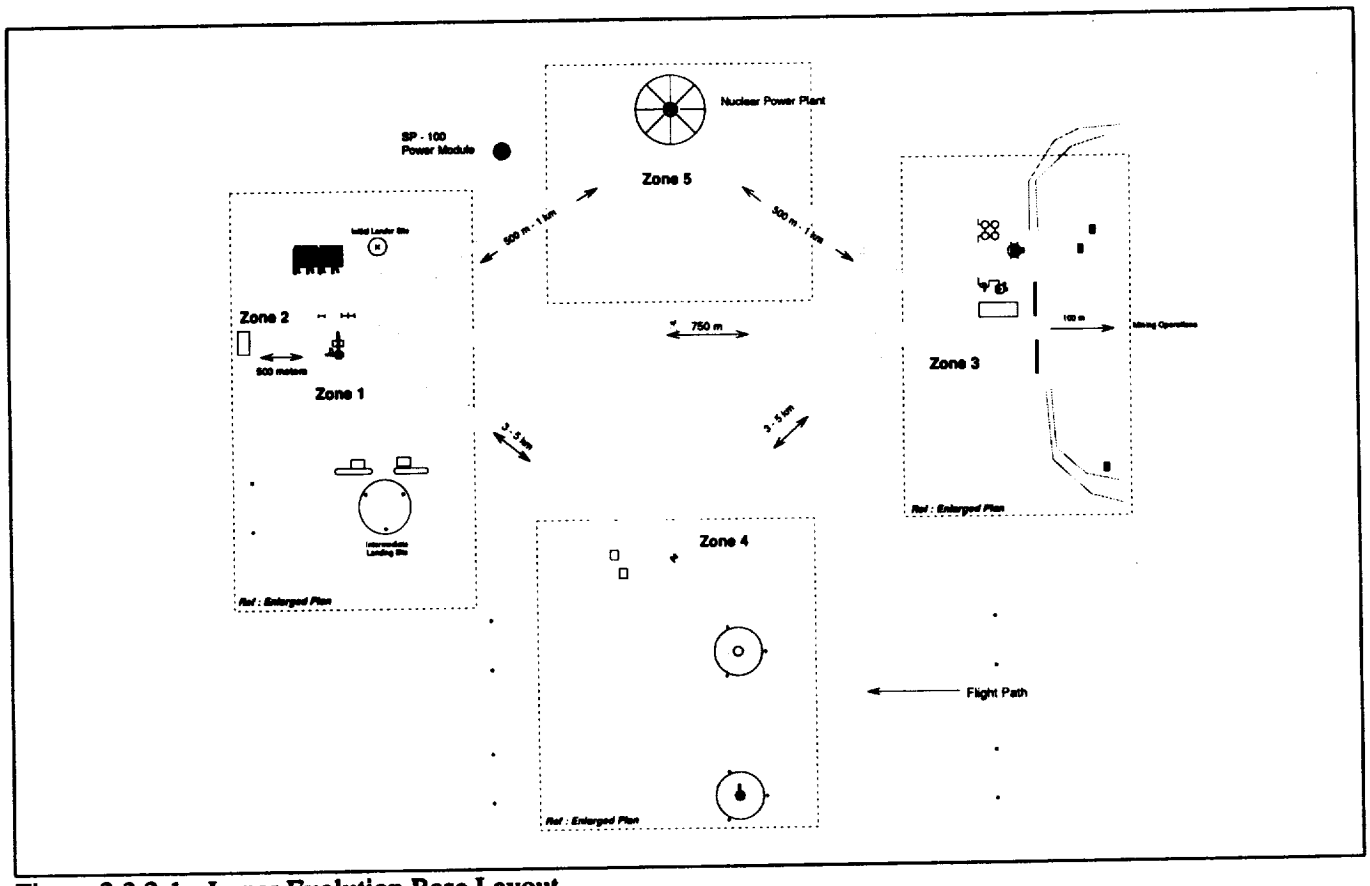



Figure 2.3.2-1.- Lunar Evolution Base Layout.

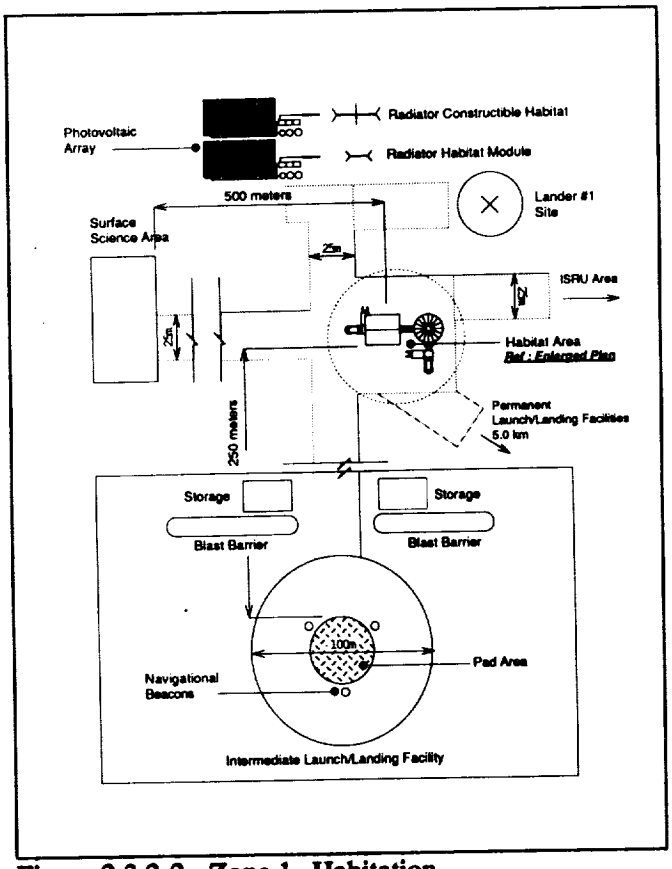



Figure 2.3.2-2.- Zone 1--Habitation.

safeguard against possible aborted landings or ejecta from landing operations. Furthermore, nuclear power plants must also be located a sufficient distance away, approximately 500 m to 1 km. The second rationale ensures provisions for pressurized facility expansion. As the base capabilities grow to include food production and crew sizes greater than twelve persons, the habitation zone will also grow to accommodate these developments. Figure 2.3.2-3 depicts zone 1 with future greenhouse and habitation facilities designated by dotted lines. Note that the habitation zone also includes the initial PVA/RFC power station, the thermal control system radiators, the central communications tower, and the initial landing pad (refer to figure 2.3.2-2). The close proximity of these support systems to the habitation zone minimizes utility cable runs and eases initial base set-up operations. The landing pads are placed 250 meters from the habitats, a reasonable distance for expendable vehicles during the emplacement phase. This distance is accessible by rover with a 1-2 minute trip at 10-15 km/hr or by walking.

Zone 2, approximately 500 meters west of the habitation zone, is an area dedicated to the science user community. The science zone provides an unobstructed surface for deploying passive science equipment independent of site

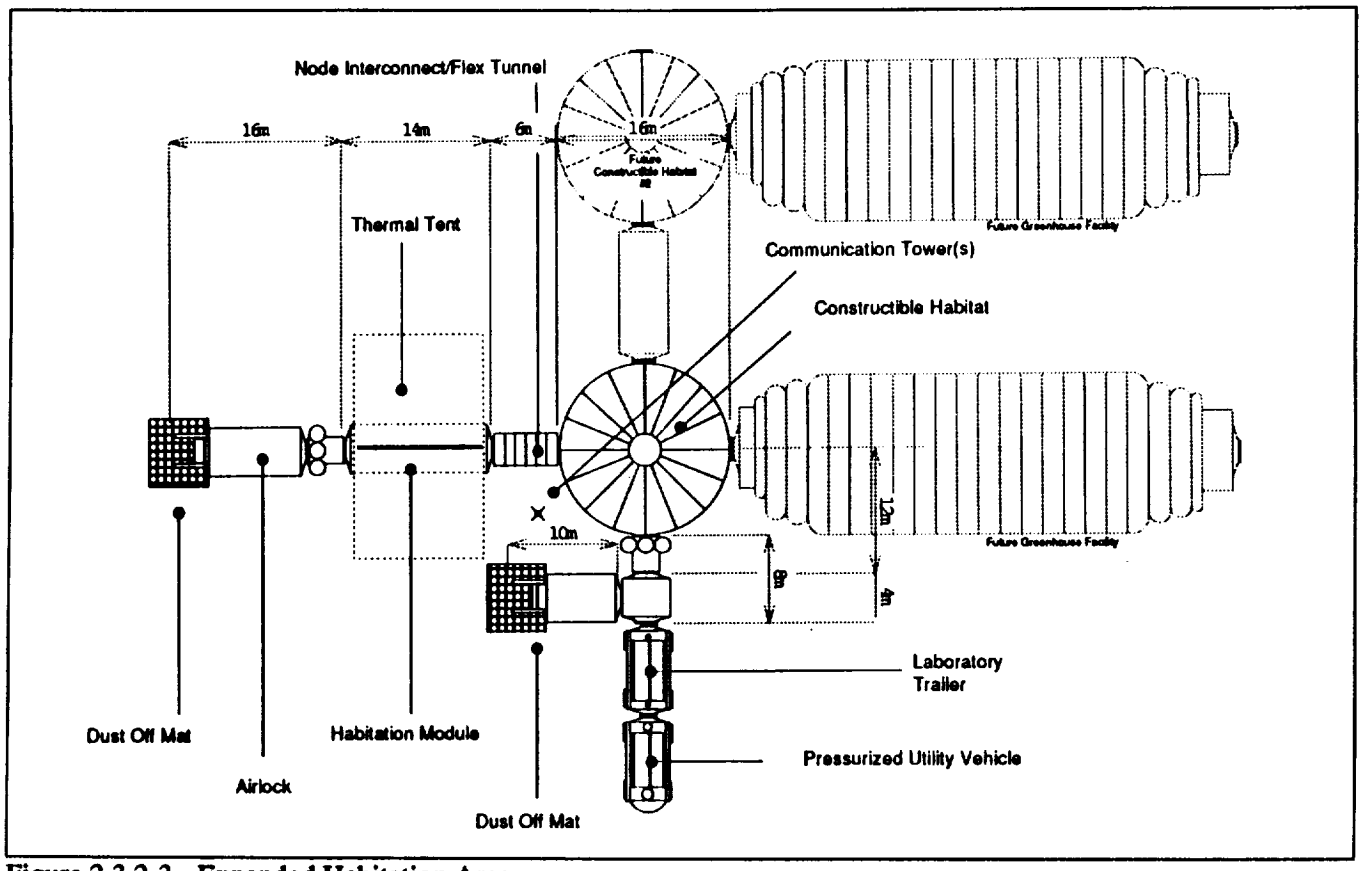



Figure 2.3.2-3.- Expanded Habitation Area.

requirements. While the planetary science equipment is placed at various remote locations, the astronomical telescopes require an area removed from activity areas yet readily accessible to the habitation zone. Instrumentation for zone 2 includes an Earth observatory, laser reflectometer, solar observatory, and optical, ultraviolet, infrared, gamma-ray, x-ray, and monitoring telescopes. Access is available via a stabilized circulation path 25 meters wide. The strategic location of zone 2 offers the science user access to the solar power supply, the communications system, the stationed utility vehicles, and the monitoring crews. Additional provisions for the area are included for dust contamination control. Placement of zone 2 with respect to the entire base is illustrated in figure 2.3.2-1.

Zone 3--ISRU, is founded during the consolidation phase and fully developed during the utilization phase. This zone, dedicated to the production of liquid oxygen, involves mining operations, processing of raw feedstock, and storing propellant. The resource utilization zone, including both pilot and production plants, maintains access to zone 1, habitation, for crew support and monitoring; and zone 4, launch and landing, for lunar excursion vehicle (LEV) propellant loading operations. The specified production rate of 100 t per year requires a mining area 92 m by 92 m and 2 m deep. Due to disruptive operations, the mining pit is located on the outer fringes of the ISRU zone, 30 meters from the process plant. This location also allows expansion for future mining activities. Surface vehicles supporting the excavation pit are provided storage and service at an adjacent protective shelter. Also located adjacent to the mining area is a tailings discharge area where tailings from the production facility are deposited by a hauler. A propellant storage facility provides buried tank storage for liquid oxygen to minimize boiloff. Liquid hydrogen is also stored to makeup process losses. An oxygen loading station, adjacent to the tanks, includes pumping equipment and a flexible hose for transferring oxygen to propellant refill vehicles. Figure 2.3.2-4 shows the layout of the ISRU zone with key hardware identified.

Zone 4 constitutes a permanent launch and landing facility operational during the consolidation phase. The lunar evolution case study requires that all reusable LEV's be based and serviced on the lunar surface. Thus, zone 4 includes both the landing pads and the service facilities necessary to maintain the LEV's at the lunar base. As seen in figure 2.3.2-5, two landing pads are aligned in a north-south orientation to accommodate east-west lander flight paths. Three navigational beacons border the perimeter of the flat, leveled surface of each pad spanning a radius of 50 meters. The pads are

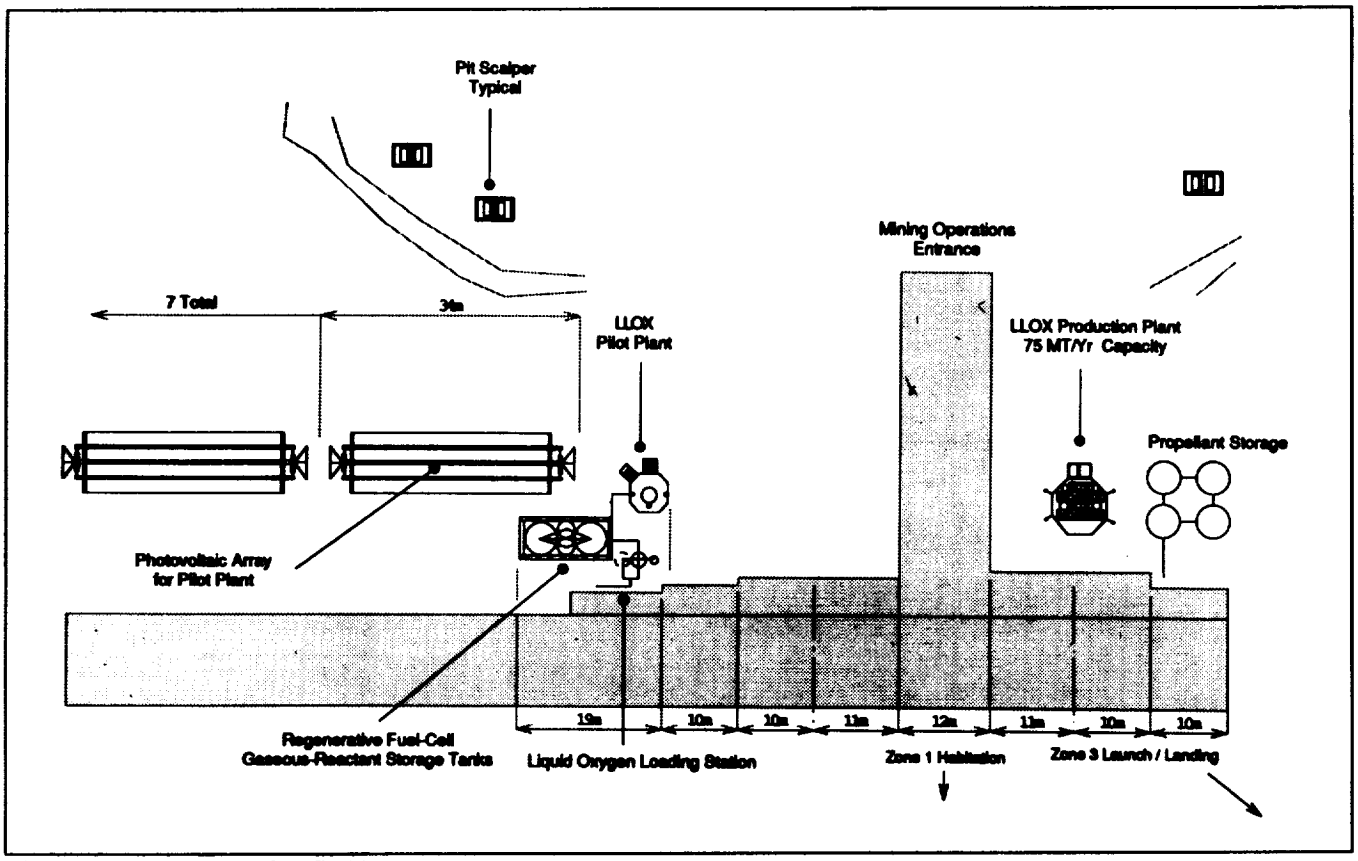



Figure 2.3.2-4.- Zone 3--ISRU.

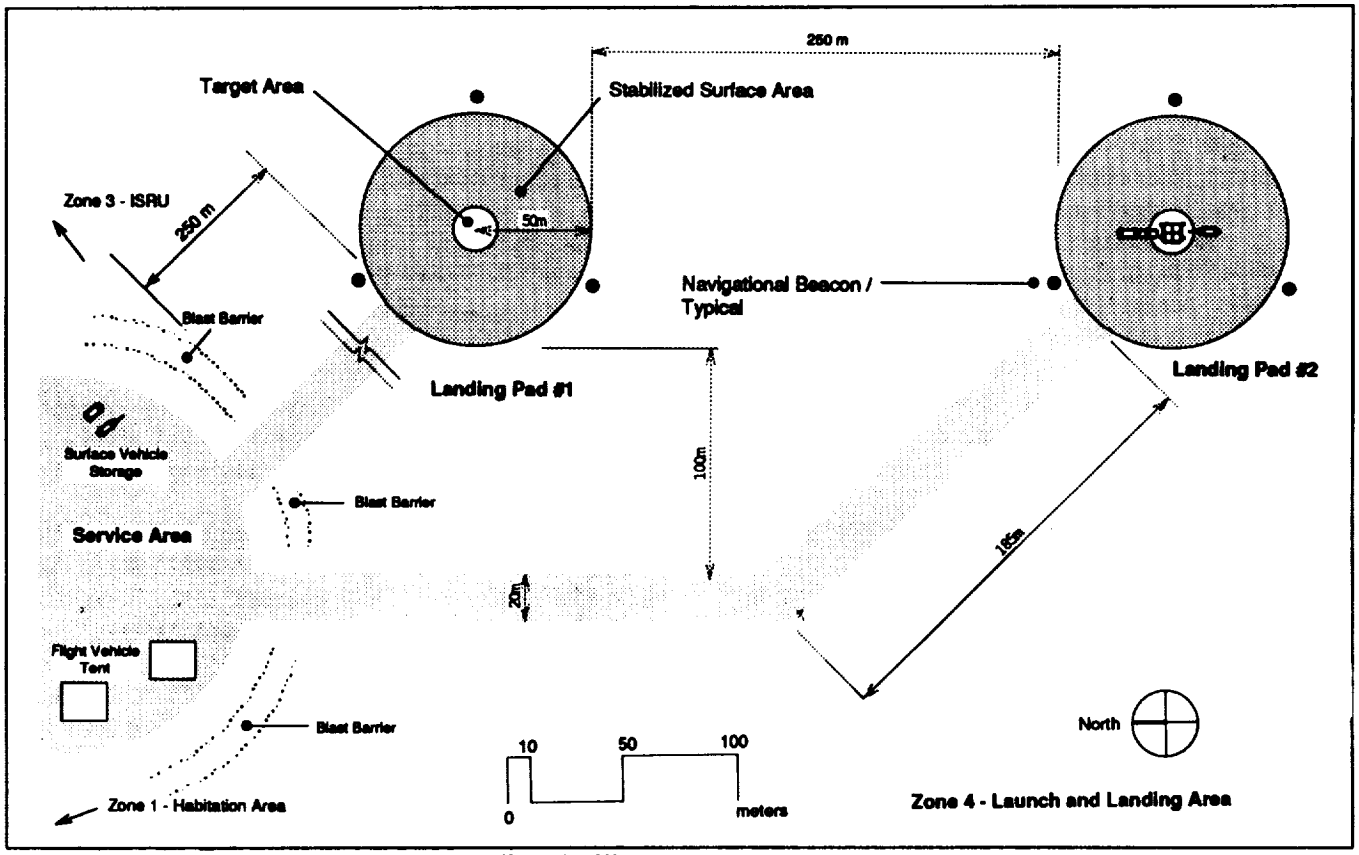



Figure 2.3.2-5.- Zone 4--Launch and Landing Facility.

located 250 meters apart to limit the possible damage by ejecta from an adjacent pad. The service area, also located 250 meters from pad #1, is protected by blast barriers to prevent equipment damage from ejecta. The service area houses the support equipment and utility vehicles necessary for LEV propellant loading and maintenance, as well as LEV storage facilities offering micrometeoroid and thermal protection. The launch and landing zone is located 5 km from the habitation and ISRU zones for reasons concerning safety and navigation errors. The 5 km distance is also within a one hour EVA walk should surface vehicle failure occur (based on a typical lunar EVA walking speed of 3-5 km per hour).

Zone 5 provides an isolated location for the two nuclear power generation systems delivered and activated during the consolidation phase. Referring to the overall base layout in figure 2.3.2-1, the power and distribution zone is placed 500 meters away from both zone 1--habitation, and zone 2--ISRU. The power sources are located as close as possible to the end user in order to eliminate excessive cabling. Appropriately, the SP-100 power module supports the consolidation phase and a fully developed 825 kW nuclear power plant during the utilization phase. For safety considerations, the nuclear power sources would be located in an excavated area below grade, possibly in a crater, depending on the local site terrain. Note that the initial power source, PVA/RFC, in zone 1 provides back-up capability once the nuclear systems are functioning.

### 2.3.3 Identification of Linkages

The activities occurring in each of the five zones are specific in nature but demand effective interaction for safe and efficient base operations. Interaction between these areas is facilitated by linkages, or circulation patterns. The main linkages are identified in terms of movement of crew, logistics, utilities, and communications.

The movement of crew is accomplished in a safe and efficient manner. The first crew is concerned with the unloading and setup of the initial habitat. Once the early base is established, the circulation of crew at the base relies on three means: 1) by foot both internal and external to the habitat, 2) by surface transportation vehicle--unpressurized vehicles for short traverses and pressurized vehicles for long-distance traverses and extended surface activities, and 3) by ballistic vehicle, for surface-to-surface exploration missions with crews of four performing extended science operations.

Logistics operations, consisting of crew resupply items and flight vehicle supplies, are ongoing activities. While the life support system evolves with greater closure, the need for Earth-supplied crew expendables continues. These expendables include perishable items requiring pressurized storage and other items that may be stored external to the habitat under a shelter. The supply items from Earth are unloaded from the cargo LEV and transported by surface vehicle to the habitation area. Note that the concept of a logistics module as identified for Space Station Freedom is not incorporated in this logistics scheme. The movement of flight vehicle supplies occurs once reusable flight vehicles are introduced in the consolidation phase. Servicing operations take place in the launch and landing service area of zone 4 with spare parts transported from cargo vehicles to a storage facility. Movement of the propellant produced in the ISRU zone requires safe transportation to the flight vehicles at the launch and landing pads.

The movement of utilities refers to the transfer of electric power from the power source to the power user. Utility runs service the habitat, liquid oxygen production plants, possible launch and landing needs, and external lighting necessary for night operations at the base. Options for utility routing include: elevated above the surface, laid on the surface (exposed), run through conduit on the surface, or buried. Concerns involve the elimination of conflicts with surface vehicle circulation patterns.

Initially, the movement of communications during the lunar evolution is minimal with the necessary equipment integrated directly into the habitat. During the consolidation phase, communications requirements increase with surface transportation traverses extending beyond 10 km and reusable landers based at the zone 4 landing pads. Movement of communications is enabled with the placement of a communication tower and a dedicated ground station central to the base. As activities expand in the five major zones and science sorties become more remote, the crew needs the ability to remain in constant contact with the central ground station.

## 2.4 PERFORMANCE ASSESSMENTS

The performance assessment section discusses the capabilities of the evolutionary lunar base as a function of time. These capabilities are compared with the usage of base support systems by various factions such as the science community, the construction crews, and the launch and landing services. The base capabilities accommodating the many users include power generation, surface transportation, pressurized volume allocation, resupply, use of locally produced oxygen, and communications coverage. The intent of the performance assessment is to verify that the base as designed meets the needs of the mission. Results show that in most areas, the base systems are adequate to satisfy the mission

model. In a few areas, however, base limitations indicate either a curtailment of manned activities or a need to change the time sequencing of system availability.

Table 2.4-I provides a general performance overview. Capabilities and support systems are organized by functional area. The specified capabilities can also be viewed as milestones within each functional area.

### 2.4.1 Power

Figure 2.4.1-1 compares the lunar daytime power required by the base activities with the power available during the case study period from 2003 to 2014. In addition, figure 2.4.1-2 represents the base power situation for the lunar nighttime. The power required by the various factions, such as science and habitats, is estimated as continuous, level-loaded, and accumulated. These gross power needs are subsequently charted against the available average amount of power being generated at a particular time. As evident from the first figure, the daytime power needs are adequately met throughout the base history. From 2003 to 2006 the power generation system is photovoltaic arrays, with an average power reaching 200 kW. The large power users at that time include the habitat facilities and surface vehicles. Note that the surface vehicles are allocated charging energy only during the lunar day until operation of the large nuclear plant. Power requirements overall are higher in the daytime as a result of increased base activity, particularly extravehicular activity (EVA).

Until 2009, nighttime power is limited to 150 kW generated by regenerative fuel cells and one SP-100.

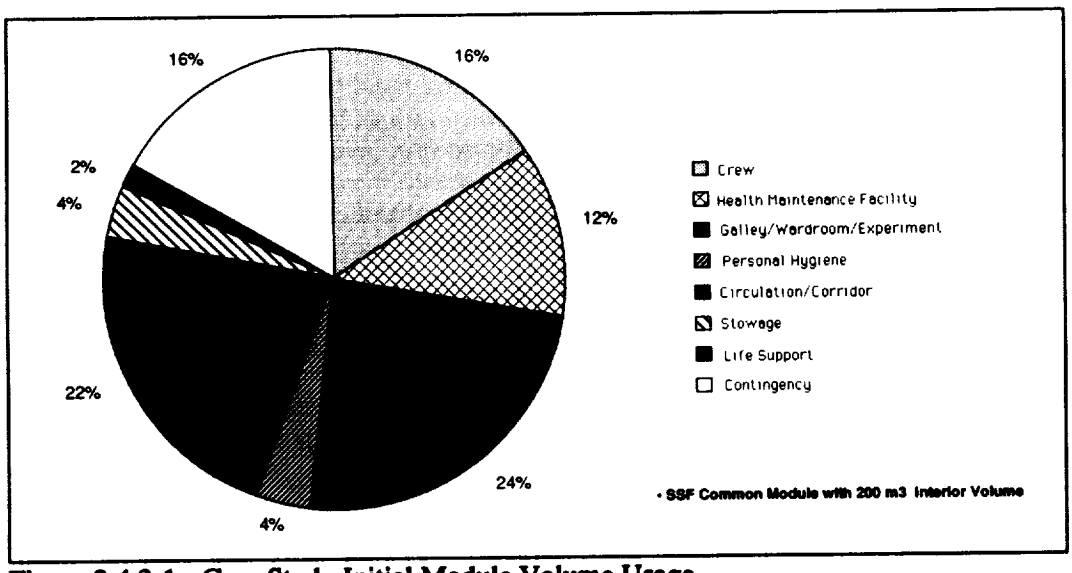



Figure 2.4.2-1.- Case Study Initial Module Volume Usage.

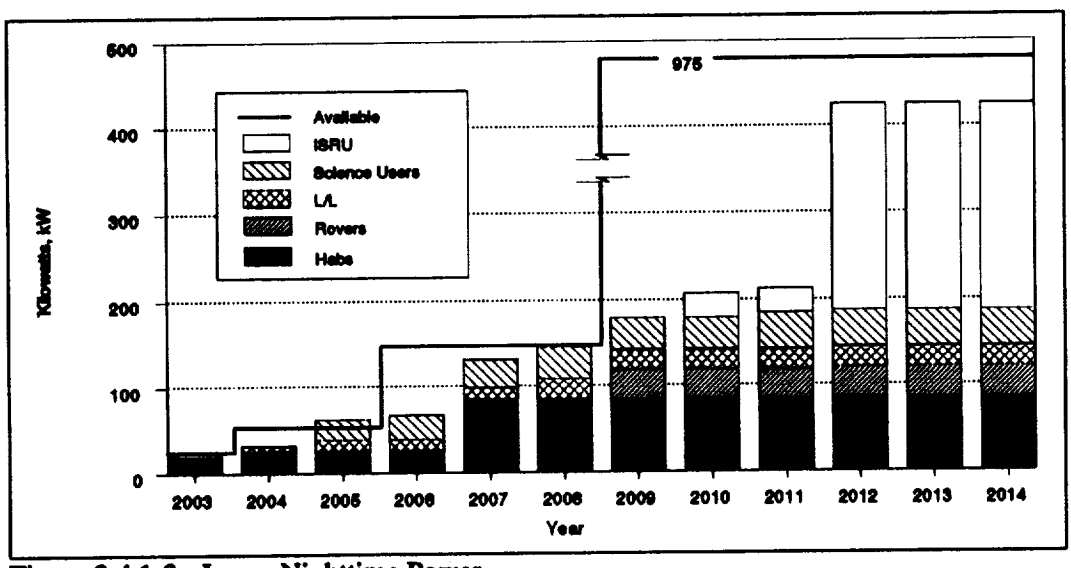



Figure 2.4.1-2.- Lunar Nighttime Power.

## TABLE 2.4-I.- LUNAR EVOLUTION PERFORMANCE OVERVIEW

| Year | Human Systems | Constr. | Surface Trans. | ISRU | Launch Landing | User Accom. | Comm./ Nav. | Energy |
|---|---|---|---|---|---|---|---|---|
| EMPLACEMENT PHASE | | | | | | | | |
| 2003 | Hab Module<br>Hab TCS | crane,<br>truck,<br>digger | | | | (Truck) | | 50/25 kW<br>PV/RFC |
| 2004 | Hab. for 4<br>airlock<br>EVA eqpt.<br>Node | Basic<br>Construction<br>hand tools | Local<br>Exploration<br>10 km UP<br>Rover | Test LLOX<br>process<br>LLOX demo | Basic lander<br>support<br>power cart<br>TC cart<br>tanks, tent | | Basic Comm/<br>Nav<br>pad marking<br>comm eqpt. | Power for Crew<br>Module Vehicles<br>cable, 50/25 kW<br>PV/RFC |
| CONSOLIDATION PHASE | | | | | | | | |
| 2005 | | utility<br>vehicle | Crew transfer<br>10 km UP<br>rover #2<br>lab trailer<br>power trailer | | Power cart<br>TC cart<br>tanks/tent<br>t-ramp | Remote<br>Exploration<br>teleop rover | Ground<br>station<br>test eqpt. | 100 kW PVA |
| 2006 | Constructible<br>Habitat | Advanced<br>Construction | | | | | | Power for large<br>Hab. science<br>SP-100<br>PMAD |
| 2007 | Hab for 12<br>TCS<br>RLSS<br>outfitting | | Regional<br>Exploration<br>utility vehicle<br>#2<br>power trailer | | | | | |
| 2008 | | | | | Enhanced<br>lander<br>support<br>lander<br>facility | | Extend<br>surface<br>comm<br>tower | |
| 2009 | | | | | | | | Power for<br>LLOX<br>Production<br>825 kW nuke<br>PMAD |
| 2010 | | | | Initiate<br>LLOX<br>Production<br>LLOX pilot<br>plant<br>beneficiation<br>eqpt.<br>mining eqpt. | | | | PMAD |
| 2011 | | | | | Refuel<br>landers<br>prop refill<br>vehicle | | | |
| UTILIZATION PHASE | | | | | | | | |
| 2012 | | | Global<br>exploration<br>far side<br>observatory<br>UP rover<br>ballistic<br>vehicle | Supply base<br>oxygen<br>LLOX plant<br>2,3,4<br>beneficiation<br>eqpt. 2.3.4 | | Far side<br>observatory | | |
| 2013 | | B.V LH2 | | | | | | |

Construction activities are curtailed at night due to these energy storage limitations. Only in 2005 do the peak demands exceed the capability during the night. However, note that the science equipment is assumed "on" all the time with no consideration for day or night level-loading. For large science power consumers, such as the gas chromatograph and mass spectrometer, usage scheduling is necessary. Once nighttime power approaches 1 MW, scheduling requirements are relaxed. Continuous operation of the oxygen production plant is possible as well as rover recharging and increased launch and landing services.

### 2.4.2 Utilization of Habitable Volume

The utilization of habitable volume is not presented on a need versus availability basis. Rather, the habitation facilities are designed around the required accommodations. Floor plans of the initial module and the constructible habitat are partitioned by the many habitation functions at the lunar base. Figure 2.4.2-1 outlines the volume usage of the initial module. Figure 2.4.2-2 illustrates a usage scheme for the constructible habitat. The interior volume of the initial module (200 $m^3$) is allocated according to the basic habitation functions: crew quarters, health maintenance facility, galley, personal hygiene, corridors, life support, and stowage. The galley area, occupying the most volume at 24 percent, includes a wardroom space and one equipment rack for scientific activity. The science users, in particular, levy the strongest requirements for pressurized volume. Although significant laboratory equipment is manifested in 2005, the mobile lab trailer suffices until the constructible habitat is operational in 2007. Disciplined laboratories, such as life sciences and geochemistry, occupy up to 15 percent of the constructible volume and demand additional area for general and computational activities. In addition to the habitation functions in the shack, the constructible, with its 2,144 $m^3$ of interior volume, also provides space for base operations support (19 percent), recreational activities (4 percent), and the previously mentioned scientific research.

### 2.4.3 Surface Transportation

The surface transportation system evolves from a limited local capability, provided by an open truck and unpressurized rovers, to full global access provided by a ballistic exploration vehicle. Intermediate capability is satisfied by two pressurized utility vehicles and an assortment of modular add-on trailers that can be configured for base support of 100 km to 1,000 km scientific missions. Note that pressurized transfer of crew from pad to base becomes available with the delivery of the first pressurized utility vehicle and tunnel ramp in 2005. Figure 2.4.3-1 compares the maximum 10 km sortie capability with the number of sorties required by the science users, launch and landing services, and operations and management (O&M). In addition, figure 2.4.3-2 illustrates a similar comparison with respect to the medium-range transportation (100 km) and the regional transportation (1,000 km).

Basically, the upper-limit data are based on an assumed capability of the unpressurized rovers to support daily sorties, and the pressurized rovers with add-ons to support weekly medium-range and monthly regional missions. No provisions for possible breakdown or loss of vehicles are included in this estimate. Note that until the large nuclear plant is delivered in 2010, vehicle charging is restricted to the lunar daytime, impacting base operations and user activity scheduling.

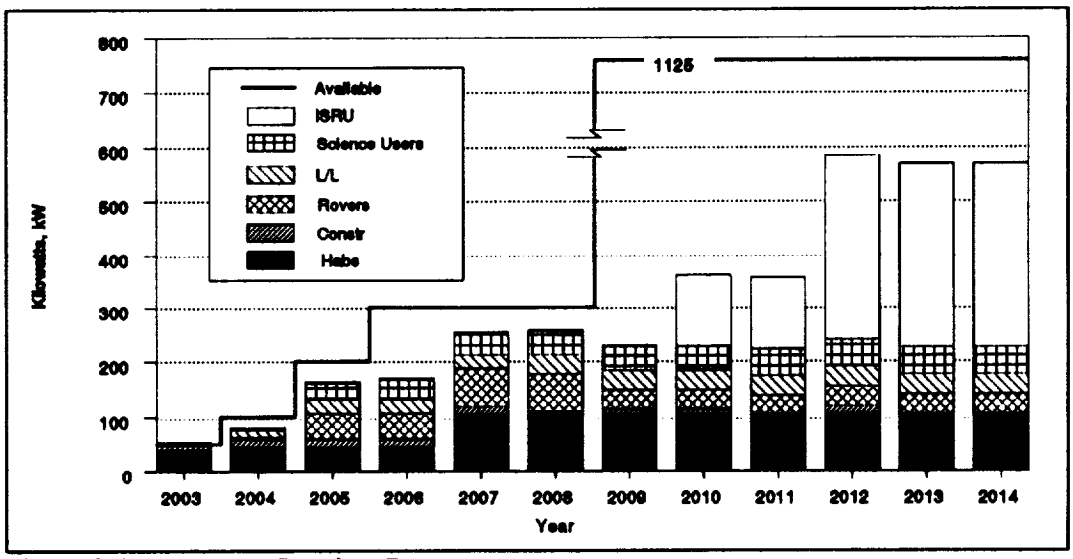



Figure 2.4.1-1.- Lunar Daytime Power.

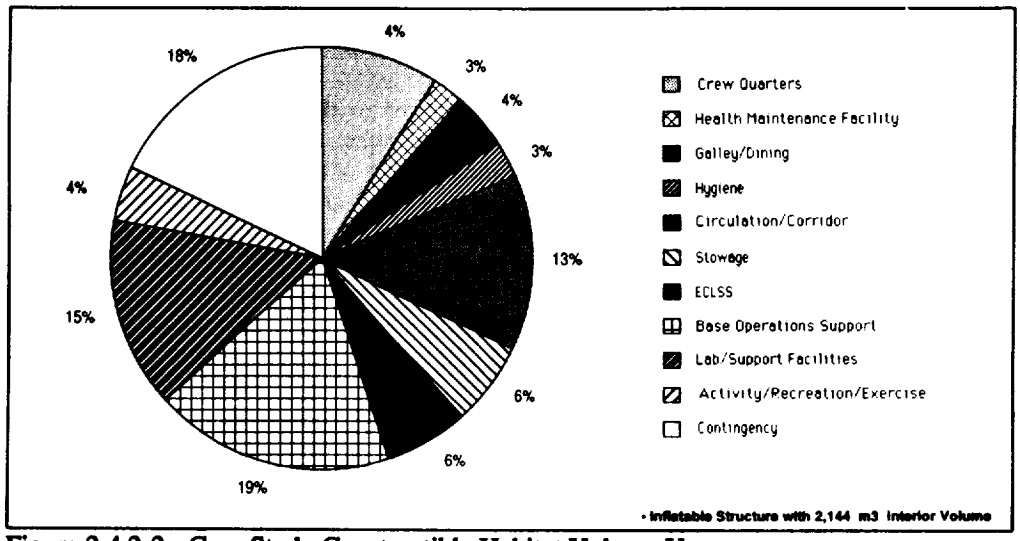



Figure 2.4.2-2.- Case Study Constructible Habitat Volume Usage.

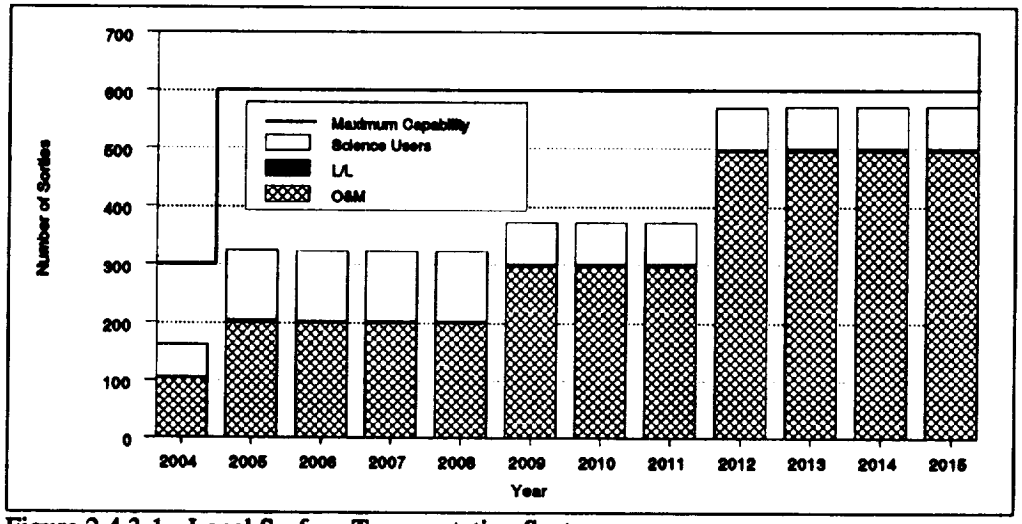



Figure 2.4.3-1.- Local Surface Transportation System.

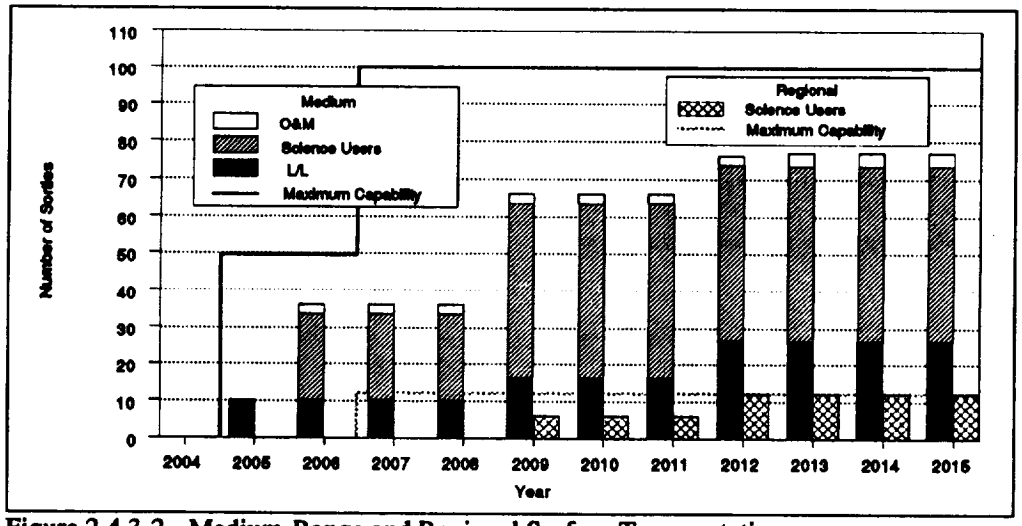



Figure 2.4.3-2.- Medium-Range and Regional Surface Transportation.

Both figures show that the base surface transportation needs never exceed the vehicle capabilities. For the local traverses, the O&M group dominates the use of the unpressurized vehicles, which is expected for maintaining the systems near the central habitation zone. Science users perform local sorties to the science zone and immediate exploration surroundings. The unpressurized rovers are used for launch and landing services, with zones 1 and 4 three to five kilometers apart, when crew transfer is not involved and for some vehicle maintenance procedures. The requirements for local transport for construction purposes are not included in this estimate, but enough margin exists to accommodate construction needs in the early active periods of the base.

The medium-range sorties are dominated by the science users for geophysical expeditions. Using the pressurized utility vehicle, laboratory trailer, and small power cart, a four-person crew is able to traverse new territories for up to four days. When the crew grows to eight in 2009, the 100 km trips occur four times a month. The number of sorties dedicated to launch and landing services is based on the number of flights per year requiring pressurized surface vehicle access. The science community is also the sole user of the regional surface transportation system, which includes the above elements plus a larger capacity power cart. These regional sorties (up to 1,000 km range) extend for periods up to 14 days, initially occurring every other month and extending to once a month in 2012 when the crew reaches twelve persons.

### 2.4.4 In Situ Resource Utilization (ISRU)

The base takes advantage of local resources through the extraction of oxygen from lunar soil, using the hydrogen reduction of ilmenite process. Oxygen serves as an oxidizer in the landers and the ballistic vehicle, and as make-up oxygen for base life support systems. Figure 2.4.4-1 shows the base oxygen needs versus the production supply. Prior to the availability of lunar-derived oxygen, all lander propellant is supplied from Earth. Once fully operational, the lunar oxygen system also enhances the base's capability to support global exploration of the Moon's surface by providing oxidizer to the ballistic vehicle. A certain amount of excess is also available to defray the effects of boil-off, leakage, and accidental loss.

Oxygen produced for life support provides airlock make-up due to leakage and loss from repressurization. A leakage rate of approximately 0.5 kg per day yields about 400 kg a year for oxygen make-up, while replenishing the crewlock after each EVA requires only a small amount. Lunar-produced oxygen also contributes to the regenerative life support system with 70 kg of oxygen per person per year, based on a functional closure of 96 percent and water make-up through food content.

Compared to the small demands imposed by the life support system, the landers and ballistic vehicle consume the majority of the oxygen. Two lander flights per year require approximately 21 t of liquid oxygen each, and the ballistic exploration vehicle requires about 37 t of oxygen, with one flight per year beginning in 2013. The broken line on the graph, denoting base oxygen production, jumps from virtually zero to 24 t per year in 2010 (pilot plant) to 96 t per year in 2012 (production plants). The quantitative benefits of producing lunar liquid oxygen for use in the space transportation system are not completely understood; however, they may turn out to be significant enough to justify initiation of production earlier in the base timeline. Accelerating ISRU in the manifest is feasible, but only at the expense of delaying other activities, such as science.

Lunar regolith, in its unprocessed state, is used advantageously as radiation protection for habitation facilities. The crew module and constructible habitat are covered with raw regolith at a thickness of 50 cm to protect from galactic cosmic rays and solar particle events. The covering option prevents carrying the shielding from Earth in the form of an aluminum shell. The mass savings represented by this scheme are estimated by calculating the equivalent mass in aluminum shielding required to achieve the same protection as 50 cm of lunar soil. For the construction shack with airlock, 177 t of aluminum is needed, whereas the constructible habitat requires about 400 t of aluminum at a thickness of 28 cm. Although a certain amount of overhead is associated with the machinery and crew required to perform the burial, the savings in Earth-launch mass justifies this ISRU option.

### 2.4.5 Communications

A performance assessment for the communications systems is not conducted as a function of time. Instead, the maximum capabilities of the base are determined per link. This format is assumed to correspond with the recommended requirements stated in the Study Requirements Document (SRD). Table 2.4.5-1 is a compliance matrix that compares the SRD data rate requirements for the lunar evolution case study with the data rate capability designed for the PSS response. The 10 by 10 matrix lists all the possible links between the lunar base (zone 1) and the mobile operations, such as EVA, rovers, and landers. Links to Earth are also specified for each surface activity and location. Two communications modes of operation are specified in the SRD: continuous (C) and periodic (P).

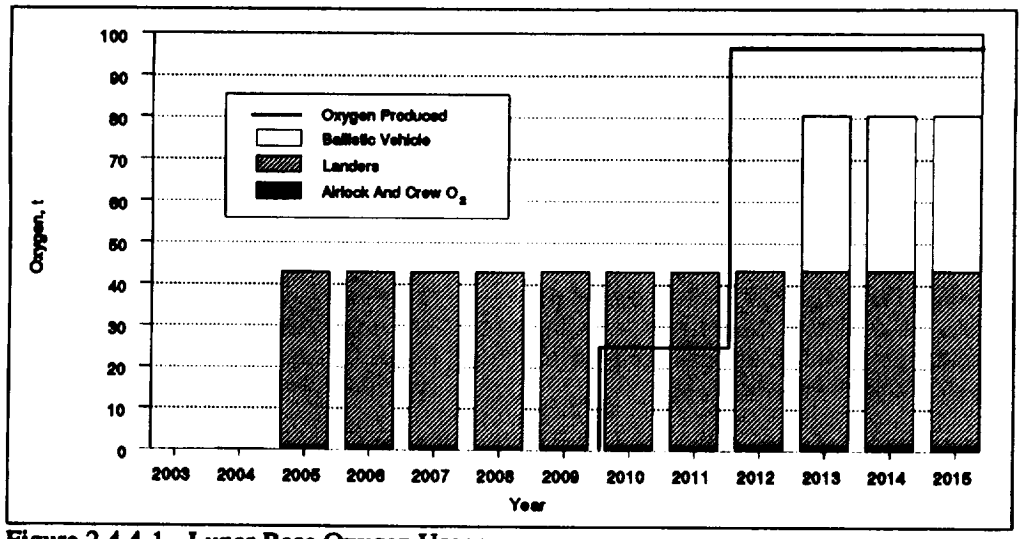


Figure 2.4.4-1.- Lunar Base Oxygen Usage.

TABLE 2.4.5-I.- COMMUNICATIONS DATA RATE COMPLIANCE

| FROM | TO | Earth Station | SSF | Earth-Moon STV | Ascent Vehicle | Lunar Lander | Lunar Base | EVA Crew | Lunar Rovers | Lunar Obsv. | Science Equip. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Earth Station | SRD<br>Cap. | P 100<br>C 100 | | P 0.02<br>C 1.5 | P 0.02<br>C 1.5 | P 0.02<br>C 1.5 | P 20<br>C 80 | P 0.02<br>C 0.04 | P 0.02<br>C 0.2 | P 1<br>C 1 | P 0.02<br>P 0.1 |
| Space Station Freedom | SRD<br>Cap. | | | P 0.02<br>P 0.02 | | P 0.02<br>P 0.02 | | | | | |
| Earth-Moon STV | SRD<br>Cap. | P 1<br>C 2.5 | P 0.02<br>P 0.02 | | P 0.02<br>P 1.5 | P 0.02<br>P 1.5 | P 0.02<br>P 2.5 | | | | |
| Ascent Vehicle | SRD<br>Cap. | P 1<br>C 2.5 | | | | | P 0.02<br>P 2.5 | | | | |
| Lunar Lander | SRD<br>Cap. | P 1<br>C 2.5 | | P 0.02<br>P 1.5 | P 0.02<br>P 1.5 | | P 0.02<br>P 2.5 | | | | |
| Lunar Base | SRD<br>Cap. | C 100<br>C 195 | P 0.02<br>P 0.02 | P 0.02<br>C 2.5 | P 0.02<br>P 1.5 | P 0.02<br>P 1.5 | | C 0.04<br>C 0.04 | C 0.02<br>C 0.2 | | |
| EVA Crew | SRD<br>Cap. | P 0.02<br>C 10 | | | | | C 1.0<br>C 10 | C 0.04<br>C 0.04 | P 0.04<br>C 10 | | |
| Lunar Rovers | SRD<br>Cap. | P 0.02<br>C 10 | | | | | C 20<br>C 20 | P 0.04<br>C 0.04 | P 0.02<br>C 0.2 | | |
| Lunar Observatory | SRD<br>Cap. | P 100<br>C 100 | | | | | | | | | |
| Science Equipment | SRD<br>Cap. | P 0.3<br>P 0.3 | | | | | | | | | |

Note that the capabilities listed equal or exceed the SRD specifications in all categories. With respect to science activities, data for particular scientific instruments are transmitted back to Earth for analysis. The question of whether the base or the science equipment provides and manages the science data transmission to Earth has not been resolved in this analysis. The most demanding use of communications is by the Moon-Earth radio interferometer (MERI), which requires 144 Mbps to transmit data, thus exceeding the 100 Mbps prescribed for the lunar observatory. A dedicated communications link for the MERI is recommended. Other astronomy data-rate needs are well within the available limit.

Except for brief "handover" periods between phased or backup support hardware (less than 1 minute), the capability exists for continuous uninterrupted transmission of one or more data types between affected elements during their operational periods. There is also a requirement to handle periodic communications transmissions. One or more data types are needed on an irregular basis, but their availability may be constrained by lunar surface geometry as well as scheduled periods of operational use and equipment duty cycles.

### 2.4.6 Manpower

The number of crew members available is crucial to the development of an evolutionary lunar base. Astronauts are required to support a variety of base functions, including construction, O&M, science users, launch and landing services, and ISRU. Figure 2.4.6-1 compares the available manpower based on the manifested yearly crew size with the manpower needs for each designated function. Manpower levels apply to both intravehicular and extravehicular tasks, but are not distinguished as such. The unit of measure for manpower is the crew day, an allocation of one crew member for a 24-hour period. The crew day includes a nominal period of eight hours for mission operations, with the remainder of time devoted to sleep, meals, hygiene, free time, and housekeeping. The following basic groundrules are used in making the manpower estimates:

- EVA's are nominally eight hours with 25 percent spent on overhead.
- Walking speed on the Moon is roughly 6 km/hr.
- Rover speed on the Moon is roughly 10 km/hr.
- Each EVA involves at least two crew members.

Across the mission timeline, a very slight margin exists for contingency operations or unexpected occurrences. In fact, the figure indicates that the first year of operations, 2004, is severely constrained, i.e. manpower needs exceed the available crew days. Construction obligations and science activities dominate the initial crew's time. The year 2006 also appears tight for operations with little opportunity for crew free time (i.e. accumulated Sundays and holidays for the year). Note that construction operations taper off by 2008, post constructible habitat, and pick up in 2009 and 2012 with the deliveries of the nuclear plant and oxygen production plants. Manpower devoted to scientific exploration is equivalent to full crew days spent away from the base. The exploration missions for 2009 through 2015 are assumed to require a crew of four persons, thus leaving four or eight crew members at the main base. Additional manpower designated as science refers to laboratory research or local EVA in the science zone. The crew days attributed to O&M include tasks such as monitoring systems, habitat and crew systems maintenance, logistics handling per flight, rover turnaround, training, and base

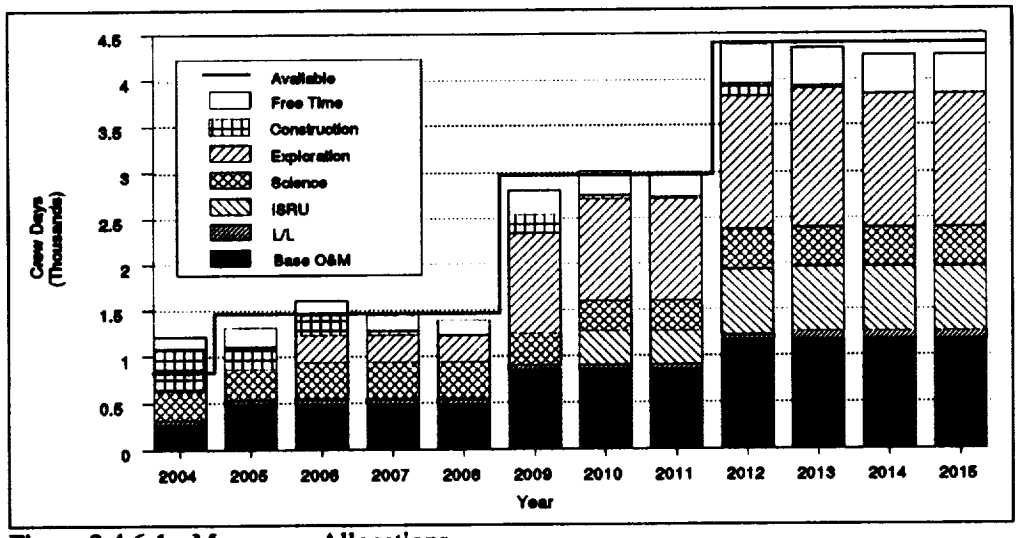


Figure 2.4.6-1.- Manpower Allocations.

management. Launch and landing services remain steady with a constant flight rate of two flights per year. The operational requirements account for vehicle turnaround and loading and off-loading flight cargo; however, loss of a landing vehicle or serious maintenance problems are not part of this estimate. Finally, the crew days required for operating the oxygen production facility are specified as eight hours per day every day of the year. For the initial pilot plant, the hours apply to one crew member; for the extended plant, the hours apply to two crew members.

### 2.4.7 Resupply

To sustain the evolutionary lunar base, periodic resupply is required in a variety of categories, including spare parts for base systems and replenishment of expendables and consumables. Figure 2.4.7-1 accounts the base resupply needs over the mission duration. The five categories of resupply are designated: crew consumables and expendables, life support consumables and expendables, and O&M spare parts. The manifest for the lunar evolution case study only designates resupply missions for life support and crew consumables. Therefore, the solid line in the figure applies to the first two categories stacked on the bar, not all of the resupply requirements. Such a comparison shows an adequate delivery of consumables. The manifested delivery of resupply items needs to be increased, particularly as the crew grows, in order to accommodate all the base resupply requirements.

Crew resupply with respect to expendables refers to clothing, hygiene supplies, health-care goods and personal items. These crew expendables equal approximately 0.7 t per person per year and subsequently increase as the crew size increases. Crew consumables simply refer to food, estimated at 0.6 t per person per year. Life support resupply includes both consumables in the form of water and gasses, especially nitrogen, and expendables such as catalysts and filters. The exact requirements depend on the type of life support system in operation at the time. The base begins with an initial life support system, characterized by 96 percent functional closure for water and gasses using a physical/-chemical approach. The system evolves to the advanced life support system in 2008 with the achievement of near 100 percent closure for oxygen and water consumables. The LSS consumables at this point consist mostly of nitrogen, with oxygen needs reduced further in 2010 with the introduction of lunar oxygen production. The ALSS is noted for a reduction in system expendables, as denoted in the figure. Yearly spare parts for base systems categorized under O&M are roughly calculated as 1/20th or 1/30th of the mass of each element, depending on whether the nominal lifetime of the element in question is 20 or 30 years (i.e., total replacement of a system over its lifetime). Further analysis will most likely lead to higher requirements for spare parts inventories. This matter is recommended for study during FY 1990.

## 2.5 PRECURSOR DATA NEEDS

The Apollo experience provided significant information on lunar surface characteristics. Consequently, the existing knowledge base on the lunar environment provides a firm basis for conceptual and preliminary engineering purposes. There are, however, a number of areas that require more detailed definition, such as resource surveys and site-specific data. New information is expected to be required for later programmatic activities such as site selection.

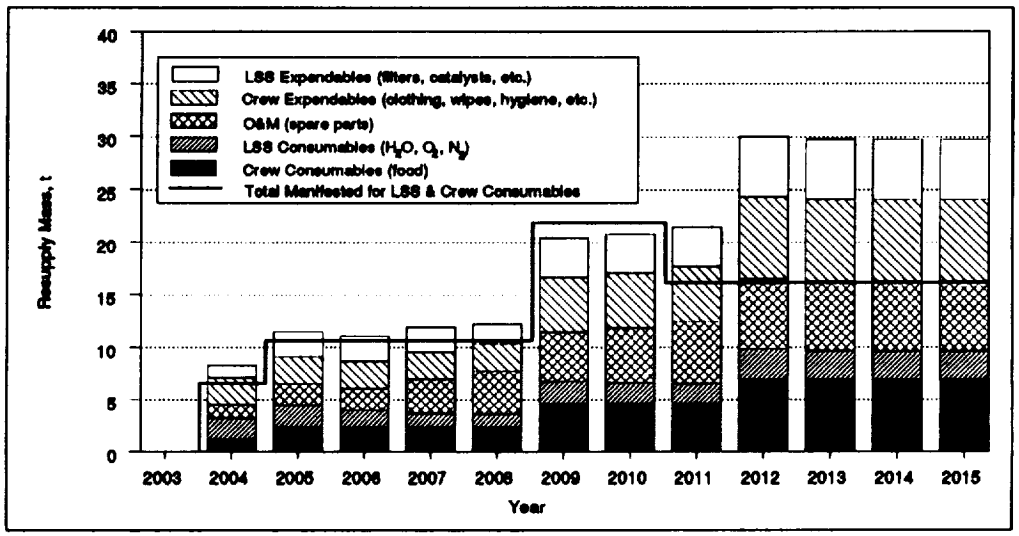



Figure 2.4.7-1.- Resupply Requirements and Deliveries.

## TABLE 2.5-I.- LUNAR EVOLUTION PRECURSOR DATA NEEDS

| Parameter | Prelim | Detail | Use | Criticality |
|---|---|---|---|---|
| **Surface Characteristics** | | | | |
| Topography<br>Slope, aspect<br>(elevation differences) | ±10% | ±2% | Structures, vehicles | Sites, traction |
| Engrng soil mechanics<br>Bearing strength, penetration resistance, gradient, porosity, cohesiveness | ±20% to depth of 6-8 m | ±5% to depth of 6-8 m | Vehicles, anchors, habitats, mining equipment | Design, resistance to withdrawal, credible digger designs |
| Angle of repose | ±8° | ±2° | Vehicles, habitats | Slopes for regolith piles, safety of slopes |
| Voids | ≥10 m | ≥2 m | Structures | Site location (crevices, lava tubes, etc) |
| Density | ±25% | ±10% | Radiation protection, structures | Loading of structures with regolith |
| Rubble size | > 1 m to 6-8 m depth | > .2 m to 6-8 8 m depth | Construction techniques, construction equipment | Sites, excavation equipment |
| Rutting and washboarding of soil | | | Vehicle mobility, road design | Need for road/path improvements |
| Substructure<br>Layers, voids | to 20 m depth | to 20 m depth | Foundation, construction equipment, ISRU | Site selection, construction equipment and techniques; hazards from subsurface conditions |
| **Resources** | | | | |
| Location & distrib. of<br>ISRU<br>Hi Ti<br>Solar wind H<br>Pyroclastic black glass | 1 km;<br>1% abs, 10% rel;<br>50 ppm limit,<br>10 ppm rel;<br>10% Apollo,<br>17 level | 100 m | ISRU | Site location, ISRU system sizing |
| Site Characteristics<br>Grain size, relative abundance of targets, useful traces, soil & small rocks | TBD | 1-10 kg, samples | ISRU | Validate maps, beneficiation validation, engineering tests |
| **Seismic Environment** | | | | |
| Activity (magnitude) | >3 Richter scale | >3 Richter scale | Habitat & facilities, foundations | Site selection, facility design |
| Wave transmission<br>Q, waveforms, frequency, dispersions | TBD | TBD | Mining & blasting | Possible damage and isolation from mining/construction activities |
| **Imagery** | | | | |
| Images | 10 m | 1-2 m | | Site selection, site design, mission planning |
| **Thermal** | | | | |
| Temperature<br>Extremes, average, diurnal (per hour) and seasonal (per month), geographic variation | ±30°K | ±5°K | EVA suits, thermal systems, materials, construction equipment | Thermal control design |
| Subsurface Temperature<br>Extremes, average, geographic variation<br>(presume constant below 1 m) | ±30°K | ±5°K (TCS)<br>±10°K (eqpt) | Mining & construction equipment, thermal systems, materials | Thermal control design |
| Heat Transmission<br>reflectivity, emmissivity, absorptivity, conductance | ±10% | ±3% | Radiator design, EVA suits, solar array concentrators | System design |
| **Electromagnetic** | | | | |
| Spectrum & intensity for Gamma, IV, X-ray, etc | TBD | TBD | Communication, materials | Frequency selection, site selection, material selection & shielding |

TABLE 2.5-I.- LUNAR EVOLUTION PRECURSOR DATA NEEDS (CONTINUED)

| Parameter | Prelim | Detail | Use | Criticality |
|---|---|---|---|---|
| Solar Flux at surface<br>Geographic<br>Seasonal<br>Diurnal | ±20% | ±5% | Photovoltaic & solar dynamic power | Sizing PVA, system selection |
| Transmission<br>Absorption<br>Refraction<br>Reflection<br>Ground effects | TBD | TBD | Communication, navigation | Frequency selection, site selection, material selection & shielding |
| **Magnetism**<br>Field strength | TBD | TBD | Navigation, communication, equipment shielding | Interference, local navigation |
| **Radiation and Particles**<br>Solar particle spectrum and flux<br>Particle types & intensity, & energy levels | OM* Joules | OM Joules | Shelters, protection, operations, materials | Material selection & shielding |
| GCR spectrum and flux<br>Particle types & intensity, & energy levels | OM Joules | OM Joules | Shelters, protection, operations, materials | Material selection & shielding |
| Micrometeoroids flux<br>Particle size, energy, frequency | OM Joules | OM Joules | Shelters, protection operations, materials | Material selection & shielding |

*order of magnitude

Table 2.5-I summarizes the precursor data needs for the lunar evolution case study. The table identifies the accuracies, uses, and criticality according to parameters of interest. The results classify needs into major categories, including thermal environment, surface features, resources, seismic environment, imagery, and electromagnetic characteristics. Within these categories, specific parameters with expected accuracy requirements characterize the level of information needed. Since accuracy needs vary according to base development phase, the table provides estimates of accuracies desired for preliminary and detailed design activities. The preliminary accuracies are more appropriate to early phases such as conceptual development and equipment design, emphasizing generic characteristics of typical site conditions--extremes, averages, normal, and exceptional. The detailed accuracies are more appropriate to activities such as site selection, certification, initial setup, environmental assessment, and simulation calibration. The table also identifies specific equipment and systems that require the precursor information as well as critical applications of the information.

A variety of systems require surface characteristics such as topography, soil mechanics, voids, rubble, and substructure information. Any surface element, whether a vehicle or habitat, requires generic information to specify design and performance envelopes. Detailed site selection and subsequent base layout demand precise information concerning the planned location. The identification of pertinent surface and subsurface features and obstacles, such as voids and large boulders, is particularly important for activities during initial emplacement when efficient productivity of equipment and operations is crucial. High resolution imaging or mapping benefits site selection, detailed base layout, and the navigational planning for exploration routes. Surveys defining compositions and distributions of potential resources are important to selecting development sites and identifying viable candidate processes. Sample returns from promising areas may be needed to verify or calibrate some in situ resource utilization processes. A characterization of the lunar electromagnetic environment aids in the selection of communication frequencies while radiation environmental data clarifies the appropriate shielding requirements.

## 2.6 TECHNOLOGY NEEDS

Technology requirements for the lunar evolution case study are identified and prioritized in a process illustrated in figure 2.6-1. As part of the overall case study development process, capabilities and systems are defined to meet the designated case study requirements.

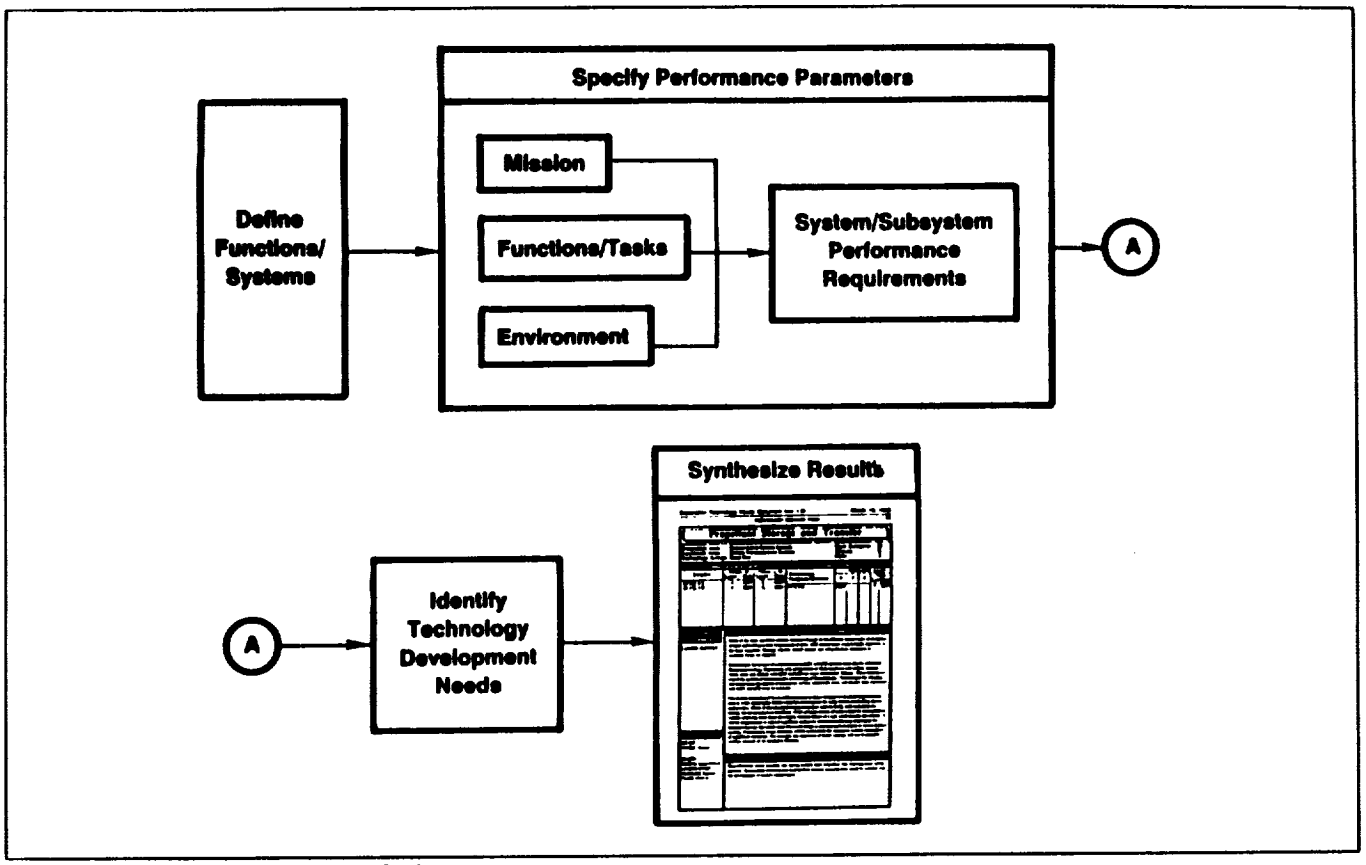



Figure 2.6-1.- Technology Needs Assessment.

Mission definition, operational task, and environmental constraints are integrated into system and subsystem performance requirements. From these requirements, areas requiring further technology development to meet the performance objectives are identified and characterized in terms of their technology need and estimated need date, as represented in table 2.6-I. Technology need is characterized either as enabling or enhancing the performance of the case study. The date at which each technology development is required was estimated as near, mid, or far term in the case study mission scenario. Table 2.6-II explains and defines the technology ranking criteria used in table 2.6-I. Each or the defined technology areas was fully reported in the OEXP technology needs database.

In this section, those technologies critical to the implementation of the lunar evolution case study are defined with resulting requirements, both qualitative and quantitative, for technology development described. Critical technologies are defined here as those technologies that: 1) have near-term development requirements to support an early emplacement schedule or to support technologies for farther-term systems with long lead-times, and 2) are defined as enabling the fulfillment of case study requirements.

For the lunar evolution case study, the following technology areas are identified as critical technologies, again referring to table 2.6-I.

- Construction and mining technologies
- Surface transportation
- Surface system power less than 1 MWe
- Surface system power greater than 1 MWe
- Dust contamination control
- EVA systems technology
- Lunar oxygen production (including mineral beneficiation and propellant storage).
- Life support (including atmosphere revitalization, contaminant control, and water and waste management).

### 2.6.1 Construction and Mining Technologies

Extraterrestrial construction and mining technologies must be developed to support lunar surface system deployment and operations. In particular, required capabilities will include soil moving, trenching, lifting, and assembly. Techniques must be defined and developed for such activities as site survey, preparation, transfer of payloads from the lander vehicle, emplacement of elements on prepared surfaces, displacing soil for shielding, mining in support of ISRU, and system -

TABLE 2.6-I.- LUNAR EVOLUTION TECHNOLOGY DEVELOPMENT AREAS

| Technology Area | Need | Time Frame | Ranking | Risk |
|---|---|---|---|---|
| Construction | Enabling | Near term | I | Medium |
| Mining | Enabling | Mid term | II | Medium |
| Surface Transportation | Enabling | Near term | I | Medium |
| Mobile Power | Enabling | Near term | III | Medium |
| Surface System Power less than 1 MWe | Enabling | Near term | I | Low |
| Surface System Power greater than 1 MWe | Enabling | Far term | I | Medium |
| Dust Contamination Control | Enhancing | Near term | III | Low |
| Extravehicular Activity | Enabling | Near term | I | Low |
| Lunar Oxygen Production | Enabling | Mid term | II | Medium |
| Mineral Beneficiation | Enabling | Mid term | II | Low |
| Propellant Storage and Transport | Enabling | Mid term | III | Medium |
| Food Production | Enhancing | Far term | III | Medium |
| Thermal Control | Enhancing | Near term | III | Medium |
| Atmosphere Revitalization | Enabling | Near term | I | Low |
| Regenerable Life Support Supporting Technologies | Enabling | Near term | I | Medium |
| Trace Contaminant Control | Enabling | Near term | I | Medium |
| Waste Management | Enabling | Near term | I | Medium |
| Water Recovery Management | Enabling | Near term | I | Medium |
| Inflatable Structure | Enhancing | Mid term | III | Medium |
| Other Lunar ISRU | | | | |
| Ceramics | Enhancing | Far term | IV | Medium |
| Metals | Enhancing | Far term | IV | Medium |
| Element Extraction | Enhancing | Far term | III | Medium |
| Hydrogen | Enhancing | Far term | IV | Medium |

TABLE 2.6-II.- EXPLORATION RESEARCH AND TECHNOLOGY RANKING CRITERIA

| | | | |
|---|---|---|---|
| Need Categories | **System/Approach** | **Common** | **Unique** |
| | Enabling | I | II |
| | Enhancing | III | IV |
| Needs Timing | **Period** | **Phase C/D** | **IOC** |
| | Near Term | Post 1994 | Pre 2004 |
| | Mid Term | Post 1997 | Pre 2007 |
| | Far Term | Post 2000 | Pre 2010 |
| Development Risk/Challenge | **Risk Level** | **Description** | |
| | High | Fundamental R&D and/or no program in place | |
| | Medium | Components and/or program in place with limited funding | |
| | Low | On schedule; program fully funded | |

| | | |
|---|---|---|
| Definitions | Common | Required by all or most pathways and approaches. Specifically, a technology must be needed for both lunar and martian scenarios in order to be in this category. |
| | Unique | Required by only one or two pathways or approaches that NASA wishes to protect the option for implementing. |
| | Enabling | Technologies that must be available for the mission to be a success either from technical feasibility and performance aspects or from an affordability aspect. |
| | Enhancing | Technologies that yield a significant net positive benefit in terms of capability and/or affordability. |

assembly and integration. Construction and mining systems may be adapted from proven terrestrial systems, but must be designed and qualified for lunar conditions. Furthermore, innovative ways must be found to reduce the mass without reducing performance of typical construction equipment. Construction technologies depend on other critical technologies, including mobile power systems and dust contamination control. Automation and robotics also impact the operation of construction and mining equipment with capabilities ranging from remote control to complete automation. A balance between human and machine avoids the undesirable use of astronauts for all surface activities. Lengthy EVA's for routine operations are impractical while rocks thrown from equipment could puncture pressure suits. Other areas to be addressed include machine element technologies, work site illumination, and environmental impact.

### 2.6.2 Surface Transportation

Several types of surface vehicles are required, including rovers, diggers, haulers, and lifters. These vehicles are required to perform local, mid-range, and long-range exploration; crew, equipment, and materials transfers; pressurized transportation; and long-duration excursion functions.

Local surface vehicles will move crew, equipment, and materials over distances of less than 10 km within the vicinity of landers and the base. Local surface vehicles may include unpressurized and pressurized rovers, trucks, and rail systems. Local surface vehicles should be able to haul an EVA crew of two individuals for a 10 km round trip over unimproved regolith. Maximum speed for a local vehicle may be 10 km/hr. It should be able to traverse a 20 degree grade. A local vehicle should provide six hours of crew life support and auxiliary power and should be rechargeable from base facilities.

Mid-range surface vehicles will transport an EVA crew of four, equipment, life support supplies for 100 hours per crew member, and 1,000 kg of other payloads for distances of 100 km over unimproved terrain. Maximum speed for a mid-range surface vehicle may be up to 20 km/hr. It should be able to traverse a 30 degree grade. This surface vehicle should provide eight hours of crew life support and auxiliary power and should be rechargeable from base facilities.

Long-range surface vehicles, such as rovers and ballistic vehicles, will transport an EVA crew of a minimum of four, equipment, life support supplies for approximately 1,000 hours per crew member, and approximately 1,000 kg of other payloads for distances of 1,000 km over unimproved terrain. Maximum speed for a long-range surface vehicle may be up to 30 km/hr. It should be able to traverse a 30 degree grade. A long-range surface vehicle should also provide a minimum of 24 hours of crew life support and auxiliary power and should be rechargeable from base facilities.

Surface vehicles for hauling, digging (soil moving, trenching, leveling), and lifting will be used for base operations, construction, mining, and to support exploration activities. Base operations, construction, and mining may include site preparation, excavations, foundations, anchoring, backfilling, lander loading and unloading, and propellant transfers. Support to exploration activities may include excavation, equipment and materials loading and unloading, and backfilling. Construction and mining surface vehicles should be self-contained, man- or tele-operated (focus on teleoperation), and should be equipped with plows, scoops, scrapers, cranes, and manipulating arms according to their functions. Construction and mining surface vehicles should employ common design where dual functions exist and should be rechargeable from base facilities.

### 2.6.3 Mobile Power

Mobile power systems (wheeled, skid mounted, portable, etc.) with power levels of 5 to 40 kWe will be required to support such applications as pressurized long-range manned rovers, construction equipment, and mining and materials transport vehicles. Current technology includes non-regenerative fuel cells; however, alternative technologies, such as nuclear reactors, isotope systems, and regenerative energy storage systems offer advantages. Characteristics of prime importance for viable mobile power sources include the mass and size, both targets for reduction, and system durability and longevity. Comparisons between technology options must also focus on the level of dependence the mobile power system has on the base (i.e. recharge requirements, regenerative needs, hydrogen/oxygen supplies).

### 2.6.4 Surface System Power

Stationary power technology for early lunar missions must be provided to support crew surface activities and base establishment. Requirements specify output of between 25 and 200 kWe, lightweight construction, erectable or deployable design, and power management and distribution capability. A solar power system suffices for early lunar operations that occur during the lunar day only; however, for continuous lunar surface activities, 14-day duty cycles are required for energy storage. Baseline power systems for the early lunar evolution phases include photovoltaic arrays for primary generation and regenerative fuel cells for energy storage.

The capability to generate and distribute power at levels of 1 to 4 MWe is required to support lunar in situ resource utilization. Nuclear reactors are baselined at multi-megawatt power levels, since the size of energy storage would be prohibitive for solar energy systems. A multi-megawatt power system for space applications has only been studied; a full-up system has yet to be tested. Key technology development needs in order of priority include: 1) conversion cycle with high-temperature (above 1300°K) materials, 2) fail-safe (during transport from Earth, surface assembly, and operation) modular design, and 3) effective shielding with lightweight or in situ materials.

### 2.6.5 Dust Contamination Control

A method of easily and effectively controlling and removing dust from EVA suits, airlock seals, and other systems (e.g., solar arrays and radiators) is required. A key concern is the introduction of lunar dust into habitable volumes. In particular, seals of airlock doors are vulnerable to interference by dust, and the habitat air revitalization system is subject to contamination. In addition, performance of sensitive equipment, such as photovoltaics and optics, are prone to degradation by dust layers. Key issues to resolve include understanding the physical properties of the dust and dust-to-surface adhesion, the impacts to systems and components due to dust contamination, and appropriate techniques to remove contaminants. There is some debate as to the classification of the dust problem as a technology concern. Whether dust control is indeed a technology requirement or simply an engineering design challenge, contamination control is critical to living and working on the lunar surface.

### 2.6.6 EVA Systems Technology

To meet the EVA requirements of the lunar evolution case study, development of lunar extravehicular mobility units (EMU) and portable life support systems (PLSS) is required. The primary technology advances required to support lunar EVA are in the areas of portable life support and materials for suit, glove, and visor that resist abrasion by dust. PLSS development emphasizes minimal expendables, mass, and volume. A critical technology need is the reduction of resupply, as the cost of transporting spares and consumables becomes prohibitive. Therefore, options for PLSS include the use of either regenerable or umbilical systems. An umbilical system is within the state of the art, but limits EVA range significantly. Selection of regenerable life support requires an extensive technology program to develop a lightweight system. Low mass is a driving criteria due to the gravity constraints of the lunar environment and a human's carrying capacity. Crew members cannot be expected to carry more than the equivalent of 20 $kg_f$ on Earth, which equates to 120 kg on the Moon. Primary design concerns for the lunar surface EMU include PLSS heat balance, mass (both PLSS and suit), and suit dust, thermal, radiation, and micrometeroid protection. Secondary design drivers include carbon dioxide recovery and reduction and PLSS recharge using lunar resources.

### 2.6.7 Lunar Oxygen Production

The technology for extracting oxygen from the lunar soil is complex, requiring a long-lead time research and development effort. Technology development is required in the areas of mining, beneficiating, processing, collection, purification, and storage. A large number of methods have been proposed, but few have had sufficient experimental work performed to allow even valid comparisons to be made. The operational production level of lunar oxygen is targeted at approximately 100 t per year to be phased by emplacing several plants with 24 t per year capacity. A high degree of automation (artificial intelligence, robotics, and/or teleoperation) is anticipated to reduce EVA cost, maintain continuous production, and increase plant efficiency. Fault detection, isolation, and reconfiguration are required design specifications for the liquid oxygen plant and future ISRU plants. Desired capabilities include machine intelligent expert recognition and decision-making systems, fault tolerant design, graceful failure techniques, modular design with hierarchical structure, and fault alarms to the module exchange level.

### 2.6.8 Life Support Supporting Technologies

Lunar life support technologies must be developed to assure the safety and well being of crews living in the hostile lunar environment. These will include regenerative technologies for atmosphere revitalization, trace contaminant control, water recovery, and waste management. In particular, integrated technologies that minimize life support system maintenance manpower and resupply mass while maximizing reliability will be required. Systems must be developed to maintain habitat atmospheres within prescribed ranges of composition, pressure, temperature, and humidity, without the need for extensive changeout of filters and catalysts. Schemes for efficient storage of carbon generated during carbon dioxide reduction will be needed. Technologies for monitoring and controlling trace chemical and microbial contaminants within the habitats will be required. A water reclamation system with 99 percent or greater recovery of potable and hygiene water can substantially reduce resupply requirements and reduce the dependence of "wet" food. Processors that convert waste materials

to ash, water, carbon dioxide, hydrogen, and nitrogen can also reduce resupply needs and simplify trash logistics within the habitats. All of these systems must be advanced beyond Space Station Freedom (SSF) baselines because SSF life support systems are based on 90-day resupply and continual maintenance; conditions that are incompatible with extraterrestrial bases.

## 2.7 PROGRAM SCHEDULES

Coordination of development activities required for planetary surface systems is critical to assuring an even and orderly buildup of lunar evolution activities throughout the duration of the scenario (i.e., consistent levels of technical activity and funding). To provide a structured approach to the coordination process, programmatic schedules are outlined to phase development activities from an overall program standpoint. The schedules also ensure that proposed system development programs are integrated with other key design and development requirements.

System development schedules are based upon the synthesized manifest for the lunar evolution case study, as previously outlined earlier in this section. In general, technology programs are managed separately by the Office of Aeronautics and Space Technology (OAST) at a generic level. An extension of OAST, the Pathfinder program, offers technology schemes pertinent to advanced mission planning. The technology programs originating from OAST are not focused specifically on a particular NASA program. Once advanced technologies are identified and developed, the particular NASA program office is responsible for integrating the technology into development of the system.

For the lunar evolution case study, programmatic schedules are presented in figures 2.7-2 through 2.7-5 for the following areas: habitation systems, construction and mining, ISRU, support and utilities, and launch and landing systems. The schedules contain information regarding development phases for each major system, estimated technology readiness dates, key test and evaluation milestones, and mission inputs to system design and development (e.g., precursor needs and user requirements). Dates are indicated to define design and development phases and post-production events such as system/vehicle integration. For this case study, the phases are designated as phase A (1 year), phase B procurement (0.5 years), phase B (1.5 years), phase C procurement (1 year), and phase C/D (5 to 7 years). Phase C/D incorporates final system design, production, and system verification. The length of development phases depends upon the complexity of the given system. In addition, prelaunch activities such as ground processing and space-based payload/vehicle integration are assumed to take one year prior to launch.

Test and evaluation requirements supporting surface system development and implementation are assumed to be accomplished at three progressively advancing levels. Initially, systems are evaluated at the breadboard level to validate proposed technical approaches and to assist in the selection of system concepts. This testing is typically performed during preliminary design stages of the system development cycle. During phase C, prototypes are fabricated and tested to verify functional performance. Finally, an extensive test program is initiated to combine evaluation of system performance, operational readiness, and logistic supportability. For consistency, these test programs are indicated on the figures with milestones for test article development during phase B, C, and D activities, noted as I, II, and III, respectively.

Technology program information relating to each of the surface systems is in the form of Pathfinder program forecasts provided by OAST. Technology readiness levels based upon OAST-supplied descriptions have been superimposed on these schedules. Implicit in the Pathfinder program forecast are the following assumptions:

- A lunar outpost will precede development of a martian program
- The human lunar program is paced by martian precursor missions
- Lunar systems are strategically focused toward martian applications.

This information is referenced to the "OAST Report for FY '89" presented at the OEXP Program Review, August 3, 1989.

Figure 2.7-1 defines the standard NASA technology readiness levels referred to by the programmatic schedules. In general, surface system technology readiness level is linked to the phase of development, such that a technology readiness level of 4 (critical function demonstrated) is required by phase B start, level 6 (prototype tested in environment) by phase C start. In several instances, the pace of the technology programs does not meet system requirements; the discrepancies between surface system needs and the projected readiness dates are noted. In addition, key data inputs into the design of the system are also indicated on the schedules. Typically these include detailed site information (soil mechanics, topography, etc.), interface requirements with other surface systems or space transportation vehicles, and design constraints such as construction capabilities.

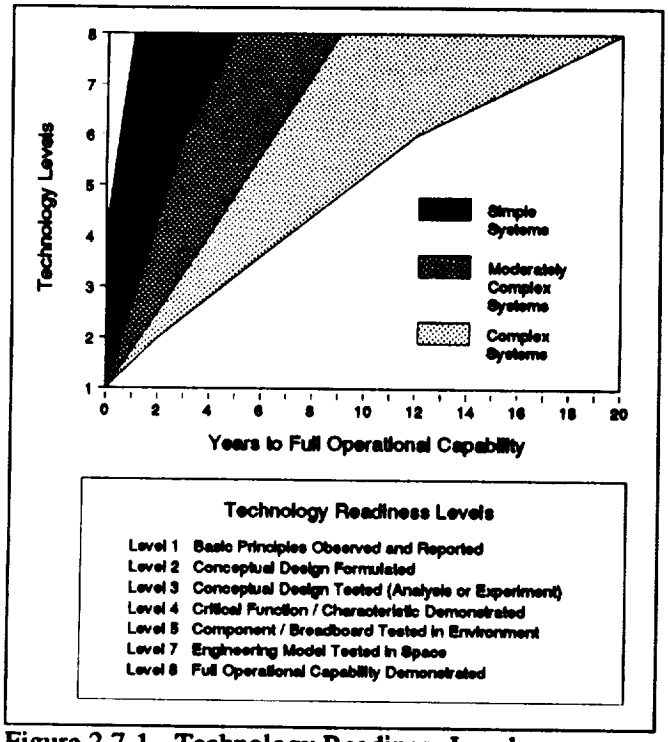



Figure 2.7-1.- Technology Readiness Levels.

Programmatic schedules for the lunar habitation systems are presented in figure 2.7-2. Key technology milestones supporting the lunar habitats are the integrated physical-chemical life support test bed, development of mission-focused food and waste requirements, and testing in a habitat breadboard. With the exception of the habitat breadboard, the technology program appears to be appropriately synchronized with system development schedules. The Pathfinder plans for habitation may need to be accelerated somewhat for the initial module to be ready in time for a 2003 delivery to LEO. However, current plans call for the module to be a derivative of the SSF common module; therefore, a modified SSF prototype could be used for this function. Ongoing technology efforts directed toward the EVA suit development appear adequate for meeting the schedule.

Timelines for development of lunar construction, mining, and ISRU systems are shown in figure 2.7-3. Technology programs that support construction systems may be a critical path in their development cycle. In particular, aspects of the Pathfinder planetary rover program (especially mobility and power sources) are important early inputs into construction system design. Mining, beneficiation, and oxygen production systems are shown on parallel development schedules. Since oxygen production requirements drive the design of the mining and beneficiation equipment, it is important that data flow freely between these separate development activities.

Programmatic schedules for the support and utilities functional area, including surface transportation, power, and communication systems, are illustrated in figure 2.7-4. The lunar-manned rover breadboard also specified in the Pathfinder planetary rover program may need to be accelerated somewhat to support delivery of a pressurized utility vehicle to LEO by the end of 2003. Power system technology programs include the Pathfinder surface power and space nuclear power programs. The SP-100 program must be focused for lunar surface application and the program continued beyond 1995 to support the early (2006) delivery of an SP-100 power module. Note that for surface transportation and nuclear power systems and construction, mining, and ISRU systems, detailed data regarding lunar surface and soil properties at the operational site(s) are required prior to phase C/D.

Launch and landing systems development plans are depicted in figure 2.7-5. Certain elements of the Pathfinder autonomous lander (precision landing and hazard avoidance) and cryogenic fluid depot programs directly relate to the lunar launch and landing systems design and development. As shown in the schedule, the technology inputs support system development in a timely manner. In addition, it is important to stress the integration of the launch and landing systems development program with that of the lunar landing vehicle.

As the FY 1989 studies progressed, it became apparent that development of surface systems and operations, such as construction and resource processing, may be more appropriately accomplished in test beds rather than in "paper studies." Issues such as risk management, integration of expert systems, and logistics support can be resolved with more confidence following an intensive test and evaluation program beginning with preliminary system design. Thus, a focused advanced development program, distinguished from OAST's advanced technology development activities, is recommended, with emphasis on system development and operational issues, such as reliability, maintainability, resupply, and interfaces.

The planetary surface system advanced development program is intended to support the development, testing, and evaluation of key surface systems characteristics by incorporating major ground-based test facilities. Three facilities are currently envisioned: a surface system development facility (SSDF), ISRU test bed (ITB), and surface system integration laboratory (SSIL). Each of these facilities has a specific function and application within the advanced system development program.

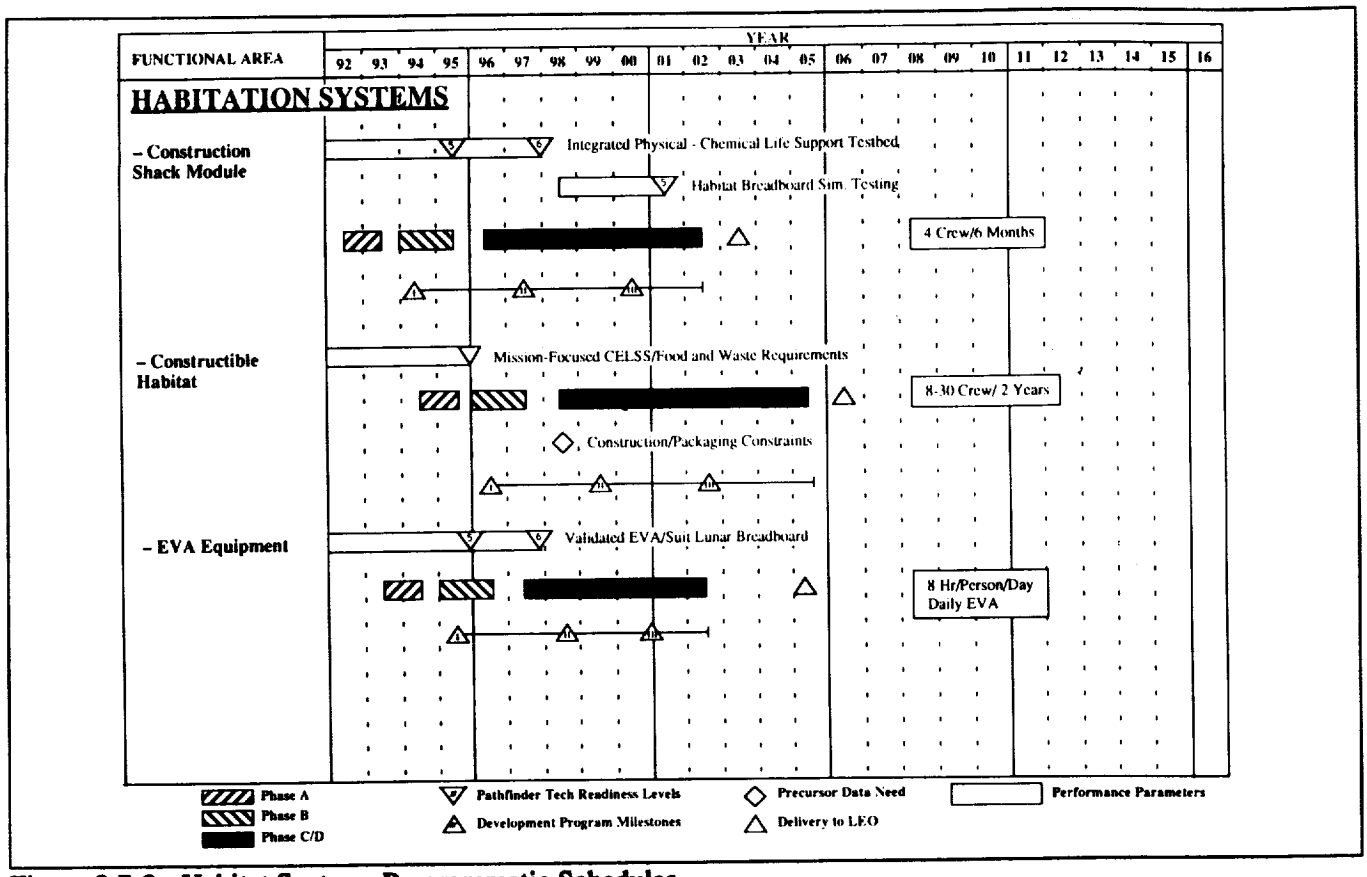



Figure 2.7-2.- Habitat Systems Programmatic Schedules.

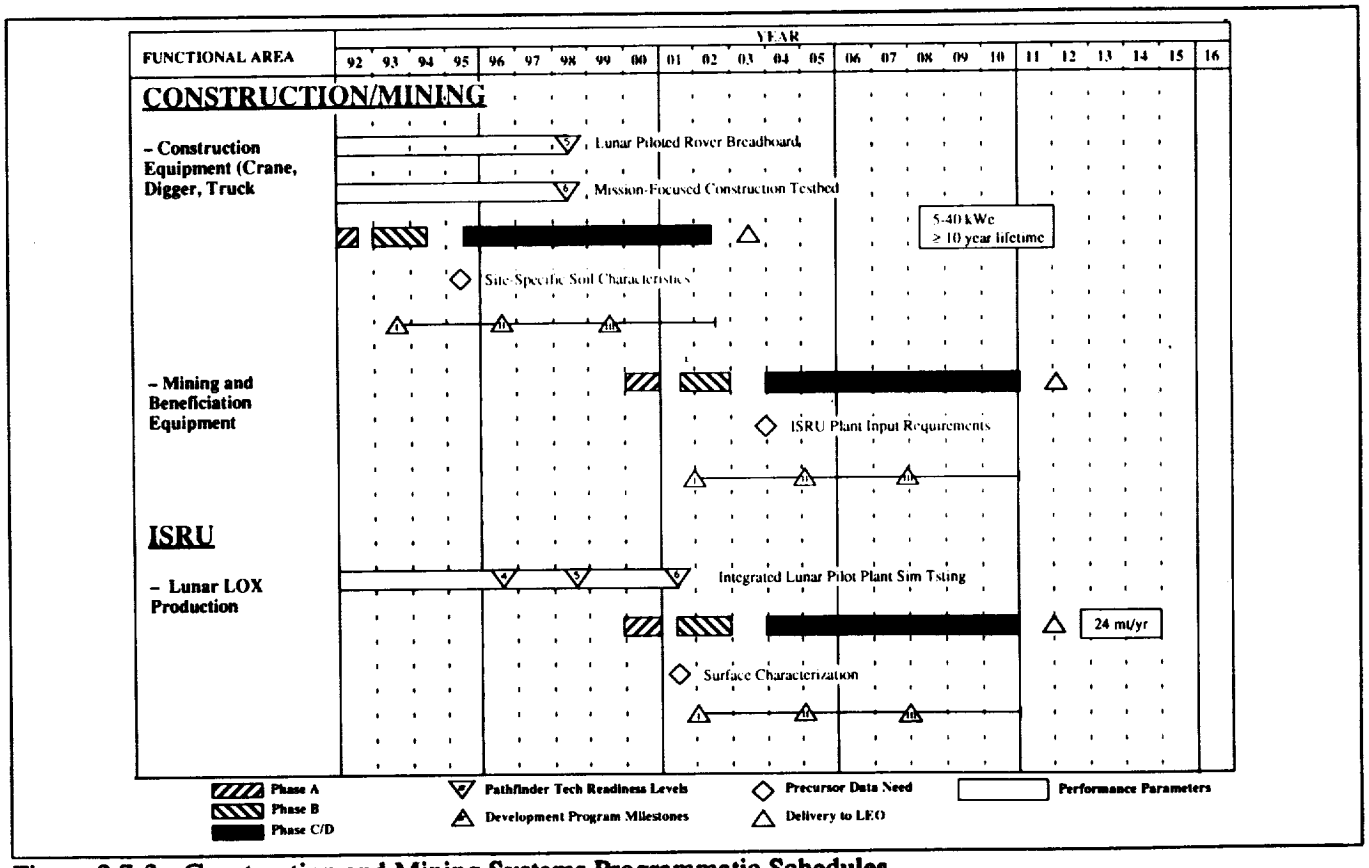



Figure 2.7-3.- Construction and Mining Systems Programmatic Schedules.

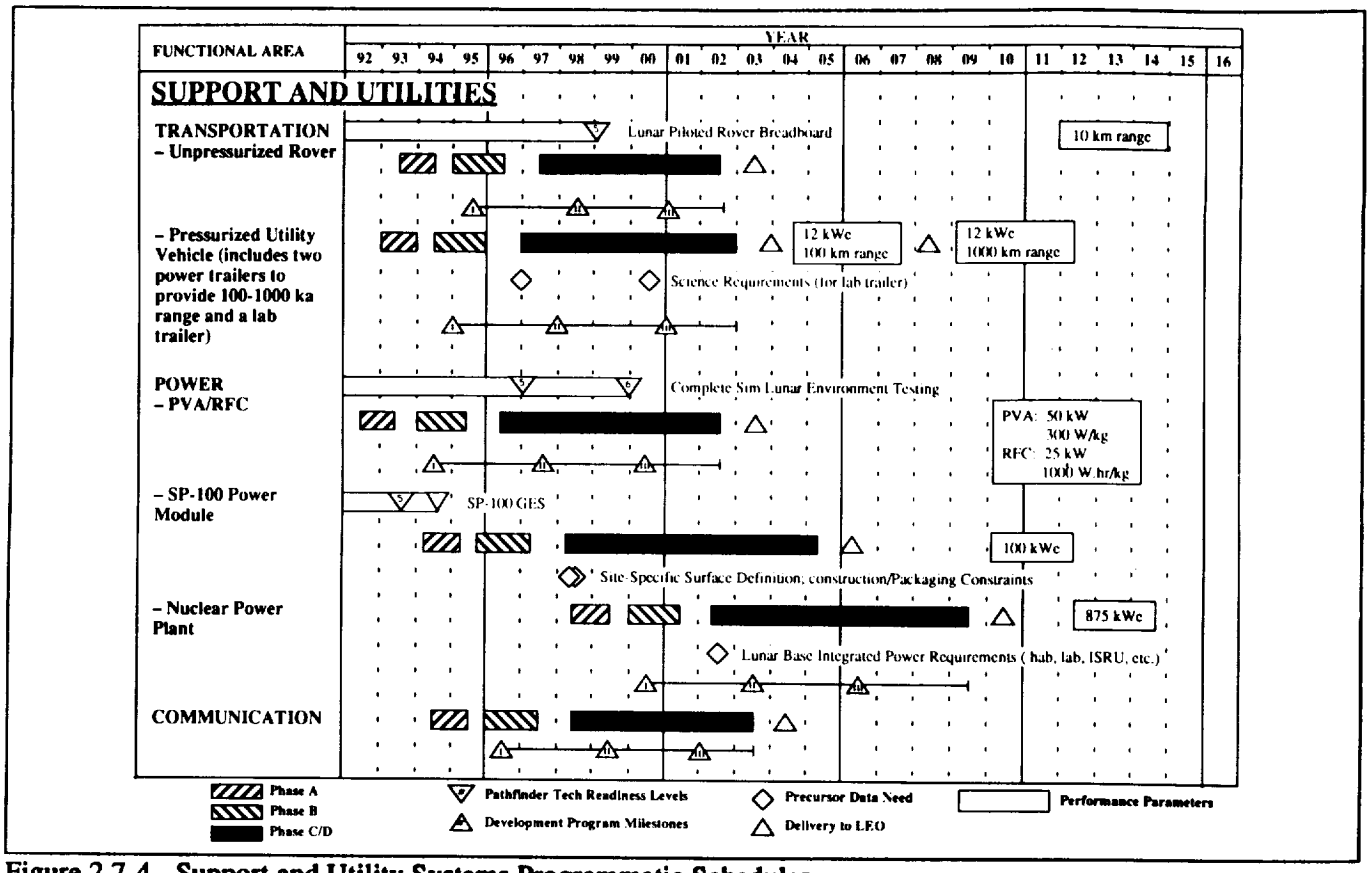



**Figure 2.7-4.- Support and Utility Systems Programmatic Schedules.**

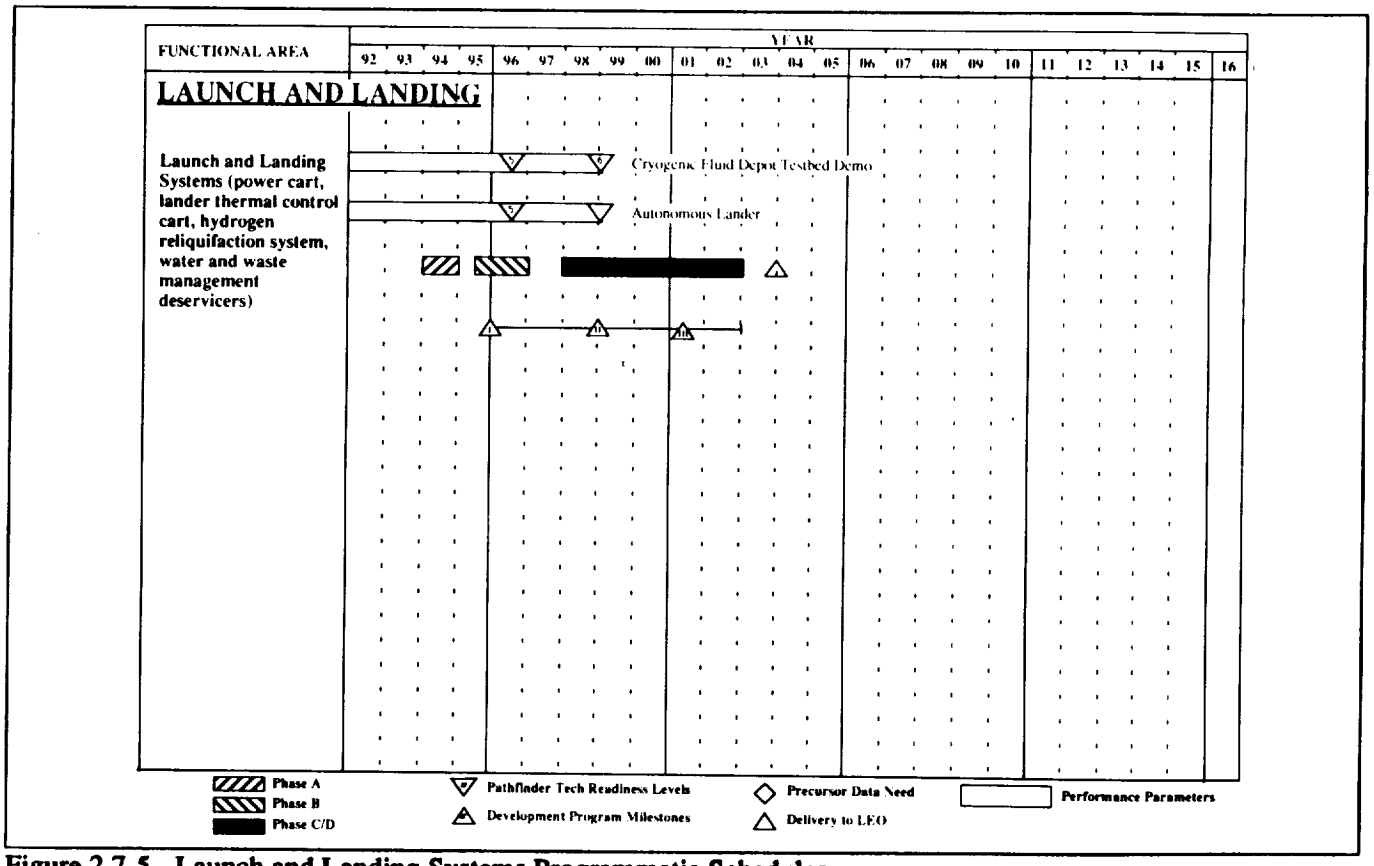


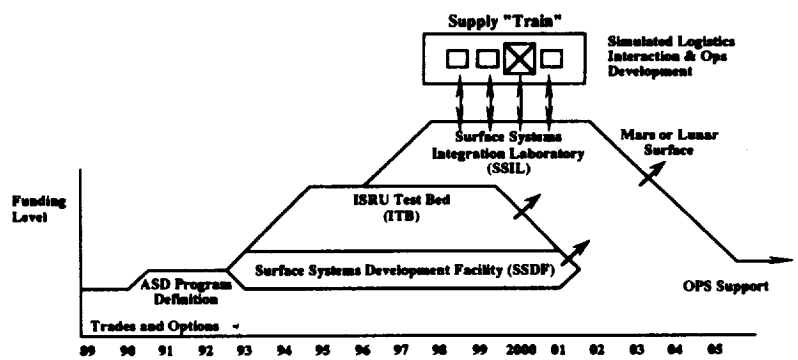

**Figure 2.7-5.- Launch and Landing Systems Programmatic Schedules.**

The SSDF would support development and evaluation of candidate systems and operational techniques. For example, construction and mining equipment would be tested, evaluated, and modified based upon technical performance and operational efficiencies. Selected pieces of equipment would perform a range of tasks from excavating pits to off-loading landers to inflating habitats.

Oxygen production from lunar soil in addition to other ISRU processes, such as hydrogen production and ceramics crafting, would be included in the ITB. Subsystem and system breadboard development testing and eventual certification of the process would be performed in the ITB. As system development progressed beyond verification, the pilot plant version would be tested and evaluated in this facility.

The SSIL would be the primary test facility for integrated system DDT&E and consideration of operational support requirements. Interactive systems test and evaluation would be performed in such areas as long-life reliability qualification, maintainability verification (maintenance requirements, timelines, support equipment, logistics, tasks and procedures), and data collection for expert systems development. Another function of the SSIL would be to assess system impacts to crew members. Examples include: EMU (performance to specifications, human factors assessment, compatibility with environment), airlock (egress/ingress operations development, assessment of dust control), and evaluation of the effects of long-term isolation and confinement.

The three facilities would be introduced systematically into the program as the increasing capabilities of each are required. This phased approach is illustrated in figure 2.7-6.




- SSDF
  - Systems Development & Evaluation
  - RLSS Development & Evaluation
  - Construction/Mining Systems OPS and Techniques Development
- ITB
  - "Breadboard" and "Brassboard" Development/Process Certification
  - Pilot Plant Development and Evaluation
- SSIL
  - Integrated System Development & Evaluation
  - Interactive Systems Test and Evaluation
    - Long Lifetimes Reliability Testing & Contingency Failures
    - Data Base for Expert Systems Development
    - Interaction with Logistics Train - Contingency Procedures Development
  - Crew Systems Development
  - Isolated Confined Environment Assessments

Figure 2.7-6.- Planet Surface System Test and Evaluation Approach.

## Section 3

# Mars Evolution Case Study

The Mars evolution case study has as its primary objective the emplacement of a permanent, self sufficient base on the surface of Mars. This goal is reached through an evolution from an initial martian outpost. Parallel to the growth of human habitation on Mars is a significant science research capability and the development of needed propellants on Phobos, a moon of Mars.

To achieve a martian outpost during the first two decades of the 21st century, three phases are involved: emplacement, consolidation, and utilization. First, emplacement of equipment will occur. This phase includes a habitat and vehicle support for a crew of up to five. A consolidation phase then follows. A propellant plant on Phobos and a Mars surface launch and landing facility will be completed. This second phase is supported by a crew of five. The last phase will see the utilization of in situ resources. A liquid oxygen plant will be completed, a regional pressurized rover capability for traverses measured in hundreds of kilometers will be available, and base permanence will be established with a crew of seven. A sketch of this base is shown in figure 3-1. Figure 3-2 shows a lander stationed at the launch and landing facility.

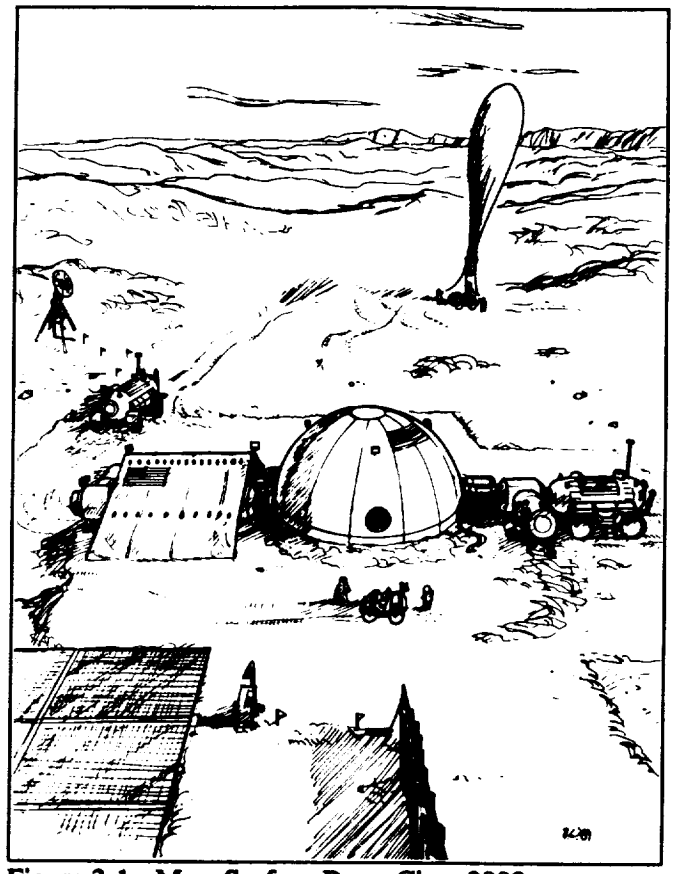


Figure 3-1.- Mars Surface Base, Circa 2008.

An iterative development process has been used for this past year by the Planetary Surface Systems Integration Agent (PSSIA) for all surface systems designed to support the Mars mission. The martian outpost recommended by the current Study Requirements Document (SRD) is a result of this process. Case study results are based on inputs from distributed studies. They are not identical, however, because of the process of integration and synthesis.

It has been recognized that efficient exploration of Mars and later the solar system and beyond depends on advanced technology to reach objectives with minimum risks. To this end, several studies were accomplished. A number of precursor missions and identification of several technology needs to satisfy current SRD requirements for the surface systems on Mars resulted from these studies. The precursor and technology requirements are covered in detail later in this discussion.

The emplacement phase will be used as a test bed for learning the techniques involved in the setup and operation of a non-terrestrial outpost in one-third gravity. Experience gained from terrestrial and lunar analog conditions will aid in preparing for this phase, with the emplacement phase providing the opportunity to apply techniques and technologies developed for a planetary surface. The goal for this phase is to establish completely self-contained and highly self-sufficient operations for local surface systems activities. The long lifeline for supply support between Earth and Mars dictates that the martian outpost be adept at self-healing.

Activities during the consolidation phase will concentrate on establishing a propellant plant on Phobos, launch and landing facilities, and a carbon dioxide electrolysis facility on Mars. The propellant plant will be the first major manufacturing effort for the Mars operation. The carbon dioxide electrolysis plant on the martian surface will produce up to 100 t/yr of liquid oxygen. It is anticipated that the Phobos plant will be teleoperated remotely from the martian outpost.

During the utilization phase, further development of in situ resources will occur. According to the PSSIA, this is essential if the Mars outpost is to establish itself as a self-sufficient entity. A pressurized rover, capable of

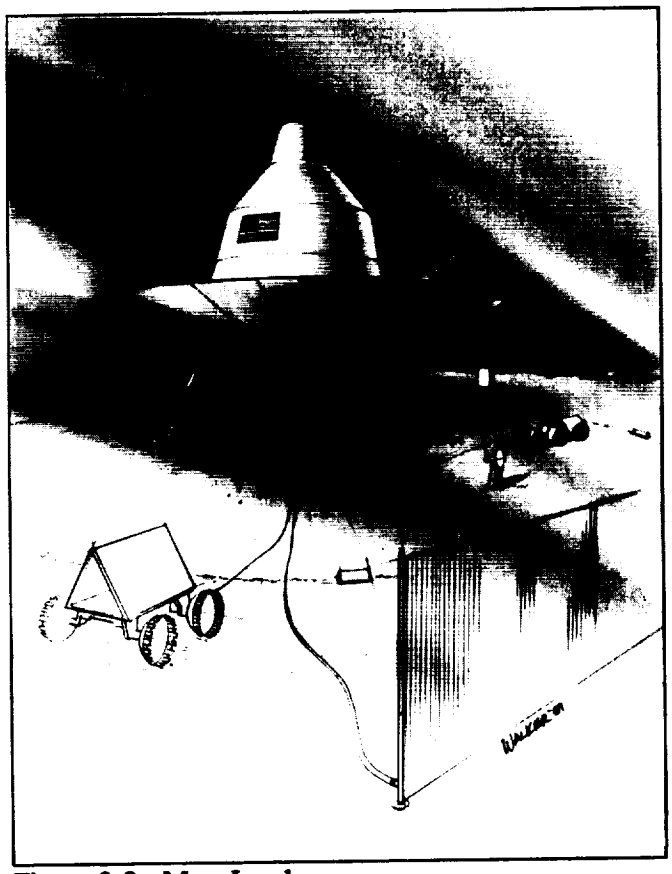


Figure 3-2.- Mars Lander.

traversing hundreds of kilometers, will be available to the crew of seven to aid in exploratory missions on the surface of Mars.

This approach by the PSSIA is in line with the stated goals of the Office of Exploration; i.e., the purpose of establishing a martian outpost is to probe the origin of life, to mine Mars, to mine Phobos, to conduct life science research, to advance technical development, and to provide human exploration of the solar system. The results of this pioneer effort will be discoveries that are expected to improve the quality of life on Earth.

## 3.1 MISSION STATEMENT

The objective of this case study is the emplacement of a permanent, self-sufficient base on the surface of Mars. Embedded within this long-range objective are the following three intermediate, evolutionary goals:

- Establish a Mars surface outpost that grows to a permanent facility.
- Develop a significant science research capability.
- Develop a martian moon gateway to serve ultimately as a resource for continued human expansion into the solar system.

The evolutionary strategy for this case study begins with the delivery of a human habitation module to the martian surface, followed by the first human mission to the surface to emplace and check out the facility. A second piloted mission with the capability for an extended crew surface stay time follows. The final phase is the development of a martian moon gateway that ultimately produces water and cryogenic propellants. The gateway supports the buildup of the outpost, with its eventual growth into a permanent, self-sustaining base. The capability for global exploration of Mars is developed as the outpost buildup proceeds.

Key features include:

- First human exploration of martian surface in 2008.
- Vehicles are assembled at a dedicated fixture in Earth orbit.
- Significant science research capability is provided.
- An initial crew size of four grows to seven.
- Chemical propulsion is the initialization reference.
- A martian moon gateway is developed, with propellant and oxidizer production.

The emplacement of a permanent, self-sufficient base on the surface of Mars will develop through three phases, each with its own distinct objectives. The objectives of each phase are described below.

Emplacement: Initial human landing, deployment, and checkout of the surface habitat module. Local human exploration activities and regional semiautonomous exploration capability.

Consolidation: Begin to exploit the local martian resources with the introduction of gateway propellant plant. Growth in crew size, Mars surface stay-time, and both human and robotic exploration capabilities.

Utilization: Base permanence established with expanded surface facilities, greater use of martian resources, and advanced propulsion technologies. Capability of global exploration of Mars demonstrated.

### 3.1.2 Mission Manifest

The mission manifest for this case study includes eight flights from the year 2005 to the year 2014. A summary of these flights is provided by table 3.1.2-I. A manifest of the delivered surface elements is shown in table 3.1.2-II. The crew manifest for the five piloted missions is shown in figure 3.1.2-1.

TABLE 3.1.2-I.- MARS EVOLUTION CASE STUDY FLIGHT SUMMARY

| Flight | Purpose | Years Launched | Crew | Payload to Surface (t) |
|---|---|---|---|---|
| 1 | Cargo | 2005 | 0 | 50 |
| 2 | Crew | 2007 | 4 | 15 |
| 3 | Crew | 2009 | 5 | 24 |
| 4 | Cargo | 2010 | 0 | 50 |
| 5 | Crew | 2011 | 5 | 22.5 |
| 6 | Crew | 2014 | 5 | 25 |
| 7 | Cargo | 2015 | 0 | 100 |
| 8 | Crew | 2016 | 7 | 25 |

### 3.1.3 Mission Requirements and PSS Response

The scenario requirements for the Mars evolution case study were established by Mission Analysis and Systems Engineering (MASE) in the SRD. The PSSIA has successfully developed a surface system architecture that meets the martian base as specified in the SRD. The MASE mission requirements and the appropriate PSS response are elucidated in table 3.1.3-I.

### 3.1.4 Achievement of Milestones

Milestones to judge the progress of the evolutionary Mars base were established by MASE in the SRD. These milestones are:

- First human exploration of Mars system and surface
- Initial habitat on Mars surface
- Initial crew size of four grows to seven
- A martian moon gateway developed, with propellant and oxidizer production
- First production of oxygen on Mars
- First production of food on Mars
- Operational status

Figure 3.1.4-1 shows the progressive timeline of an evolutionary martian base. Milestones are marked on this timeline.

## 3.2 MARTIAN SURFACE SYSTEM SELECTION

As previously noted, the martian surface system elements were selected in response to the requirements specified in the MASE SRD and the integrated mission manifest. Elements were categorized according to the functional areas devised by the PSSIA.

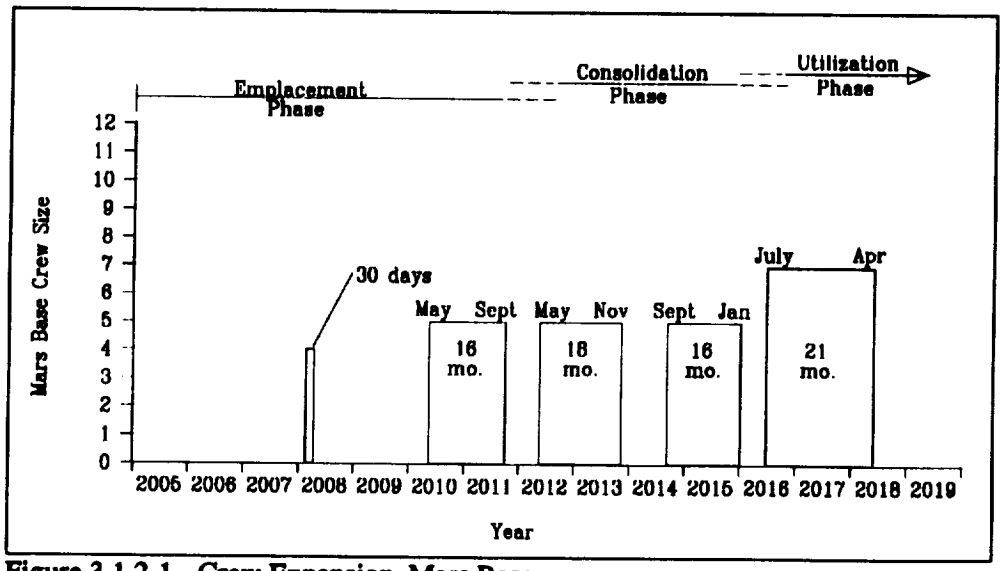



Figure 3.1.2-1.- Crew Expansion, Mars Base.

## TABLE 3.1.2-II.- ELEMENT MANIFEST

| Surface Systems | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Support Element Name** | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| Habitation Module | | 1 | | | | | | | | | | | | |
| Airlock | | 1 | | | | | | | | | | | | |
| Unpressurized Rover | | | | 2 | | | | | | | | | | |
| Thermal Control System | | 1 | | | | | | | | | | | | |
| PVA/RFC (50 kw, 50 kw) | | 1 | | | | | | | | | | | | |
| PVA/RFC (50 kw, 25 kw) | | | | 1 | | | | | | | | | | |
| Crane | | 1 | | | | | | | | | | | | |
| Digger | | 1 | | | | | | | | | | | | |
| Truck | | 1 | | | | | | | | | | | | |
| Fuel Cell Power Carts | | | | | | | 1 | | | | | | | |
| Thermal Control Carts | | | | | | | 1 | | | | | | | |
| Thermal Tents | | | | | | | 1 | | | | | | | |
| Pressurized Tunnel Ramp | | | | | | | 1 | | | | | | | |
| Pressurized Rover | | | | | | 1 | 1 | | | | | | | |
| Unmanned Local Rover | | 1 | | | | 1 | | | | | | | | |
| Communications Equipment | | 1 | | | | 1 | 1 | | | | | | | |
| Communications Tower | | | | | | 1 | 1 | | | | | | | |
| Cable (1.3 km) | | 1 | | | | | | | | | | | | |
| Navigation Beacons | | 2 | | 2 | | | 1 | | | | | | | |
| EMU Equipment | | | | 4 | | 5 | | 5 | | 5 | | | 7 | |
| Mars LOX Demonstration Plant | | | | | | | | | | | 1 | | | |
| Nuclear Power Plant | | | | | | | | | | | 1 | | | |
| Constructible Habitat | | | | | | | | | | | 1 | | | |
| Constructible Thermal Control | | | | | | | | | | | 1 | | | |
| Constructible Regenerative LSS | | | | | | | | | | | 1 | | | |
| Constructible Outfitting | | | | | | | | | | | 1 | | | |
| Off-Loading Equipment | | | | | | | 1 | | | | | | | |
| Phobos Propellant Plant | | | | | | | 1 | | | | | | | |
| Phobos Servicing Equipment | | | | | | | 1 | | | | | | | |
| Ballistic Vehicle | | | | | | | | | | | 1 | | | |
| **Science Element Name** | | | | | | | | | | | | | | |
| Geologic Exploration Equipment | | | | 1 | | 1 | | 1 | | | 2 | | 2 | |
| Geophysical/Atmospheric Station | | | | 1 | | | | | | | | | 2 | |
| Traverse Exploration Package | | | | 1 | | | 1 | | | | | | 2 | |
| Portable Geophysical Package | | | | 2 | | 1 | | 1 | | | 2 | | 2 | |
| Visible/Infrared Imager | | | | 2 | | | | | | | | | 2 | |
| Meteorological Balloons | | | | 4 | | 6 | 12 | | | | | | | |
| Life Support Demonstration | | | | 1 | | | | | | | | | 8 | |
| Food Demonstration | | | | | | 1 | | | | | | | | |
| Fields and Particles Instruments | | | | | | 1 | | | | | | | | |
| Upper Atmospheric Balloons | | | | | | 3 | 12 | | | | | | | |
| Sounding Rockets | | | | | | 3 | 12 | | | | | | | |
| Biomedical Laboratory Instruments | | | | 1 | | | | | | 1 | | | | |
| Analytical Science Laboratory | | | | | | 1 | | | | | | | | |
| Plant/Animal/Microbe Laboratory | | | | | | | | | | 1 | | | | |
| Contamination/Isolation Laboratory | | | | | | | | | | 1 | | | | |

## TABLE 3.1.3-I.- MISSION REQUIREMENTS AND PSS RESPONSE

| Requirement | Response |
|---|---|
| EMPLACEMENT PHASE | |
| Human Systems | |
| • Establish habitable facility with the capability to support a crew of five up to 18 months. | • Habitat module, airlock, consumables, PVA/RFC, cable |
| • Crew exploration of Phobos and Deimos. | • Phobos EMU's |
| • Provide radiation shielding using local resources. | • Digger, truck, crane |
| Construction | |
| • Provide, to the extent possible, automated placement of the initial habitat. | |
| • Provide capability to unload/assemble/construct/secure/checkout habitat, science payloads, and other Mars surface systems. | • Telerobotic and autonomous construction equipment |
| Surface Transportation | |
| • Provide capability for surface transport of crew and cargo with 10 km range. | • Unpressurized rover, truck |
| • Crew collects site data and samples on Phobos and Deimos | • Phobos PMV |
| User Accommodations | |
| • Telerobotic rover on Mars surface explores and collects samples for Earth under crew control. | • Manifest rover |
| • Provide capability to employ scientific experiments. | |
| • Crew collects extensive geophysical and environmental data. Selects surface and subsurface samples for Earth return, and performs selected science experiments. | • Unpressurized rover |
| CONSOLIDATION PHASE | |
| Human Systems | |
| • Maintain habitable facility for 5 up to 18 months | • Habitat, consumables |
| Construction | |
| • Deployment of Phobos propellant plant and Mars cargo lander. | • Automated plant |
| Surface Transportation | |
| • Provide 100 km sortie capability. | • Pressurized rover |
| In Situ Resource Utilization | |
| • Provide water extraction and cryogenic propellant production plant on Phobos with 600 t/yr production capability to support gateway operations. Plant operates under robotic control. | • Phobos propellant plant |
| User Accommodations | |
| • Provide science exploration. | • Unpressurized and pressurized rovers. |
| UTILIZATION PHASE | |
| Human Systems | |
| • Provide habitat for up to 12 for up to 24 months. | • Constructible habitat |
| Construction | |
| • Constructible habitat. | • Crane, IVA tools |
| In Situ Resource Utilization | |
| • Phobos propellant production. | • Phobos plant |
| • Mars oxygen production demonstration. | • Demonstration plant |
| User Accommodations | |
| • Science | |

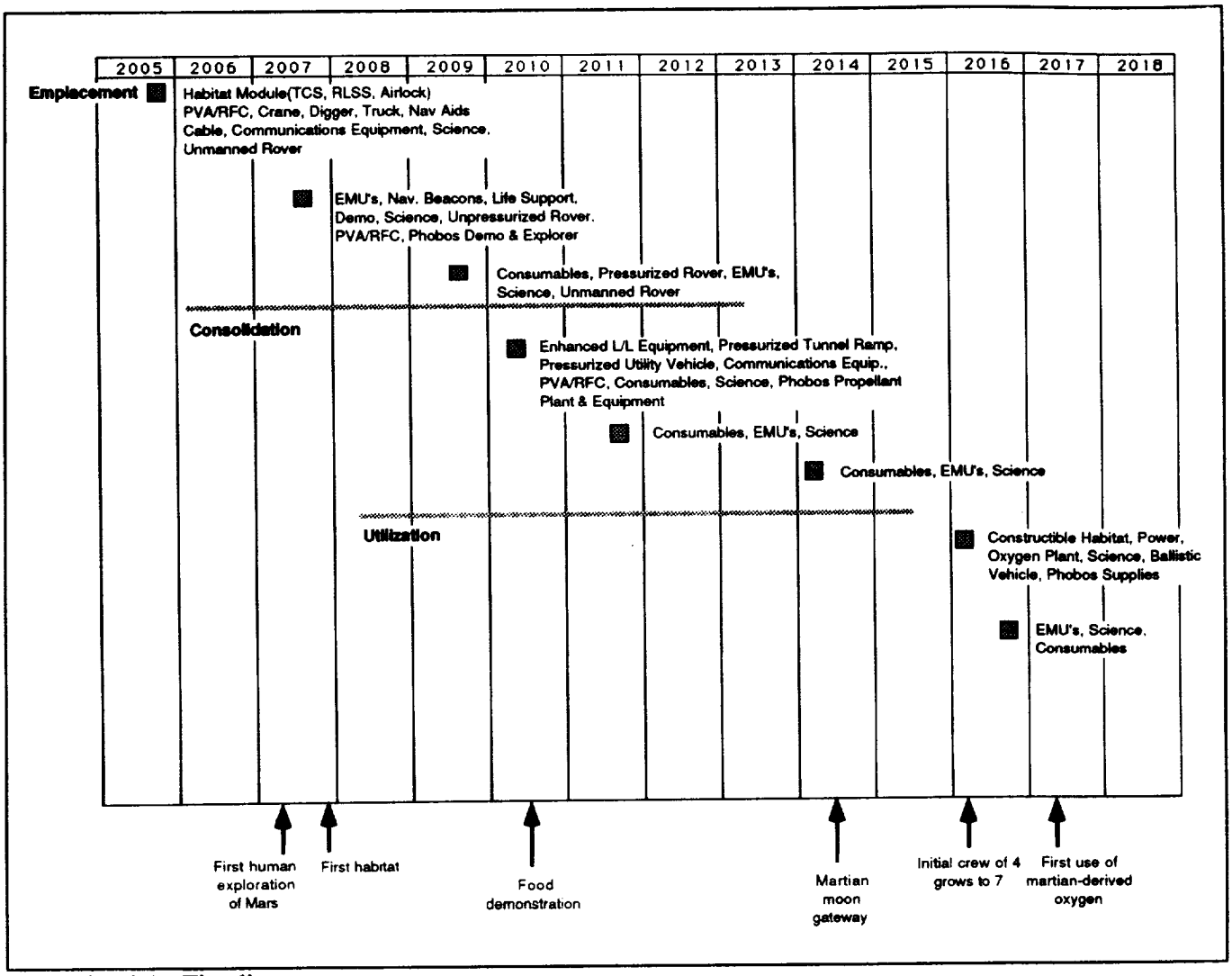



Figure 3.1.4-1.- Timeline.

Table 3.2-I summarizes the major elements selected for the Mars evolution case study with an accompanying brief functional description and estimates for mass, power required, and volume. The science equipment manifested for the base is not selected by the PSS office, since it is not considered surface systems support. However, to provide a complete picture of the elements located at the base, table 3.2-II lists the major science users with corresponding mass, power required, and volume values.

### 3.2.1 Habitation

During the emplacement phase of the Mars base, a Space Station Freedom-derived common module (4.5 m x 13.7 m) is selected for the initial habitat. The single module provides shelter for crews of up to five persons for durations of 30 days to 18 months. The module interior is adapted to the constraints of the 1/3 gravity environment with specifications for sleeping berths, galley, health maintenance facility, and storage space. Volume limitations restrict the amount of space for science users to approximately one rack. Residence in the module is highlighted by the predominance of construction operations.

The initial module is designed as a self-contained structure, including the life support system, thermal control system, and logistics supplies. Only the primary power source is located external to the habitat. This prefabricated, all-in-one approach is necessary in order to allow crews to focus their time and attention on base establishment and surface science activities. The module is delivered to Mars on a cargo lander and placed on the surface (robotically), such that the first crew need only to connect the power supply and certify the module for pressurized occupation.

As the base grows, the requirements for pressurized volume for crew accommodations, lab equipment, work-

TABLE 3.2-I.- SELECTED MARS SURFACE ELEMENTS

| Element | Mass (t) | Volume ($m^3$) | Power Req. (kW) | Functional Description |
|---|---|---|---|---|
| EMU | 0.23 | 1.04 | S/C* | Allow EVA surface activity. |
| PMU | 0.735 | 2.15 | S/C | Allow EVA at Phobos. Provide MMU-like capability. |
| Unpressurized Rover | 1.1 | 15 | 4 | Provide means of local transportation in base area (10 km). |
| Navigational Beacons | 0.1 | 0.1 | S/C | Provide in-flight navigational assistance. |
| Unmanned Rover | 3.0 | 15 | S/C | Provide scientific access to remote sites. Provide surface reconnaissance to assist in base site selection. |
| Habitat Module | 18.8 | 200 | 30 | Provide a safe habitat for a crew of 5 for up to 18 months. Provide safe haven opportunity in later base phases. |
| Construction Machinery | | | | |
| Crane | 3.8 | 273 | 5.0 | Provide a means of surface assembly and habitat construction. |
| Truck | 3.8 | 45 | 5.0 | |
| Digger | 3.8 | 95 | 5.0 | |
| Cable | 1.5 | 2 | N/A | Provide interface with utilities for zones. |
| Photovoltaic Array & Regenerative Fuel Cells | 4.0 | 150 | S/C | Provide energy needs of base based on energy requirements of habitat areas and ISRU processes. |
| Communications Equipment | 0.5 | 0.1 | 1 | Provide a means for surface to air communications. |
| Pressurized Rover | 6.5 | 144 | 13 | Provide a means for carrying crew, tools, and materials to construction sites. Provide capability for manned visits to remote scientific sites. Provide a means to reducing EVA time in overall base operations. |
| Food Demonstration | 0.5 | 0.5 | 7.0 | Assess the feasibility of eliminating resupply needs. |
| Life Support Demonstration | 0.2 | 0.5 | 5.0 | Assess the feasibility of ALSS and MLSS concepts. |
| Tunnel Ramp | 2.8 | 63 | 2 | Provide pressurized transfer between landing vehicles and pressurized surface vehicles. |
| Off-Loading Equipment | 12.5 | 300 | 10 | Provide a means of unloading cargo from MEV's. |
| Vehicle Servicing Equipment | | | | |
| Thermal Control Cart | 2.5 | 8 | 6 | Provide a means of servicing MEV on the surface of Mars. |
| Power Cart | 2.5 | 8 | 6 | |
| Vehicle Tent | 1 | 1 | N/A | Protect MEV on surface of Mars. |
| Propellant Plant at Phobos | 30 | 220 | 1,067 | Provide propellant for TEI. |
| Refill & Servicing Equipment at Phobos | 14 | 168 | 20 | Provide a means for refueling and servicing flight vehicles at Mars Gateway. |
| Constructible Habitat | 53.7 | 1022 | 60 | Provide larger habitable volume for increased crew size and longer surface stays. |
| Oxygen Plant | 10.6 | 200 | 744 | Provide a means of utilizing in situ resources. |
| Ballistic Vehicle | 12.0 | 160 | 20 | Provide a means for global science and exploration (derived from MEV). |
| Nuclear Power System | 23.5 | 46 | N/A | Provide bare energy needs for expanded habitat areas and ISRU processes. |

* self-contained

space, and storage increase substantially. A 16 meter diameter constructible habitat is defined for the second generation of base habitation, as opposed to a multiple common module configuration. A direct comparison between the constructible and modular approaches is presented in figure 3.2.1-1. The 16 meter diameter habitat provides the volume equivalent of 11 common modules, with a structural mass slightly greater than three modules. Even if the base expanded through the use of multiple linked modules, at some time a single large volume would be desired instead of corridor-like living spaces.

The reference concept provides living accommodations for twelve persons, although the martian evolution case study configuration calls for seven. The habitat requires roughly one year to construct. Construction tasks include excavating the site, inflating the structure, installing the life support and thermal control systems, outfitting the interior, connecting utilities, and emplacing

TABLE 3.2-II.- MARTIAN SCIENCE USER ELEMENTS

| User Elements | Launch Mass (kg) | Power Required (kw) | Press. Volume ($m^3$) | Oper. IVA (hrs/wk) | Oper. EVA (hrs/oper) |
|---|---|---|---|---|---|
| Traverse Exploration Package | 110 | 0.3 | 0 | 0 | 6 |
| Geological and Atmospheric Station | 150 | 0 | 0 | 0 | 6 |
| Geological Exploration Equipment | 100 | 0 | 0 | 0 | 6 |
| Portable Geo. Exploration Package--shallow | 1,220 | 0.4 | 0.0 | 0 | 6 |
| Portable Geo. Exploration Package--deep | 50 | 0.4 | 0.0 | 0 | 6 |
| Meteorological Balloons | 25 | 0 | 0 | 0 | 3 |
| Upper Atmosphere Balloons | 200 | 0 | 0 | 0 | 3 |
| Upper Atmosphere Sounding Rocket | 100 | 0 | 0 | 0 | 6 |
| Semi-Autonomous Rover | 2,900 | 0.5 | 0 | 16 | 0 |
| Sieves and Soil Penetrometer | 200 | 0 | 0 | 0 | 3 |
| Laser Light-Detecting Radar | 100 | 0 | 0 | 0 | 3 |
| Fields and Particles | 100 | 0 | 0 | 0 | 3 |
| Biomedical Instruments | 1,000 | 4.2 | 7 | 8 | 0 |
| Geochemical Analytical Lab | 1,200 | 10.7 | 6.5 | 16 | 0 |
| Microbial Plant/Animal Lab | 8,000 | 11.4 | 20 | 12 | 0 |
| Contamination/Isolation Lab | 400 | 3.6 | 1.7 | 4 | 0 |

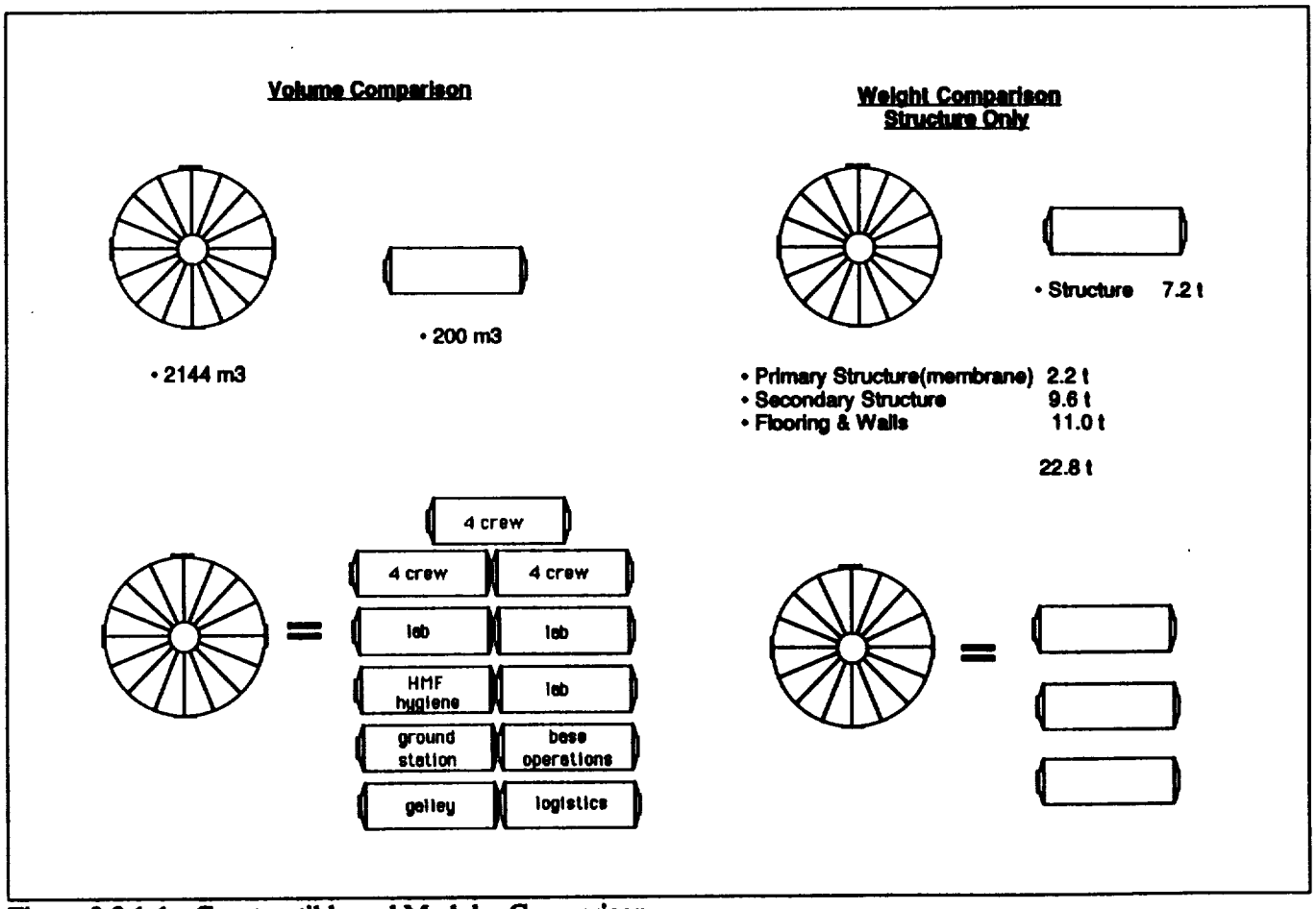



Figure 3.2.1-1.- Constructible and Modular Comparison.

radiation protection. The inflatable sphere is selected from a variety of options due to mature design definition and extensive study.

### 3.2.2 Extravehicular Activity (EVA) Systems

The development of the martian base requires frequent EVA's for purposes of base construction, operation, maintenance, and scientific exploration. An extravehicular mobility unit (EMU) consisting of a pressure suit and portable life support system (PLSS) developed specifically for the martian environment is central to the EVA system. Figure 3.2.2-1 shows a concept for an EMU. EVA systems are further enhanced with Shuttle-type hand tools and unpressurized rovers for local area access.

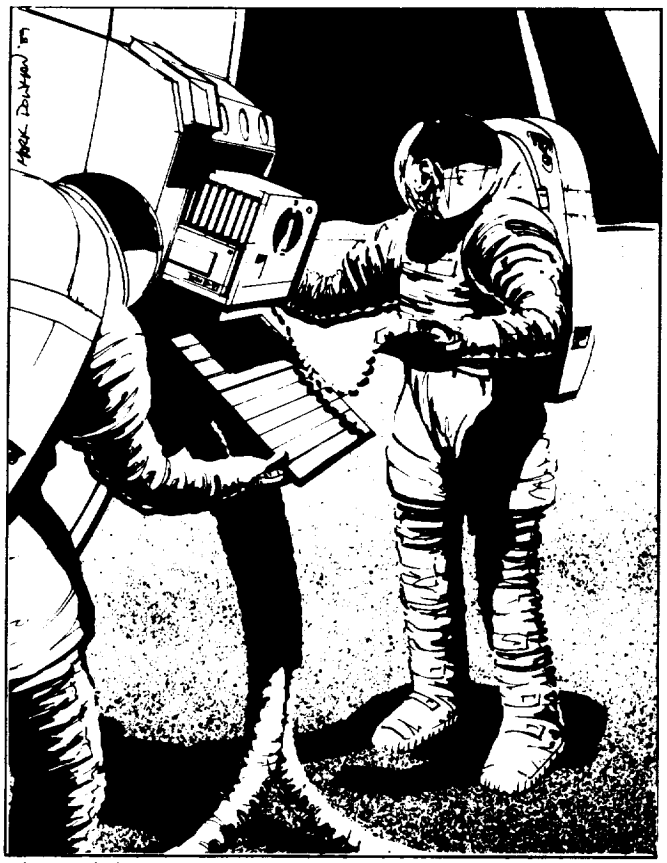


Figure 3.2.2-1.- Extravehicular Mobility Unit.

Key requirements for non-orbital EMU's include minimum weight and volume, long-term durability and reliability, and efficient servicing and maintenance. The PLSS design is driven by the case study emphasis on reduction of resupply logistics, thus leading to the choice of a regenerative system. The human carrying capacity limits the martian PLSS mass to 53 kg, compared to the Space Station Freedom (SSF) regenerable PLSS of 195 kg mass. In order to use SSF technology, additional options are employed on Mars, such as changeable ice packs for thermal cooling and umbilical connections from the rover. Factors affecting the design further include suit versus habitat pressure levels, currently baselined at 57.2 kPa and 101.3 kPa (8.3 psi and 14.7 psi) respectively, and the duration of the EVA, set at eight hours for the martian case study.

The airlock design facilitates EVA operations. Martian dust contamination in the pressurized facilities is a major concern. A dust porch with brushes and grates is located outside of the airlock for overgarment removal. Furthermore, a dual airlock layout, with a crew lock and an equipment lock, keeps any remaining dust in the outer lock. Two airlocks are manifested to support EVA activities from both the construction shack and the constructible habitat.

To explore and develop Phobos, a new means of traversing must be designed, given the unique environment of Phobos. The Phobos maneuvering unit (PMU) will allow two crew to navigate about the Phobian surface. This unit (covered in more detail in section 5.4) is derived from the manned maneuvering unit (MMU). The PMU has a total mass of 735 kg and a $\Delta V$ capability of 75 m/s.

### 3.2.3 Life Support Systems

The life support system selected for the evolutionary martian base is a regenerable physical-chemical system. This system evolves in two phases, initial and advanced, as the base expands to include larger crews. The initial life support system (ILSS), a derivation of the SSF system, is integrated into the construction shack servicing a crew of five. The ILSS is required to provide a functional closure level of 95 percent, i.e. 95 percent of water and air are recovered through the system. Resupplies for ILSS include nitrogen, food, and system and crew expendables.

With the construction of the inflatable habitat, an advanced life support system (ALSS) is installed to service crews extending to seven persons. The ALSS marks improvements over the ILSS by advancing the recovery of materials from solid wastes and reducing resupply of system expendables. As the base develops the capability to produce martian-derived oxygen, the ALSS utilizes that oxygen in the regenerable system, thus achieving a functional closure level of approximately 99 percent. Resupplies are still required for nitrogen, food, and crew expendables.

Although not defined in the Mars evolution case study, the next phase of life support includes food production. The mature life support system (MLSS) integrates the physical-chemical systems with a bioregenerative

approach as an attempt to increase base self-sufficiency. In addition to providing air and water loop closure, the MLSS starts to close the food loop. Initiating this approach demands a more advanced base with larger crews and extensive pressurized facilities.

### 3.2.4 Thermal Control System

Thermal control systems (TCS) for the initial habitation module and constructible habitat require active measures as opposed to passive. The TCS must actively acquire internal equipment and metabolic heat loads and reject these loads to the external environment. Heat pumps, required on the Moon, can be avoided on Mars due to the cold environment and the short martian day. Unique martian parameters critical to TCS design include extreme changes in surface and atmospheric temperatures, changing winds, and degradation of surface properties. During periods of low temperature, low solar flux, and high wind, the mode of heat transfer may be convection dominated. During periods of high temperature, high solar flux, and low atmospheric free convection, the mode of transfer may be radiation dominated.

For radiative purposes, the martian environment is a good heat dump and a horizontal radiator may be used. If dust contamination is a concern, vertical radiators with appropriate wind shields or square radiators oriented parallel to the prevailing wind direction may be used.

The soil temperature at a depth of 24 cm differs negligibly from the average surface temperature. Thus, the martian regolith can provide significant thermal protection. With at least a 25 cm cover of regolith, the initial habitation module would be relatively unaffected by the fluctuating, cold environment. Approximately 10 kW of input heat from the base power system in conjunction with an internal TCS based on Space Station Freedom technology could maintain a comfortable temperature inside the module.

### 3.2.5 Radiation Protection

Surface crews will need protection from the constant galactic cosmic ray (GCR) background and infrequent but life-threatening solar particle events. The martian atmosphere, though thin, provides excellent protection except at the zenith. Recent studies indicate that for crew stay times of less than one year, no GCR protection will be required (Nachtway, 1989). Longer stay times will require GCR protection at some level. Solar particle events can be treated on a contingency basis due to their short duration: a temporary shielded shelter should be adequate. However, once full GCR protection is provided, solar particle events are automatically protected against.

In light of short crew stay times in the crew module, no GCR protection is baselined. Solar particle event protection is in the form of a shielded area in one end of the module. As base capabilities permit, the module will be covered with regolith at some later point in the development of the base.

Since crews reside in the constructible for up to two years, GCR protection will be required for this structure. Much more work needs to be done to determine the biological effects of a given flux of galactic cosmic ray particles. The current estimate of the amount of regolith needed for adequate shielding is 2 meters or less. The constructible is provided with such a layer. Further study will compare various options such as simple piling, sand (regolith) bags, continuous coil bags, and retaining walls or forms. Simple piling will involve moving much regolith due to the low slump angle, and the other methods listed represent a mass penalty for such items as bags and panels.

### 3.2.6 Energy

Studies over the past few decades indicate that an evolutionary base can be initiated at a power level on the order of 50 kWe, with eventual growth into the multi-megawatt range. Candidate power systems for a Mars base must be evaluated on the basis of specific energy (power per unit mass), total system mass, technology availability, and safety. Other criteria will also be addressed.

For the initial crew module, photovoltaic (solar) power is baselined. Regenerative fuel cells (RFC's) charge from the photovoltaic array (PVA) during the day, thereby providing both daytime and nighttime power. The experience that has been gained with space solar and fuel cell power systems can be applied to provide a very safe and highly reliable surface power system. Such a system could suffer the loss of any number of individual photo cells, and still provide power from the remaining undamaged cells.

The PVA's can be deployed robotically before the first crew arrives. The crew need only make the final connections and verify the operation of the array and fuel cells.

In contrast to the lunar case, the martian day night cycle (virtually the same as terrestrial) does not impose a heavy burden on the night time power supply. The initial power system, which delivers 50 kWe day and night, is 2.0 t array and less than 2.0 t regenerative fuel cells.

As base power demands grow, photovoltaic systems become unwieldy. Above 500 kWe, nuclear power

offers a much better system mass than fuel cells. The constructible habitat is a major power user, both day and night, so a nuclear reactor adapted for planetary surfaces was chosen for delivery before the habitat is completed. It provides 1,000 kWe continuously.

Full scale oxygen production will require power in the megawatt range. Plant mass is reduced if operation is round-the-clock. This consideration, plus the higher specific power for nuclear systems as compared to solar, lead to the selection of a large nuclear plant for base power in the late consolidation phase and beyond.

Energy distribution is by cable, estimated as 4/0 aluminum conductor. Other enhancements/options under study include high frequency transmission to reduce losses, beamed power, and use of reactor waste heat in materials processing.

### 3.2.7 Assembly and Construction

The characterization of the martian base as a permanent facility implies the need for assembly and construction capabilities for long-term structures. Such capabilities include lifting of massive payloads, carrying payloads to the emplacement site, and regolith moving/excavating for site preparation. Selected assembly and construction equipment also share common functions with machinery for resource mining and lander payload unloading.

The analysis performed for this year's case studies in the area of assembly and construction does not address specific equipment design. Instead, the focus was placed on defining the requirements for base construction. Therefore, the equipment selected to support construction operations was estimated from previous studies while other design concepts are still under study. The equipment manifested in the first cargo flight, 2005 included a crane to manage off-loading payloads, a digger for surface preparation, and a truck for payload surface transport. Each of these pieces weighs approximately 4 t and supports the construction and assembly during the emplacement and consolidation phases. Under the heading of lander facility upgrades, enhanced off-loading equipment is delivered in 2011 to assist construction and placement of the nuclear plant and oxygen production facilities.

An alternative to using individual pieces of machinery for particular tasks is to employ a prime mover or mobile platform outfitted with a number of removable and replaceable implements. The range of implements for multipurpose functions include reverse clam-shell digger, robotic arm, drill assembly, and grader blade. Further characterization of the equipment in terms of mass, power and productivity is required before an element selection can be performed. Section 6.2 provides an in-depth discussion regarding construction operations for the Mars evolution case study. Operations analyses are based on particular tasks, productivity levels, and assumed equipment functions.

### 3.2.8 Surface Transportation

Surface transportation of varying degrees is required throughout base development for the transport of both crew and cargo. With the delivery of the first crew in 2008, an unpressurized, manned rover is included. The four-wheeled vehicle selected resembles the Apollo rover. The vehicle satisfies local crew transport, within 10 km of the base, for extravehicular surface activities and carrying equipment in the vicinity. The rover's payload capacity includes two suited crew and 250 kg of payload or four suited crew with minimal payload. Further characteristics include a 100 km range, a 10 km/hr speed, a 20 degree maximum climbing grade, and a 10 hour maximum sortie time. Two of these unpressurized rovers are delivered in the first two years, with a third added in 2012.

A pressurized utility vehicle arrives in 2011 to support base establishment efforts. The four-wheeled mobile module selected for the martian case study transports crews of four with a mid-range of approximately 100 km. The pressurized rover, equipped with an airlock, provides the following capabilities - 72 hours maximum sortie time, support for a 1,000 kg payload, support for one EVA per day, and a 10 km/hr speed. The pressurized utility vehicle satisfies the transportation needs for mid-range scientific excursions, taxi trips to and from the base and landing pad, and EVA reduction work for construction and maintenance operations. A small 14 kW power trailer (fuel cell energy storage) and a pressurized laboratory unit are also manifested early in the base development, extending the science excursion capabilities. A second PUV is delivered in 2014, outfitted with a larger 25 kW power trailer. The power extension increases the vehicle's capabilities to 1000 km and expedition times up to 14 days. The PUV also has the capability to dock directly to the habitats, providing pressurized transfer of crew between rover and habitat. Combined with the tunnel ramp (delivered in 2009), crew are able to transfer from the PUV to the lander without having to incur the overhead of EVA.

During the utilization phase, access to remote locations on Mars (such as the poles) for scientific expeditions is scheduled. Due to the danger and demands inherent in long duration excursions away from the base, rovers are unsuitable for such long traverses. One ballistic vehicle is manifested in 2018 to accomplish these remote reconnaissance missions. The ballistic vehicle is a

variation on the martian landing vehicles, which support the martian orbit to Phobos route. Although not considered a surface element, the ballistic vehicle utilizes the locally produced propellants to satisfy its steep fuel requirement.

### 3.2.9 In Situ Resource Utilization

It has long been realized that potentially substantial savings/enhancements can be obtained through the use of locally produced items, provided they are of sufficiently high value to justify the overhead of the production facilities. Oxygen exists on Mars (for example) in the form of atmospheric $CO_2$, and in $CO_2$ and water ice. It is expected that extraction of this resource will be beneficial through its use as lander fuel and life support makeup.

Several competing concepts for processes exist for martian oxygen production. Atmospheric carbon dioxide electrolysis is a straightforward, site-independent process. As this process has been subject to the most analysis in recent years, it is the best choice as a departure point for further analysis of a total oxygen producing base architecture.

The capability to produce oxygen is developed all at once with the delivery of a plant on flight 7.

### 3.2.10 Launch and Landing Systems

All martian landers in this case study are baselined as expendable. As such, only minimal lander support is required on the martian surface. This support consists primarily of unloading the cargo, then preparing the vehicle for ascent at the end of the surface stay.

All launch/landing support equipment is delivered on flight 4. This consists of off-loading equipment, and a set of vehicle servicing equipment. Also delivered is a pressurized tunnel ramp which, in conjunction with the pressurized rovers, enables IVA crew transfer from lander to base and back.

### 3.2.11 User Accommodations

Table 3.2-II, as previously listed, describes the variety of science equipment to be emplaced on the martian surface. The specific science elements are defined by MASE as part of the case study objectives. Therefore, the PSS office is not responsible for selecting science equipment like other surface systems. Rather the function of the user accommodations area is to ensure that user elements receive the required support from the established base systems. Support for user activities comes in the form of pressurized volume, power, communications, surface transportation, and crew. Results of user accommodations at the Mars base are discussed in section 3.4.

### 3.2.12 Telecommunications, Navigation, and Information Management (TNIM)

Various navigation and communication capabilities must be provided to satisfy base requirements. The exact specifications depend on the total two-way traffic needs.

A full description of the base TNIM system can be found in section 5.7. Briefly, it consists initially of a single rack of communications equipment in the crew module. Pad markers and navigation beacons dot the landing areas. When the constructible habitat is built, a ground station is delivered. A communications tower is erected to extend surface-to-surface communications. In addition, a package of electronic test equipment is delivered.

## 3.3 BASE SITE AND LAYOUT

The following subsections discuss preliminary site selection and layout of the surface base.

### 3.3.1 Site Selection

The Mars evolution base site will be located on the equator, 33.5°W longitude at the Chryse Basin complex. The site is close to one tributary of the Valles Marines and is approximately 1,500 km from the Viking I landing site. The terrain in the vicinity of the Viking I lander is a rocky desert with rock fragments ranging from centimeters to a meter in diameter. There are drifts of sandy material between rocky areas, and they are encased in thin crusts of weakly cemented material. The rocks are angular and coarsely pitted. No impact craters are visible in the vicinity, and none are expected less than 50 m in diameter due to the protective effects of the Martian atmosphere. The Chryse location will likely require clearing and leveling due to the presence of rocks and slightly uneven terrain. The following provides a general characterization of the martian environment and then discusses the base site.

#### 3.3.1.1 Terrain

There is a limited amount of data about the martian surface. The material to date stems from data received from the Viking landers and orbiting satellites. Thus there is uncertainty regarding the terrain of Mars except for the areas near the Viking landing sites. There are two general types of surfaces on a global scale: surfaces with high densities of craters greater than 50 km in diameter and younger surfaces on which craters greater than 50 km in diameter are rare. The Mars surface

terrain is further divided into two characteristic terrain regions: the relatively smooth maria that account for about 17 percent of the surface, and the highlands that make up the remainder of the surface. In the maria regions, the slopes are from 0 to 10 angular degrees with a standard deviation of 3.7 degrees; in the highlands, the terrain slopes from 0 to 23 degrees with a standard deviation of 4.5 to 6 degrees and higher. Canyons, valleys, and volcanic mountains will present extreme contrasts in relief, including slopes exceeding 32 degrees with local rocky ledges and cliffs.

### 3.3.1.2 Atmospheric

A summary of the percentages of the martian atmosphere are given in table 3.3.1-I (Meyer and McKay, 1984). The average surface pressure is 6.1 mb as compared to 1,013 mb on Earth. Surface pressure varies seasonally up to 30 percent and daily up to 15 percent due to precipitation and sublimation of carbon dioxide and water. The pressure ranges from 5.9 to 15 mb. At the Viking I landing site, 2 km below the Mars elevation datum plane, the surface pressure ranged from 6.9 mb at southern midwinter to 9 mb at the end of the southern spring. The pressure varies from the summit of Olympus Mons to the floor of Hellas by a factor of ten.

TABLE 3.3.1-I.- COMPOSITION OF MARTIAN ATMOSPHERE

| Component | Percent by Mass |
|---|---|
| $CO_2$ | 96.6 |
| $N_2$ | 1.74 |
| Ar | 1.47 |
| $O_2$ | 0.0958 |
| CO | 0.04516 |
| $H_2O$ | 0.06 |

### 3.3.1.3 Meteorology

Dust storms originate in the southern hemisphere when the occasional cross-equatorial merging of Hadley circulation cells allows regional slope-related dust storms to feed into the northern hemisphere. Although no reliable prediction model exists, when they occur the dust storms appear to be related to southern spring and summer when solar radiation (perihelion) is 45 percent stronger than in winter (aphelion). Global storms have a meridional speed of about 10 m/s (36 km/hr), and they insert dust to altitudes greater than 40 km, where particles remain suspended for weeks or months. The optical depth changes from a prestorm value of 0.5 to as high as 6 at the peak of storm activity. Dust concentrations increase very sharply at the start of each storm, and for the more intense storms the sun is actually obscured. Although light at the surface is significantly attenuated by major dust storms, Viking lander operations indicate that extravehicular activity (EVA) would not be significantly affected (Henry Moore, USGS, personal communication). Regional dust storms begin in areas where steep slopes or thermal gradients trigger high local winds such as those in the southern summer near the polar cap. Local northern hemisphere dust storms, triggered by baroclinic wave activity, cover about 104 $km^2$ and occur between latitudes 15°N and 35°N. Detailed planning of base and science site locations should include consideration of potential slope winds. Frost appears each night (-123°C) at the Viking II site, possibly blown there with dust. Winter carbon dioxide frost extends from the poles to latitudes 45°S and 50°N.

### 3.3.1.4 Dust

The presence of dust on Mars poses an environmental problem for routine operation. Martian dust has a sandy consistency, coarser than the powdery dust of the Moon. The dust and surface material must be kept out of the crew habitat, EVA suit joints and fabric, tools, radiators, and sensitive equipment. Unprotected bearings and other parts moving in contact soon lose their functional characteristics when infiltrated with dust.

### 3.3.1.5 Resources

The availability of resources on the martian surface, as discovered by the Viking landers, is given in tables 3.3.1-II and 3.3.1-III (McKay, 1984).

### 3.3.1.6 Seismic Environment

The Viking landers established that the seismic background noise on Mars due to winds and atmospheric pressure fluctuations is very low. The data on martian seismicity is still preliminary. Indications are that Mars is probably less active than Earth.

### 3.3.1.7 Thermal

Temperature on Mars reaches a minimum just before dawn and a maximum just after the sun's zenith. The southern summer is about 30 degrees warmer than the northern, reaching a maximum of 22°C in midsummer at latitudes 25°S. Temperatures are above 0°C in a wide range of latitude. The coldest winter temperature is about -133°C) on the southern polar caps. The variable martian surface temperatures are a function of solar illumination and shadows. The range of temperatures has been reported to be -143 to +27°C). The temperature beneath a rock at the Viking II site was calculated to

TABLE 3.3.1-II.- ELEMENTAL COMPOSITION OF THE VIKING I LANDER SITE

| Element | Percent by Mass |
|---|---|
| Si | 20.9 ± 2.5 |
| Fe | 12.7 ± 2.0 |
| Mg | 5.0 ± 2.5 |
| Ca | 4.0 ± 0.8 |
| S | 3.1 ± 0.5 |
| Al | 3.0 ± 0.9 |
| Cl | 0.7 ± 0.3 |
| Ti | 0.51 ± 0.2 |
| K | <0.25 |
| L* | 50.1 ± 4.3 |
| X** | 8.4 ± 7.8 |
| Y | 70 ± 30 ppm |
| Sr | 60 ± 30 ppm |
| Rb | <30 ppm |
| Zr | <30 ppm |

*L is the sum of all elements not directly determined.
**If the detected elements are all present as their common oxides (Cl excepted) then X is the sum of components not directly detected, including $H_2O$, NaO, $CO_2$, and $NO_x$.

TABLE 3.3.1-III.- CHEMISTRY OF THE VIKING I LANDER SITE

| Compound | Percent by Mass |
|---|---|
| $SiO_2$ | 44.7 |
| $Fe_2O_3$ | 18.2 |
| MgO | 8.3 |
| $SO_3$ | 7.7 |
| $Al_2O_3$ | 5.7 |
| CaO | 5.6 |
| $TiO_2$ | 0.9 |
| Cl | 0.7 |
| $K_2O$ | <0.3 |
| Total | 91.8 |

be -43°C). Major surface temperature differences can be experienced at the same time on different sides of a piece of equipment depending on its orientation with respect to solar illumination and deep space.

### 3.3.1.8 Radiation and Particles

Mars is exposed to the continuous flux of galactic cosmic radiation (GCR) and to frequent periods of intense solar energetic particle activity. GCR fluxes on the martian surface are about half their intensity on the lunar surface because of the protection provided by a thin carbon dioxide atmosphere. Solar energetic particle (SEP) fluxes are attenuated by a considerably larger factor. All particles fluxes on the martian surface, just as on the lunar surface, are reduced an additional 50 percent because they are blocked below the horizon. Thus, the major requirement for radiation shielding is in the vertical overhead direction, since the martian atmosphere provides protection for angles close to horizontal. The GCR flux is between 0.5 and 1.3 particles/cm$^2$'s, depending on solar activity. Solar protons pose a significant risk to inadequately shielded crewmembers; however, the martian atmosphere pressure is approximately 20 g/cm$^2$ of carbon dioxide, a significant shielding mass. Ultraviolet wavelengths of 190 to 300 mm penetrate the martian atmosphere and reach the surface.

### 3.3.1.9 Phobos

Phobos, an egg-shaped moon of Mars, has a mean diameter of 21 km. The surface is heavily cratered and has three predominate craters from 5 km to 10 km across. The smooth cross section of grooves on Phobos and the lack of ledges within craters suggest no significant change in the strength of materials to depths to 100 m. The period of the moon is 7 hours, 39 minutes. The moon's orbit is changing and tidal effects are causing a secular acceleration, bringing Phobos closer to Mars. Within the next 100 million years, Phobos will either break apart or crash into the planet. The density of the moon is a low 2.0 g/cm$^3$. In the past, Phobos was believed to be composed of a water-rich carbonaceous chondrite. Viking data with Earth-based radar have shown results that deny the existence of a water rich material, however. There is very low gravity on the surface, with accelerations of 0.3 cm/sec$^2$ to 0.5 cm/sec$_2$ and an escape velocity of 15 m/sec.

### 3.3.1.10 Deimos

Deimos, a potato-shaped moon of Mars, has a mean diameter of 13 km. It is heavily cratered, but has more subdued relief than Phobos. The surface has been found to be covered by 5 to 10 m of sediment in many craters and may be considerably deeper. As with Phobos, the strength of the surface material changes little to a depth of 100 m. The period of the moon is 30 hours, 18 minutes. Deimos' orbit is carrying it farther away from Mars, in contrast to that of Phobos. As with Phobos, Viking data with Earth-based radar have refuted the previous belief that Deimos is composed of a water-rich carbonaceous chondrite. There is very low gravity (0.3 cm/sec$^2$) and an escape velocity of 10m/sec.

### 3.3.2 Base Layout

The actual layout for the Mars evolution base is an assemblage of elements selected to meet the mission objectives of MASE. The elements are grouped into physical areas referred to as zones. Each zone is identified by a function or activity. Zones are set up to group the appropriate elements and activities together in order to optimize base operations and functional linkages between systems. The Mars base has four major zones: zone 1--habitation, zone 2--science users, zone 3--in situ resource utilization (ISRU), and zone 4--launch and landing. The overall Mars evolution base layout is depicted in figure 3.3.2-1, including zone locations and orientations.

#### 3.3.2.1 Zoning Rationales

The base layout involves a zoning into key activity centers. Zoning allows certain activities to take place only within a specified area. Zoning is influenced by two sets of rationales: 1) an overall base rationale, and 2) unique rationales pertinent to the zones of habitation, science users, ISRU, launch and landing, and power. These rationales set necessary guidelines for the actual site plan of the Mars evolution base.

The site layout responds to two key overall base rationales. The primary rationale is the concern for crew safety and the isolation of the main crew quarters from hazardous activities. The habitat must be isolated from ISRU activities that involve processing and cryogenic storage. The habitat must be at least 3 to 5 kilometers from any future launch and landing pads so that it is protected from any possible aborted landings. It should also be far enough away so that any ejecta from landings does not reach the habitat. Nuclear power plants must be located a sufficient distance from areas where crew members are either living or working.

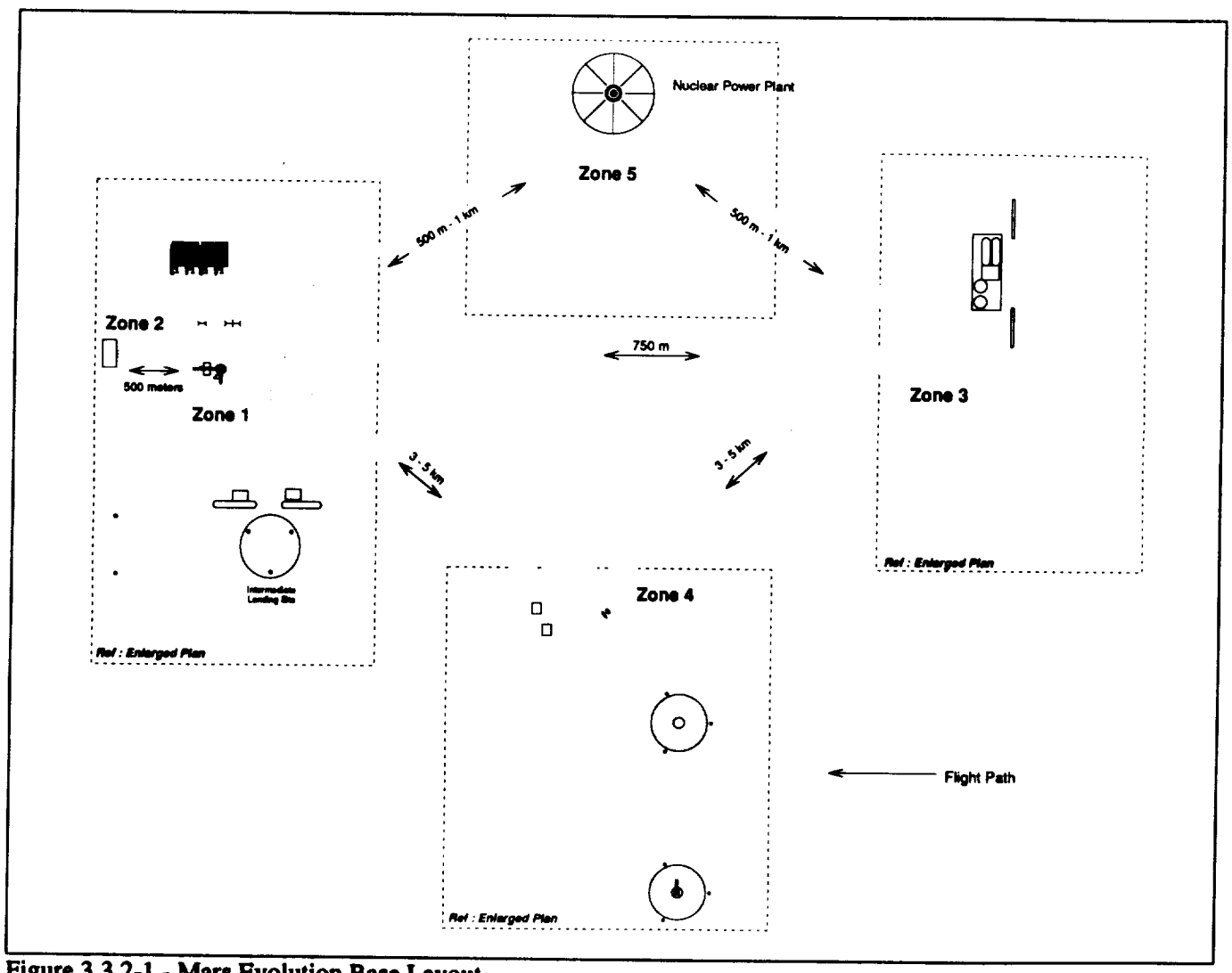



Figure 3.3.2-1.- Mars Evolution Base Layout.

The second rationale is the concern for future growth. The benchmarks set by MASE demand that the base not be limited in its capabilities. Any layout should allow expansion to take place. A successful demonstration of food production on the martian surface would certainly indicate that greenhouse facilities would be feasible. The ability to add more habitat space is important because future activities might warrant an increase in crew size. Surface vehicle storage will be needed as the fleet of vehicles increases and because of the harshness of the martian environment. The site layout should accommodate this contingency. Other rationales for the base layout are unique to each identified zone.

3.3.2.1.1 Zone 1--Habitat - The crew quarters must be the safe haven of the base. The crew, however must support and have access to all activities at the base. The functions of the habitat area include: the actual crew living accommodations, the life support system for the crew, and the thermal control system for the habitat. There must be immediate access to surface vehicles, both pressurized and unpressurized. This is needed for emergency exists in case of a hazardous situation in the habitat. Also it will limit EVA time necessary for going from the habitat to the vehicle. Initial base communications elements, such as a ground station and communication tower are required to be located so as to provide immediate access by crewmembers--preferably IVA. Initial landing pads will be located 250 to 400 meters from the base, but precautions will have to be taken to protect reflective and optical surfaces on base equipment. This distance allows for a 1 to 2 minute trip by unpressurized rover from the landing site and habitat at speeds of 10 to 15 kilometers per hour. Crews should be able to walk between vehicles and the base site in case of rover failure. The zone 1--habitation area site plan is shown in figures 3.3.2-2 and 3.3.2-3.

3.3.2.1.2 Zone 2--Science Users - The science users zone is a dedicated area approximately 500 meters from zone 1--habitat. It is meant to provide an unobstructed surface for deploying passive science equipment. Access is provided by a stabilized circulation path 25 meters wide. Zone 2 is west of zone 1. It requires some barriers for dust contamination control. The science users' area location is shown in the overall base layout, figure 3.3.2-1.

3.3.2.1.3 Zone 3--ISRU - The zone dedicated to resource utilization involves the production of oxygen from the carbon dioxide from the martian atmosphere and storage of the product. This zone must have access to zone 1--habitation for support by manned operations and monitoring. It must also have access to zone 4--launch and landing for flight vehicle refueling support. Surface vehicles supporting the operations must be able

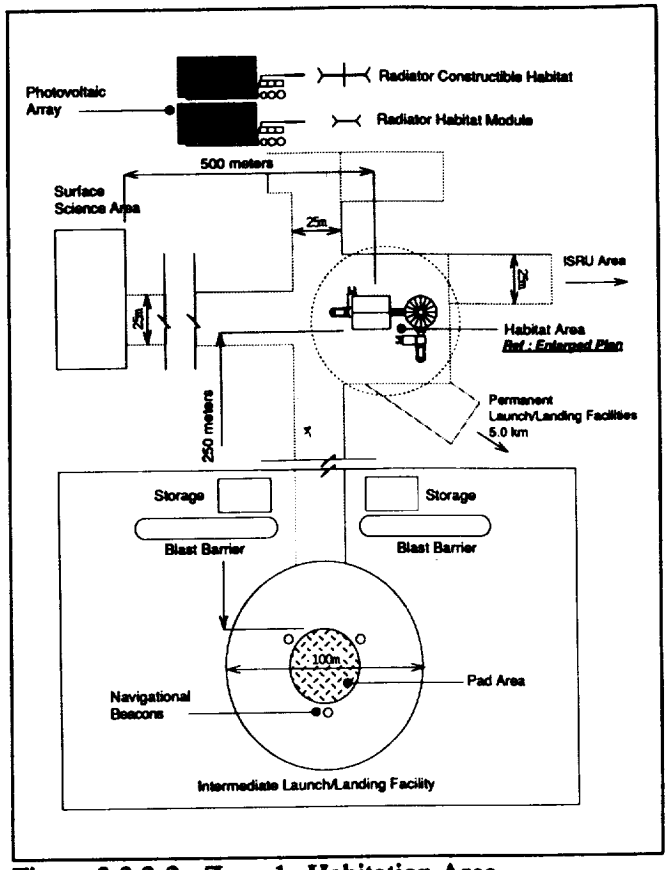



Figure 3.3.2-2.- Zone 1--Habitation Area.

to be stored and serviced under protective cover. The liquified oxygen product is stored in buried tanks to minimize boiloff. An oxygen loading station is located adjacent to the tanks. This station includes pumping equipment and a flexible hose for loading of the oxygen to transfer vehicles. The zone 3 site plan is shown in figure 3.3.2-4.

3.3.2.1.4 Zone 4--Launch and Landing - During early operations, landing facilities will be coupled closely with overall base operations, mainly in the habitat area. Until pressurized transfer from vehicle to base is available, EVA will be needed to get crews and payloads to the base. This will be accomplished with the landing pad sites shown in zone 1--habitation. During the consolidation phase, more permanent launch and landing facilities will be developed constituting zone 4. This zone will consist of two landing pads. The pads are aligned in a north-south orientation to accommodate flight paths from the east of the landers. These landing pads will be a flat, leveled, stabilized surface with a 50 meter radius. Three pad markers will be placed on the perimeter of each pad. The pads are 250 meters apart to limit the possible damage of an adjacent pad from ejecta. Usable items would have to be outside of a 250 meter radius of each pad to prevent damage from ejecta caused

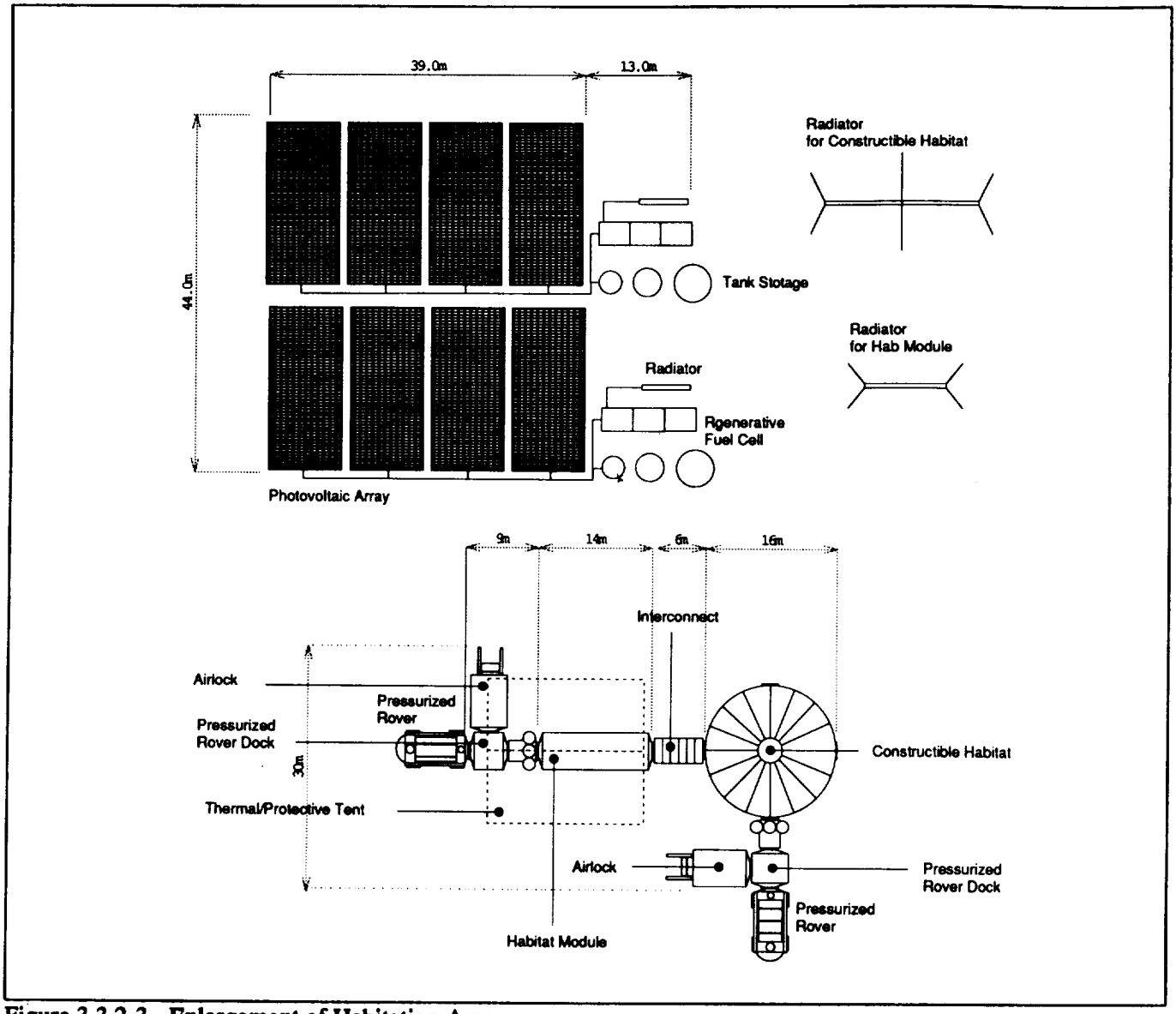



Figure 3.3.2-3.- Enlargement of Habitation Area.

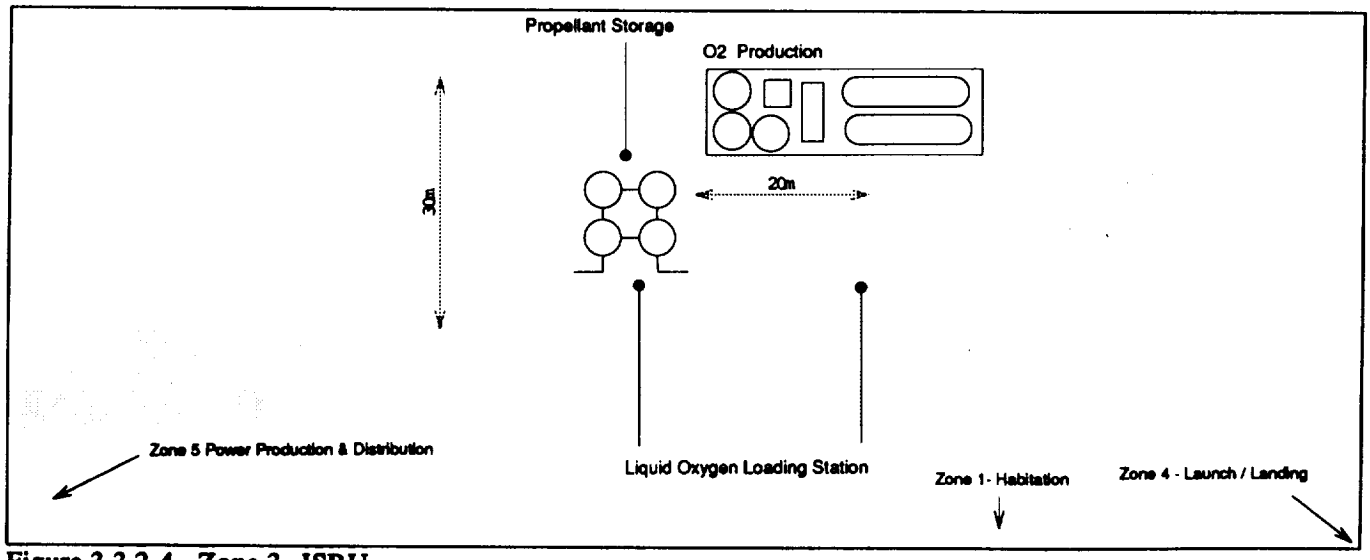



Figure 3.3.2-4.- Zone 3--ISRU.

by landings. Therefore, blast barriers would have to be provided. The launch and landing zone would be located 5 kilometers from the habitat zone and ISRU zone. This accommodates safety and navigation errors and is within a 1 hour EVA walk should surface vehicle failure occur. This is based on a typical EVA walking speed of 3 to 5 kilometers per hour. The 5 kilometer distance also lessens the need for facility and equipment protection devices in these zones. The zone 4 site plan is shown in figure 3.3.2-5.

3.3.2.1.5 <u>Power Production and Distribution</u> - The energy requirements of the Mars evolution base will be met with two types of power sources. The source for the habitat module and constructible habitat will be a solar power/regenerative fuel cell system and will be located as near the habitat as possible. This is because of the immediate concern of providing a safe, easily deployed power source with minimal EVA time for the crew. This power source is included in zone 1--habitat. Energy requirements for zone 3--ISRU require delivery and installation of a nuclear power plant. This should also meet other power needs generated by zone 4--launch and landing.

### 3.3.3 Identification of Linkages

The activities in the areas identified in section 3.3.2 are specific in nature but all must interact effectively for safe and efficient base operations. The interaction between these areas are facilitated by linkages, or circulation patterns. The main linkages are identified in terms of movement--movement of crew, logistics, utilities, and communications.

The movement of crew is accomplished in a safe and efficient manner. The first crew is involved with site selection, but the second crew of 5 is responsible for the unloading and setup of the initial habitat. Once that is in place, the circulation of crew at the base takes place by two means: 1) by foot, internal and external to the habitat, and 2) by surface transportation vehicle, unpressurized vehicles for short traverses and pressurized vehicles for long-distance traverses and extended surface activities.

Movement of crew resupply items is an ongoing activity. While the life support system evolves into greater closure, there is a continued need for delivery of consumables for the crews. This includes more perishable items that require pressurized storage and other items

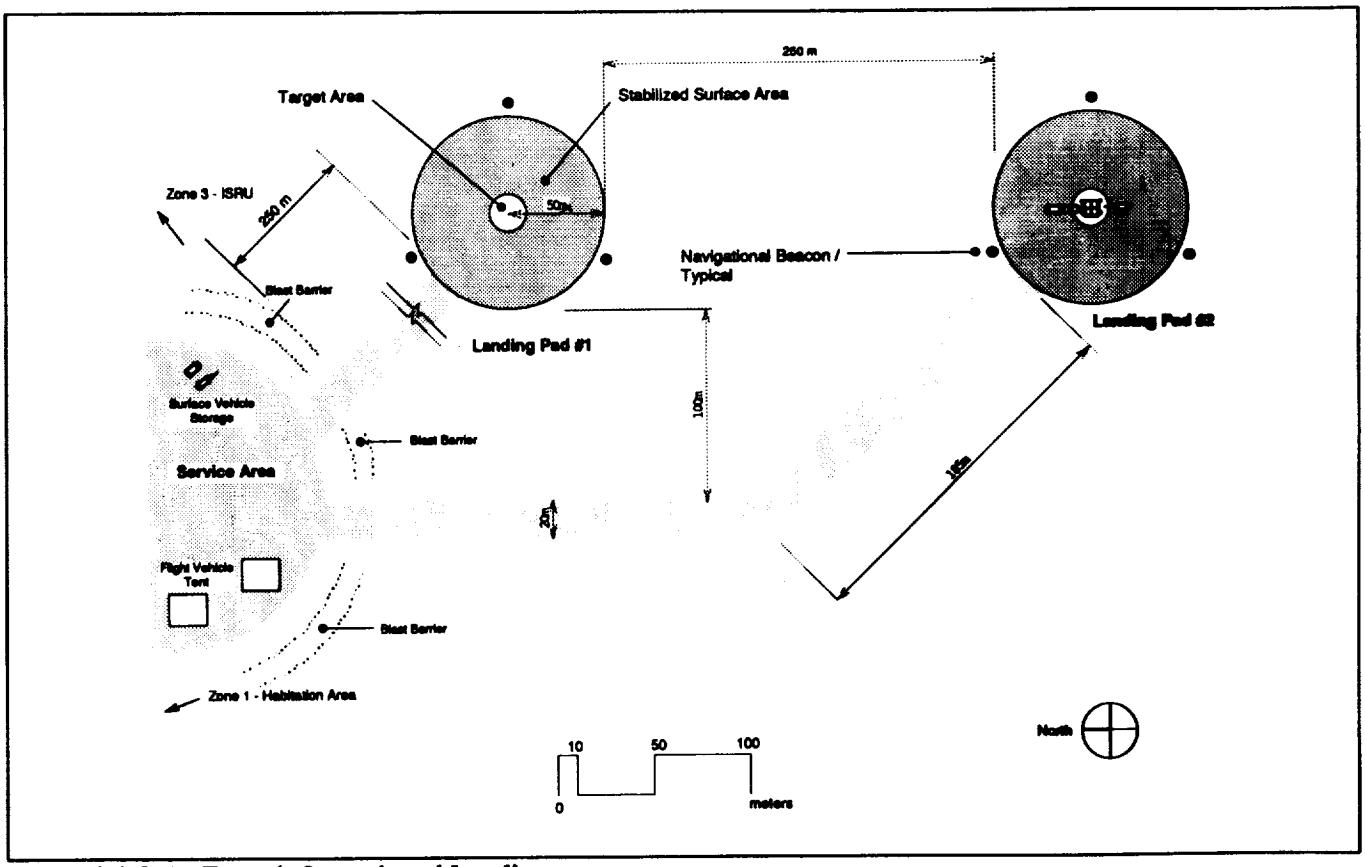



Figure 3.3.2-5.- Zone 4--Launch and Landing.

that may be stored external to the habitat, but under some type of shelter. These supplies must be unloaded from the cargo landers and transported by surface vehicle to the habitat area. The movement of maintenance supplies increases when the useful lifetimes of equipment and surface vehicles are approached. Storage of spare parts necessary for these servicing activities must be accommodated. The propellant produced in the ISRU area needs to be safely transported to the flight vehicles at the launch and landing area.

Movement of utilities refers to the transfer of electric power from the power source to the power user. The distribution of the power generated by the solar and nuclear power sources must take place in as efficient a manner as possible to optimize the power generated. Utility runs primarily service the habitat and propellant production plant in the ISRU area. External lighting necessary for night operations at the base might have to be accommodated. The routing of utilities can be either elevated, exposed at grade, run through conduit at grade, or buried below grade. Routing depends on possible conflicts with surface vehicle circulation patterns.

Communications needs for the Mars evolution case are initially minor. The equipment required to move this information is integrated into the habitat. As needs increase, more equipment is manifested to support base operations. Surface transportation that involves longer traverses requires the placement of communication towers and a dedicated ground station central to the base. As activities increase in the areas of habitation and ISRU, the crew must have the ability to remain in constant contact even though they may be located in different areas of the base.

## 3.4 MARS EVOLUTION PERFORMANCE ASSESSMENT

This section discusses the temporal capabilities of the evolutionary Mars base. These capabilities are compared to the expected usage of base systems as derived from operations analyses. The major functional areas of the evolutionary Mars base treated in this section are power, habitation volume, surface transportation, in situ resource utilization (ISRU), communications, manpower, and resupply. The results of these comparisons show that, in most areas, the base systems are adequate to satisfy the mission model. In a few cases, however, the base systems are matched to the requirements. Also, in the resupply analysis, limitations indicated suggest a need to change the time sequencing of the system availability or an update to the mission model.

Figure 3.4-1 depicts the capabilities of the Mars base from the first flight in 2005 through the eighth flight in 2016. The overview is organized by functional area with elements and capabilities shown as a function of mission phase. The remainder of this section deals with the comparison of the usage of each major type of base system with the design capability of the system. The net result of these comparisons is the verification that the base as designed meets the needs of the mission.

### 3.4.1 Power

The initial power at the evolutionary Mars base is photovoltaic with regenerative fuel cells providing storage and nighttime power. Mars has a distinct advantage over the Moon in that its night is roughly 12 hours long versus a 14 day lunar night. Hence, the energy storage problem is substantially easier. The first two flights provide Mars with a 100 kWe daytime output and 75 kWe night. Figure 3.4.1-1 shows the estimates of the continuous level-loaded power required by each element of the base power grid. Times when available power is in short supply can be alleviated somewhat by allotting charging power to vehicles either only in the day or only in the night. Through 2016, none of the surface crews overlap, so base power systems may be placed in a low-level dormant state between missions.

Constraints on the total mass delivered to the martian surface limit the overall power system. PVA/RFC systems are baselined through 2016. At this time, the requirements of a martian oxygen plant imply that a megawatt class energy system be provided. A nuclear power system based on SP-100 technology and using local materials for shielding, is thought to be an attractive design solution.

### 3.4.2 Utilization of Habitable Volume

The utilization of habitation volume was analyzed by considering a functional breakdown of the floor plans of the crew module and constructible habitat. Figures 3.4.2-1 and 3.4.2-2 show this breakdown. Space is extremely limited in the crew module. In particular, there is no workshop and only one rack devoted to user science. However, space is also available in the two pressurized rovers for source user equipment. As the constructible habitat is finished, more than adequate living and working space becomes available and exceeds the needs of the mission. At that time, the initial crew module is available for storage and as a safe haven.

### 3.4.3 Surface Transportation

The surface transportation system evolves from a limited local capacity as provided by two unpressurized rovers, to full global access provided by a ballistic exploration vehicle (derived from a piloted lander). Intermedi-

TABLE 3.4-I.- MARS EVOLUTION PERFORMANCE OVERVIEW

| Year | Human Systems | Constr. | Surface Trans. | ISRU | User Accom. | Comm./ Nav. | Energy |
|---|---|---|---|---|---|---|---|
| EMPLACEMENT PHASE | | | | | | | |
| 2005 | | crane, truck, digger | Local Exploration Emplacement 10 km unpressurized rover | | unmanned rover | | 50/50 kW PVA/RFC |
| 2007 | Hab. for 5 airlock, EVA equipment node | Basic Construction hand tools | | test Phobos ISPP process | Geo./atm. stations | Basic Comm/Nav pad marking, nav. beacons, comm. equip. | Power for Crew Module Vehicles cable, 50/25 kW PVA/RFC |
| 2009 | | utility vehicle | Local Exploration lab trailer, power trailer, 100 km unpressurized rover | | Remote Exploration teleoperated rover | ground station, test equip. | |
| 2010 | | | | | meteorological exps. | | |
| 2011 | | | | | | | |
| CONSOLIDATION PHASE | | | | | | | |
| 2012 | | Advanced Construction | 1,000 km unpressurized rover | Phobos ISPP | Regional Exploration | Extend Surface Communications | |
| 2013 | | | | | | | |
| 2014 | | | | Phobos props. for TEI | plant, animal, & microbe lab | | |
| 2015 | Constructible habitat | | | | | | |
| UTILIZATION PHASE | | | | | | | |
| 2016 | Hab. for 7 TCS, RLSS outfitting | | Global Exploration ballistic vehicle | Mars Oxygen Facility | Global Exploration | MW power system | |
| 2017 | | | | | | | |
| 2018 | | | | | | | |
| 2019 | | | | | | | |

ate capability is provided by two pressurized utility vehicles which can be configured for base support or 100 km scientific explorations. Also, the pressurized transfer of crew from lander to base becomes available after these vehicles are present at Mars. Figures 3.4.3-1 and 3.4.3-2 show the sortie capabilities of the surface transportation system as the base evolves.

The data is based on the capability of the unpressurized rovers to support local and daily sorties while the pressurized rovers (with add-ons) can support weekly local and regional missions. However, care must be taken in recharging the vehicles in some years. Daytime and nightime vehicle and charging is allowed in most years (see section 3.4.1).

Launch and landing sorties are those needed to unload landers. Science sorties are to emplace science packages. Exploration sorties are field exploration trips. O&M sorties are local trips that include base emplacement, repair, replace, and monitor activities. These types of sorties are detailed in section 6.0.

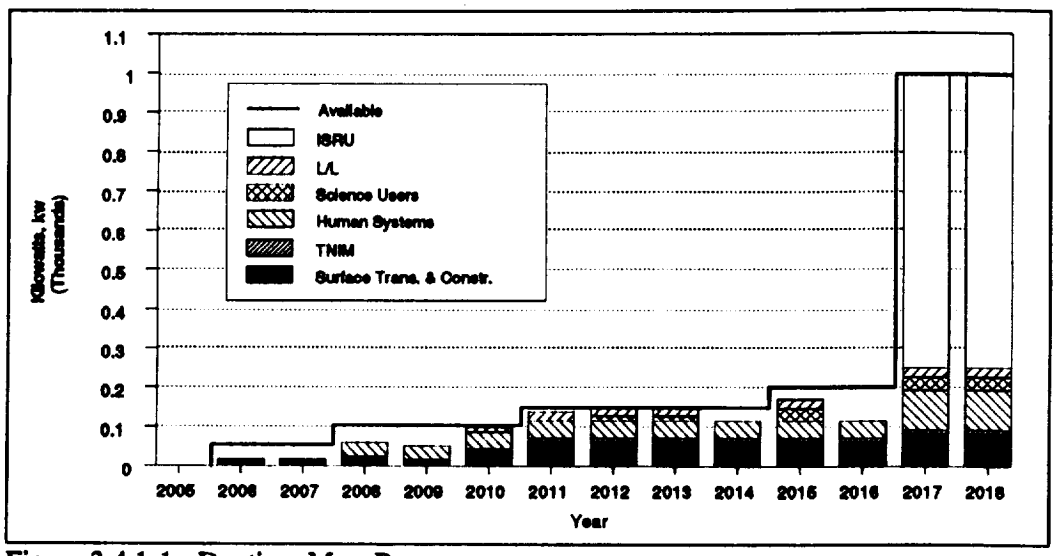



Figure 3.4.1-1.- Daytime Mars Power.

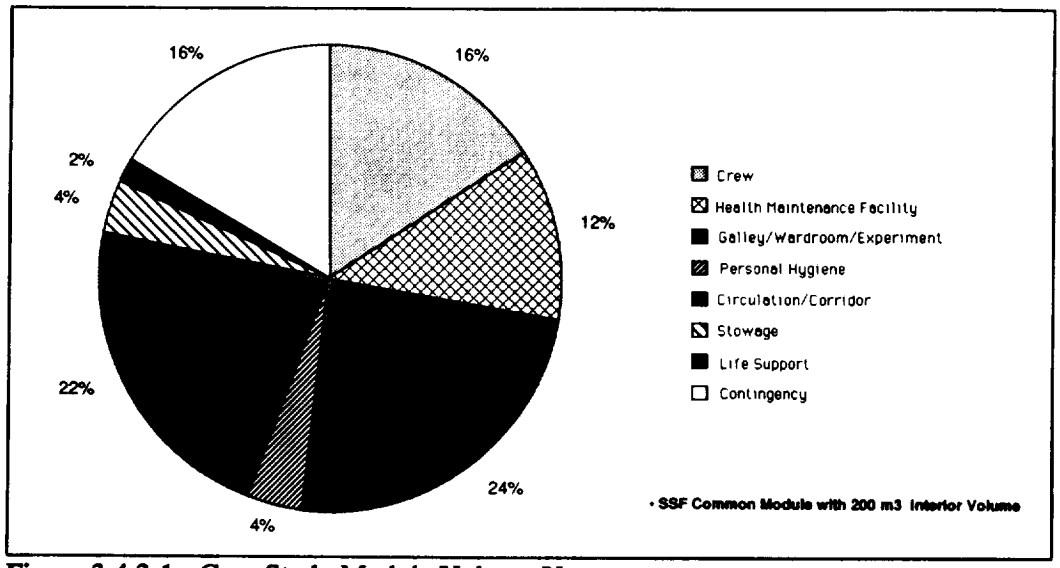



Figure 3.4.2-1.- Case Study Module Volume Usage.

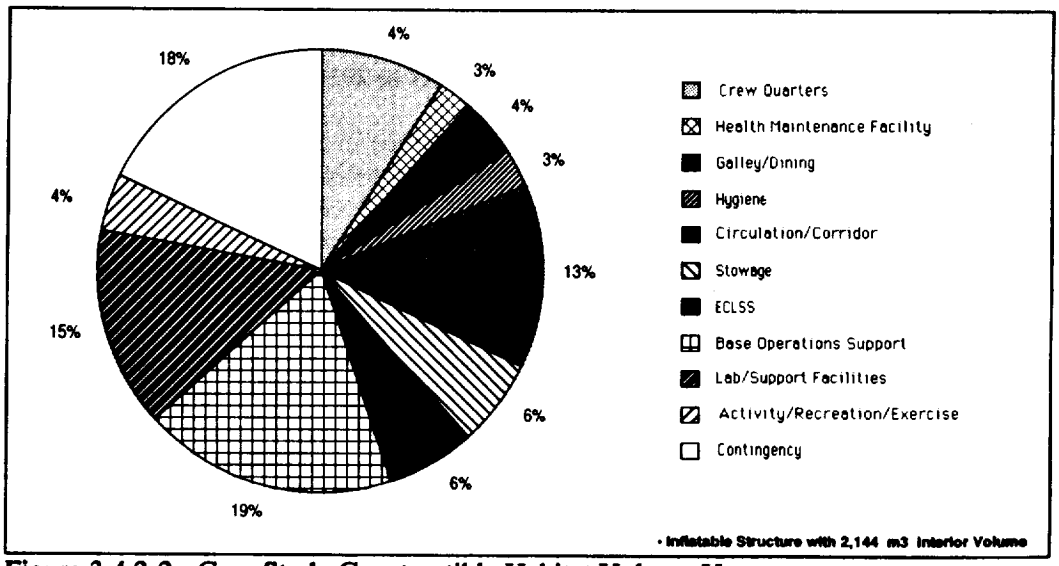



Figure 3.4.2-2.- Case Study Constructible Habitat Volume Usage.

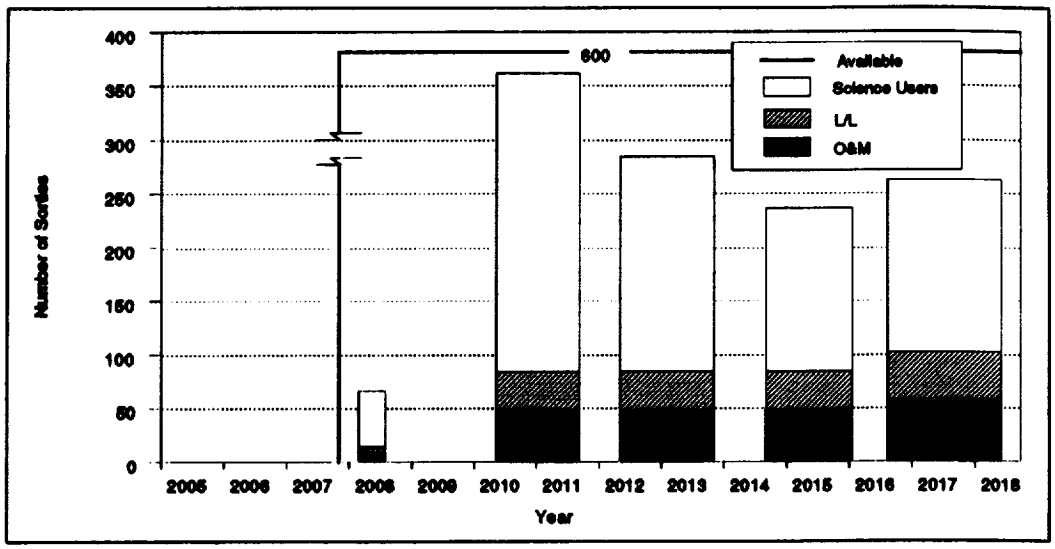


Figure 3.4.3-1.- Unpressurized Rover.

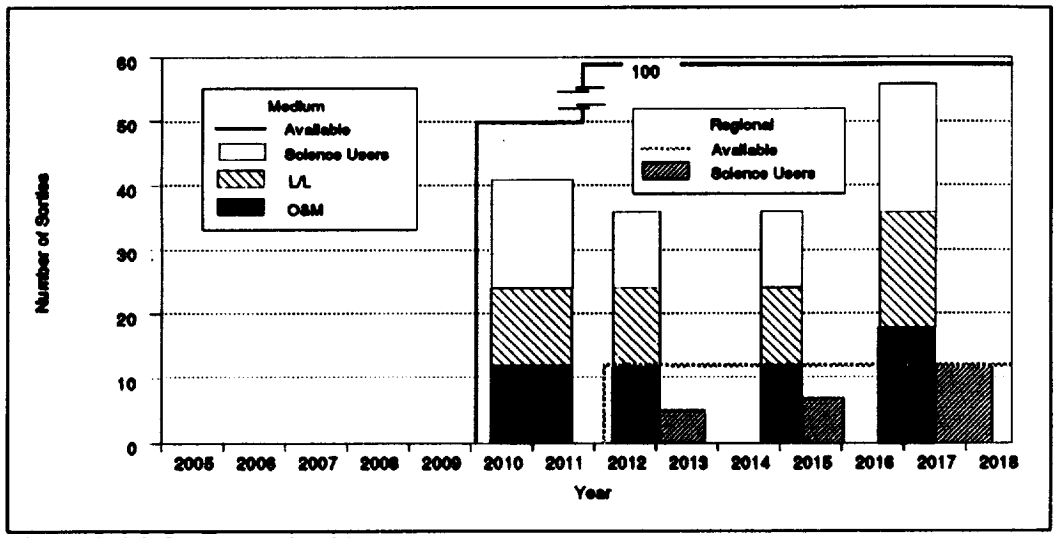


Figure 3.4.3-2.- Pressurized Rover.

### 3.4.4 In Situ Resource Utilization

The base takes advantage of local resources through the extraction of oxygen from the martian atmosphere and Phobos. This commodity is used as oxidizer for the landers (and later the ballistic vehicle) and also provides makeup oxygen for base life support systems. Oxygen can be extracted from polar or sub-surface water ice, or it can be derived from the atmosphere. Electrolysis of atmospheric $CO_2$ is presently the best understood process, and was thus chosen for the analysis of base systems.

Figure 3.4.4-1 shows the base oxygen need vs supply. Life support oxygen makeup is very small compared to the major users, which are the landers. The broken line on the graph denotes base oxygen production, which jumps from virtually zero to 100 t/year shortly after delivery in 2016.

Prior to the availability of martian derived oxygen, all lander propellant must be brought from Earth. Once fully operational, the martian oxygen system not only supplies this need, but also enhances the base's capability to support global exploration of the martian surface, by providing propellant to the ballistic vehicle. A certain amount of excess is also available to defray the effects of boil off, leakage, catastrophic loss, etc. Operation of the system will also demonstrate the feasibility of producing oxygen on Mars for use in other exploration vehicles (which of course would require expansion of the production capacity).

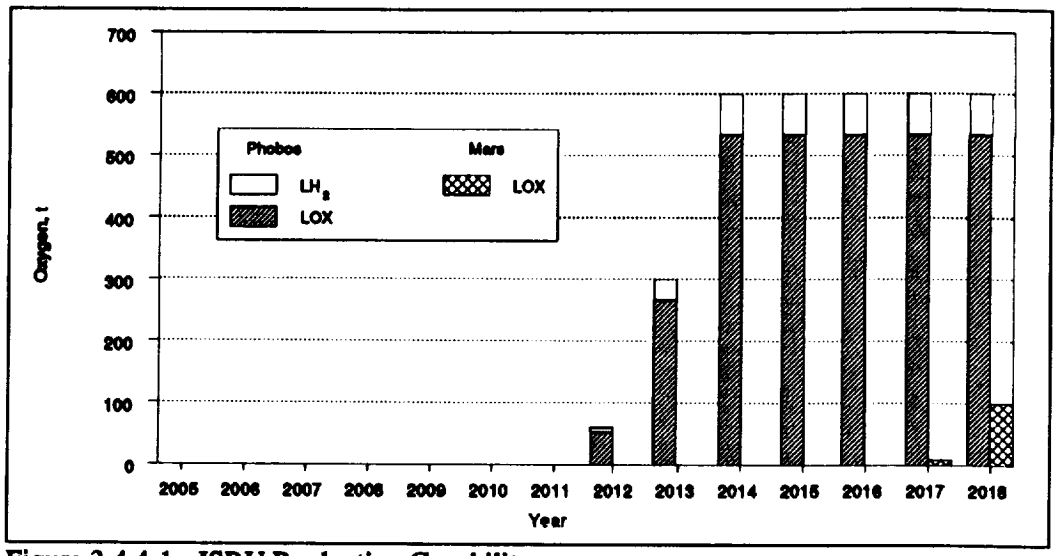


Figure 3.4.4-1.- ISRU Production Capability.

The quantitative benefits of producing martian liquid oxygen for use in the space transportation system are not completely understood, but they may turn out to be great enough to justify initiation of production earlier in the base timeline. This is feasible, but with the given dilivery constraints, would have to come at the expense of delaying other activities, such as science.

Martian resources are advantageously used in another way; the crew module and constructible are covered with raw regolith to provide radiation protection. The exact thickness of shielding required is under study, and may vary anywhere between zero and five meters regolith. Assuming that 2 meters of raw regolith is required, the mass savings represented by this scheme can be estimated by calculating the equivalent mass in aluminum shielding required to achieve the same protection. This comes out to 270 t for the module and constructible. Though a certain amount of overhead is associated with the required machinery and crew time, Earth launch mass is reduced by an amount substantially similar to this.

### 3.4.5 Communications and Navigation

The communications surface systems of the Mars evolution case study are designed to meet the MASE requirements. Three areas of concern are specified: Earth-to-Mars; Mars-to-Earth, and local Mars teleoperated devices. All areas must support these devices. The response of the PSSIA design to the case study needs are shown in figures 3.4.5-1, 3.4.5-2, and 3.4.5-3. In all areas, the needs are met by the design. More information on this system is presented in section 5.7.

### 3.4.6 Manpower

Crew activities, both EVA and IVA, will be required to support a variety of base functions. These include base construction, operation and maintenance (O&M), user science, launch/landing, and ISRU. The comparison of available crew time versus operational estimates is shown in figure 3.4.6-1. A detailed discussion of base operations and nominal crew activities can be found in Section 6.2.

The comparisons show that, unlike the intensive lunar evolution case study, the crew time is sufficient to satisfy the mission model. Many of the base construction tasks are automated or telerobotic (see section 5.10). Also, in the phasing of the Mars evolution case study, launch and landing activities are limited to the unloading of cargo from landers. As the timeline in the study ends, other launch and landing activities, such as propellant loading, are just beginning (see section 5.11 for more detail). The user science information concerns EVA and IVA time with local and regional traverses also considered (see section 5.12 for more information). O&M estimates were made in compliance with the analysis of yearly spares discussed in the next section.

Finally, an important note to this section is that time at the Space Station Freedom and/or base analog will assist in this type of analysis for crew, equipment, and experience.

### 3.4.7 Resupply

Resupply items are brought on every flight. These include spare parts for base systems and the replenishment of expendables and consumables for life support and crew items.

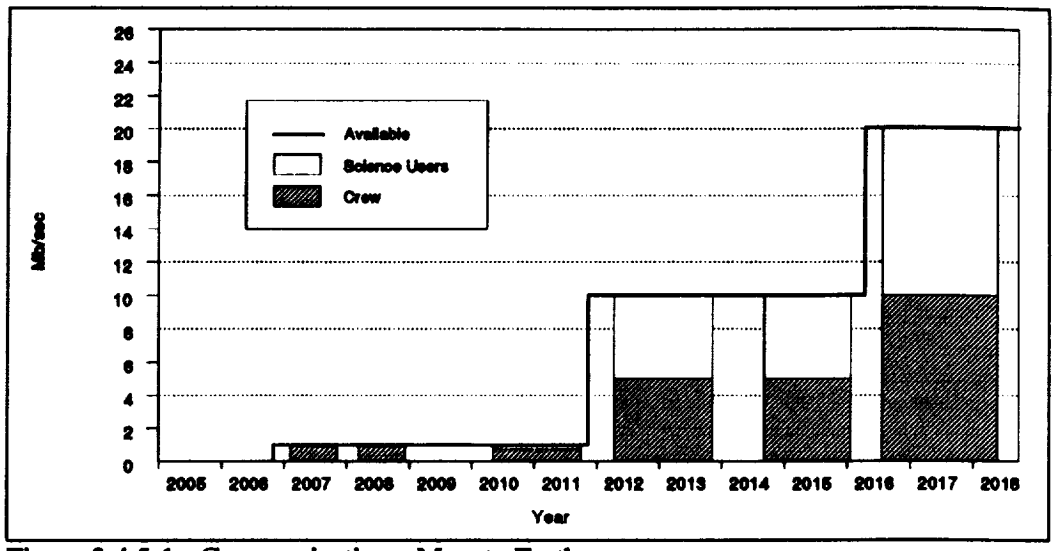



Figure 3.4.5-1.- Communications, Mars to Earth.

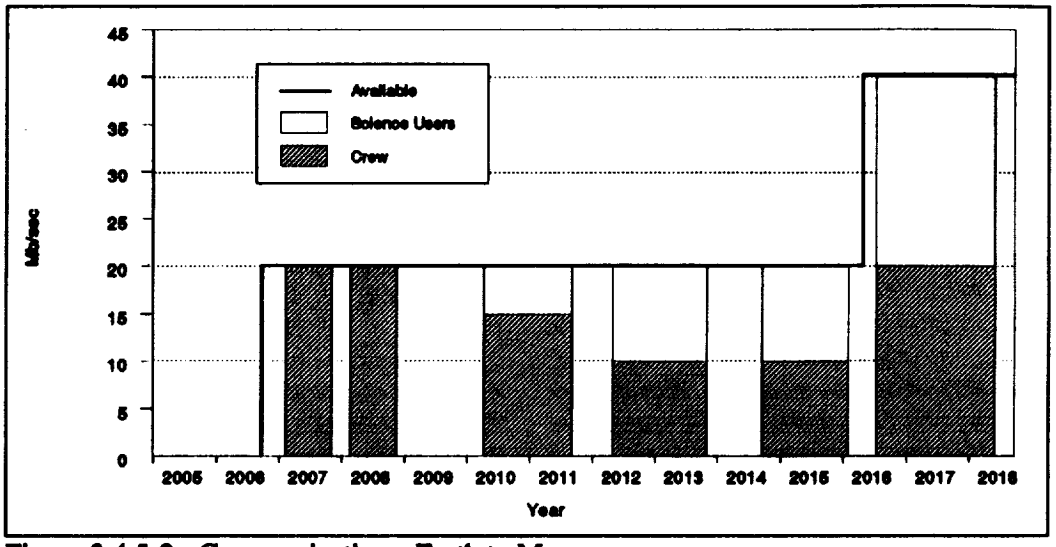



Figure 3.4.5-2.- Communications, Earth to Mars.

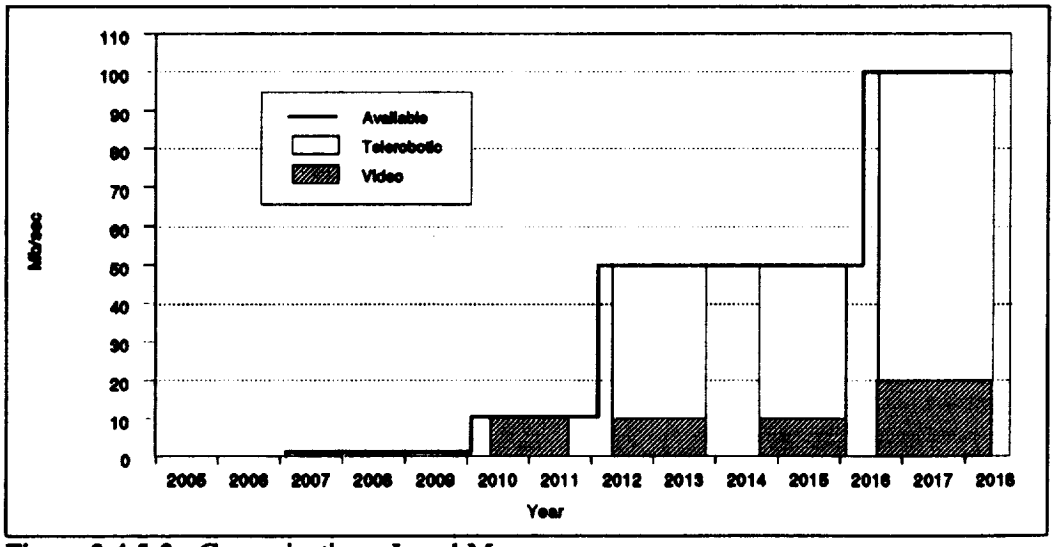



Figure 3.4.5-3.- Comunications, Local Mars.

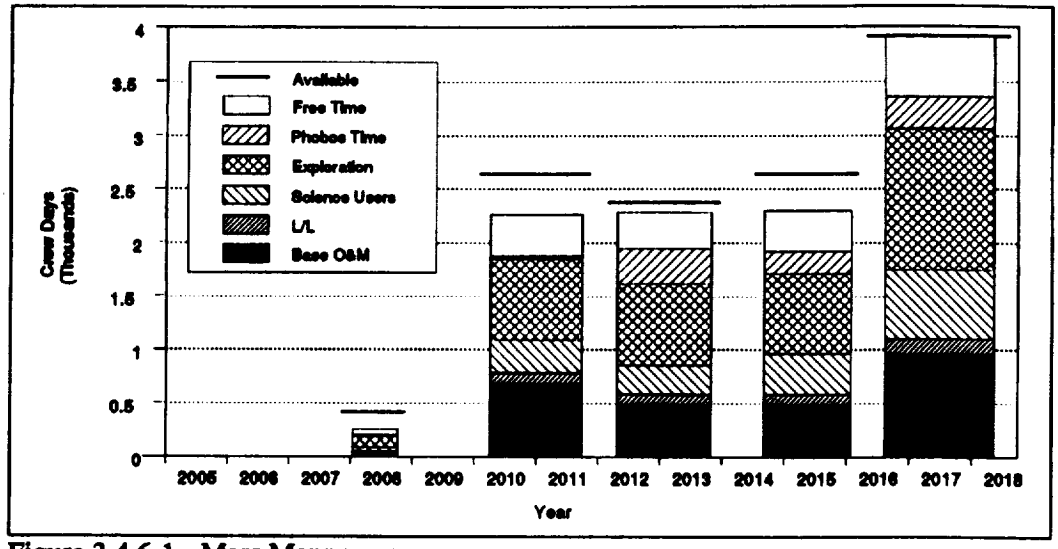


Figure 3.4.6-1.- Mars Manpower.

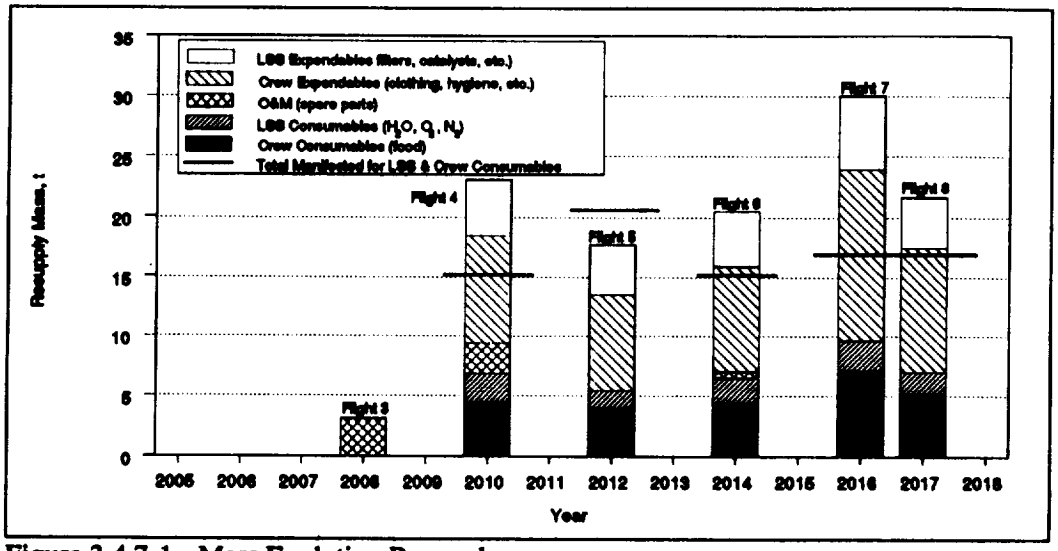


Figure 3.4.7-1.- Mars Evolution Resupply.

Crew items include clothing and hygiene supplies (crew expendables) and food (crew consumables). Life support resupply includes such items as water and gases (LSS consumables) and catalysts and filters (LSS expendables). The exact resupply requirements depend on the type of life support system in operation at the time. The base initially has a Space Station Freedom type LSS which is characterized by 96 percent closure for water and gases (initial RLSS). This system evolves to the advanced RLSS with the achievement of near 100 percent closure for those items. A full description of the assumptions and life support systems is available in section 5.3.

Yearly spares (O&M) for base systems were roughly calculated as 1/20th or 1/30th of the mass of each element, depending on whether the element's nominal lifetime was 20 or 30 years (i.e., total replacement of a system over its lifetime). Further strategies and analyses will be needed to optimize a spare parts inventory.

Figure 3.4.7-1 depicts the total base resupply per year compared to the manifested amount. The comparison appears good with the base needs for consumables and expendables versus the mission model. In most cases, the addition of O&M inventory adds more mass than manifested. This fact suggests an updated analysis of the manifest and O&M assumptions need to be performed in subsequent studies.

## 3.5 PRECURSOR DATA NEEDS

Less is known about Mars and its satellites than the Moon. The martian system also introduces a number of

new considerations. The more important ones include the martian atmosphere and meteorology, more rugged terrain, the chemical environments, and the microgravity of the satellites. The existing knowledge base on the martian system provides some basis for conceptual and preliminary engineering purposes, but there are many areas where knowledge is inadequate. Significantly more detailed information is needed to reduce risks and to mature the definition of many surface elements. With the current understanding, it appears feasible to develop some systems such as basic EVA systems, rovers, and initial habitat modules. There would, however, be substantial uncertainty as to the systems operational performance. Some systems, e.g., a Phobos propellant plant, require basic information about the moon's surface before any serious designs can begin.

Table 3.5-I is a summary characterization of the engineering data needs for the Mars evolution case. It reflects a preliminary analysis of data needs, accuracies, uses, and criticality.

The site specific and detailed data needs mentioned in the lunar evolution case study apply as well to the Mars evolution case study. In the martian case, more generic information is also needed. A characterization of the finer surface and subsurface details is critical in areas such as surface transportation, construction, and equipment anchoring or placement. To design vehicles with performance envelopes compatible with mission needs, it is important to understand what general sorts of obstacles and terrains they must negotiate. Construction equipment and techniques require a characterization of the surface and subsurface features to assess excavation and surface preparation. Approaches to both construction and equipment anchoring are likely to be very different if the surface is loose regolith with small rocks as opposed to a rubble of sizeable boulders.
A characterization of the environment is important to assess potential advantages and hazards. The availability of key resources such as martian permafrost can greatly influence base location and system architecture. Martian meteorology concerns include the effects of weather on operations and the static and dynamic loading of structures by wind and dust. The chemical environment will influence selection of materials as well as the need for contamination control of habitats and systems. The electromagnetic and radiation environment will influence selecting communication frequencies and shielding needs.

## 3.6 TECHNOLOGY NEEDS

The technology assessment process and resulting technology development requirements for the Mars evolution case study are similar to those described for its lunar counterpart (see section 2.6). Areas requiring technology development are depicted in Table 3.6-I. (See table 2.6-II for an explanation of technology ranking criteria.) In particular, the critical technology development needs for the Mars evolution case study include:

- Construction and mining technologies
- Surface transportation
- Mobile power
- Surface system power
- Dust contamination control
- EVA systems technology
- Phobos water extraction
- Life support (including atmosphere revitalization, containment control, water and waste management).

### 3.6.1 Construction and Mining Technologies

Construction techniques and system technologies must be developed to support deployment and operations of the Mars evolution case study. In particular, soil moving, trenching, lifting, and assembly capabilities are required. Techniques must be defined and developed for such activities as site survey; preparation of surface (leveling, trenching, etc.) for placement of base elements; lifting and transfer of payloads from the lander vehicle; emplacement of surface elements on the prepared site; and erecting, assembling, and integrating surface systems. Construction systems may be adapted from proven terrestrial systems, but must be designed and qualified for Mars conditions, and innovative ways must be found to reduce the mass of typical construction equipment. Technology development requirements include mobile power systems, dust contamination control, and automation and robotics. Operation of construction equipment will range from remote control to complete automation, as it will be undesirable to locate astronauts near the equipment (lengthy EVA's for routine operations are impractical, rocks thrown from equipment could puncture pressure suits, etc.). Other areas which must be addressed are machine element technologies, work site illumination, and environmental impact.

### 3.6.2 Surface Transportation

Several types of surface vehicles are required, including rovers, diggers, haulers, and lifters. These vehicles are required to perform local, mid-range, and long-range exploration; crew, equipment, and materials transfers; pressurized transportation; and long-duration excursion functions.

Local surface vehicles will move crew, equipment, and materials over distances of less than 10 km within the vicinity of landers and the base. Local surface vehicles

# TABLE 3.5-I.- SUMMARY OF MARS EVOLUTION PRECURSOR NEEDS

| Parameter | Prelim | Detail | Use | Criticality |
|---|---|---|---|---|
| **Mars Atmosphere** | | | | |
| Components<br>major components, geographic distributions, seasonal variations, diurnal variations | TBD | TBD | ISRU, materials, TCS | - Potential for ISRU<br>- Materials compatibility and selection<br>- Component sensitivity to contamination |
| Temperature<br>extremes, average, diurnal (per hour) and seasonal (per month), geographic variation | ±30°K | ±5°K | EVA suits, thermal systems, materials, construction equipment | - Thermal control design |
| Pressure<br>extremes, average, diurnal (per hour) and seasonal (per month), geographic variation | 7 torr ±50% | 7 torr ±50% | EVA suits, ISRU | - Evaporative heat transfer<br>- ISRU input |
| **Mars Meteorology** | | | | |
| Wind<br>speed<br>direction<br>extremes, averages, seasonal variations | OM<br>±15° | ±10 m/s<br>±15° | Operations, structures, antennas, arrays | - "Normal" operational design specifications<br>- Loading for towers, arrays, etc.<br>- Risks for damage or operations interruptions |
| Storms<br>wind speed, types, frequency, severity, duration, extremes, averages | OM m/s | OM m/s | Operations, structures, antennas, arrays | - Contingency operations and special precautions |
| Dust and Particles<br>size & distribution, mass, speed, concentration, composition | OM | OM | Structures, vehicles, equipment protection | - Infiltration damage<br>- Loading (dynamic & static)<br>- Entrainment |
| **Surface Characteristics** | | | | |
| Topography<br>slope, aspect (elevation differences) | ±10% | ±2% | Structures, vehicles | - Sites<br>- Traction |
| Toxicity & Corrosiveness<br>pH, chemical reactivity, trace elements | TBD | TBD | Materials, shielding, human systems | - Material selection & protection<br>- Crew hazards |
| Engineering Soil<br>mechanics, bearing strength, penetration resistance, gradient, porosity, cohesiveness | ±20% to depth of 6-8m | ±5% to depth of 6-8m | Vehicles, anchors, habitats, mining equipment | - Design<br>- Resistance to withdrawal<br>- Credible digger designs |
| Angle of Respose | ±8° | ±2° | vehicles, habitats | - Slopes for regolith piles<br>- Safety of slopes |
| Voids | ≥10m | ≥2m | Structures | - Site location (crevices, lava tubes, etc) |
| Density | ±25% | ±10% | Radiation protection<br>Structures | - Loading of structures with regolith |
| Rubble size | >1 m to 6-8 m depth | >.2 m to 6-8 m depth | Construction techniques, construction equipment | - Sites<br>- Excavation equipment |
| Rutting and Washboarding of Soil | | | Vehicle mobility, road design | - Need for road/path improvements |
| Substructure<br>Layers, voids, permafrost depth | to 20 m depth | to 20 m depth | Foundation, construction, equipment, ISRU | - Site selection, construction equipment and techniques<br>- Hazards from subsurface conditions<br>- ISRU usage of permafrost |
| **Mars Resources** | | | | |
| Location and Dist. of ISRU ice or permafrost | 10 km<br>0.1% | 300 m | ISRU | - Water is major target for ISRU application<br>- Site location |
| Mineralogy & Chemistry<br>types of minerals, relative abundances, volatile abundance: S, halogens, extent of water bearing minerals | TBD | Samples | ISRU | - Process identification, selection, verification |

## TABLE 3.5-I.- SUMMARY OF MARS EVOLUTION PRECURSOR NEEDS (CONTINUED)

| Parameter | Prelim | Detail | Use | Criticality |
|---|---|---|---|---|
| **Phobos Resources** | | | | |
| Mineralogy & Chemistry types of minerals, relative abundances, volatile abundance: S, halogens, extent of water bearing minerals | Variations over 100 m<br><br>1% rel differences for major elements & water | Samples | ISRU | - Process feasibility & credibility<br>- Process identification, selection, verification<br>- Site selection |
| **Seismic Environment** | | | | |
| Activity (Magnitude) | >3 Richter Scale | >3 Richter Scale | Habitat & facilities, foundations | - Site selection<br>- Facility design |
| Wave Transmission Q, waveforms, frequency, dispersions | TBD | TBD | Mining & Blasting | - Possible damage and isolation from mining/construction activities |
| **Imagery** | | | | |
| Images | 10 m | 1-2 m | | - Site selection<br>- Site design<br>- Mission planning |
| **Thermal** | | | | |
| Temperature extremes, average, diurnal (per hours) and seasonal (per month) geographic variation | ±30°K | ±5°K | EVA suits, thermal systems, materials, construction equipment | - Thermal control design |
| Subsurface Temperature profile, extremes, average, diurnal (per hour) and seasonal (per month), geographic variation | ±30°K | ±5°K (TCS)<br>±10°K (eqpt) | Mining & construction equipment, thermal systems, materials | - Thermal control design |
| Heat Transmission reflectivity, emissivity, absorptivity, conductance | ±10% | ±3% | Radiator design, EVA suits, solar array concentrators | - System design |
| **Electromagnetic** | | | | |
| Spectrum & Intensity for Gamma, UV, X-ray, etc. | TBD | TBD | Communication, materials | - Frequency selection<br>- Site selection<br>- Material selection & shielding |
| Solar Flux at Surface geographic, seasonal, diurnal, weather | ±20% | ±5% | Photovoltaic and solar dynamic power, greenhouses | - Sizing PVA<br>- System selection |
| Transmission absorption, refraction, reflection, ground effects | TBD | TBD | Communication, navigation | - Frequency selection<br>- Equipment design |
| **Magnetism** | | | | |
| Field Strength | TBD | TBD | Navigation, communication, equipment shielding | - Interference<br>- Local navigation |
| **Phobos Gravity** | | | | |
| Field and Anomalies | TBD | TBD | Navigation, surface transportation | - Local navigation, flight planning |
| **Radiation and Particles** | | | | |
| Solar Particle Spectrum and Flux particle types and intensity, and energy levels | OM* ev | OM ev | Shelters, protection, operations, materials | - Material selection & shielding |
| GCR Spectrum and Flux particle types and intensity, and energy levels | OM ev | OM ev | Shelters, protection, operations, materials | - Material selection & shielding |
| Micrometeoroids Flux particle size, energy frequency | OM Joules | OM (J) | Shelters, protection, operations materials | - Material selection & shielding |

*order of magnitude

TABLE 3.6-I.- MARS EVOLUTION TECHNOLOGY DEVELOPMENT AREAS

| Technology Area | Need | Time Frame | Ranking | Risk |
|---|---|---|---|---|
| Construction | Enabling | Near term | I | Medium |
| Mining | Enabling | Mid term | II | Medium |
| Surface Transportation | Enabling | Near term | I | Medium |
| Mobile Power | Enabling | Near term | III | Medium |
| Surface Power less than 1 MWe | Enabling | Near term | I | Low |
| Surface Power greater than 1 MWe | Enabling | Far term | I | Medium |
| Dust Contamination Control | Enhancing | Near term | III | Low |
| Extravehicular Activity | Enabling | Near term | I | Low |
| Phobos Water Extraction | Enhancing | Far term | IV | Medium |
| Mars Water Extraction | Enabling | Mid term | II | Medium |
| Mars Oxygen Production | Enabling | Mid term | II | Medium |
| Mineral Beneficiation | Enabling | Mid term | II | Low |
| Propellant Storage and Transport | Enabling | Mid term | III | Medium |
| Food Production | Enhancing | Far term | III | Medium |
| Thermal Control | Enhancing | Near term | III | Medium |
| Atmosphere Revitalization | Enabling | Near term | I | Low |
| Regenerable Life Support Supporting Technologies | Enabling | Near term | I | Medium |
| Trace Contaminant Control | Enabling | Near term | I | Medium |
| Waste Management | Enabling | Near term | I | Medium |
| Water Recovery Management | Enabling | Near term | I | Medium |
| Inflatable Structures | Enhancing | Mid term | III | Medium |
| Other Martian ISRU | | | | |
| Ceramics | Enhancing | Far term | IV | Medium |
| Metals | Enhancing | Far term | IV | Medium |
| Element extraction | Enhancing | Far term | III | Medium |
| Hydrogen | Enhancing | Far term | IV | Medium |

may include unpressurized and pressurized rovers, trucks, and rail systems. Local surface vehicles should be able to haul an EVA crew of two individuals for a 10 km round trip over unimproved regolith. Maximum speed for a local vehicle may be 10 km/hr. It should be able to traverse a 20 degree grade. A local vehicle should provide six hours of crew life support and auxiliary power and should be rechargeable from base facilities.

Mid-range surface vehicles will transport an EVA crew of four, equipment, life support supplies for 100 hours per crew member, and 1,000 kg of other payloads for distances of 100 km over unimproved terrain. Maximum speed for a mid-range surface vehicle may be up to 20 km/hr. It should be able to traverse a 30 degree grade. This surface vehicle should provide eight hours of crew life support and auxiliary power and should be rechargeable from base facilities.

Long-range surface vehicles, such as rovers and ballistic vehicles, will transport an EVA crew of a minimum of four, equipment, life support supplies for approximately 1,000 hours per crew member, and approximately 1,000 kg of other payloads for distances of 1,000 km over unimproved terrain. Maximum speed for a long-range surface vehicle may be up to 30 km/hr. It should be able to traverse a 30 degree grade. A long-range surface vehicle should also provide a minimum of 24 hours of crew life support and auxiliary power and should be rechargeable from base facilities.

Surface vehicles for hauling, digging (soil moving, trenching, leveling), and lifting will be used for base operations, construction, mining, and to support exploration activities. Base operations, construction, and mining may include site preparation, excavations, foundations, anchoring, backfilling, lander loading and unloading, and propellant transfers. Support to exploration activities may include excavation, equipment and materials loading and unloading, and backfilling. Construction and mining surface vehicles should be self-contained, man- or tele-operated (focus on teleoperation), and should be equipped with plows, scoops, scrapers, cranes, and manipulating arms according to their functions. Construction and mining surface ve-

hicles should employ common design where dual functions exist and should be rechargeable from base facilities.

### 3.6.3 Mobile Power

Mobile power systems (wheeled, skid mounted, portable, etc.) with power levels of 5 to 40 kWe will be required to support such applications as pressurized long-range manned rovers, construction equipment, and mining/-materials transport vehicles. The baseline power system utilized in the Mars evolution system definitions in this report is non-regenerative fuel cells. Alternative technologies include nuclear reactors, isotope systems, and systems using regenerative energy storage.

### 3.6.4 Surface System Power

Stationary power technology for the Mars evolution case study must be provided in support of crew surface activities. Requirements specify output of between 25 and 100 kWe, lightweight construction, erectable or deployable design, and power management/distribution capability. Baseline power systems for the early Mars evolution phases include photovoltaic arrays for primary generation and regenerative fuel cells for energy storage. Technology alternatives include solar dynamic systems and nuclear reactors. For continuous power output during nighttime periods, solar power systems must be supplemented with an energy storage capability (Shuttle fuel cell, utilization of native martian materials in a CO-$O_2$ solid-oxide fuel cell, etc.).

The capability to generate and distribute power at levels of 1 to 4 MWe is required to support martian in situ resource utilization. Nuclear reactors are baselined at multi-megawatt power levels, since the size of the energy storage unit would be prohibitive for solar energy systems. A multi-megawatt power system for space applications has only been studies; a full-up system has yet to be tested. Key technology development needs in order of priority include: 1) conversion cycle with high temperature materials (above 1,300°K), 2) fail-safe modular design for transport from Earth, surface assembly, and operation, and 3) effective shielding with lightweight or in-situ materials.

### 3.6.5 Dust Contamination Control

A method of easily and effectively controlling/removing dust and dirt from EVA suits, airlock seals, and other systems (e.g., solar arrays) is required. A key concern is the introduction of dust into habitable volumes. In particular, seals of airlock doors are vulnerable to interference by dust, and the interior of habitats and other areas must be kept reasonably clean. In addition, equipment performance (photovoltaics, optics, radiators, etc.) will be degraded by dust layers. A basic understanding of the physical properties of the martian surface and dust-to-surface adhesion, of the impacts to systems and components due to dust contamination, and of appropriate techniques to remove contaminants must be developed. Dust contamination control is critical to living and working on the martian surface, particularly with respect to long-term surface operations.

### 3.6.6 EVA Systems Technology

To meet the EVA requirements of the Mars evolution case study, development of martian EVA suits and portable life support systems is required. The primary technology needs in support of EVA systems are in the areas of: 1) a low-mass, portable life support system, and 2) materials development for suit, glove, and visor that are resistant to abrasions by dust over long periods of time and which facilitate cleaning methods.

As with the lunar evolution case study, a technology development program for the portable life support system (PLSS) must emphasize minimizing mass, volume, and particularly resupply requirements, as the cost of transporting spares and consumables will be prohibitive. Therefore, options for PLSS include the use of either regenerable or umbilical systems. An umbilical system is within the state of the art, but will limit significantly EVA range. Selection of regenerable life support requires an extensive technology program to develop a lightweight system (low mass is a driver since crew members cannot be expected to carry more than the equivalent of 20 kg on Earth, which equates to 53 kg mass on the martian surface). The requirement for a lightweight suit is even more critical for Mars applications than for similar lunar EVA requirements, because the martian surface gravitational acceleration is roughly twice that of the Moon.

EVA suits for long-duration martian missions will require capabilities beyond those being developed for the Space Station suit. These requirements include development of durable, high-strength, low-mass materials; an improved low-mass thermal storage system, improved long-life thermal/micrometeoroid garment materials which are impenetrable to dust; improved suit bearings to seal out dust; improved low-torque, low-maintenance lower torso joints; improved durability boot sole materials; and variable transmittance electrochromic systems to automatically adjust the sun visor.

### 3.6.7 Phobos Water Extraction

The technology for extracting water from the surface of Phobos is currently undefined, but will be complex and



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require significant research and development activities. Technology development will be required in the areas of mining, beneficiating, processing, collection, purification, and storage. The system must be capable of fully automated, unattended operation for periods of several years. Fault detection, isolation, and reconfiguration is required for the plant. Desired capabilities include machine intelligent expert recognition and decision-making systems, fault tolerant design, graceful failure techniques, modular design and hierarchical structure where possible, and fault alarms to the module exchange level.

### 3.6.8 Life Suport Supporting Technologies

Life support supporting technologies for Mars must be developed to ensure the safety and well being of crews living in the hostile martian environment. These will include regenerative technologies for atmosphere revitalization, trace contaminant control, water recovery, and waste management. In particular, integrated technologies that minimize life support system maintenance manpower and resupply mass while maximizing reliability will be required. Systems must be developed to maintain habitat atmospheres within prescribed ranges of compostion, pressure, temperature, and humidity, without the need for extensive changeout of filters and catalysts. Schemes for efficient storage of carbon generated during carbon dioxide reduction will be needed. Tehcnoloiges for monitoring and controlling trace chemical and microbial contaminants within the habitats will be required. A water reclamation system with 99 percent or greater recovery of potable and hygiene water can substantially reduce resupply requirements and reduce the dependence of "wet" food. Processors that convert waste materials to ash, water, carbon dioxide, hydrogen, and nitrogen can also reduce resupply needs and simplifiy trash logistics within the habitats. All of these systems must be advanced beyond Space Station Freedom (SSF) and lunar baselines. SSF and lunar life support systems are based on their close proximity to Earth; conditions which are incompatible with a martian base development effort.

## 3.7 PROGRAM SCHEDULES

Programmatic schedules for the Mars evolution case study are presented in this section. These schedules include timelines for systems development, technology programs, advanced development, and precursor engineering and science data needs.

For the Mars evolution case study, programmatic schedules are presented in six functional areas: habitation systems, construction and mining, in situ resource utilization (ISRU), support and utilities, launch and landing, and user accommodation. Each schedule contains information regarding system development phases for each major system, estimated technology readiness dates, key test and evaluation milestones, and mission inputs to system design and development (e.g., precursor needs and user requirements). Conceptual design, detailed design, and development phases are defined, and are consistent with the definitions used in the lunar evolution case study (section 2.7):

| | |
|---|---|
| Phase A | 1 year |
| Phase B procurement | 0.5 year |
| Phase B | 1.5 year |
| Phase C procurement | 1 year |
| Phase C/D | 5 to 7 years |
| Prelaunch activities | 1 year |

As in the lunar evolution case study, the length of phase C/D, which incorporates final system design, production, and system verification, depends upon the complexity of the particular system. Prelaunch activities include ground processing, launch to LEO, and space-based payload/vehicle integration.

Test and evaluation requirements are indicated on the schedules beginning in phase B and continuing through final system delivery.

Technology program projections were provided by OAST in the form of Pathfinder program element schedules. The schedules were based on a presumed integrated program beginning with a lunar outpost leading toward human Mars missions. In particular, the following set of assumptions was used by OAST for planning purposes:

- A lunar outpost will precede development of a martian program
- The human lunar program is paced by martian precursor missions
- Lunar systems are strategically focused toward martian applications.

In the interpretation of the technology program timelines, it was assumed that because the Mars evolution case study does not include a precursor lunar program, the effort currently slated toward lunar technology development could be devoted instead to Mars applications. Therefore when a particular Pathfinder program element is focused on the earlier lunar program, it is so noted on the schedules and described in terms of a Mars focus in the ensuing discussion.

For consistency across case studies, technology development needs were tied to system development phases as in the lunar evolution case study; i.e., a technology

readiness level of 4 (critical function demonstrated) would be required by phase B start; level 6 (prototype tested in environment) by phase C start. (See figure 2.7.1-1 for an explanation of NASA techology readiness levels.) Any discrepancies between surface system development needs and projected technology readiness dates are noted.

Finally, key precursor engineering and science data inputs into system design are indicated on the schedules. These include detailed site information, interface requirements with other surface systems or space transportation vehicles, user requirements, and other design constraints.

Timelines for the development of martian habitation systems are presented in figure 3.7-1. Key technology milestones supporting the martian evolution habitats are the integrated physical-chemical life support test bed and habitat breadboard. The Pathfinder surface habitats and construction element may need to be accelerated somewhat for the habitat module to meet its schedule. However, it is anticipated that the habitat module will be a derivative of the Space Station module and a major program effort may not be required as modified Station prototypes could be used for this function. The surface habitats and construction program schedule appears to correspond well with the design and development of the constructible habitat and should provide valuable inputs regarding construction techniques and constraints. The Pathfinder EVA/suits activity as currently scheduled provide sufficient time for inputs to system development.

Schedules for construction, mining, and in situ resource utilization systems are shown in figure 3.7-2. As discussed in the lunar evolution case study (section 2.7), early inputs from technology programs which support construction systems development will be important. Based on the underlying assumptions for Pathfinder schedule development, the early piloted rover breadboard (planetary rover program element) is focused on lunar applications. To support this case study, the program should be given a martian evolution focus, so that key aspects of this program (particularly mobility and mobile power) can be accommodated in the design of martian construction systems. Similarly, the resource processing pilot plant technology program should be redirected toward Phobos propellant and martian oxygen production capabilities. With this focus, the planning schedules presented should be adequate for ISRU system development.

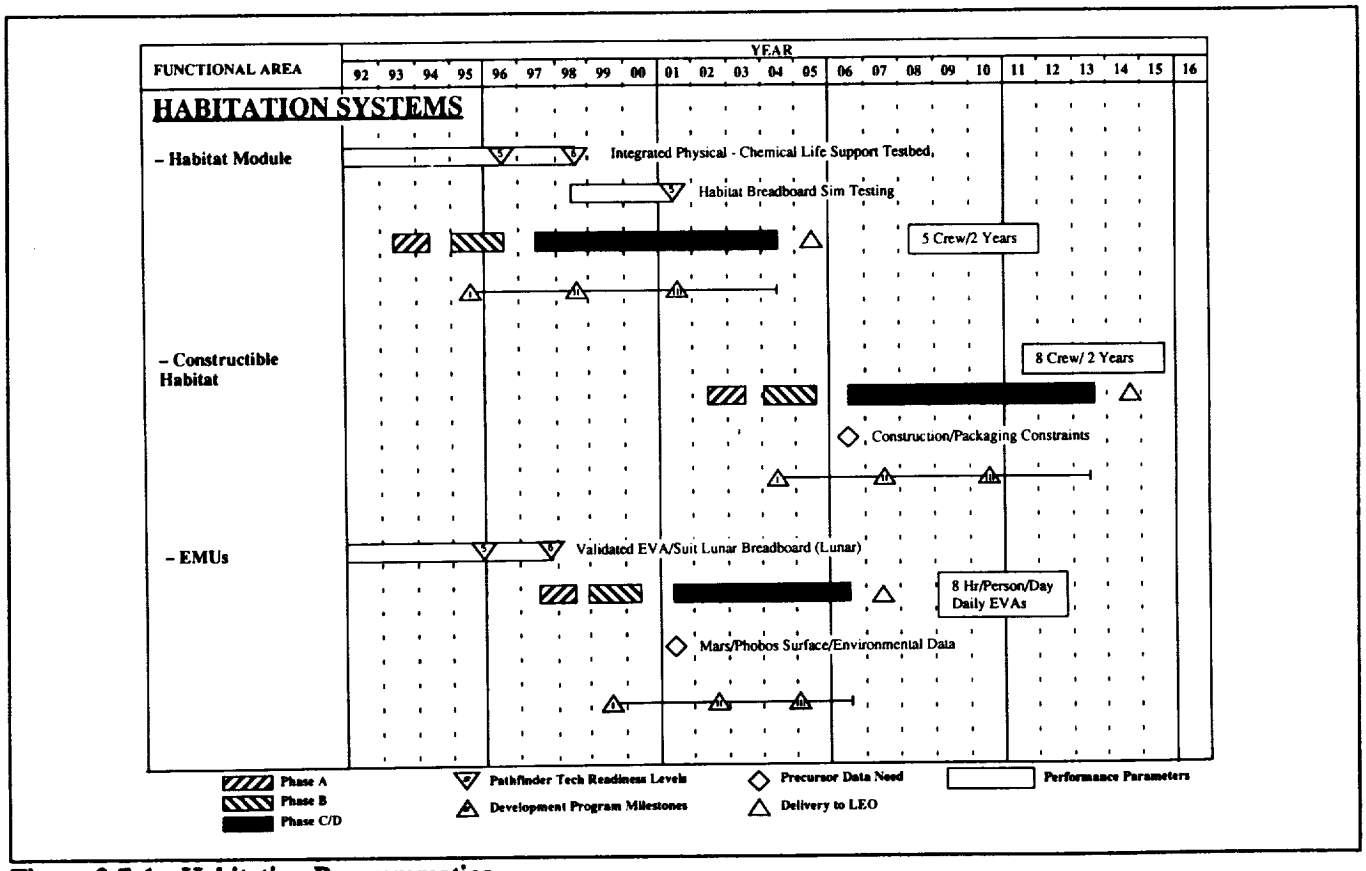



Figure 3.7-1.- Habitation Programmatics.

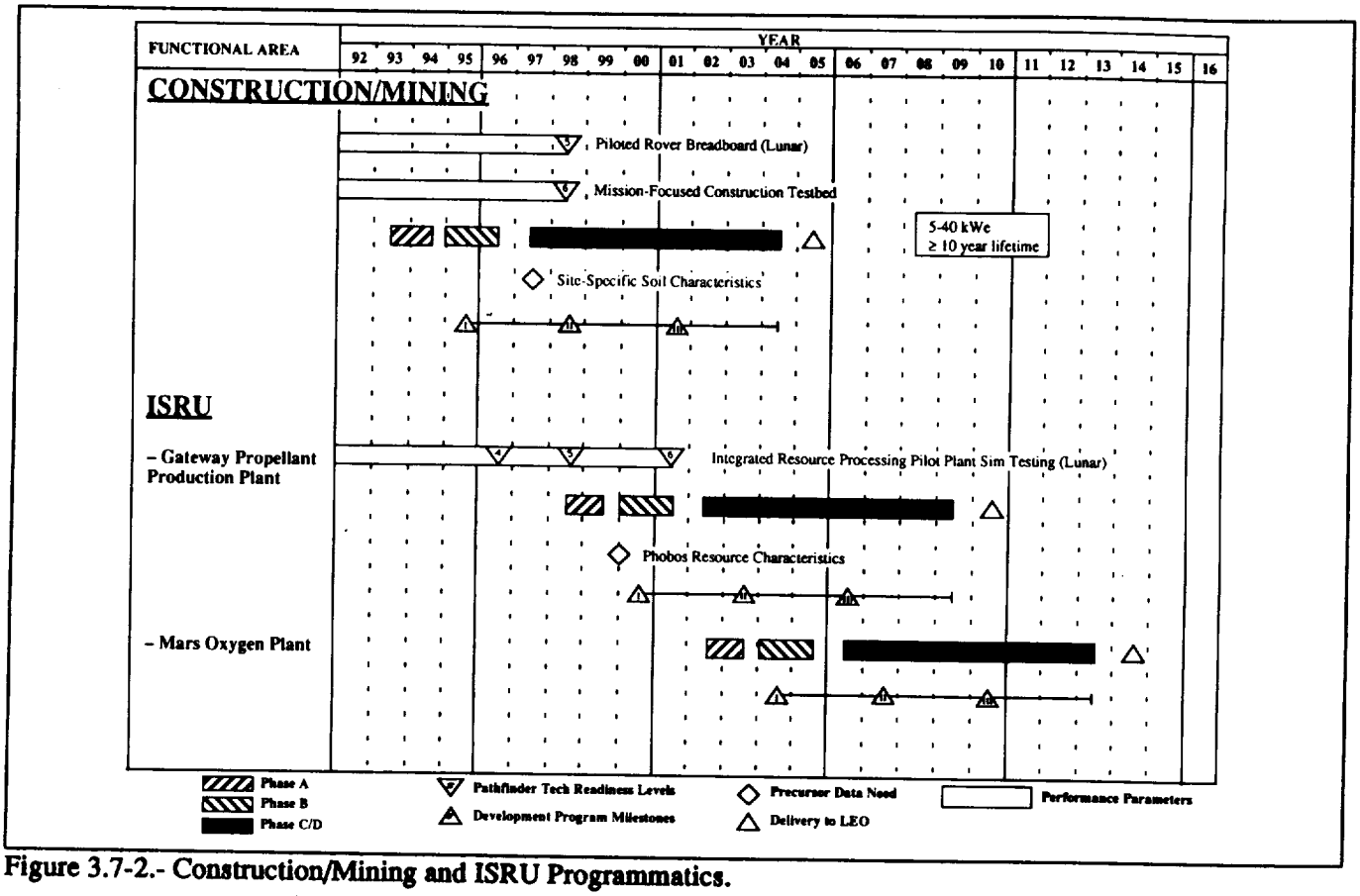



Figure 3.7-2.- Construction/Mining and ISRU Programmatics.

Programmatic schedules for the support and utilities functional area, incorporating the surface transportation, power, and telecommunication, navigation, and information management systems, are depicted in figure 3.7-3. As noted in the construction/mining discussion, the piloted rover breadboard specified in the pathfinder planetary rover program is currently focused toward a lunar rover and should be redirected toward this martian application. Assuming a timely redirection, the technology program should support the delivery of the pressurized rover to LEO in 2007. Development of the unpressurized rover should not rely significantly upon the piloted rover breadboard as it is expected to utilize previous rover operational and technology development experience. The key power system technology program is the pathfinder surface power program, which must also be redirected towards a martian emphasis. Environmental data (atmospheric, meteorological, dust, etc.) at the selected site is required prior to phase C/D start to support power system design.

Development plans for launch and landing systems and user accommodation are depicted in figure 3.7-4. Portions of Pathfinder autonomous lander (precision landing and hazard avoidance) and cryogenic fluid depot programs will directly support launch and landing systems design and development. Currently defined technology demonstrations appear adequate to meet system development milestones. It will also be important to integrate the launch and landing systems development program with that of the Mars lander/ascent vehicle.

The schedule for the Pathfinder planetary rover program as currently defined should be pushed by a year or so to impact early design studies for the unmanned rover. Specific site data, such as surface and terrain characteristics, and science objectives and requirements should be understood by phase C/D start in order to impact rover design.

For the reasons cited in the Lunar evolution case study an advanced development program to evaluate surface system and operations would also greatly benefit the martian evolution program. Advanced development focused on the operations and integration of martian evolution systems would be a crucial program element, more so than for a lunar mission scenario. Issues of safety and system reliability become more critical as time between opportunities for rescue and repair increase. The long trip duration restricts repair and maintenance operations to the crewmembers and, in turn, places strict reliability and redundancy requirements on the surface systems.

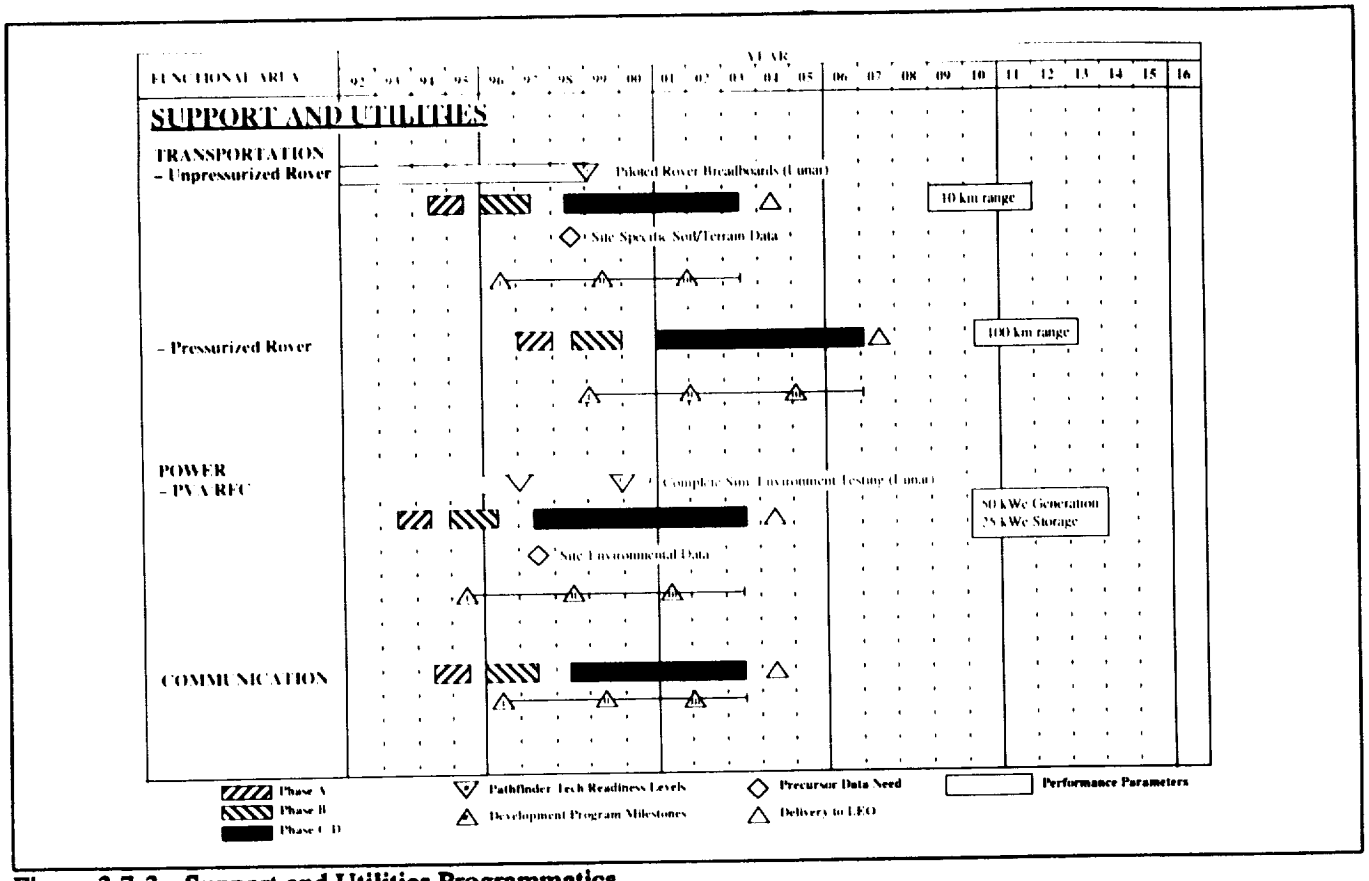



Figure 3.7-3.- Support and Utilities Programmatics.

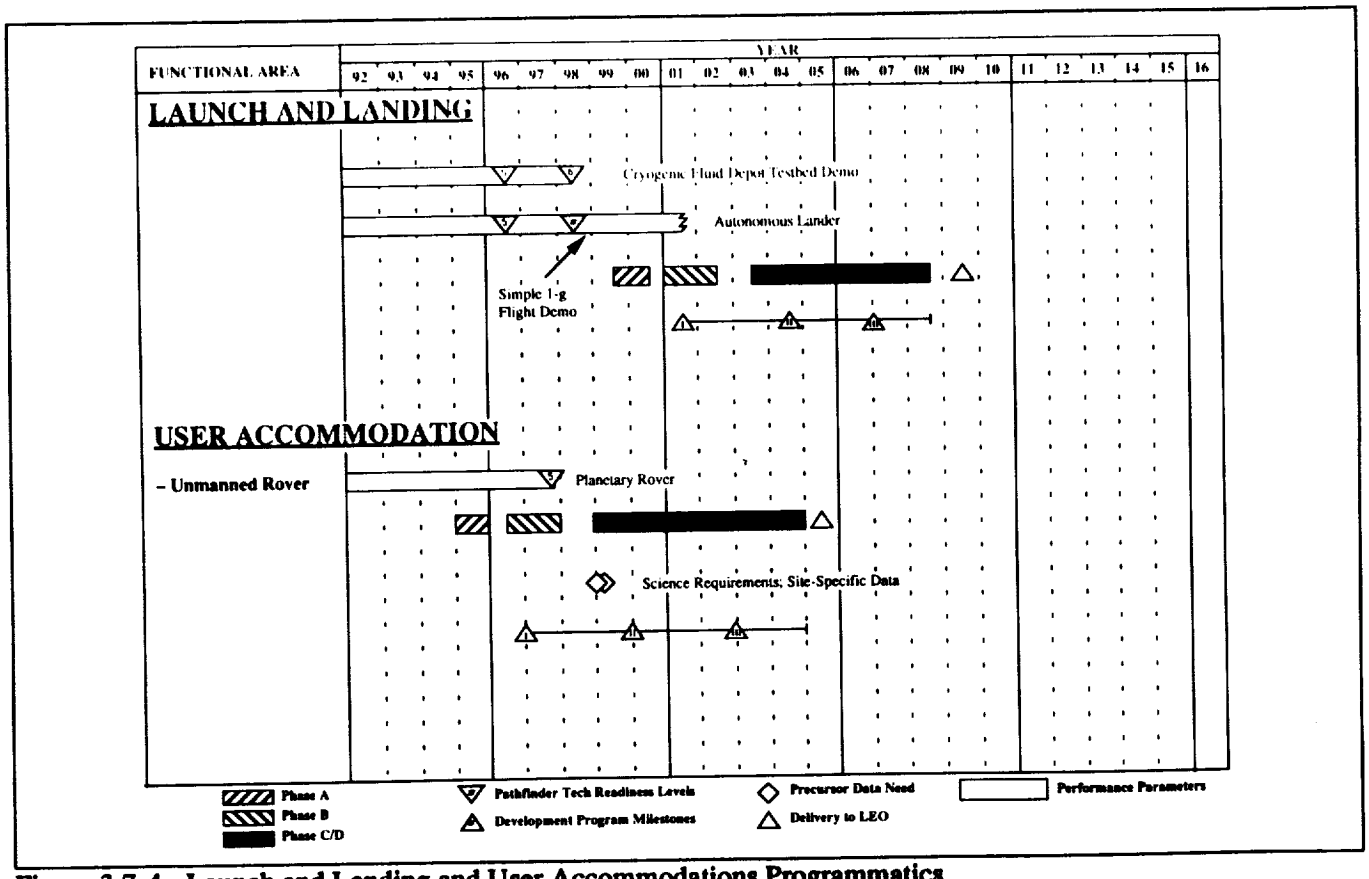



Figure 3.7-4.- Launch and Landing and User Accommodations Programmatics.

The planetary surface system advanced development program described in section 2.7 would support the development, testing, and evaluation of technical, operational, and support characteristics of martian evolution surface systems. The reader is referred to section 2.7 for further details.

## Section 4

# Mars Expedition Case Study

The Mars expedition case study, as defined by the Mission Analysis and System Engineering (MASE) team, focuses on the first landing of humans on the planet Mars. The term "expedition" defines the mission as a one-time journey of a select group of persons with a specific intention. According to the case study, the Mars expedition provides man a first encounter with another planet and an outstanding scientific investigative opportunity.

In response to the MASE case study definition, the Planetary Surface Systems (PSS) office characterized the Mars mission in terms of system elements, precursor data needs, technology needs, and system schedules. The process of system element selection was dictated by the requirements outlined in the Study Requirements Document (SRD) and the MASE manifest definition. Because of the brevity of this expedition mission, few surface systems are required to accomplish the objectives. Therefore, the PSS analysis for this case study is not extensive. Case study results are based on inputs from distributed studies. They are not identical, however, because of the process of integration and systhesis.

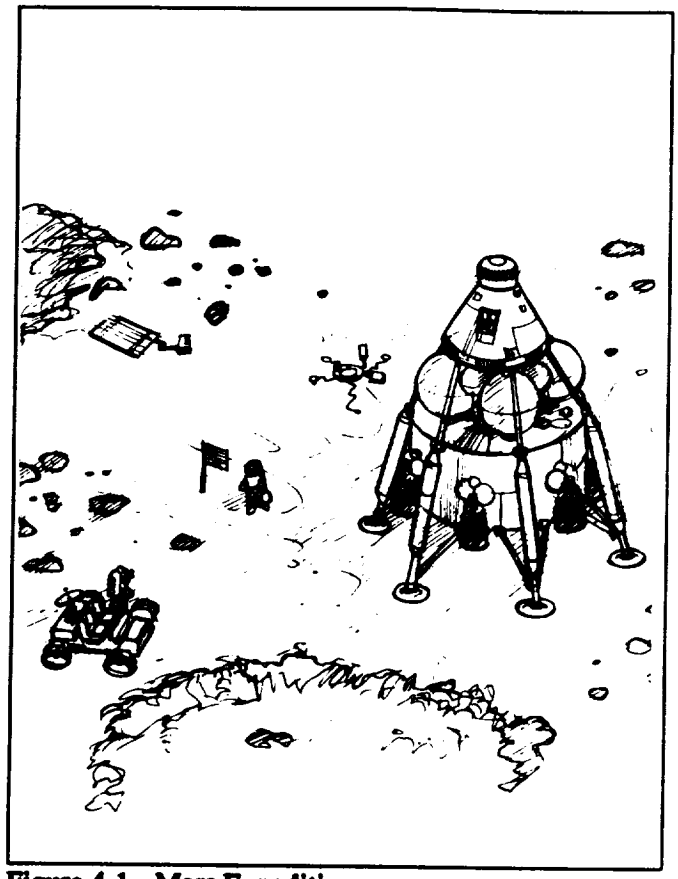


Figure 4-1.- Mars Expedition.

## 4.1 MISSION STATEMENT

The principal objective set by MASE in the Mars expedition case study is one of initial exploration. The single mission focuses on the first successful landing of humans on Mars with a safe return to Earth. In addition, the mission provides the capability to: 1) study the environment, features, and materials of Mars to expand our knowledge of the solar system and, 2) survey the potential for using martian resources. The expedition mission relies on a single, expendable vehicle strategy in which the transfer vehicle, ascent/descent vehicle, and all supporting systems are launched intact. The three person crew travels to Mars via an opposition-class trajectory with a free flyby abort capability. The mission duration in the Mars system spans 30 days, 20 of which are spent on the martian surface. The nominal round trip time is less than 18 months. Figure 4-1 illustrates the first human landing on the martian surface and the accompanying support elements.

The specified expedition consists of a single mission divided into 11 phases. These phases are: Earth to orbit, Earth orbit operations, Earth to Mars transfer, Mars capture, Prelanding Mars orbit operations, descent and landing, Mars surface activities, ascent and docking with orbiter, Mars orbit pre-departure operations, Mars to Earth transfer, and Earth capture/entry/landing. Only phase 7, Mars surface activites, applies to the PSS studies.

The approach by the PSSIA is concurrent with the office of exploration's goals; i.e., the reasons for sending a manned expedition to Mars are to probe the origin of life, conduct scientific research, advance technical development, and provide human exploration of the solar system. Such a pioneering expedition paves the way for future manned exploration and the possibility of settlement on Mars.

### 4.1.1 Mission Manifest

Unlike the lunar and Mars evolution case studies, the Mars expedition does not span multiple years with the intent of establishing permanent infrastructure on an extraterrestrial surface. The system architecture for the Mars expedition is static in nature. It is designed as a single program, but with the potential for being a precursor mission to a more developed program. The expedi-

tion flight opportunities include four possible launch dates: September 2002, June 2004, September 2007, and November 2010.

All cargo, consumables, and crew support are delivered at one time in the Mars piloted vehicle and subsequently in the lander. The lander itself functions as the center of operations during the 20-day stay time. The science program dominates the surface activities, with the crew conducting a reconnaissance of Mars in the allotted time period. The crew spends the first few days on the surface inside the lander in order to acclimate themselves to the martian gravitational environment after the long transit time in zero gravity. During this acclimation period, the crew deploys the scientific instrumented rover and operates it remotely. The rover inspects the vehicle for structural damage and collects soil and rock samples. While in the lander, crew members also document their location through a series of photographs from the window and the open-hatch. The crew's first extravehicular activity (EVA) is dedicated to deploying the portable geophysical package and scouting the immediate landing site. Two crew members on four separate EVA's use the unpressurized rover to perform geological sampling and mapping of the martian surface. Highlights of the four traverses include the north and south canyon wall landslides, a dominant crater, and a dunes field. Also during the surface visit, a single crew member on four individual EVA's deploys meteorological balloons for atmospheric studies.

### 4.1.2 Mission Requirements and PSS Response

The surface elements designated to support the Mars expedition are a response to systems requirements and mission objectives. Specific system requirements are levied in the SRD, the original source for focused case study specifications. These requirements form the basis for systematic selection of the appropriate elements to support a particular activity. Table 4.1.2-I lists the requirements as referenced to the SRD and the PSS surface systems' response. The requirements and matching responses are organized according to functional area.

## 4.2 MARS SURFACE SYSTEMS SELECTION

As previously noted, the martian surface system elements are selected in response to the requirements specified in the MASE SRD and the integrated mission manifest. The selection process for the few expedition elements is not based on detailed parametric analysis or extensive trade studies due to the preliminary nature of the data and the time constraints of the study period. The system choice is based on the maturity level of the designs available and on mission suitability. In the case of the Mars expedition elements, mission suitability is used as the criteria. Mission suitability is judged in terms of measuring how well an element's features and performance match the requirements and objectives outlined for the case study.

Table 4.2-I summarizes the key elements selected for the Mars expedition case study with an accompanying brief functional description and estimates for mass, power required, and volume. The science equipment manifested for the mission is not selected by the PSS office, since it is not considered surface systems support. But, since the focus of the mission is science opportunity, the table lists science user information to provide a complete picture of the elements delivered to the martian surface with the crew.

### 4.2.1 Habitation

Since the crew's stay on the martian surface will be only 20 days, there is no need for a dedicated habitation facility. During the expedition, the crew resides in the Mars excursion vehicle (MEV), specifically the descent portion of the vehicle. The MEV is responsible for transporting and housing the crew as well as carrying the manifested surface systems cargo and science equipment.

### 4.2.2 Extravehicular Activity (EVA) Systems

The exploration of the landing area necessitates frequent EVA's for purposes of deploying scientific instruments, collecting samples, scouting the terrain, and documenting the occasion. As per the SRD, each crew member is assigned five six-hour EVA's during the surface stay time. An extravehicular mobility unit (EMU) consisting of a pressure suit and portable life support system (PLSS) developed specifically for the martian environment is central to the EVA system. EVA systems are further enhanced with Shuttle-type hand tools and an unpressurized rover for local area access.

Key requirements for non-orbital EMU's include minimum weight and volume, reliability, and efficient maintenance. The PLSS design is driven by the emphasis to minimize the consumables storage (due to the limited cargo space on the MEV), thus leading to the choice of a regenerative system. The human carrying capacity limits the PLSS mass to 20 $kg_f$--53 kg on Mars--compared to the Space Station Freedom (SSF) regenerable PLSS of 195 kg. In order to use SSF technology, additional options must be considered for Mars EVA's, such as changeable ice packs for thermal cooling or umbilical connections from the rover. Factors affecting the design further include suit versus lander pressure levels, currently set at 57.2 kPa and 101.3 kPa

## TABLE 4.1.2-I.- SURFACE SYSTEMS REQUIREMENTS COMPLIANCE

| Requirement | Response |
|---|---|
| **Human Systems** | |
| • Provide radiation protection for three crew members using minimum equipment. | • Interior outfitting of the lander |
| • Provide martian surface EVA equipment to support five 6-hour EVA's per crew member. | • 3 EMU's with portable life support systems, EVA tools |
| **Construction** | |
| No requirements. | |
| **Surface Transportation** | |
| • Transport crew and cargo locally in support of science activities. | • Unpressurized rover |
| **In Situ Resource Utilization** | |
| No requirements | |
| **Launch and Landing Services** | |
| No requirements. | |
| **User Accommodations** | |
| • Enable a capable suite of expedition science equipment. | • Instrumented rover, geologic and geophysics equipment, meterological ballons, atmospheric stations, biomedical lab |
| **Power** | |
| No requirements. | |
| **TNIM** | |
| • Provide periodic transmit capability for 0.2 Mbps from Mars lander to Earth, 0.4 Mbps from Mars lander to EVA crew, and 0.2 Mbps from Mars lander to the Mars piloted vehicle. | • Antenna mounted to lander |

## TABLE 4.2-I.- SELECTED MARS EXPEDITION SURFACE ELEMENTS

| Element | Mass (t) | Power (kWe) | Volume ($m^3$) | Functional Description |
|---|---|---|---|---|
| Extravehicular Mobility Unit | 0.23 | S/C | 1.04 | Allow EVA surface activity |
| Unpressurized Rover | 1.1 | 4 | 15 | Provide means of local transportation (10 km) |
| Unmanned Rover | 3 | 0.5 | 15 | Provide scientific access to remote sites |
| Geologic Exploration Equipment | 0.1 | 0 | 0.25 | Sample collection instruments |
| Portable Geophysics Package | 1.2 | 0.8 | 0.25 | Seismic test, spectrometers, electromagnetic sounders |
| Atmospheric Station | 0.15 | 0 | - - | Provide geophysical data:gravity, temp., pressure, seismicivity, etc. |
| Meteorological Balloon | 0.2 | 0 | - - | Provide meteorological data: humidity, wind, particulate, etc. |
| Biomedical Lab Instruments | 0.5 | 2 | 3 | Health maintenance testing and medical observations |

S/C = self-contained.

(8.3 psi and 14.7 psi) respectively, and the duration of the EVA, designated as 6 hours for the expedition case study.

### 4.2.3 Life Support Systems

Life support for the crew while performing intravehicular activities on the surface is provided by the MEV. As stated above, EVA life support is managed by the PLSS associated with the EVA systems.

### 4.2.4 Thermal Control Systems

Similarly to the life support systems, the thermal control systems for surface habitation is provided by the MEV, while the EMU's contain internal thermal control mechanisms (water coolant loop or changeable ice packs).

### 4.2.5 Radiation Protection

According to the SRD, radiation protection must be provided for the crew using minimum equipment. The logistics of the situation imply that the MEV supplies the protection with strategic placement of vehicle internal and external hardware. The inherent protection offered by the martian atmosphere prevents the galactic cosmic rays from being a significant radiation threat. Furthermore, due to the short mission duration and strategic mission planning, the possibility of a solar particle event occurring is remote. Artificial radiation shielding is not deemed necessary.

### 4.2.6 Power

An external power source is not required for the expedition operations. The MEV supplies power for habitation support while the crew is on the surface. In addition, the unpressurized rover uses rechargeable batteries (4 kWe) which interface with the MEV main power generation system. The science equipment uses self-contained power sources.

### 4.2.7 Assembly and Construction

The operations defined for the twenty-day Mars expedition do not require assembly or construction of surface infrastructure. The rover, both the unpressurized and scientific, are delivered intact. The scientific equipment and instrumentation consist of self-contained packages which involve simple deployment instructions.

### 4.2.8 Surface Transportation

In order to enhance the exploration capability of the three-person team, an unpressurized rover is manifested as surface support equipment. The rover provides crew mobility for scientific equipment deployment, including meteorological balloon launches and atmospheric station set-up. The four-wheeled vehicle selected resembles the Apollo rover. The rover's payload capacity includes two suited crew and 500 kg of payload or the three crew members with a lesser payload. Vehicle characteristics include a 20 km range per sortie, a 10 km/hr speed, a 20 degree maximum climbing grade, 100 km range between recharges, and a 10 hour maximum sortie time. Figure 4.2.8-1 shows a concept for an unpressurized rover.

### 4.2.9 In Situ Resource Utilization

The objectives of the Mars expedition case study do not include utilizing the local resources. The crew operates self-sufficiently with all supplies and consumables manifested from Earth. Although a demonstration of resource use is not required for the mission, investigation of martian soil for future chemical processing is part of the scientific research effort.

### 4.2.10 Launch and Landing Services

The Mars expedition mission consists of a single MEV landing at the Ganges Chasma. The landing vehicle is characterized as a self-contained, expendable vehicle with both ascent and descent stages. All launch and landing requirements, whether navigation or thermal control, are met by the MEV hardware. Propellant transfer operations are not necessary. Furthermore, since additional landings are not specified, preparation of a dedicated launch and landing site is not performed.

### 4.2.11 User Accommodations

Various science users are targeted for the Mars expedition, including geology, geophysics, and atmospheric sciences. The crew is responsible for transporting and operating a geologic field equipment package to accomplish rudimentary geologic mapping, structural characterization, geomorphology, and soil sampling. In the field of geophysics, the crew deploys a network of geophysical stations in order to map the seismic, electric, magnetic, and gravitational properties of the martian surface. Four meteorological balloons are manifested to acquire atmospheric data. To aid the crew in performing scientific activities, a telerobotic, instrumented rover conducts independent exploration traverses providing photographic data, sample collection, and records of surface features. The accommodations offered to the science community are basically all the surface systems selected--EVA systems, unpressurized rover, and assembly hand tools.

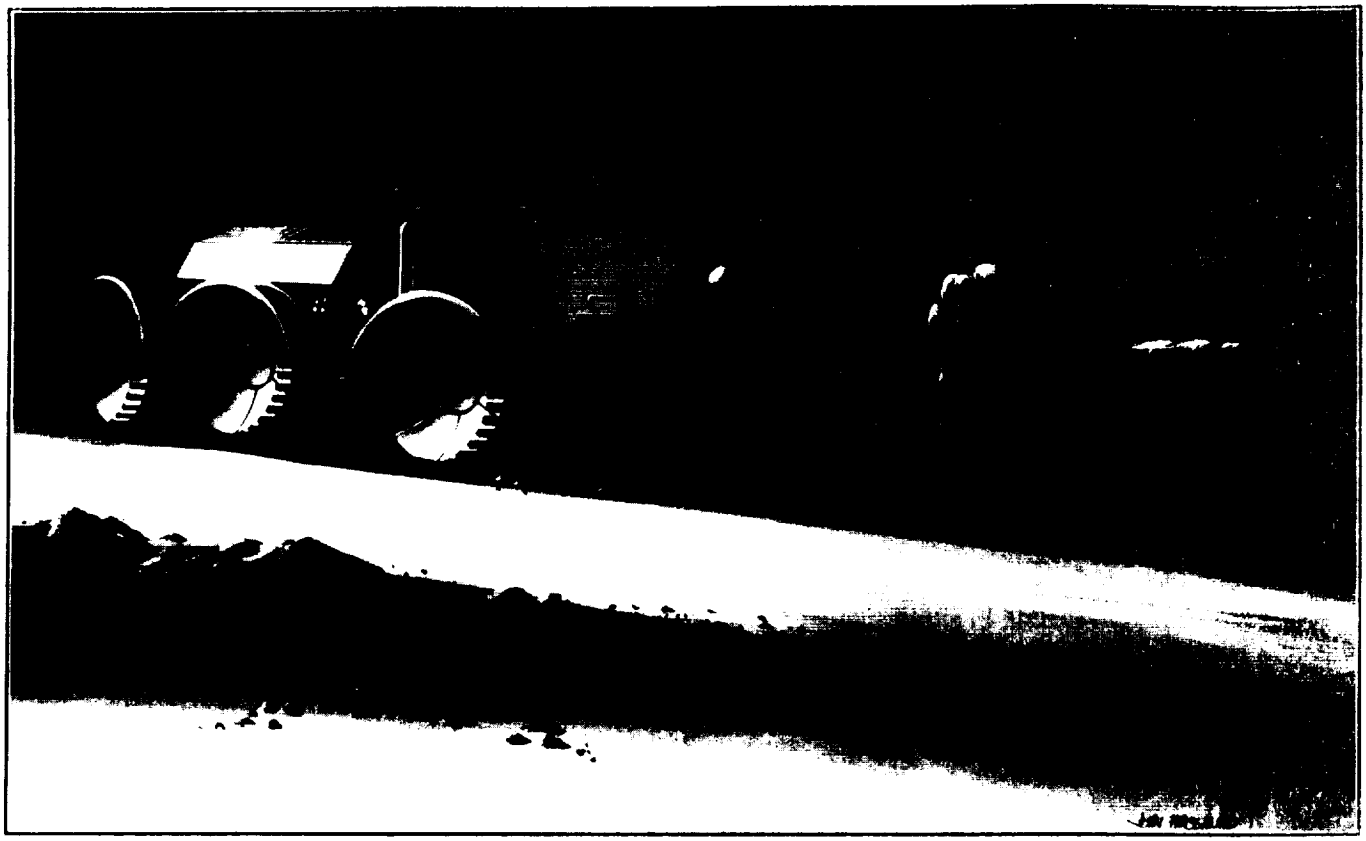


Figure 4.2.8.-1.- Unpressurized Rover.

### 4.2.12 Telecommunications, Navigation, and Information Management (TNIM)

Dedicated communications equipment is not considered for surface support. Instead, communications capabilities are built into certain systems. Such systems include the lander, unpressurized rover, the EMU's, and remote science instrumentation. Separate equipment for surface communications is not required. The SRD specifically defines the following periodic transmit capabilities: 0.2 Mbps from Mars lander to Earth, 0.4 Mbps from Mars lander to EVA crew, and 0.2 Mbps from Mars lander to the Mars piloted vehicle. To satisfy these requirements, a common ultra high frequency (UHF)/Ka reflector antenna with a 0.45 m diameter and a maximum link capacity of 10 Mbps is installed on the lander.

## 4.3 BASE SITE

The Mars expedition landing site is located near the martian equator at 8.3°S latitude and 44.2°W longitude in an area refered to as Ganges Chasma. This site provides an exemplary terrain for reference in scientific and operational studies. Viking orbiter photographic data highlights exceptional landslides, some of enormous size, along the canyon walls. As a landing site, the Ganges Chasma offers sample collection from two enormous landslides on the north and south canyon walls.

Generally, the terrain on Mars is categorized in two types: surfaces with high densities of craters greater than 50 km in diameter and younger surfaces with few craters of such large dimension. The terrain is further divided into two characteristic regions: the relatively smooth maria accounting for about 17 percent of the surface, and the highlands making up the remainder. In the maria regions, the slopes are from 0 to 10 angular degrees with a standard deviation of 3.7 degrees. In the highlands, the terrain slopes from 0 to 23 degrees with a standard deviation of 4.5 to 6 degrees and higher. Canyons, valleys, and volcanic mountains present extreme contrasts in relief, including slopes exceeding 32 degrees with local rocky ledges and cliffs. Additional environmental data for Mars is discussed further in section 3.3.

## 4.4 PERFORMANCE ASSESSMENT

The performance assessment section, as defined earlier for the lunar and Mars evolution case studies, discusses the capabilities on the surface as a function of time. This topic of discussion is not appropriate for the Mars expedition since the mission sequence is so short. Capabilities on the surface do not grow in response to increased demands over a period of time. Rather, the expedition case study contains specific requirements solved with specific point designs. The previous section

on surface systems selection clarifies the point designs (EVA systems, rovers, science equipment); therefore, a performance assessment is not necessary.

## 4.5 PRECURSOR DATA NEEDS

Since surface activity is less extensive in the Mars expedition case study, the precursor data needs are a subset of those identified for the Mars evolution case study, discussed in section 3. Key environmental data relating to surface mobility include slope and aspect of topography, soil mechanics, angle of repose, and thermal loading. With an emphasis on EVA during the brief mission duration, factors affecting EMU and portable life support design, such as diurnal and seasonal temperatures, pressure variations, and corrosiveness of dust particles are most important. A characterization of the surface regolith and fine-scale details is required to assess the viability of using in situ resources for emergency radiation protection. Finally, to ensure safety during the first manned operations on Mars, meteorological data is necessary, particularly severity of storms, wind speeds, and seasonal characteristics.

## 4.6 MARS EXPEDITION TECHNOLOGY REQUIREMENTS

The transient nature of the Mars expedition surface systems means that technological advancements are unnecessary in many areas. Two areas, however, are identified where advancements in technology would provide improved technical performance: dust contamination control and EVA systems.

### 4.6.1 Dust Contamination Control

A method of easily and effectively controlling and removing dust from EMU's, airlock seals, and other systems is required. For the Mars expedition case study, a key concern is the introduction of martian dust into the habitable lander. In particular, seals of airlock hatches are vulnerable to interference by dust, and the lander's air revitalization system is subject to contamination. In addition, performance of sensitive equipment, such as optical imagers and scientific gauges, is prone to degradation by dust layers. Key issues to resolve include understanding the physical properties of the dust and dust-to-surface adhesion, the impacts to systems and components due to dust contamination, and appropriate techniques of removing contaminants.

### 4.6.2 EVA Systems Technology

To meet the EVA requirements of the Mars expedition, martian EMU's and portable life support systems must be developed. Technology development must emphasize minimal expendables, mass, and volume. A critical technology need is reduction of consumables, as transportation of consumables directly reduces the amount of other payloads that can be delivered. Options for PLSS include the use of either regenerable or umbilical systems. The umbilical system is within the state of the art, but significantly limits the EVA range. Selection of regenerable life support requires an extensive technology program to develop a lightweight system of no more than 53 kg mass. Key drivers for the martian surface EMU include an effective heat balance system, reduction of the total system mass (PLSS and EMU), and protection from thermal and radiation factors. With the expedition team frequently performing EVA's, advances in EMU and PLSS maintainability and recharging efficiency are necessary for ease of mission success.

## 4.7 MARS EXPEDITION PROGRAM SCHEDULES

Program schedules for the Mars expedition case study are presented with the following timelines: systems development, technology programs, advanced development, and precursor engineering and science data needs. Because of the limited surface system requirements in this case study, a single schedule (figure 4.7-1) illustrates programmatic information in three functional areas: human systems, support and utilities, and user accommodation. In the figure, data is presented on system development phases for each major system, estimated technology readiness dates, key test and evaluation milestones, and mission inputs to system design and development (e.g., precursor needs and user requirements). The phases tracing the development of hardware are defined below, consistent with the definitions used in the MASE case study synthesis:

| | |
|---|---|
| Phase A | 1 year |
| Phase B procurement | 0.5 year |
| Phase B | 1.5 years |
| Phase C procurement | 1 year |
| Phase C/D | 6 years |
| Prelaunch activities | 1 year. |

Phase C/D, as defined here, incorporates final system design, production, and system verification. Prelaunch activities include ground processing, launch to low Earth orbit (LEO), and space-based payload and vehicle integration.

Test and evaluation requirements are indicated on the schedules beginning in phase B and continuing through final system delivery. Technology program projections are derived from Pathfinder program element schedules. The Pathfinder schedules are based on a presumed integrated program beginning with a lunar outpost

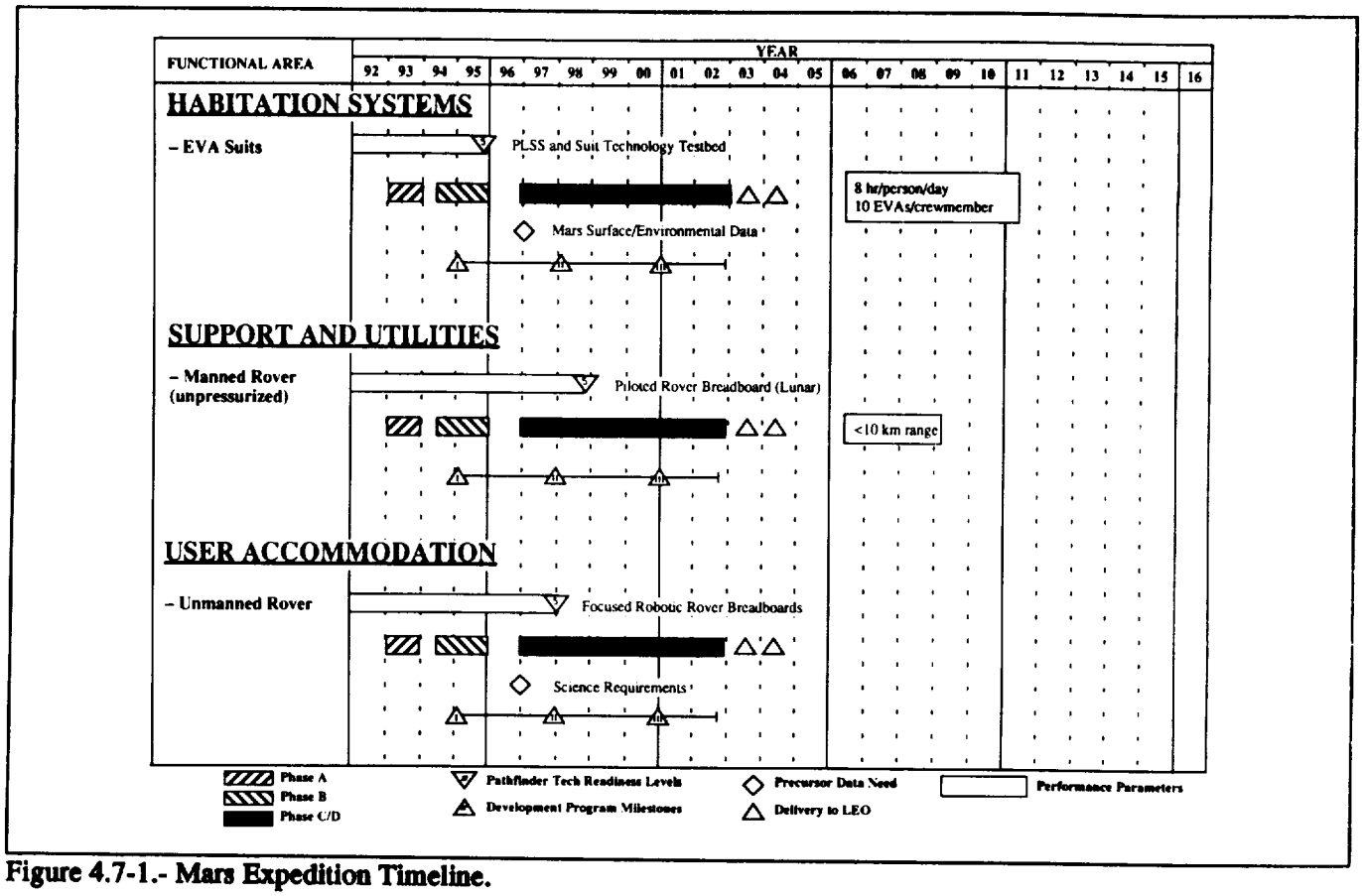



Figure 4.7-1.- Mars Expedition Timeline.

leading toward piloted Mars missions. The following set of assumptions apply:

- A lunar outpost will precede development of a Mars program
- The piloted lunar program is paced by Mars precursor missions
- Lunar systems are strategically focused toward Mars applications.

The Mars expedition case study is not founded on a precursor lunar program. Therefore, the interpretation of the technology program timelines assumes the effort slated toward lunar technology development is instead devoted to martian applications. As a result, when a particular Pathfinder program element is focused on the earlier lunar program, it is so noted on the schedules and described in terms of a martian focus in the ensuing discussion.

For consistency across case studies, technology development needs are tied to system development phases. For example, a technology readiness level of 4 (critical function demonstrated) is required by phase B start and level 6 (prototype tested in environment) by phase C start. (See figure 2.7.1-1 for a discussion of the NASA technology readiness levels.) Any discrepancies between surface system development needs and projected technology readiness dates are noted. Finally, key precursor engineering and science data inputs into system design are indicated on the schedules. These include detailed site information and user requirements.

The requirement for Mars surface human systems is the EMU. Ongoing technology efforts in the Pathfinder EMU program appear to be adequate to meet schedule requirements. Precursor data regarding dust characteristics, atmospheric temperatures and pressures, and other environmental information would support the design and development of the suit and ancillary EVA support equipment.

Support and utilities requirements for this case study are fulfilled by the unpressurized manned rover. The Pathfinder planetary rover program indicates a breadboard for a piloted lunar rover becoming operational during phase C activities. However, because of the relatively simple nature of local operational requirements, this rover should benefit significantly from the experience gained from the Apollo rover as well as future work scheduled for robotic rover development in the late 1990's. Data on the martian surface and terrain characteristics is desireable by phase C/D start, but it

may be possible to build a usable rover without new surface data.

The unmanned rover for science exploration provides support for the user accommodation category. The focused robotic rover analysis, a subset of the Pathfinder planetary rover program, may need to be accelerated such that the scientific rover can be completed in time for its scheduled delivery to LEO. Scientific objectives and requirements must be determined by the start of 1997, in order to influence the final rover configuration and performance.

## Section 5

# Distributed Studies of Equipment and Subsystems

This section describes the results of the distributed studies conducted on equipment and subsystems required to support manned operations on both Mars and the Moon. These equipment and subsystems studies were directed toward, but not necessarily limited by, the parameters of each of the preceeding case studies. Some of the studies focused more on services and accommodations than on the equipment itself (sections 5.10, 5.11, and 5.12).

Habitats (5.1) are catagorized as two types, modules and constructibles. Conceptual designs were produced for each and design factors were explored in some depth. Airlocks are also addressed.

The extravehicular activity (EVA) systems (5.2) study consists of an extra-vehicular mobility unit (EMU) and its associated portable life support system (PLSS). Design parameters for the weight and durability of the EMU as well as the weight and capacity of the PLSS are given with regard to increasing EVA productivity in varying gravity environments.

Life support systems (5.3) studies describe three basic levels in system sophistication and scope. The initial life support system (ILSS) is the baseline regenerable system of the construction shack, requiring resupply in food, nitrogen, and water. It is followed by an advanced life support system (ALSS) which is in turn followed by a mature life support system (MLSS). The MLSS is a sophisticated system that maintians a high level of closure and satisfies the demands of large crews by using biological systems such as those that support the growth and harvest of plant crops and animals.

The thermal control systems (5.4) study analyzes a two-loop cascaded vapor cycle system (VCS) and its ability to deal with the heat transfer problems inherent with the selection of a lower latitude site for a manned lunar base.

The radiation protection study (5.5) indicates that the lunar surface crews will require protection from galactic cosmic rays and solar flares, as well as the high energy secondary particle radiation generated by fragmentation interactions with the shielding material itself. Radiation dose levels can be lowered to 15-20 rem/yr by covering the lunar habitats with a 50 cm thick regolith layer. For Mars the atmosphere may provide sufficient protection without employing any additional shielding.

Power requirements (5.6) for both the martian and lunar bases are given in the power study. Base elements and their power requirements and candidate power systems are discussed.

The telecommunications, navigation, and information management (TNIM) systems (5.7) section describes concepts for both lunar and martian TNIM systems. The lunar concept is composed of two segments: the tracking and data acquisition (T&DA) system and the lunar exploration data system (LEDS). Systems reference architecture and controls are characterized, as are parameters for communications linkages.

The surface transportation section (5.8) provides parameters for various surface vehicles, such as unpressurized and pressurized rovers, unmanned and manned rovers, an auxiliary power cart and an experiment and sample trailer. Systems such as thermal control, locomotion, radiation protection, power, and life support for manned rovers are discussed.

The in situ resource utilization (ISRU) study (5.9) provides approximate sizes, masses, and power consumptions for the lunar hydrogen and oxygen production and martian oxygen production processes. Production rates, process comparisons, and mining equipment are discussed.

The study on assembly and construction equipment (5.10) gives the need for design parameters based on site specifics and describes the quantitative data (soil mechanics, abrasiveness, terrain slopes, etc.) required of future precursor missions. Ideas such as combining small multi-use equipment to perform infrequent peak effort construction activities are proposed.

The section on launch and landing services (5.11) gives a description of the flight vehicle turnaround on the lunar surface during the consolidation and utilization phases of base development, identifies the surface support equipment required, and identifies areas requiring further study.

User accommodations (5.12) are analyzed for the three main disciplines of study at both the lunar and Mars bases: astronomy, planetary science and life science. The phasing of science activities with respect to the emplacement, consolidation, and utilization phases of base

development, as well as equipment manifests, experiment descriptions, and crew involvement, are discussed.

## 5.1 HABITATS

The purpose of the habitat is to provide a living and working environment on the surface of the Moon or Mars. It must provide a pressurized, thermally-controlled, radiation-free environment with enough space to accommodate work and leisure comfortably. The initial discussion centers on the factors that bear on the choice of various habitat options. Modular and constructable habitats are then examined in detail.

Emphasis was placed on lunar habitat concepts as a stepping stone to martian habitats. The concepts that follow are chiefly lunar, but with slight modification they could be considered martian. In the absence of specific numbers and concepts for the martian base, the lunar concepts provide a good first guess.

### 5.1.1 Habitat Design Characteristics

In any optimization problem, one must define the characteristics to be optimized. The suitability of a lunar habitat can be measured by a number of parameters, including failure resilience, reliability, habitability, transportability, constructibility, and maintainability. Other parameters can also be included. In order to proceed with the design process, each must be defined by an optimization criterion. In other words, each of these characteristics suggests some ideal configuration. Looking at each criterion individually, one can determine what best satisifies that criterion. The concepts can then be compared to identify any criteria that are in conflict.

#### 5.1.1.1 Failure Resilience

The habitat should be fail safe. If a failure occurs, quick action should be possible to limit the impact of the failure.

The failure that is of the greatest concern in a lunar habitat is a catastrophic failure of the pressure vessel, allowing a large volume of air to escape quickly. A sufficiently large puncture failure would be difficult to repair immediately, due to the unpredictable nature of the hole, the rapid loss of pressure, and the high-speed airflow in the vicinity. There are other hazards and failures. Fire or other atmosphere contamination is a serious problem perhaps more probable than a large puncture. The best way to deal with all of these problems may be to seal off the affected area, allow the sealed volume to depressurize, and attempt a repair later. Redundant habitable volume is required for this procedure. From the standpoint of resilience, a highly modular configuration would be optimal, so a ruptured or smoke-filled module could be isolated with minimal effect on the rest of the habitat.

#### 5.1.1.2 Reliability

The failure rate should be low, and the chance of a catastrophic failure should be remote.

Again, the greatest concern is a failure of the pressure vessel. Other concerns would be high leakage rates through seals and structure. The reliability criterion is different from failure resilience. Designing for resilience means designing the structure to withstand failure; designing for high reliability means designing to prevent failure.

Apart from a meteoroid puncture, the threat of which can be effectively eliminated with a thick layer of soil, the habitat wall will most likely fail due to some defect, brought to a critical point by some event, perhaps very minor. This hypothesis is supported by the body of data on pressure vessel failures. These data suggest that most such failures are the result of defects in seams and welds.

Seams and welds occur wherever discontinuous pieces of material are joined. The total length of such joints on a pressure vessel is proportional to the surface area (because many discrete pieces are required to form the surface) and to the number of attach points (such as hatches, windows, and other fittings). By minimizing the sum length of the seams and welds, the pressure vessel is made more reliable.

A habitat with the minimum length of welds, seams, and seals would have the minimum surface area for its contained volume. In other words, it would be spherical. It would also have as few hatches and windows as possible.

Concerning the choice between constructables and modules, it is not obvious which structure would be the most reliable over the long term. As discussed above, the large number of seals, seams, and welds associated with multiple module structures is a cause for concern. Whether a large pressure vessel of a simpler shape and design can be assembled on the lunar surface to be more reliable than a series of Earth-constructed modules is an open question. An inflatable can eliminate lunar assembly of the pressure vessel and the welded seams, but will a simpler fabric structure with different types of seams and seals instead of welds be more reliable over 20 or 30 years than a welded metal structure with more seams? This question cannot be definitively answered at this

time and is recommended for further study during FY 1990.

#### 5.1.1.3 Habitability

The habitat should provide an open, flexible environment. Habitability is a measure of the habitat's usefulness as a place to live and work. On a stay of any significant duration, poor habitability lowers crew performance and morale.

Because of the somewhat unpredicatable nature of the crew and the work to be done, the best way to ensure continued usefulness of the habitat is to design it so that it may be reconfigured to meet new needs as they arise. Besides making the crew's work more efficient, it will benefit them psychologically by giving them control over their immediate environment. Providing flexibility in the design, so that the crew members can implement their own solutions to any problems of space or interior arrangement that arise, is a desirable goal in engineering the lunar habitat. The concept of open volume is a key element in this philosophy of flexible design. There should be enough space to rearrange the interior and to expand the capabilities of the base without major exterior construction.

The walls of the pressure vessel form the ultimate boundary in which the crew must work. They can arrange rooms inside, but they cannot rearrange the walls of the pressure vessel. To optimize for habitability, the pressure vessel should be unconfining: opposite sides of the habitat should be as far from each other as possible. Consequently, a large volume in a single pressure vessel is desirable.

#### 5.1.1.4 Transportability

The habitat should be partitionable into discrete payloads, and provide the most usable volume per unit mass. The habitat must be compatible with the transportation system. Vehicle designs should be optimized in view of their lifetime manifest, not to carry rare, anomolously large payloads. Therefore, the habitat must be designed in transportable pieces. In previous studies, the mass of a modular habitat has driven the cargo-carrying capacity of the lander.

Here there are several choices. The pressure vessel can be partitioned into multiple modules with or without integrated interiors. Several sizes and shapes are possible. Alternatively, the pressure vessel may be collapsible, with the interior fittings transported separately for installation on-site. Assembly of a large pressure vessel on-site is also a possiblity. All approaches represent a necessary compromise to the constructibility criteria.

The mass of a pressure vessel depends upon its geometry and the interior pressure. A sphere is the most efficient shape for a pressure vessel. A spherical habitat will, therefore, have the highest volume to mass ratio of any geometry.

#### 5.1.1.5 Constructibility

The habitat should require a minimum of time, manpower, and support equipment to construct or expand it. The tasks required for these activities should be simple, few, and quick. Extravehicular activity (EVA) should be minimized, as should reliance on complex or bulky equipment. A habitat optimized for this constraint would be a single, self-contained unit simply set down on the lunar surface. The next best situation might be a few modules with integral interiors. Next might come a large inflatable with an interior to be installed in pieces. The least desirable situation would be a pressure vessel that must be assembled, with an interior assembled inside it.

The ability to construct objects on the lunar surface is desirable if the long term goals of the base include large numbers of people staying for long periods. Sooner or later, construction techniques on the lunar surface must be developed. Habitats requiring some lunar surface construction work can be viewed as investments in the distant future of the base. In a program of this nature, emphasis is often placed on reducing the initial development cost as much as possible. For this reason, minimal construction is assumed desirable for early habitats.

#### 5.1.1.6 Maintainability

The habitat must be easily repairable in the event of defect or damage from some unexpected source. Ideally, the habitat structure should require no maintenance, though making this assumption without a working history for the particular design in the particular environment has often been a serious error. The structure should be designed to require little or no maintenance, but must also be capable of being inspected, maintained, and repaired in the event the unexpected occurs.

Corrosion, major puncture, chronic leakage, fire, and accident damage are all possible situations requiring maintenance or repair actions. One viewpoint on space maintenance is that only replacement of modularized units should be attempted on the lunar surface with the exception of major structure. True replacement of major structure may favor a modularized approach to habitat construction. Holes of reasonable size should be repairable by welding or other patching techniques. In any case, a structure with enough volume to allow access to

all the walls, seals, and seams for inspection and possible repair is desirable. In addition to access from the interior, access to the exterior of the structure is also desirable for inspection purposes.

### 5.1.2 Selection of Habitat Configuration

The previously discussed criteria must be evaluated in the presence of design requirements. The systems requirements document (SRD) called for crews of two to twelve, with stays of up to two years. The volume needed to meet these requirements is subject to debate, but with twelve people staying for two years, a good argument can be made for large volumes. As stay time increases, large volumes become mandatory. This favors schemes that deliver large volumes per unit - mass. The large spherical habitat described in the following sections may be difficult to assemble internally, but eleven Space Station Freedom-size modules would be required to achieve the same volume.

Safety has been first priority in all NASA manned programs to date. This corresponds to the failure resilence and reliability criteria. Mission success has often been given second priority. This corresponds to reliability and maintainability. Habitability becomes a mission success issue for large crews and long stay times. If mission success is second, cost is third priority. The habitat must be transportable and constructable within the budget allotted. Habitability is a cost issue for short stay times and small crews.

Habitability favors a single, large pressure vessel. Failure resilence favors the modular approach. A single large habitat with a safe haven is an architecture that incorporates elements of both solutions. Other possibilities and rationales exist, but this architecture using a large constructible habitat with an inflatable pressure vessel and one or more modules as safe havens and initial construction facilities was chosen for further study.

### 5.1.3 Design Considerations

Once the basic configuration is chosen, specific design issues posed by a habitat must be addressed. The design is influenced architecturally by the activities carried on within the habitat. It is also influenced by the physical forces imposed on the structure and by the environment in which it operates. Finally, the transportation system to be used remains a key design factor. An examination of these design considerations follows.

#### 5.1.3.1 Architectural

As used here, architectural factors are those that influence the volume and form of the habitat. The physical and psychological needs of humans in a confined environment must be balanced against the physical limitations of a pneumatic structure.

Habitable volume is space that is pressurized, climate controlled, and protected from radiation. The amount of habitable volume needed depends on many factors: the number of crew members, what they will be doing, and how much discomfort and inconvenience they can be expected to endure.

#### 5.1.3.2 Structural

Structural design issues arise from the nature of the structure itself, relatively independent of the environment. A pneumatic structure imposes certain constraints on its designers, regardless of its secondary functions or its environment. Chief among these considerations are the membrane stress, the leakage rate, and the puncture resistance.

A pneumatic structure is stressed primarily by its internal pressure, overshadowing external forces such as gravity. The internal pressure creates stress in the wall of the inflatable, called the membrane stress, measured in Newtons per meter. It depends on both the internal pressure and the local radius of curvature. In a sphere, the membrane stress is given by:

$$\text{stress} = 0.5\ (\text{pressure} \times \text{radius})$$

There are similar equations for the stress in a cylinder or torus.

The internal pressure to be maintained in the habitat depends on many factors, but will probably be between 70 and 101.3 kPa (10.1 and 14.7 psi).

Aside from resisting the membrane stress due to the internal pressure, the structure must also be sealed against leakage. The wall material must be impermeable to air, and care must be taken in the design of hardware interfaces (such as hatches or windows) to limit potential leak locations.

#### 5.1.3.3 Environmental

When designing a lunar habitat, the effects of the lunar environment over a long period of time must be considered. Radiation, temperature extremes, vacuum, and meteoroids all act to erode the integrity of the structure over time.

The surface of the Moon, not protected by the thick atmosphere and strong magnetic field of Earth, is exposed to high levels of radiation from space. The

radiation hazard comes from two sources of different character: galactic cosmic radiation--"background" radiation that permeates space at roughly constant levels; and solar energetic particle events that produce extremely high levels of radiation for short periods of time. Radiation can affect both crew and equipment, including the materials used in the habitat. Possible protection from radiation includes shielding the habitat with either an effective thickness of structural material or other internal stores (as part of the habitat design) or planetary soil.

The habitat material must be insensitive to temperature swings from 100 to 400°K (darkness to full sunlight). While the material will stay at room temperature and pressure during normal base operation, it may be exposed to more extreme conditions during transport and deployment, or in the event of a major malfunction, in which case the base may be completely shut down for some period of time. Some materials give off gases in a vacuum, possibly affecting their physical properties over time. Base material design must account for this.

If the base is properly shielded from radiation, it is more than adequately shielded against micrometeoroids. Only a few centimeters of soil are required for this purpose. Impacts large enough to penetrate several meters of soil are extremely rare.

A habitat designed for the martian environment will deal with a somewhat different set of constraints. Mars has approximately twice the gravity and enough atmosphere to provide substantial radiation shielding and blow dust, but not enough to create an external pressure of any structural significance. Temperature extremes are moderated by the atmosphere and by a much shorter day/night cycle. Materials face a different set of compatability problems. The martian surface material and topography both appear to be significantly different from the Moon.

### 5.1.4 Constructible Habitat

A constructible habitat is one that is constructed to some significant degree on the lunar surface. In most of the following discussion, this refers to an inflatable sphere, which is actually a deployable pressure vessel with a constructed interior. Numerous other options are possible. In general, the larger the pressure vessel becomes, the more parts go into the construction of the habitat, due principally to the problem of transporting and deploying large and massive single structures.

A constructible configuration offers an alternative to the multi-modular approach as crew sizes expand in mature base phases. An inflatable, flexible pressure vessel that may be folded compactly for transport and then deployed to its full size on delivery is proposed. A conceptual design of a constructible lunar habitat with an inflatable pressure vessel has been developed in order to provide a focus for discussion of habitation issues as they apply to constructibles.

The constructible habitat is a base operations center, a mission operations facility and habitation facility all in one pressure vessel. This habitat is designed for twelve permanent crew members with stay times ranging from six months to twenty-four months per rotation.

The constructible habitat is comprised of a spherical pneumatic envelope (the primary structure) and an internal structure (the secondary structure). The inflatable envelope's function as the primary structure is that of a pressure vessel, designed to withstand a pressure of 101.3 kPa (14.7 psia). The internal structure's function is to support the internal equipment, furnishings and crew members. Figure 5.1.4-1 provides a cross-sectional view of the inflatable habitat, with particular detail given to the many structural components. Also included in the illustration are the overall dimensions of the habitat and of each floor.

#### 5.1.4.1 Structure

The inflatable wall of the constructible must be made of high-strength fabrics that can withstand high membrane stress when pressurized, but remain flexible when unpressurized. This conceptual design uses a multiple-ply fabric with a non-permeable bladder inside and a thermal coating on the exterior. The exact choice of fabrics requires further study. One possible design uses a three-ply laminate of Beta cloth, Kevlar and Spectra fibers, and coated Nomex cloth. The Beta cloth resists the harsh external environment; the Kevlar and Spectra take the pressure load; and the coated Nomex provides a fire-retardant inner surface. An impermeable layer under the Nomex will prevent air loss.

The internal structure is composed of six telescoping, hexagonal core columns that rise veritically from the bottom to the top of the sphere. Six peripheral rib structures attach the outer edges of each floor together. Six radial floor beams, laid horizontally, support each floor. Circumferential joists, intermittent floor joists and secondary bracing are also included. Figure 5.1.4-2 illustrates a typical framing plan for one floor. The habitat is supported by a mat foundation that transfers all the loading from the interior to the exterior support structure at seven hard points. The initial structural sizing analysis used a T851 aluminum alloy, similar to the metal used for the lunar rovers of Apollo.

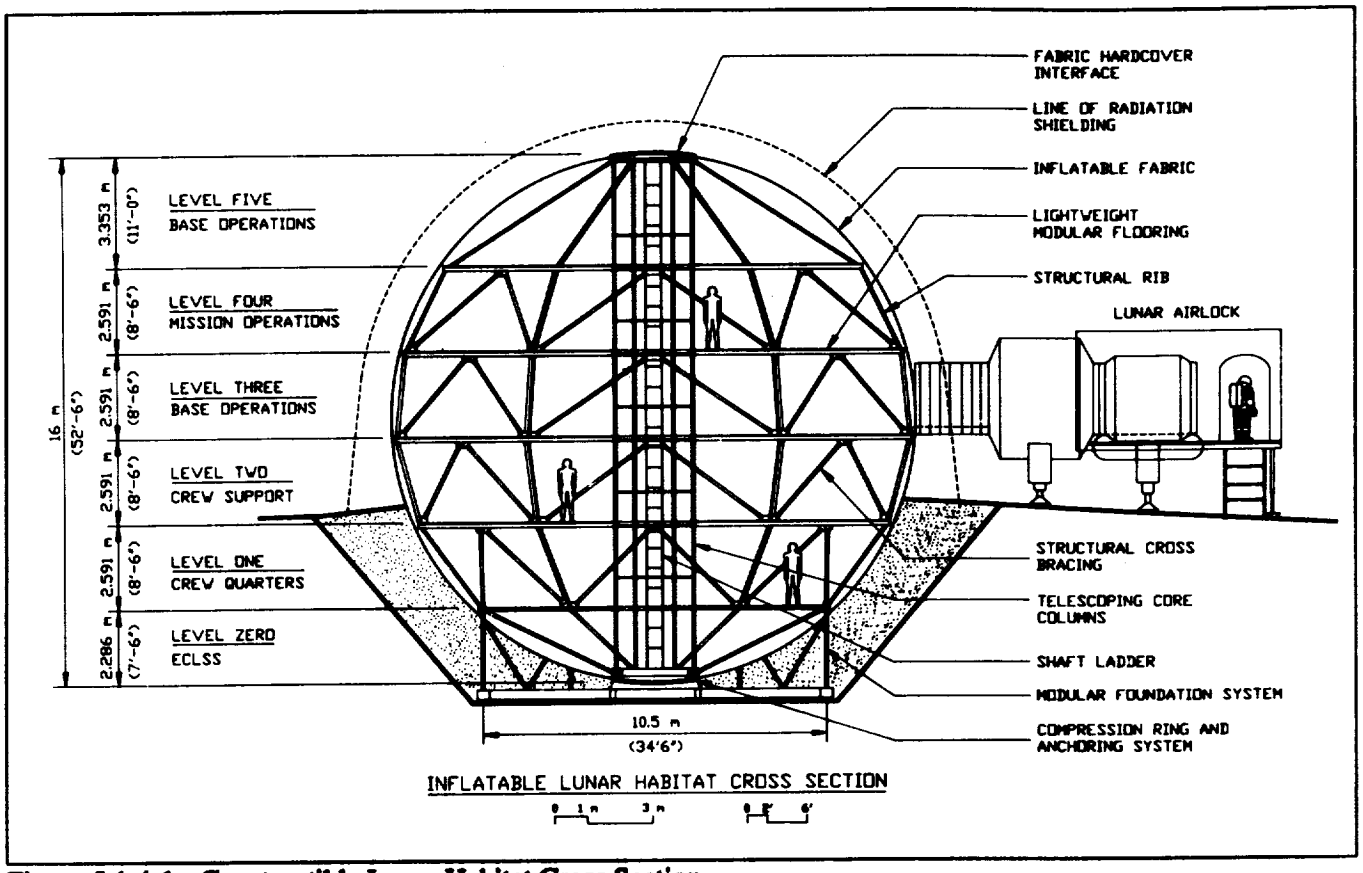



**Figure 5.1.4-1.- Constructible Lunar Habitat Cross Section.**

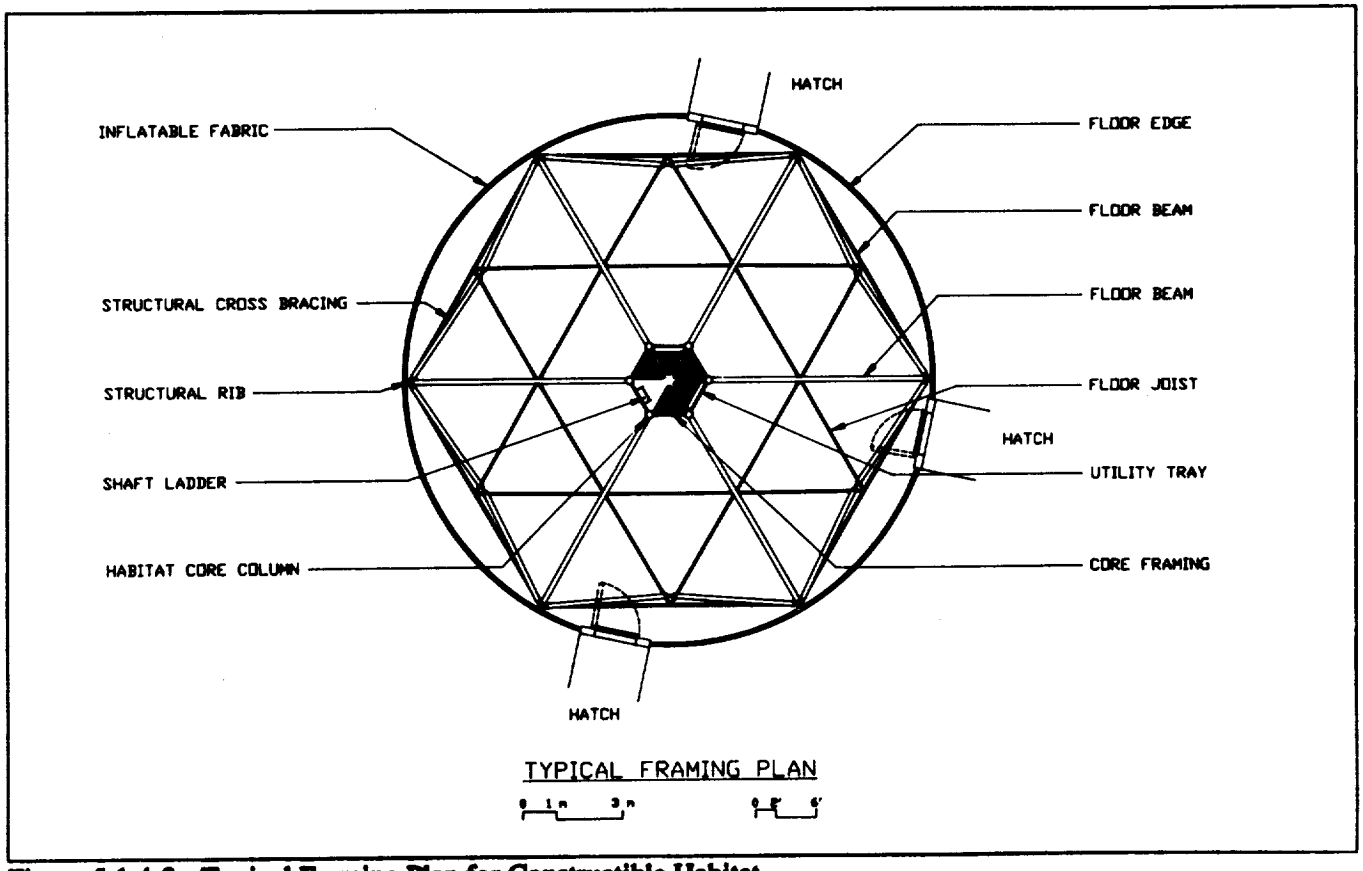



**Figure 5.1.4-2.- Typical Framing Plan for Constructible Habitat.**

### 5.1.4.2 Architecture

The initial habitat module, or construction shack, is connected to the constructible habitat by a pressurized tunnel. This initial habitat is the size of a Space Station Freedom module and will be used by construction crews during base build-up. After the constructible habitat is livable, the shack is retrofited as a radiation storm shelter or safe haven.

The constructible habitat provides a living and working environment for a crew of twelve. It is a 16 m diameter sphere containing 2,145 $m^3$. Five levels of living and working areas make up the 740 $m^2$ of floor space. The floor-to-bottom of beam clearance is 2.44 meters. This head height is preliminary based on Langley's research and Apollo studies of lunar (1/6 g) locomotion (see section 5.1.5.3.7). Additional study is required to confirm the required headroom for a habitat in the lunar and martian environments. A 2 m diameter vertical circulation shaft at the center allows for transfer of crew and equipment. This shaft is comprised of six columns, five grated landings at each level, a ladder and two utility chases (trays). The crew will move vertically through the shaft using a ladder, while equipment and furnishings are hoisted by a block and tackle system located at the shaft's top.

The constructible habitat is divided into functional areas according to activities. These areas of activities are: crew quarters, crew support, base operations, mission operations, internal stowage, environmental control and life support systems, circulation, and a contingency for technological growth. The five levels are designed with respect to these activities. Figure 5.1.4-3 graphically displays the volume allocations for the entire constructible habitat. Base operations occupy the largest portion of the habitat.

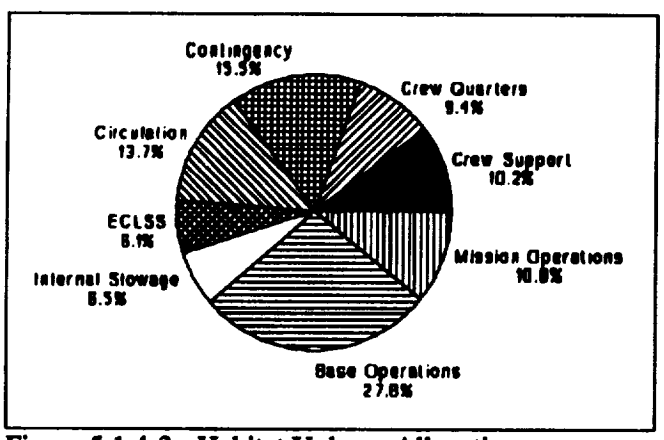



Figure 5.1.4-3.- Habitat Volume Allocation.

Level one, at the bottom of the habitat, is the crew quarters level and has 87.7 $m^2$ of floor space. Level two is the crew support level and has 159.6 $m^2$. Level three is the base operations center; it has 189.4 $m^2$ of floor space. Level four is the mission operations facility, which has 177 $m^2$. Level five, 122 $m^2$, is used for crew training and quiet space. Five water closets are distributed over four levels; thus a water closet-to-crew member ratio of 1:2.4. Two showers and five lavatories make up the remaining personal hygiene facilities. The crew quarters and crew support areas are located near the bottom of the habitat to decrease the amount of radiation the crew will be exposed to over the mission stay.

5.1.4.2.1 <u>Level One--Crew Quarters</u> - Level one has ten crew quarters of 15.8 $m^3$ each and two personal hygiene facilities, as shown in figure 5.1.4-4. Each crew quarter comes with a bed and two lunar functional racks. The lunar functional racks are about half the size of a Space Station Freedom rack, which is required because of the non-zero gravitational forces. Personal decor items and interchangeable wall panels will enhance the psychological environment of each crew quarter.

5.1.4.2.2. <u>Level Two--Crew Support</u> - Level two is the crew support level, including the base and science leader's quarters, a galley, dining/wardroom, activities/recreation room, health maintenance/medical facility (HMF), exercise area, personal hygiene and a laundry/housekeeping room. Figure 5.1.4-5 shows a plan view of this level.

Exercise equipment, such as a bicycle ergometer and treadmill, will provide the necessary aerobic, strength and skeletal loading exercises. Motivational devices are used in conjunction with the exercise apparatus. An HMF provides medical and dental facilities for both preventive and emergency care as well as life sciences research support.

The activities/recreation area is used for two purposes. First, it is used for socializing during off-duty time; activities such as playing games, watching movies, listening to music and conversing occur here. Also, this area doubles as an assembly area for crew meetings, training and tele-conferencing.

The dining facility seats 12 crew members at one time, with additional seating at the island counter. The dining area doubles as a wardroom.

The adjacent galley provides a food preparation surface, refrigerator/ freezer rack, ambient food stowage, trash compactor, dishwasher, ovens, handwasher, and automated inventory control units among other kitchen appliances.

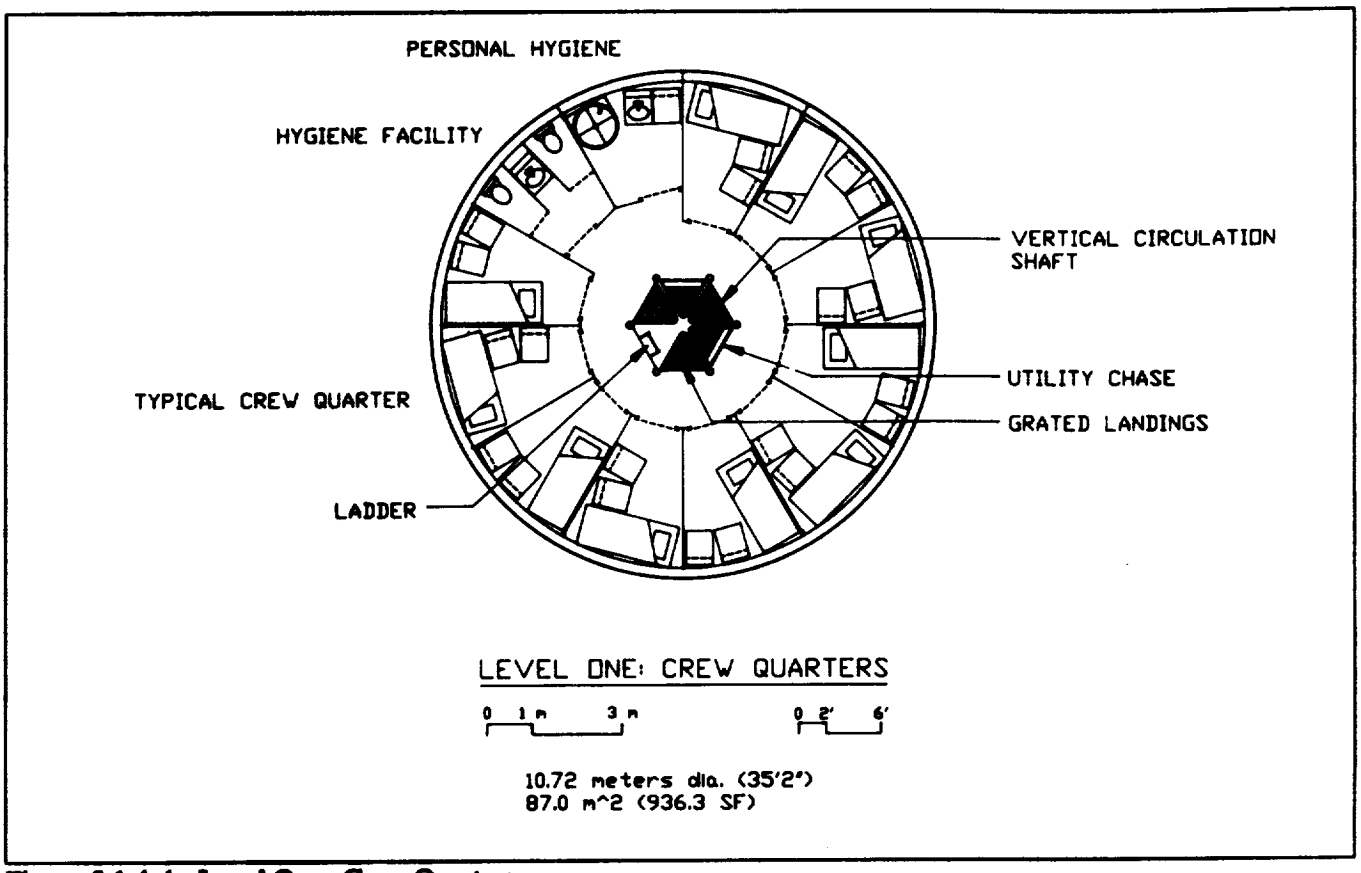



**Figure 5.1.4-4.- Level One--Crew Quarters.**

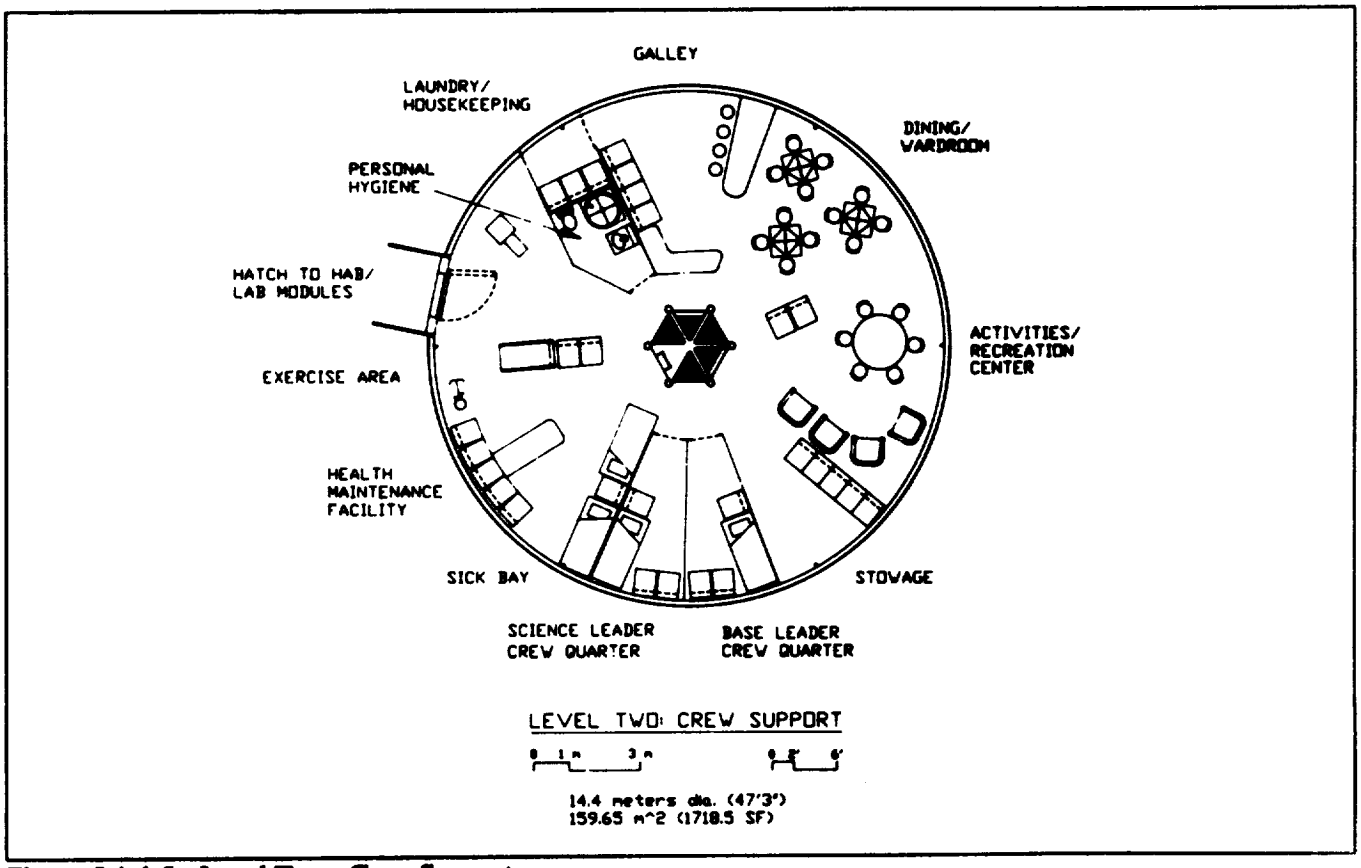



**Figure 5.1.4-5.- Level Two--Crew Support.**

The laundry/housekeeping facility is adjacent to the galley and has a mop sink, washer, dryer, and housekeeping tools. The tools kept in this area include vacuum cleaners, mops, wipes, and disinfectant cleansers.

Level two has a personal hygiene facility and two crew quarters. The hygiene facility is equipped with a shower, water closet, lavoratory, and stowage for dry and wet wipes, clothes, towels, and body cleansers. The crew quarters on this level are for the base and science leaders and have the same furnishings as the crew quarters on level one.

5.1.4.2.3 Level Three--Base Operations Center - Level three, depicted in figure 5.1.4-6, consists of the base operations center, an EVA support and maintenance facility, a computer facility, stowage, spare parts, and a personal hygiene facility. Three hatches are on this level. One hatch leads to the airlock; another leads to the pressurized rover berthing interface; the third is for the logistics module. The hatch interfaces are hard interfaces providing pass-through ports as well as sealed connections for the hatch doors. Each hatch door is 1.27 m wide by 1.67 m high.

The base operations center is where most of the base activities inside and outside the habitat are monitored. It contains the base and science leaders' workstations and several general workstations.

A typical workstation has communication capabilities and monitors for telerobotic operations. Each workstation has access to the base information and data management systems. One of the workstation units required by base operations is for tracking and communications for surface operations and lander flight operations. Another workstation is for EVA operations and monitoring. A general workstation will be used for keeping track of cargo processing and handling, consumable resupply, and communications. Monitoring racks and stations will be required to process large amounts of data being received at the base from experiments and observatories. The environmental control and life support operations center will monitor the power generation and distribution, thermal control, and fluids management systems.

The EVA support and maintenance facility has an important function. Each crewmember will have his suit personally fitted while stationed at the base. Four EVA suits are kept in the airlock; the remaining suits are kept

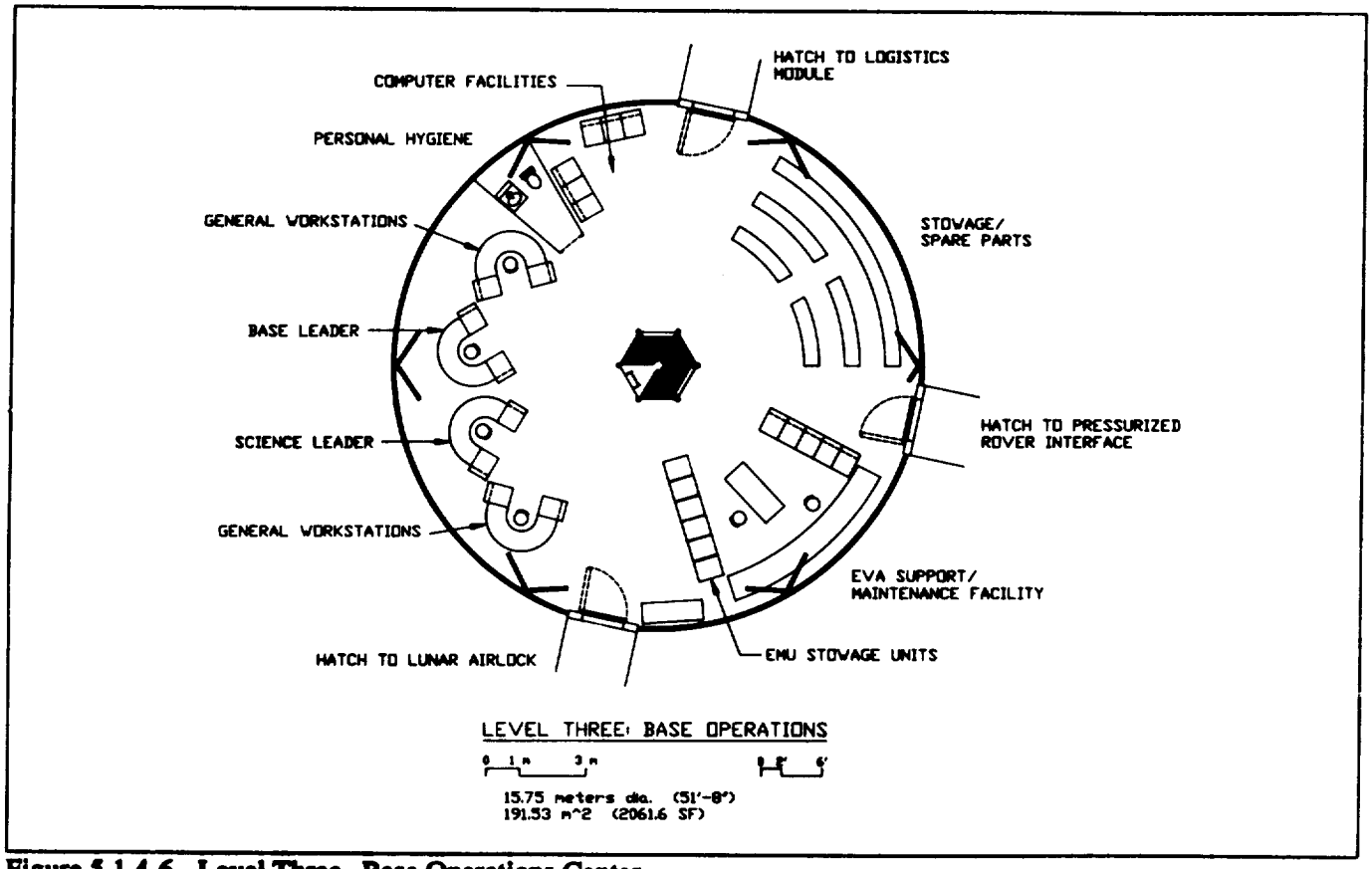



Figure 5.1.4-6.- Level Three--Base Operations Center.

in suit racks, which are also used for drying purposes. A support facility such as this one has provisions to clean, dry, and repair suits and to perform preventive maintenance and systems checks before the suits are stowed. This area has a suit table or work bench, monitoring and analysis racks, a counter with sink, individual suit racks, and tools. A small stowage room is adjacent to this facility for special EVA suit parts.

The maintenance portion of the EVA facility is a necessary part of keeping the base operational. Equipment, tools, and electronics will all require maintenance and repair periodically. In addition, systems checks on experiments, instruments modifications, and other small tasks will be performed. The maintenance area includes a work counter, a flow bench, sink, computers, monitoring racks, and tools.

The stowage/spare parts area is adjacent to the EVA support and maintenance facility and has easy access to it. The amount of required spare parts and internal stowage depends upon how logistic resupplies are delivered and stowed at the base.

5.1.4.2.4 Level Four--Mission Operations - Level four is the mission operations center, where the science laboratories are located. Laboratories are provided for two main categories of research--life sciences and geochemistry/petrology sciences. This level has the life science lab, geochemistry and petrology lab, astronomy and astrophysics area, personal hygiene facility, and stowage. Figure 5.1.4-7 shows the level four plan view.

The life science lab has work counters, computer and monitoring racks, animal holding racks, a small centrifuge, a glove box, and a preparation counter that includes a double sink. Equipment for monitoring and computer racks will flank one side of the lab work surface.

The geochemistry and petrology lab has the same amount of work counter space as the life sciences. Included in this laboratory are computer and monitoring racks, a flow bench for sample preparation, and a separate preparation room. The enclosed preparation room is for control of dust due to the rock saw, thin section maker and thin section sander. Other equipment used in this lab include a scanning electron microscope, a gas chromatograph, mass spectrometer, binocular microscopes, and scales.

Astronomy and astrophysics will be monitored through a workstation on this level. This workstation will monitor each lunar observatory and communicate simultaneously with observatory stations on Earth.

5.1.4.2.5 Level Five--Base Operations - Level five is used for crew training, library research, quiet space, and lunar observing (see figure 5.1.4-8). Also included on this level is a mechanical room and open free space. The mechanical room will support and compliment the environment control and life support subsystems at the bottom of the habitat.

The library is used by the crew members to research information, read, contemplate and relax in a semi-private environment. This space can be divided into two smaller spaces by a folding partition. Video and computer capability is available for Earth communication and for monitoring lunar exploration and EVA activities.

An observatory station is proposed for the crew's entertainment and psychological benefit, as well as for general monitoring of the lunar surface. The baseline constructible habitat has no windows, and thus requires some means for crew members to observe the lunar landscape or Earth. The viewing station concept combines exterior cameras, placed on top of the habitat, around the lunar landscape and even planetary probes, with image projection on the domed part of the inflatable skin. The result is a dynamic large screen projection in which the user(s) can define what they want to see. Another possibility would be to construct a Space Station Freedom-type cupola on top of the constructible for direct viewing. This concept, however, poses numerous complications.

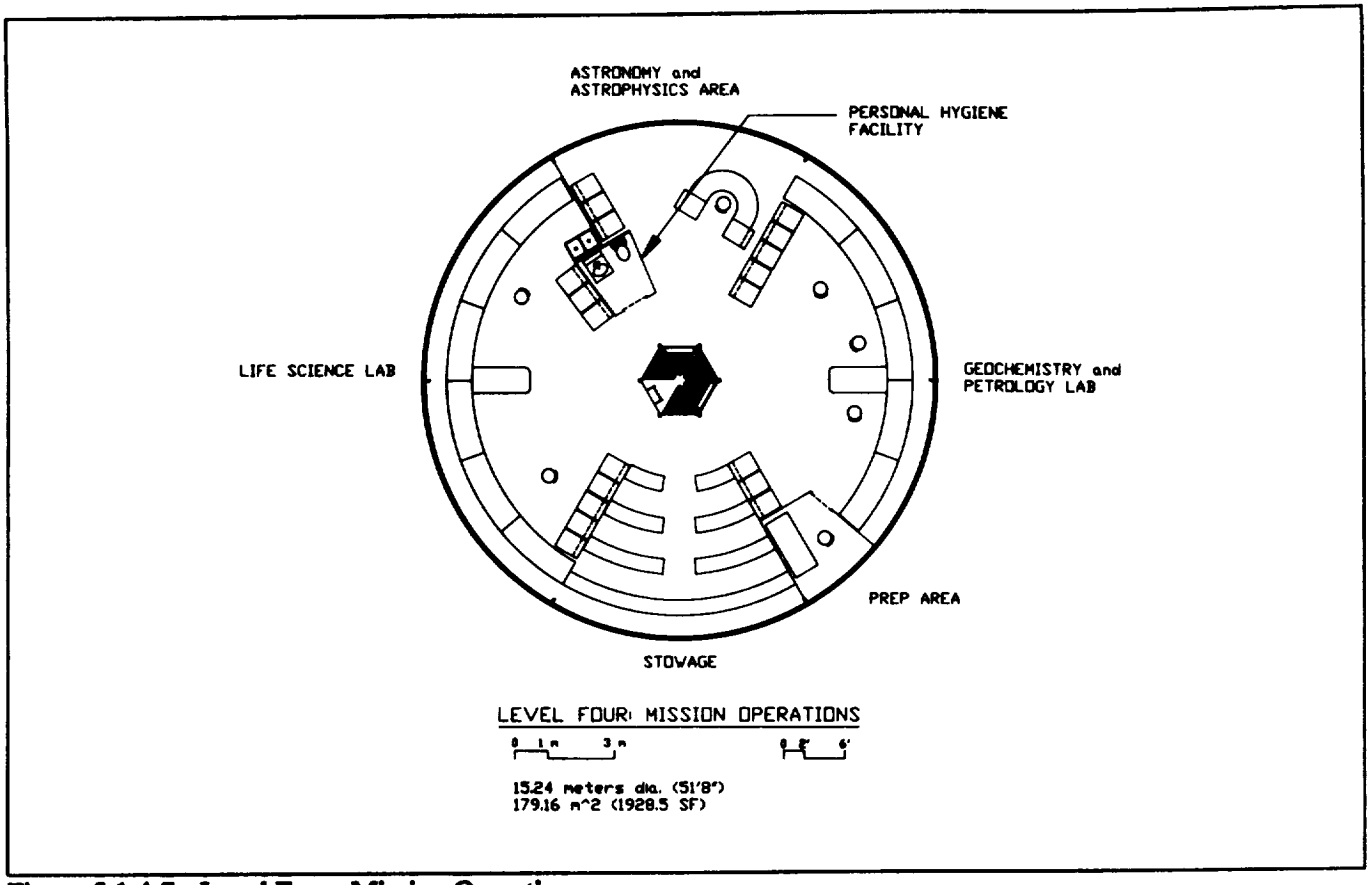



**Figure 5.1.4-7.- Level Four--Mission Operations.**

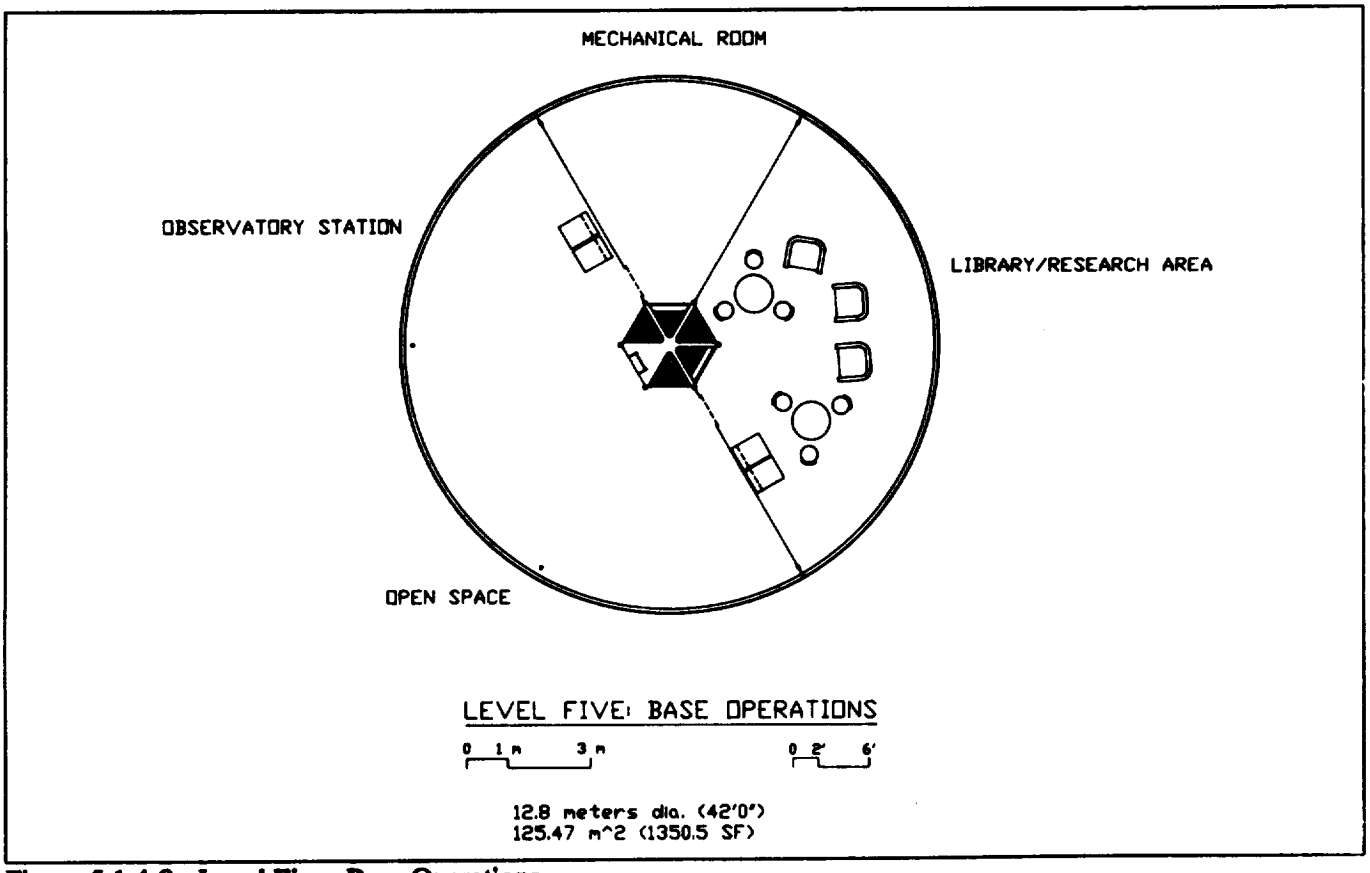



**Figure 5.1.4-8.- Level Five--Base Operations.**

### 5.1.4.3 Mass Estimate

Table 5.1.4-I shows a first order mass estimate of the constructible habitat.

TABLE 5.1.4-I.- CONSTRUCTIBLE HABITAT MASS ESTIMATE

| | Mass (kg) |
|---|---|
| Furnishings and Equipment by Level | |
| Level One | 2,405 |
| Level Two | 4,808 |
| Level Three | 4,056 |
| Level Four | 6,765 |
| Level Five | 934 |
| **Subtotal** | **18,968** |
| Contingency (20 percent) | 3,794 |
| **Total Furnishings and Equipment** | **22,762** |
| TCS | 5,497 |
| ECLSS | 14,035 |
| Inflatable Structure | 2,420 |
| Internal Structure and Mat Foundation | 4,829 |
| **Total Constructible Lunar Habitat** | **49,543** |

### 5.1.4.4 Alternative Interior Architecture

Figure 5.1.4-9 shows a cross-sectional view of an alternative concept for the constructible habitat interior. The numbers below correspond to the numbers on the figure The key features of this concept are:

5.1.4.4.1 Level One--Crew Quarters - Each crew member has a private compartment for sleeping, relaxing or working. Personal items are stowed in the compartment. The crew quarters are located on a low level to provide the maximum shielding from radiation.

5.1.4.4.2 Level Two--Wardroom/Galley - The wardroom is a general purpose area with seating for all twelve crew for structured, on-duty activities such as dining, meetings, and training sessions; and off-duty activities such as games, entertainment, and casual socializing. A galley for food preparation is located adjacent to the wardroom. Full meals for the entire crew or simple snacks can be quickly and efficiently accommodated.

5.1.4.4.3 Level Three--Life Sciences Lab - A fully equipped life sciences laboratory allows scientist astronauts to study the adaptation of various species of plants and animals to the planetary environment. This information is critical to understanding human capability to live for extended periods in reduced gravity. The ability to raise plants and animals for food is also a subject of close study.

Lab space is provided for testing and demonstrating applications research. The illustrated example lab includes a small pilot plant which can extract oxygen from lunar soil. Additional lab space, not shown, is provided for crew medical care.

Advanced developments are depicted with a hydroponics garden providing fresh vegetables for food as well as recycling exhaled carbon dioxide to provide breathing oxygen. All wastes are recycled to reclaim as many useable resources as possible. In addition, the green plants add color and vitality to the interior environment.

5.1.4.4.4 Level Four--Base Operations Center - The base operations center is responsible for service activity monitoring and control. These activities include the operation of pressurized rovers, the landing and launch of manned and unmanned vehicles, and the operation of surface experiment packages. Communication with Earth, vehicles in transit, EVA crewman and surface vehicles also takes place in this area. Habitat systems are monitored and controlled from the base operations center. The data management system for the base is located on level four.

The habitat is equipped with a small clean room. This facility allows lunar samples to be studied without exposing them to the atmosphere and environmental contaminants of the habitat.

5.1.4.4.5 Level Five--Exercise Room - A reduced gravity environment demands crew fitness to maintain cardiovascular conditioning and exercise to prevent bone and muscle deterioration. An exercise facility, considered part of the overall medical facility, is contained in the constructible for routine health maintenance programs. A banked track that allows an astronaut to run almost parallel to the floor as he gains speed surrounds level five. Exercise machines use hydraulics and pneumatics for resistance, since weights would be bulky in low gravity. Large, flat panel television screens provide information and entertainment while exercising. The area under the track is used for storage lockers.

5.1.4.4.6 Airlock - The airlock connects to level three of the habitat. It doubles as a hyperbaric chamber for treating rare EVA medical emergencies like the bends. The airlock is large enough to accommodate up to four astronauts at one time. The suits are stowed in the airlock when not in use.

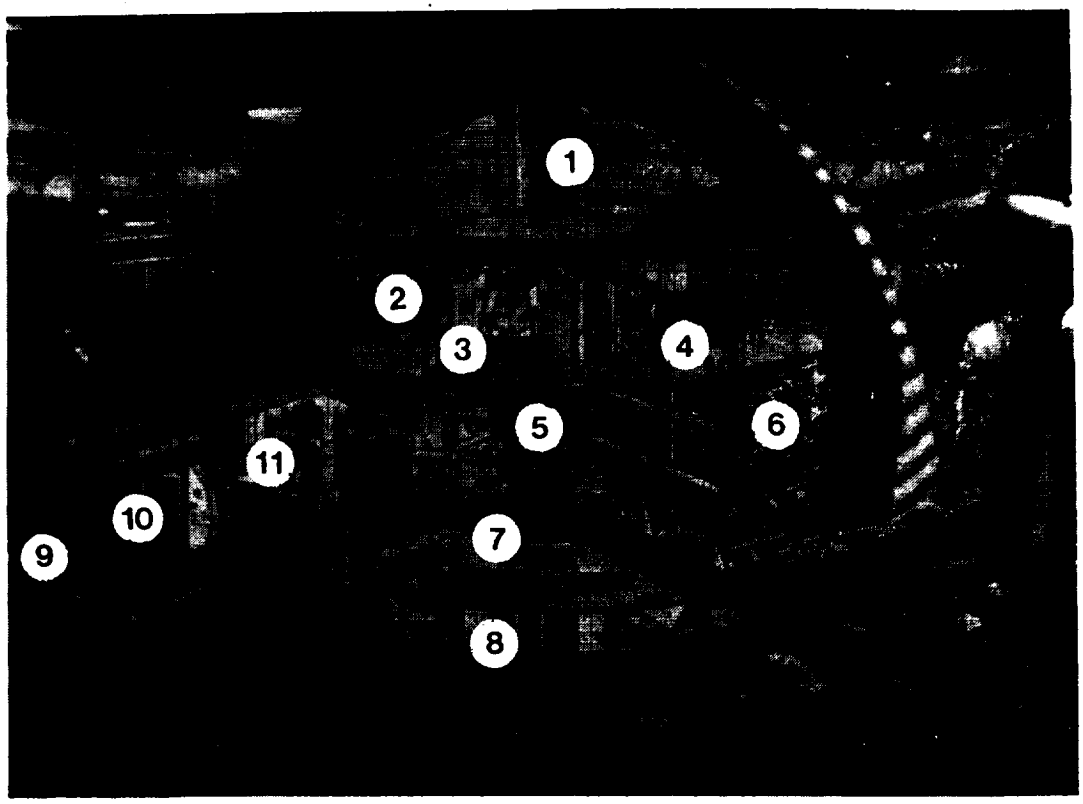


Figure 5.1.4-9.- Alternative Interior Layout for Inflatable.

5.1.4.4.7 Dust Lock - The presence of dust on both the lunar and martian surfaces presents major problems for EVA crew. As much dust as possible must be removed before reentering the habitat. Thus, an unpressurized dust lock is situated between the airlock and the open lunar environment. The astronauts pass through electrostatic wickets that remove much of the dust. A perforated metal "porch" allows dust to fall through. Once inside the dust lock, the astronaut removes his white coveralls. This outer garment provides an extra layer of dust control and protects the precision moving joints of the space suit from the gritty dust. An air shower removes remaining dust with strong jets of air.

### 5.1.4.5 Inflatable Skin Construction Options

Figure 5.1.4-10 shows a series of options for assembling an inflatable habitat skin. Five spherical approaches--basketball, soccer ball, volleyball, globe, and latticed globe--are shown. Two other shapes, the torus and cylinder, are also shown. Criteria for selecting an approach include the number of seams, seam stress points, and the number of different shapes that must be manufactured.

### 5.1.4.6 Constructible Habitat Conclusion

The constuctible habitat marks the beginning of a true commitment to a permanent settlement on the Moon. Much of the controversy concerning this size and type of structure revolves around the question of how big and permanent the base should be. This concept attempts to meet the requirements calling for a large, essentially permanent base (12 crew, 24 month rotation), designed as a stepping stone to an even larger lunar and eventually a martian base. If the base becomes much smaller or less permanent or is not used as a testbed for future expansion, then other concepts may be more appropriate.

Many issues remain unresolved, but areas that require further study have been identified. The interiors of the constructible habitat are defined enough to integrate subsystems, draft emergency procedures, and develop system "quick fixes."

A computer-generated animation of the lunar outpost and habitat interior design is available from the Johnson Space Center, Public Affairs Office. It is 6 minutes, 18 seconds in length and shows the outpost exterior configuration as well as the interior design. For ordering a copy, use the reference master No. 117084.

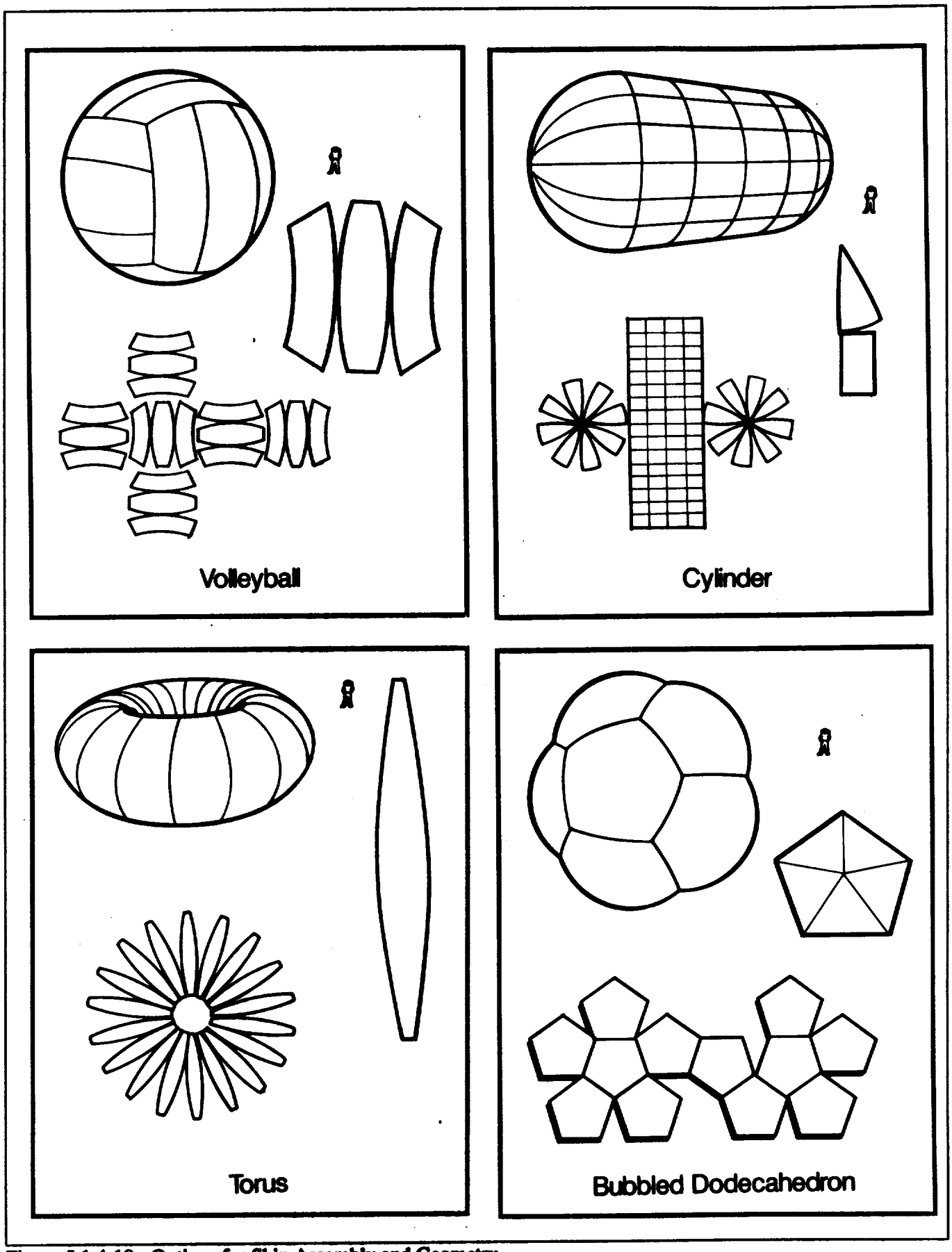



Figure 5.1.4-10.- Options for Skin Assembly and Geometry.

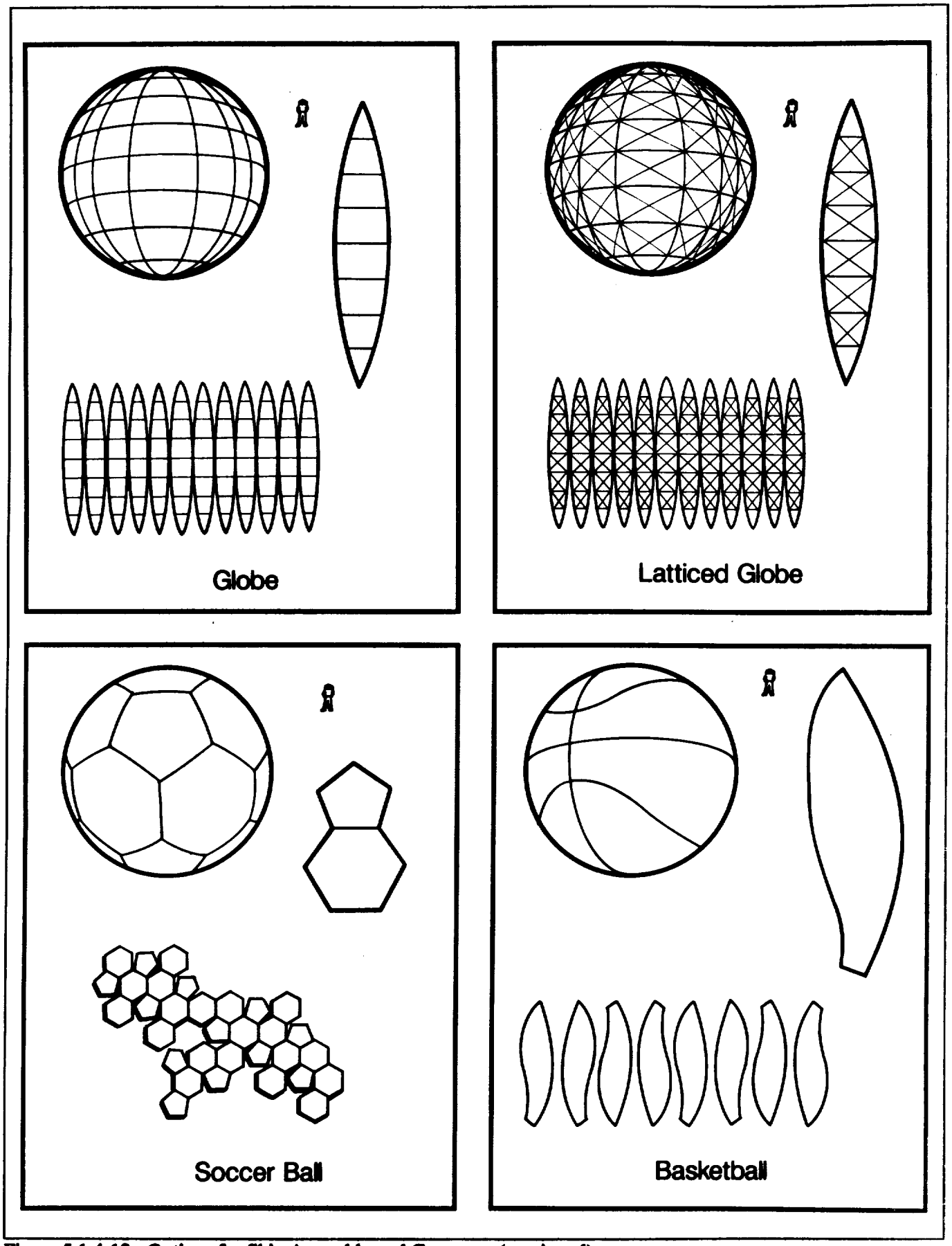



Figure 5.1.4-10.- Options for Skin Assembly and Geometry (continued).

### 5.1.5 Modular Habitats

This section describes a study of the design of a human habitat for planetary application. The modular approach is the current standard for the Space Station program for a variety of reasons, chiefly involving transport and assembly. As construction in space becomes more advanced, other options come available, such as inflatables, interiors to be assembled at the base, and use of in situ resources. If modules are to be used, they will be fabricated on Earth and transported to their final destination. If modules are used to house the entire base, arrangement becomes an important factor. If dual egress is desired for safety reasons, the modules will have to be arranged in either a square or triangular grid pattern to complete the loop. For a lunar base, the modules will have to be covered with regolith for radiation protection, which becomes an important factor in the deployment of the module.

The requirements for this study were to use a Space Station Freedom-size module (4.5 m x 13.7 m) and airlock to be outfitted for a crew of four with tours of duty in excess of 30 to 60 days. The purpose of the initial module is to provide housing while the crew constructs the remaining portions of the base (lunar or martian). The next phase of habitation is envisioned as being constructible, with subsequent phases using in situ resources (cast, sintered or spun basalt).

The design of the initial module assumes that the transportation system to place it on the surface and get it into position at the chosen site is available. Since the purpose of this section is to derive the design of the initial module, this section investigates human impacts on the design with a limited discussion of site preparation and module deployment.

#### 5.1.5.1 Site Preparation

Site preparation for the initial module will must be minimal. Due to transportable mass constraints, regolith-moving machinery may not be available initially. As a result, the module will have to contain adjustable hardware to transfer loads to the surface as well as compensating for topographical imperfections through a leveling device (see figure 5.1.5-1). If site preparation must be done, robotics should be employed to reduce EVA time.

#### 5.1.5.2 Deployment

Deployment of the initial module is an important aspect of the buildup process. Since EVA time is costly and hazardous, the module and airlock must be deployed and connected in such a manner as to ensure functional connections with limited human interaction. Once the module has been landed and transported to the site, it will be put in place by a crane with a large boom and subsequently leveled by the leveling device (figure 5.1.5-1).

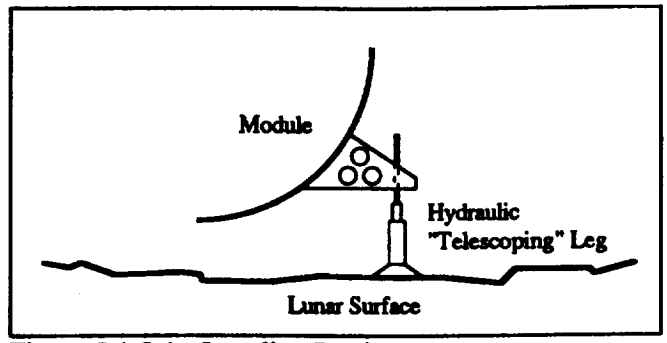


Figure 5.1.5-1.- Leveling Device.

The initial module is envisioned as becoming a radiation storm shelter and safe haven upon completion of the large habitat. Therefore, radiation protection against solar flares must be provided in the initial deployment sequence. Radiation protection is provided through the use of a containment system, which is deployed as shown in figure 5.1.5-2. The containment system is essentially a "tilt-wall" construction concept that is held up by tension cables. Once in place, the regolith is infilled through the use of a conveyor system.

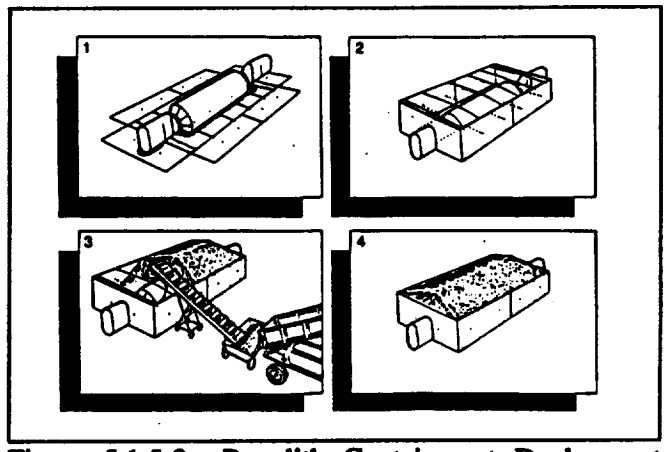


Figure 5.1.5-2.- Regolith Containment Deployment Sequence.

#### 5.1.5.3 Interior Architecture

Proper design and interior layout of human habitation areas are imperative to the proper functioning and success of a planetary base. The reduced gravity level (0.16 g or 0.38 g) affects human locomotion by changing walking and running gaits, posture, and traction. This in turn affects interior architecture by changing the design

of corridors, floors, ceiling heights, stairs and possibly even chairs.

5.1.5.3.1 Locomotion - Walking velocities in partial gravity are lower than on Earth. The speed at which walking changes to running is also lower. Walking in partial gravity becomes impractical and slow. In partial gravity running, the speed is considerably slower than Earth gravity (6.04 m/sec on Earth vs. 3.99 m/sec on th Moon--Margaria and Cavagna, 1964). According to 0.16 g simulations, the most comfortable gait is loping at a speed of 3 m/sec, versus 1.2 m/sec walking on Earth (Hewes, Spady and Harris, 1966). This is due to the reduced energy requirements needed to accelerate.

5.1.5.3.2 Posture - Human posture in reduced gravity differs from posture on Earth. As speed is increased in lunar gravity, the angle of forward body inclination gets progressively larger. For example, the inclination of a sprinting gait on Earth is 10 degrees, while the same gait on the Moon is 60 degrees (Hewes, Spady and Harris, 1966).

5.1.5.3.3 Traction - The reduction of traction can make human balance and locomotion hazardous in any environment. With the reduction of gravity, a person experiences a reduction in the friction between himself and the ground. This can become a serious hazard because astronauts cannot rapidly change positions to avoid moving or falling objects or gain a surer foothold or handhold while in a precarious position (Hewes and Spady, 1964). Another constraint affecting locomotion is that the inertial force required to start moving from a complete stop is the same as it is in 1g; therefore, the subject must overcome the same inertial force in reduced gravity as in Earth gravity while having less traction.

5.1.5.3.4 Modular Rack - The Space Station Freedom interior architecture works well in a microgravity environment where walking surfaces are not required and large massive racks can easily be maneuvered. Crew facilities in Freedom are accommodated by a modular rack system where the crew can sleep in any orientation due to the lack of gravity. In partial gravity (0.16 g or 0.38 g), this system breaks down. The 680 kg equipment racks on Freedom become less moveable because they would weigh 109 $kg_f$. on the Moon and 258 $kg_f$ on Mars. Also, the volume contained in the rack is too small to accommodate a crew member in partial gravity who must sleep horizontally as well as having a stand-up volume for donning and doffing of clothing. As a result, a new internal configuration and rack system is proposed for partial gravity application to accommodate both laboratory and habitation uses.

A standard Freedom rack is 1.07 m x 1 m x 2.13 m. A rack for use on the lunar surface can be reduced in size to 0.75 m x 1 m x 2.13 m, which weighs approximately 74.8 $kg_f$ when fully outfitted with scientific equipment. For martian application, the rack size will probably have to be reduced even futher. This will allow two astronauts to more easily maneuver the racks for installation and reconfiguration.

5.1.5.3.5 Corridor - Since starting and stopping distances increase due to reduced gravity, corridors should be clear of obstructions. They should employ hand mobility aids to control direction and speed. Therefore, the optimal configuration is an isolated corridor with no equipment or furnishings to interfere with crew mobility.

5.1.5.3.6 Floor Surfaces - The reduction of traction is a problem that can be overcome through careful design. Floor surfaces should be designed with a course surface that adheres to shoes with a traction sole. One possible concept is an astroturf-type floor surface and rubber cleated shoes.

5.1.5.3.7 Ceiling Heights - Humans bounce higher when walking and running in reduced gravity, thus requiring a sufficient ceiling height for head clearance. During normal walking in 0.16 g (worst case between lunar and martian applications), humans will probably bounce no higher than 2.44 m (standard earth ceiling height) because of their body inclination of approximately 20 degrees. At a sprinting speed in 0.16 g (which will be rare inside a habitat), the forward body inclination is approximately 60 degrees. However, as seen from the Apollo program, loping at a speed of about 3 m/sec is the most comfortable with a forward body inclination of approximately 45 degrees. Figure 5.1.5-3 shows an analysis of both walking and loping gaits in 0.16 g, which shows that a ceiling height of 2.44 m will probably be sufficient. In small, enclosed spaces, such as the crew quarters and the personal hygiene facilities, a 2.13 m ceiling height will probably be sufficient because of the minimum amount of locomotion within those spaces. One safety factor that can be employed is a padding system on the ceiling in case the astronauts do bounce too high initially, before adaptation occurs.

5.1.5.3.8 Staircases - Tests have shown that humans can jump 3.7 to 4.3 m vertically in 0.16 g when unencumbered by a spacesuit, while they can only jump 51 to 56 cm on Earth (Hewes and Spady, 1964 and Spady and Krasnow, 1966). In the same series of tests, it was found that the easiest way to ascend and descend stairs with a landing height of 1.25 m was simply to jump. These results are not surprising because the vertical distance of 1.25 m in 0.16 g corresponds to 20 cm in earth gravity, or a standard stair riser height. If we assume a maximum

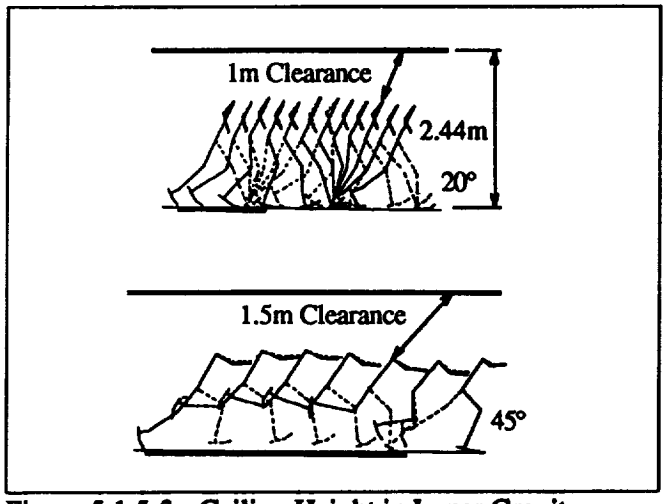


Figure 5.1.5-3.- Ceiling Height in Lunar Gravity.

strength deterioration of 67 percent (Keller and Strauss, 1988), then the stair risers would be required at about 41 cm spacings. Therefore, we can conclude that stairs in lunar gravity should be designed with a riser height spacing of somewhere between 41 cm and 1.25 m (figure 5.1.5-4), depending on the length of stay and deterioration, which is a subject for further study. For application to 0.38 g, studies have yet to be performed to determine jump heights.

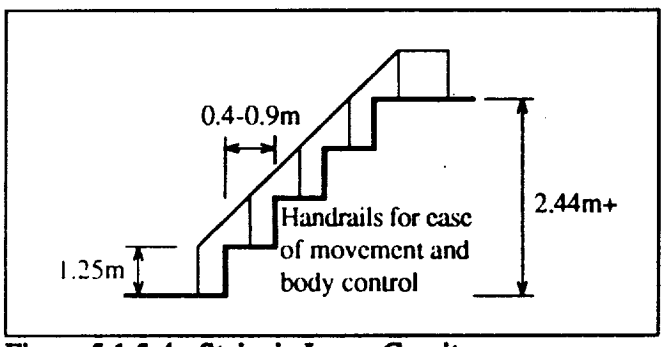


Figure 5.1.5-4.- Stairs in Lunar Gravity.

5.1.5.3.9 Chairs - Due to reduced gravity, a normal and comfortable sitting position will probably be different than that of Earth gravity. Earth gravity pulls the body into a near 90 degree normal and comfortable sitting position. In microgravity, the body assumes a neutral position that is very different from the position taken in Earth gravity. Therefore, it can be assumed that the body will probably take a position somewhere in between the normal and neutral positions. Figure 5.1.5-5 shows a partial gravity chair, which was designed in speculation of what the body might do in 0.16 g. It stands to reason that the body would take a position closer to the neutral body position, which could be accommodated by a chair that simply supports the body at the knees and the buttocks/thigh region.

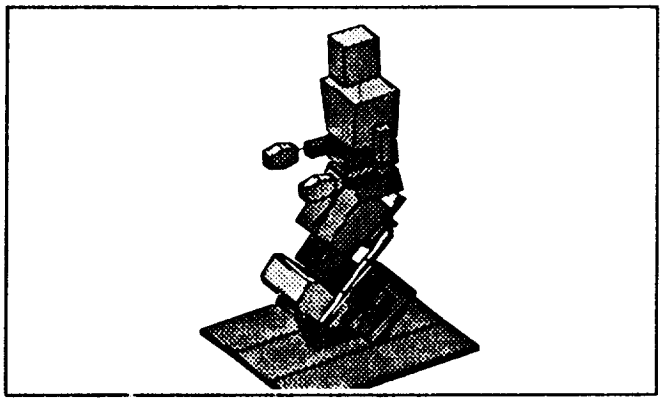


Figure 5.1.5-5.- Lunar Gravity Sitting.

### 5.1.5.4 Facility Design

This section describes a concept for the interior arrangement and the environmental control and life support system (ECLSS). A side corridor and a supercritical water oxidation ECLSS are proposed.

5.1.5.4.1 Corridor - The corridor for the construction shack is located on one side of the module (figure 5.1.5-6), in contrast to the central corridor found on Freedom. The corridor is located on the side so that larger spaces can be arranged in the module without interference from circulation, which would split the spaces in a central aisle configuration. Also, due to the reduced gravity conditions, a clear and unobstructed path is needed, which is difficult to achieve with a central corridor. The volume required for the corridor is approximately 45 $m^3$.

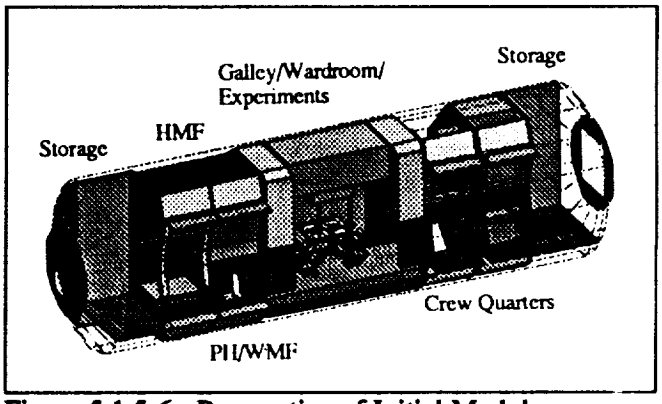


Figure 5.1.5-6.- Perspective of Initial Module.

5.1.5.4.2 Crew Quarters - There are four private crew quarters in the construction shack to accommodate the crew. The quarters are stacked. Each stacked configuration of two quarters takes up two rack widths, or 1.5 m (see figure 5.1.5-7). Each quarters contains a bed

that can fold to a reclining position for reading, personal storage space and a stand-up space for donning and doffing of clothing. The volume of each of the crew quarters is approximately 8 $m^3$, which yields a volume of 32 $m^3$ total for four crew quarters. Launch mass of the crew quarters is about 60 kg each, or 240 kg total.

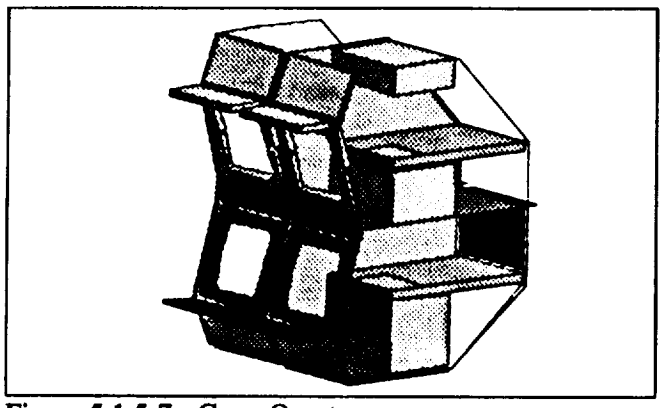


Figure 5.1.5-7.- Crew Quarters.

The entrances to the crew quarters are angled to the corridor for easy crew access. No stairs or ladders are needed because the vertical distance up or down is no more than 1.2 m. Handles on the interior and corridor side of the quarters will help the crew with ingress and egress. The handles on the corridor side of the quarters can also double as starting and stopping aids for locomotion in the corridor.

5.1.5.4.3 <u>Health Maintenance Facility/Personal Hygiene/Waste Management Facility</u> - These facilities take the same amount of space as the crew quarters, or four rack widths (3.0 m). The HMF takes 75 percent of this volume. The personal hygiene/waste management facility is located in the lower 25 percent of the configuration (see figure 5.1.5-8). The HMF consists of a bed, a stand-up space and equipment and supplies storage. The personal hygiene/waste management facility has provisions for body cleansing and waste disposal. As in the crew quarters, no stairs or ladders are required, but handles will also be used on the interior and exterior of the facilities for ease of egress. The HMF requires a volume of 24 $m^3$; the personal hygiene/-waste management facilities take up about 8 $m^3$ for a total of 32 $m^3$. Launch mass for these facilities are 475 kg and 210 kg, respectively, or 685 kg total.

5.1.5.4.4 <u>Galley/Wardroom/Experiments</u> - The galley, wardroom and experimental areas are combined in a multi-use space in the central portion of the module (see figure 5.1.5-9). The entire space takes up a total of 6 rack lengths, or 4.5 m, for a total volume of 48 $m^3$. The food storage and preparation areas of the galley are located in the volumes above the table. The storage

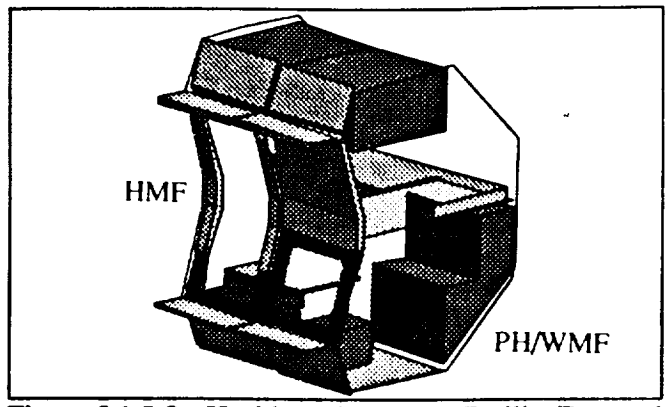



Figure 5.1.5-8.- Health Maintenance Facility/Personal Hygiene/Waste Management Facility.

incorporates a pull-down storage system, like that of the Space Station Freedom. The wardroom table is retractable so that the space can be used for casual conversation as well as work space for monitoring experiments. The table has recessions to stabilize trays and cups while eating. The wardroom chairs can swivel 180 degrees so that they can double as wardroom sitting as well as seats to monitor experiments. The scientific equipment is located in the racks that enclose the galley/wardroom area. They serve as a barrier to the space as well as being functional. Final launch mass for the galley/wardroom/experimental area is 4,150 kg, including four experimental racks.

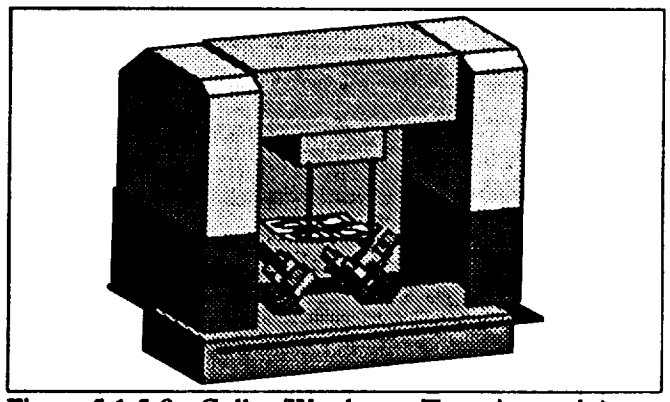


Figure 5.1.5-9.- Galley/Wardroom/Experimental Area.

5.1.5.4.5 <u>Public Storage</u> - Public storage is located at the ends of the module in the closeouts. Storage includes things such as equipment, contingency food, trash, spare parts, etc. EVA suit storage is located in the airlock. Volume allocated for public storage is approximately 7 $m^3$, or 3.5 $m^3$ in each storage area.

5.1.5.4.6 <u>Environmental Control and Life Support System (ECLSS)</u> - Possibly the best system for plane-

tary application is the supercritical water oxidation (SCWO) system (Guerra, 1988). The advantage of this system is that it closes the water and oxygen loops through a single process rather than an integration of separate technologies. Volume for this type of ECLSS system is 3.3 $m^3$ and has a launch mass of 1,440 kg. ECLSS equipment would be located in the floor racks from where mechanical pipes would be channeled throughout the module. Water and oxygen storage would be located outside the module.

5.1.5.4.7 Structure - The total volume of the module is approximately 200 $m^3$, with the structure and mechanical chase space taking the remaining 32.7 $m^3$. The launch mass for the structure is approximately 7,200 kg, which brings the total launch mass of the construction shack to 13,715 kg. Table 5.1.5-I summarizes mass and volume estimates.

TABLE 5.1.5-I.- MODULAR HABITAT MASS AND VOLUME ESTIMATE

| Item | Mass (kg) | Volume ($m^3$) |
|---|---|---|
| Corridor | - | 45 |
| Crew Quarters (4) | 240 | 32 |
| Health Maintenance Facility | 475 | 24 |
| Personal Hygiene/Waste Mgmt. | 210 | 8 |
| Galley Wardroom | 4,150 | 48 |
| Public Stowage | - | 7 |
| ECLSS (SCWO) | 1,440 | 3.3 |
| Primary and Secondary Structure | 7,200 | - |
| Struct. and Mech. Chase Space | - | 32.7 |
| **Total** | **13,715** | **200** |

### 5.1.5.5 Overall Modular Habitat Features

The initial lunar modular habitat, or "construction shack," is designed to support crews of four astronauts during missions of at least ten days in duration. The habitat shown in figure 5.1.5-10 is based on a Space Station Freedom common module adapted for use on the lunar surface. Figure 5.1.5-11 shows an interior layout of the module. The construction shack provides a base of operations while larger, more permanent facilities are being constructed. A large constructible habitat will be built adjacent to the construction shack. When it is complete, the initial habitat will be reconfigured to serve other purposes including providing a safe haven in the event of an emergency.

The major features of the modular habitat in figure 5.1.5-10 are discussed below. The numbered paragraphs in the following discussion match the numbers on the figure.

1. Solar panels provide the power needed to operate the habitat. The panels tilt to maintain alignment with the direction of sunlight.

2. Radiators eliminate excess heat from the habitat and its equipment. The radiator panels tilt to keep their surfaces out of the sunlight.

3. A smaller airlock provides a secondary means of ingress and egress in the event that the primary airlock cannot be used. The primary airlock is located on the other end of the module, nearest to the construction site.

4. Tanks containing pressurized gasses to produce water and breathing air are located outside the shell of the module.

5. Four crew compartments provide for sleep and privacy. The compartments are surrounded by racks of equipment and stowage to enhance radiation shielding. The walls of the compartment are made of lightweight, easily removed panels. This allows them to be taken down quickly to provide unrestricted access to the secondary airlock.

6. The wardroom is separated from the sleep compartments by a buffer of several racks. The wardroom provides a place for sharing meals and for meetings and discussions. A compact galley is located in this area for food preparation and storage. A large, flat panel display provides entertainment and information. A crew in the vehicle can use this display to monitor and support the construction activities going on outside.

7. A health maintenance facility provides the basic needs for monitoring and maintaining the health of the crew. Exercise equipment allows them to keep their cardiovascular systems in shape and to prevent the debilitating effects of living in an environment having 1/6th the gravity experienced on Earth. Additional facilities, such as personal hygiene and waste management, are located on the near side of the corridor. An enlarged view of the health maintenance facility is provided in figure 5.1.5-12.

8. Essential subsystems, such as the environmental control and life support system, are located in modular racks in the ceiling. This provides added radiation protection and preserves side racks for workstations and other equipment needing frequent crew access.

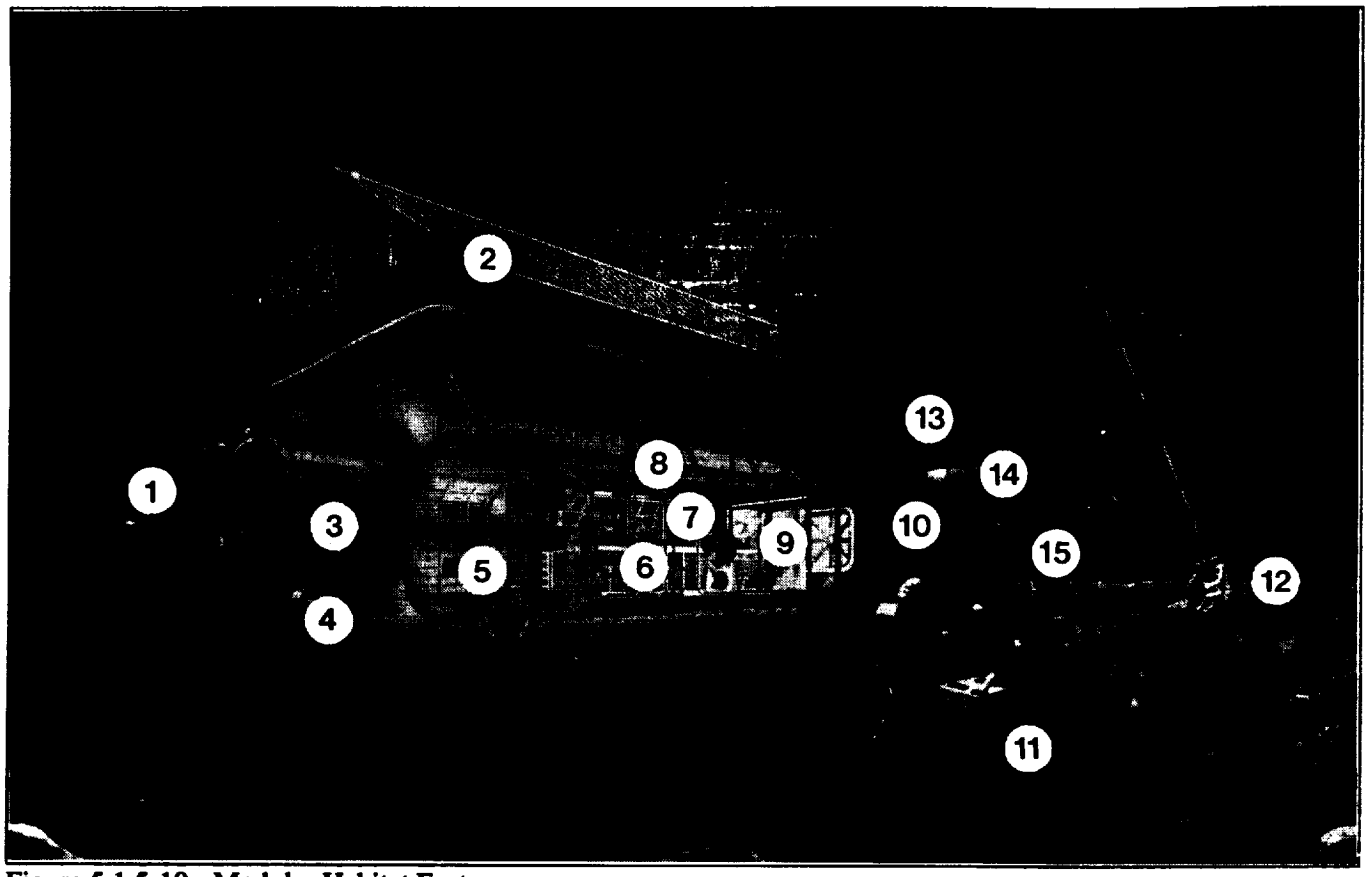



Figure 5.1.5-10.- Modular Habitat Features.

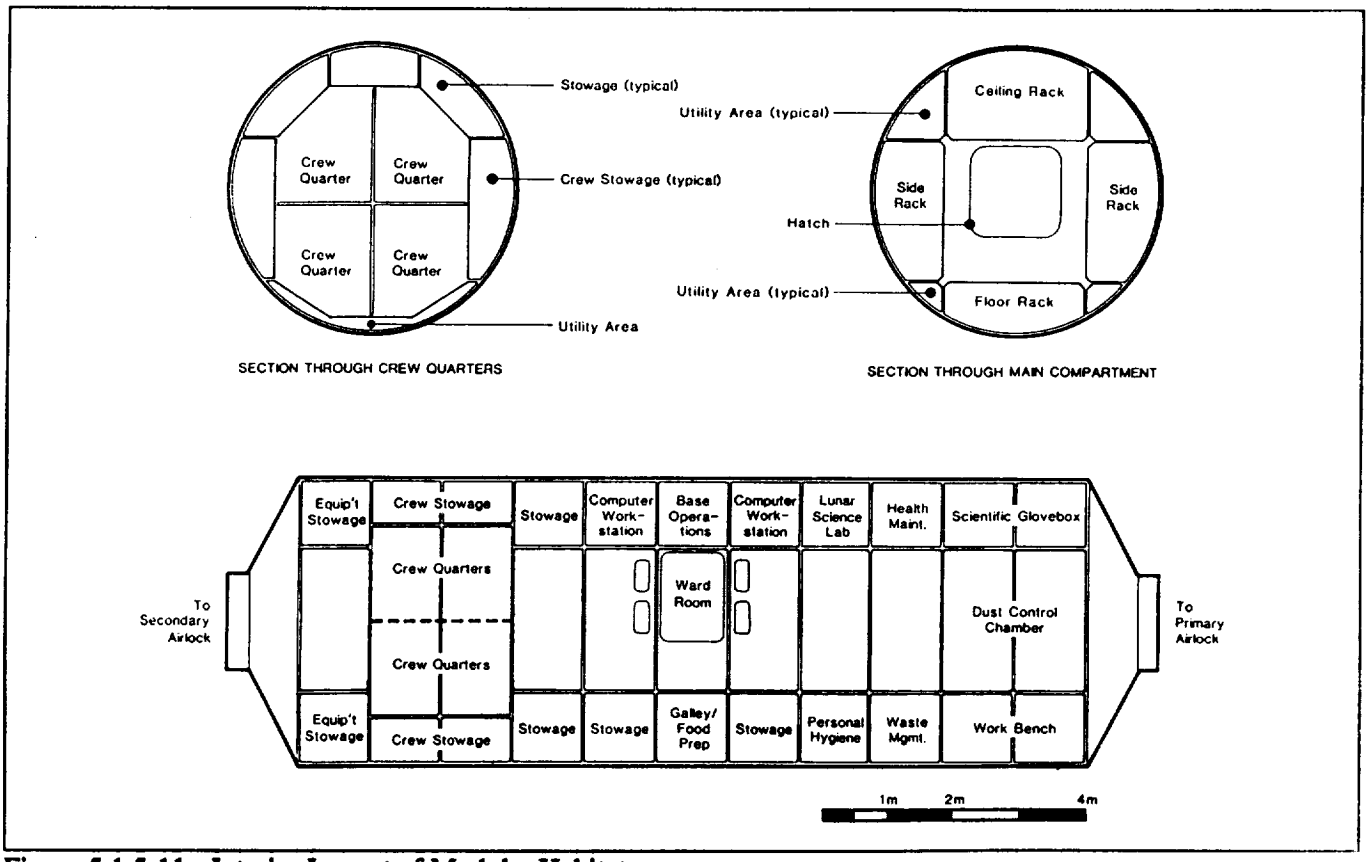



Figure 5.1.5-11.- Interior Layout of Modular Habitat.

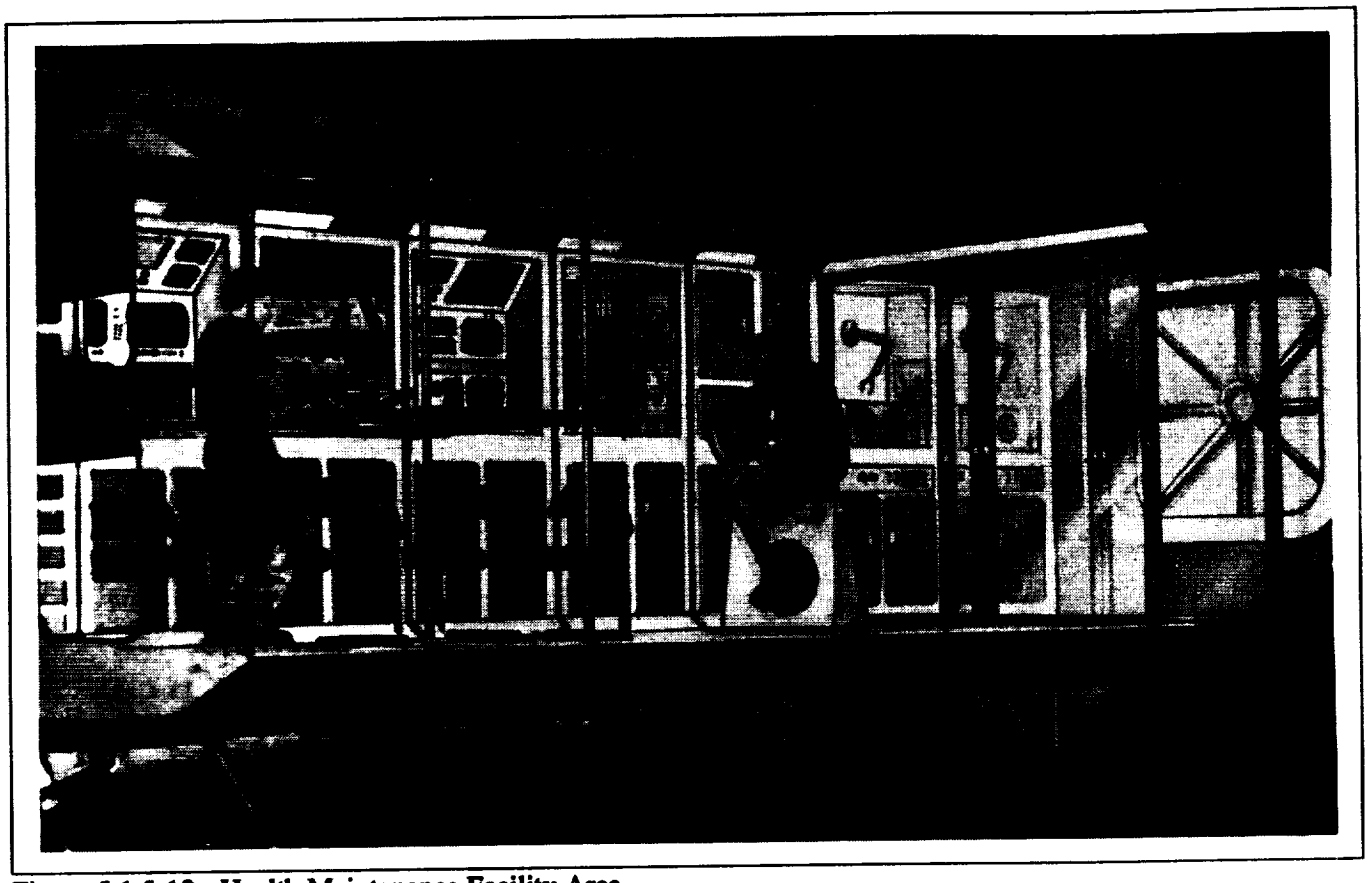


Figure 5.1.5-12.- Health Maintenance Facility Area.

9. Sliding transparent panels made of lightweight materials provide a barrier against the fine powdery dust that covers the lunar surface. Great care must be taken to keep this dust from contaminating the living environment. Glove boxes located in equipment racks in these compartments allow tools, equipment, and scientific samples to be handled without coming in direct contact with the crew. After items go through a two-stage cleaning process, they can be brought inside the living environment.

10. One meter diameter fabric bags are filled with lunar soil, to provide protection from harmful galactic radiation. The bags are supported by modular trusswork similar in design to that used to construct Space Station Freedom.

11. The primary airlock is used to don and doff the bulky pressure suits needed when performing EVA. The suits are stored and maintained in this airlock.

12. Television cameras are mounted in strategic locations to provide a panoramic view of the surrounding planetary landscape.

13. Before entering the airlock, astronauts pass through electrostatic wickets to remove much of the dust covering their suits.

### 5.1.5.6 Modular Habitat Conclusions

The various parameters of human habitation in a partial gravity environment have been identified and a concept has been proposed that meets the criteria set forth by these parameters as well as the mission scenario.

Human habitation in a partial gravity environment, such as the Moon or Mars, poses new challenges that have been addressed in this section. However, many of the design parameters brought forth by this study warrant further investigation to test hypotheses (see below). The design solutions in this report do provide a basis for speculation and testing of theories, which can be investigated further as mission goals and scenarios become more specific.

The following areas require further research:

- Partial gravity locomotion and human performance
- Partial gravity physiological adaptation
- Confinement/isolation effects on volumes
- Module deployment techniques
- Radiation protection techniques and options
- Long-term habitability

### 5.1.6 Airlocks

The purpose of an airlock is to provide a special facility to handle the transition of crew from intravehicular activity (IVA) to extravehicular activity (EVA) and vice versa. A lunar airlock requires additional areas and equipment to handle the dust contamination problem. The airlock has three functional areas; the dust-off facility (front porch), the crew lock, and the equipment lock.

Depending on the lunar suits used and the habitat pressure, pre-breathing requires 30 minutes to 3.5 hours. The crew lock can accommodate two crew members at one time, with suit storage of four EMU's in the equipment lock.

#### 5.1.6.1 Structure

Figure 5.1.6-1 shows a concept for the airlock. The airlock is a dual-chambered structure composed of two pressurized modules (equipment and crew lock) and a deployable dust-off canopy. The airlock also consists of a metal grated deck, deck beams, adjustable support legs, a connection tunnel with berthing interfaces and steps. The pressurized modules are of Space Station Freedom technology using similar structural concepts, but sized for 1/6 gravity loading.

Three adjustable legs support and stabilize the airlock. The equipment lock is supported by two legs. The crew lock is supported by the equipment lock and one adjustable leg or column. The EVA dust-off area has a metal grated deck to allow dust to be removed and fall through the grating. Two metal beams, which support the dust-off facility, are supported by the equipment lock and adjustable legs on the dust-off facility. The EVA dust-off facility is deployable on integral tracks alongside the equipment lock. When packaged for transport, the airlock is 4.45 meters in diameter and 8 meters long.

#### 5.1.6.2 Architecture

The airlock has three functional areas. They are the equipment lock, crew lock and dust-off facility (porch). Elements of an airlock are an equipment lock, a crew lock, two purging tanks, a connection tunnel, berthing and hatch interfaces, adjustable legs for leveling, and an EVA dust-off facility.

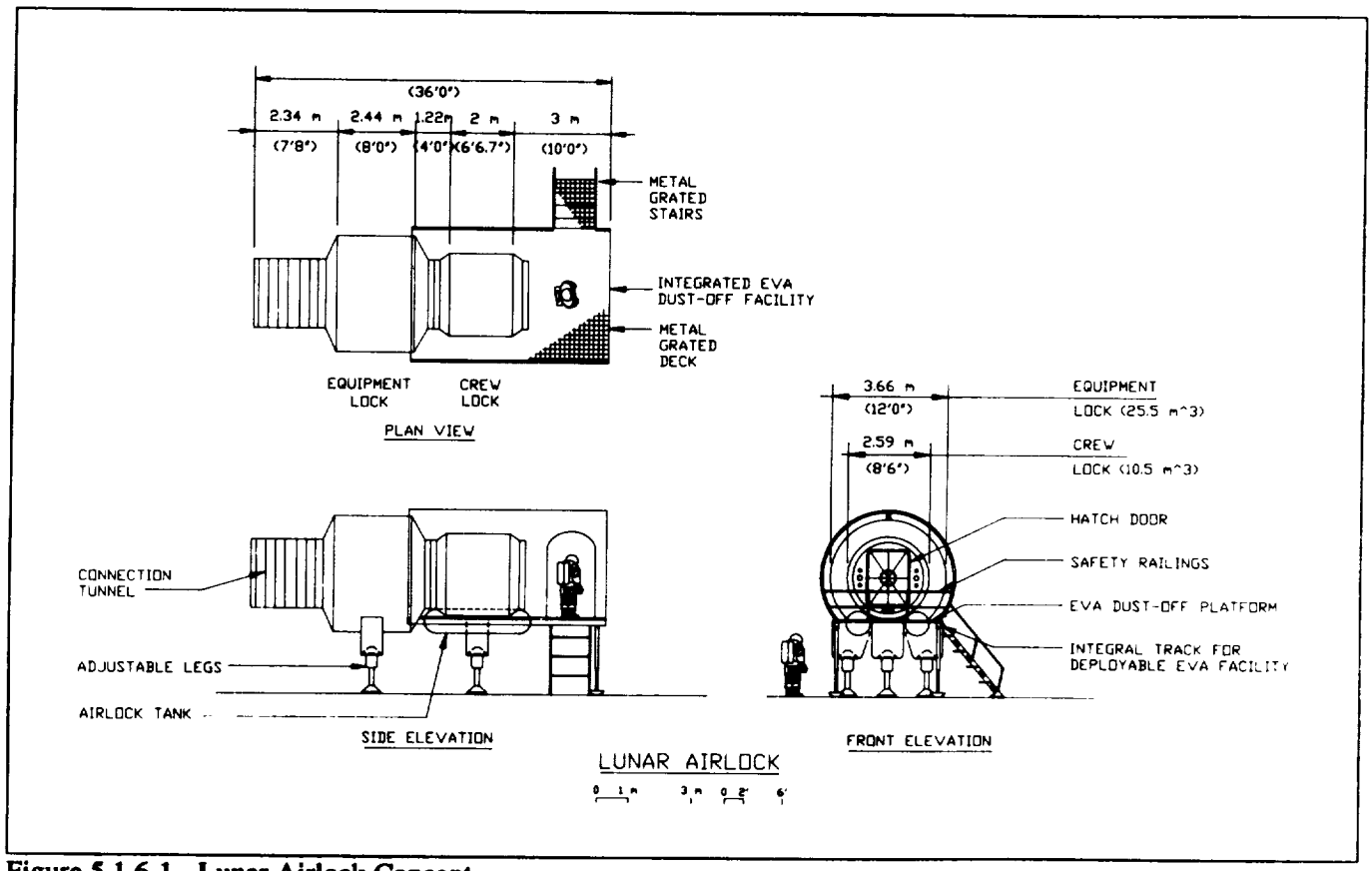



Figure 5.1.6-1.- Lunar Airlock Concept.

The equipment lock is a 3.66 m diameter by 2.44 m long module with two diametrically opposed 2 meter (80 in.) openings for berthing ports. One port, connected to the tunnel, is outfitted with a hatch and mechanisms to attach the pressurized tunnel. The other port is equipped with a hatch and the mechanisms to connect the equipment lock to the crew lock. The equipment lock provides for donning, doffing and stowing of four extravehicular mobility units (EMU's), or EVA suits, and for stowage of ancillary EVA equipment. Two donning stations provide fixtures (supports) for the rear entry suit operation. Four portable life support systems (PLSS's) are stowed and verified in the equipment lock before connection to the EMU's. This chamber has the regenerative life support system, consisting of four equipment racks for checking EMU's. These four racks accommodate control functions for communications, power, lighting, data management, and airlock depressurization and repressurization.

The outer chamber of the airlock is the crew lock. Here the crew purges the chamber's air into tanks and then transfers from a pressurized environment to the vacuum of the lunar environment. This lock is a 2.59 meter diameter by two meter long module with two diametrically opposed 2 meter (80 inch) openings for berthing ports. One port is connected to the equipment lock; the other is used for ingress and egress from the airlock. The hatch doors are 1.27 x 1.67 meters and are automatically seal controlled with manual override mechanisms. The crew lock chamber has a grated floor to allow lunar dust that enters the area to settle into the collection area. Once full, the trap door is opened for disposal of accumulated soil. The crew lock has a fold-down cot for an ill crew member to receive treatment, when the lock is used as a hyperbaric chamber.

The dust-off facility is where the bulk dust is removed and the EVA suit overalls are removed before entering the crew lock chamber. This area has provisions for hanging and stowing various EVA hand tools. Other tools in this area are for EMU dust removal. The dust-off canopy is deployed from its stowed position with the help of three track rails. These tracks are located on the exterior shell of the equipment lock. The canopy is pulled out and the metal deck drops into place ready to be used. The stairs are then dropped into an operational position.

### 5.1.6.3 Mass Estimate

Table 5.1.6-I provides a first order mass estimate for the airlock.

TABLE 5.1.6-I.- AIRLOCK MASS ESTIMATE

| Item | Unit Mass (kg) | Quan. | Item Mass (kg) |
|---|---|---|---|
| Structure | | | |
| Equipment Lock Module | 500 | 1 | 500 |
| Crew Lock Module | 203 | 1 | 203 |
| Dust-off Canopy | 227 | 1 | 227 |
| Dust-off Flooring & Beams | 25 | 1 | 25 |
| Steps and Railings | 12 | 1 | 12 |
| Hatch & Berthing Assy. | 231 | 2 | 462 |
| Vacuum Pumps | 62 | 1 | 62 |
| Purging Tanks | 76 | 2 | 152 |
| Equipment Racks | 120 | 4 | 480 |
| Adjustable Airlock Legs | 50 | 3 | 150 |
| Adjustable Porch Legs | 30 | 2 | 60 |
| Flexible Pressurized Tunnel | 70 | 1 | 70 |
| **Subtotal** | | | **2,403** |
| Contingency (20 percent) | | | 481 |
| Consumables | | | 362 |
| **Total Mass** | | | **3,246** |

### 5.1.6.4 Airlock Conclusions

The lunar airlock is a key element of lunar base infrastructure. A rugged, mature design is essential, particularly to the constructible concepts, for the practical construction and operation of the base.

## 5.2 EXTRAVEHICULAR ACTIVITY (EVA) SYSTEMS

The primary EVA system is the extravehicular mobility unit (EMU). The Phobos maneuvering unit (PMU), similar to the Shuttle manned maneuvering unit (MMU), is also included.

### 5.2.1 Extravehicular Mobility Unit (EMU)

A safe and reliable extravehicular activity system is necessary to meet the requirements of exploration missions. The routine exploration of planetary surfaces, along with establishing and operating bases will depend on the ability to perform EVA. An EMU consisting of a pressure suit and portable life support system (PLSS) developed specifically for the constraints of lunar and Mars missions is central to the EVA system. A rugged, highly reliable, mobile, reusable, and easily serviced EVA suit and compact PLSS must meet the general requirements shown in table 5.2.1-I.

TABLE 5.2.1-I.- EVA SYSTEM REQUIREMENTS

**Pressure Suit**
- Protection from hazards of new mission environments
- Appropriate pressure to eliminate bends risk and pre-breathe
- Long-term durability and reliability
- Wearer comfort and confidence
- Easy don/doff
- Minimal servicing and maintenance
- Simple resizing

**Portable Life Support System**
- Minimize use of expendables
- Provide a high level of reliability and safety
- Minimize weight and volume by efficient packaging
- Provide ease of maintenance and repair during the mission
- Maintain all aspects of the micro-climate within desired ranges for crew health, safety, and comfort

The design of the pressure suit must facilitate mobility on the planetary surface. Suits for orbital operations have not been designed for use in a gravity field, but have been optimized for mobility in a weightless environment. Improved suit mobility in the lower torso is necessary for traversing in the 1/6- and 1/3-g environments of the Moon and Mars. Irregular surfaces, steep slopes, and low traction add to the need for good lower torso mobility. To add extra mobility capabilities, aids such as walking sticks will also be necessary. Other factors in the design of the suit are discussed below.

EVA systems for the two surfaces will have some differences, particularly in the specific design of the PLSS. The hot and cold extremes of the lunar environment and the atmosphere and frequent dust storms of Mars change heat rejection requirements.

The extra gravity of the martian surface is also expected to result in higher metabolic rates for the EVA crew. Other differences will be the degree of necessary radiation protection.

One of the major factors contributing to the productivity of the EVA crew members will be the ability to wear the EMU for extended work periods. In order to facilitate maximum productivity for the EVA crew, the weight of the EMU must be minimized. Table 5.2.1-II shows the mass, operating pressure, and type of life support (open-loop vs. regenerable) for the EMU's of past and current programs.

The major load to the EVA crew member is the weight of the back-mounted PLSS, as the weight of the pressure suit is more distributed. If not properly designed, the PLSS can cause a center of gravity problem for the crew member. Based on U.S. Occupational Safety and Health Administration standards, the weight of the PLSS should be limited to 20 $kg_f$ (45 $lb_f$) on the planetary surface. This places the limit at 121 kg mass for a lunar PLSS and 53 kg mass for Mars. A reasonable goal for the mass of the suit for either surface is 36 kg. This results in a total EMU mass of 159 kg for the Moon and 98 kg for Mars. The weight limitation is a driving requirement in the PLSS design.

Long-term reliability and durability are other major factors in EMU design for lunar and martian exploration. Lunar and orbital EVA's to date have lasted less than 22 hours per suit. Exploration missions may impose requirements of hundreds of hours. Suit and PLSS design must permit regular maintenance for the duration of the mission. Current suits for orbital operations require hours of ground-based maintenance between uses. The dusty environment of the Moon and Mars will make this even more challenging. Bearings and joints must be protected from dust; suit materials must be selected for compatibility with the dusty environment. An additional concern is contamination of the habitat with dust by carrying it in after an EVA. Operational procedures and airlock systems must be developed to prohibit this. A dust porch where the crew can remove overgarments, and remove as much dust as possible with brushes and grates located outside the airlock is recommended. A dual airlock concept would keep any remaining dust in the outer airlock. Forced air circulation might be necessary in this outer lock.

The design of a PLSS for lunar and martian exploration is complicated by several factors. With emphasis on base closure and reduction in resupply logistics, the expendables associated with an open-loop system must be examined. With extended mission times and daily EVA's, the overhead of an open-loop life support system becomes more prohibitive. The requirement for this type of system for each person on an eight-hour EVA is 1.22 kg of lithium hydroxide for $CO_2$ removal, 0.63 kg of oxygen, and 5.5 to 7 kg of water for cooling. For a six month mission, with two crewmembers going on EVA six days a week, the water requirement alone comes to over 1,800 kg. This indicates that an open-loop system may not be practical for long duration missions and that regenerable life support may be necessary.

As table 5.2.1-II indicates, the mass of a regenerable system is significantly higher than that of an open-loop system with current technology. This problem must be solved to meet the stated mass limitation. Decreasing the duration of a regenerable PLSS does not proportion-

TABLE 5.2.1-II.- EMU MASS, CURRENT AND HISTORICAL

| Program | Suit Mass (kg) | PLSS Mass (kg) | Total EMU (kg) | Operating Pressure (kPa) (psi) | Life Support |
|---|---|---|---|---|---|
| Apollo | 27 | 61 | 88 | 25.9 (3.75) | open loop |
| Shuttle | 50 | 73 | 123 | 29.6 (4.3) | open loop |
| Space Station | 91 | 195 | 286 | 57.2 (8.3) | regenerable |

ally decrease the mass as shown in table 5.2.1-III. Much of the mass of current regenerable systems is due to the thermal control unit (70-90 kg). Partial duration (two or four hour) ice packs to provide the required cooling may be an option to make a regenerable system meet the weight limit. These replacement packs would have a simple interface for change-out or recharging in place. Another measure to extend EVA productivity is to provide life support via umbilical connection from the rover while the EVA crew is traveling to a work site. Reliance on the rover would save the reserve capabilities of the PLSS for when the crew is away from the rover.

TABLE 5.2.1-III.- WEIGHT OF REGENERABLE SPACE STATION TECHNOLOGY PLSS

| Duration (hrs) | Earth Weight ($kg_f$) | Moon Weight ($kg_f$) | Mars Weight ($kg_f$) |
|---|---|---|---|
| 8 | 195 | 33 | 72 |
| 4 | 148 | 25 | 55 |
| 2 | 111 | 19 | 41 |
| 1 | 84 | 15 | 31 |

Note: Earth weight in kilograms-force ($kg_f$) is equivalent to mass in kilograms (kg).

Another major issue that will strongly affect the design of the suit and PLSS is the pressure chosen for the habitat. Using normal Earth air composition of 78 percent nitrogen and 21 percent oxygen, cabin and suit pressures should be chosen that allow zero-prebreathe EVA with a low probability of decompression sickness (the bends). Lower suit pressures maximize EMU dexterity and reduce fatigue. However, the zero-prebreathe requirement closely ties the suit pressure to the habitat pressure, as shown in figure 5.2.1-1. The risk of decompression sickness is determined by the value R, which is equal to the partial pressure of nitrogen in the tissues at the beginning of a decompression divided by the total final pressure of the suit. Higher R values indicate a higher bends risk. From the perspective of maximizing EVA productivity for the routine exploration of planetary surfaces, a habitat pressure lower than normal Earth atmosphere, 101.3 kPa (14.7 psi), enabling a suit pressure below the corresponding suit pressure of 57.3 kPa (8.3 psi) would be optimal. The final habitat pressure and atmosphere composition will depend on many other factors including flammability, oxygen toxicity, and air density required for cooling.

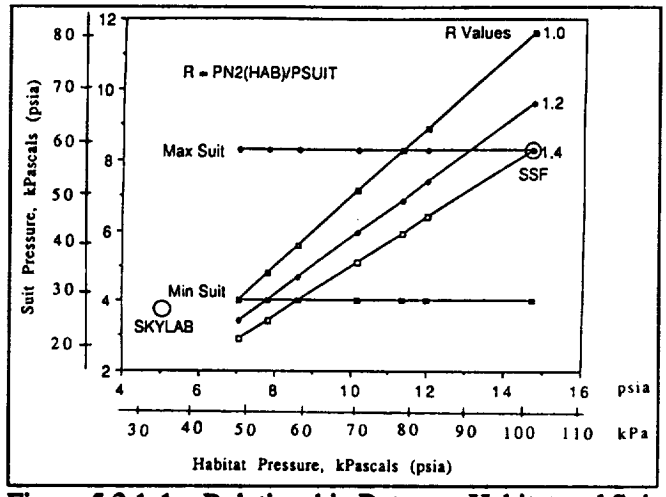



Figure 5.2.1-1.- Relationship Between Habitat and Suit Pressures.

The EMU design must meet many challenging and some conflicting requirements. EVA productivity will be maximized by the following:

- provide capability for 8-10 hour EVA work periods to minimize overhead
- provide consumable resupply via umbilicals to rover
- improve suit lower torso mobility and glove dexterity to provide enhanced working capability
- reduce the EMU weight by using lightweight construction materials and alternate PLSS concepts
- trade-offs between various suit and habitat pressures
- mobility aids for traversing rough terrain.

Another challenge is the amount of integration necessary between the EVA system and other base systems. As mentioned above, the rover and the EMU will have a crucial interface for life support consumable supply. The PLSS and the rover will also have complex interfaces with the base life support system for recharge and regeneration.

### 5.2.2 Phobos Maneuvering Unit (PMU)

The Phobos maneuvering unit (PMU) will transport EVA crews of two to four up to 6 kilometers from the main spacecraft to locations on the surface of Phobos. It is similar to the Shuttle manned maneuvering unit (MMU), but larger and with more capability, perhaps holding a crew of two.

The martian moon Phobos cannot be walked on or landed on in the classical sense. It must be docked with and flown around, thus the necessity for an MMU-type device. Phobos has 0.001 Earth gravities on the surface, a day of 7 hours, 29 minutes, and a maximum diameter of 28 km. The horizon is 270 meters away for a tall man standing.

A variety of systems make up the PMU. Table 5.2.2-I lists a first estimate of the required equipment. Table 5.2.2-II gives an estimated mass, power, and volume. Figure 5.2.2-1 shows one concept of the PMU. Significant questions, such as how to land and anchor to the surface of Phobos, how much flying and navigation can be done by visual reference, and how to communicate over the horizon still require more work, though concepts have been developed. The nature of the surface of Phobos, still unknown, is critical to anchoring and landing system design.

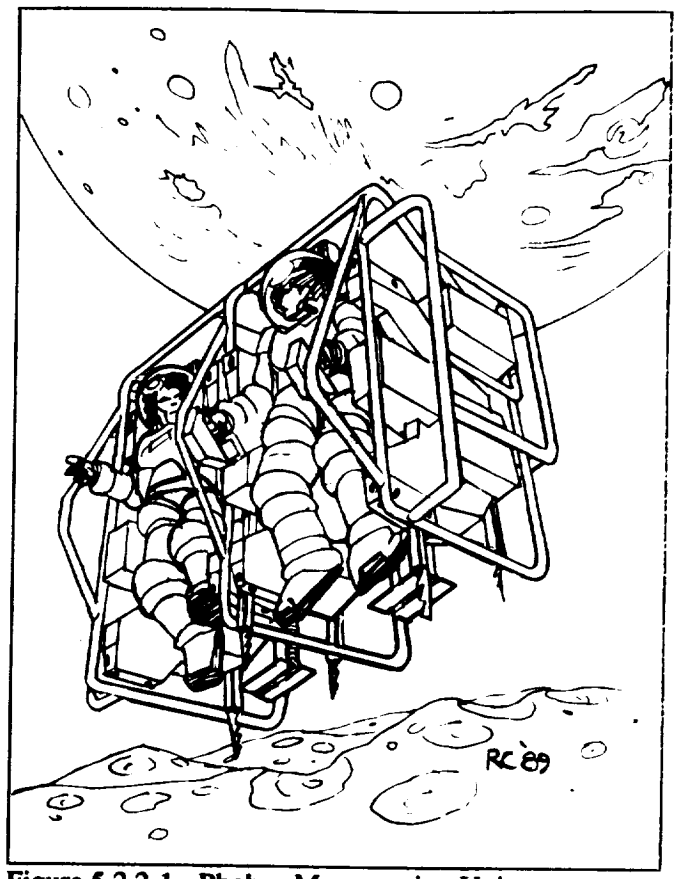


Figure 5.2.2-1.- Phobos Maneuvering Unit.

TABLE 5.2.2-I.- REQUIRED SYSTEMS FOR PHOBOS MANEUVERING UNIT

- Radar or laser rangefinder (range, range-rate) and or laser altimeter
- Inertial reference system (IRS) provides attitude and position
- Power supply - two silver-zinc batteries and power conditioner
- Helmet-mounted display (HMD) for use with the IRS
- Floodlights
- Flight instruments: artificial horizon, turn/yaw indicator
- Surface maps
- Targeting computer - interacts with navigation sensors
- Additional consumables or power for EMU--plug in
- Communications pole antennae (several for distribution) and/or near Phobos relay satellites
- Navigation beacons (several for distribution) and/or near-Phobos relay satellites
- Drop packages (science, utility) with stabilization, propulsion, anchoring means
- Ground operations boom (GOB) for anchoring PMU to Phobos--telescoping, two-axis rotation
- Cold-gas propulsion system for attitude and translation (>75 m/sec delta velocity capability)

TABLE 5.2.2-II.- PMU MASS, POWER, AND VOLUME ESTIMATES

| Item | Mass (kg) | Power (W) | Volume ($m^3$) |
|---|---|---|---|
| MMU (two) | 307 | 95 | 1.46 |
| Larger tanks | 71 | - | 0.30 |
| Added propellant | 136 | - | - |
| R/R-dot system | 4.5 | 25 | 0.0082 |
| Inertial reference system | 8.2 | 85 | 0.0082 |
| Grapple and boom | 68 | TBD | TBD |
| Science packages (six) | 55 | - | 0.34 |
| Extra batteries (six) | 27 | - | 0.015 |
| Floodlights | 7 | 500 | 0.010 |
| **Total** | **684** | **705** | **2.14** |

## 5.3 LIFE SUPPORT SYSTEMS

The life support systems (LSS) studies in this section describe three systems of increasing sophistication and scope. As a martian or lunar base develops in size, complexity and crew, so too must the LSS. The three systems studied in this section are the initial life support system (ILSS), the advanced life support system (ALSS), and the mature life support system (MLSS). Table 5.3-I documents the major subsystem differences between the three LSS types.

Closure of life support systems must be carefully defined. In this report, closure generally means functional closure, which refers strictly to the air and water loops. A typical number for this type of closure is 96 percent. Another way to discuss closure is system closure, which refers to everything; food, expendables, nitrogen, etc. With respect to these studies, system closure is probably a low percentage.

The ILSS is the baseline system that is integrated in the construction shack phase of a manned base. A regenerable physical-chemical system, the ILSS is a derivation of a Space Station Freedom system that will already be demonstrated as efficient and reliable. Although having a water and air loop closure of 96 percent, the ILSS still requires food, nitrogen and system expendables to be resupplied. Since the pressurized areas of the base have some atmosphere leakage, and some loss of atmosphere occurs with use of the airlock, oxygen and water must also be supplied.

The ALSS, another regenerable physical-chemical system, will later replace the ILSS because of its improved level of system closure and reliability. Other improvements may include super critical water oxidation (SCWO) technology, recovery of materials from solid wastes and reduced resupply of system expendables. The ALSS study considered three levels of integration of in situ resource utilization (ISRU). In case 1, the ALSS is independent of any ISRU products; case

TABLE 5.3-I.- LUNAR AND MARTIAN BASE RLSS COMPARISIONS

| Subsystem and Component | RLSS Type Initial | Adv.* | Mature |
|---|---|---|---|
| Carbon Dioxide Removal | | | |
| Regenerable Concentration and Storage | L M | L M | L M |
| Reduction to Water | L M | L M | L M |
| Plant Photosynthesis | | | L M |
| Oxygen Generation | | | |
| Cryogenic Resupply | L M | L | |
| Static Feed Water Electrolysis | L M | L M | L M |
| Super Critical Water Oxidation | L M | L M | L M |
| In Situ Resource Utilization | | M | L M |
| Plant Photosynthesis | | | L M |
| Nitrogen Supply | | | |
| Cryogenic Resupply | L M | L M | L M |
| Potable Water | | | |
| Storage and Resupply | L M | L | |
| Condensed Humidity | L M | L M | L M |
| Carbon Dioxide Reduction | L M | L M | L M |
| Recycled Water | L M | L M | L M |
| In Situ Resource Utilization | | M | L M |
| Hygiene Water | | | |
| Storage and Resupply | L M | L | |
| Recycled Hygiene Water | L M | L M | L M |
| Recycled Urine Water | L M | L M | L M |
| Contaminants | | | |
| Regenerable Absorbants | L M | | |
| Catalytic Oxidation | | L M | L M |
| Food | | | |
| Storage and Resupply | L M | L M | L M |
| Plant Crops | | | L M |
| Crew Expendables | | | |
| Storage and Resupply | L M | L M | L M |
| RLSS Expendables | | | |
| Storage and Resupply | L M | L M | L M |

L--lunar base M--martian base

*case 1 ALSS

2 utilizes ISRU products; case 3 integrates ALSS and ISRU system equipment as well as using ISRU products.

The MLSS is a highly sophisticated system that may not be incorporated into the base until well after a case 3 ALSS has been in operation. The MLSS will incorporate all of the capabilities of the physical-chemical ALSS with an extensive controlled ecological life support system (CELSS). In addition to enhancing the atmosphere regeneration capabilities, the MLSS may satisfy the food demands of large crews by utilizing biological systems such as those that support the growth and harvest of plant crops and animals. The CELSS component of the MLSS also aids in the reprocessing of potable water from waste water and lead to a larger system buffer/reservoir for consumables.

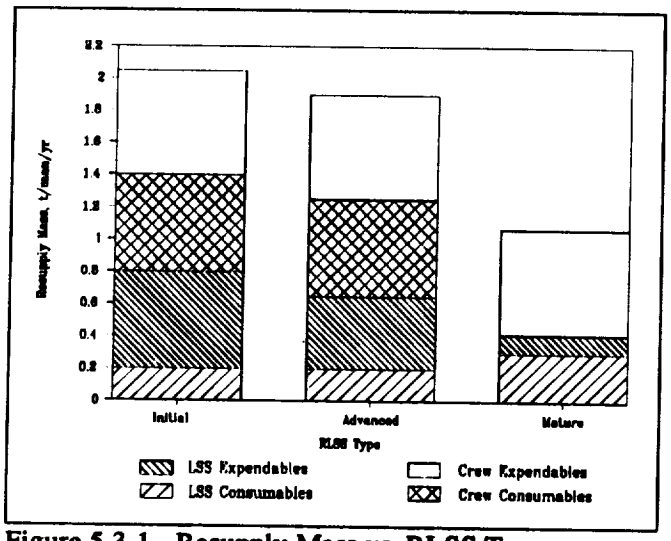



Figure 5.3-1.- Resupply Mass vs. RLSS Type.

Figure 5.3-1 compares the mass of resupply items needed to support one crewmember for one year for each regenerative life support system (RLSS) studied. Table 5.3-II provides the numeric mass values. As can be seen, LSS expendables (filters, catalysts, canisters, etc.) and LSS consumables (oxygen, nitrogen, and water) resupply decreases in amount when the ILSS is upgraded to an ALSS. This decrease occurs without a significant increase in system mass. With the onset of the MLSS, crew consumables (food) resupply is totally satisfied by the system. Although the initial mass of the MLSS and its needed reservoir of consumables may be high, its mass savings for crew consumables is significant enough to make an eventual mass payback.

Perhaps surprisingly, ISRU products used by the ALSS may not significantly reduce the LSS consumable resupply, however a case 3 ALSS may show a significant savings on initial payload masses for the subsystem equipment due to sharing. In addition, ISRU production

TABLE 5.3-II.- LUNAR AND MARTIAN RESUPPLY SUMMARY

| RLSS Type | Resupply Type | Lunar Base* | Martian Base* |
|---|---|---|---|
| Initial | Consumables | 0.80 | 0.80 |
| | Expendables | 1.25 | 1.25 |
| | **Total** | **2.05** | **2.05** |
| Advanced | Consumables | 0.80 | 0.70 |
| | Expendables | 1.10 | 1.10 |
| | **Total** | **1.90** | **1.80** |
| Mature | Consumables | 0.30 | 0.30 |
| | Expendables | 0.77 | 0.77 |
| | **Total** | **1.07** | **1.07** |

*Values are metric tonnes per man per year.

of nitrogen, although not considered in this report, would greatly reduce the LSS consumable resupply. Although nitrogen is not a metabolic requirement and does not require regeneration, it is the major component (80 percent) of the crew atmosphere in this study. Nitrogen loss due to habitat leakage, airlock use, and cabin repressurization is considerable and becomes a large component of the LSS consumable resupply. Because Mars has an atmosphere containing partial pressures of carbon dioxide, water, and nitrogen, it is possible that ISRU products may be used with the ALSS earlier in the base development.

### 5.3.1 Initial Life Support System

For an initial base, a life support system provides regenerable air revitalization and water management. Food is resupplied and wastes are collected and stored. To insure reliability, proven regenerable technologies are used.

Design parameters for the initial life support system (ILSS) were modelled using the environmental control and life support system design model program (ESDM). Figure 5.3.1-1 shows the mass flow diagram for the ILSS, sized for a crew of eight. The ILSS requires a resupply of nitrogen ($N_2$) and food solids for crew maintenance, and various filters and chemicals for ILSS maintenance. It is important to note that no water ($H_2O$) resupply is necessary in this case. The analysis was based on the assumption that the food supplied to the crew is 45 percent frozen, 30 percent canned, and 25 percent dry. The water contained in this type of diet replaces water lost by inefficiencies in the system.

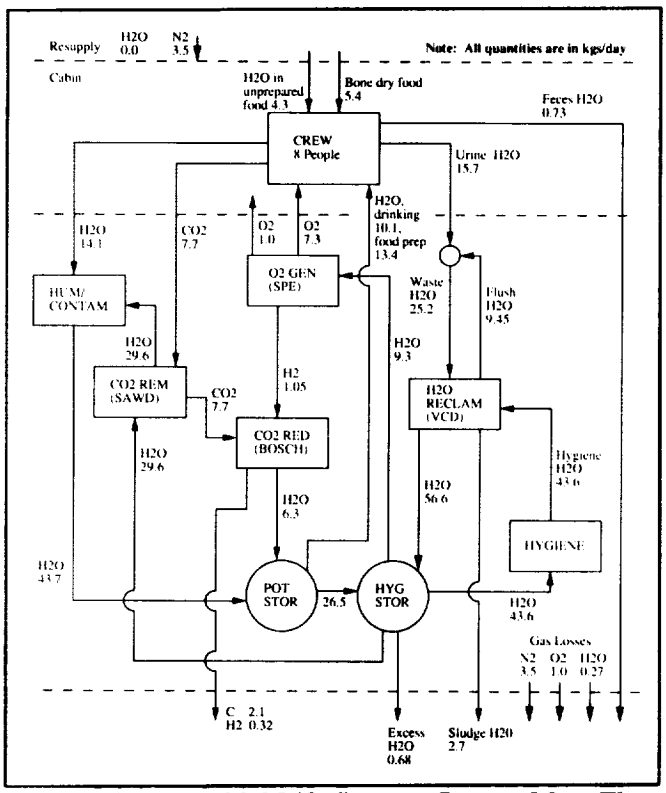



Figure 5.3.1-1.- Initial Life Support System Mass Flow Diagram (for crew of eight).

Table 5.3.1-I summarizes the sizing, power, and resupply requirements of the ILSS. This ILSS fits inside the initial module and sustains a crew of eight. An ILSS with the described subsystems for a crew of eight weighs a total of 2,233 kg with a volume of 7.3 $m^3$ and an average power requirement of 4,869 Watts. The majority of resupply weight, 1,288 kg total/90 days, is filters for the wash water recovery system.

This system analysis was done in reference to a lunar base. For a martian base, the carbon dioxide system is different due to the high partial pressure of $CO_2$ in the planet's atmosphere. If oxygen production from the atmospheric carbon dioxide proves practical, it may be possible to eliminate $CO_2$ concentration and reduction in the habitat. Also, oxygen generation by water electrolysis may not be necessary. Otherwise, the overall life support approaches are the same.

### 5.3.2 Advanced Life Support Systems

Advanced life support systems (ALSS's) will be designed to increase base closure, reducing the dependency of the base on Earth resupply. Increasing efficiency (percent recovery) of state-of-the-art air and water management systems will not significantly decrease launch weights. However, technology improvements are necessary to 1) reduce resupply of expendables (such as filters and chemicals), 2) include recovery of useful materials from solid wastes, and 3) improve system reliability and maintainability. Three ALSS approaches have been studied. In situ resource utilization (ISRU) is employed to varying degrees in the three cases. In Case 1, the ALSS is independent from ISRU. Case 2 utilizes products from ISRU, but does not supply materials or share processing units with ISRU. Case 3 integrates the ALSS and ISRU systems. The case 3 ISRU process is the hydrogen reduction of ilmenite (lunar only). Block flow diagrams of selected cases are shown in figures 5.3.2-1 and 2.

Each of the three cases includes a contamination/humidity control block, an air revitalization subsystem which performs carbon dioxide removal and oxygen generation, and a water reclamation subsystem. The air revitalization subsystem is identical in all three cases. The water reclamation subsystems differ because of the varying degrees of ISRU integration. In Case 1, water is recovered from hygiene water and waste products by supercritical water oxidation (SCWO). SCWO is a process that converts organic waste material to carbon dioxide and water using high temperature and pressure. Other sources of water are condensation of cabin water vapor, reduction of carbon dioxide, and a 1 percent resupply (3 kg water/day). In Case 2, the ISRU unit is an oxygen source for the ALSS; therefore, water does not contribute to oxygen regeneration and no water resupply is necessary. In Case 3, material flows from the ALSS to the ISRU system as well as in the opposite direction. As in Case 2, the integration with ISRU enables elimination of water resupply. However, in this case SCWO and oxygen generation (solid polymer electrolyte (SPE) water electrolysis) are sized not only for life support requirements, but also for lunar base (propellant) oxygen production (150 t oxygen/year). Also, solid wastes and waste water are sent from the ALSS to the SCWO in the integrated ISRU reactor for processing.

There are several differences between the ILSS and the ALSS. One difference is that more extensive extravehicular activity (EVA) was assumed for the more advanced base. Another difference is the requirement for a dishwasher and clothes washer in the more advanced base. This increases the amount of water that must be processed, and therefore the amount that is lost due to inefficiencies in the system. Other differences include the incorporation of solid waste treatment in the advanced system through the SCWO.

Compared to the ILSS, the Case 1 ALSS uses SCWO for water recovery. This system also decomposes solid wastes. This will require added weight and volume for

TABLE 5.3.1-I.- INITIAL LIFE SUPPORT SYSTEM PARAMETERS

| Subsystem, Process | Mass (kg) | Volume ($m^3$) | Avg. Power (W) | 90-Day Resupply (kg) |
|---|---|---|---|---|
| Potable water supply, VCD | 178 | 0.53 | 128 | |
| treatment chemicals | | | | 85.3 |
| Wash Water Supply, Multifiltration | 106 | 0.68 | 0 | |
| filters, active charcoal, iodine | | | | 640.0 |
| Potable Water treatment | 19 | 0.03 | 50 | |
| filters active charcoal, iodine | | | | 19.0 |
| Wash Water Treatment | 19 | 0.03 | 50 | |
| filters active charcoal, iodine | | | | 19.0 |
| Water Quality, Monitor | 56 | 0.09 | 100 | |
| chemicals | | | | 50.0 |
| Potable Water Storage | 319 | 0.46 | 12 | |
| Wash Water Storage | 122 | 0.23 | 6 | |
| Waste Management | 41 | 0.34 | 36 | |
| body wipes | | | | 90.9 |
| Waste Water Holding | 45 | 0.22 | 0 | |
| Waste Wash Holding | 45 | 0.22 | 0 | |
| Oxygen Supply, SPE | 246 | 0.47 | 2,357 | |
| deionizer/purifier | | | | 5.7 |
| Nitrogen Supply, Cryo storage | 199 | 0.28 | 6 | |
| Nitrogen and tank | | | | 85.6 |
| Carbon Dioxide Removal, SAWD | 176 | 0.64 | 1,022 | |
| Carbon Dioxide Reduction, Bosch | 120 | 0.60 | 385 | |
| catalyst and cartridges | | | | 262.8 |
| Air Humidity Control, Low Temp Cond. | 47 | 0.21 | 79 | |
| Contaminant Control, Cat. Oxydizer | 97 | 0.34 | 80 | |
| charcoal, LiOH, purafil | | | | 27.3 |
| Ventilation, Ventilator | 236 | 1.27 | 580 | |
| Air Exchange, Exchanger | 8 | 0.04 | 100 | |
| Microbial Controller | 7 | 0.003 | | |
| biocide | | | | 2.7 |
| Air Pressure, Controller | 82 | 0.43 | 100 | |
| Air Composition, Monitor | 23 | 0.11 | 60 | |
| Fire Detection, Detector | 42 | 0.11 | 100 | |
| **Total** | **2,233** | **7.33** | **4,869** | **1,288.3** |

Notes: Sustains crew of eight.
No redundant hardware included in analysis.

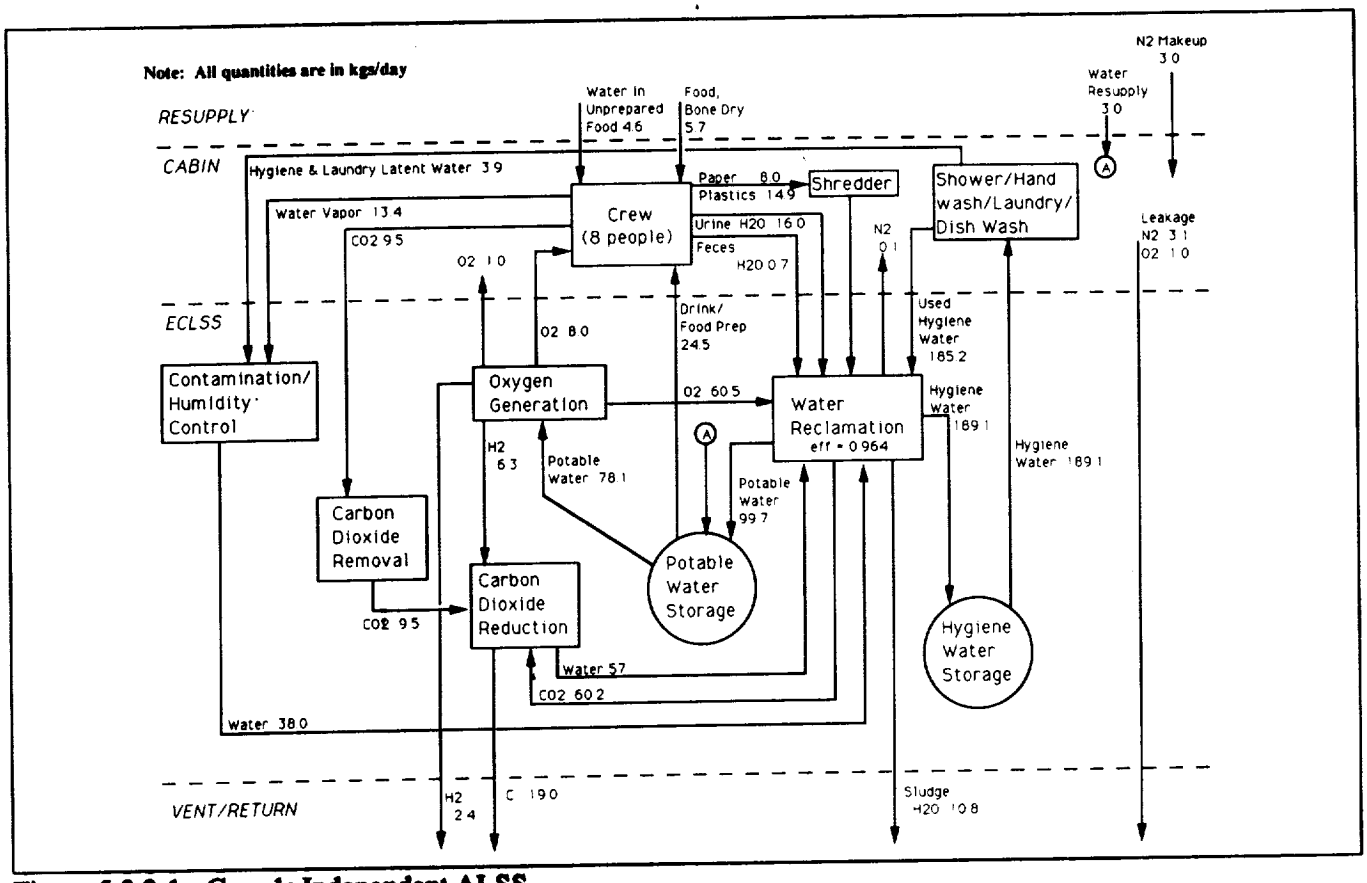



**Figure 5.3.2-1.- Case 1: Independent ALSS.**

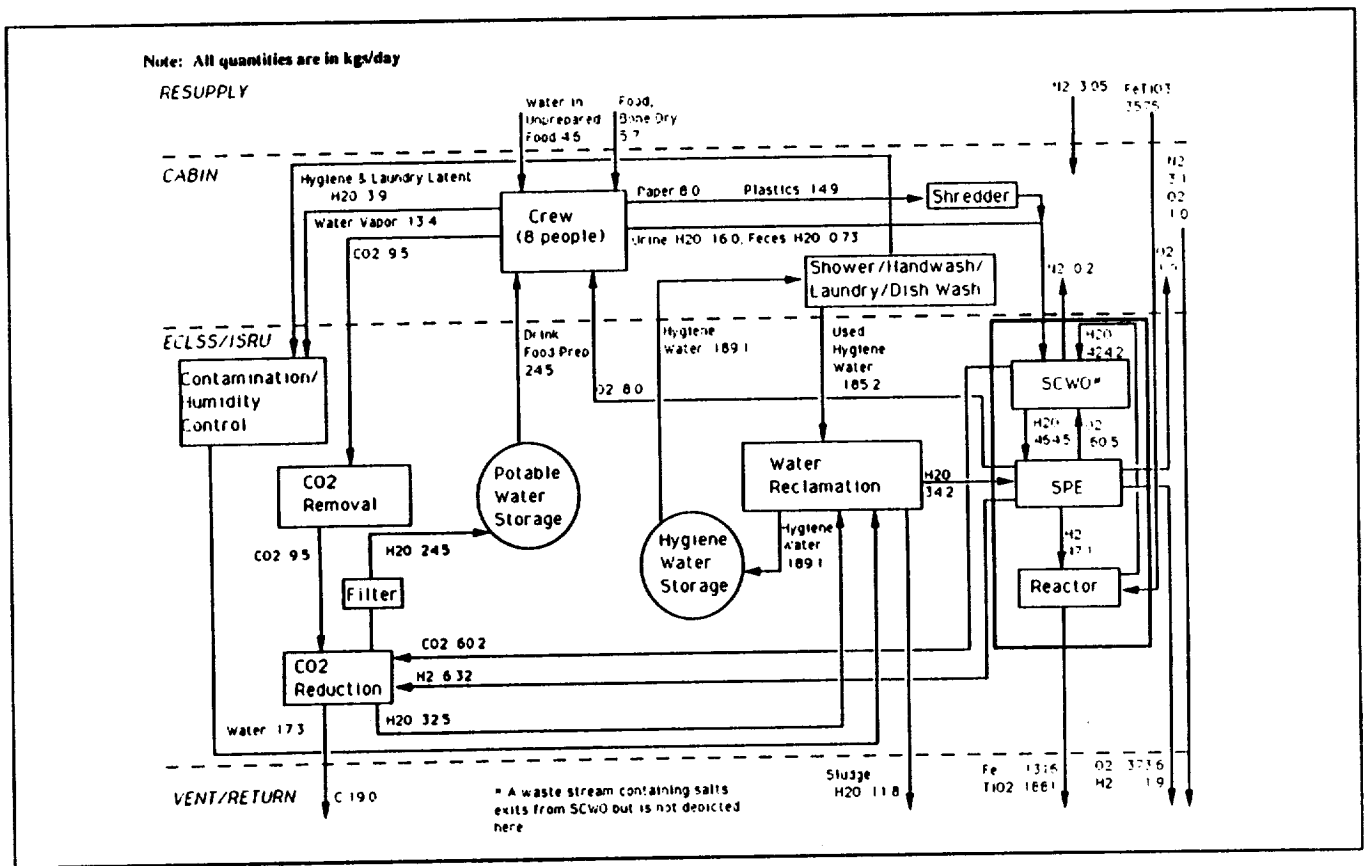



**Figure 5.3.2-2.- Case 3: Integrated ALSS/ISRU.**

the water recovery system but may reduce required storage volumes. However, water resupply is necessary because of the increased amount of water to be processed by the system and the increased EVA requirements. Table 5.3.2-I summarizes the sizing, power, and resupply requirements for the Case 1 ALSS. The ALSS in Case 2 has fewer systems than the ILSS because some of the ALS systems, such as the SPE, have been taken over by the ISRU. Also, since oxygen is supplied by the ISRU, the requirement for an oxygen generation unit is eliminated. Therefore, the carbon dioxide reduction unit is no longer required and carbon dioxide is a by product of the ALSS. Table 5.3.2-II lists the various requirements for the Case 2 ALSS. In Case 3, the ALSS and ISRU share a common SCWO, SPE, and ilmenite reactor. This synergism reduces redundancy between the two functional systems. Another advantage of the integration is that it allows for emergency reserves of necessary life support materials, oxygen and water, increasing operational flexibility and reducing dependency on backup systems. Table 5.3.2-III summarizes the subsystem parameters for the Case 3 ALSS.

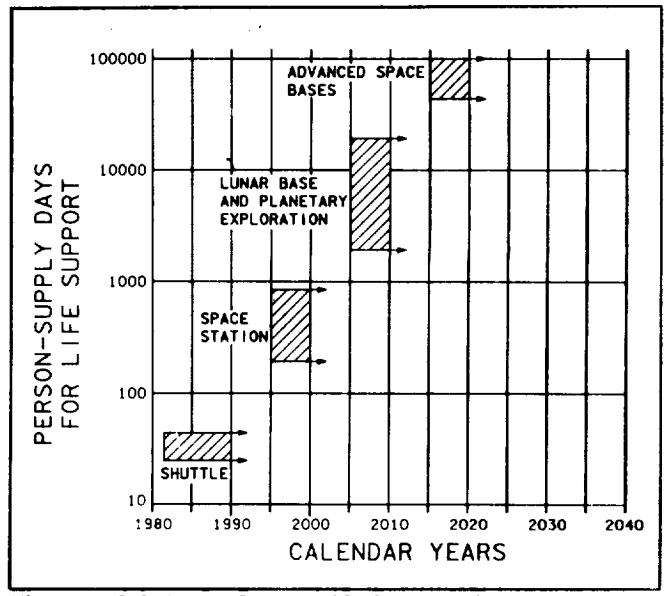


Figure 5.3.3-1.- In-Space Life Support Systems.

### 5.3.3 Mature Life Support Systems

The next step in human exploration of the Moon and Mars requires a new kind of life support system. Figure 5.3.3-1 shows the regimes of life support operations for the space Shuttle and the Space Station Freedom in terms of the product of crew size (person) and resupply (supply days). Because of longer stays and increasingly bigger crew sizes, a greater degree of self-sufficiency will be required to reduce resupply from the Earth for lunar or planetary exploration. The life support system that meets these future requirements is called a controlled ecological life support system (CELSS).

CELSS is an integrated life support system of bioregenerative and physical-chemical regenerative components for air, water, food, and waste recycle in a safe, reliable manner. Figure 5.3.3-2 is a general diagram of such a system. The "crew space" represents the human habitat. The "plant space" is the home for not only higher plants but also algae or animals as specified for an optimal food production scenario. The harvest crops (lettuce, tomatoes, strawberries, wheat, rice, white or sweet potatoes, soybeans, peanuts, peas, sugar beets, chard, cabbage) are either consumed fresh or processed while the excess is stored. The wastes generated in the system are processed and the recovered materials such as water or nutrients are recycled back as consumables. Any system process mass losses (e.g. oxygen) are made up either with local materials processing or resupply.

A candidate first-generation CELSS is described in Figure 5.3.3-3. The plant space in this system is shown as "greenhouse." An integrated operation is achieved with air, water, and waste processing and food production. Diversity in air and water processing is achieved by the use of both physical-chemical and biological means. Diversity in food supply is provided by fresh harvest from the greenhouse and already stored food. Maximum safety and reliability are obvious requirements. Most life support functions are accomplished by the built-in diversity of configurations and modes of operation of the system. Several functions (e.g. carbon dioxide removal and reduction) are performed in different ways at the same time. One option (physical-chemical) is able to take over the load usually handled by the other (biological). A lower maximum carbon dioxide concentration in crew air (0.2 percent) is available than in Space Station Freedom. High quality potable water is produced for the crew by the use of a combined electrolyzer/fuel cell system. The fuel cell reliability is enhanced with redundancy.

The mass estimate for the greenhouse internals and the associated equipment is 9.2 t for a 4-person system (see table 5.3.3-I). The greenhouse is expected to be the majority of the mass of the system.

Figure 5.3.3-4 compares the improvements in launch mass for a 4-person CELSS since 1981. The 1989 line is shown along with those for 1981 and 1987 corresponding to a 3 percent resupply rate, i.e. 0.13 kg per day. Garbage and feces recycle for nutrient recovery and local materials for makeup can be incorporated later in stages to further reduce resupply if deemed to be optimal.

TABLE 5.3.2-I.- ADVANCED LIFE SUPPORT SYSTEM PARAMETERS (CASE 1)

| Subsystem, Process | Mass (kg) | Volume ($m^3$) | Avg. Power (W) | 90-Day Resupply (kg) |
|---|---|---|---|---|
| Supercritical water oxidation | 153 | 0.35 | 334 | 30.3 |
| Shredder | 110 | 1.50 | 7 | 1.7 |
| Potable water treatment | 19 | 0.03 | 50 | |
| filters active charcoal, iodine | | | | 19.0 |
| Water quality, monitor | 56 | 0.09 | 100 | |
| chemicals | | | | 50.0 |
| Potable water storage | 319 | 0.46 | 12 | |
| Wash water storage | 122 | 0.23 | 6 | |
| Waste management | 41 | 0.34 | 36 | |
| body wipes | | | | 90.9 |
| Waste water holding | 45 | 0.22 | 0 | |
| Waste wash holding | 45 | 0.22 | 0 | |
| Oxygen supply, SPE | 246 | 0.47 | 2,357 | |
| deionizer/purifier | | | | 5.7 |
| Nitrogen supply, cryo storage | 199 | 0.28 | 6 | |
| Nitrogen and tank | | | | 85.6 |
| Carbon dioxide removal, liquid amine | 105 | 0.50 | 570 | |
| Carbon dioxide reduction, Bosch | 120 | 0.60 | 385 | |
| catalyst and cartridges | | | | 262.8 |
| Air humidity control, low temp cond. | 47 | 0.21 | 79 | |
| Contaminant control, cat. oxydizer | 97 | 0.34 | 80 | |
| charcoal, LiOH, purafil | | | | 27.3 |
| Ventilation, ventilator | 236 | 1.27 | 580 | |
| Air exchange, exchanger | 8 | 0.04 | 100 | |
| Microbial controller | 7 | 0.003 | 0 | |
| biocide | | | | 2.7 |
| Air pressure, controller | 82 | 0.43 | 100 | |
| Air composition, monitor | 23 | 0.11 | 60 | |
| Fire detection, detector | 42 | 0.11 | 100 | |
| **Total** | **2,122** | **7.8** | **4,962** | **576.0** |

Notes: Sustains crew of eight.
No redundant hardware included in analysis.

TABLE 5.3.2-II.- ADVANCED LIFE SUPPORT SYSTEM PARAMETERS (CASE 2)

| Subsystem, Process | Mass (kg) | Volume ($m^3$) | Avg. Power (W) | 90-Day Resupply (kg) |
|---|---|---|---|---|
| Supercritical water oxidation | 153 | 0.35 | 334 | 30.3 |
| Shredder | 110 | 1.50 | 7 | 1.7 |
| Potable water treatment | 19 | 0.03 | 50 | |
| filters active charcoal, iodine | | | | 19.0 |
| Water quality, monitor | 56 | 0.09 | 100 | |
| chemicals | | | | 50.0 |
| Potable water storage | 319 | 0.46 | 12 | |
| Wash water storage | 122 | 0.23 | 6 | |
| Waste management | 41 | 0.34 | 36 | |
| body wipes | | | | 90.9 |
| Waste water holding | 45 | 0.22 | 0 | |
| Waste wash holding | 45 | 0.22 | 0 | |
| Nitrogen supply, cryo storage | 199 | 0.28 | 6 | |
| Nitrogen and tank | | | | 85.6 |
| Carbon dioxide removal, liquid amine | 105 | 0.50 | 570 | |
| Air humidity control, low temp cond. | 47 | 0.21 | 79 | |
| Contaminant control, cat. oxydizer | 97 | 0.34 | 80 | |
| charcoal, LiOH, purafil | | | | 27.3 |
| Ventilation, ventilator | 236 | 1.27 | 580 | |
| Air exchange, exchanger | 8 | 0.04 | 100 | |
| Microbial controller | 7 | 0.003 | 0 | |
| biocide | | | | 2.7 |
| Air pressure, controller | 82 | 0.43 | 100 | |
| Air composition, monitor | 23 | 0.11 | 60 | |
| Fire detection, detector | 42 | 0.11 | 100 | |
| **Total** | **1,756** | **6.7** | **2,220** | **307.5** |

Notes: Sustains crew of eight.
No redundant hardware included in analysis.

TABLE 5.3.2-III.- ADVANCED LIFE SUPPORT SYSTEM PARAMETERS (CASE 3)

| Subsystem, Process | Mass (kg) | Volume ($m^3$) | Avg. Power (W) | 90-Day Resupply (kg) |
|---|---|---|---|---|
| Supercritical water oxidation | 153 | 0.35 | 334 | 30.3 |
| Shredder | 110 | 1.50 | 7 | 1.7 |
| Wash water supply, multifiltration | 106 | 0.68 | 0 | |
| filters, active charcoal, iodine | | | | 640.0 |
| Potable water treatment | 19 | 0.03 | 50 | |
| filters active charcoal, iodine | | | | 19.0 |
| Water quality, monitor | 56 | 0.09 | 100 | |
| chemicals | | | | 50.0 |
| Potable water storage | 319 | 0.46 | 12 | |
| Wash water storage | 122 | 0.23 | 6 | |
| Waste management | 41 | 0.34 | 36 | |
| body wipes | | | | 90.9 |
| Waste water holding | 45 | 0.22 | 0 | |
| Waste wash holding | 45 | 0.22 | 0 | |
| Oxygen supply, SPE | 2,683 | 5.13 | 25,707 | |
| Nitrogen supply, cryo storage | 199 | 0.28 | 6 | |
| nitrogen and tank | | | | 85.6 |
| Carbon dioxide removal, liquid amine | 105 | 0.50 | 570 | |
| Carbon dioxide removal, Bosch | 120 | 0.60 | 385 | |
| catalyst and cartridges | | | | 262.8 |
| Air humidity control, low temp cond. | 47 | 0.21 | 79 | |
| Contaminant control, cat. oxydizer | 97 | 0.34 | 80 | |
| charcoal, LiOH, purafil | | | | 27.3 |
| Ventilation, ventilator | 236 | 1.27 | 580 | |
| Air exchange, exchanger | 8 | 0.04 | 100 | |
| Microbial controller | 7 | 0.003 | 0 | |
| biocide | | | | 2.7 |
| Air pressure, controller | 82 | 0.43 | 100 | |
| Air composition, monitor | 23 | 0.11 | 60 | |
| Fire detection, detector | 42 | 0.11 | 100 | |
| Reactor, ilmenite | 4,574 | 11.15 | 127,300 | |
| **Total** | **9,252** | **24.34** | **155,700** | **1,216.1** |

Notes: Sustains crew of eight and ilmenite reduction for liquid oxygen production (150 t/yr).
No redundant hardware included in analysis.

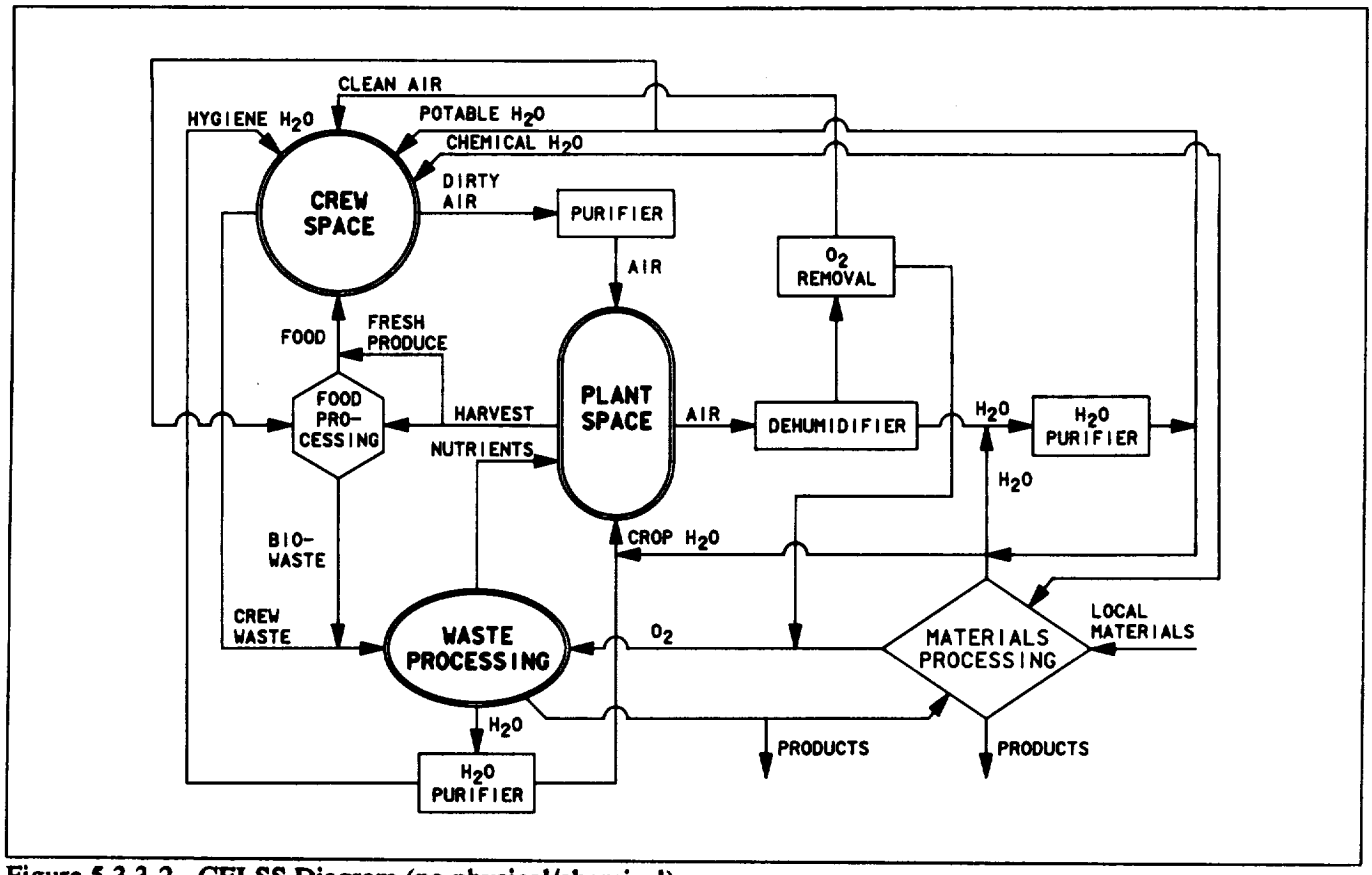



Figure 5.3.3-2.- CELSS Diagram (no physical/chemical).

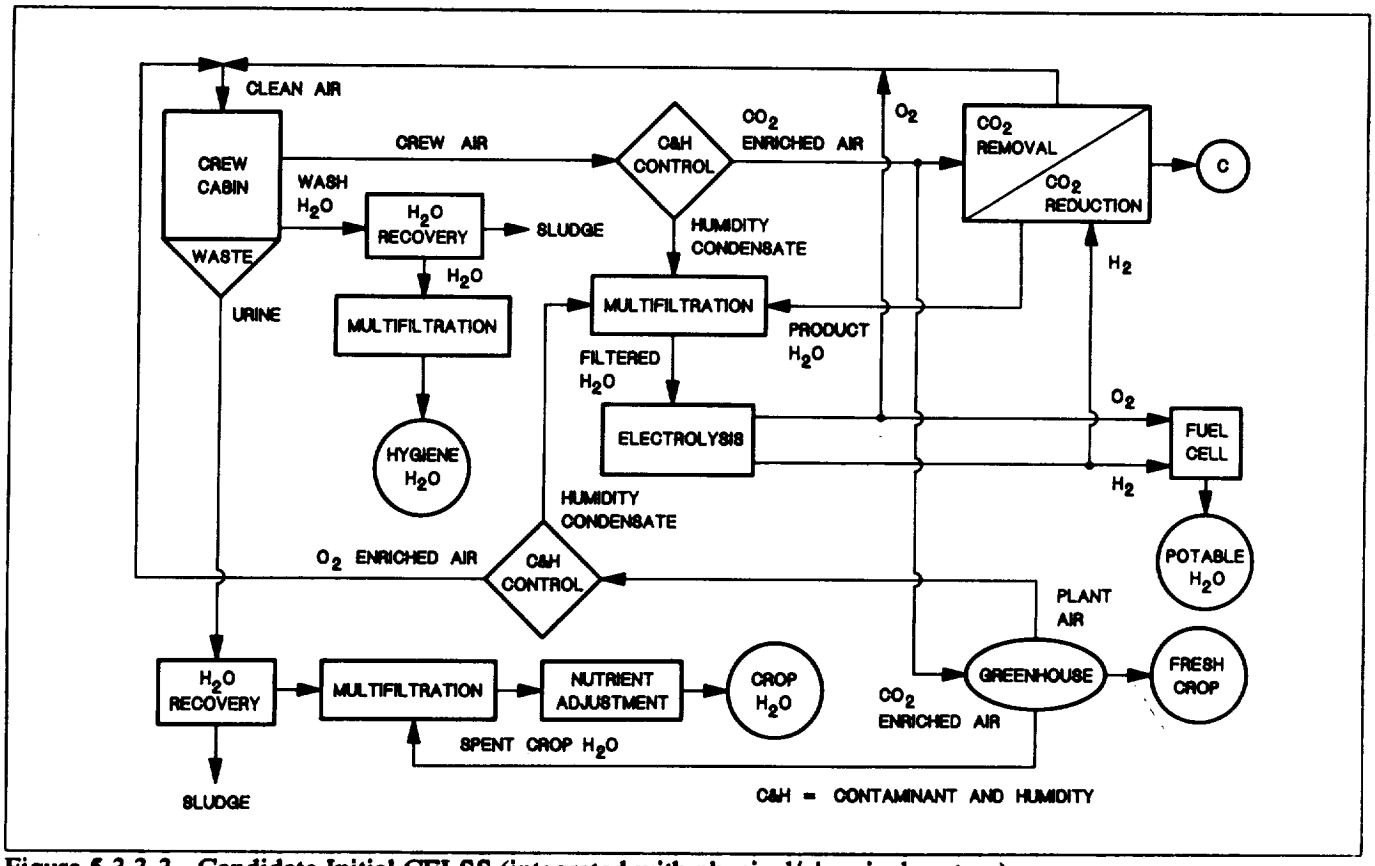



Figure 5.3.3-3.- Candidate Initial CELSS (integrated with physical/chemical system).

TABLE 5.3.3-I.- MASS CALCULATIONS FOR A FOUR-PERSON GREENHOUSE

| Item | Mass (kg) |
|---|---|
| Module shell | 2,712 |
| Berthing port | 68 |
| Plant growth structure | 720 |
| Equipment (lights, controls, etc.) | 2,673 |
| Harvest processing equipment | 538 |
| Water reservoir | 2,000 |
| Water tanks | 380 |
| **Total** | **9,159** |

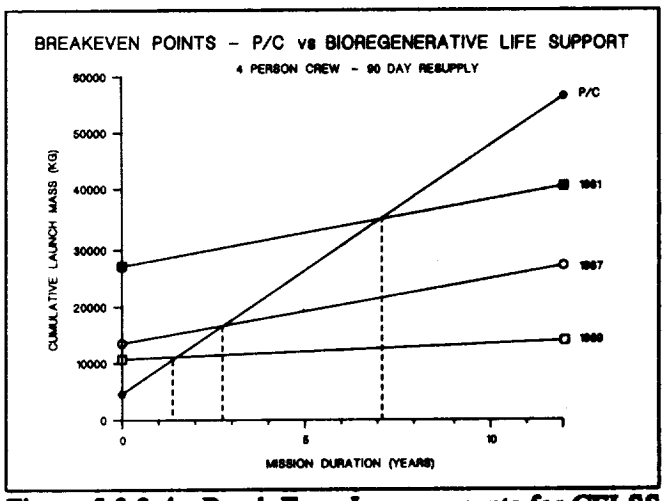



Figure 5.3.3-4.- Break Even Improvements for CELSS (4-person crew, 90-day resupply).

## 5.4 THERMAL CONTROL SYSTEMS

The lunar and martian thermal environments are significantly different from Earth. Thermal control systems must, therefore, be devised to allow people and equipment to function. These systems will be critical and essential to a surface base. This section describes preliminary design work for these systems.

### 5.4.1 Lunar Thermal Control Systems

The Moon's thermal environment changes markedly from day to night and from location to location. The lunar day lasts approximately 28 terrestrial days, with 14 days of sunlight and 14 days of darkness. This results in a very hot daytime environment and a very cold nighttime environment. As shown in figure 5.4.1-1, the surface temperature extremes range from 374°K (101°C) at lunar noon to 120°K (-153°C) during the lunar night. The equatorial and lower latitudinal locations experience the most varying thermal environment, while polar and higher latitudinal sites experience a relatively constant thermal environment over a day/night cycle.

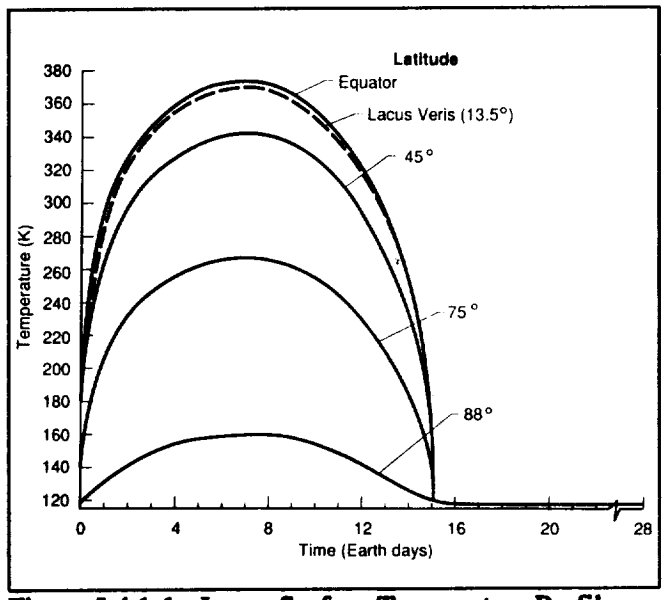



Figure 5.4.1-1.- Lunar Surface Temperature Profile

A lunar thermal control system must be able to actively acquire internal equipment and metabolic heat loads and reject these heat loads to the environment. Internal heat loads can be readily acquired using Space Station Freedom acquisition technology consisting of two single-phase pumped water loops operating at 2°C and 21°C, respectively. Rejection of heat to the environment at a polar site is relatively straightforward. Heat rejection in the equatorial and lower latitudinal regions is more difficult because of the extreme external temperatures.

An analysis was performed to determine the variation in the rejection capability for radiators over the lunar day for three orientations. The rejection capability of the radiators can be estimated using an effective sink temperature, which is a function of radiator orientation and surface properties and also represents the added effects of cold space, the solar flux, and the infrared flux. If the final rejection temperature of the radiator is above the sink temperature, heat can be rejected to the environment; however, if the final rejection temperature is below the sink temperature, no heat can be rejected. The orientations examined included a horizontal radiator insulated from the lunar surface and vertical radiators oriented either perpendicular or parallel to the plane of the solar ecliptic. The radiators were assumed to have an end-of-life solar absorptivity of 0.3 and an infrared emissivity of 0.85. The sink temperature profiles are plotted for radiators located both at the polar and lower

latitudinal regions in figures 5.4.1-2 and 5.4.1-3, respectively.

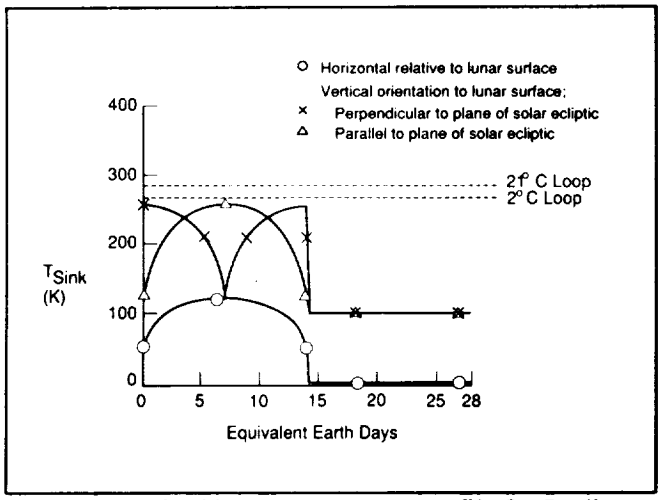



Figure 5.4.1-2.- Sink Temperature Profile for Radiators at the South Pole.

As shown in figure 5.4.1-2, the final rejection temperatures of the two acquisition loops (assuming an 8°C temperature drop to the radiator) for a horizontal radiator located at the pole are well above the environmental sink temperature; therefore, a high rejection capability from the radiator is obtainable. However, as shown in figure 5.4.1-3, the final rejection temperatures of the two acquisition loops for all radiation orientations in the lower latitudinal region are well below the environmental sink temperature for a large part of the lunar day and well above the final rejection temperature during the lunar night. This implies that radiators operating at 2°C or 21°C will not reject heat during part of the lunar day in the lower latitudes. Two possible solutions exist to achieve daytime positive heat rejection for the lower latitudes. One is to lower the environmental sink temperature below the radiator rejection temperature. The second is to raise the rejection temperature above the environmental sink temperature.

Several methods that can lower the environmental sink temperature include the use of surface insulating blankets, sun shields, or reflectors that can reduce the solar and infrared flux striking the radiators. The selection of any one of these techniques or combination of techniques will ultimately depend upon the location of the base, topographical features of the site, and mission objectives. One disadvantage of these techniques is the problem of dust adherence to the reflecting and insulating surfaces, which can significantly decrease the rejection capability of the system and can cause serious thermal control disfunction. Another disadvantage is the dependence on the site selection.

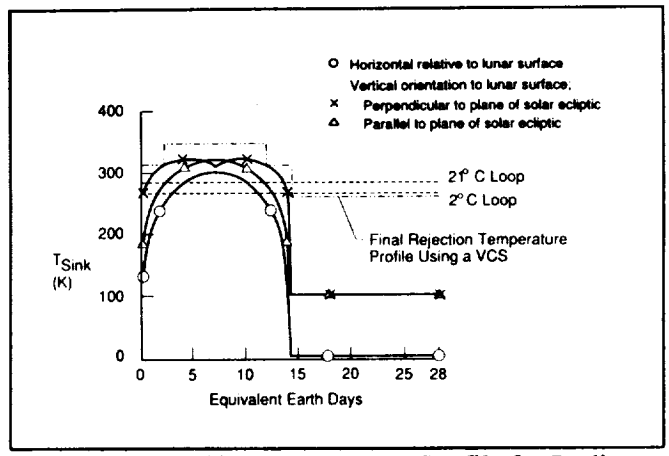



Figure 5.4.1-3.- Sink Temperature Profile for Radiators at Lower Latitude Sites.

A more versatile alternative to lowering the sink temperature is to raise the radiator rejection temperature significantly above the existing sink temperature. This can be accomplished by the use of a heat pump system. One heat pump evaluated is a two-loop cascaded vapor cycle system (VCS) for daytime operation with a bypass loop to prevent the over-rejection of heat during nighttime operation. A schematic of this system is shown in figure 5.4.1-4. The cascaded system will allow for stagewise operation; that is, each stage can be run as an increased rejection temperature is needed to reject to the increasing sink temperature encountered over the lunar day. This will enable the radiator to operate at a more constant heat flux. During days 0-2 and 12-14, the second stage of the cascaded system will be operating while the first-stage compressor is bypassed, resulting in a final rejection temperature of 37°C. During days 3-11, both compressor loops will be in operation, resulting in a final rejection temperature of 87°C. At night (days 14-28), no compressor loops will be used. The final rejection temperature profile is shown in figure 5.4.1-3. As shown in the figure, the final rejection temperature is significantly above the daytime sink temperatures for both the vertical radiator oriented parallel to the plane of the solar ecliptic and the horizontal radiator. The resulting radiator rejection capability for radiators oriented parallel to the plane of a solar ecliptic in the lower latitudinal region are plotted in figure 5.4.1-5. The major disadvantage of a heat pump system is its high power requirement.

A thermal control system was conceptually designed for the lunar construction shack and for the constructible habitat discussed in section 5.1 for a lower latitudinal site. The total heat loads assumed for the construction shack and constructible habitat were 25 kW and 65 kW,

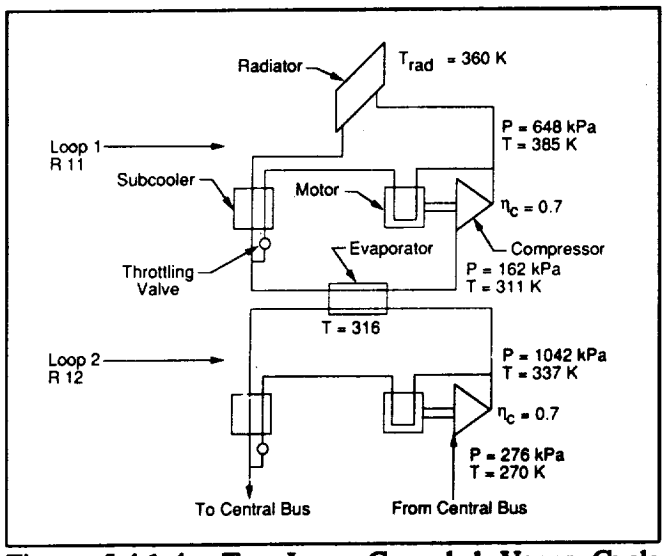



Figure 5.4.1-4.- Two-Loop Cascaded Vapor Cycle System.

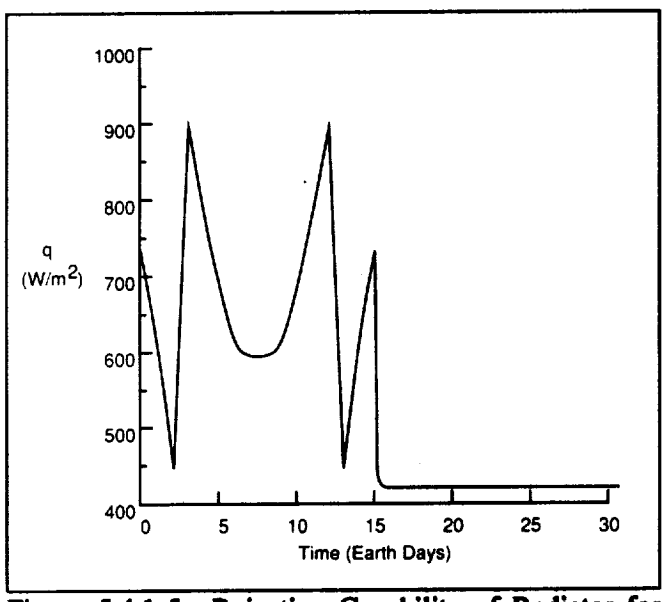



Figure 5.4.1-5.- Rejection Capability of Radiator for Two-Loop Cascaded VCS.

respectively. The internal acquisition subsystem was sized using Space Station Freedom-derived acquisition technology. The rejection subsystem was sized using a two-stage VCS (as described above) and vertically mounted radiators oriented parallel to the plane of the solar ecliptic. The construction shack required a radiator area of 70 $m^2$; the constructible habitat required 175 $m^2$. The transport loop connecting both acquisition loops to the VCS is a two-phase pumped freon 12 loop operating at -3°C. The power associated with the transport and rejection subsystems is shown in figure 5.4.1-6. The thermal control system mass, volume, and power estimates are shown in table 5.4.1-I.

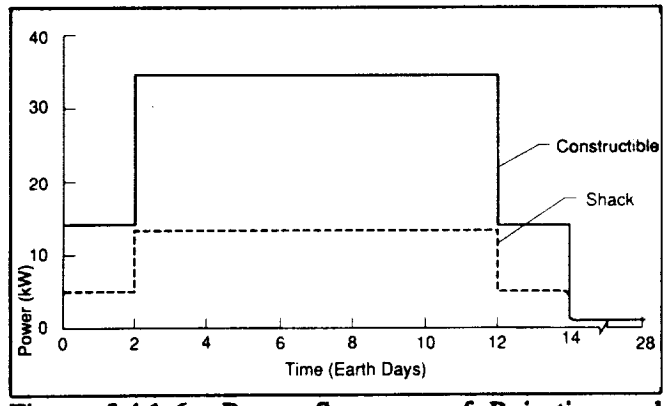



Figure 5.4.1-6.- Power Summary of Rejection and Transport Subsystems for Module and Constructible.

TABLE 5.4.1-I.-
THERMAL CONTROL SYSTEM ESTIMATES

| Item | Mass (kg) | Volume ($m^3$) | Peak Power (kW) |
|---|---|---|---|
| Shack (25 kW) | | | |
| Acquisition | 740 | 0.5 | 0.5 |
| Transportation | 260 | 2.3 | 0.1 |
| Heat Pump | 50 | 1.1 | 13.2 |
| Rejection | 900 | 2.7 | 0.0 |
| **Total** | **1,950** | **6.6** | **13.8** |
| Constructible (65 kW) | | | |
| Acquisition | 2,250 | 0.8 | 1.8 |
| Transportation | 640 | 4.7 | 0.01 |
| Heat Pump | 80 | 1.3 | 34.2 |
| Rejection | 2,300 | 6.8 | 0.0 |
| **Total** | **5,270** | **13.6** | **36.1** |

### 5.4.2 Martian Thermal Control Systems

The martian thermal environment is very dynamic, with a multitude of thermal conditions affected by the season, time of day, and location. Active thermal control components and other surface systems will be exposed to solar radiation, surface infrared radiation, free convection, and blowing wind, dust, and sand. The thermal control system (TCS) components on the surface must be designed to withstand the varying conditions. Base components buried sufficiently under the martian regolith will be protected from the extreme thermal, dust, and radiation conditions of the surface. The design of the thermal control system will depend upon the martian

surface conditions encountered as well as the system design and mission objectives.

The thermal control system must maintain the habitable areas of the base at a comfortable temperature for the crew. To accomplish this, the TCS must actively acquire internal equipment and metabolic heat loads and reject these loads to the external environment. The cold environment of Mars should provide a sufficient heat dump, avoiding the heat pumps that may be required on the Moon. However, the design of the TCS for Mars may be challenging due to the extreme changes in the surface and atmosphere temperatures, the changing winds, and the degradation of surface properties. During periods of low temperatures, low solar flux, and high wind speeds, the mode of heat transfer may be convection-dominated; while, during periods of high temperatures, high solar flux, and low atmospheric free convection, the mode of heat transfer may be radiation-dominated.

The surface temperature of Mars experiences large diurnal and seasonal extremes. In the southern hemisphere, the added effects of the polar tilt and large orbital eccentricity produce maximum surface temperatures approximately 30°K higher than those in the northern hemisphere, where the eccentricity offsets the effect of the polar tilt. The maximum temperature approaches 295°K at 25 degrees south latitude in midsummer. The minimum surface temperature approaches 140°K at the southern cap in midwinter. The equatorial region experiences a relatively small annual temperature variation, with latitudes of approximately 20 degrees north experiencing the smallest annual variation. The daily maximum, mean, and minimum surface temperatures over a martian year for 25 degrees south latitude and the equator are shown in figure 5.4.2-1.

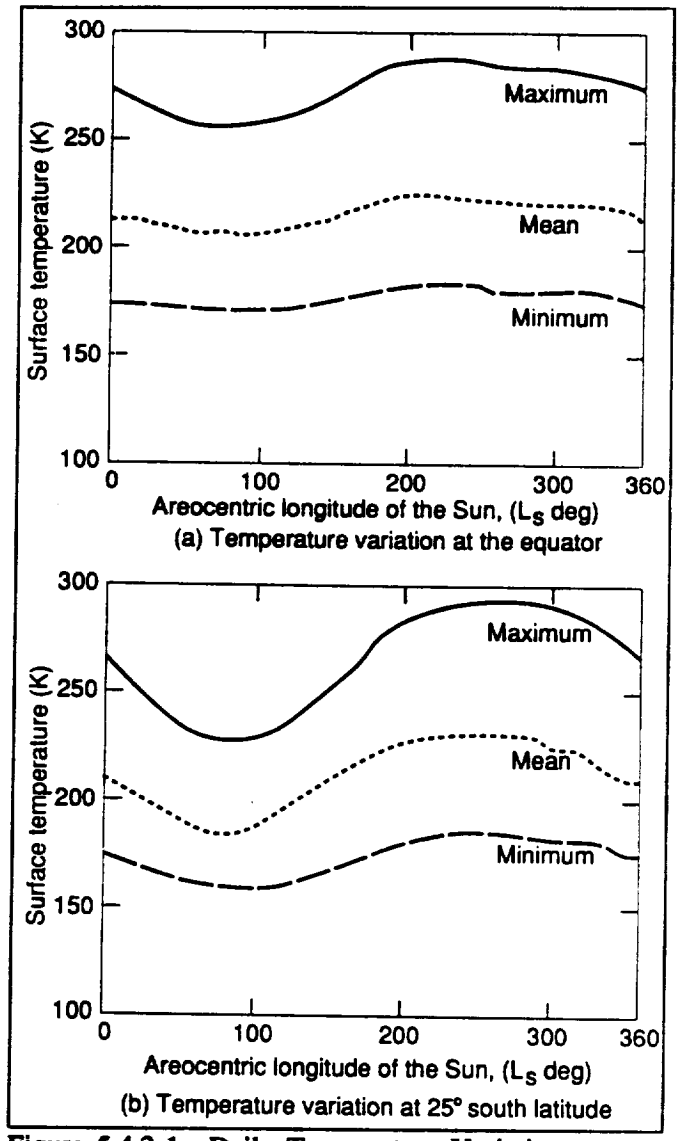



**Figure 5.4.2-1.- Daily Temperature Variations over a Martian Year.**

The subsurface temperature range decreases exponentially with depth. The temperature at a depth of 24 cm differs negligibly from the average surface temperature. Thus, the Mars regolith can provide significant thermal protection as well as minimize the crew's cumulative radiation dosage. The total heat gains and losses between the buried portions of the base and the external environment will depend upon the base site and the specific weather conditions.

The martian atmosphere is continually changing. It experiences a large daily temperature range and daily variations in the magnitude and direction of the winds. The atmospheric temperature range is less dramatic than the surface temperature range over a martian sol. The minimum and mean atmospheric temperatures are close to these temperatures on the ground, but the maximum air temperature is quite lower than the maximum ground temperature. At an equatorial site, the atmospheric temperature varies from approximately 190°K to 245°K, with an average temperature of approximately 215°K. Ultimately, the diurnal range will depend upon the site location, season, and weather conditions.

The winds on Mars are difficult to predict and are a widely varying parameter. The conditions can be calm on the surface or the winds can gust up to 30 m/s. At Viking lander sites, the winds averaged from 2 to 7 m/s in the summer with speeds reaching as high as 9.5 m/s. In the fall, the winds averaged approximately 5 m/s with daily maximums of 10 m/s. With the onset of a dust storm, the winds can average 17 m/s with gusts as high

as 30 m/s. Insensitivity to wind speed and direction may be desired in the thermal control system.

There are numerous and widely varying parameters affecting the thermal control system design. The TCS should be designed to operate for the maximum and minimum heat loss conditions anticipated. Once a particular site is selected and the expected weather conditions are defined, designing the thermal control system will be greatly simplified.

## 5.5 RADIATION PROTECTION

A major consideration for lunar and martian long-term habitation is radiation. The Earth's magnetosphere protects its inhabitants from harmful radiation, but this protection is not present on the Moon or Mars. With no atmosphere, natural radiation protection on the Moon is non-existent. Mars' thin atmosphere affords some protection, but not enough for sustained human habitation. The feasability of both lunar and martian habitation relies on a thorough understanding of the radiation problem and a viable protection scheme.

Radiation occurs in many forms and at different energy levels. Different types of radiation with equivalent energies may produce different degrees of biological damage. The standard unit of measure for the biological damage potential of a radiation dose is the roentgen equivalent in man, or rem. A rem is the amount of radiation that results in a biological effect equivalent to 1 rad of X radiation.

The National Council on Radiation Protection (NCRP) sets standards on the amount of radiation humans can sustain. The lowest limit (first to be exceeded) is the dose to the blood-forming organs (BFO). The NCRP BFO limit for astronauts is currently set at 50 rem per year, not to exceed 25 rem in a 30-day period.

There are two major sources of ionizing radiation in the free-space environment: galactic cosmic rays (GCR's) and solar flares. GCR's are an omnidirectional flux of protons (82-85 percent), alpha particles (12-14 percent), and heavier nuclei (1-2 percent) arriving from interstellar sources, such as supernovae. Most of the incurred doses from GCR's result from stripped nuclei of the chemical elements. The energy distribution of these ions is less well known, but measurements have been used to specify working models of the particle flux-energy distributions.

Solar particle events are explosions of the sun's chromosphere resulting in the expulsion of high-energy protons. These particle events are commonly called solar flares. The number and intensity of solar particle events vary directly with the 11-year solar sunspot cycle. Large events are more frequent immediately before and after periods of peak sunspot activity, or solar maximum. The largest events occur infrequently, about one or two per solar cycle. Recent analyses have employed fluence (time-integrated) spectra for three of the largest events observed in the last half-century. The free-space energy spectra of the GCR and fluence spectra for three large solar proton events as used in the present analyses are given in figure 5.5-1.

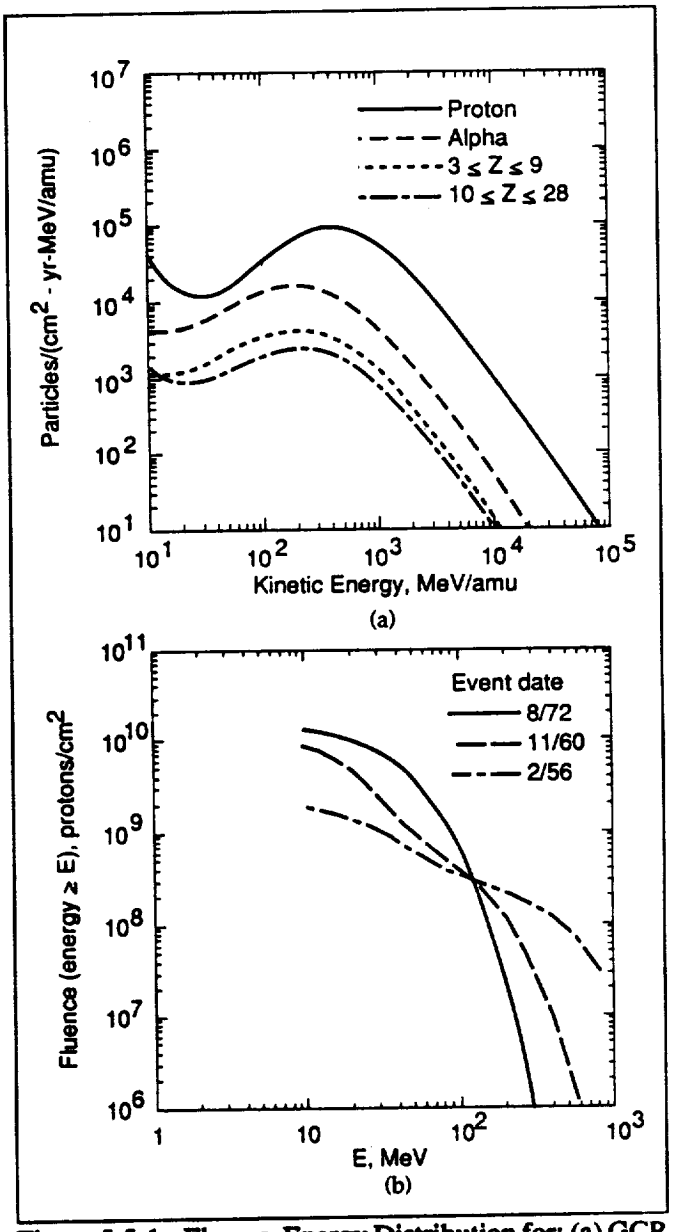



Figure 5.5-1.- Flux vs. Energy Distribution for: (a) GCR Nuclei During Solar Minimum, and (b) Protons for Three Large Solar Particle Events.

### 5.5.1 Lunar Radiation Protection

An object on the surface of the Moon receives some radiation shielding from the mass of the Moon itself. In other respects, however, the lunar surface is unprotected. With no atmosphere or trapped radiation belts, the radiation environment on the lunar surface is essentially the same as the free-space environment discussed above.

#### 5.5.1.1 Transport Codes and Regolith Model

The Langley Research Center nucleon and heavy-ion transport codes have been used to estimate shielding requirements for lunar habitats. These codes simulate the propagation of primary ions along with subsequent generations of fragmented particles in the shield medium, resulting in predictions of the attenuated particle fluxes. These final particle distributions are then used in computing the corresponding doses in human tissue. An obvious choice for shield material is the lunar regolith, since it is expected that large shield masses will be required. The results presented here apply to a regolith composition of the oxides of silicon (Si), aluminum (Al), iron (Fe), and magnesium (Mg) with selected atomic abundances of: 61% O, 19% Si, 8% Al, 6% Fe, and 6% Mg. The regolith bulk density is assumed to be 1.5 g/cc. This composition is based on an approximate average of Apollo return sample constituents, and does not represent soil properties at any specific location. However, shield properties for soils with moderately different compositions should be comparable to those given in this section.

#### 5.5.1.2 Computed Dosimetric Data

The effectiveness of a shielding material is indicated by the variation of a delivered radiation dose as a function of shield thickness for radiation incident normal to slab shields. Figure 5.5.1-1 shows the BFO dose-equivalent as a function of regolith slab thickness for the GCR components. It is seen that for thin layers, most of the dose results from the energy deposition by heavy ions. As the thickness of the shield increases, the delivered dose becomes dominated by secondary nucleons. Secondary radiation is generated when high energy particles strike the medium, releasing numerous lower energy particles. These secondary particles, particularly neutrons, are more penetrating than the heavier ions of the primary radiation source. As the figure shows, the radiation dose from neutrons actually increases for thicker shields. As a consequence, shield effectiveness decreases; that is, dose reduction per layer thickness increment becomes lower. For the GCR dose, a 50-cm regolith shield is predicted to reduce the free-space (unshielded) dose by about 60 percent.

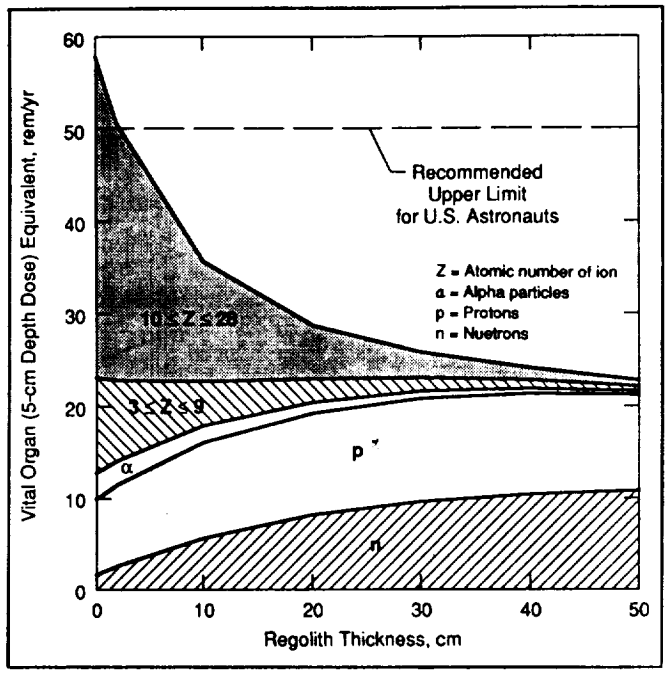



Figure 5.5.1-1.- BFO Annual Dose-Equivalent Contributions From Specified Particles.

Similar slab-dosimetric data for three large particle event spectra are shown in figure 5.5.1-2. The results indicate that dose variation with shield thickness is very sensitive to initial spectral distributions. The large event of August 1972 produced higher proton fluxes than ever before observed, and predicted doses for little or no shielding fall into the lethality category. However, this event showed a relative paucity of high-energy particles. Thick shields reduce predicted doses to very low levels.

While the total unshielded dose due to the February 1956 event is far from a lethal value, the abundance of very high energy particles results in high penetration of very thick shields. All of the dosimetric data herein has been evaluated on the basis of radiobiological quality factors specified by the International Commission on Radiological Protection in their report ICRP-26.

#### 5.5.1.3 Preliminary Results for Habitat Configurations

Two conceptual lunar habitats, shielded with regolith, were analyzed on the basis of annual GCR dose and time-integrated dose for individual particle events. These configurations are shown in figure 5.5.1-3 in their modeled shielded geometries. While the radiation fields may be isotropic in free space (and this has been assumed in the present analyses), the attenuated radiation in the habitat interiors is usually very anisotropic, and directionality around a given target point can be very important in a dose determination. The total dose at a point is found by performing the appropriate solid-angle

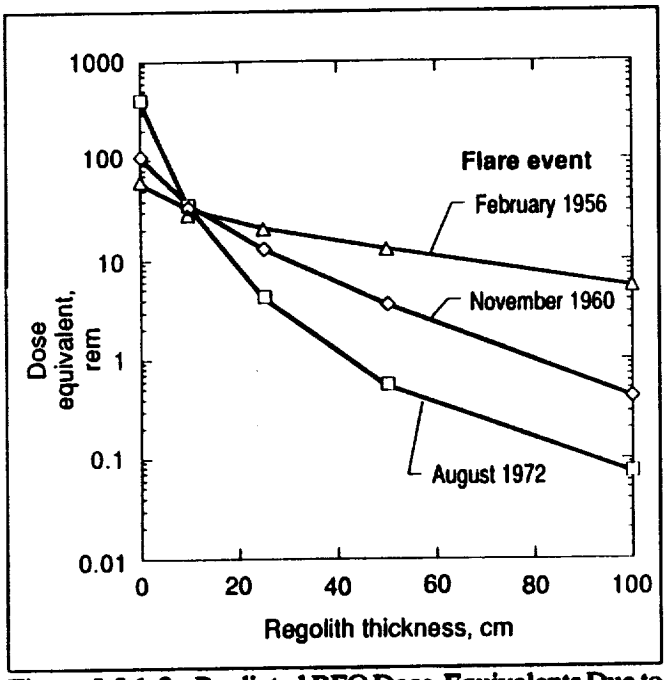



Figure 5.5.1-2.- Predicted BFO Dose-Equivalents Due to Large Solar Particle Events.

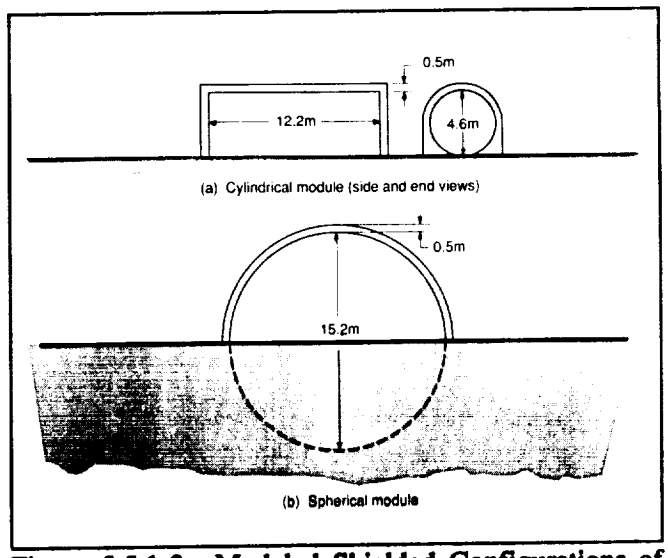



Figure 5.5.1-3.- Modeled Shielded Configurations of Candidate Lunar Habitation Modules.

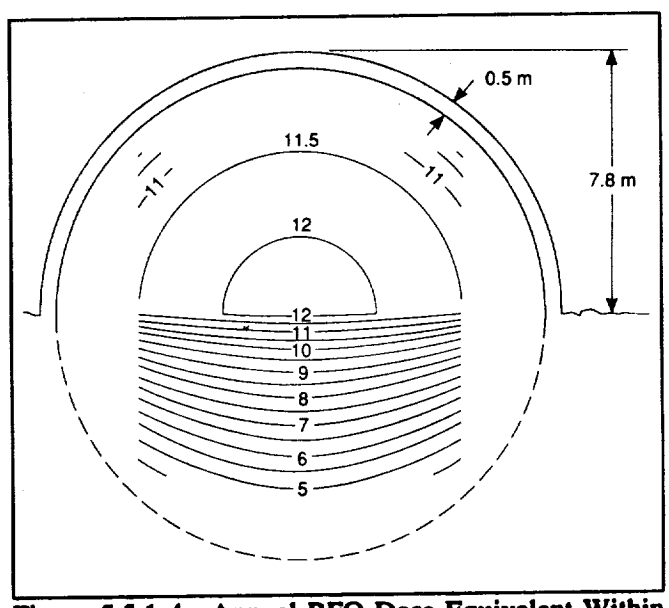



Figure 5.5.1-4.- Annual BFO Dose-Equivalent Within Shielded, Half-Buried Sphere.

integration for the directional dose pattern. If this procedure is performed for a sufficient grid of interior target points, a map of the dose pattern within the configuration may be constructed. Such a dose pattern is shown in figure 5.5.1-4 for the half-buried sphere with a 50-cm regolith shield on the portion above ground level. The maximum annual dose level from GCR's near the center of the sphere is predicted to be somewhat in excess of 12 rem/yr. The shielding effect due to partial burial is clearly in evidence. Similar types of dose patterns were exhibited for the particle event spectra.

For the shielded cylindrical configuration on the lunar surface, dose variations from point to point in the interior are not large (minima and maxima differ by 15 to 20 percent). The GCR dose maximum in the cylinder is predicted to be 11.5 rem/yr. Table 5.5.1-I gives a summary of dose levels at the centers of the spherical and cylindrical configurations due to the three particle events.

### 5.5.1.4 Lunar Radiation Protection Conclusions

The analyses and subsequent results described in this section have indicated that candidate lunar habitat configurations shielded with a 50-cm thick regolith layer are subject to annual dose levels of 11.5 to 12 rem/yr from GCR's, and up to 7.5 rem for a very large solar particle event. If one large event per year is assumed, total annual dose levels are on the order of 15-20 rem/yr.

While GCR and particle events constitute the most important radiation hazards, and the predicted combined levels are substantially below the current astronaut limits, additional aspects of the radiation issue should be mentioned. First, large uncertainties in transport cross-sections presently exist, and when compounded with additional environmental uncertainties, lead to overall uncertainties which may conceivably be as large as a factor of two. Furthermore, additional radiation exposures may be important contributors: e.g., possible fission power sources; smaller (but more numerous) solar particle events; and neutron backscattering pro-

TABLE 5.5.1-I.- BFO DOSE-EQUIVALENT PREDICTIONS FOR THREE LARGE EVENTS

| Event Date | Shield Thickness (cm) | Predicted Dose Cylinder Center (rem) | Predicted Dose Sphere Center (rem) |
|---|---|---|---|
| 1956 | 50 | 7.48 | 7.04 |
| | 100 | 2.70 | 2.94 |
| 1960 | 50 | 1.60 | 1.90 |
| | 100 | 0.16 | 0.23 |
| 1972 | 50 | 0.25 | 0.30 |
| | 100 | 0.03 | 0.04 |

cesses (not accounted for in these analyses). These sources should be addressed in future studies.

### 5.5.2 Martian Radiation Protection

Methods for dealing with ionizing space radiation on the martian surface have many similarities to those applied to the lunar surface. The same sources of most hazardous energetic particles, i.e., galactic cosmic rays and large solar particle events, appear to be equally important for Mars. The composition of the martian regolith, while somewhat different from that of the Moon, should behave in a manner comparable to the lunar soil insofar as shielding properties are concerned. Mars, like the Moon, is devoid of an intrinsic magnetic field of sufficient strength to influence charged particles trajectories. On the other hand, there are important differences: Mars has an atmosphere, and is situated in the solar system approximately 1.5 times farther from the Sun.

Since Mars has no trapped radiation belts, the charged particle environment outside the atmosphere is made up of solar wind particles, flare particles and the GCR constituents. Ordinary solar wind particle energies are too low to be of concern as a radiation hazard in comparison with flare particles, and cannot penetrate the martian atmosphere. This is not the case for GCR and energetic flare particles, and in the ensuing analysis of martian atmosphere attenuation, the free space environment is taken to be identical to that used in the lunar evolution studies. GCR intensities are not thought to vary significantly in the part of the solar system occupied by the terrestrial planets. Although some evidence exists that flare intensities decrease with increasing distance from the Sun, little is known about the specific mechanism. Therefore, the assumption used here that flare intensities at Earth are comparable to those in the martian vicinity is probably conservative.

#### 5.5.2.1 Martian Atmosphere Models

Results provided by the Viking missions have been of great value in defining the martian atmospheric structure and composition. Since the thin martian atmosphere can undergo significant seasonal density variations, the impact on attenuation of radiation can be large. In the present study, two atmospheric models based on the Viking data have been used: a mid-latitude, cool, low pressure profile; and a mid-latitude, warm, high pressure model. These two models should provide an estimate of the variation in radiation intensities at the surface. The vertical temperature and pressure profiles for these models are shown in figure 5.5.2-1. For these analyses, the atmospheric composition has been taken to be pure carbon dioxide.

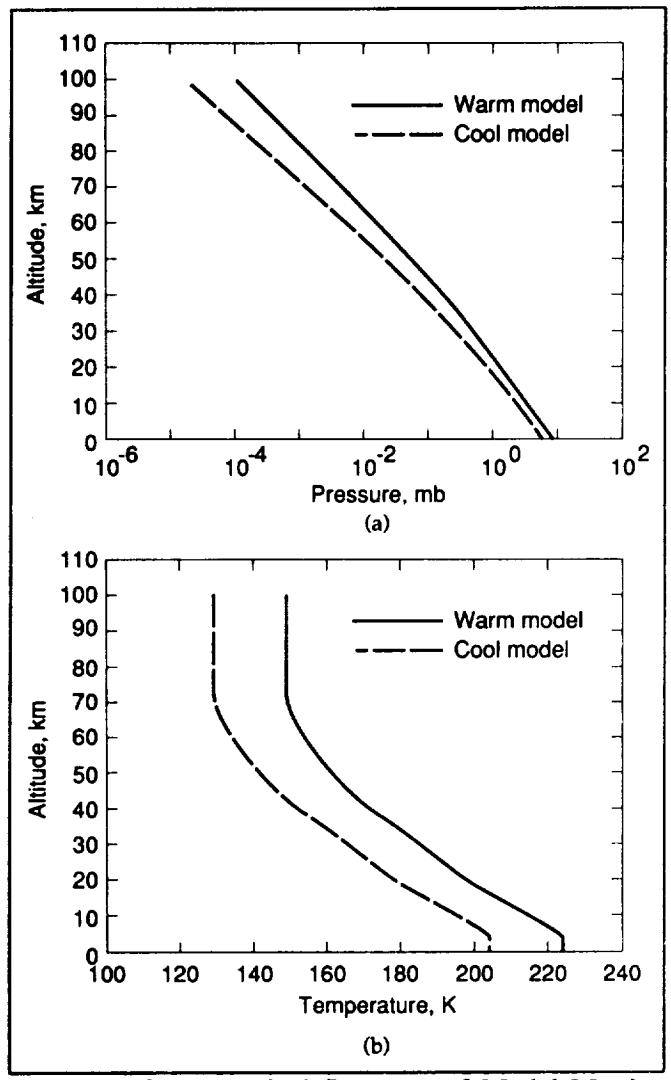



Figure 5.5.2-1. Vertical Structure of Model Martian Atmospheres.

#### 5.5.2.2 Transport Codes and Application to Atmospheric Attenuation

The Langley Research Center nucleon and heavy-ion transport programs were used to simulate the propagation of charged primary particles and their by-products through the carbon dioxide atmosphere. In the vertical direction, the low-pressure model provides approximately 16 g/cm² effective shielding, and the high-pressure model approximately 22 g/cm². Sample model output for GCR-initiated flux/energy distributions are shown in figure 5.5.2-2 for a 25 g/cm² amount of carbon dioxide. Most noteworthy are the substantial fluxes of neutrons and protons produced by the fragmenting heavier ions. For radiation incident from any direction, the atmospheric mass elements were integrated along specific slant paths to define the effective shield mass for a given zenith angle. A spherical shell geometry was assumed for the atmosphere.

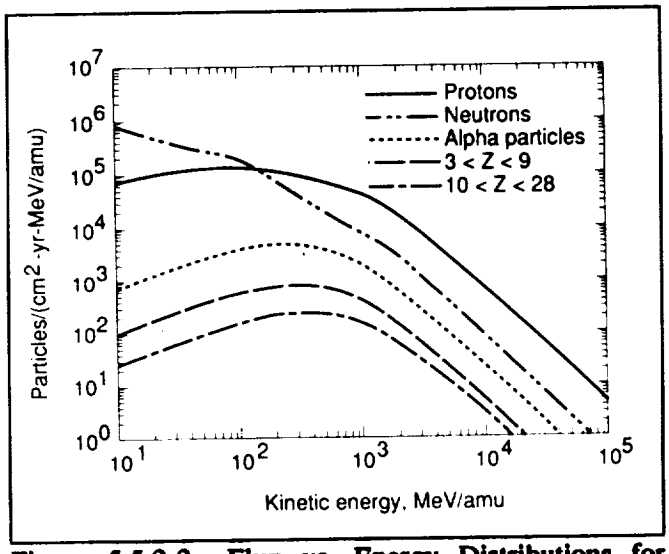



Figure 5.5.2-2.- Flux vs. Energy Distributions for Particles Due to GCR's After Traverse of 25 g/cm² in Carbon Dioxide.

#### 5.5.2.3 Ground-Level and High-Altitude Dose Results

Directional dose patterns were computed for the GCR and solar particle event spectra for zenith angles between 0 and 90 degrees in 5-degree increments. Total doses were calculated by numerical integration over the solid angle elements. Evaluations were made for both skin dose and vital organ (or blood-forming organ, BFO) dose. The BFO dose is taken as that incurred after an additional traverse of 5 g/cm² simulated human tissue. Predicted effects of altitude were also investigated by computing doses at both ground level and at 8 km. Table 5.5.2-I summarizes these results. Dosimetric quantities are in rem (rem/yr for GCR) and have been evaluated according to the International Commission on Radiological Protection quality factors specified in their report ICRP-26. In the table, for a given constituent calculation, the difference between skin dose and BFO dose is indicative of the self-shielding effect of the human body. The larger degree of shielding for the high-pressure model is readily apparent. Spectral influences are also evident in the results: less sensitivity to martian attenuation is shown for those fluxes having relatively large high-energy components, such as the GCR and the February 1956 particle event. Altitude effects are also seen to be important. The BFO dose for the August 1972 particle event exceeds the annual GCR dose at 8 km in the low pressure model. In general, the presence of the atmosphere is of significant benefit in radiation shielding.

#### 5.5.2.4 Martian Evolution Radiation Protection Conclusions

In the results given previously, one may construe a conservative yearly dose prediction as the sum of the annual GCR dose and the dose due to one large particle event. For the most favorable shielding case (high-pressure model, 0 km), the total BFO dose may approach 20 rem/yr. For the low-pressure, high-altitude case, the annual BFO dose may be as high as 34 rem. These dose predictions imply that the atmosphere of Mars alone provides shielding sufficient to maintain annual BFO dose levels below the current 50 rem/yr limit for U.S. astronauts. However, as with the lunar numbers discussed previously, it must be emphasized that the foregoing results are preliminary and should be considered as current best estimates which may be subject to uncertainties on the order of a factor of two.

### 5.5.3 Martian Expedition

An early martian expedition scenario calls for a crew time of twenty days on the surface. According to the radiation dose predictions given in the Mars evolution section (see table 5.5.2-I), the cumulative BFO dose due to galactic cosmic rays is approximately 1 rem for one month on the martian surface, even with little or no shielding. However, if such a mission takes place during a solar maximum period (2002 AD ± 3 yr or 2013 AD ± 3 yr), the likelihood of encountering a large solar particle event increases substantially. Assuming one large particle event per solar cycle and an active solar period of 5.5 years, the chance of seeing a large particle event in one month is about 1 in 65. As shown in table 5.5.2-I, a highly penetrating particle event such as occurred in February 1956 could result in a BFO dose of about 10 rem. Such a dose in itself is not thought to be very serious, but since most of the cumulative dose for a martian expedition of this type will be incurred in transit

TABLE 5.5.2.-I- PREDICTED DOSE-EQUIVALENT QUANITIES IN THE MARTIAN ATMOSPHERE FOR COSMIC RAYS AND LARGE SOLAR PARTICLE EVENTS

| Radiation Type | Dose-Equivalent Quantity | High Pressure Model | | Low Pressure Model | |
|---|---|---|---|---|---|
| | | 0 km | 8 km | 0 km | 8 km |
| GCR | Skin | 11.35 | 15.79 | 13.22 | 18.92 |
| | BFO | 10.49 | 13.72 | 11.90 | 15.79 |
| Solar Particle Event 8/72 | Skin | 3.92 | 21.06 | 9.02 | 46.22 |
| | BFO | 2.24 | 9.55 | 4.61 | 18.54 |
| Solar Particle Event 11/60 | Skin | 6.41 | 14.80 | 9.74 | 21.90 |
| | BFO | 4.98 | 10.61 | 7.31 | 14.84 |
| Solar Particle Event 2/56 | Skin | 9.22 | 13.33 | 11.02 | 16.22 |
| | BFO | 8.45 | 11.68 | 9.93 | 13.57 |

Note: Values are rem/year for GCR, rem/event for particle events.

between Earth and Mars, sustaining a dose of 10 rem during the brief time on the surface is highly undesirable. It is assumed that flare alert and monitoring devices will be available. If so, crew members may take advantage of suitable terrain features or the lander module itself for shelter. In the event of a flare occurrence, such measures could substantially reduce the incurred dose.

## 5.6 ELECTRICAL POWER

This year's study effort involved evaluation of power systems and electrical power distribution concepts to support housing, transportation, construction, and workshop facilities required for exploration of the surfaces of Mars, Phobos, Deimos, and Earth's moon. Planetary surface power systems will be required to supply power for surface equipment, operations, and activities. Applications for stationary power systems span such elements as expeditionary landed habitats to fully operational bases with processing capabilities. Power levels range from about 500 W to about 1 MW. The unique characteristics that prevail on the planetary surfaces that are currently contemplated for human exploration and development pose significant challenges to power system design and selection.

Varied environmental conditions will be encountered. For example, the Moon has large variations in diurnal temperatures, tenacious dust, no atmosphere, and a 712 hour diurnal period. Mars has a low density, carbon dioxide atmosphere, prevailing winds, both global and local dust storms, and generally cold temperatures. The martian moons have very low gravity and periodic eclipses. These unique features must be factored into the design process once the power system option is chosen.

### 5.6.1 Stationary Power

Stationary power systems find applications on the surface of the Moon, Mars, and possibly in the vicinity of Phobos or Deimos. There are several strategies for surface power system activation. First, deployable or quick-setup systems that astronauts can assemble with minimal effort are needed. Power systems designs must be such that tens of kilowatts can be activated to support housekeeping power needs. Such systems could be roll-out arrays or inflatable array structures. As the power requirements expand beyond the initial capability, the photovoltaic/energy storage system must be expanded or alternate options for the additional power must be implemented. One such option, particularly for lunar applications, is to land a nuclear power system to augment the array. Large nuclear systems (0.5 - 1.0 MW) will most likely require an existing construction capability and dedicated crew for assembly. An alternative is a lander vehicle/reactor integrated system that can supply high power shortly after landing.

The selection of one power system technology over another can be dependent on such second order effects as deployment time, evolutionary growth potential, and global location on the planet surface. Determining the global environment of Mars and how it will affect the power system is of particular interest. Solar insolation that falls on the surface is a function of latitude, season,

and both local and global dust occultation. These atmospheric conditions cause performance variations in arrays and heat rejection surfaces. Furthermore, the diurnal light/dark ratio changes with the planet's location about the Sun. Therefore, the array size and stored energy required are greatly influenced by the particular site chosen for exploration, since the crew will undoubtedly remain on the martian surface during night periods. A model of these environmental conditions can be utilized to size the power system components for any landing site selected.

Power system components can also be affected by other factors as well. The diurnal temperature range as a function of latitude and season is needed. In the case of arrays and radiators, accumulated dust will degrade performance. The degradation must be estimated so that the design can either accommodate the dust or eliminate or minimize the effects. Also, a determination must be made as to whether atmospheric and soil compositions are detrimental to the materials used to build the power system components and support structures.

### 5.6.2 Mobile Power

Power systems for mobile applications have the same environmental conditions issues as the stationary systems. However, additional factors must be considered for mobile applications. For example, long-range rovers may require integrated or on-board power systems since they will be away from a base power supply for recharging. Construction or mining vehicles will probably remain near the site and can be powered by a dedicated system that is periodically recharged by the base power system. The vehicle could remain for the required recharge period or possibly exchange storage systems to increase the vehicle's utility value.

Integrated power systems are capable of long excursions or even global access for planetary exploration. Small scientific as well as larger pressurized crew rovers are candidate applications. Photovoltaic or nuclear power generation can be considered. The nuclear options include radioisotope thermoelectric generators (RTG), dynamic isotope power systems (DIPS), and reactors. Figures of merit for each technology for a range of power levels and operating times should be quantified.

Dedicated power systems generally find applications in vehicles that remain in the vicinity of the base. The power system would consist of on-board energy storage and a dedicated portion of the base's generating power capability for recharging, either changeable power packs or the on-board system. Electrochemical or mechanical storage devices can be considered. Viable technologies include batteries, fuel cells, and flywheels. Viable technologies find applicability to various power levels and duty cycles.

### 5.6.3 Power Requirements for Representative Lunar Evolution Elements

The power requirements for a small number of representative elements are discussed. The essentials of these requirements are summarized in table 5.6.6-I. Table 5.6.3-I contains a more complete list of possible lunar evolution elements and the estimated power they may require from the base system during the day and night. In some cases, more complete power requirement data is available in sections addressing individual elements - i.e., see the surface transportation section (5.8) for breakdowns of pressurized and unpressurized rover power requirements.

Cargo vehicles will land first, placing a habitat, rovers, trucks, cranes, and diggers at an appropriate landing site. Several months later, humans will arrive to activate, adjust, and test these essential elements with the aid of extravehicular mobility units (EMU's).

The lunar EMU system will include advancements over previous Apollo systems and will require more power. An eight-hour mission will require 500 W from a power system that must be rechargeable in 15 hours to enable daily operation. Over 200 cycles (one year's worth) must be provided from one power source.

The initial lunar habitat will provide shelter and laboratory facilities for a crew of four for up to 6 months continuously. The power system must be capable of providing 30 kW average during day and night with a peaking capability of 50 kW during lunar daytime hours.

An unmanned robotic rover will be active during the lunar day and inactive during the lunar night. It will need 1 kW average during the day (1.5 kW peak) and 100 W at night. The rover's power system shall contain energy for a 6 month continuous cycle without refueling.

An unpressurized manned rover will be capable of carrying a crew of two as far as 10 km from the base (the walk-back limit). Total traverse distance may be more in the range of 50 to 100 km between recharges. It may require 3 kW peak power with an average requirement of 1 kW. A typical cycle will occur during the lunar day and last 8 hours. Daily use (Earth days) allows a maximum recharge time of 15 hours on the power system.

The preliminary ground breaking and assembly will be accomplished by a lunar digger and crane linked by a short range, large capacity truck. The digger and crane

TABLE 5.6.3-I.- LUNAR EVOLUTION ELEMENTS POWER REQUIRED FROM BASE

| Element | Estimated Power Required from Base (kWe) Day | Night | Element | Estimated Power Required from Base (kWe) Day | Night |
|---|---|---|---|---|---|
| Unpressurized Rover | 4 | 0 | Node | 5 | 5 |
| Pressurized Rover with Train | 40 | 0 | Inflatable Habitat (TCS, RLSS) | 60 | 60 |
| Power Trailer | | | Lunar Oxygen Demonstration | 2.9 | 0 |
| Habitation/Laboratory Trailer | | | Pilot Beneficiation Plant | 49 | 0 |
| Experiment Trailer | | | Oxygen Pilot Plant | 63 | 9 |
| Power Trailer 2 | 20 | 0 | Mining System | 19 | 19 |
| Ballistic Vehicle | 1 | 1 | Modular Beneficiation System | 25 | 25 |
| Crane/Digger and Truck | 15 | 0 | Modular Plant | 45 | 45 |
| Utility Vehicle | 10 | 0 | Laser Reflector | self-contained power | |
| Power Cart | 5 | 0 | Solar Observatory | 3 | 0 |
| Thermal Control System Cart | gets power from cart | | IR Telescope | 1.2 | 1.2 |
| Tanks/Liquifier | 7 | 7 | UV Telescope | 4 | 4 |
| Transfer Ramp (2 uses/yr) | 1 | 0 | X-Ray Telescope | 1 | 1 |
| Propellant Refill Veh. (4 uses/yr) | 1 | 0 | Earth Observatory | 3 | 3 |
| Lander Facility | 10 | 10 | Monitoring Telescope | 0.5 | 0.5 |
| Pad Markers | self-contained power | | Optical Telescope | 4 | 4 |
| Nav. Beacons/Transponders | self-contained power | | MERI | 0.7 | 0.7 |
| Communications Equipment | 0.30 | 0.30 | Gamma Ray Telescope | 0.3 | 0.3 |
| Communications Tower | 0 | 0.30 | Particles and Fields Instrument | 1 | 1 |
| Ground Station (communications) | 1 | 1 | Teleoperated Rover | 3 | 0 |
| Test Equipment | 0.10 | 0.10 | Analytical Science Lab. | 10 | 10 |
| Construction Shack | 40 | 20 | Biomedical Lab. | 4.2 | 4.2 |
| (ECLSS, TCS, Airlock) | | | Plant/Animal Lab. | 4 | 4 |

will need 50 kW for one minute peaks for 100 cycles in an eight hour period. They can share the same power system since they are operated in close proximity and in alternation. The truck will need 25 kW for 4 hour cycles linking the crane and digger. Thirty cycles are needed for the truck. The truck can carry the power system of the crane and digger.

As more humans and elements are integrated into a lunar outpost, a 1 MW power plant will be required as a central source of electrical power. Human elements, construction facilities, propellant-production pilot plants, and laboratories will be sustained by this source. As a redundancy feature, an independent 50 kW back-up power system will be provided, primarily for the habitat.

A fully operational lunar base with multiple elements will have to be integrated into a compatible power distribution scheme for assuring utmost reliability and efficiency. The key requirements and goals are high environmental tolerance and autonomy, easy deployability and maintainability, and growth potential with various interfaces.

### 5.6.4 Power Requirements for Representative Mars Evolution Elements

The power requirements for a small number of representative elements are discussed. The essentials of these requirements are summarized in table 5.6.6-II.

A human expedition to Mars will focus its activities around a martian habitat module for a crew of four with tours of duty starting at one month and growing to one to two years. The module will require 30 kW average with 50 kW peaking capability. The landing site will be at the martian equator, which has equal day and night periods (approximately 12 hours) year round.

The astronauts will venture out on daily EVA's with martian EMU's that will need 500 W average power for 8 hours. The power system will be different from the lunar EMU system due to different thermal conditions and the increased importance of low mass in the increased gravity.

An unpressurized rover will be used to carry a crew of two up to 10 km from the base similar to the lunar rover. The total traverse distance between recharges will be on the order of 50 to 100 km. The rover will need 1 kW

average power with 3 kW peak power capability for 8 hours on a once daily cycle basis.

With the expansion towards a martian outpost, distances between launch/landing facilities, scientific laboratories, construction sites, and habitats will be traversed by a pressurized rover with a 100 km range and crew capacity of four. This rover will be designed for a maximum sortie of 72 hours with a 15 kW average power requirement for 48 mobile hours and 8 kW while resting for 24 hours.

A martian crane/digger/truck network with similar requirements to the lunar network will be put in place.

The exploration of Phobos will require a manned maneuvering unit (MMU) adaptable to the martian EMU. The MMU will require 500 W for 8 hours such that its power system should be identical.

A fully operational martian base will require a centralized 1 MW power plant capable of continuous, near autonomous operation for fifteen years. The martian habitats and workshops will be supplemented with back-up power (100 kW) as a redundancy feature.

### 5.6.5 Power System Options and Criteria

Desired power levels, operating times, and life expectancies were determined from various case studies for the particular applications. These applications ranged from stationary to mobile with power levels in hundreds of Watts to megawatts. To satisfy these requirements, many power generation systems and storage devices were examined. These included: solar, chemical, isotopic, and nuclear. Some of these devices have been highly developed and qualified for space; others require advanced development programs to mature them to the qualification stage. For both power generation and storage systems, technologies were identified that appear to satisfy the various power levels.

Table 5.6.5-I lays out the options for power generation, storage, distribution, conversion, and management and conditioning. Table 5.6.5-II lists the functional requirements that must be determined for each system. Tables 5.6.6-I and 5.6.6-II show specific option selections in representative cases, with estimated weights and volumes. The case studies have been useful in determining power levels, life support requirements, and environmental conditions that may affect the operation and life of power systems. Meaningful trades will be made once a viable scenario has been developed using the systems deemed most adaptable to the planet environment and likely to be available in the late 1990's and early 2000's.

TABLE 5.6.5-I.- POWER SYSTEM TECHNOLOGIES FOR SURFACE SYSTEMS

| Generation Options | Conversion Options |
|---|---|
| Solar | Photovoltaic--silicon, gallium arsenide, Indium phosphide<br>Solar Dynamic--Brayton, Stirling, organic Rankine |
| Nuclear (SP-100)<br>(other reactor types) | Static--thermoelectric, thermionic, Amtec<br>Dynamic--Brayton, Stirling, liquid metal Rankine |
| Isotopic | Static--thermoelectric (RTG), Amtec<br>Dynamic--Brayton, Stirling, organic Rankine |
| **Storage Options** | Primary--batteries, fuel cells<br>Secondary--batteries, fuel cells, mechanical, thermal |
| **Distribution Options** | Cables<br>Free Space Transmission (beamed power)--laser, microwave |
| **Power Management and Conditioning Options** | Current Level<br>Voltage Level<br>AC/DC<br>Frequency |

Most existing devices have been developed for orbiting spacecraft and probes into outer space. Power levels have been limited to hundreds of Watts except for applications such as the Shuttle and Space Laboratory that have power levels in the 10 to 25 kW range. Except for batteries, fuel cells, solar photovoltaic devices and isotopic systems, other potential power systems have short lives and/or are in development and not qualified for space applications. Power systems for use in surface applications may be different due to the changes in environment and application. Choosing the power system option is a readily accomplished task, but the availability of that chosen option may be beyond a mission's manifest date. A desired power option may not be in active development or may be at a very low level, precluding its use in the projected time frame. It appears that a system must be in active development or starting in the very near term to be seriously considered for a mission in the late 1990's and early 2000's. Every effort should be made to see that work on developing power technology of interest to this program should be continued at a meaningful level.

TABLE 5.6.5-II.- POWER SYSTEM FUNCTIONAL REQUIREMENTS

- Load Power Profile (Magnitude. vs. Time)
- Total Lifetime
- Recharge Allowed
  - Number of Recharges
  - Recharge Time
- Set-up Time
- Dormancy/Restart Capability
- Maintainability
- Load Power Characteristics
  - Regulation
  - Wave Shape
  - Voltage Level
  - Harmonic Factor
- Element Environment Constraints
  - Radiation
  - Thermal
  - Vibration
  - EMI
- Reliability
- Survivability
- Effluence Limitation
- Extraterrestrial Assembly
- Pre-Launch Qualification and Testing
- Safety
- Other Operational and Environmental Constraints

Power systems were evaluated with regard to power and energy profile and environmental, design, and technological constraints. The mass and volume limits that can be accommodated in the transport vehicle determine the modularity sizing of the system.

During its lifetime, the power system will be exposed to various thermal, radiation, and mechanical environments during launch, delivery, extraterrestrial landing, assembly, activation, operation, and disposal phases. The system must be designed to withstand these conditions.

Design constraints include safety, reliability, maintainability, and survivability of the system and vary greatly if the system is manned. The technological readiness of a system is an important selection factor particularly when considering development effort, number of flight units, and operational needs.

### 5.6.6 Selected Power Systems

Table 5.6.6-I shows selected power systems with mass and volume estimates used to meet various preliminary requirements for the lunar evolution study. Table 5.6.6-II shows the same thing for Mars.

### 5.6.7 Power Distribution Concepts

Two concepts for distributing electrical power within an extraterrestrial surface base--transmission via conductors and through free space by microwave or laser--are discussed. Thermal energy distribution should also be optimized, but was omitted from this initial study due to lack of thermal parameters for many surface elements.

#### 5.6.7.1 Transmission Via Power Conductors

Present NASA space power activities concentrate on the alternating current (AC) option (400 Hz or 20 kHz), whereas in Europe, direct current (DC) (150 V) systems are preferred. Each of these systems has certain advantages and disadvantages. The AC option only needs a transformer instead of a DC/DC converter to change voltage level. Since a high-frequency AC system has a low energy cycle, well below the lethal level, ground fault interrupt is easy. This permits a high system voltage. A high-frequency AC distribution system will weigh less than a low-frequency AC system due to the size of the transformers required. Finally, conversion of power at the generator to high-frequency AC will require large static inverters which will increase mass, complexity, and development effort.

Any extraterrestrial outpost will benefit from the terrestrial power distribution experience. The mass of the outpost system will depend on the operating voltage, acceptable voltage drops, frequency, conductor material, and, of course, the distances between the sources and users. However, the biggest concern remains the sheer mass of the extensive network of cables that would be required barring any breakthroughs in high current density superconductors.

#### 5.6.7.2 Free Space Transmission

Microwave and laser power transmission systems have many advantages over conductor transmission systems because they require no mass in the form of wire conductors between the source of energy and the point of consumption. The direction of energy transfer can be changed by repointing the transmission antenna. The system does not lose energy in its transfer through the vacuum of space. Finally, the mass of the conversion devices at the transmitting and receiving points is a trade-off with conductor mass.

5.6.7.2.1 Microwave Power Transmission - This technology has steadily evolved over a period of more than three decades. Its basic principles and technological basis are well established. The transmission of power is achieved at the 2.4-2.5 GHz band of frequen-

TABLE 5.6.6-I.- LUNAR POWER SYSTEM ELEMENTS

| Element | Avg. Power (kW) | Peak Power (kW) | Op. Time | Power Source Prelim. Choice | Est. Mass (t) | Est. Vol. ($m^3$) | Remarks |
|---|---|---|---|---|---|---|---|
| EMU | 500 | - | 8 hr | SPE fuel cell | 0.07 | 0.05 | gaseous $O_2/H_2$, 15 hr recharge |
| Habitat | 30 | 50 | contin. | Nuclear reactor & power conv. unit | 4.0 | 27.0 | solar as option |
| Robotic Rover | 1 | 1.5 | 6 mo | Photovoltaic & batteries | 0.427 | 0.23 | 100 W required for night hibernation |
| Unpress. Manned Rover | 1 | 3 | 8 hr | Photovoltaic & batteries | 0.12 | 0.07 | 15 hr recharge |
| Crane/Digger and Truck | | 50/25 | 8 hr | Photovoltaic & regen. FC | 1.07 | 1.39 | crane--50 kW for 1 min., 100 cycles in 8 hr; truck--25 kW for 4 hr. |
| Power Plant | 1,000 | - | 15 yr | Nuclear reactor & power conv. unit | 14.9 | 291 | 50 kW backup req. |

cies. This band of frequencies is chosen because of the availability of relatively lower cost components at these frequencies. Moreover, the efficiency of the components at these frequencies is higher than could be obtained at higher frequencies. The process begins with DC power being converted into microwave power, followed by transmission of the microwave power from the transmitting aperture to the receiving aperture, and terminating with absorption and conversion back to DC power. Laboratory tests have reported an overall DC to DC efficiency of 54 percent. With additional development effort, efficiencies in the 70 to 80 percent range can be achieved, as well as extended component lifetime.

5.6.7.2.2 Laser Power Transmission - Laser concepts involve energy transmitted at laser frequencies rather than at microwave frequencies. These concepts have not yet been defined to the level of microwave concepts. At present, several approaches are being considered, including electric discharge and free-electron lasers. Laser diode array systems could provide efficiencies in the range of 20 percent, DC to DC.

Electric discharge lasers require electric power to drive a high voltage discharge that pumps the laser medium to

TABLE 5.6.6-II.- MARTIAN POWER SYSTEM ELEMENTS

| Element | Avg. Power (kW) | Peak Power (kW) | Op. Time | Power Source Prelim. Choice | Est. Mass (t) | Est. Vol. ($m^3$) | Remarks |
|---|---|---|---|---|---|---|---|
| Habitat | 30 | 50 | contin. | Nuclear reactor | 4.0 | 27.0 | |
| EMU | 0.5 | - | 8 hr | Fuel cell (FC) | 0.07 | 0.05 | gaseous $H_2/O_2$ |
| MMU | 0.5 | - | 8 hr | Fuel cell | 0.07 | 0.05 | |
| Unpress. Manned Rover | 1 | 3 | 8 hr | Photovoltaic & regen. FC | 0.27 | 1.2 | |
| Pressurized Rover | 13 | 15 | 72 | DIPS | 0.98 | 10.5 | |
| Crane/Digger and Truck | | 50/25 | 8 hr | Photovoltaic & regen. FC | 1.07 | 1.39 | crane--50 kW for 2 min., 100 cycles in 8 hr; truck--25 kW for 4 hr. |
| Habitat/Workshop | 100 | | contin. | Nuclear reactor & power conv. unit | 6.8 | 18.0 | |
| Power Plant | 1,000 | - | 15 yr | Nuclear reactor & power conv. unit | 23.5 | 46 | |

an excited discharge state and to circulate the lasant through a cooling loop to remove waste heat. Mass and cost factors of this method are not yet as competitive as the microwave method.

In the free-electron laser concept, an electron beam is formed (using a kylstron as the electron source which is accelerated in an RF cavity) that produces laser frequency energy upon passing through a magnetic field that causes lateral electron movement. The beam is directed to mirror assemblies that form a laser beam which is directed to a receiving station. This system appears to provide the highest efficiency and lowest mass of all laser systems studied.

### 5.6.8 Precursors

Precursor activities, as they relate to power systems, can be defined as any information gathering required to predict the performance of a power system during the lifetime of the mission. This is of significant importance since a power system will be operating for long periods of time on various planet surfaces to support future exploration activities. For example, environmental conditions on the Moon and Mars will need to be considered when making power system selections. This requires a detailed knowledge base of pertinent environmental conditions including:

- atmospheric composition
- surface composition
- temperature range and rate of change
- wind (if any) velocities and direction
- pressure
- radiation
- insolation
- dust effects
- diurnal cycles
- partial gravity
- heat sink temperatures

These factors affect the selection of a system or component and help define how it is designed, modified, constructed, and used.

Dust appears to a factor that can adversely affect the performance of the power and distribution systems on both the Moon and Mars. The concern is the tenacity with which it clings to surfaces. This can impair heat transfer from panels and mask solar cell and collector panels, reducing efficiency in both cases and resulting in intolerable reductions in performance. Winds on Mars can move dust around and probably into and on anything that is not sealed, while on the Moon mechanical agitation will create clouds or puffs. Dust may also be caused by engines, walking, riding, digging, or almost any operation that disturbs the surface. This was a real problem in Apollo and new solutions must be found.

Temperature will have an effect on all surface system elements. The major concern may not be the extreme specific values but rather the range, which on the Moon is 230°C, from -130°C to 100°C, and on Mars is 140°C, from -120°C to 20°C. This problem is most severe on the Moon, where the day-night cycle is long. If a system on the Moon is not operated during the night, it may never operate again due to freezing and/or cracking of structural materials, and the system itself. Our experience to date on the Moon has been for short periods of time, whereas our goal is for years of stable operation. Temperature must either be controlled for stable operation at all times or material selection and use will be a critical factor in uncontrolled environments. Thermal effects on out-gassing of electrical conductors could produce partial local atmospheres that also must be considered.

Soil composition is an important consideration. An accurate analysis is necessary to determine whether soil can be used as shielding material for radiation from reactors at habitats and from solar events. Composition also will determine whether necessary compounds are available in substantial quantities to produce reactants for some power sources. The type of electrical distribution system may also hinge on the characteristics of the surface and soil composition, since buried cables may be used for distribution from power systems. The soil composition will influence the selection of materials that are used to manufacture structures and power system components.

This environmental definition must precede testing of potential power systems for surface applications. Potential systems may be able to provided the necessary power, but must be modified to withstand the environment and provide adequate operating life. Most systems examined are still in the developmental stages with unproven performance, particularly in a relevant environment. Knowledge of the total environment will allow testing of power and storage systems in a relevant manner. The test data must then be factored into the final designs so that reliable power systems for planetary exploration can be achieved.

## 5.7 TELECOMMUNICATIONS, NAVIGATION, AND INFORMATION MANAGEMENT (TNIM)

This section discusses the progress that has been made to identify and document TNIM architectures and system designs to mission requirements. The emphasis this year for TNIM has been telecommunications. As the program develops, more will be known about requirements

for navigation and information management. Trade studies will be conducted next year concerning navigational architectures and sizing for the information management system. In addition, with maturity, the communications systems will also be updated.

Office of Space Operations support for the Planetary Surface Systems Integration Agent is divided between Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL). GSFC is responsible for developing TNIM architectures and designs for the lunar base. JPL is responsible for TNIM architectures and designs for Mars, Phobos, and Deimos activities.

GSFC developed a spreadsheet that includes all communications circuit requirements by user group. It also developed a lunar surface systems communications architecture in which local communications is satisfied with an ultra high frequency (UHF) system having an antenna atop a 30 meter tower. The radio range is for an area 10 km in all directions from the antenna.

All communications beyond the surface of the Moon and that which must be relayed beyond line-of-sight of the base camp are satisfied by two relay satellites located at libration point one (LP-1, near side of Moon) and libration point two (LP-2, far side of Moon). The satellites also serve as navigational information sources. Solar powered navigational beacons will be installed at the launch and landing facility and other locations as deemed necessary.

JPL developed the TNIM architecture and design for Mars and its moons. JPL's communications design considerations included frequency selection, data compression/coding needs, transmitter vs. antenna size trades, footprint vs. satellite altitude trades, satellite configuration, Mars-Earth link capacity vs. mission range trades, emergency communications strategy, and link characteristics.

The navigation design considerations consisted of system design, navigation requirements, segment elements, data types, segment application to mission phases (emplacement, consolidation, and utilization), and surface navigation.

JPL developed a model for mission operations functions that will be used to formulate the basis for information management partitioning and sizing. Trade studies in this area are scheduled for next year.

### 5.7.1 Lunar Surface TNIM System Concept

The lunar evolution case study describes an ambitious and complex human mission to the Moon. It requires diverse equipment, vehicles, and instruments. All lunar mission elements require telecommunications, navigational, and information management systems to function.

#### 5.7.1.1 Lunar Surface Tracking and Data Acquisitions and Data Processing Needs

The system segment that performs all communications and tracking functions has been designated the tracking and data acquisitions (T&DA) system. Collectively, the data processing systems comprise the other segment, the lunar exploration data system (LEDS).

Surface users of the T&DA and data processing systems are not completely defined, but a reference model of lunar surface elements has been identified to establish the services necessary for lunar exploration. Table 5.7.1-I summarizes this lunar element reference model. The full range of surface lunar elements is classified into six groups, with the locations for element servicing indicated.

TABLE 5.7.1-I.- LUNAR SURFACE ELEMENT MODEL

| Lunar Surface Element Group | Number of Elements | Location |
|---|---|---|
| Habitat and Support Equipment | 4 | Outpost |
| Mining and Manufacturing Equipment | 4 | Outpost |
| Robotic Rovers | 10 | Outpost Dispersed |
| Crew Rovers | 2 | Dispersed |
| Science Equipment | 30 | Outpost Dispersed |
| Observatory Equipment | 25 | Outpost Farside |

Possible T&DA and data processing requirements are derived from an analysis of lunar element needs. At this stage of analysis, more specific needs are identified for communications systems than for navigational and data systems. The major drivers of the lunar exploration communications system are the number of links required to serve the user community and the return data rates (from those users) on those links. Derived link and data traffic needs can be used to conceptually design a

communications and navigational architecture to serve the lunar elements. The link requirements estimated for surface elements are illustrated in figure 5.7.1-1.

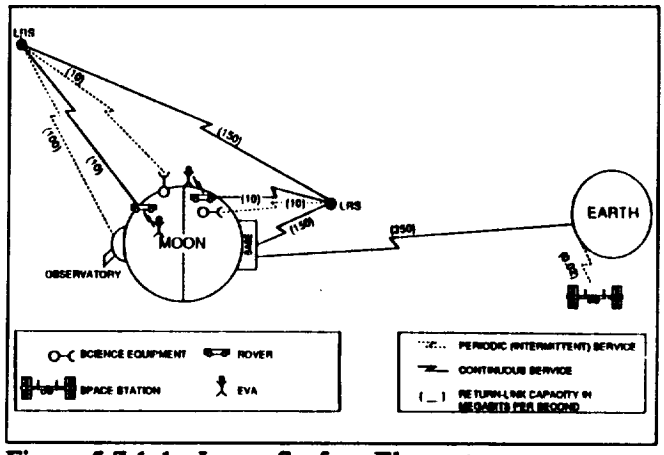



Figure 5.7.1-1.- Lunar Surface Elements.

Elements at the lunar base need communications among one another to allow for routine autonomous operations on the surface. They also need communications with Earth, transportation vehicles, long-distance rovers, and elements elsewhere on the lunar surface.

As shown in figure 5.7.1-1, Earth-bound data from the lunar base is multiplexed with data from other lunar elements and transmitted to Earth via a 350-Mbps trunk line. Links also are provided between the lunar base and all other elements on the lunar surface.

Many operations of lunar equipment are automated and may be controlled from the Moon. However, low-rate engineering status report data must be transmitted to Earth. Higher rate engineering and video data from equipment at the base may occasionally require transmission to Earth to deal with malfunctions requiring terrestrial intervention. Scientific and astronomical equipment generate large quantities of data that need transmission to Earth. Scientists on Earth must generate commands to exercise at least partial control of the scientific instruments. Range safety for approaching transportation vehicles also is needed at the base.

Data processing and control centers that monitor the lunar elements at the base are needed on Earth and the Moon. Scientific instruments are proposed for dispersed locations on the lunar surface. These instruments require periodic transmission--at relatively low data rates--of scientific and engineering data to Earth-based control centers. Position determination is required for all surface elements, and instrument data restoration and other low-level data processing are required when the data is returned to Earth.

Astronomical instruments, particularly a very low frequency (VLF) array, are proposed for emplacement at an observatory on the far side of the Moon. These instruments require transmission of large amounts of scientific and engineering data at high rates from a location on the Moon that is shielded from direct view of Earth. A link must be available to the far-side observatory to accommodate return data rates of at least 100 Mbps. The astronomical instruments require control centers on Earth and lunar surface position determination. In addition, the capability must exist to restore and reconstruct the large quantities of scientific data received on Earth.

Long-distance robotic and crew rovers will explore remote areas of the lunar surface. Rovers require nearly continuous engineering, video, and scientific data transmission to the base and to Earth from locations all over the Moon's near and far sides. Robotic rovers also require remote control from the lunar base and/or Earth. A rover requires a link capable of providing tracking service and supporting return data rates of at least 10 Mbps. This link must be available for continuous service when the rover is operating, and serves as a relay for any extravehicular activities (EVA's) by rover crew members. Data processing systems on both the lunar and terrestrial surfaces are needed for these rovers.

### 5.7.1.2 Lunar T&DA System Reference Architecture

This subsection describes a candidate T&DA reference architecture to serve the entire lunar exploration mission. The highlighted architecture appears in figure 5.7.1-2. Although it is designed to accommodate the data rate needs identified for this case study, it would be feasible to increase the antenna sizes or power to support much higher aggregate data rates up to 6 Mbps, assuming the transmitters and receivers are capable of processing the bandwidth. Elements of this architecture will be designed to primarily support the T&DA requirements of the surface elements.

A single geosynchronous relay satellite (GRS) in an inclined orbit provides the primary relay for all communications between the Moon and Earth by linking a United States-based ground terminal (GT) with the near-side lunar surface terminal (LST) located at the lunar base. Near-side lunar elements are supported by the near-side LST and by a lunar relay satellite (LRS) in halo orbit about the L1 libration point. Far-side lunar elements are similarly supported by a far-side LST, co-located with the far-side observatory, and an LRS in halo orbit about the L2 libration point.

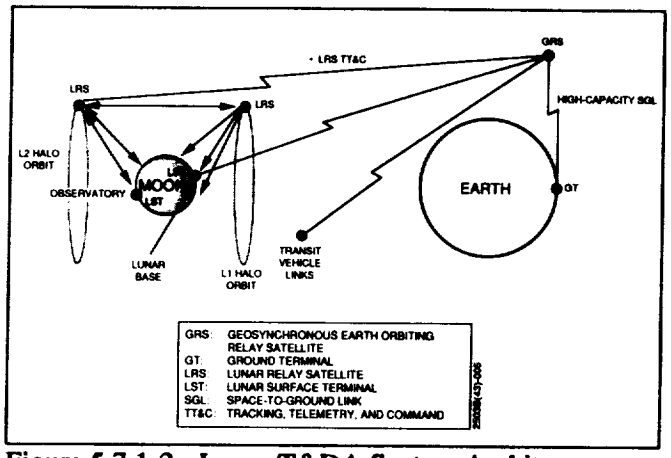



Figure 5.7.1-2.- Lunar T&DA System Architecture.

The communications and navigational needs of lunar surface elements are supported in different ways, depending on user location. All lunar vicinity communications are routed via the near-side LST, thereby enabling local control and monitoring at the base. The LST returns selected data to Earth via the GRS using time-division multiplexed (TDM) channels.

Users within 10 kilometers of the near-side LST are linked to it by hardwired interfaces and a broadband ultra high frequency (UHF) wide area network (WAN). This provides connectivity between lunar elements and the near-side lunar base, thus allowing the base to support local control and monitoring functions. Near-side users farther than 10 kilometers from the LST relay their data to the LST via radio frequency (RF) links to the L1 LRS.

Far-side users within 10 kilometers of the far-side LST are linked to it by hardwired interfaces. The LST then relays the data to the L2 LRS. Users farther than 10 kilometers from the LST transmit their data via RF links directly to the L2 LRS. The L2 LRS relays all data via crosslinks to the L1 LRS, which in turn relays the data to the near-side LST.

Communications links to all lunar elements are at Ka-band, with a 20-MHz bandwidth provided for both forward and return channels for user and tracking data. Navigation for lunar elements supported by LRS or GRS RF links is made possible by 1-way forward, 1-way return, or 2-way tracking, depending on the capabilities of the lunar element.

To reduce operational complexity, GRS's and LRS's support all communications by frequency-translated (bent-pipe) links with no demodulation or other processing performed onboard. The LST's and the GT act as data terminals, demodulating and modulating communications signals and providing distribution functions. In addition, the near-side LST acts as a major processing center, supporting the near-side base as the center for lunar operations. As a result, end-to-end communications between Earth and the Moon never involve more than three links before demodulation and processing or remodulation.

Some users of the T&DA system will need to provide various levels of data processing, including data compression, data storage, and data buffering, to remain within coverage and capacity limits imposed by the system. For example, scientific instruments on the lunar surface will need to buffer their data until a T&DA contact can be scheduled for data communications. Capacity limitations and conflicts between users may further require that some lunar elements be denied service during particular periods. For example, when three transport vehicles are in low lunar orbit (LLO) and simultaneous crew surface activities require support, service to surface instruments may be delayed.

### 5.7.1.3 Description of Surface T&DA System Elements

The major surface elements of the T&DA system include the LST located at the near-side base and an LST located at the far-side observatory. The significant characteristics of the surface elements of the T&DA reference architecture are listed in table 5.7.1-II.

In addition, antennas are required on all surface elements not hardwired to an LST. UHF whip antennas are proposed for elements at the lunar base; Ka-band antennas are proposed for scientific instruments and rovers that are located beyond 10 kilometers of the LST. The mass, power, and volume required for communications equipment by major groups of surface elements and T&DA system elements are shown in table 5.7.1-III. These characteristics are shown by the mission phase that the equipment will be required on the lunar surface. Further definition of the equipment mass, power, and volume characteristics will be provided in future work.

5.7.1.3.1 <u>Near-Side Lunar Surface Terminal</u> - The near-side LST is to be co-located with the near-side lunar base, directly servicing the surface habitats, scientific facility, mining facility, and observatory facility. Moreover, the near-side LST interacts with the near-side LRS to support both near-side and far-side elements, with local lunar communications routed through the near-side LST. The near-side LST thus serves as a communications center for all lunar activities, in addition to providing the primary Moon-to-Earth communications link. Forward communications from Earth are demultiplexed and distributed to lunar ele-

TABLE 5.7.1-II.- CHARACTERISTICS OF T&DA SYSTEM SURFACE ELEMENTS

| System Element | Supporting Subsystem | Application |
|---|---|---|
| Near-Side Lunar Surface Terminal | 1 LST-GT antenna<br>4 m diameter, Ka-band (32.5 GHz) | Supports Moon-Earth communications link to GRS |
| | 1 LST-LRS antenna<br>3 m diameter, Ka-band (32.5 GHz) | Supports link to near-side LRS and thereby far-side users, the farside LST, and near-side users beyond 10 km of near-side LST |
| | Wide Area Network<br>UHF (400 to 800 MHz)<br>30 m antenna mast provides<br>10 km line-of-sight visibility | Supports lunar users within 10 km of near-side LST |
| | Hardwire interfaces<br>(fiber optic or coaxial cable) | Supports high data rate users within 10 km of near-side LST |
| Far-Side Lunar Surface Terminal | 1 far-side LRS antenna<br>1.5 m diameter, Ka-band (32.5 GHz) | Supports link to far-side LRS |
| | Hardwire interfaces<br>(fiber optic or coaxial cable) | Supports far-side users within 10 km of far-side LST |
| Lunar Element Antennas and Receivers | Long-distance rover antennas<br>75 cm diameter, Ka-band (32.5 GHz) | Supports link to LRS's |
| | Distributed science instrument antennas<br>20 cm diameter, Ka-band (32.5 GHz) | Supports links to LRS's |

TABLE 5.7.1-III.- SURFACE COMMUNICATIONS EQUIPMENT FOR THE LUNAR EVOLUTION CASE STUDY

| | Mass (kg) | Power Cons. (W) | Stowed Vol. ($m^3$) |
|---|---|---|---|
| Nearside Lunar Base | 344 | 1,300 | 1.01 |
| VLF Radio Telescope | 6 | 100 | 0.02 |
| Long-Distance Rovers | 36 | 150 | 0.15 |
| Selenophysical Stations | 64 | 560 | 0.32 |
| Near-Side Lunar Surface Term. | 1,070 | 1,150 | 16.00 |
| Far-Side Lunar Surface Term. | 150 | 225 | 4.00 |
| Total | 1,670 | 3,485 | 21.50 |

ments, and return communications from the Moon are multiplexed and formatted for relay to the GRS.

Lunar elements within 10 kilometers of the near-side LST, including human audiovisual and scientific instrument command/telemetry data, communicate using a broadband UHF (400- to 800-MHz) WAN supported by redundant 30-meter antenna masts (see figure 5.7.1-3) weighing less than 300 kg and consuming 250 W each. Low duty cycle and data rate users share a packet-switched broadcast channel. A dedicated bandwidth is allocated for circuits requiring high data rates (more than 1 Mbps) and voice/video channels. A UHF WAN allows dynamic allocation of service to the near-side lunar elements, which are within line of sight of a 30-meter tower. It does not inhibit the mobility of either the users or the near-side LST.

A 3-meter Ka-band (32.5-GHz) antenna supports forward and return communications with the near-side LRS, where the link to the LRS is the frequency-division multiplexed (FDM) composite of near-side and far-side channels. All return communications relayed by the near-side LRS to the near-side LST are demodulated there, with range and range-rate extraction performed to support 1-way or 2-way return tracking for near-side and/or far-side lunar elements. Return communications used by the near-side base (e.g., a long-distance rover video) are distributed locally by the near-side LST using

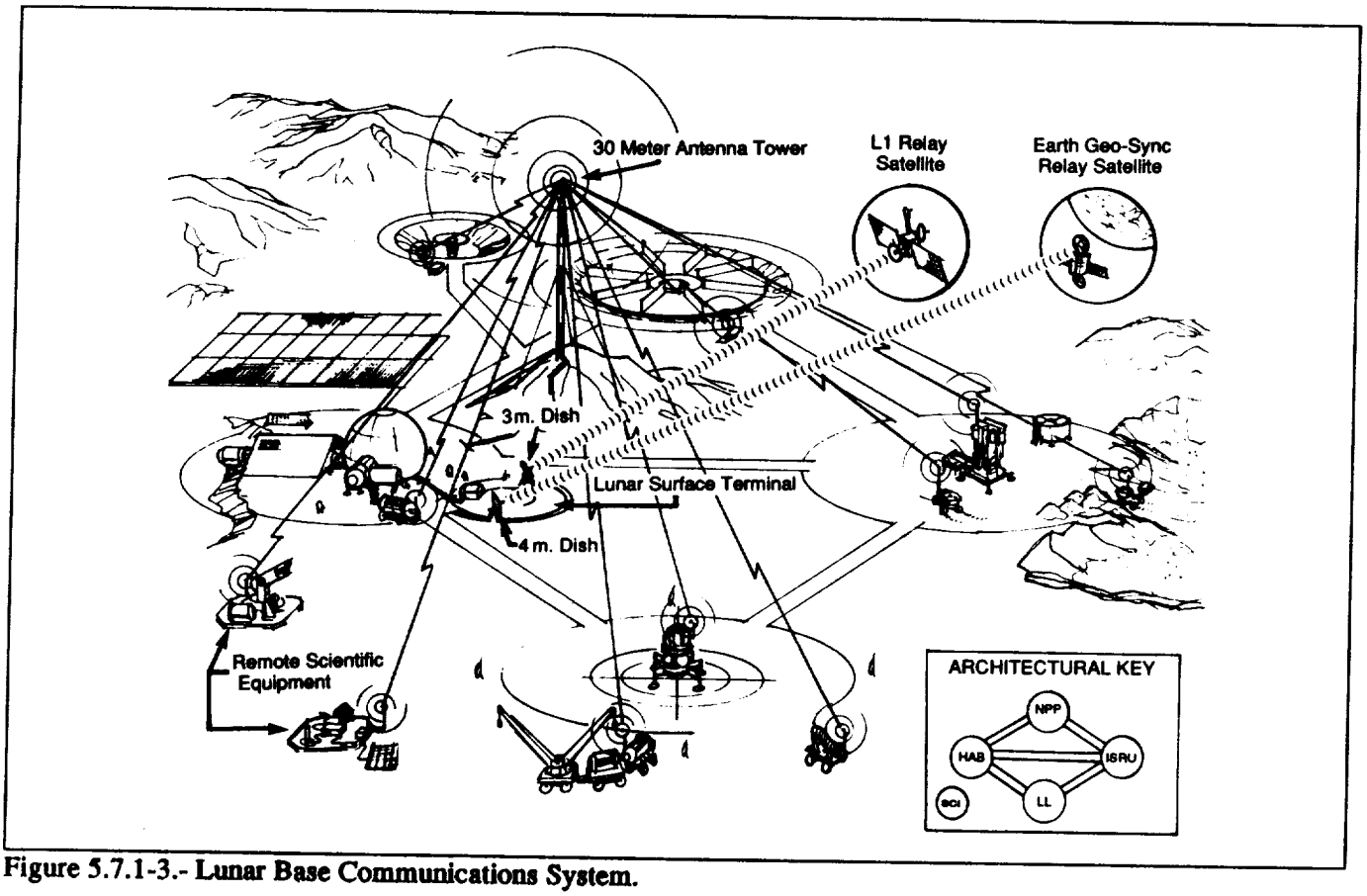



Figure 5.7.1-3.- Lunar Base Communications System.

the UHF network. Return communications destined for Earth are demodulated and multiplexed with other data for remodulation and trunk transmission.

The primary 350-Mbps return and 90-Mbps forward TDM links to the GRS are supported by a 4- meter, Ka-band (32.5-GHz) antenna at the near-side LST. The near-side LST, including the UHF antenna towers, is estimated to weigh 1,100 kg and consume 1,150 W of power. All forward communications from Earth are demodulated and demultiplexed to allow routing and distribution to lunar elements at the near-side base or remodulation and relay to the LRS's.

5.7.1.3.2 <u>Far-side Lunar Surface Terminal</u> - The far-side LST is co-located with the far-side lunar observatory, directly servicing the VLF array and possibly other users through hardwire interfaces. It is simpler than the near-side LST. Fiber-optic or coaxial cables link lunar elements within a 10-kilometer radius of the far-side LST.

A 1.5-meter Ka-band antenna supports forward and return communications with the L2 LRS. It transmits a 100-Mbps TDM return link and receives less than a 1-Mbps TDM forward link. Forward communications received from the L2 LRS are demodulated and distributed to the appropriate far-side lunar elements. Far-side return communications are multiplexed, concentrated, and formatted for transmission to the L2 LRS. The far-side LST is estimated to weigh 150 kg and consume 225 W of power.

5.7.1.3.3 <u>Lunar Element Antennas and Transceivers</u> - Lunar elements not located within 10 kilometers of the near-side or far-side LST communicate via LRS's in halo orbit around an L1 or L2 libration point. These elements require Ka-band (32.5-GHz) antennas for communications and tracking.

Long-distance rovers will require 75 cm dish antennas consuming approximately 50 W. Dispersed science instruments will require small 20-cm dish antennas consuming less than 10 W each.

Lunar elements located at the near-side base will use whip antennas to communicate with the central UHF antenna. Antennas and transceivers for all elements located at the lunar base are estimated to weigh more than 350 kg and consume more than 1.3 kW of power.

5.7.1.4 T&DA System Options and Technology Issues

A variety of system options are possible, reflecting incremental changes in the capabilities presented previously, as well as more substantive alternatives to the overall reference architecture. For example, if the near-side LRS will not be included, the size of rover and science antennas must be increased.

The capabilities of a UHF WAN must be further analyzed and compared to alternatives such as optical cables or the use of LRS's for communications within the base. Service of surface elements must be studied to determine whether UHF, hardwiring, or use of an LRS is optimal.

Alternative operations concepts must also be considered. A major issue is how much of the data generated on the lunar surface must be transmitted to Earth, and how autonomous the lunar operations can be.

The T&DA reference architecture apparently does not pose significant technological risks for the anticipated time frame early in the 21st century. Technology development is needed for such features as the near-side LST UHF broadband WAN; data compression for video and scientific data; source coding techniques for data reliability and privacy; and compact, lightweight antennas, tracking systems, transceivers, and communications systems and data systems automation for lunar elements. Any newly developed technology requires flight readiness demonstrations prior to use.

The near-side LST WAN requires development of low-cost, low-mass, and low-power consumption network transceivers to support the envisioned mix of video, voice, and data communications.

Data compression and source coding techniques depend on the characteristics of the original source data. Low-cost compact signal processors need to be developed to allow lunar elements to generate high-quality video data compressed to 10 Mbps. Lunar surface elements require development of low-cost, low-mass, and low-power consumption transceivers.

### 5.7.1.5 Data Processing System Concept

This subsection describes a preliminary system concept for the LEDS that is based on three high-level interactive data system functions: T&DA control, lunar element operations control, and telemetry restoration (see figure 5.7.1-4). The data processing system interconnects and interacts with Moon-based elements and with Earth-, space-, or Moon-based users of lunar elements. The lunar surface element--rover, scientific instrument, or astronaut--is analogous to a spacecraft tracked by NASA's current T&DA system. The lunar element user is analogous to an existing NASA project control or scientific operations center. This user is located on Earth, on Space Station Freedom, in lunar orbit, or at the lunar base (such as might be required for a tele-operated robotics application).

The system concept identified here includes Earth- and Moon-based data processing system elements. Reliability and serviceability concerns for space-based segments are mitigated by placing the principal space computational element at the lunar base.

5.7.1.5.1 <u>T&DA System Control</u> - T&DA control actively plans and drives the physical T&DA system, providing customers virtual communications circuits for a specified duration (termed an "event"). Each event serviced is processed through four phases: service authorization, scheduling, service, and service accounting.

All information flows are established through local switching centers similar to a private branch exchange. These switching centers establish virtual circuits among customers using local and trunk circuits. Users of the T&DA control system include lunar elements, operations control, and data processing and storage. To protect the network from inadvertent errors, T&DA control does not directly interface to lunar element users.

The concept includes switching centers located at both the Earth GT and the LST, linked via high-bandwidth radio links sufficient to accommodate aggregate nominal communications traffic loads. These trunk circuits are presumed to be a scarce resource; their use by lunar elements must be scheduled. Each switching center controls numerous local circuits having ample data rates, with users assigned for specific authorized service periods. In cases where user visibility is restricted, user tracking must be scheduled to enable the assigned circuit.

In this concept, the switching center located at the GT services Earth-based users requiring communications with surface elements. The switching center at the LST services all lunar surface sites, lunar EVA's, and lunar rovers. Both have either direct circuits or circuits relayed via lunar orbiting relay satellites at halo L1 and L2 locations. The switching center at the LST also is the primary communications center for lunar base range safety.

5.7.1.5.2 <u>Lunar Element Operations Control</u> - As illustrated in figure 5.7.1-3, a major function of the data processing system is to provide operations control for the lunar elements. This function needs to be provided by a distributed architecture with data processing sys-

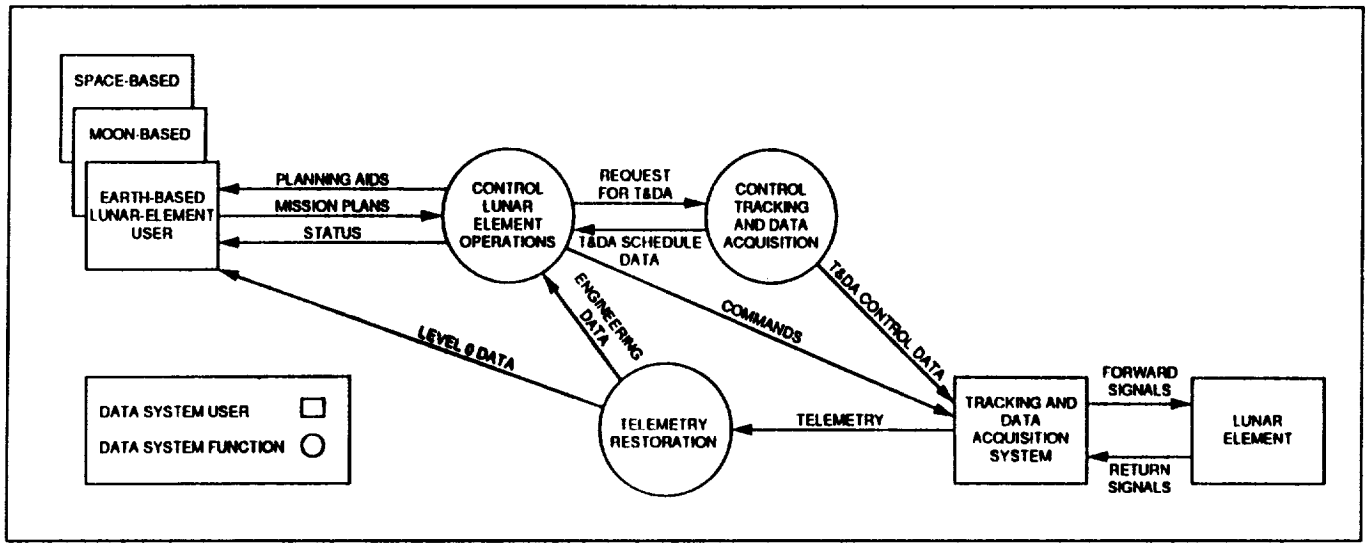



Figure 5.7.1-4.- Lunar Exploration Data Processing System.

tems at both the lunar base and on Earth. Operations control includes providing mission planning support, generating commands for real-time or planned activities, and monitoring the status of mission elements. In addition to these major functions, it also supports simulation, integration testing, and software development.

5.7.1.5.3 Telemetry Restoration - The telemetry restoration function receives all telemetered data streams from the lunar element, converts them into usable form, and makes them available to users of that data. Telemetered data streams include scientific instrument, engineering (e.g., health and safety and/or other ancillary data), voice, and video data.

To make data available to the users, the data streams must be recovered and separated into data packets. Minor transmission errors must also be corrected. Ancillary data requires processing, short-term storage, and distribution to the appropriate users. Health, safety, and other engineering parameters are separated and passed to both operations control and the lunar element user. Instrument data goes directly to investigators and other users. Because both terrestrial and lunar users need this data, telemetry restoration must be supported at both locations. The function might be located at the gateways to local networks or other surface distribution gateways such as the LST.

### 5.7.1.6 Future Lunar TNIM Focus

A concept has been developed for providing TNIM support for lunar surface operations. Details of how this support will be provided, and of the communications and data systems hardware required for that support, must be further developed.

Data system requirements to support surface operations must be carefully assessed and data system architectures developed that can provide the operations control, telemetry processing and autonomy required for affordable lunar exploration. These systems can have major impacts on the user service, life cycle costs and the technological feasibility and risk of the TNIM system.

It is important that analysis of TNIM requirements and development and evaluation of alternative system concepts and architectures to satisfy those requirements continue. Continuing studies of TNIM systems to support surface operations will focus on:

- A detailed information management and data systems study
- Development of operations concepts
- Continued trade studies and refinement of T&DA system designs.

## 5.7.2 Martian TNIM

The objective of the martian planetary surface TNIM support is to provide suitable surface subsystem design concepts that are compatible with the overall TNIM system design and architecture.

### 5.7.2.1 Telecommunications Design and Performance

The primary support effort for this study has been applied to communications utilizing external links. Only preliminary consideration has been given to direct intercommunications between elements on the surface. Many

surface science and operations requirements will be refined in the future, permitting a more complete telecommunications design. This more complete martian design will most likely resemble the lunar design.

Figure 5.7.2-1 illustrates the primary external telecommunications link architecture used for the surface elements at an established base on Mars. Only one of two required relay satellites is shown in the figure. The Ka-band links are used for high-rate data, whereas the broadbeam UHF links are used for large area coverage, low-rate data. (Similar links are available for a martian expedition, but are limited to the lander element on the surface.) In addition to the primary links shown in figure 5.7.2-1, broadbeam links via UHF are available between the relay satellites and the mars piloted vehicle (MPV) and science packages on Mars, Phobos and Deimos. Emergency links are available with the surface elements directly to and from the Earth via X-band.

The point design link characteristics for each surface element are summarized in table 5.7.2-I for the expedition and evolution cases. The antenna sizes, link applications, transmit and receive frequencies, data rates, and transmit RF power are all tabulated. Note that for the evolution case, the rovers and habitat each have the capability to receive a 50 Mbps data rate to support local telerobotic operations; however, 50 Mbps is the maximum relay satellite or MPV combined transmission capability for multiple beams over a single antenna. The performance of links with the MPV is based on a 33,000 km range. Table 5.7.2-II provides total DC power, mass, and volume for each surface element. These numbers are based on analogies to current spacecraft hardware and estimates of what may be available in the future.

Figure 5.7.2-2 illustrates the trade space considered in developing point designs for the local Mars high-rate links with the surface system elements. Required RF power and pointing accuracy are presented as a function of data rate and antenna diameter for transmission to the relay satellites and MPV. Because of the relatively short communications range and the high frequency employed for these links, relatively modest antenna size and transmitter power are sufficient: 0.45-m diameter directive antenna and 3- to 16-W RF power. The resulting antenna pointing requirement is about 0.5 degrees, which is well within mechanical pointing capability. If it is desirable to reduce the antenna size and relax the pointing requirement, the trade data of figure 5.7.2-2 provides a quick means to estimate the

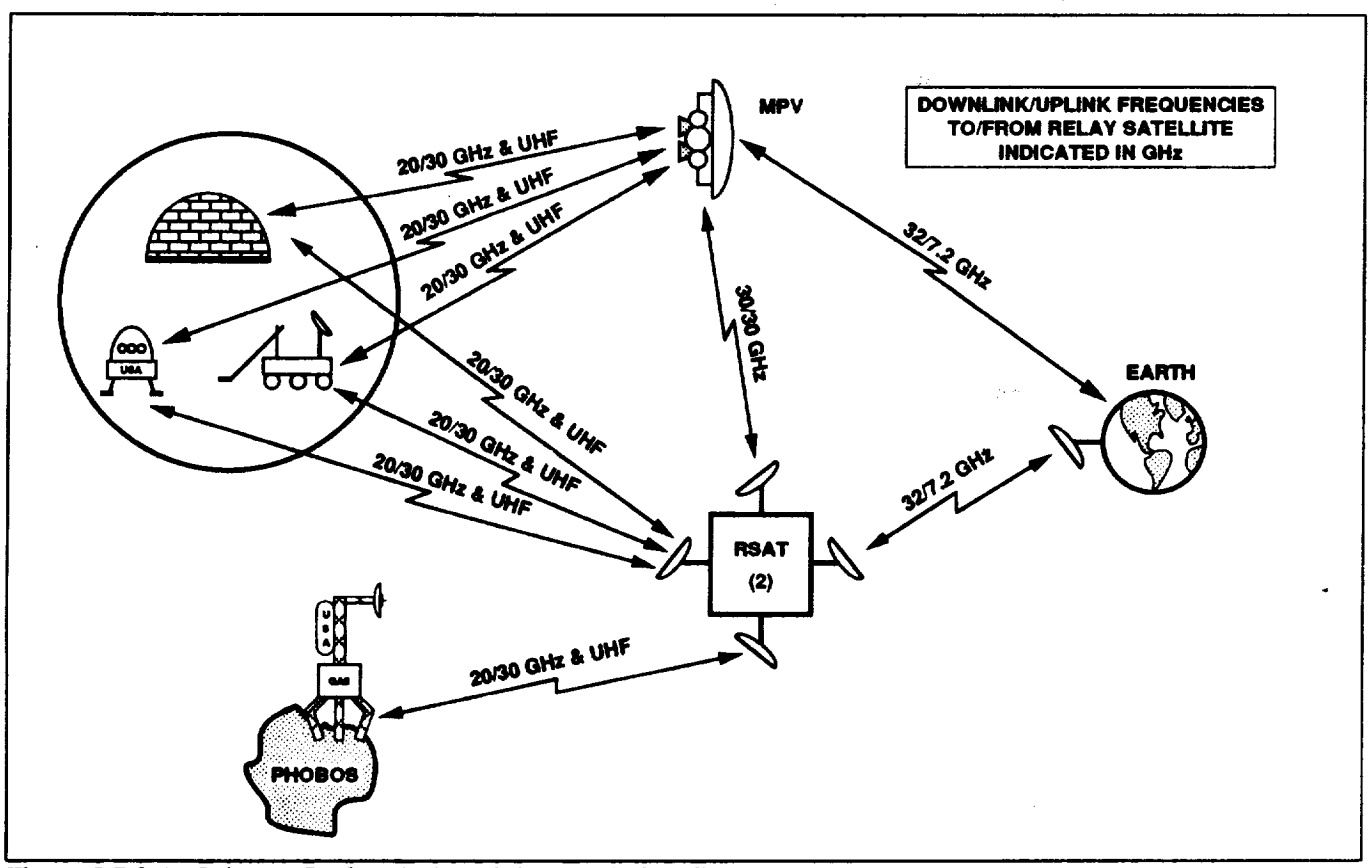



Figure 5.7.2-1.- Primary Surface Relay Links--Evolution Case.

TABLE 5.7.2-I.- TELECOM LINK CHARACTERISTICS FOR SURFACE SYSTEM ELEMENTS

| Case | Element | Link With | Ant. Size (m) | Frequency Xmit/Rcv (GHz) | Xmit Pwr. (W) | Link Cap. Xmit/Rcv (kbps) | Comments |
|---|---|---|---|---|---|---|---|
| Martian Expedition (Earth @ 1.6 au) | Lander (MCSV) | RSAT/MPV | 0.45 | 30/20 | 4 | 10,000/10,000 | Common UHF/Ka reflector |
| | | RSAT/MPV | 0.20 | 0.8/0.8 | 30 | 20/20 | |
| | | Earth | LGA | 8.4/7.2 | (50) | 0.006/0.203 | For emergency |
| Martian Evolution (Earth @ 2.5 au) | Habitat | RSAT/MPV | 0.45 | 30/20 | 16 | 50,000/50,000 | Common UHF/Ka reflector |
| | | RSAT/MPV | 0.20 | 0.8/0.8 | 30 | 20/20 | |
| | | Earth | LGA | 8.4/7.2 | (50) | 0.005/0.083 | For emergency |
| | Rover | RSAT/MPV | 0.45 | 30/20 | 7 | 20,000/50,000 | Common UHF/Ka reflector |
| | | RSAT/MPV | 0.20 | 0.8/0.8 | 30 | 20/20 | |
| | | Earth | LGA | 8.4/7.2 | (50) | 0.005/0.083 | For emergency |
| | Production Plant (Phobos) | RSAT | 0.10 | 30/20 | 4 | 500/500 | |
| | | RSAT or | 0.20 | 0.8/0.8 | 5 | 1/1 | |
| | | MCSV | 0.20 | 0.8/0.8 | (5) | 50/50 | Assumes 500 km range |
| | Science Package (Mars & Phobos) | RSAT/MPV | 0.80 | 0.8/0.8 | 5 | 1/1 | |

Notes: () indicates capability provided for emergency; normally inactive link.

TABLE 5.7.2-II.- MASS, POWER, AND VOLUME OF SURFACE SYSTEM ELEMENTS

| Comm. System | Mass (kg) | Normal Power (W) | Emerg. Power (W) | Volume ($m^3$) |
|---|---|---|---|---|
| Lander | 79 | 161 | 207 | 0.10 |
| Habitat | 96 | 212 | 207 | 0.10 |
| Rover | 92 | 174 | 207 | 0.10 |
| Production Plant | 60 | 61 | N/A | 0.05 |
| Science Package | 24 | 30 | N/A | 0.03 |

Notes:
N/A = Not applicable; emergency capability not provided.
Masses do not include data compression and data storage.
Volumes do not include antennas.

impact on transmitter power. It should be noted, however, that multipath effects become more severe as the gain of the main lobe is reduced.

As indicated in table 5.7.2-I, the martian TNIM design also provides emergency capability using low-gain antennas on the surface elements for X-band transmission direct to Earth (6 bps) or UHF/Ka-band via a martian relay satellite (20 kbps). Consideration should also be given to providing a backup high-rate Ka-band subsystem at the habitat base, which utilizes a several-meter diameter, high gain antenna similar to the 5 m directional antenna incorporated in the relay satellite point design for direct communications with Earth. Such a system could provide emergency high-rate communications as well as augment normal relay link capability during the daily periods when Earth is in view from the habitat.

The results of very preliminary analysis have been obtained for direct surface-to-surface communications utilizing a 30 m tower at the base station to support links with rovers, EVA astronauts, and science packages. Figure 5.7.2-3 shows direct surface communications link margin as a function of range out to 20 km. Martian soil electrical characteristics are assumed to be equivalent to very dry Earth soil. The grazing angle propagation path results in nearly complete cancellation of the direct signal by the ground-reflected signal causing the received signal strength to fall off as $1/(\text{range})^4$. Beyond 20 km for 10 MHz operation, or beyond 10 km for 100 MHz operation, there are additional losses due to the curvature of the surface of Mars. These effects will be assessed in a more detailed study, as well as the possibility of using the martian ionosphere for daytime communications out to a range of 1,000 km from the base.

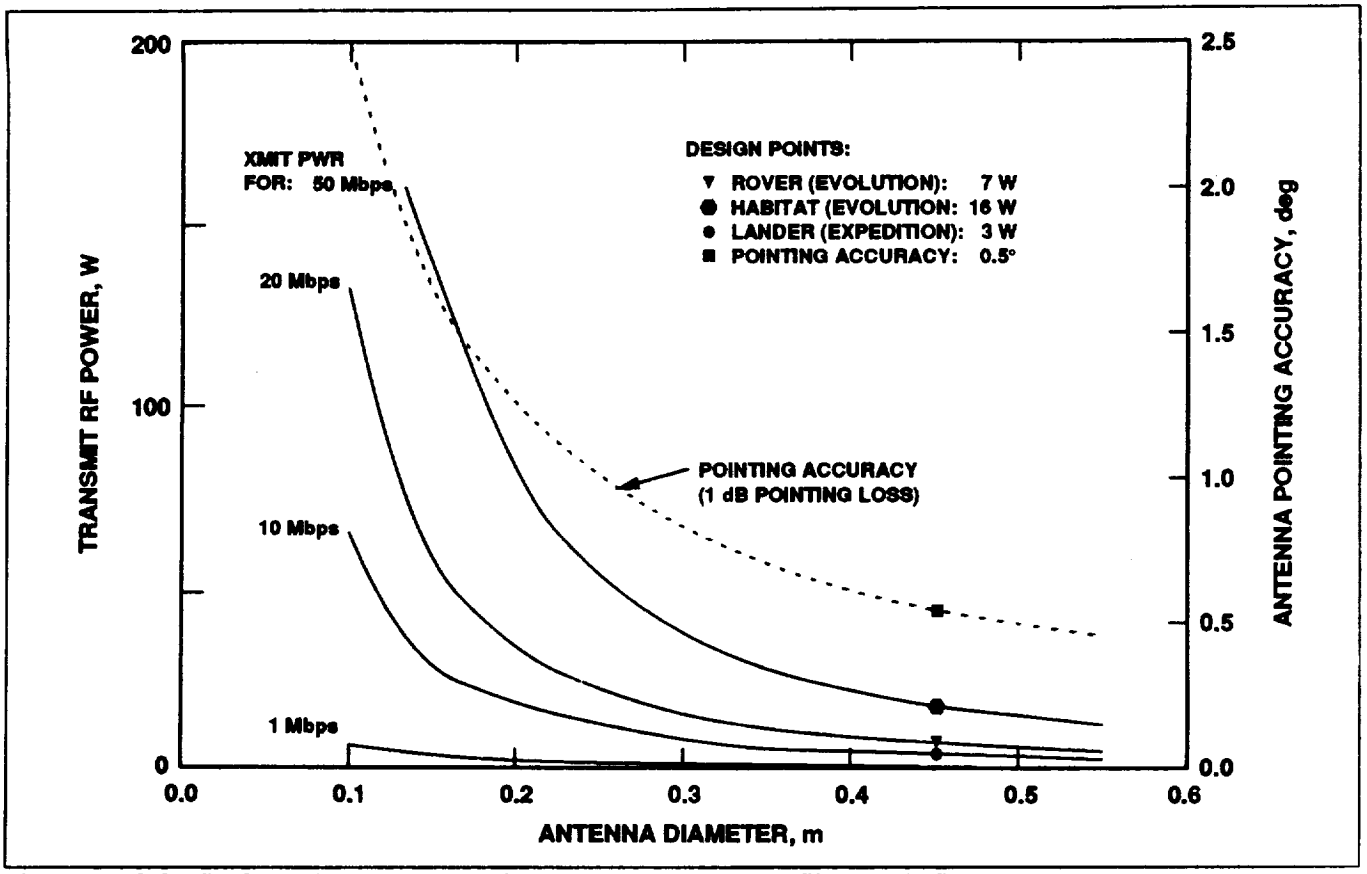



Figure 5.7.2-2.- Surface Elements Transmitter Power and Antenna Size Trade Space.

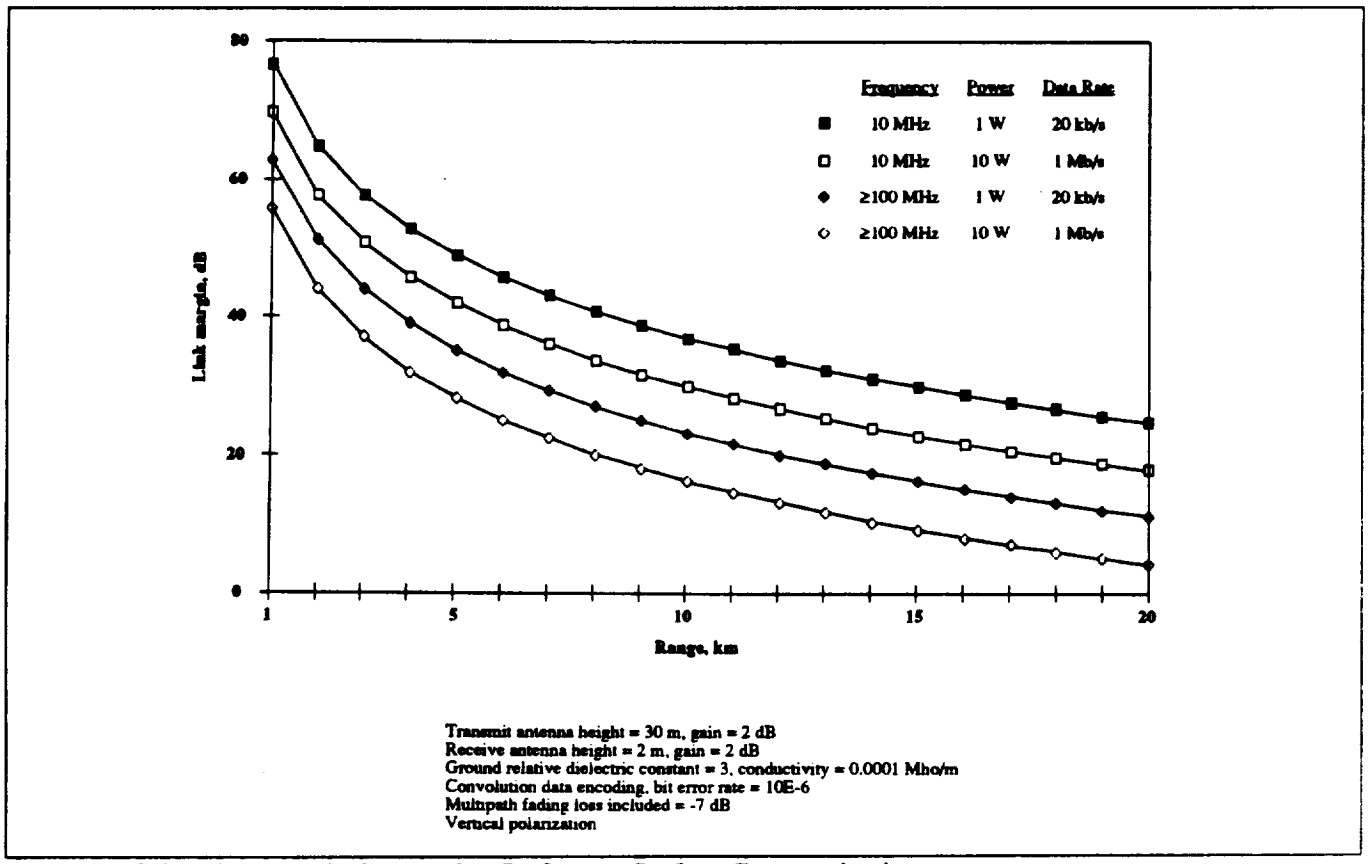



Figure 5.7.2-3.- Link Margin for Martian Surface-to-Surface Communications.

#### 5.7.2.2 Navigation

The initial Mars navigation system will consist of Segment I, Earth-based navigation (similar to the current Earth-based planetary navigation system), and Segment II, on-board navigation, which satisfies the need for real-time navigation during critical operations (e,g., aero-capture, landing, and long-range roving). Segment III, to be deployed for later flights, includes global navigation beacons/transponders on Mars, Phobos, and Deimos. The habitat and the rovers are also equipped with similar beacons or transponders for relative range or doppler data. In addition, a navigation center is established in the habitat with tracking and computational facilities to provide TDRSS-like navigation support during emergencies. In a later phase, several navigation satellites are deployed about Mars in two or more stages to provide real-time GPS-like navigation. This network has a role similar to that of the Earth-based navigation system, but supports real-time operations in the martian system. It will consist of a network of navigation satellites and global surface beacons. Segment III not only provides assistance to the on-board navigation system for highly accurate real-time navigation, but also independently provides full navigational support or computational support to any vehicle during emergencies.

Martian navigation system performance estimates have included preliminary consideration of two areas of interest: landing accuracy and relative separation accuracy of surface system elements.

Landing accuracy of 10 m ($3\sigma$) has been assumed as a requirement for hazard avoidance. Preliminary navigation analysis indicates this requirement can be achieved with an on-board navigation system that uses real-time tracking of landing beacons and/or a succession of optical landmarks that have already been mapped to the landing site. A single landing beacon (e.g., as may be deployed by a penetrator or precursor rover) may suffice for the first landing, after which a suitable array of landing beacons must be deployed in the neighborhood of a designated landing site.

For a nominal habitat-to-rover separation of 50 km, it is estimated that an on-board navigation system could determine the separation distance to an accuracy of about 25 m (RSS) using real-time doppler with a single orbiting spacecraft. This estimate assumes favorable geometry (separation direction normal to orbiter track). Separation accuracy for less favorable geometry and for other conditions will be estimated in future study efforts.

#### 5.7.2.3 Information Management (IM) Architecture

Surface habitat information management is part of a mission distributed-processor IM system containing "library," "post office," and utility functions. The high-level IM architecture is shown in figure 5.7.2-4. The utility functions move data between the library, post office, other surface terminals, and external terminals. The IM provides data quality and priority assessment, coding/decoding, routing, and storage/recall functions for Mars surface elements. The IM also supports a mode whereby the surface habitat may be the control center for Mars in situ mission operations, including telecom relay network reconfiguration. All human operator interfaces to co-located user subsystems are managed by those subsystems, not via IM; IM is normally transparent to the user. Using functional redundancy methodology, IM incorporates routing options that provide several alternate paths to other system terminals. Thus, a key characteristic of the IM/telecom capability is that it is the last to fail. Data includes science, engineering, navigation, and mission operations information (including control and acquisition predicts). Data compression is provided by the source subsystems. The IM operation is normally automatic, but a human operator override mode is provided. The local IM configuration can also be controlled by vehicles in situ, or by Earth operations.

#### 5.7.2.4 Martian TNIM Technology Needs

Central to the high-rate communication links to Earth, either direct or via relay, is the availabilty of Ka-band technology permitting use of smaller (1/2 size), lighter (1/3 weight), high-gain antennas for surface systems. Lower transmitter power is also an option, for which efficient Ka-band power amplifier technology in the 5 to 10 W performance range is needed. Small size, light-weight processors, $10^{12}$ bit memory, data compression, high performance code/decode methodologies, and very large scale integration (VLSI) technology are also key to support mission surface processing and surface IM functions.

#### 5.7.2.5 Future Martian TNIM Focus

Future surface TNIM system support will assume a definitive Mars surface science configuration and operations plan. The martian TNIM focus will include the following: 1) develop surface telecom architecture and system performance estimates, 2) provide a detailed equipment performance data base including mass, power, and volume needs, 3) develop a plan for normalizing user data needs to ensure low peak-to-average data rates and efficient channel use, 4) develop rover and landing beacon navigation designs, 5) provide cost estimation support for surface TNIM systems, and 6)

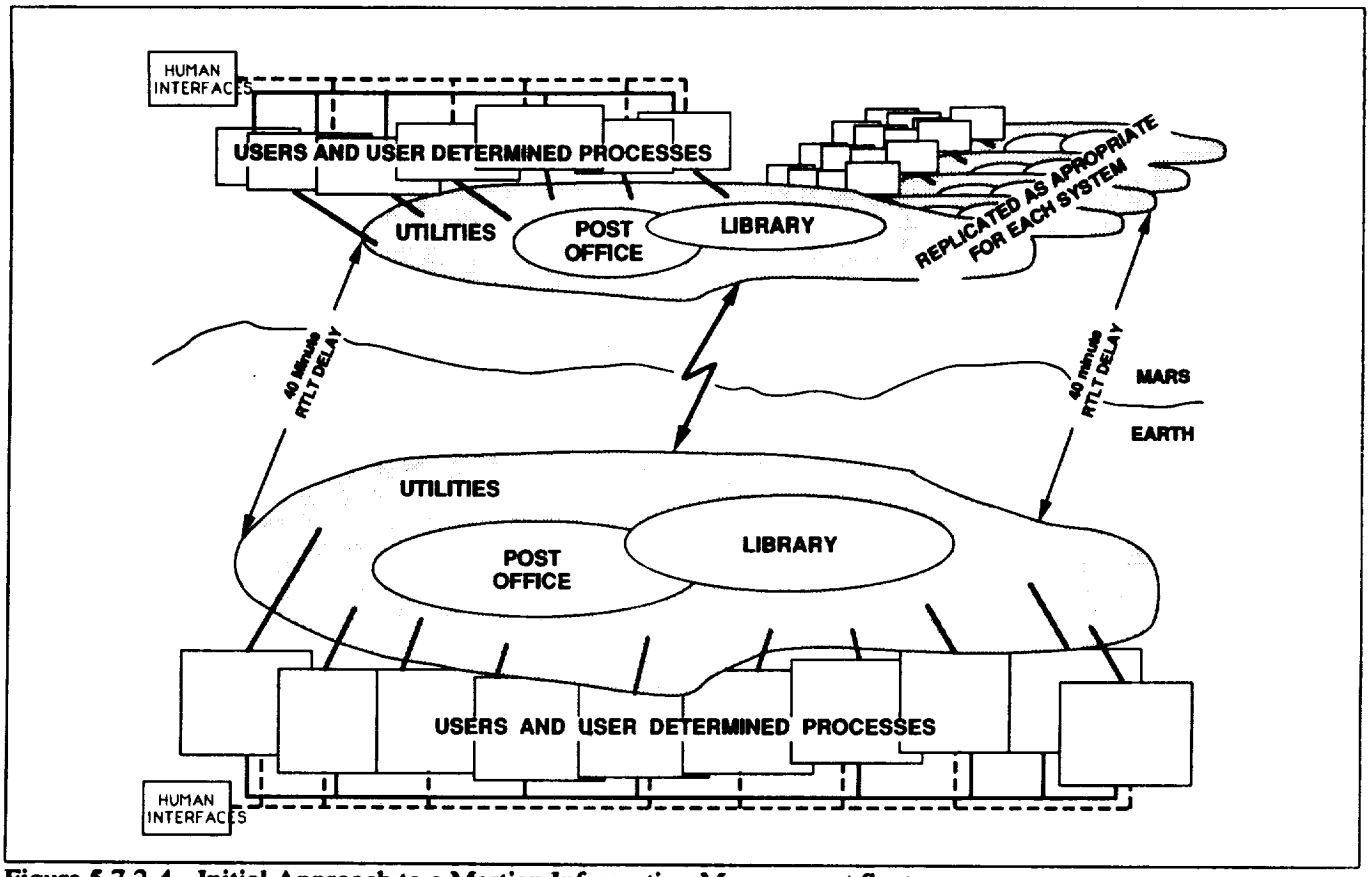



Figure 5.7.2-4.- Initial Approach to a Martian Information Management System.

update TNIM technology needs based on a refined martian surface system plan.

## 5.8 SURFACE TRANSPORTATION

Although ample work has been done recently on lunar and martian surface transportation, the majority of the work performed to date, particularly with respect to manned surface vehicles, was done before and during the Apollo program. A historical discussion is, therefore, in order.

The Apollo lunar rover flew on the last three missions. The total program cost 12.9 million (then-year) dollars. The first rover was delivered 17 months after contract award in 1971. Lunar mobility work started much earlier in the 1950's, however. The Apollo rover massed 210 kg empty and 726 kg loaded. Silver zinc batteries powered four 1/4 h.p. motors located on each wheel. The wheels were made of piano wire and guaranteed to last 200 km. The longest total distance traveled was 36 km on Apollo 17. The vehicle was capable of traveling 92 km on the non-rechargeable batteries. The average rover speed was 8 km/hr and the maximum speed was 18 km/hr. The vehicle became difficult to steer above 10 km/hr due to traction loss caused by the low lunar gravity. Heat was stored in a wax-like phase change material and then rejected when the rover was idle through a mirror radiator. The rovers completed their missions successfully on all three flights. Systems that need improvement for the next version include the wire wheels (they throw dust), the radiator (it is too sensitive to dust), and the hand grip steering.

Numerous studies defined Apollo follow-on vehicles. The Mobile Lunar Laboratory (MOLAB) program devised small pressurized vehicles capable of supporting a crew of two for up to 6 weeks. Figure 5.8-1 shows the general configuration. Several working models and full sized chassis were built and still exist in museums (see figures 5.8-2 and 3). The Grumman MOLAB vehicle is in the Cradle of Aviation Museum on Long Island. Several vehicles are in the Alabama Space and Rocket Center. JPL also has possession of an unpressurized Grumman rover. Much of this work was done in the 1960's prior to the actual Apollo flights. A 1965 literature survey (Romano, 1965) identified 47 well developed concepts for small pressurized lunar rovers.

Serious future work in this area must endeavor to start at least where Apollo left off. Test data, trade studies, and other thought that went into the Apollo era vehicles must be collected. Some of this has been done, but much more work is required. An inexpensive way to quickly

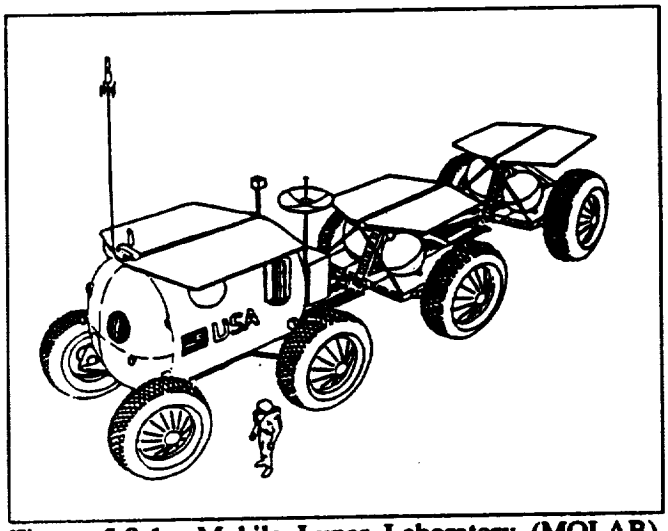



Figure 5.8-1.- Mobile Lunar Laboratory (MOLAB), (Romano, 1965).

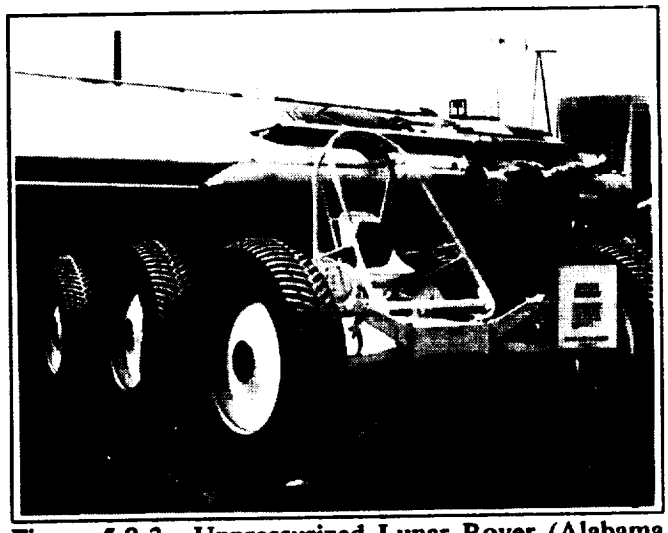


Figure 5.8-3.- Unpressurized Lunar Rover (Alabama Space and Rocket Center).

Figure 5.8-2.- Pressurized Lunar Rover (Alabama Space and Rocket Center).

make progress beyond the paper study stage would be to borrow some of the prototype and test vehicles from various museums and NASA storage and run them again. This would help develop a new generation of engineers with practical knowledge of the real problems.

The Soviet Lunokhod rovers were the only unmanned planetary rovers that actually flew. The Surveyor Lunar Rover Vehicle (SLRV), a similar U.S. device, was cancelled when delays caused it to overlap the manned program. Considerable work has been done on a small Mars rover in recent years and several working models have been built.

Table 5.8-I provides key numbers for a variety of existing and proposed pressurized and unpressurized manned rovers and unmanned rovers for reference.

### 5.8.1 Differences Between Moon and Mars

Far more information and design work exists for lunar vehicles. For this reason, the concepts presented, with the exception of the unmanned rover, will focus on the lunar work and should be scaled according to the following rules of thumb to estimate what is required on Mars.

#### 5.8.1.1 Radiators

To the first order, high temperature radiators (running at above 400°K) are approximately the same size for the Moon and Mars (Davis, 1986). A low temperature radiator used in the daytime on the Moon will require roughly twice the area of a low temperature daytime martian radiator putting out equal wattage. Low temperature radiators used at night on the Moon and Mars are roughly the same size.

#### 5.8.1.2 Locomotion Energy Requirements

To the first order, a martian rover requires twice the energy an equivalent lunar rover needs to go the same distance at the same speed. This assumes the same mass vehicle, the same soil (which is not the case) and the same surface contact pressure (meaning the wheel surface contact area must be twice as much on Mars for the same mass vehicle). A flat surface is assumed. Most of the locomotion energy goes into the wheel/soil interaction. The 2 times greater martian gravity roughly doubles this loss if all other parameters are held constant.

TABLE 5.8-I.- SURFACE TRANSPORTATION SYSTEM PARAMETERS

| | Built | Flown | Gross Mass (kg) | Max. Power (kw) | Tot. No. Wheels | Total Traverse (km) | No. Crew | Cabin Volume ($m^3$/crew) | Duration | Power Source | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unmanned Rovers | | | | | | | | | | | |
| SLRV | Yes | No | | | 6 | | - | - | PV/Battery | | |
| Lunokhod | Yes | 2 | 840 | | 8 | 100s? | None | - | Months | PV/Battery | |
| MRSR Moderate | No | No | 700 | 0.5 | 6 | 20-40 | None | - | Months | RTG | 1 |
| MRSR Maximum | No | No | 1,500 | 1.0 | 6 | >100 | None | - | Months | RTG | 1 |
| Martin Walking Beam | No | No | 667 | 0.5 | - | >100 | None | - | Months | RTG | 2 |
| Mars Base Rover | No | No | 758 | 0.5 | 6 | >400 | None | - | Years | RTG | |
| Unpress. Manned | | | | | | | | | | | |
| Apollo Lunar Rover | 10? | 3 | 726 | ~1 | 4 | 65 | 2 | - | 78 hrs | Silver -Zinc Bat. | |
| Apollo follow-on | Yes | No | 1,000 | 3 | 6 | 32 | 2 | - | 6 hrs/sortie | RTG/Batteries | 3 |
| Grumman DLRV | Yes | No | 682 | | 4 | | 1 | - | 24 hrs | RTG/Batteries | 3 |
| Local Transportation | No | No | 1,400 | 2.2 | 6 | 50 | 2-4 | - | 7 hrs/sortie | Lithium-Metal Sulfide Batteries | 4 |
| Press. Manned | | | | | | | | | | | |
| MOLAB | Yes? | No | 3,610 | 5 | 6 | 400 | 2 | 6 | 14 days | Fuel Cells/Cryo | 3 |
| MOLAB + | No | No | 7,730 | 9 | 8 | 3,200 | 2 | 6 | 84 days | Fuel Cells/Cryo | 3 |
| GM DRL | No | No | 11,000 | - | 6 | - | 4 | 7 | 30 days | Nuclear | 3 |
| MOSAP PCRV | No | No | 5,020 | 12 | 4 | 500 | 4 | 9 | 3 days | Fuel Cells/Cryo | 4 |
| MOSAP Train | No | No | 24,700 | 32 | 16 | 3,000 | 4+ | 22 | 40 days | Fuel Cells/Cryo | 4 |
| Grumman MOLAB | Yes | No | | 3.6 | 4 | 100 | 2 | | 14 days | Fuel Cells/Cryo | 5 |
| Many others | | | | | | | | | | | |

References
1. Mars Rover Sample Return, March Review Board Meeting, March 2-3, 1988 Vol. 1.
2. Mars Rover/Sample Return (MRSR) Rover Mobility and Surface Rendezvous Studies, Martin Marietta, Denver, Final Report, Oct. 1988.
3. Romano, S., Surface Transportation Systems for Lunar Operations, GM Defense Research Laboratories, Soc. of Automotive Engineers, 650838, Oct. 4, 1965.
4. Lunar Surface Transportation Systems Conceptual Design, NASA Contract No. NAS9-17878, EEI Report No. 88-188, July 7, 1988.
5. Private comm. from Ed Markow, Grumman, prototype now in the possession of Cradle of Avaition Museum on Long Island, N.Y.

### 5.8.1.3 Soil Properties and Terrain

Measured engineering properties of the lunar regolith, accurate maps of representative parts of the lunar surface, and actual test data will allow the accurate prediction of lunar vehicle energy needs. There are no direct measurements of martian engineering soil properties. Although energy usage can be estimated through rules of thumb as given above and with more sophisticated calculations, real test data will be required to design with a certainty comparable to that possible for the Moon.

The lunar terrain is better understood and has fewer obstacles than the martian terrain. Water erosion and more active vulcanism will make Mars more difficult to navigate.

### 5.8.1.4 Micrometeoroid and Radiation Protection

The martian atmosphere will provide significant protection, particularly from the sides, that is not available on the Moon. Shielding equivalent to 16 to 22 gm/cm$^2$ is provided directly above and more from the sides at the lower elevations, depending on a variety of parameters. A solar-flare storm shelter in a long range pressurized rover is therefore barely needed on Mars if one adopts a shielding requirement of 20 gms/cm$^2$. Micrometeoroid protection requirements will also be significantly less on Mars because of atmospheric shielding. A long range pressurized lunar rover design must deal far more seriously with radiation and micrometeoriod protection.

### 5.8.1.5 The Same Vehicle for Mars and the Moon?

In theory, it is possible to build a surface rover that will work on both the Moon and Mars. A vehicle to do both jobs will suffer penalties at both locations over dedicated equipment, however. The radiator size will be driven by the lunar day requirements. The power system, suspension, and structure must be designed for martian gravity. Redundancy, safety, and rescue considerations will be more difficult on Mars. Brake design, steering, and traction considerations will be controlled by lunar traction constraints.

## 5.8.2 Unpressurized Manned Rover

A great deal of unpressurized rover work was performed before and during the Apollo program. The major difference between the Apollo lunar rover and a rover required for a lunar base is the lifetime of the vehicle and the need for servicing and maintenance. The Apollo rover could only travel 91 km total on non-rechargable batteries. The wheels were only guaranteed for 200 km

total. It was a zero-maintenance, short-time, disposable vehicle. The next generation rover will need to operate for five--perhaps ten--years on the lunar surface, a much more difficult requirement.

An unpressurized rover required for a Mars mission may initially be more like the Apollo lunar rover, disposable after a fairly short mission, depending on the exact mission requirements.

### 5.8.2.1 Requirements - Unpressurizd Manned Rover

Table 5.8.2-I provides a set of proposed requirements from several sources.

### 5.8.2.2 System Trades - Unpressurized Manned Rover

The major trades concerning an unpressurized manned rover involve the means of locomotion, type of power supply, and type of thermal control.

5.8.2.2.1 Locomotion Trades - The range of locomotion options includes wheeled vehicles (with two, three, four, or six wheels), multi-unit and single-unit vehicles, loop wheeled vehicles, tracked vehicles, walkers, hoppers and other more exotic devices such as tumbleweeds. In general, the range discussed above runs from low complexity, low maintenance (two or four wheels) to high complexity/high maintenance (walker). The high complexity and maintenance buys the capability to climb steep slopes (45 to 50 degrees for walkers versus 25 degrees for four wheels) and deal with other difficult terrain.

Here on Earth, the complex/high maintenance vehicles (tracked vehicles for instance) are only used when terrain or other circumstances demand them. The requirements stated thus far do not demand unusual terrain climbing capability, therefore wheels are the obvious choice. The number of wheels is again a function of terrain demands. A four wheel vehicle is adequate to meet the requirements given. Two or three wheels are thrown out for safety reasons. Six wheels with a two-unit vehicle provides terrain capability beyond that called for in the requirements at the expense of some additional power consumption. A four wheeled vehicle with a trailer was chosen as the baseline concept.

The type of wheel is another major choice. Piano wire wheels were used for the Apollo lunar rover, but they threw dust and had a limited lifetime. Inflated tires were used on the Apollo equipment cart. It may be difficult to find an elastic material that will stand up to the lunar thermal cycle on a regular basis for many years. This has led to a preference for flexing metal wheels. Cone wheels, as shown on the manned rover concepts to follow (figures 5.8.2-1 and 5.8.3-1), were developed by

TABLE 5.8.2-I.- UNPRESSURIZED MANNED ROVER REQUIREMENTS

| Requirement | Source |
|---|---|
| Unpressurized traverse distance limited to walk back range (10 km) | SRD, modified |
| Minimum crew of two for distances over 1 km | SRD |
| Payload - 2 EVA crew and 500 kg or 4 EVA crew (1,000 kg total) | SRD |
| Nominal 20 km round trip per sortie | SRD |
| Maximum climbing grade of 20 degrees | SRD |
| Nominal maximum speed of 10 km/hr | SRD |
| 6 hours of life support and auxiliary power | PSSRD |
| Rechargeable or regenerable at base, daily use | PSSRD |
| 48 hours of life support supplies per person | PSSRD |
| Nominal maximum sortie of 10 hours | PSSRD |
| Base has two rovers | PSSRD |
| Hardware lifetime of 10 years | Proposed addition |
| Number of battery recharges = 3,000 = 10 yrs x 300/yr | Proposed addition |
| Maximum range between recharges = 100 km | Proposed addition |
| Minimum maintenance more important than minimum weight | Proposed addition |

Notes:
SRD = Systems Requirements Document
PSSRD = Planetary Surface Systems Requirements Document

Grumman for lunar application using a fiberglass material. Fiberglass cone wheels, tested by Grumman for U.S. army applications in Vietnam lasted 16,000 miles before failure (Markow, 1989). For ten year life on the lunar surface steel and titanium cone wheels deserve study. Some analytical work was done on metal cone wheels by Grumman (Markow, 1989). Grumman also did extensive analytical and experimental work on the metal-elastic wheel in the 1960's and clearly demonstrated the merits of a "soft" wheel for low gravity, lunar soil-type applications (Markow, 1989). More development work is required to obtain a long-life wheel.

5.8.2.2.2 Power Trades - The Apollo rover required roughly 1 kW average power and stored 9 kWhr in silver-zinc batteries, most of which went to locomotion. The concept proposed in the following section uses roughly 2.4 kW peak power and stores 24 kWhr of energy. Given this range, numerous battery options are possible. Trades involve weight versus number of cycles versus development dollars. This is similar to the electric car problem without the cost constraints of mass-produced vehicles.

Table 5.8.2.-II. lists a variety of batteries and some approximate numbers that describe their performance. The batteries divide into two major classes: 1) the existing, fairly well-understood group with 20 to 40 Whr/kg, and 2) the developmental and proposed group with 100 to 200 Whr/kg. A practical, multi-cycle battery in the range of 100 Whr/kg is desired and is assumed to be achievable. This number is therefore used in the concept proposed later. More work on this subject is required.

5.8.2.2.3 Thermal Control Trades - The Apollo lunar rover used a waxy phase change material to store thermal energy and radiate it away while sitting in the shade of the lander after a traverse. The radiators were very sensitive to dust contamination and required a dust cover. A small radiator was possible, though, since the vehicle did not have to radiate peak power while in motion. This approach may not work as well for a longer-life vehicle with a somewhat harder duty cycle. Other options include a much larger real-time radiator (perhaps as much as 5 $m^2$) or water boilers. If a small fuel cell is used for power, a heat exchanger will be required to turn liquid oxygen and hydrogen into gases. This system might also be used to cool the vehicle.

### 5.8.2.3 Concept - Unpressurized Manned Rover

Figure 5.8.2-1 shows a concept for an unpressurized manned rover. This strawman concept was developed using the previously stated requirements and the following rules of thumb.

The empty mass of the vehicle is sized based on estimated empty mass to payload mass ratios. The actual ratio for the Apollo lunar rover was 0.44. For a next generation lunar rover, a longer lasting, more rugged vehicle is needed. The ratio is estimated as 0.65. Since the same payload mass weighs roughly twice as much on Mars as on the Moon, the first estimate ratio for Mars is 1.30.

TABLE 5.8.2-II.- BATTERY OPTIONS

| Type | Whr/kg | Kg for 10 kWhr | Est. Life Cycles | Comments | Ref. |
|---|---|---|---|---|---|
| Lead-acid | 29 | 345 | 1,600 | | 1 |
| Nickel-cadmium | 24 | 417 | 2,000 | | 1 |
| Nickel-iron | 23 | 430 | 2,000 | | 1 |
| Nickel-hydrogen | 37.5 | 267 | | Self-discharge rate is high | 2 |
| $H_2/O_2$ fuel cell | 35 | 286 | | 9,600 Whr, 2,000 hr life | 3 |
| Silver-zinc | 150? | 67 | 1,000? | | |
| Silver-zinc | 200? | 30 | 200? | Likes 0°C for storage | 1 |
| Lithium-alloy/FeS | 100 to 220? | 100 to 45 | 1,000? | High temp. (400 to 500°C) | 2 |
| Na-S | 400 | 25 | 3000 | High temp. (300 to 400°C) | 4 |

References:

1. Batteries and Energy Systems, Charles L. Mantel, PhD., McGraw-Hill, 1983.
2. Handbook of Batteries and Fuel Cells, David Linden, ed., McGraw-Hill, 1984.
3. S. Barry Trout, personal communication.
4. Eric Darcy, NASA JSC, personal communication.

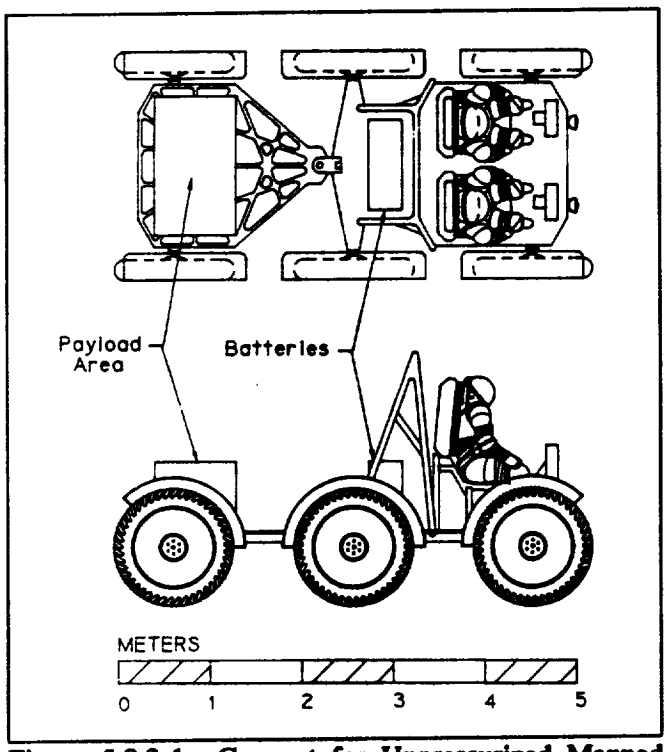


Figure 5.8.2-1.- Concept for Unpressurized Manned Rover.

Peak power is estimated as linear with mass, using 1 kW per 726 kg mass (from the Apollo lunar rover), giving 1.4 W/kg of loaded mass for the lunar case. Mars is roughly double this again, or 2.8 W/kg of loaded mass.

Locomotion energy is estimated using 0.08 Whr/kg/km taken from the Apollo rover. Doubling this for Mars gives 0.16 Whr/kg/km. In addition to locomotion energy, another 600 Watts or so for 10 hours is needed to power other systems.

Given these rules of thumb and the requirement for 1,000 kg payload and 100 km range, Table 5.8.2-III can be derived.

#### 5.8.2.4 Technology Development Required

The heart of the technology development issues are lifetime and maintenance on the lunar surface. Specific needs are: 1) a high energy density battery capable of many thousands of cycles in the lunar and martian environments, 2) a radiator system insensitive to dust, particularly lunar dust, 3) wheels capable of handling the lunar and martian environments and a minimum of 30,000 km (300 one hundred km trips), and 4) a complete vehicle system with enough history of operation that its maintenance and spare requirements are well understood with respect to vehicle lifetime.

#### 5.8.2.5 Precursor Data Required

The lunar case is well understood since a similar vehicle has already been built and tested on the Moon.

Engineering soil properties, such as penetration gradients and cohesion, representative traverse profiles, and terrain characteristics, are needed for Mars. Soil properties derived from direct bevameter/penetrometer data for several different representative soil types are desired. Traverse profile and terrain data includes typical rock distribution and slope data. A servicable vehicle can be built without this data, but not a design that will provide optimum service and minimum maintenance for many years. The lunar data set available to the designers of the Apollo rover was not much more than we have on Mars today, but the Apollo rover was a short-lived vehicle.

#### 5.8.2.6 Resupply Requirements

Resupply requirements could include wheels (every few 1,000 km?), batteries (every few years) or perhaps fuel cell reactants (liquid hydrogen and oxygen) and the fuel cell itself every few years.

### 5.8.3 Pressurized Rovers

A pressurized manned rover will be a key element in a planetary surface base. Its uses may range from a short range taxi to a long range exploration vehicle of months duration. It is unclear at present whether one vehicle can be made to cover all of these needs. The needs fall into three categories, based primarily on the range of the vehicle.

A short- or mid-range vehicle will taxi crew between the base and other facilities such as a lander or propellant plant. It will serve as a work platform, for extravehicular activity (EVA) safety and monitoring and other functions that may reduce or eliminate EVA. Only a few tens of kilometers of range is required and an endurance on the order of one day. The vehicle must have a highly functional airlock and docking system that allows it to dock with pressurized structures. It might have to accommodate up to ten people on a short taxi run.

A long range vehicle will be desired for science and exploration and distant servicing. A farside radio telescope might just be within reach of such a vehicle. A minimum of three people must be supported for a month or more. Total traverse distance would be around 3,000 km using a non-regenerative oxygen/hydrogen fuel cell power supply. Beyond this range, the required tankage becomes unreasonably large.

TABLE 5.8.2-III.- UNPRESSURIZED ROVER WEIGHT AND PERFORMANCE--FIRST ORDER ESTIMATES

| Item | Lunar Estimate | Martian Estimate |
|---|---|---|
| Empty Mass, kg | 650 | 1,300 |
| Payload, kg | 1,000 | 1,000 |
| Loaded Mass, kg | 1,650 | 2,300 |
| Peak Power, kW | 2.3 | 6.4 |
| Locomotion Energy Storage, kWhr | 13.2 | 36.8 |
| Other Energy Storage, kWhr | 6.0 | 6.0 |
| Total Energy Storage, kWhr | 19.2 | 42.8 |
| Average Power required (for 10 hours in motion), kW | 1.9 | 4.3 |
| Battery Mass, kg (@ 100 Whr/kg) | 192 | 428 |

A very long range traverse vehicle would be required to explore large fractions of the planetary surface from a single base. The crew would be a minimum of three people with life support for two or more months. The total traverse distance would be in the range of 10,000 km. (The Moon's circumference is 11,200 km; Mars' is 22,600 km.) Either a fuel cell system with resupply from orbit or caches, or one of several nuclear systems ranging from the dynamic isotope power supply (DIPS) to a light water reactor on wheels, would be needed. This vehicle is essentially a mobile base.

### 5.8.3.1 Requirements

Table 5.8.3-I lists the requirements, derived from various sources.

### 5.8.3.2 System Trades - Pressurized Rover

The major trades for a pressurized vehicle involve the power system, locomotion, overall configuration, thermal control, EVA/airlock operations, radiation shielding, and environmental control system configuration.

5.8.3.2.1 Overall Configuration - Configuration options include several dedicated vehicles versus one vehicle expandable with trailers in a train configuration. Another option would use multiple independent vehicles traveling together instead of a train configuration. Other trades involve science versus construction needs. At the present level of detail, a single vehicle for the short range and a train for long range tasks seems possible and desirable from a cost standpoint. This will be the initial choice until diverging needs or more detailed knowledge show the need for a different configuration.

For the very long-range mission (10,000 km), other options in addition to a surface traverse deserve study such as landing from orbit with a short-range rover.

5.8.3.2.2 Power System Trades - The short-range lunar vehicles will require 5 to 10 kW average power. A 3,000 km train configuration might require 30 kW average power. Batteries are within reason for the short range vehicle. At 100 Whr/kg (discussed in previous section), 72 hours of 10 kW level power will mass 7,200 kg.

The dynamic isotope power supply (DIPS) is another attractive option. This device is an isotopic heat source with a small heat engine power converter. If estimates of 17 W/kg (Propulsion, 1989) prove correct, a 16 kWe system that would provide continuous power for many years would mass only 919 kg. The availability of the plutonium isotope is severely limited however, and the plutonium itself is a dangerous and controversial material.

The favorite power option, used in the concept, is a non-regenerable shuttle-type fuel cell using liquid oxygen and hydrogen reactants. The mass of a 10 kw system with 42 days (1,008 hrs) of reactants is 6,440 kg, with a 2.45 meter diameter liquid hydrogen tank. A 10 kW system can be roughly scaled according to the formula:

$$\text{Mass (10 kW)} = 236 + (0.4 \text{ kg reactant/kWhr})^* \text{ kWhr needed} + \text{tankage}$$

Current cell life is around 2,000 hours. Upgrades may extend this to 10 to 20,000 hours. Note that a 7 kW fuel cell for the orbiter costs around 2 million dollars.

TABLE 5.8.3-I.- REQUIREMENTS FOR PRESSURIZED ROVER

| General Requirements | Source |
|---|---|
| Rover will support crew health maintenance needs. | SRD |
| Rover will provide solar flare shielding. | SRD |
| Rover will provide EVA capability. | SRD |
| Rover will be able to sustain a loss of IVA access. | SRD |
| Rovers with over 10 km traverse will be pressurized and incorporate work/rest and life support for all crew. | SRD |
| 10 year lifetime desired with 90% usage factor. | Proposed addition |
| Support a minimum of 1 EVA per day. | Proposed addition |
| Manipulators and sample handling glove box required. | Proposed addition |
| Tool and sample transfer airlock required. | Proposed addition |
| Minimum of dual redundancy for all life-critical systems. | Proposed addition |
| TBD vol., power, and mass reserved for science equipment. | Proposed addition |
| Maximum slope capability - forward 20°, sideways 10°. | Proposed addition |
| Maximum speed - 10 km/hr for Moon, faster for Mars. | Proposed addition |
| TBD gms/cm$^2$ shielding required on lunar surface. | Proposed addition |
| TBD gms/cm$^2$ shielding required on martian surface. | Proposed addition |
| Rover must function after quiescent period of up to 4 years. | Proposed addition |
| A mid-range rover can travel approximately 100 km. | PSSRD |
| A long-range rover can travel over 1,000 km. | PSSRD |
| **Mid-Range Rover Requirements** | |
| Crew consists of 4 with EVA suits and 100 hrs life support/crew. | PSSRD |
| 1,000 kg other payload to be included. | PSSRD |
| Nominal maximum sortie lasts 72 hours. | PSSRD |
| Can be used daily. | PSSRD |
| May serve as contingency habitation for four. | PSSRD |
| Serves as mobile work station and includes power tools. | PSSRD |

Photovoltaics provide another option. A 10 kW gallium arsenide array requires 41.2 m$^2$ on the lunar surface, approximately 3 m wide by 14 m long. Although difficult to handle, the array is light weight (364 kg). An array for a martian vehicle would be significantly larger because of the reduced solar irradiation and the increased power needs. For the lunar case, if a non-regenerative fuel cell is used at night in conjunction with a gallium arsenide array for daytime power, the total mass is around 3,000 kg for 1,008 hours (42 days). The weight is attractive, but because of the size of the array, and the need for a large radiator in the same place, this option was not chosen for the conceptual design that follows. Multi-layer solar cells that absorb several different frequencies of light at different levels are being developed that may double the efficiency of the gallium arsenide array and thus reduce the area. This plus serious work concerning power reduction might make this option a winner. The power section of this book proposes photovoltaic/regenerable fuel cell systems for rover applications.

5.8.3.2.3 Locomotion - The situation for the pressurized vehicle is essentially the same as for the much smaller unpressurized rover, except that due to the size and mass of this vehicle, it is much less likely to travel in areas with rugged terrain or steep slopes. More conservative operation is likely, which again points to wheels. A four-wheel concept, expandable in a train of four-wheel, self-propelled vehicles was chosen for the concept shown in the following subsection, though good arguments can be made for systems capable of somewhat more rugged terrain which might use six-wheel vehicles with more elaborate suspension systems.

5.8.3.2.4 Thermal Control - A pressurized vehicle that serves as living space for a month or more will have difficulty storing heat and require more or less constant radiating capability. The size of the radiator may be a problem. If 5 kw heat rejection is required, the radiator might be in the range of 60 m$^2$. The whole surface of vehicle may have to be a radiator that is insensitive to

dust. Waste water might also be boiled away for cooling. A non-regenerative oxygen/hydrogen fuel cell may produce excess water.

5.8.3.2.5 <u>EVA and Airlocks</u> - Maintenance and recharge of EVA suits for numerous EVAs on a long traverse is a problem. A suit refurbishing device, such as planned for Space Station Freedom may or may not be appropriate. Another approach is to reduce the number of EVA's to a minimum and build a special suit. Number and size of airlocks is another issue. The simplest, lightest approach is one small airlock, such as shown in the concept sketches.

5.8.3.2.6 <u>Radiation Protection</u> - For long traverses on the lunar surface, solar flare radiation protection is an issue. Shielding on the order of 20 g/cm$^2$ is assumed to be required. This results in as much as 1,500 kg of mass per crewmember for a shelter built of dedicated material. This requirement becomes unreasonably massive for a crew of three or four. One solution is to use consumables, water, radiators, trash, and perhaps fuel cell reactants to provide shielding. A pantry/water storage storm shelter may be possible through a combination of clever packing and interior arrangement.

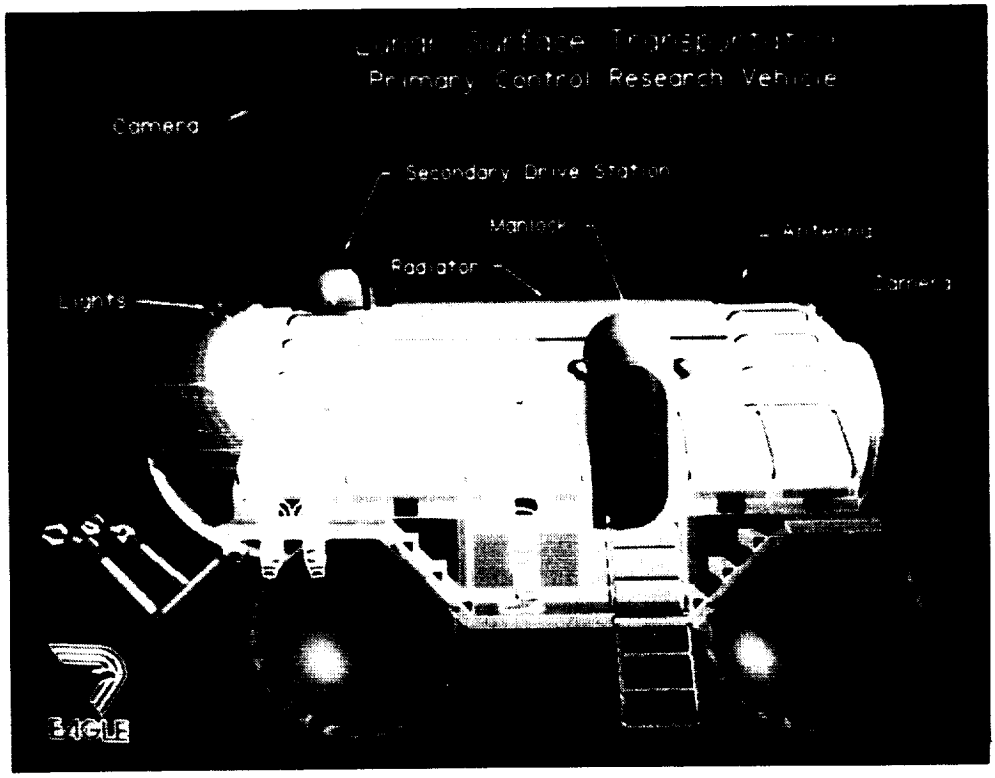
5.8.3.2.7 <u>ECLSS</u> - For any short excursion, an open ECLSS is the obvious choice. Rough calculations indicate that as endurance increases to one or two months for several people, closure becomes desired if minimum mass is the goal. One proposal for these longer duration missions is to use an open system and return the majority of the waste (which is water) to the base for recycling.

### 5.8.3.3 Concept - Pressurized Lunar Rover

Figure 5.8.3.-1 shows two views of a pressurized rover concept for lunar missions. This single vehicle is all that is necessary for short range excursions, taxi trips, EVA reduction work, etc. Endurance between reactant resupply is one or two days. This vehicle can also serve as the lead vehicle in a train that would be assembled for long excursions. The train, led by the primary vehicle will consist of an additional habitation unit, and trailers for science equipment and additional power. In the train configuration endurance might be up to a month.

Table 5.8.3-II shows the characteristics of each element in the train. The train can be configured as required for the mission. Each element is self-powered with drive motors on each wheel. This is because the low lunar gravity makes towing difficult.

Table 5.8.3-III shows a first order weight statement for a pressurized manned lunar rover concept. Table 5.8.3-IV shows a power requirements estimate for the primary vehicle and for a habitation trailer. The habitation trailer is similar to the primary vehicle and could even be an additional primary vehicle. Figure 5.8.3.-2 shows two ways the vehicle might be configured for a long traverse, using either a second primary vehicle or a specialized habitation module. The extra vehicle adds volume required for additional storage and living space as well as redundancy needed for a long traverse.



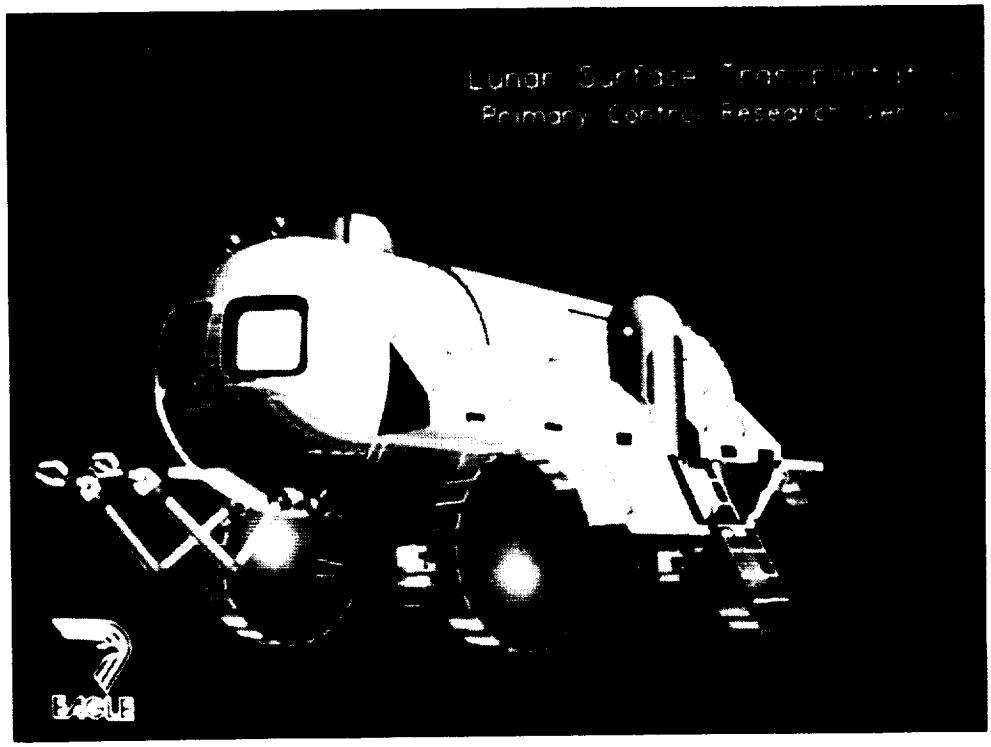




**Figure 5.8.3-1.- Concept for Pressurized Manned Surface Rover--Primary Vehicle.**

## TABLE 5.8.3-II.- TRAIN ELEMENTS--PRESSURIZED LUNAR ROVER

| Element | Stored Energy (kWhr) | Mass (kg) | Avg. Power (kW) | Peak Power (kW) |
|---|---|---|---|---|
| Primary Vehicle | 208 | 5,600 | 9 | 12 |
| Habitation Unit | 208 | 5,600 | 9 | |
| Power Cart, 25 kW maximum | 7,000 | 5,224 | 5 | 6 |
| Power Cart, 14 kW maximum | 1,500 | 1,345 | 1.4 | 2 |
| Experiment/Sample Trailer | self-pwrd. | 3,000 | 3 | 4 |
| **Total** | | **20,769** | **27.4** | |

Notes: Total energy storage for the above train is 8,916 kWhr. At 24.4 kW average power (the experiment/sample trailer is self-powered), the train can run for 365 hours (15 days). At 10 km/hr, maximum range is 3,650 km. Endurance can be increased, but range decreases with frequent stops.

If two 25 kW power carts are used, the total energy stored is 14,416 kWhr. At 28 kW avg. power, this train can run for 515 hours (21 days). This corresponds to a 5,150 km maximum range.

## TABLE 5.8.3-III.- FIRST ORDER WEIGHT STATEMENT--PRESSURIZED MANNED LUNAR ROVER

| Part | Mass (kg) |
|---|---|
| Structure and Pressure Vessel | |
| Inner Shell | 490 |
| Outer Shell | 500 |
| Other Structure | 200 |
| Insulation | 130 |
| Active Thermal System | |
| Radiator | 160 |
| Pump | 20 |
| Heat Exchanger | 50 |
| Piping | 100 |
| Refrigerant | 300 |
| Power System | |
| Hydrogen Tanks | 20 |
| Oxygen Tanks | 15 |
| Water Tanks (incl. potable) | 40 |
| Reactants (208 kw-hrs) | 75 |
| Fuel Cell | 704 |
| Power Distribution | 100 |
| Wheels and Locomotion | 300 |
| Airlock | 230 |
| Galley | 70 |
| Personal Hygiene | 90 |
| Emergency Equipment | 30 |
| Avionics | 90 |
| ECLSS | 200 |
| Drive Stations | 80 |
| Workstation | 40 |
| Sleep Quarters | 60 |
| Crew | 360 |
| EMU's (3) | 680 |
| Experiments and Payload | 500 |
| **Total** | **5,634** |

## TABLE 5.8.3-IV.- POWER ESTIMATE--PRESSURIZED MANNED LUNAR ROVER AND HABITATION MODULE

| Subsystem | Primary Vehicle (W) | Habitation Trailer (W) |
|---|---|---|
| Operation and Drive Station | | |
| Computers | 200 | 100 |
| Communication | 140 | 70 |
| GN&C | 200 | 100 |
| ECLSS | | |
| Air Revitalization | 10 | 10 |
| Water Coolant Loop Pump (1) | 60 | 60 |
| Air Pressure Control | 10 | 10 |
| Active Thermal Control | | |
| Cold Plate Pump (1) | 60 | 60 |
| Circulation Fans (10) | 140 | 140 |
| Freon Coolant Loop Pumps (2) | 700 | 700 |
| Hygiene Station | | |
| Water Pump | 50 | 50 |
| Commode | 50 | 50 |
| Galley | | |
| Oven, Microwave (peak 700 W) | 700 | 700 |
| Refrigerator | 400 | 400 |
| Water Heater | 70 | 400 |
| Lighting | | |
| Interior 15,16.5 Fluorescent | 250 | 250 |
| Exterior | 1,000 | 1,000 |
| Experiments | 1,000 | 1,000 |
| Drive Motors | 6,000 | 6,000 |
| Miscellaneous | 1,000 | 1,000 |
| Peak (sum total) | 12,040 | 12,100 |
| Parked (Est.) | 3,500 | 3,500 |
| Underway (Average) | 9,000 | 9,000 |

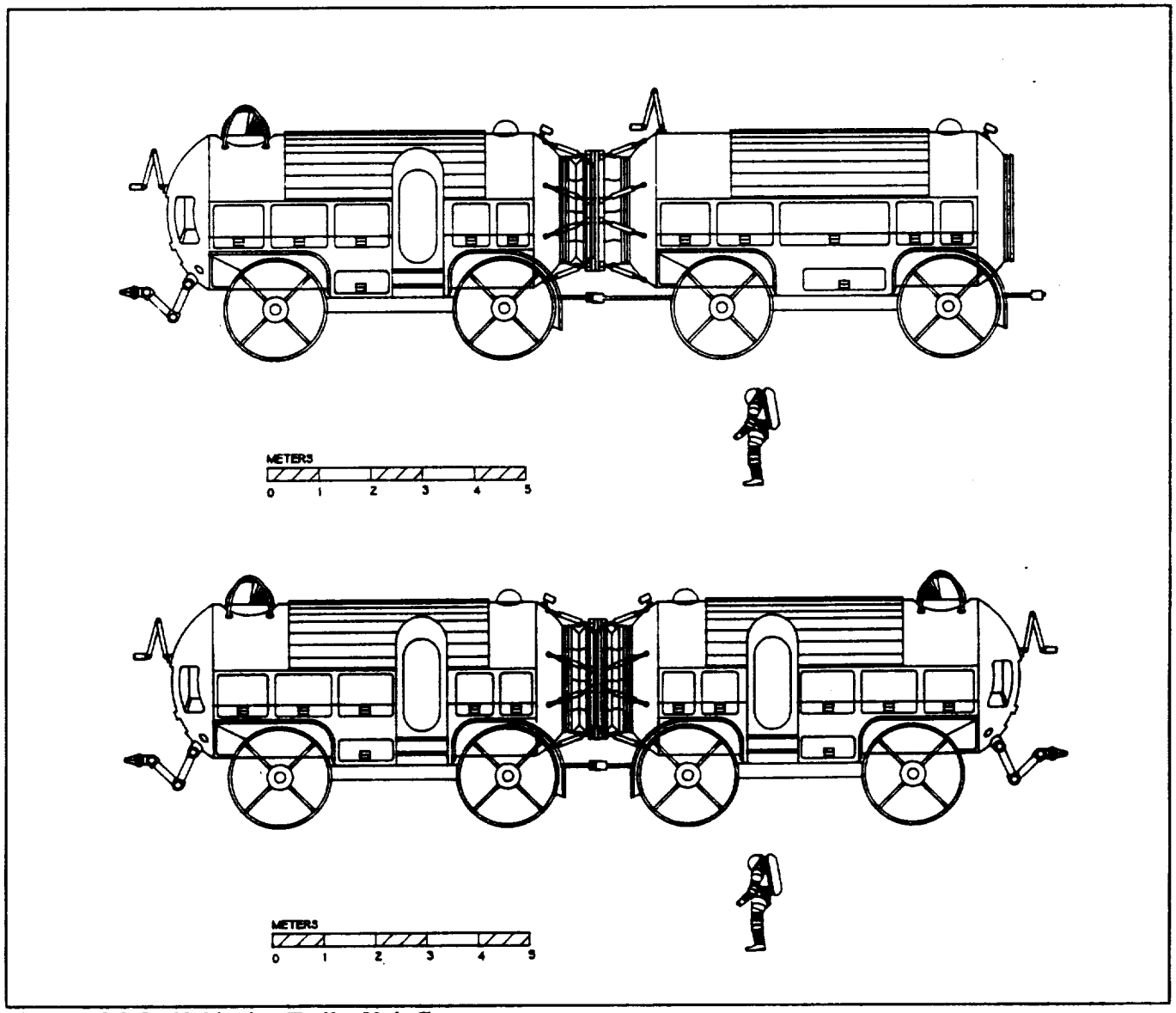



Figure 5.8.3-2.- Habitation Trailer Unit Concepts.

Figure 5.8.3-3 shows auxiliary power cart configurations for a small and large cart. The carts provide the energy storage required for long traverses. Table 5.8.3-V is a first order weight statement for the carts. Figure 5.8.3-4 shows a sample experiment cart. Wherever overhead space is not needed for radiators, solar arrays will be placed to increase endurance and provide a small redundant power source.

### 5.8.3.4 Pressurized Rover Interior Habitability Features

Figures 5.8.3-5 and 5.8.3-6 show concepts for the primary vehicle interior and other features developed by JSC Crew Systems Division. The vehicle shown in this figure is proposed for a crew of 4 for up to two weeks. It is 8 meters long and has a volume of 144 cubic meters. Austere habitation features are provided along with essential vehicle systems, communications and mission support facilities. Some features of this vehicle (numbers correspond to the figure) are:

1. Two remote manipulator arms are mounted to the front of the vehicle and can be used for a variety of purposes including the retrieval of samples for close-up viewing through the vehicle's windows. Samples of special interest can be collected using the scientific airlock (Item 4). Stereo cameras record images and provide a flexible viewing capability to the drivers. Special-purpose end-effectors can be interchanged to accomplish a variety of tasks including grasping, scooping, and cutting.

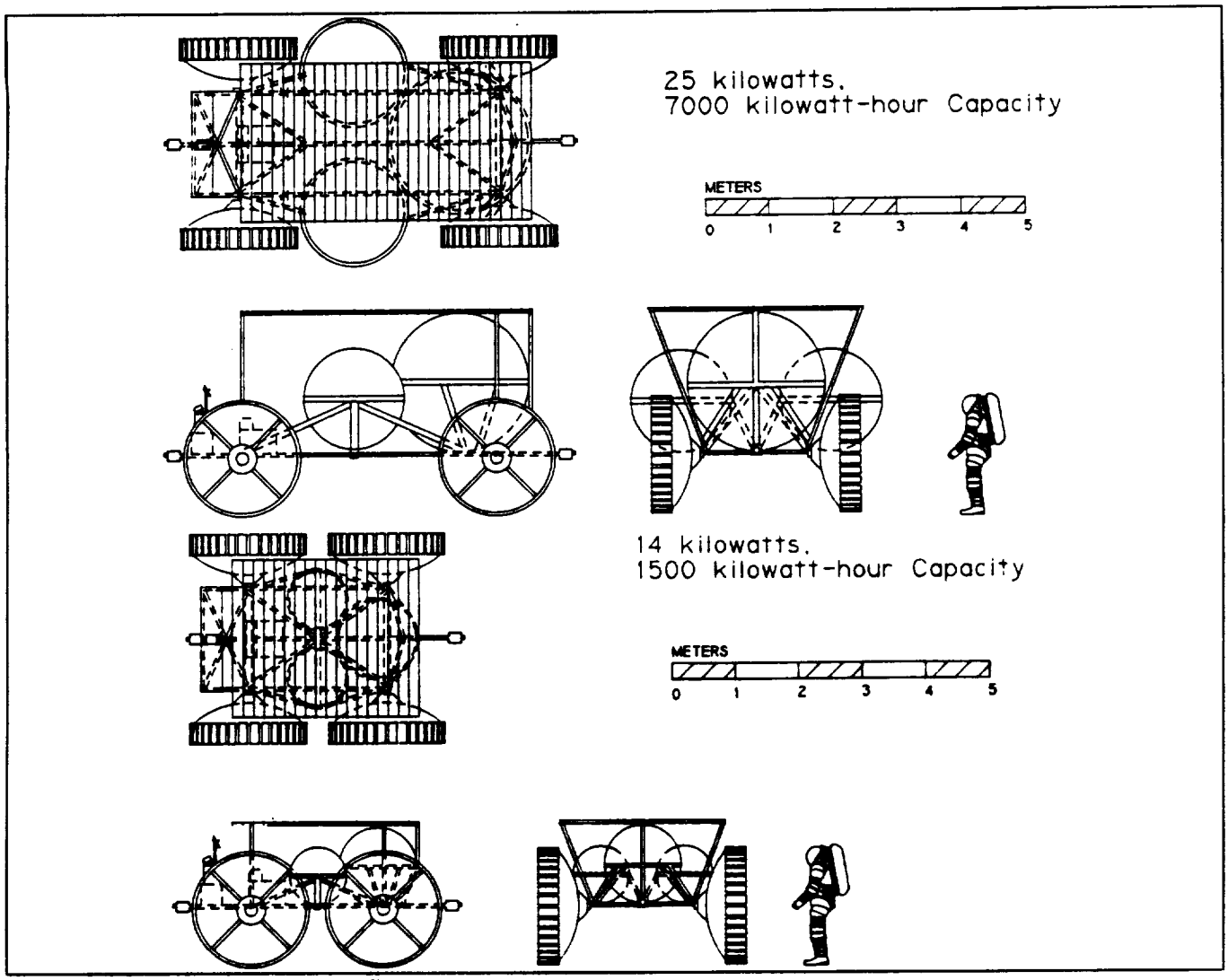



**Figure 5.8.3-3.- Auxiliary Power Carts.**

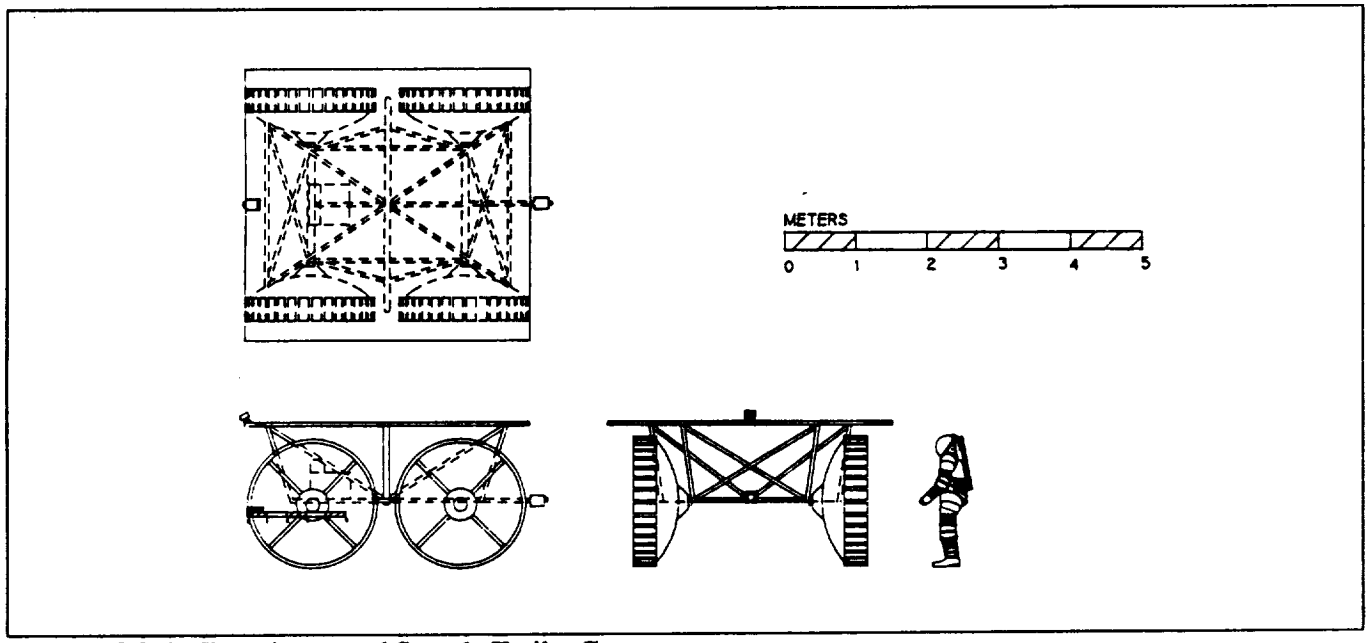



**Figure 5.8.3-4.- Experiment and Sample Trailer Concept.**

TABLE 5.8.3-V.- AUXILIARY POWER CART WEIGHT STATEMENTS

| | 14 kW Cart | 25 kW Cart |
|---|---|---|
| Capacity | 1,500 kWhr | 7,000 kWhr |
| Dry Mass | | |
| Tanks | | |
| Hydrogen | 144 kg | 672 kg |
| Oxygen | 115 kg | 540 kg |
| Water | 120 kg | 560 kg |
| Fuel Cell | 236 kg | 472 kg |
| Solar Panel (1 kW) | 40 kg | |
| Solar Panel (4 kW) | | 160 kg |
| Cart | 150 kg | 300 kg |
| Total Dry Mass | 805 kg | 2,704 kg |
| Reactants | 540 kg | 2,520 kg |
| **Total** | **1,345 kg** | **5,150 kg** |
| Tank Diameters | | |
| Hydrogen | 1.3 m | 2.3 m |
| Oxygen | 1.1 m | 1.7 m |
| Water | 1.1 m | 1.7 m |

2. A modular tool/instrument package can be interchanged to accomplish a variety of mission objectives. In the configuration pictured, a core drill is installed for drilling into the lunar surface and retrieving samples from a range of depths. Other modular components include a scoop/shovel, blade/scraper, digger and auger drill.

3. Two driver's stations are located at the front of the vehicle. The drivers use joysticks to control the speed and direction of the vehicle while in motion. The same joysticks can be switched electronically to control the operation of the manipulator arms when the vehicle is stationary. The lightweight seats are mounted on a shock-absorbing frame and can be reclined to form cots for sleeping. The seats adjust from front-to-back and side-to-side as well as rotate 360 degrees. This adjustability provides convenient ingress/egress and access to both the driver's station controls and the side-mounted workstations. Windows provide the drivers with a good view of the terrain in front of the vehicle.

4. A scientific airlock is located at the front of the vehicle in a position where its drawer can be opened to accept samples from either the manipulator arms or the core drill. The samples can be maintained in a vacuum or placed in nitrogen-filled containers.

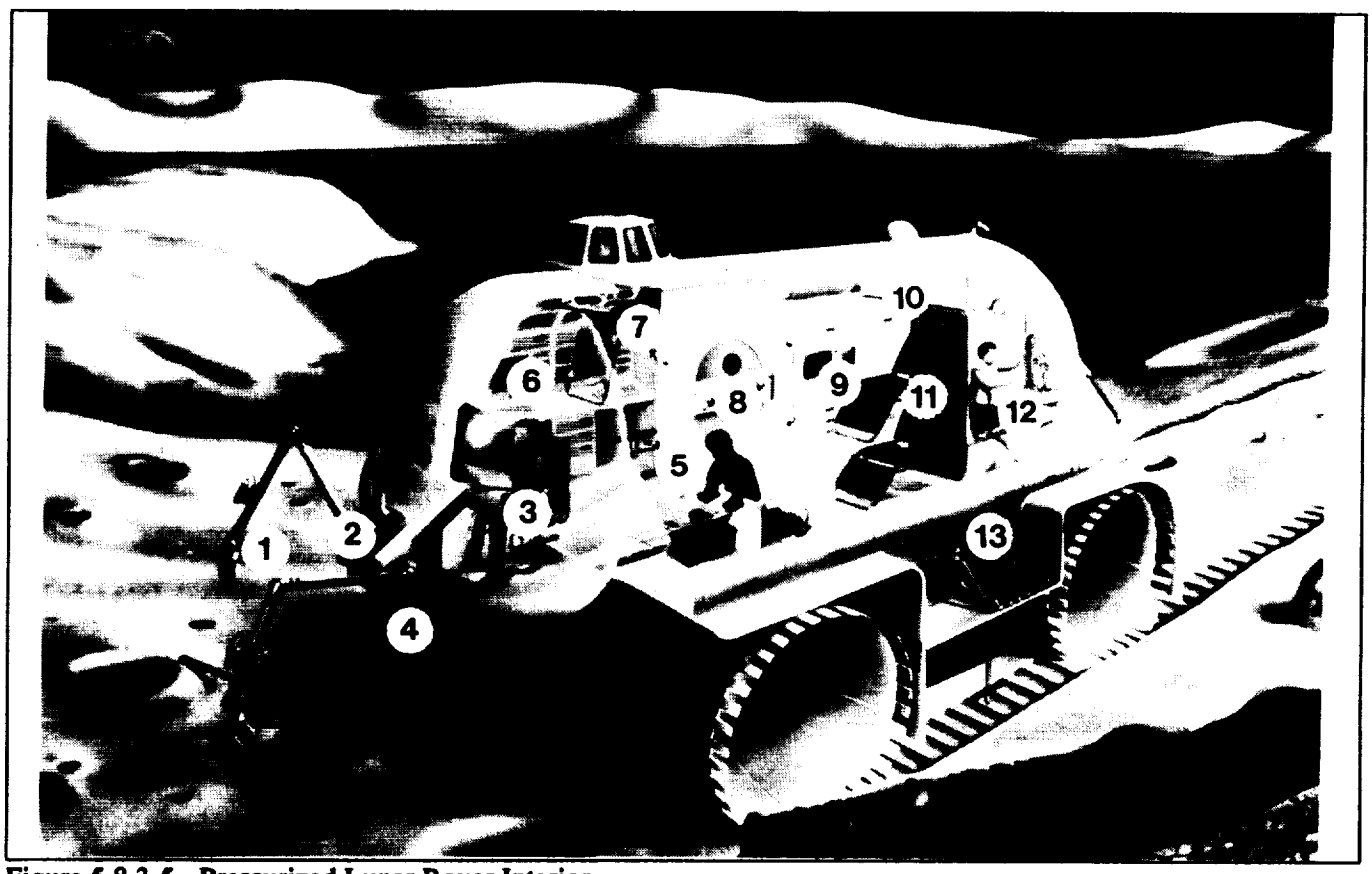


Figure 5.8.3-5.- Pressurized Lunar Rover Interior.

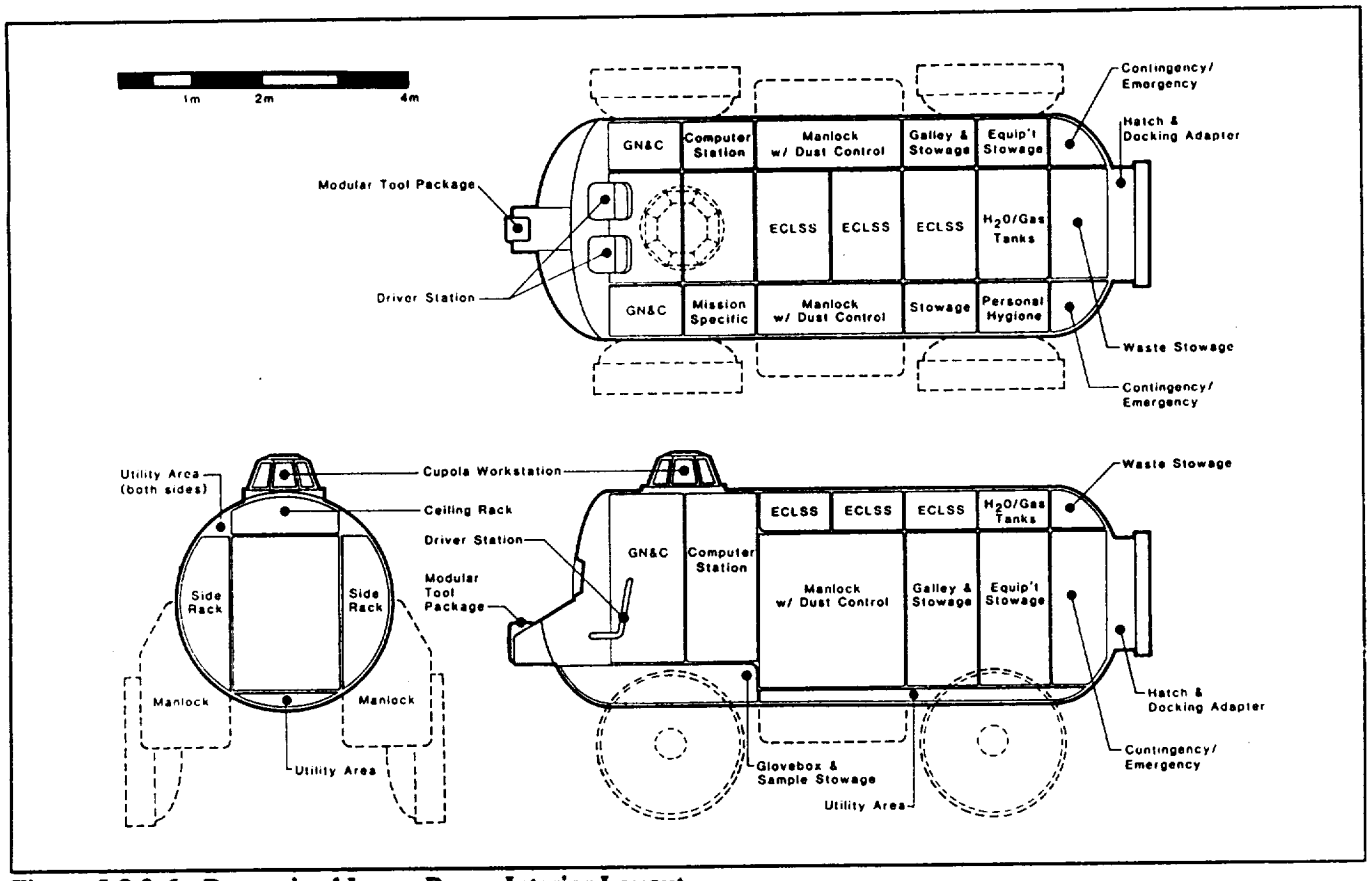



Figure 5.8.3-6.- Pressurized Lunar Rover Interior Layout.

5. A manually-operated conveyor belt allows the samples to be moved toward the rear of the vehicle for tagging and analysis. A glove box allows the samples to be manipulated without depressurizing the vehicle or cross-contaminating either the samples or the vehicle interior.

6. Modular rack-mounted workstations are located along the sides of the vehicle. The two front stations are easily accessible from the drivers' seats. Stowable perch seats are available for use at the other stations. The functions of the workstations include navigation, communication, data management and vehicle systems monitoring and control. In addition, the workstations can be configured to support mission-specific science investigations.

7. A workstation, located in the cupola, provides a higher vantage point for navigation and long-range observation. Windows in the cupola provide a panoramic view. A folding perch stows out of the way when not in use. A general purpose keyboard/computer interface provides a versatile control and display capability.

8. EVA manlocks are located in the side of the vehicle. The manlocks enclose a minimal volume in order to conserve as much air as possible during depressurization and repressurization. EVA suits are stowed in the manlocks when not in use. The manlocks also provide a dust-off area where surface dust can be contained and filtered to keep it from entering the cabin environment. This airlock concept is somewhat different from the one shown in figures 5.8.3-1 and 2. A manlock is more of a form-fitting airlock that conserves air and perhaps allows a blowdown system at the expense of a more complex seal. The airlocks shown in figures 5.8.3-1 and 2 on the sides of the vehicle are just low volume airlocks with simpler seals.

9. A compact galley incorporates the facilities needed for preparing meals including rehydrating freeze-dried food and microwaving meals. Water dispensers provide both hot and chilled potable water. Food and supplies are stowed in the galley area.

10. At the rear of the vehicle, the floor is lowered and the overhead space is used for equipment and stowage. Fluids, gasses and dense equipment are located in tanks and stowage lockers in the ceiling to provide increased radiation shielding.

11. Sitting and sleeping for passengers is provided by lightweight deployable units made of tubular aluminum

frames with stretched fabric surfaces. When not in use the seats can be folded up and stowed out of the way.

12. A compact personal hygiene facility is located at the rear of the rover. Tubular aluminum and fabric panels can be deployed for privacy and stowed when not needed. Since partial gravity allows water to drain normally, a simple hand-held shower can be used in the compartment with a floor drain to collect the water. This is a welcome amenity during a two-week mission with frequent dusty EVA's. Molded plastic fixtures shed water and simplify cleanup.

13. EVA jump seats allow suited crewmembers to remain outside during short, slow traverses, This maximizes the efficiency of EVA's by minimizing the number of times the vehicle must be depressurized and repressurized. A folding ladder provides access to exterior stowage compartments over the wheel fenders.

#### 5.8.3.5 Technology Development Required--Pressurized Rover

Long-lead technology development work is needed in several areas:

- A wheel capable of a minimum of 10,000 km (3 long traverses) that can take the lunar or martian environment for a period of 10 years must be developed.
- A radiator system that is not unreasonably large and is insensitive to dust is needed.
- A surface docking system is required to dock pressurized vehicles onto habitats and each other such that IVA transfers can be easily made. The vehicles will be operating on unprepared surfaces.
- A highly reliable, long-life fuel cell capable of taking years of bumping around such as would occur on successive surface traverses must be developed.
- A test bed vehicle with enough operational history here on Earth such that maintenance and wear issues can be understood well in advance is needed.

#### 5.8.3.6 Precursor Data Required

For this large a vehicle, more data on the surface of Mars may be mandatory. Engineering soil properties and general terrain information will be needed to comfortably design a long range traverse vehicle. A short range pressurized rover might be fabricated without this data. A successful long-range traverse on the Moon or Mars will require high resolution mapping (better than 1 meter resolution) of the lunar and martian terrain.

#### 5.8.3.7 Resupply Requirements

The vehicle will require fuel cell reactants at frequent intervals, replacement of the fuel cells themselves every 2 to 20 thousand hours, replacement of ECLSS consumables, suit refurbishment, new wheels, and perhaps suspension and gearbox parts at intervals, and other small parts.

### 5.8.4 Martian Surface Rover

An unmanned martian rover may be part of the early Mars landings, perhaps left behind after initial landings or operated remotely to extend the effective range of the crews. Preliminary requirements include a total maximum mass limit of 2.9 metric tons, 200 kg of which should be devoted to scientific payload. The rover should be operable telerobotically by the crew to deploy scientific payloads and to conduct local geological experiments. The rover must also have the capability to autonomously conduct a traverse up to 400 km total distance for the purpose of collecting geological samples and mapping the martian terrain after the crew leaves. The rover would rendezvous with the next manned Mars mission to deliver the samples collected.

Because of the similarity of the requirements stated to recent requirements for the Mars rover sample return (MRSR) mission rover and because of the extensive MRSR rover work already carried out, the MRSR rover was used as a guide and an extrapolation point from which to develop a manned mission, unmanned rover conceptual design. Table 5.8.4-I compares the basic requirements for the MRSR rover (Mars, 1988) with the manned mission, unmanned rover requirements.

The manned mission rover concept, like the MRSR rover, has a non-articulated, 6 wheel (1 meter) chassis. The rover should be able to negotiate 1 m vertical steps and 1 m wide crevasses. Attention may be required concerning the amount of shock the payload receives while the rover traverses rugged terrain.

Two modular radioisotope thermoelectric generators (RTG's) providing 500 watts of nominal power and 350 Whr $LiTiS_2$ batteries provide the electrical power. RTG's were chosen due to their proven reliability and operational lifetime (years). Solar arrays would provide the same power at less weight, however, the large area of the solar arrays required, 42 $m^2$, makes them too fragile for traversing over the rugged martian terrain.

TABLE 5.8.4-I.- UNMANNED ROVER REQUIREMENTS - MRSR AND MANNED MISSION ROVER

| | MRSR | Manned Mission rover |
|---|---|---|
| Speed | >1 km/day | - |
| Range | >100 km | 400 km |
| Operational Lifetime | >3 years | >2 years |
| Payload Mass | >150 kg | 200 kg |
| Obstacle Crossing | 1 m vertical steps | 1 m vertical steps |
| | 1 m wide crevasses | 1 m wide crevasses |
| Positioning | within 50 m of a point 10 km distant | - |
| | within 10 cm locally | - |

The manned mission rover concept will be able to operate telerobotically and in a semi-autonomous mode (supervisory control only) after the crew leaves. The rover should be able to negotiate a path chosen by the operator, via camera, with contingency interference only. This is desirable because the time delay in communication to and from Earth or other remote sites would endanger the rover and limit its usefulness. The rover should have, as per the MRSR design, the ability to position itself within 50 meters of a point 10 km distant and to within 10 cm of a point locally.

Mass and power estimates for the manned mission rover concept are given in table 5.8.4-II. These mass and power estimated were scaled from the MRSR 1996 Mission concept (Mars, 1986). Figure 5.12.4-3 in the user accommodations section (5.12) shows the unmanned rover concept.

TABLE 5.8.4-II.- MANNED MISSION, UNMANNED ROVER MASS AND POWER ESTIMATES

| Subsystem | Mass (kg) | Power (W) |
|---|---|---|
| Structure | 92.0 | |
| Telecommunications | 30.1 | 137.0 |
| Power | 145.5 | 18.0 |
| Command and Data | 20.0 | 18.0 |
| Locomotion and Vehicle Control | 88.8 | 140.0 |
| Cabling | 24.0 | |
| Thermal Control | 18.0 | |
| Mechanical Devices | 44.3 | 10.0 |
| Data Storage | 17.8 | 18.0 |
| Science and Sample Acquisition | 236.5 | 149.7 |
| **Subtotal** | **717.0** | **490.7** |
| Contingency | 50.0 | |
| **Rover Total** | **767.0** | **490.7** |

## 5.9 IN SITU RESOURCE UTILIZATION (ISRU)

In all human expansion to date, permanent settlements of any kind have required extensive use of locally derived resources. The President has set a long term goal of a permanent lunar surface outpost or base. The word "permanent" implies the eventual incorporation of lunar surface propellant production. The significant question becomes when to incorporate it, early or late in the base evolution. Recent work indicates that even for a small base with only a few landings per year of a reusable lunar lander (surface based), benefits from lunar propellant production can be significant. Propellant production equipment can be made simple and small if adequate time is allowed to develop it. Lifetime and maintenance are key issues that require long term operation of the equipment on Earth first. To benefit from locally derived resources using low cost equipment, one must consider serious technology development work on lunar propellant production early in the program.

Volume I of the annual report presents the results of an extensive parameter study of the cost benefits of the use of lunar oxygen but a simple calculation is also possible for use of lunar oxygen in a reusable lunar lander. First assume the plant is not there and oxygen for the landers will have to be shipped to the lunar surface. A good argument can be made for only counting shipping cost to low lunar orbit, but other complications are involved; therefore, shipment is assumed to go to the lunar surface. Assume 3 lander flights per year (each requiring 25 t of oxygen to make the round trip--lunar orbit to lunar surface and back) and an optimistic Earth surface to low earth orbit (LEO) cost of $1,000/lbm. $1,000/lb is a reasonable lower limit for Earth launch cost (Evans, 1989). Shuttle C is predicted to cost around $3,000/lb; the Shuttle currently costs around $7,000/lb to get from the surface of the Earth to 220 nm circular, 28.5°.

Basic physical principles require 6 units of propellant in LEO for every unit delivered to the lunar surface. So, for a first approximation, the cost of transporting a unit

mass from Earth's surface to the lunar surface is six times the cost of transporting the same mass to LEO. Therefore, using the $1,000/lb Earth-to-LEO figure cited above, the cost of placing mass on the lunar surface becomes 6 x $1,000/lb, or $6,000/lb. This converts to $13.2 million per metric ton. This is a conservative figure since it ignores the cost of Space Station Freedom services and LEO-to-lunar surface transportation.

The cost to deliver lander oxygen to the lunar surface is calculated as follows. The requirement for lander oxygen is 75 t/yr, based on 25 t per flight and 3 flights per year. At $13.2 million per metric ton, the cost is 75 x $13.2, or $990 million. The cost over ten years is $9,900 million.

We can also compute roughly what it would cost to get the same oxygen with a lunar plant. The cost of design, development, test, engineering, production, and spares for ten years (using Price H cost model software) is $1,500 million. The initial emplacement transport costs (assuming 45 t of plant, power, mining equipment--see Table 5.9.1-V) are $600 million. The operations costs for 10 years (200 to 300 people on Earth--see Support, 1989) are $500 million. Resupply transport costs for 10 years (4.5 t/yr--see Support, 1989) are $600 million. Adding together the above costs, the total 10 year life cycle cost of producing oxygen on the Moon is $3,200 million (1,500 + 600 + 500 + 600). This calculation does not take costs of money into account.

As demonstrated above, the savings of lunar plant production versus Earth transport over 10 years are roughly $6,700 million (9,900-3,200). Significant savings will start even in the first year of operation and payback will occur by the fourth year. The key number is the Earth surface to lunar surface transport cost. In all probability, it will be higher than the 6,000 $/lbm used above. This will make the oxygen plant even more attractive. The only really significant number in the oxygen plant cost is the DDT&E and production. Any other number can be multiplied by 3 or more without changing the results much. This all assumes a reusable, lunar surface-based lander. Other options exist and will change the answer somewhat.

Savings in the range of $5 to $10 billion are not as impressive when compared to a $100 billion total program cost. Other advantages local resource utilization contribute to the program such as flexibility, safety, and building a development base for later human expansion are difficult to quantify but also deserve consideration.

### 5.9.1 Lunar Oxygen

The oxygen propellant plant interacts closely with the base and the transportation system. Past plant concepts with production rates in the range of 1,000 t/yr were designed to produce oxygen for use beyond lunar orbit. Current thought concentrates on oxygen usage chiefly in the lander and perhaps in the Earth to lunar orbit transfer vehicles. This reduces the production rate required significantly and makes the whole operation much smaller. Table 5.9.1-I shows the current target values and reasonable ranges within which the oxygen production plant must fall for a variety of parameters.

The current manifest shows the oxygen production facility arrival date as 2010, well after the base has been founded. Arguments for earlier introduction into the manifest can be made, but if the base does operate for 5 or more years with no propellant plant, a small mass allotment should be maintained in the manifest for ISRU demonstration and validation equipment, on the order of 500 kg/year.

In the following sections the various processes are described and compared in a simple manner. The technology readiness level and understanding of the processes varies widely. Picking a winner at this time is inappropriate. Three reference processes are also described in more detail.

#### 5.9.1.1 Status of Various Lunar Oxygen Processes

Numerous processes have been proposed for extracting oxygen from lunar soil. The 1989 ISRU workshop evaluated 15 of these processes and recommended 8 for further study (Christiansen/Highlights, 1989). Table 5.9.1-II lists the processes in order of ranking and briefly explains each.

Table 5.9.1-III shows how the ranking was done. Four criteria were weighted more heavily than others: process simplicity, maintainability, yield (amount mined per unit of $O_2$ produced), and resupply requirements. Performance paramaters, such as process weight and power for a given production rate, are important comparison criteria. They were not included, though, because reported mass and power estimates for the various processes lack a consistent basis to allow comparisons. Weights and power estimates for some processes are based on simple calculations, while others have detailed weight statements and years of work behind them. In general, the longer a process is studied, the heavier it becomes.

## TABLE 5.9.1-I.- GENERAL REQUIREMENTS FOR LUNAR OXYGEN PLANT

| Requirement | Reasonable Range | Target Value |
|---|---|---|
| Production rate, t/yr (11 to 28 t per lander mission) | 20 to 200 | 100 |
| Plant lifetime, years | 10 to 20 | 20 |
| Lunar surface operations crew, persons | 0 to 3 | 2 part-time |
| Dedicated Earth surface ops. crew, persons | 30 to 300 | 150 |
| Reasonable resupply, t/yr | 0 to 10 | less than 1 |
| First plant delivery date | 2004 to 2015 | 2010 |
| Maximum mass of pre-assembled module, t | 10 to 30 | 25 |

## TABLE 5.9.1-II.- CANDIDATE OXYGEN EXTRACTION PROCESSES

Numbers in parenthesis are the weighted sum evaluation from Table 5.9.1-III

| Process | Reaction |
|---|---|
| Fluxed Electrolysis (46) | Lunar soil is melted in the presence of a molten salt. Oxygen is removed from the melt by electrolysis. |
| Vapor Phase Reduction (42) | Turn bulk lunar soil into vapor. Condense out unwanted material. Trap oxygen. |
| $H_2$ Redn. of Ilmenite (41) | Ilmenite is separated from lunar soil. Hydrogen reacts with Ilmenite to form water. The water is then electrolyzed to form hydrogen (recycled) and oxygen. |
| Volatile Extraction (41) | Lunar soil is heated to remove solar wind hydrogen. Hydrogen reacts with oxygen in ilmenite to form water. Water is electrolyzed. |
| Carbothermal Reduction (40) | Oxygen in lunar silcates is removed by methane to form carbon monoxide. Carbon monoxide reacted with hydrogen to form methane and water. Water is electrolyzed. |
| Ion Separation (40) | Bulk lunar soil is vaporized, then ionized. Impurities in ion form are removed with electrostatic separator. |
| Magma Electrolysis (37) | Melt lunar soil and directly remove oxygen by electrolysis. |
| Magma Partial Oxidation (37) | Lunar soil is melted in the presence of air or oxygen. Resulting iron oxides are magnetically separated out and dissolved in mineral acids. This solution is then electrolyzed to yield iron and oxygen. |
| Lithium Reduction (35) | Oxygen is removed from lunar oxides with lithium producing $Li_2O$. Oxygen is then separated from the lithium by electrolysis. |
| Methane/Water Ilmenite Reduction (34) | Ilmenite is heated in the presence of water and methane to form water and other products. The water is then electrolyzed. |
| Hydroflouric Acid Leach (33) | Lunar soil is leached with hydrofluoric acid to separate the oxygen and other components. Numerous by products are formed from which the fluorine must be removed. |
| Hydrogen Sulfide Reduction (30) | Oxygen is removed from lunar materials using hydrogen sulfide to form various sulfides and water. The water is electrolyzed. |
| Carbochlorination (30) | Ilmenite and/or Anorthite is combined with carbon and chlorine to form various compounds including CO which is split to get the oxygen and carbon. |
| Caustic Electrolysis (30) | Lunar soil is combined with NaOH to form various compounds. Alkali oxide/hydroxide is then electrolyzed to get the oxygen. There are several metal byproducts. |
| Fluorine Exchange (29) | Lunar oxides are combined with fluorine to form various fluorides and oxygen. The fluorides are then broken down to get the oxygen back. There are several metal byproducts. |

# TABLE 5.9.1-III.- RELATIVE COMPARISON OF LUNAR OXYGEN PRODUCTION PROCESSES

(Christiansen/1989 ISRU Workshop Highlights)

| Criteria: | Maturity | Feedstock Req. | Yield | Reactant Resupply | By Products | Complexity | Reliability | Energy Req. | Weighted Sum | Cutoff 37 | Non-Weighted Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Weighing Factor: | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | | | |
| Process | | | | | | | | | | | |
| 1. Ilmenite Redn. by $H_2$ | 4 | 1 | 4 | 8 | 2 | 10 | 10 | 2 | 41 | 41 | 25 |
| 2. Carbothermal Redn. | 4 | 5 | 6 | 6 | 3 | 8 | 6 | 2 | 40 | 40 | 27 |
| 3. Volatile Extraction | 3 | 3 | 2 | 10 | 1 | 8 | 10 | 4 | 41 | 41 | 26 |
| 4. Hydrogen Sulfide Redn | 3 | 3 | 6 | 6 | 2 | 6 | 2 | 2 | 30 | | 20 |
| 5. Carbochlorination | 2 | 5 | 10 | 2 | 5 | 2 | 2 | 2 | 30 | | 22 |
| 6. Fluorine Exchange | 2 | 5 | 8 | 2 | 4 | 2 | 4 | 2 | 29 | | 21 |
| 7. Hydrofluoric Acid Leach | 3 | 5 | 8 | 4 | 5 | 2 | 4 | 2 | 33 | | 24 |
| 8. Magma Electrolysis | 3 | 3 | 6 | 10 | 2 | 10 | 2 | 1 | 37 | 37 | 23 |
| 9. Caustic Electrolysis | 2 | 5 | 6 | 6 | 3 | 2 | 4 | 2 | 30 | | 21 |
| 10. Lithium Reduction | 2 | 5 | 6 | 6 | 2 | 8 | 4 | 2 | 35 | | 23 |
| 11. Fluxed Electrolysis | 3 | 5 | 10 | 8 | 3 | 10 | 6 | 1 | 46 | 46 | 29 |
| 12. Vapor Phase Reduction | 2 | 5 | 4 | 10 | 2 | 10 | 6 | 3 | 42 | 42 | 27 |
| 13. Ion Separation | 2 | 5 | 8 | 6 | 4 | 10 | 4 | 1 | 40 | 40 | 26 |
| 14. Magma Partial Oxidation | 1 | 3 | 6 | 8 | 3 | 6 | 8 | 2 | 37 | 37 | 23 |
| 15. Methane/Water Ilm. Red. | 2 | 1 | 4 | 6 | 1 | 10 | 8 | 2 | 34 | | 20 |

| Criterion | Description | Scoring (unweighted) |
|---|---|---|
| 1. Maturity | Technology readiness level. | 1=Basic principles and/or theory exists, 2=Process conceptual design exists, 3=Experiments and Lab-scale demonstrations, 4=Component validation in laboratory, 5=Component validation in relevant environment. |
| 2. Feedstock Requirements | Ability of process to use varied feedstock materials. | 1=low feedstock flexibility--1 mineral, 5=all minerals--capability to go anywhere |
| 3. Yield | Oxygen extracted per feedstock | 1=low yield, 3=medium, 5=high yield. |
| 4. Reactant Resupply | Reactant recovery potential and resupply requirements. | 1=difficult, multiple step ops, dense reactants; 3=medium; 5=easy, low density reactant. |
| 5. By Products | Types and quantities of useful by products. Consider simplest $O_2$ production scheme and resulting unprocessed by products. | 1=one useful by product, 5=five or more. |
| 6. Complexity | Simplicity of $O_2$ process scheme, in terms of the number of major process steps/units (development and operations costs, process viability, reliability). | 1=9 + major steps, 2=7 or 8 steps, 3=5 or 6 steps, 4=3 or 4, 5=2 or fewer steps. |
| 7. Reliability | Relative maintainability of process compared in terms of the severity of process conditions (lifetime, maintainability). | 1=high temperature/highly-corrosive, 3=non-corrosive/moderate temps, 5=low temp non-corrosive. |
| 8. Energy Requirements | Required state of power needs; i.e. thermal vs. electric. Large thermal requirements indicate leverage potential from heat recovery and energy management techniques, nuclear-power waste heat recovery. | 1=100% electric power, 2=>50% electric, 3=primarily high-temperature thermal, 4= >50% high temperature, 5=100% low temperature thermal. |

Criteria not considered: Product purity, Autonomous Ops Capability (continuous vs. batch processes)

Important criteria to be evaluated after more detailed study: Mass/Production and Power/Production ratios, Stowed Volume, Operations and Setup Manpower requirements, Costs and Savings.

Other criteria to consider: 1/6-gravity effects, process dependent differences in program to full-scale O2 production, need for lunar pilot plant vs. first lunar demonstration plant.



C-3

Table 5.9.1-IV shows a preliminary collection of process weight and other parameters for the top five processes. Three of these processes (hydrogen reduction of ilmenite, magma and fluxed electrolysis) are described in more detail in the following tables and figures. Selection of these five and three is based more on the availability of data rather than on precise ranking. Vapor phase reduction, which ranked highly, is omitted because it is discussed in the lunar hydrogen section (5.9.2).

The hydrogen reduction of ilmenite process has consumed the majority of the resources spent on this subject to date and is the current baseline. At least three groups are actively working on this process. The verification of 1/6 gravity operation of a fluidized bed reactor occured in 1989 and is a major breakthrough which will allow a much better system design. Hydrogen reduction of ilmenite is the only process that is well understood at a high level of detail.

A number of the other processes listed which are poorly understood at present could significantly reduce the mining requirement and equipment complexity if they prove practical. These processes deserve more development work. It is difficult to effectively compare one process to another until the real limitations and overall parameters of each process are understood at the same technology readiness level. Selection of a process as the winner is premature at this time.

TABLE 5.9.1-IV.- LUNAR OXYGEN PROCESS ELEMENT SUMMARY

(Christiansen/1989 ISRU Workshop Highlights)

Basis: 150 t $O_2$/yr production rate

| | Feedstock type | Mass (t) | Power (kW) | Avg. Power (kW) | Peak Power (kw) | Standby Vol. ($m^3$) | Op. Life (yr) | Est. Resupply (t/yr) |
|---|---|---|---|---|---|---|---|---|
| 1. Ilmenite Reduction by $H_2$ | Ilmenite | | | | | | | |
| a. Reactor | | 23 | 150 | 450 | 15 | 43 | | 2 |
| b. $H_2O$ Electrolysis Cell | | 1.3 | 210 | 210 | 0 | 2.5 | 5 | |
| c. Reactor Auxiliaries | | 6 | 40 | 40 | 2 | | | 0.6 |
| d. $O_2$ Liquefaction | | 12 | 30 | 30 | 3 | | | |
| Total | | 42.3 | 430 | 730 | 20 | 45.5 | | 2.6 |
| 2. Carbothermal Reduction | No restrictions (Silicates, FeO reduced) (estimates include reactors, $H_2O$ electrolysis, $O_2$ Liquefaction) | | | | | | | |
| Total | | 13.3 | 386 | 463 | | | 10 | |
| 3. Fluxed Electrolysis | No restrictions (all oxides reduced) | | | | | | | |
| a. Electrolysis Cells | | 55 | 252 | 252 | 210 | 15 | 6 | |
| b. Metal Separation | | 10 | 10 | 10 | 10 | 2 | 6 | |
| c. $O_2$ Purification Unit | | 2 | 1 | 1 | 1 | | 6 | |
| Total | | 67 | 263 | 263 | 221 | 17 | | |
| 4. Magma Electrolysis | Lo-Ti mare basalts, most highlands (anorthositic soils, A16, not acceptable) feed: 4.8 t per t $O_2$ produced. | | | | | | | |
| a. Electrolysis Cell | | 8 | 300 | | | 1 | 10 | |
| b. Containment & Feed | | 2 | | | | | | |
| Total | | 10 | 300 | | | 1 | | |
| 5. Magma Partial Oxidation | No Restrictions (high FeO preferred) Feed: 34 t per t $O_2$ produced. | | | | | | | |
| a. Melting, Oxidation, Cooling | | 0.5 | 65 | 65 | 0 | 1.72 | | |
| b. Grinding, Magnetic Separation | | 1.6 | 16 | 16 | 0 | 0.83 | | |
| c. Acid Dissolution, Electrolysis | | 2.05 | 312 | 312 | 0 | 2.02 | | |
| Total | | 4.15 | 393 | 393 | 0 | 4.57 | 20 | <1 |

### 5.9.1.2 Lunar Oxygen Reference System 1 - Hydrogen Reduction of Ilmenite Propellant Plant

Table 5.9.1-V describes the basic paramaters for the hydrogen reduction of ilmenite propellant plant (based on a Carboteck, Inc. design, 1989 ISRU workshop results, and designs and calculations by E. Christiansen). The plant process has soil feedstock and nuclear power. The plant first separates the small fraction of ilmenite (about 5 percent) from the rest of the soil. Alternatively, crushed basalt containing up to 20 percent ilmenite can be used as feedstock. Since the ilmenite is slightly magnetic, a magnetic separator separates the ilmenite from the soil. The non-ilmenite fraction of the soil is discarded. A high and low pressure feed hopper system then feeds the ilmenite into the top of a three-stage fluidized bed reactor. Inside the reactor, the ilmenite is heated to about 1,000°C. The ilmenite flows down the

**TABLE 5.9.1-V.- HYDROGEN REDUCTION OF ILMENITE**

(based on a Carboteck, Inc. design, 1989 ISRU workshop results, and designs and calculations by E. Christiansen)

| | |
|---|---|
| Annual Liquid Oxygen Production (t) | 100 |
| Process Plant Duty Cycle | 0.9 |
| Plant Liquid Oxygen Capacity (kg/hr) | 12.7 |
| Ilmenite in Soil (vol.%) | 5% |
| Ilmenite in Soil (wt.%) | 8% |
| Oversize (Wt.% Greater than 0.9 mm) | 11% |
| Undersize (Wt.% less than 30 micron) | 45% |
| Ilmenite Recovery in Beneficiation | 98% |
| Available oxygen in ilmenite | 10.5% |
| Reactor Conversion Efficiency | 90% |
| Mining Rate (t/yr) | 30,640 |
| Mining Duty Cycle | 35% |

| | Number | Total Mass (kg) | Power (kW) | Feed Rate (t/hr) | Vol. ($m^3$) | Comments |
|---|---|---|---|---|---|---|
| Front-End Loaders | 1 | 2,600 | 22 | | 21 | based on min. bucket size of 0.5 $m^3$ |
| Haulers | 2 | 2,000 | 6 | | 50 | based on minimum volume of 4.5 $m^3$ |
| Feed Bin | 1 | 4,880 | 0 | 9.993 | 900 | sized for operation during lunar night |
| Coarse Screen | 1 | 165 | 5 | 3.886 | 3 | reduces feed to less than 0.9 mm |
| Fine Screen | 1 | 3,000 | 90 | 3.448 | 60 | removes particles less than 0.030 mm |
| Storage Hopper | 1 | 100 | 0 | 1.705 | 80 | allows for 3 day hold-up time |
| Magnetic Sep. | 1 | 1,780 | 2 | 1.705 | 2 | 3 stage induced magnetic roll separator |
| Reactor Lo-P Hopper | 1 | 20 | 0 | 0.149 | 5.6 | holds 3 days supply of ilmenite feed |
| Hi-P Feed Hopper | 1 | 160 | 0 | 0.149 | 5.6 | holds 3 days supply of ilmenite feed |
| Reactor | 1 | 2,640 | 44 | 0.149 | 5.9 | 0.45 m internal diameter, 6.1 m high |
| Electric Heater | 1 | 240 | 0 | 0.0247 | 1.3 | maximum temperature of 1650 Kelvin |
| Electrolysis Cell | 1 | 440 | 70 | 0.0143 | 0.7 | operates at 1270 Kelvin |
| Blower | 1 | 60 | 1 | 0.0247 | 0.02 | mass flow: 25 kg/hr, exit press.: 1 MPa |
| Cyclone Separators | 3 | 5 | 0 | | 0.02 | simple method of solids separation |
| Solids Settler | 1 | 210 | 0 | 0.136 | 3.5 | 2 days storage, length/diam. ratio: 2 |
| Tailings Conveyor | 1 | 23 | 0.01 | 1.319 | 0.2 | V-belt, total flow: 1320 kg/hr |
| Oxygen Liquifier | 1 | 450 | 10 | 0.0223 | 0.4 | Stirling cycle refrigerator |
| Storage Tanks | 2 | 670 | 0 | | 18.3 | each tank has a 16.4 MT capacity |
| Process Piping | | 450 | 0 | | 0.1 | |
| $LH_2$ Storage Tank | 1 | 30 | 0 | | 1.0 | internal diameter 1.15 m |
| $H_2$ Heater | 1 | 0.1 | 0.01 | | 0.01 | maximum temperature of 1650 Kelvin |
| $H_2$ Blower | 1 | 7 | 0.01 | | 0.01 | mass flow: 0.012 kg/hr,exit press.:1 MPa |
| TSC/Radiator | 1 | 3,620 | 0 | | 1.8 | heat rejection: 65 kW,surface area: 181$m^2$ |
| Subtotal | | 23,550 | 250 | | 1,167 | |
| Contingency | 30% | 7,100 | 75 | | 350 | |
| **Process Total** | | **30,650** | **325** | | **1,517** | |
| | | | (kg/kWe) | | | |
| Nuclear Power | | 6,300 | 19.6 | | 3 | Los Alamos study (Keaton, 1985) |
| **Total Plant & Power** | | **37,000** | | | **1,520** | |

three stages of the reactor while hydrogen gas flows up past the ilmenite. The hydrogen reacts with the ilmenite to form water vapor. An electrolysis cell separates the water vapor into hydrogen and oxygen. The oxygen is liquified and stored. The hydrogen is fed back into the bottom of the reactor. A solids settler removes the reactor residuals (ilmenite, rutile, and iron) from the bottom of the reactor. Figure 5.9.1-1 shows the process in diagram form.

Figure 5.9.1-2 shows a 100 t/yr plant and pit. The pit is roughly 2 meters deep and 100 meters on each side. This is the volume that must be excavated to produce 25 t of oxygen, or approximately one lander load.

### 5.9.1.3 Lunar Oxygen Reference System 2 - Molten Silicate (Magma) Electrolysis

The plant process electrolyzes molten lunar materials to directly produce oxygen and a mixed metal alloy of iron and silicon. Figure 5.9.1-3 shows the process schematic. This process is based on a concept from L. Haskins and work by E. Christiansen, 1989.

Table 5.9.1-VI provides process parameters and estimates of mass and power. The process operates on unbeneficiated soil. Only particles greater than 1 cm need to be removed prior to feeding the electrolysis cell. Soils derived from low-titanium mare basalts and most highland soils can be used. Nearly pure anorthite, such as the Apollo 16 soil, would not be an acceptable feedstock. No flux is required. The process is conceptualized to involve feeding sized lunar materials through a containment structure that encloses an open electrolysis cell. Oxygen is piped from the enclosure to an oxygen liquefaction/storage facility. Slag and metal are removed and collected for possible further processing (possibilities include: pouring metal or slag directly into molds on a conveyor or mobile slag/metal pots transporting the molten material to a downstream processing or disposal area.)

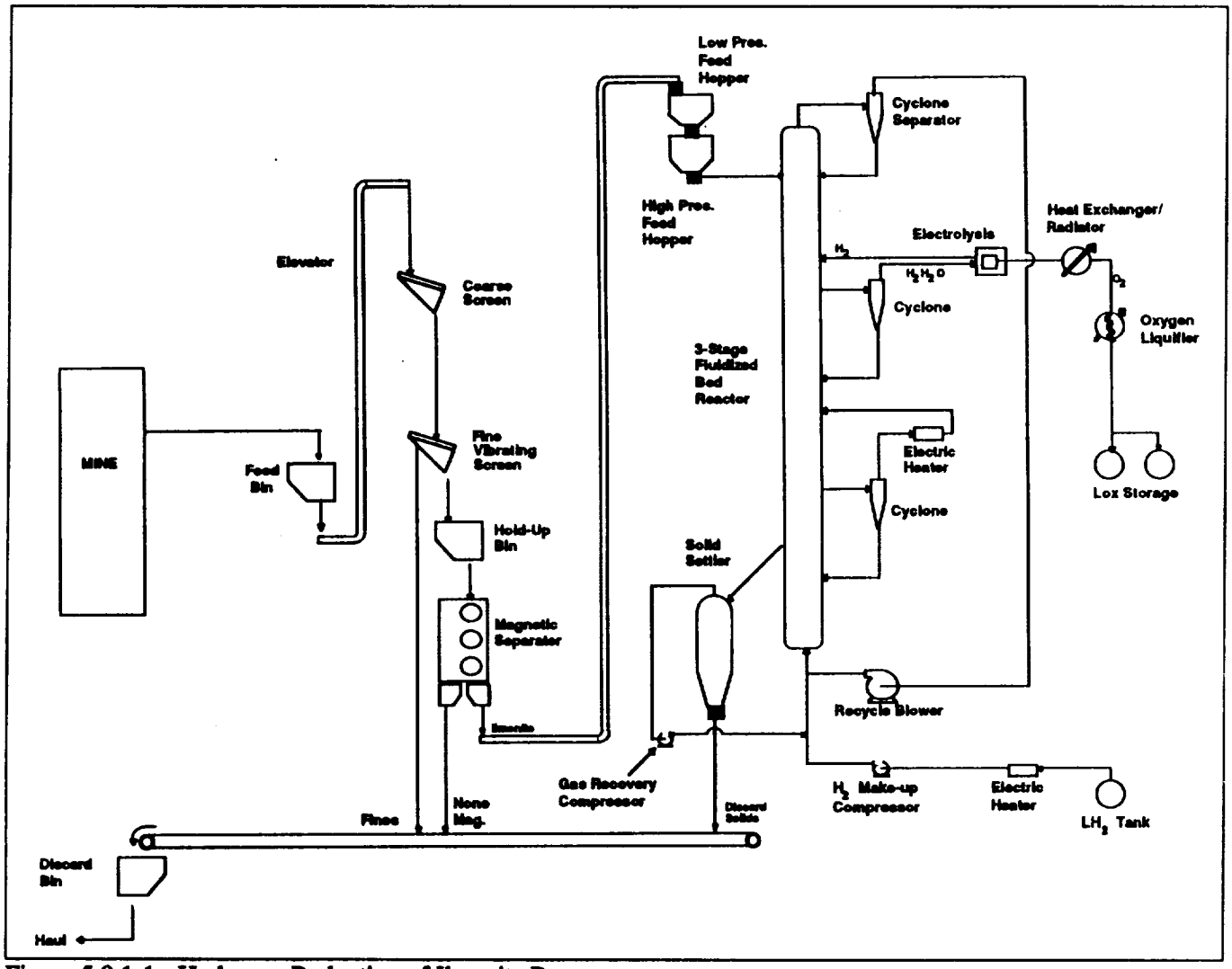


Figure 5.9.1-1.- Hydrogen Reduction of Ilmenite Process.

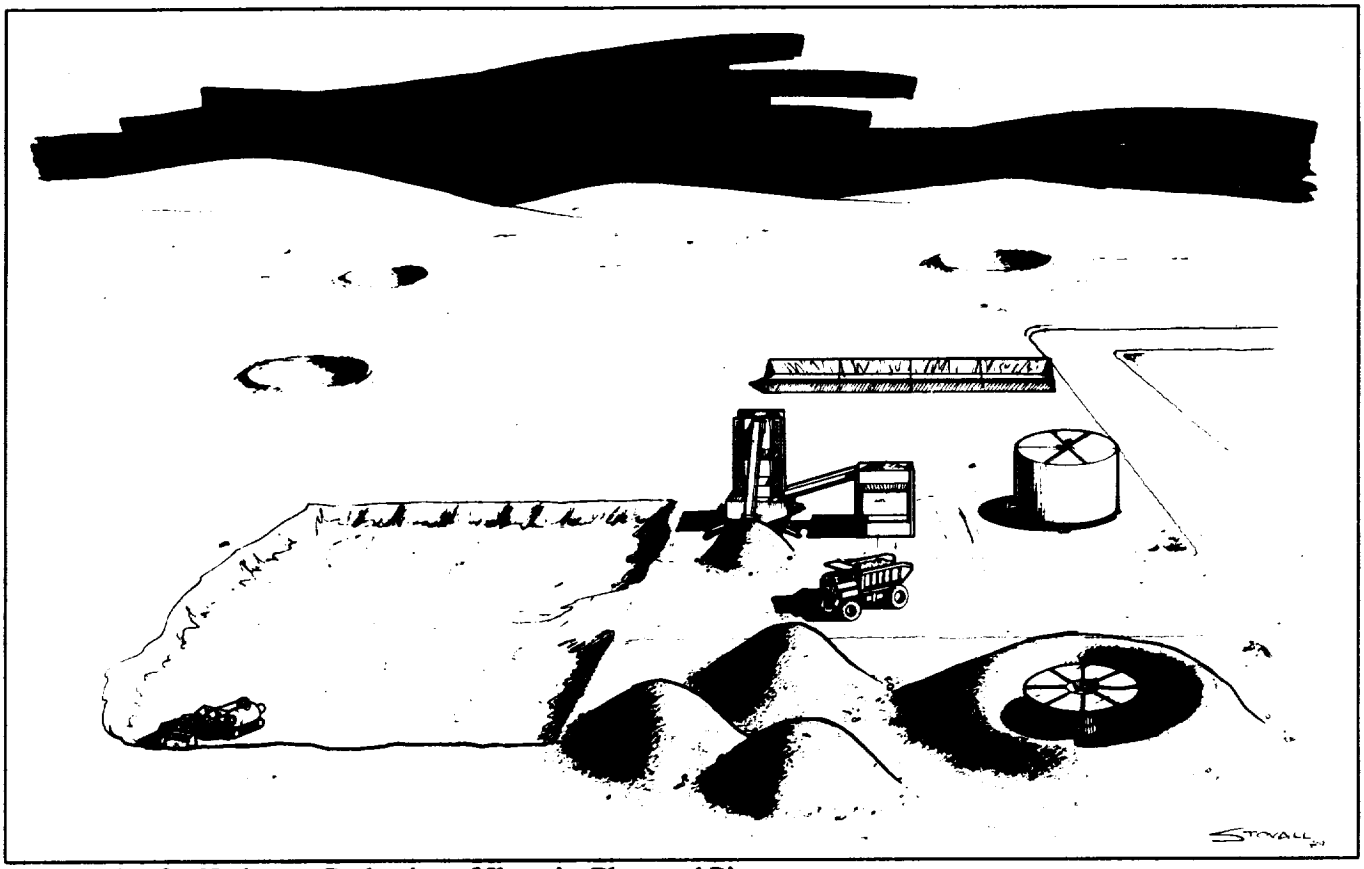


Figure 5.9.1-2.- Hydrogen Reduction of Ilmenite Plant and Pit.

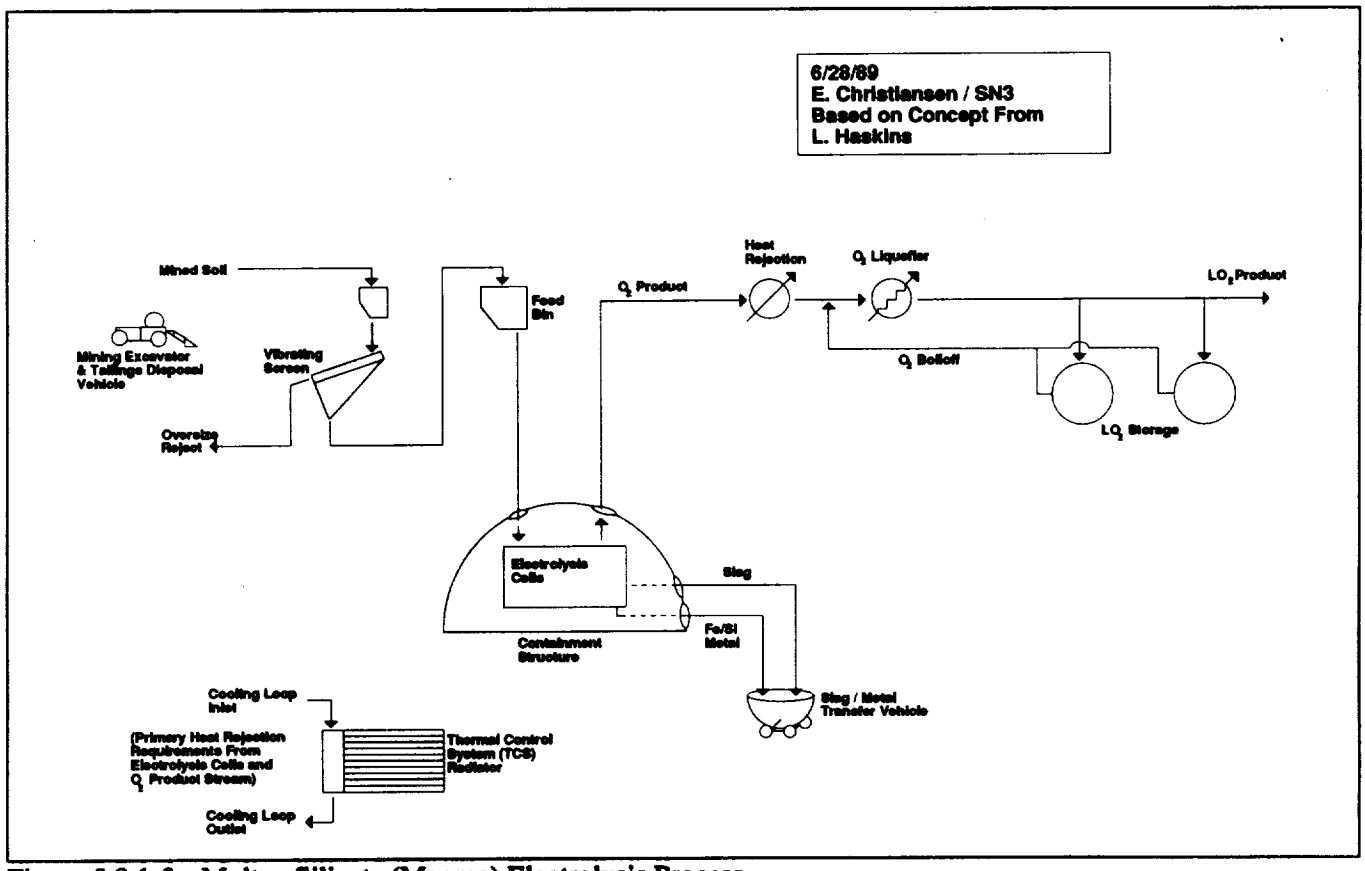



Figure 5.9.1-3.- Molten Silicate (Magma) Electrolysis Process.

## TABLE 5.9.1-VI.- MOLTEN SILICATE (MAGMA) ELECTROLYSIS

(Based on a concept from L. Haskins and work by E. Christiansen, 1989.)

| | | | | | |
|---|---|---|---|---|---|
| Annual liquid oxygen production | 100 | mt | Fe/Si produced | 17.57 | kg/hr |
| Process plant duty cycle | 90 | % | Slag produced | 51.76 | kg/hr |
| Plant liquid oxygen capcity | 12.68 | kg/hr | Mining rate | 659.8 | t/yr |
| Electrolysis solids feed | 82.01 | kg/hr | Mining duty cycle | 35 | % |
| Iron produced | 8.60 | kg/hr | Operating temperature | 1,350 | °C |
| Silicon produced | 8.97 | kg/hr | | | |

| | Number | Total Mass (kg) | Total Power (kw) | Total Deployed Volume ($m^3$) | Dimensions (Each) Length (m) | Dia/W (m) | Height (m) | Total Stowed Volume ($m^3$) | Heat Rejected (kWt) |
|---|---|---|---|---|---|---|---|---|---|
| Excavator | 1 | 2,160 | 1 | 12 | 3.79 | 1.84 | 1.73 | 6 | |
| Vibrating screen | 1 | 14 | 0.1 | 0.1 | 0.40 | 0.25 | 0.40 | 0.1 | |
| Feed bin | 1 | 120 | 0 | 33 | | 2.75 | 5.49 | 33 | |
| Electrolysis cell | 1 | 7,873 | 193 | 1 | 1.58 | 0.79 | 0.79 | 1 | 96 |
| Containment structure | 1 | 63 | 0 | 33 | | 5.00 | 2.50 | 0.3 | |
| Slag/metal cars | 2 | 448 | 1 | 1 | 0.75 | 0.75 | 0.87 | 0.4 | |
| $O_2$ liquefier | 1 | 323 | 7 | 1 | 2.70 | 0.68 | | 1 | 14 |
| $O_2$ storage tanks | 2 | 446 | 0 | 17 | | 2.55 | | 17 | |
| TCS/radiator | 1 | 4,123 | 0 | 5 | 45.81 | 4.50 | | 1 | |
| subtotal | | 15,570 | 202 | 103 | | | | 60 | 110 |
| Contingency | 30% | 4,670 | 61 | 31 | | | | 18 | |
| **Process Total** | | **20,240** | **263** | **134** | | | | **78** | **110** |
| Nuclear Power | 1 | 4,790 | | 2 | | | | 2 | 2,570 |
| **Total Process With Power** | | **25,030** | | **136** | | | | **80** | **2,680** |

The electrodes on the electrolysis cell are made of platinum to minimize corrosion. The lifetime of the electrodes is unknown and is the chief technical question that must be answered to evaluate the technical feasibility of this process. The cell is open, therefore, the oxygen is collected by the containment structure. The containment structure is large enough to allow manned access to the electrolysis cell. The containment structure has entry ports for the soil feed and exit ports for the slag and hot metal. These ports require good seals to avoid excessive loss of materials. The structure is made of impermeable flexible material. This structural material allows for low stored volume. However, since the structure needs to be easily deployed, ceramic fabrics with suitable films/-coatings (to avoid oxygen loss) should be considered. The operating temperature of the process is 1,350°C.

This process will also work on silicates on Phobos or Deimos.

### 5.9.1.4 Lunar Oxygen Reference System 3 - Fluxed (Molten Salt) Electrolysis

The fluxed electrolysis propellant plant is a high yield process which reduces all oxides. Some terrestrial experience in the aluminum industry applies to the process. However, several unconventional processing requirements exist. Further development of the inert electrodes is required. The lifetime of the equipment may also be limited by the process conditions.

The fluxed electrolysis plant is based on work by EMEC Consultants and E. Christiansen. Figure 5.9.1-4 shows a schematic of the process. Figure 5.9.1-5 shows an overall plant layout. Compare the pit size in this plant to the pit in figure 5.9.1-2 for the hydrogen reduction of ilmenite process. Both pits show the amount of material that must be mined to produce 25 t of oxygen. The molten salt electrolysis requires significantly less mining, but the ilmenite reduction mining requirement is by no means unreasonable.

A large single electrolysis cell may be the most weight-efficient design for a 100 t/yr plant. The cell uses soil that has not been beneficiated. Mass estimates given below in Table 5.9.1-VII include busbars, process equipment, and housing structure. The cells operate in a sealed structure at 0.5 to 1.0 atm pressure. Figure 5.9.1-6 shows a concept for the cell and containment. The entire system fits on a shuttle pallet and requires very little assembly.

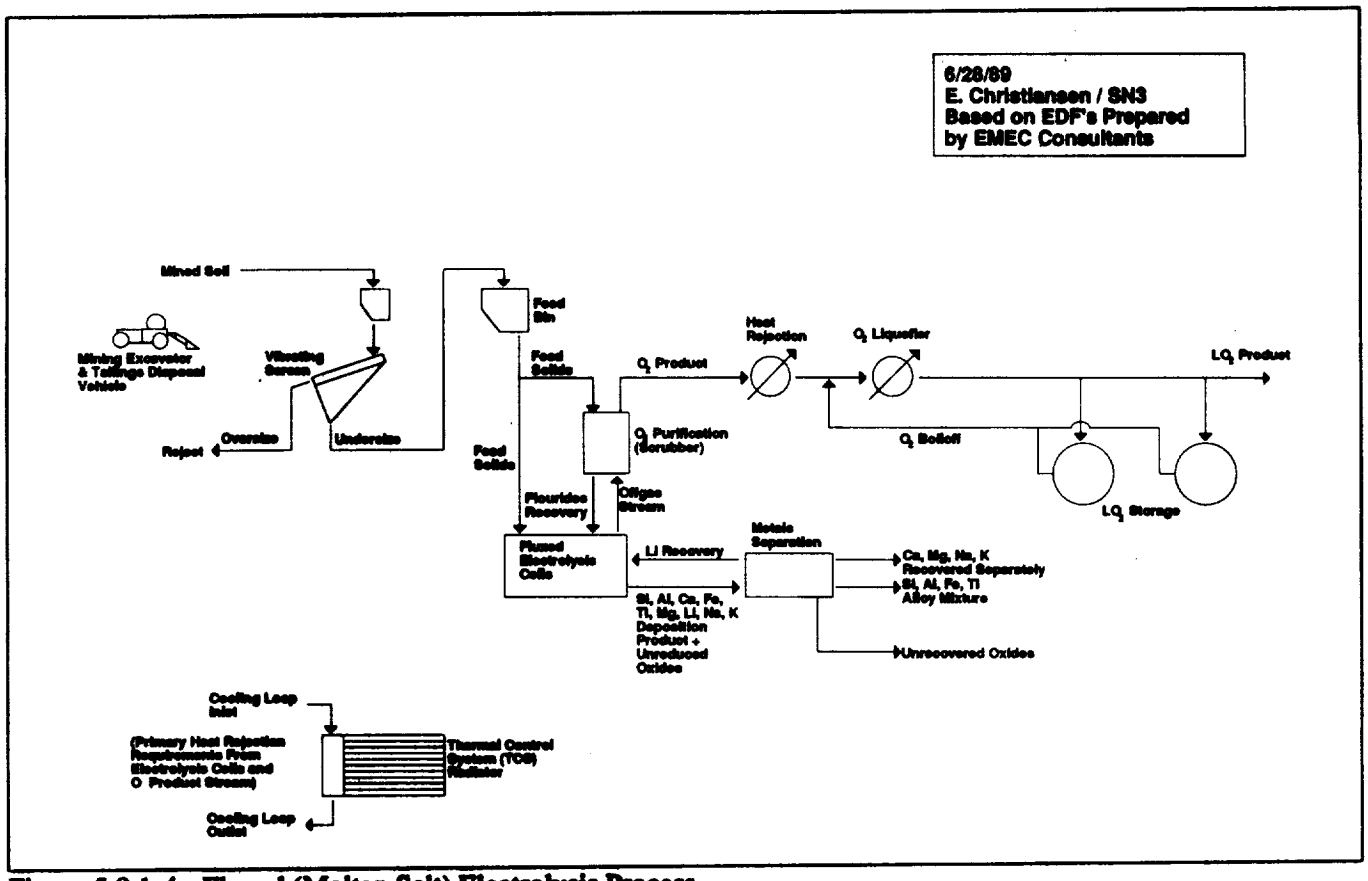



Figure 5.9.1-4.- Fluxed (Molten Salt) Electrolysis Process.

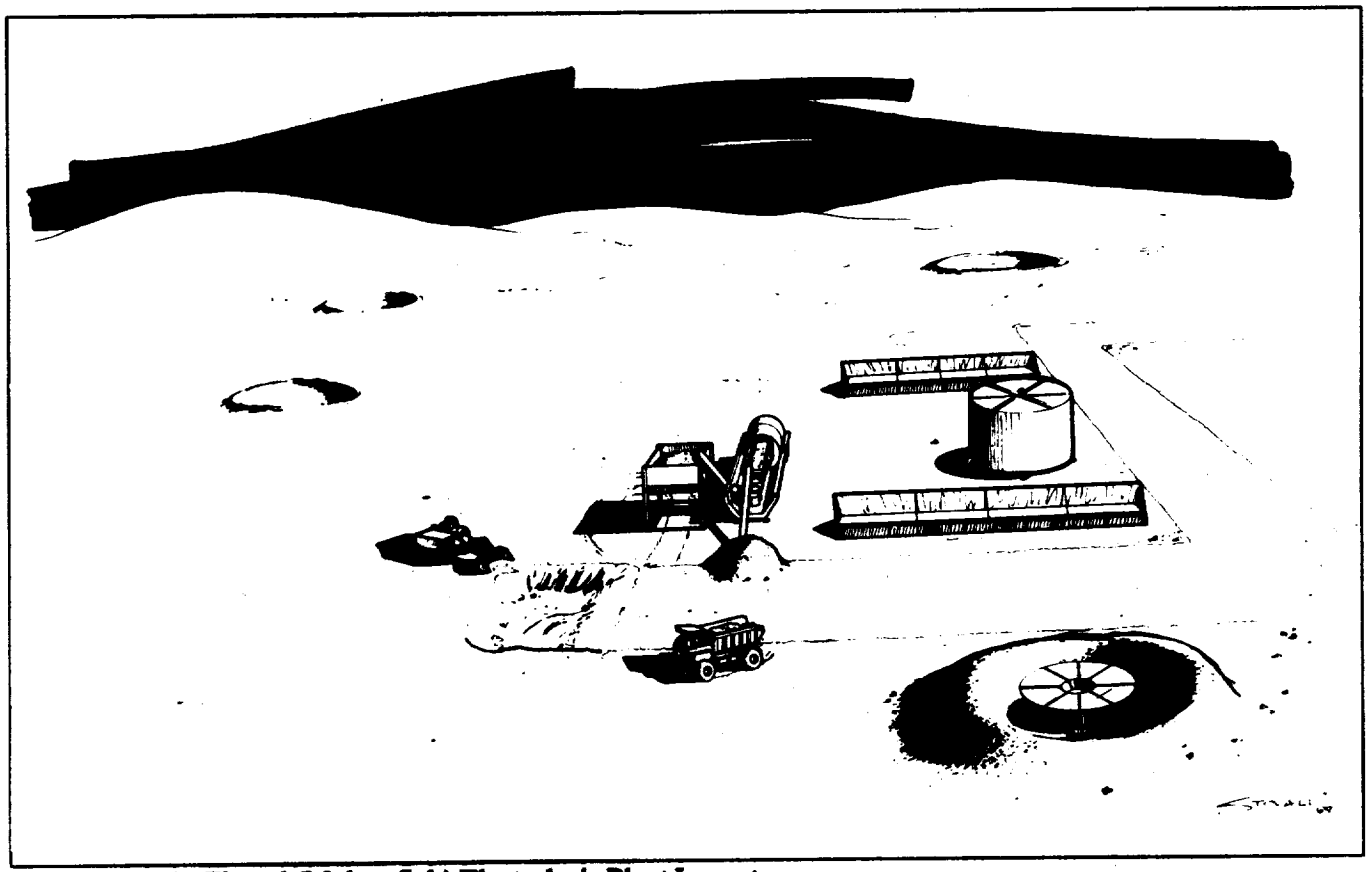


Figure 5.9.1-5.- Fluxed (Molten Salt) Electrolysis Plant Layout.

## TABLE 5.9.1-VII.- FLUXED (MOLTEN SALT) ELECTROLYSIS

(Based on work by EMEC Consultants, R. Keller, and E. Christiansen, 1989.)

| | | | | |
|---|---|---|---|---|
| Annual liquid oxygen production | 100 | t | | |
| Process plant duty cycle | 90 | % | | |
| Plant liquid oxygen capacity | 12.68 | kg/hr | | |
| Electrolysis solids feed | 30.50 | kg/hr | 240.5 | t/yr |
| Si, Al, Fe, Ti alloy produced | 12.14 | kg/hr | 95.7 | t/yr |
| Ca, Mg, Na, K pure produced | 4.15 | kg/hr | 32.7 | t/yr |
| Unreduced oxide slag | 1.53 | kg/hr | 12.0 | t/yr |
| Mining duty cycle | 35 | % | | |
| Mining rate | 245.4 | t/yr | | |

| | Number | Total Mass (kg) | Total Power (kw) | Total Deployed Volume ($m^3$) | Dimensions (Each) Len. (m) | Diam./W (m) | Ht. (m) | Total Stowed Vol. ($m^3$) | Heat Rejected (kWt) |
|---|---|---|---|---|---|---|---|---|---|
| Excavator | 1 | 2,160 | 0.4 | 12 | 3.79 | 1.84 | 1.73 | 6 | |
| Screen | 1 | 14 | 0.1 | 0.1 | 0.40 | 0.25 | 0.40 | 0.1 | |
| Feed bin | 1 | 249 | 0 | 98 | | 3.96 | 7.92 | 98 | |
| Electrolysis cells | 4 | 30,000 | 168.0 | 15 | 2.00 | 1.25 | 1.50 | 15 | 64 |
| Metal seperation/flux rec. | 1 | 6,667 | 6.7 | 7 | 1.88 | 1.88 | 1.88 | 7 | |
| Oxygen purification | 1 | 1,333 | 0.1 | 1 | 1.10 | 1.10 | 1.10 | 1 | |
| $O_2$ liquefier | 1 | 323 | 7.4 | 1 | 2.70 | 0.68 | | 1 | 11 |
| $O_2$ storage tanks | 2 | 446 | 0 | 17 | | 2.55 | | 17 | |
| TCS/radiator | 1 | 2,808 | 0 | 4 | 31.21 | 4.50 | | 1 | |
| subtotal | | 44,000 | 183 | 155 | | | | 146 | 75 |
| Contingency | 30% | 13,200 | 55 | 47 | | | | 44 | |
| **Process Total** | | **57,200** | **238** | **202** | | | | **190** | **75** |
| Nuclear Power | 1 | 5,910 | | 3 | | | | 3 | 5,295 |
| **Total Process with Power** | | **63,100** | | **205** | | | | **193** | **5,375** |

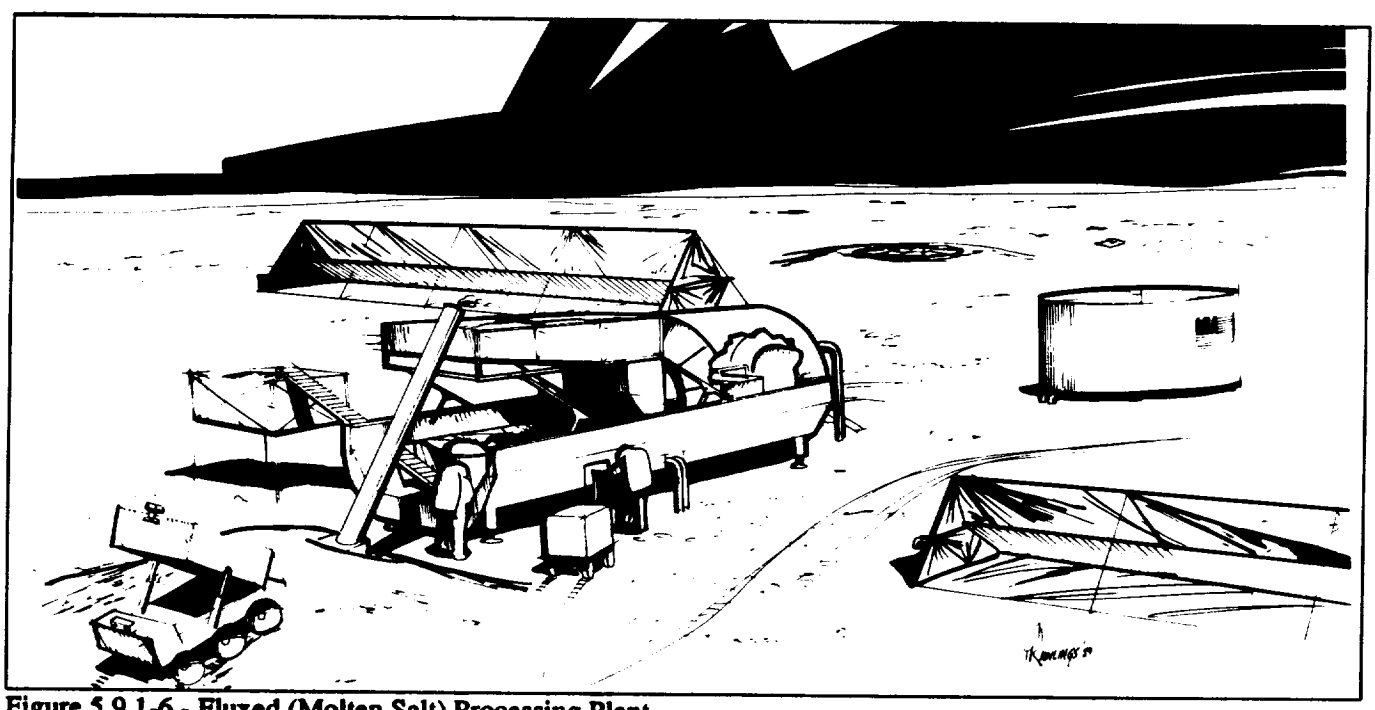


Figure 5.9.1-6.- Fluxed (Molten Salt) Processing Plant.

The operating temperature of the process is between 600°C and 700°C. The metal separation equipment separates the cathodic products of the electrolysis cell by vacuum distillation. The recovery of lithium is essential for the process. Lithium can also be recovered from the cathodic products and returned to the process by allowing the other products to solidify and returning the still liquid lithium to the melt (at about 180 °C). This may be a simpler system when the desired product is only oxygen. Na, K, Ca, Mg are obtained in pure element form if the vacuum distillation separation option is employed. The oxygen purification unit works by adsorption of fluorine impurities in the oxygen product in process solids feed. The unit recovers the fluoride components of the electrolyte.

A significant advantage of this process is that it would work anywhere on the Moon and on silicates elsewhere in the solar system, such as on Phobos or Deimos.

### 5.9.1.5 Lunar Oxygen Mining Systems

Numerous options for the mining equipment have been proposed by different studies. The consensus of the 1989 Construction and Mining Workshop (Podnieks, 1989) was that the following three options are the most promising:

- Front end loader and hauler
- Front end loader and pipe conveyor
- Single combination load and haul vehicle

Of these three options, the front end loader and hauler combination is the most discussed and best understood option.

A three-drum slusher was ruled out due to difficulties in placing pylons, changing mine sites, and moving the slusher sideways. The three-drum slusher is also less stable than the other possible equipment. The slusher approach also still needs a hauler to carry away process tailings and to transport mined material from the central collection point to the front end of the plant.

The mining equipment is assumed to be telerobotically controlled from Earth with redundant and override control from the lunar base. Due to the time delay between the lunar surface and Earth, the equipment will have enough on-board intelligence to perform its tasks with only supervisory control. Each vehicle will have a set of preprogrammed functions such as travel to plant, dump load, travel to mine, etc. The teleoperators on Earth simply tell the vehicles to execute certain functions, monitor their progress, and make minor corrections. This type of control will require significant advancement in telerobotics and automation.

The mining equipment is assumed to be powered by fuel cells. The fuel cells have enough reactants to last 14 days, allowing the vehicle to mine unrecharged for an entire lunar day. Maintenance and recharging takes place during the lunar night.

Mining will only be done during the lunar day because of illumination and thermal problems. Illuminating the mine site requires a large amount of power. At night, metals in the mining equipment become brittle unless heated. For a 100 t/yr oxygen output using hydrogen reduction of ilmenite, roughly 30,640 metric tons of soil per year must be mined. The equipment can be sized for operation during 70 percent of the available daylight hours (3,066 hours per year). Of the remaining 30 percent of the time, 15 percent is used for maintenance and repairs (657 hours per year). Terrestrial mining equipment, such as a front end loader, is down between 3 and 20 percent of the total available operating time. A conservative estimate of the downtime for lunar surface mining equipment is 15 percent of total daylight hours (657 hours per year). Thus, the mining equipment is not used for the remaining 657 hours per year. This extra time can be used for major repairs of the equipment, the mining requirements of additional propellant plants, or construction tasks for the lunar base.

5.9.1.5.1 <u>Front End Loader</u> - The front end loader (FEL) is a dedicated telerobotic mining vehicle. It is sized according to the mining duty cycle and the amount of raw material it is required to excavate. For a duty cycle of 35 percent and a mining rate of 33,000 t/yr, the vehicle's mass, power, and volume are estimated to be in the range of 2,600 kg, 22 kW, and 21 $m^3$. These values are calculated based on a minimum bucket size of 0.5 $m^3$. Using these minimum values, the FEL only requires 40 percent of the allocated mining duty cycle time. Therefore, one FEL can supply the mining requirements of two of the baseline propellant plants.

Figure 5.9.1-7 shows a larger front end loader and a hauler, more in the range of 5 t for the FEL and 3 t for the hauler. These vehicles are mannable, but not normally manned and may be used for other purposes around the base.

5.9.1.5.2 <u>Haulers</u> - The hauler is a telerobotic transport vehicle. The hauler is filled by the FEL at the mining site. It then travels to the process feed bin, dumps the load, collects a load of tailings from the tails discharge bin, dumps the tails at a discharge area, and returns to the mining site to start the cycle over again. The estimated mass, power, and volume of the hauler are 1,000 kg, 3 kW, and 25 $m^3$, respectively. The hauler holds 7.7 t of soil (4.5 $m^3$). This is the assumed mini-

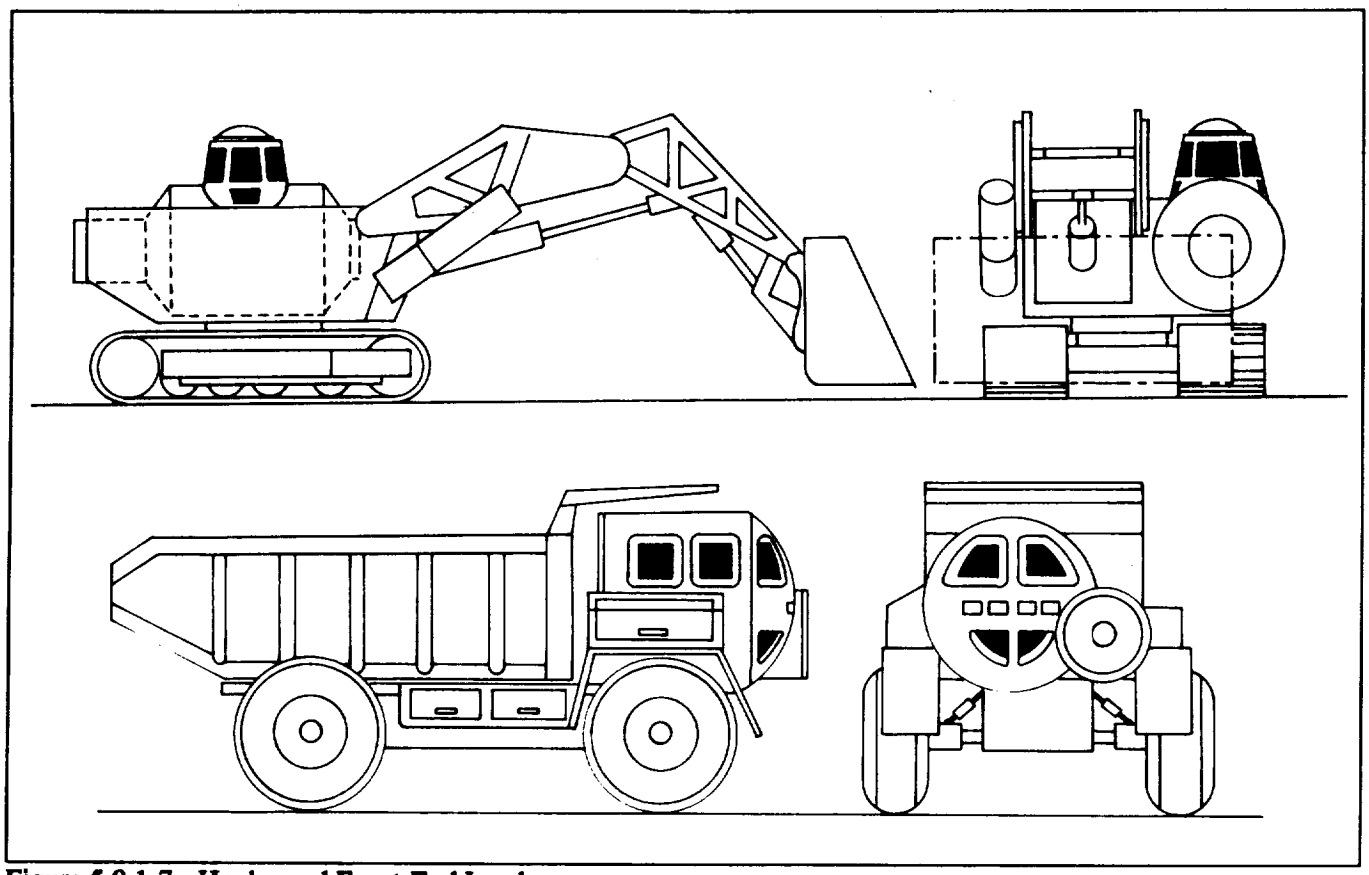


Figure 5.9.1-7.- Hauler and Front-End Loader.

mum feasible size hauler; two may be required.

### 5.9.2 Lunar Hydrogen

Previous studies have shown that the use of lunar produced hydrogen can significantly increase the mass payback ratio and other figures of merit that are used to evaluate such processes in various scenarios. Hydrogen is deposited on the Moon by the solar wind only in small quantities, but deposits are associated with maturity (and to some extent titanium), which can be remotely mapped. The longstanding concern was that hydrogen would be too difficult to extract in useful quantities, however recent work has shown that this is not the case. A reasonable hydrogen recovery scheme can be devised and will even fit within the scope of the current manifest. Table 5.9.2-I shows the basic requirements for a small hydrogen production plant.

Figure 5.9.2-1 shows a candidate process and the approximate mass and power of a 15 t/yr lunar hydrogen recovery system. The lunar soil is collected by a scraper. The fraction of the soil less than 0.05 mm in diameter that contains 80 percent of the hydrogen is separated from the rest and heated to 600°C which releases most of the hydrogen. The hydrogen is heated in a staged fluidized bed reactor that recovers 50 percent of the required heat. The recovered heat raises the temperature of the new material coming into the reactor. The heat transfer to the charge is accomplished by the heated gas stream. 70 percent of the hydrogen is released and reacts with oxygen in the ilmenite to form water vapor. The water vapor is then electrolyzed into hydrogen and oxygen gas. The gas is then liquified. Nitrogen and carbon may also be recovered as by products of this process. Table 5.9.2-II shows the basic parameters and assumptions of the process. The oxygen production rate shown in the table (120 t/yr) assumes 0.5 percent of the charge is ilmenite that is reduced by evolved hydrogen. Hydrogen gas will be recycled through the reaction vessel to attain this extent of reduction.

Nuclear power is assumed. No waste heat from the nuclear power plant is assumed available to the process plant, though the nuclear power plant will produce nine times the generated electrical power in waste heat at 600°C. Use of the waste heat in the process could significantly reduce the power plant mass. The nuclear power mass estimate includes the reactor, power conversion, instrument-rated shielding, and radiator. Process mass and power estimates include all major equipment downstream from beneficiation; such as feed and

TABLE 5.9.2-I.- REQUIREMENTS FOR LUNAR HYDROGEN PRODUCTION PLANT

| Requirement | Reasonable Range | Target Value |
|---|---|---|
| Hydrogen production rate, metric tons/year (2 to 5 metric tons per lander mission) | 4 to 40 | 15 |
| Plant lifetime, years | 10 to 20 | 20 |
| Lunar surface ops. crew, persons | 0 to 3 | 2 part-time |
| Dedicated Earth surface ops. crew, persons | 30 to 300 | 150 |
| Reasonable resupply, metric tons/year | 0 to 10 | less than 1 |
| Production plant delivery, date | 2010 to 2020 | 2013 |
| Max. mass of pre-assembled module, m tons | 10 to 30 | 25 |

discharge bins, reactor vessels, water electrolysis, gas purification ($H_2S$ removal), $O_2$ and $H_2$ liquefaction refrigerators, cryogen storage, and thermal control system.

The mining system is a key part of the process, though it is small by terrestrial standards. A surface scraper (see figure 5.9.2-2) removes the upper fraction of a meter, fills a transporter bed and takes the material to a stockpile. It may then be loaded with tailings to return to the pit. For the parameters shown in Table 5.9.2-II, the duty cycle is 178 days per year, 20 hours per day, during the lunar day only. Power is provided to the scraper by an overhead trolley with cables and supports estimated to weigh 2 t. The bucket capacity is 8.7 $m^3$ or 13 t. The system was roughly designed and sized at the 1989 mining and construction workshop and more work is required to produced a more accurate estimate.

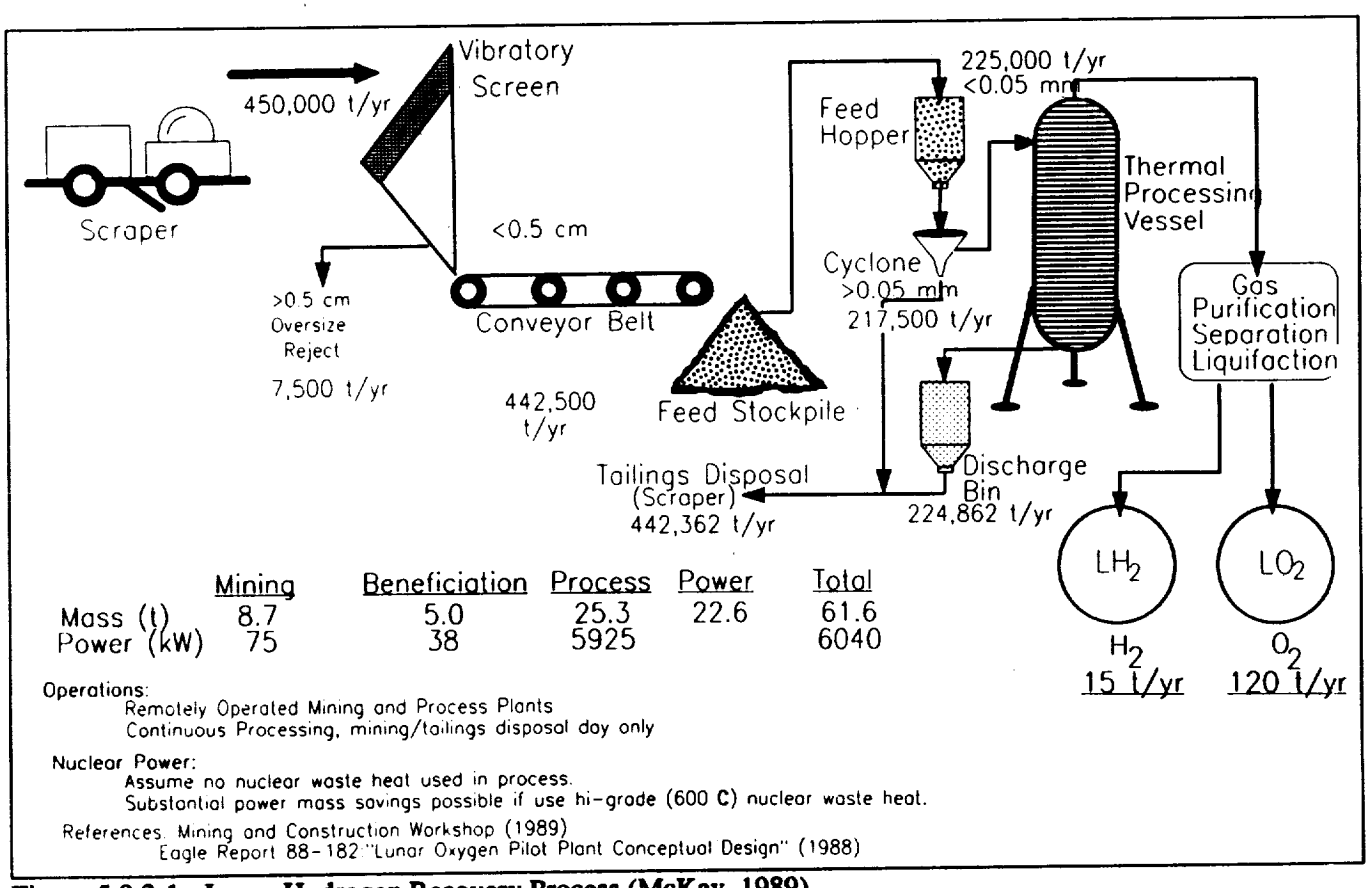



Figure 5.9.2-1.- Lunar Hydrogen Recovery Process (McKay, 1989).

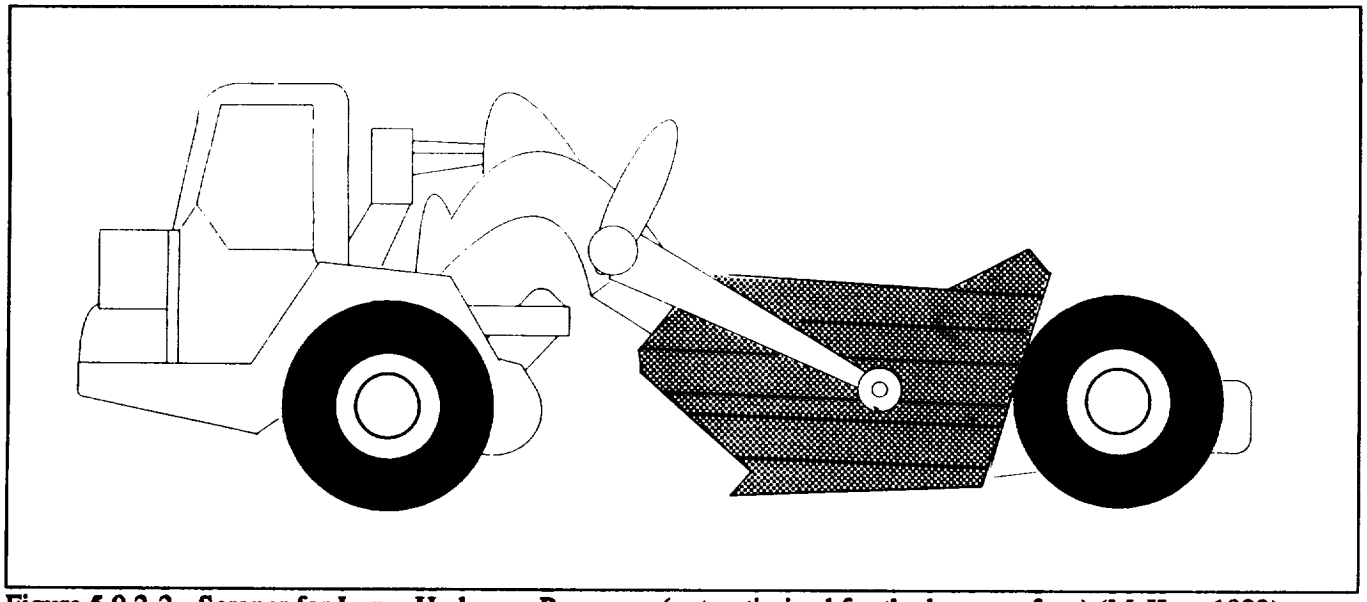


Figure 5.9.2-2.- Scraper for Lunar Hydrogen Recovery (not optimized for the lunar surface) (McKay, 1989).

TABLE 5.9.2-II.- LUNAR HYDROGEN RECOVERY PROCESS

| | |
|---|---|
| Hydrogen production rate, t/yr | 18 |
| Oxygen production rate, t/yr | 120 |
| Mining rate, t/yr | 450,000 |
| Scraper mass | 8.7 |
| Scraper average power, kW | 75 |
| Scraper peak power, kW | 93 |
| Scraper payload, t | 13 |
| Total Plant mass, t | 62 |
| Mining, t | 8.7 |
| Beneficiation, t | 5 |
| Process, t | 25.3 |
| Power, t | 22.6 |
| Total Power Required, kW | 6,040 |
| Mining, kW | 75 |
| Beneficiation, kW | 38 |
| Process, kW | 5,925 |

To produce 18 t of hydrogen per year, the scraper must mine an area 300 meters by 250 meters to a depth of 3 meters. This is roughly the area of 15 football fields. 450,000 t/yr is a small mining operation by terrestrial standards, about the size of a typical sand and gravel operation. The Anaconda Twin Buttes mine near Tuscon moves 200,000 t/day (Cummins, 1973) with 80 ton scrapers loading a conveyor that loads trucks.

### 5.9.3 Lunar Ceramics

Building materials such as bricks, paving tiles, and blocks may be constructed on the lunar surface using a sintering process. In one version of this process, a selected fraction of the lunar soil is compressed and heated to 1,100 to 1,300°C (Shirley, 1988). Glass forms and glues the compacted soil together. Equipment on the surface of the Earth designed for this type of job might weight 25 to 34 t and require 375 kW. Such a machine might take in 3,800 t/yr of mined material, reject 200 t with a screen and produce 210,000 blocks per year (40 x 20 x 10 cm, 17.5 kg) (Shirley, 1988). This would be enough block to pave a road 3 meters wide and 5 or 6 km long. The machine would operate 24 hours per day, 330 days per year, and produce roughly 26 blocks/hour. The blocks would be expected to be suitable for loads on the order of 690 N/cm$^2$ (1,000 psi).

Experimental work with lunar simulants should be done. Testing of the produced block in its proposed application is also needed. Production of lunar ceramics should be demonstrated and validated with a small test unit delivered on an early flight.

### 5.9.4 Lunar Metals

Metals in a crude state appear as a by product of several of the oxygen processes. Figure 5.9.4-1 shows metallic iron and a titanium oxide phase in a porous matrix, a solids product of the ilmenite reduction process. Most impurities stay in the titanium phase. The iron can be extracted by melting or by the carbonyl vapor extraction technique which can also be used for fabrication. One oxygen production process (fluxed magma electrolysis) can produce relatively pure silicon metal (>99% Si). Refined and machined metals and alloys will not be easily produced on the lunar surface in the near future, but low quality metals, byproducts of the oxygen pro-

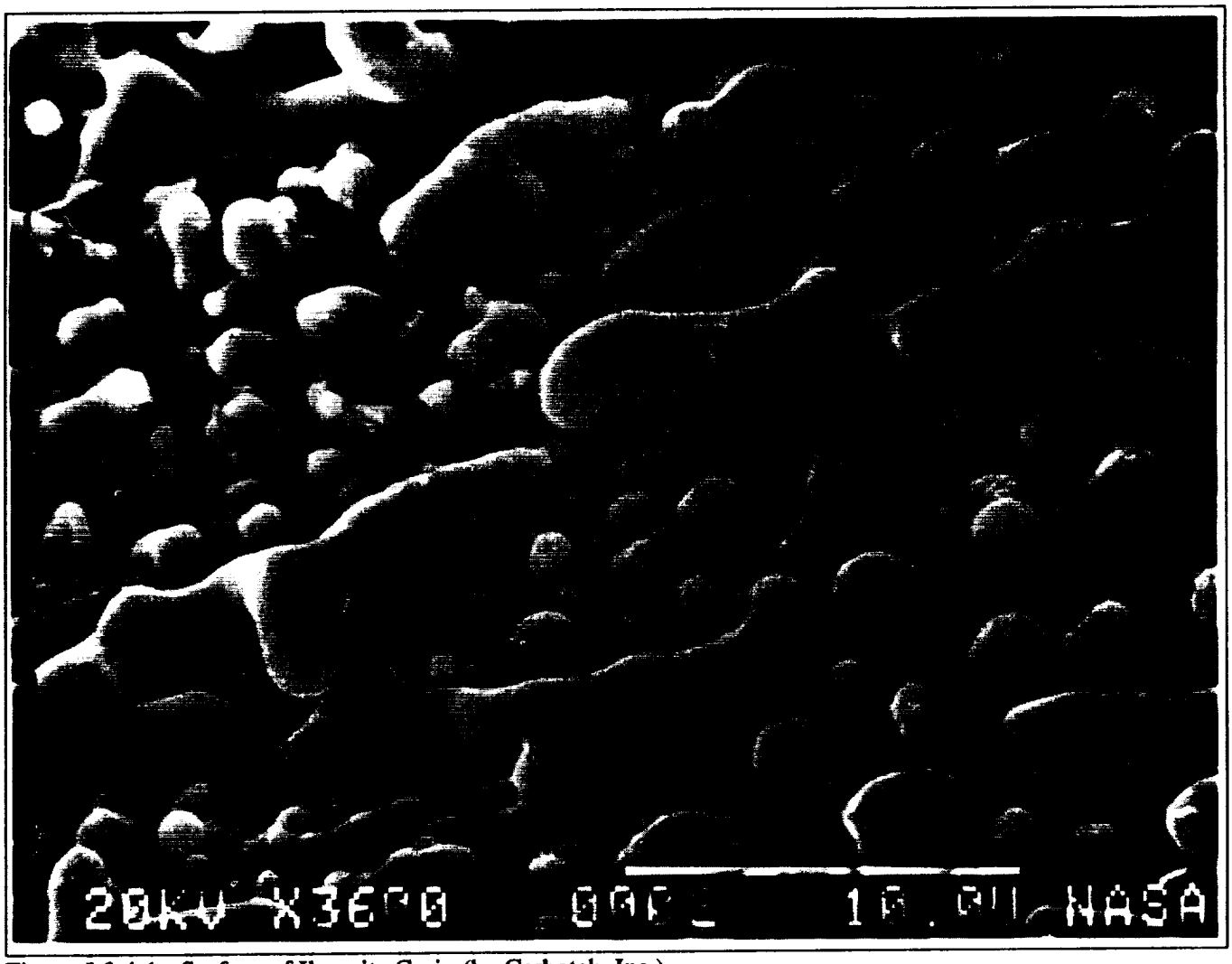



Figure 5.9.4-1.- Surface of Ilmenite Grain (by Carbotek, Inc.).
(Bright, rounded features are metallic iron. Darker areas are titanium oxide and pore space.)

cesses may be just as easily cast into some useful shape as discarded. Examples include paving tiles, weights, bricks, and perhaps even beams or thick walls. Production of metals should be demonstrated and validated with a small test unit delivered on an early flight.

### 5.9.5 Phobos/Deimos Oxygen and Hydrogen Production

Previous studies (Babb, 1986) have shown that Phobos and Deimos may be the most useful sources of extraterrestrial propellant to support trans-Mars operations. The propellant would be used for the trans-Earth injection and Earth-orbit insertion burns and perhaps in the lander.

The propellant plant would be delivered early in a scenario involving a long series of missions to Mars. Production would be on the order of 100 t of propellant per mission, which would occur not closer than two years apart.

Both martian moons have regolith layers, with a minimum thickness of 10 meters. The moons show specteral data similar to a type II carbonaceous chondrite type body. If these moons are really made of carbonacious chondrite materials, significant quantities of water and other volatiles may be bound in the minerals and can be extracted by heating. A search for the water band on Deimos was unsuccessful at the 5 percent water detection level, however. Water bound in the minerals is not greater than 5 percent and may be zero. The spectral data may only indicate the nature of reworked surface material. More pristine material may be present at depth. The true nature of Phobos and Deimos must be discovered with a precursor mission or by other means before significant progress can be made in this area. Before the demise of the Soviet Phobos mission, a number of spectral images of Phobos were acquired. After careful analysis, they may reveal something about the water of Phobos.

Several concepts for mining the Martian moons have been proposed:

### 5.9.5.1 Big Melter

Figure 5.9.5-1 shows a concept for a Phobos miner that melts into the surface and extracts the volatiles. Los Alamos National Laboratory (LANL) has built prototypes of hole melters. They can produce an impermeable glass-line borehole. The volatiles produced are condensed and separated. The system is nuclear-electric powered. The melter uses resistance heating however. The plant moves across the surface of Phobos in microgravity conditions using long legs with grappling devices on the feet.

Figure 5.9.5-1.- Phobos/Deimos Propellant Plant--Big Melter.

For a production of 100 t/yr of liquid oxygen and 12.6 t/yr of liquid hydrogen, the plant is estimated to weigh 56 t, including nuclear power plant and a 21 t man-rated shield. 290 kWe are required for the melter and process.

### 5.9.5.2 Scraper/Fixed Processing Plant

Figure 5.9.5-2 shows a different plant concept that uses a plant and power source fixed to the surface to process water brought to it by a mobile scraper into oxygen and hydrogen. A drag scraper moves along anchored cables to collect regolith. The regolith is heated on-board the mobile scraper to extract water. A trailing cable supplies power to the mobile scraper.

This concept allows a remote nuclear power source that can use the local terrain for shielding. A docking port is mounted on the surface to allow propellant transfer to a spacecraft. Manipulators on a truss structure enable remote plant maintenance activities.

### 5.9.5.3 In Situ Water Production from Subsurface

Figure 5.9.5-3 shows another plant concept. This concept assumes the regolith is depleted in volatiles and that subsurface material must be reached. A technology similar to terrestrial in situ coal gasification is proposed. Drilled boreholes on the periphery of the site contain heaters. Evolved volatile gases flow out of a central bore hole. A fixed plant processes the water into liquid hydrogen and oxygen. The fixed surface location allows a remote nuclear power plant that uses local terrain for shielding. Again, a docking module is mounted to the surface to allow propellant transfer.

## 5.9.6 Martian Surface Propellant Production

In addition to the propellant potential at Phobos and Deimos, the martian surface offers useful resources for extraterrestrial propellant. The propellant would be used to support martian operations, particularly the martian ascent vehicle.

Mars offers two commodities--atmosphere and land. The general abundance of volatiles on Mars and its size result in the presence of a thin atmosphere comprised chiefly of carbon dioxide with small amounts of water vapor, nitrogen, argon, and other gases. The atmosphere, available everywhere on the martian surface, constitutes a resource ($CO_2$) that can be used for the production of life-supporting oxygen, potable water, and vehicle propellant. In addition to the atmosphere, large accumulations of volatiles, particularly water, are possibly present on Mars. Important reservoirs may include the regolith of the cratered highlands, the polar layered deposits, and geochemically bound water in silicates.

The production of oxygen from the martian atmosphere is a reasonably well-understood process (Frisbee, 1986) which can be developed with low risk and without much additional precursor data. On the other hand, processes to acquire and electrolyze water should be considered but require substantial precursor data to confirm the presence of near-surface water. Data on permafrost, soil

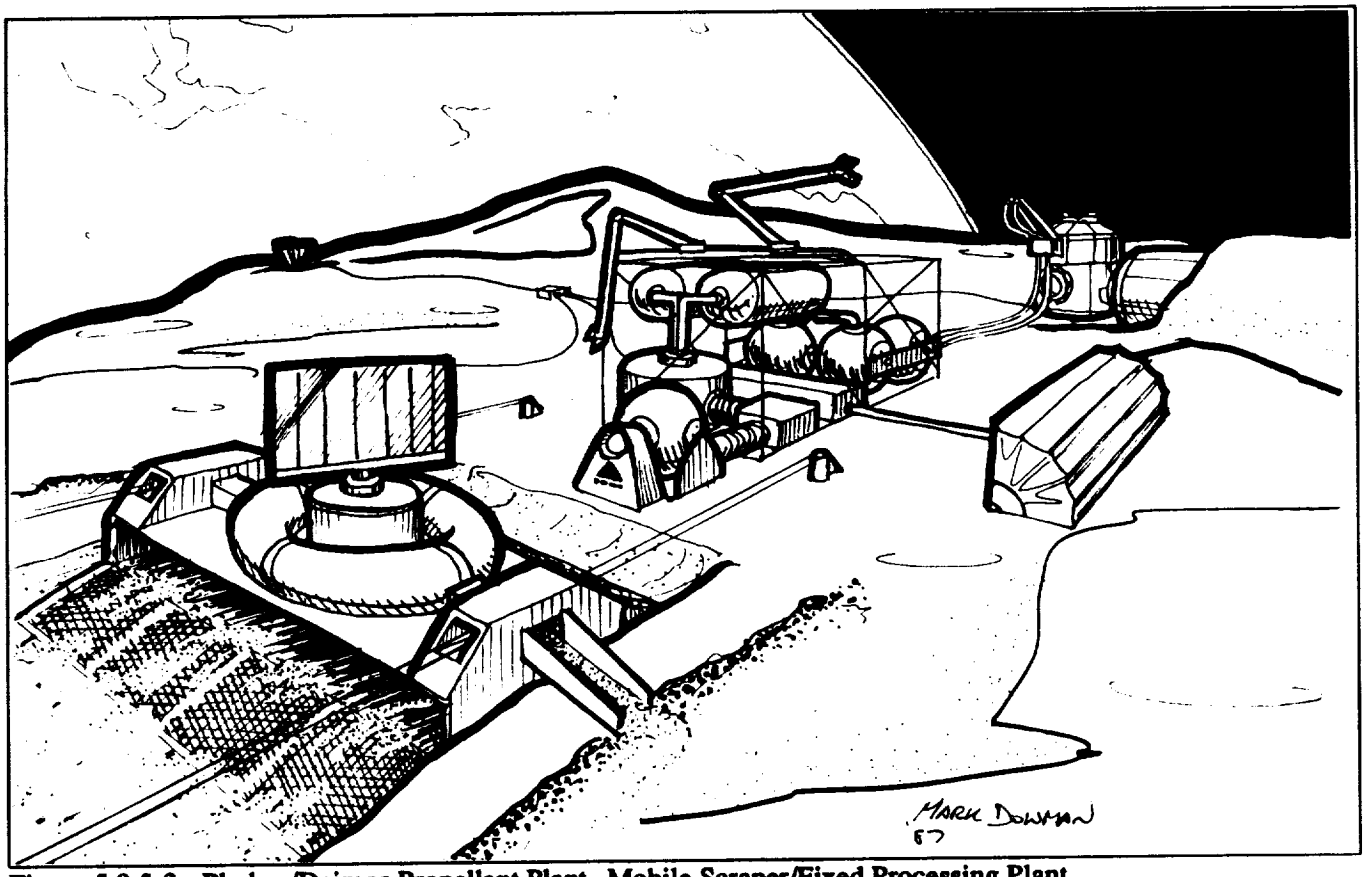



Figure 5.9.5-2.- Phobos/Deimos Propellant Plant--Mobile Scraper/Fixed Processing Plant.

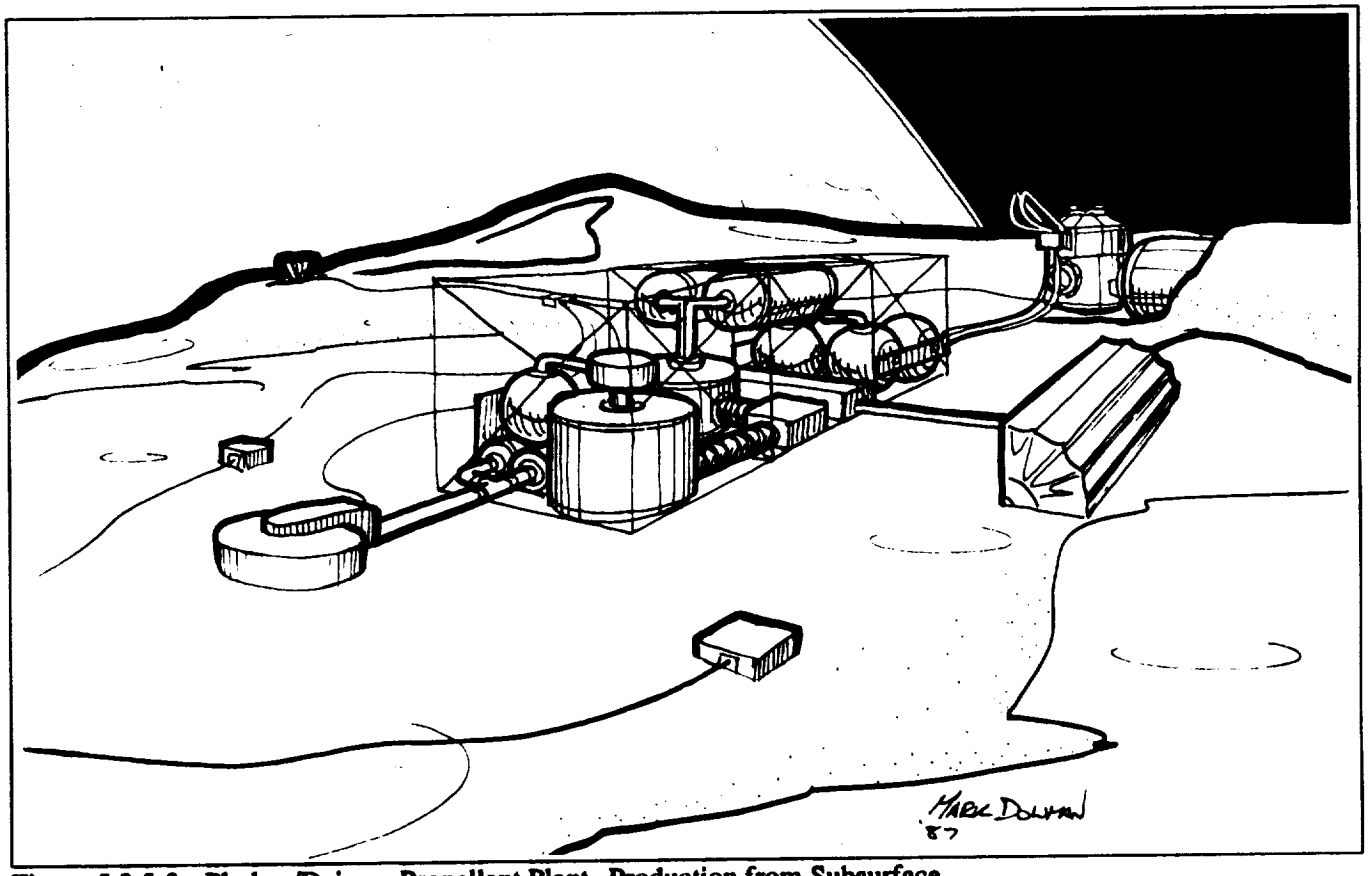



Figure 5.9.5-3.- Phobos/Deimos Propellant Plant--Production from Subsurface.

composition, and geotechnical properties are necessary in order to develop viable water extraction processes.

### 5.9.6.1 Atmosphere Carbon Dioxide Conversion to Oxygen

Carbon dioxide from the martian atmosphere is a highly desirable resource since it is available at any location on the planet in high concentrations (95.3 percent by volume with lesser amounts of nitrogen, argon, and oxygen). Atmosphere reduction to produce oxygen is a straight forward process (Frisbee, 1986) in comparison to oxygen extraction from the martian soil which would require significant soil processing techniques.

Figure 5.9.6-1 shows a schematic diagram of the flow chart for the oxygen production system. Note that the values shown in the diagram represent a system production rate of 10 kg of oxygen per day. The $CO_2$ reduction process thermally dissociates the martian atmosphere into CO and $O_2$ with a 30 percent conversion. The CO and unreacted $CO_2$ produced in the process are vented after the reaction. This $O_2$ production process is comprised of the following steps:

a. Filter $CO_2$ from the martian atmosphere to remove dust particles >0.1 nm, particularly sulphur,
b. Compress the gas from about 7 mbar to 7 bar,
c. Heat the gas at 1000°C to thermally decompose the $CO_2$ into CO and $O_2$,
d. Extract the $O_2$ from the gas mixture, and
e. Compress the $O_2$ to 28 bar and liquefy for storage at -153°C.

The key to the $CO_2$ reduction process is the zirconia membrane cell subsystem responsible for the oxygen extraction. In this subsystem, the $CO_2$ is thermally dissociated and then the resulting $O_2$ is electrochemically pumped across the zirconia membrane by applying a suitable voltage to the membrane. A two-fold redundancy factor is recommended for the membrane subsystem, with possible failures including electrical shorting between electrodes and mechanical failure resulting in gas leakage.

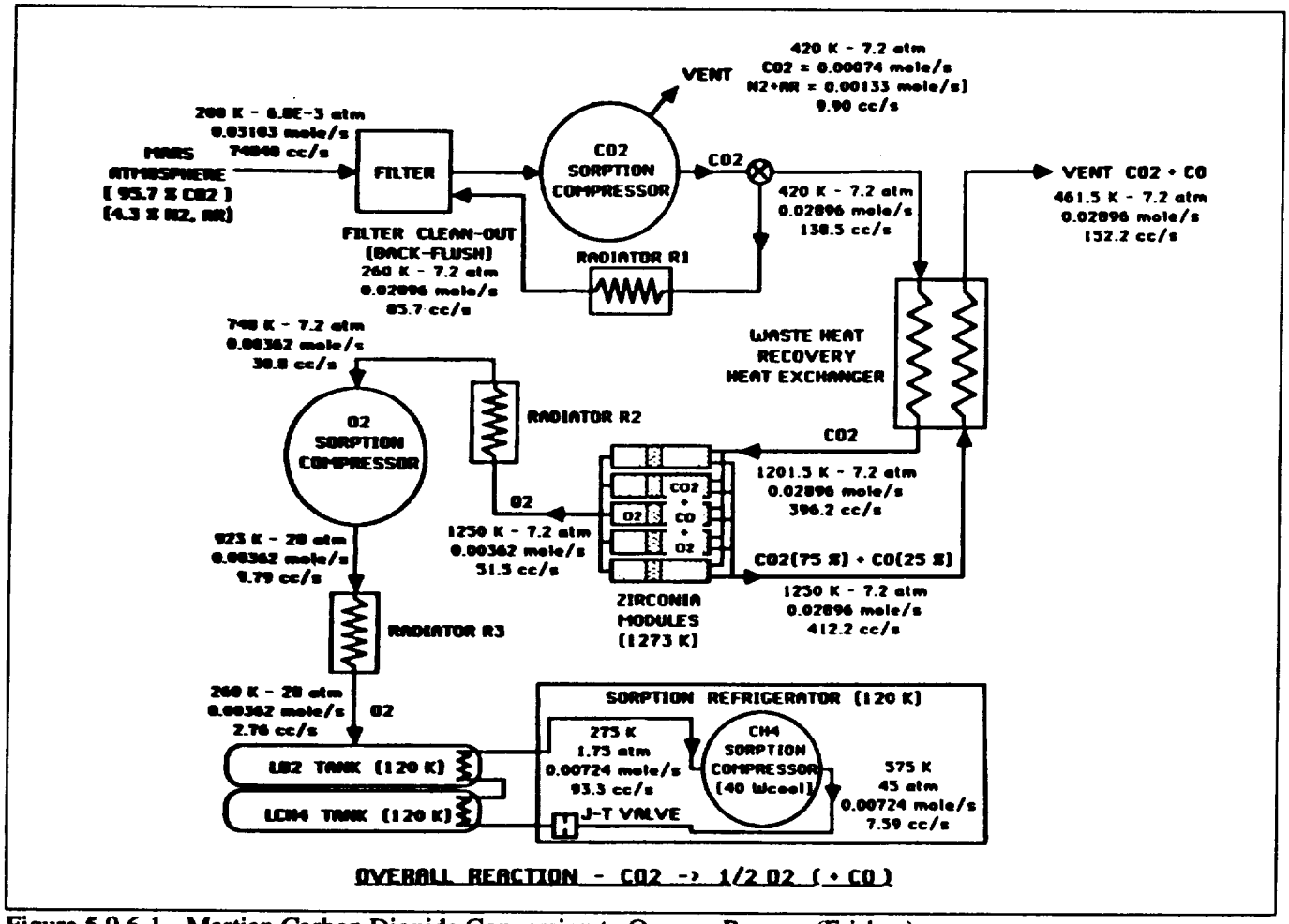



Figure 5.9.6-1.- Martian Carbon Dioxide Conversion to Oxygen Process (Frisbee). (Values are for a 10 kg $O_2$/day system).

Table 5.9.6-I summarizes the subsystem characteristics for the $CO_2$ reduction process for a 300 kg $O_2$/day system. For a production rate of 100 t/yr of liquid oxygen, the total process plant is estimated to weigh 18.2 t including a nuclear power source of 3.4 t. The power required to implement the process is 273 kW, with an associated thermal power requirement of >600°K.

Although this exemplary oxygen production system appears readily feasible, issues of reliability and autonomy for operational periods of up to one year need to be analyzed. Precursor data on dust density and size distribution would also be necessary for adequate filter designs.

### 5.9.7 Precursor Data

Precursor data is required to successfully design some of the plants proposed.

#### 5.9.7.1 Moon

The kind and extent of precursor data needed from the Moon is somewhat dependent on the technology developed to extract oxygen and other useful materials. If we return to an Apollo site, these requirements are partially or completely met. However, any other site will require some additional precursor data. With current technology and forecasts of development, we would need the following kinds of data:

5.9.7.1.1 **Location and Distribution of High Titanium Areas** - The following data is needed for the proposed ilmenite reduction process for lunar oxygen production. A survey of titanium abundance from orbit to locate the highest titanium areas and look for possible concentrations of ilmenite (gravity concentrations in flows or sills) which might greatly simplify mining and benefication is required. Titanium abundances in percent must be acquired with a detection limit of 1 percent and relative differences of 10 percent discernable. The titanium or ilmenite concentration location must be known within a spatial resolution of 100 meters for selected areas and 1 km moon-wide.

5.9.7.1.2 **Location and Distribution of Solar Wind Hydrogen** - This requires a survey from orbit to detect and map solar wind hydrogen. If sensors cannot be developed to directly measure this hydrogen, indirect abundances can be inferred from soil maturity maps (based on optical spectral data) combined with titanium maps. Recent data has shown a good correlation between maturity, chemical composition, and solar wind hydrogen. Location of solar wind hydrogen concentrations significantly above average values would greatly enhance propellant production. Specific data requirements include hydrogen concentration in parts per million with a minimum detection limit of 50 ppm and relative difference discrimination of 10 ppm absolute. The hydrogen concentrations should be located within a spatial resolution of 1 km Moon-wide, and 100 meters for selected areas. This survey may be of equal or greater importance than a search for ice at the lunar poles.

TABLE 5.9.6-I.- $CO_2$ REDUCTION SYSTEM SCALING (300 KG $O_2$/DAY SYSTEM)

| Subsystem | Mass (kg) | Power (kWe) | Power (kWt) | Volume ($m^3$) |
|---|---|---|---|---|
| Filter | 150 | -- | -- | 0.75 |
| Zirconia Cells | 1,680 | 37.7 | 124.8 | 0.47 |
| $CO_2$ Sorption Compressor | 5,316 | 9 | -- | 0.66 |
| $O_2$ Sorption Compressor | 663 | -- | 37.8 | 0.18 |
| Sorption Refrigerator | 3,924 | 36.6 | -- | 0.12 |
| Radiators | 75 | -- | -- | -- |
| Heat Exchanger | 48 | -- | 2.1 | 0.34 |
| Computer | 60 | 0.3 | -- | -- |
| Tubing | 180 | -- | -- | -- |
| Heat Source (1,273°C)* | 1,383 | -- | -- | 6.09 |
| Subtotal | 13,479 | 83.6 | 164.7 | 8.61 |
| Contingency (@ 10%) | 1,348 | 8.4 | 16.5 | |
| Total | 14,827 | 92.0 | 181.2 | 8.61 |

*provides 164.7 kWt

5.9.7.1.3 Automated Sample Return From Selected Sites Mapped as High in Titanium and Hydrogen - Such samples would validate map values and provide samples for other engineering tests. Samples from candidate sites could be used to validate beneficiation methods and oxygen and hydrogen production methods designed for use at those sites and will provide such information as the grain size of target minerals, the relative abundance of target minerals, and the relative abundance of other useful materials such as carbon and nitrogen. Samples returned should include both soil and small rocks. Masses can be relatively small: in the 1 to 10 kg range. Much larger samples (100's of kg) would be useful but not critical to technology validation experiments and testing. While precursor sample return is not totally enabling for the ISRU mission, it would greatly enhance the confidence in ISRU systems.

5.9.7.1.4 Lunar Soil Engineering Properties at Depths up to 8 Meters at Candidate Base Sites - These data are necessary to validate design of diggers, coring devices, and penetrators, and for the design of ore transport vehicles. Specific properties include bearing strength, porosity, density, cohesiveness, and change of these properties with depth. This information is absolutely necessary before diggers can be designed with complete confidence that they will work. If such data cannot be acquired with unmanned precursor missions, it should be acquired on the first manned return mission.

5.9.7.1.5 Maps of Volcanic Pyroclastic Black Glass - This glass is enriched in many kinds of volatiles (sulfur, halogens, volatile metals), and may be suitable for volatile recovery (both volcanic volatiles and solar wind implanted volatiles) and also may be highly suitable for oxygen production by one or more techniques currently under investigation. Resolution should be 1 km Moon-wide and 100 meters for selected areas. Minimum detection limits should be 10 percent Apollo 17-type glass.

5.9.7.1.6 Additional Data on Samples already in Hand - Such data include the volume and weight percent of ilmenite in soils, cores, and rocks, the abundance of solar wind hydrogen in regolith breccias and cores, the thermal release patterns and kinetics of release for important volatiles including hydrogen, nitrogen and carbon oxides, and the sintering and melting temperatures of a number of soil compositions.

### 5.9.7.2 Phobos and Deimos

Information is needed concerning the composition of Phobos and Deimos and concerning the engineering properties of the regolith.

5.9.7.2.1 Mineralogy and Chemistry of Phobos/-Deimos Material - Sample return is absolutely necessary before any serious ISRU systems can be built. The current total lack of knowledge of mineralogy, water content, and other volatile content limits the credibility of any proposed system for producing volatiles. The required data can partially be provided by remote analysis, but sample return is much more desirable. Specific information includes minerals present, relative abundance of each, bulk chemistry for major elements, water abundance, abundance of CO or CO2, and variation of these properties with depth to at least 3 meters. Extent of variation from place to place is also a requirement. Resolution of 100 meters is required for mapping these variations. Relative differences of 1 percent for major elements and for water should be detectable.

5.9.7.2.2 Engineering Soil Mechanics Data - For any serious mining and processing system design, a requirement exists for basic engineering data. Specific properties include regolith bearing strength, porosity, density, cohesiveness, and change of these properties with depth. This information is absolutely necessary before diggers can be designed with complete confidence that they will work.

### 5.9.7.3 Mars

Composition and engineering properties of martian surface material is needed.

5.9.7.3.1 Location and Mapping of Near-surface Ice or Permafrost - Such data will greatly influence the location of a martian base and will determine the type and scaling of any ISRU plant for producing propellant or water for life support. Resolution of 10 km global and 300 meters for selected areas is a requirement. Detection limit of 0.1 percent water is a requirement. Water (or permafrost) is the major target of a Mars survey for any ISRU application.

5.9.7.3.2 Mineralogy and Chemistry of Mars Materials - This can only be done with a sample return. Key data requirements are the types of minerals present, the relative abundances of each, the extent of water-bearing minerals, and the abundance of volatiles such as sulphur and halogens. Sampling should be from sites mapped with a high resolution orbiter for water and permafrost.

5.9.7.3.3 Engineering Soil Mechanics Data - For any serious mining and processing system design and for base and road construction, a requirement exists for basic engineering data. Specific properties include bearing strength, porosity, density, cohesiveness, and change of these properties with depth. This information

is absolutely necessary before diggers can be designed with complete confidence that they will work.

### 5.9.8 Technology Development Requirements

Technology development is required for a number of lunar surface processes and for Phobos/Diemos and martian surface propellant production.

#### 5.9.8.1 Moon

Oxygen and volatile extraction as well as ceramic and metal production technologies need work.

5.9.8.1.1 Technology for Oxygen Production - Development is required of basic methods for oxygen extraction from a variety of lunar materials, and the development of related technologies to collect feedstock (mining related technologies), transport feedstock, perform sizing, grinding, and mineral beneficiation if needed, collect and purify oxygen, liquify oxygen, transport and store oxygen under lunar surface conditions.

Examples of areas requiring technology development include reduction of ilmenite by hydrogen and carbon monoxide, electrolysis of magma and fluxed magma, and magnetic concentration of ilmenite.

5.9.8.1.2 Technology for Hydrogen Extraction - Hydrogen must be extracted from lunar soils. It must be collected then, separated from other gases such as nitrogen and carbon monoxide. Possible extraction methods include heating, mechanical abrasion, and microbial techniques. Little data exists on the optimum conditions for thermal extraction, and essentially no data exists on the other methods. If thermal methods are used, the high solids through-put requires that highly efficient heat conservation be employed.

5.9.8.1.3 Production of Ceramic Materials from Lunar Resources - Ceramic materials include sintered or fused lunar soil, concrete, cements, or other non-metallic structural material made from lunar soils or rocks. Processes include a sintering system similar to a brick-making unit, a melting and casting system, and a cement production system. Some ceramic material may be manufactured as a byproduct to the oxygen or hydrogen production process.

5.9.8.1.4 Production of Metals from Lunar Resources - Metals such as silicon, aluminum, iron, and titanium are abundant in lunar materials. These metals are combined with oxygen to form oxides or silicates. One or more of these metals will be produced as a byproduct of oxygen production (see Figure 5.9.4-1). Additionally, metallic iron exists in the soil and can be extracted without chemical reduction of oxides and silicates. Systems must be developed to collect metal byproduct of oxygen production and to turn it into useful forms through methods such as simple casting. Systems must be developed to concentrate metallic iron from soil, perhaps as a synergistic intermediate step in oxygen or hydrogen production.

5.9.8.1.5 Mineral Concentration and Size Separation (beneficiation) - Many proposed processes for the production of propellants using lunar hydrogen or oxygen require that some specific mineral be concentrated (beneficiation) or that some specific size fraction be used. Considerable technology exists for doing this for common terrestrial mining and mineral processing. This technology must be applied to lunar materials in the lunar environment, and ways must be found to minimize mass and provide reliable automation and robotics to operate and maintain these systems.

5.9.8.1.6 Mining and Transport of Lunar Resources - The production of lunar oxygen and lunar hydrogen both require that lunar materials be mined and transported to the processing site. Mining systems may be adapted from proven terrestrial systems, but must be designed and qualified for lunar conditions, and innovative ways must be found to reduce mass of typical mining systems. Use of automation and robotics is especially critical for lunar mining and transport systems.

#### 5.9.8.2 Phobos and Deimos

Water, if it exists, must be extracted from Phobos or Deimos, and must be electrolyzed into hydrogen and oxygen for use as propellant in the Mars/Earth transportation system. The propellant production system requires a processor, probably thermal, and a method for transporting large amounts of solids into and out of the processor. Water must be collected and electrolyzed.

#### 5.9.8.3 Extraction of Oxygen from Martian Atmosphere

Mars atmosphere consists mainly of carbon dioxide. This gas can be electrolyzed or otherwise chemically reacted to produce oxygen. The most suitable method for this process must be developed and validated.

### 5.9.9 Conclusions

- The ilmenite process still has the most extensive engineering data available for credible systems designs.

- The major drawback of the ilmenite process is the requirement for a beneficiated ilmenite-rich feedstock. This will be hard to do with typical lunar soils. Options include developing more efficient beneficiation and mining basalt and grinding it.

- The production of oxygen by magma electrolysis using technology adapted from the aluminum industry is developing as a potential viable alternative to hydrogen reduction of ilmenite. This process should be at least developed and funded to a level where it can be fairly compared with ilmenite reduction.

- Lunar hydrogen mining looks much more practical than had previously been thought in the light of recent work.

- The broad consensus of the ISRU community is that what has been proposed in terms of lunar and martian mining and processing in the last year can be done. There are no show stoppers. Nevertheless, actual technology development work must be done in some areas before much more real progress can be made. Technology development, systems studies, and precursor data are all closely interelated and one cannot proceed too far without equal progress in the other areas.

- Recent work shows that lunar oxygen can be cost effective even with a small base in certain scenarios. Addition of lunar hydrogen is predicted to be cost effective as well.

- The use of ISRU propellants for Phobos/Deimos missions cannot be supported or made credible without extensive precursor data including sample return and regolith geotechnical data. In view of recent data showing low or zero levels of water on Deimos, the system design of and ISRU plant based on bound water processes should not proceed further without definitive precursor data.

- The technology for extracting oxygen from Mars atmosphere is reasonably well developed, although much additional work is necessary before flight hardware can be designed. Precursor data on atmospheric dust properties is needed.

- The production of oxygen from lunar materials should be demonstrated and validated with a small test unit delivered on an early flight, preferably the first return flight. The release, separation, and collection of lunar volatiles should also be demonstrated and validated with a small test unit delivered on an early flight.

## 5.10 ASSEMBLY AND CONSTRUCTION EQUIPMENT

Assembly and construction on an extra-terrestrial planetary surface for habitation, power, experiments, and other surface equipment will be a new experience for humanity. What kind of equipment is appropriate, the techniques to be used, and the real difficulty of such work is still being debated. Though it may be desirable, particulary early in the program, to hold assembly and construction to an absolute minimum, eventually techniques and equipment will have to be developed if a surface base is going to progress beyond the two to four person stage. This section addresses assembly and construction in a general way, outlining the concepts and thought that came out of this year's work.

### 5.10.1 The Moon and Mars and Construction Equipment

Although the environmental conditions of the Moon and Mars are different, the same functional needs are required for the development of construction equipment. For example, construction equipment is required to lift, haul, dig (soil moving, trenching, leveling), pave, and survive exposure to environmental conditions whether it is on the Moon or Mars. Thus, lunar and martian construction equipment can be developed from common designs. This reduces development time and supply support (e.g. spare parts, second sources, maintenance, manufacturing base). Pertinent design factors are addressed in the following paragraphs. Principal differences have to do with the hard vacuum of the Moon compared with the tenuous martian atmosphere, the long lunar day (28 terrestrial days) compared to the shorter martian day (25 hours), the existence of a substantial amount of fine grained dust on the Moon and the absence of such dust on Mars (although fine sand and small rubble are prevalent) and the difference in gravity. There are no winds that will exert external loads on equipment or structures on the Moon; there is evidence that very large area storms of long duration and high wind velocities with much entrained sand occur on Mars. Such storms must be accounted for in the design of structures and equipment and their emplacement, anchorage, and foundations.

The design of construction equipment is dictated by gravity, terrain slope, the functions that the equipment must perform, and the rate that it must perform them. Details of this nature have been considered to a conceptual design of equipment and assembly because in many cases sufficient information and data are not available to permit proceeding beyond that stage. It appears that gravity is one of the most significant factors; the gravity field of Mars is about twice that of the Moon. Whether

all construction equipment should be designed for the more severe gravity case of Mars is a matter of conjecture. It may be possible to design a more capable or robust piece of equipment that would be usable either place, and thus reduce the effort of providing construction equipment that would be compatible with both. A single design, analysis, and evaluation effort may save both time and cost with potentially minor mass penalties for the Moon and would close the time between Moon and Mars occupations. Also considered is the potential for using the same equipment alternately for both construction and mining. This approach is generally feasible particularly for lower volume extraction plants.

Mars' atmosphere is composed mostly of carbon dioxide. There are indications that this gas freezes out during the martian night. This may result in essentially frozen soils having properties that must be considered in the design of the construction equipment. In addition, and quite different from the Moon, the martian atmosphere and soil appear to contain corrosive constituents that may be aggressive toward contact materials, and thus corrosion of equipment and structural components may be a factor. Materials for the construction and assembly equipment will have to be selected based on the corrosive properties of the soil in addition to other criteria.

The temperature extremes on both planetary bodies is an additional criterion that must be used in materials selection. The high daytime temperature on the Moon and the low temperature at night on both the Moon and Mars will require judicious selection to avoid such factors as low temperature brittleness.

Construction on Phobos is likely to consist only of providing adequate anchorage and very limited equipment for mobility, lifting, or hauling. Construction on Phobos has not been considered to a great extent or in detail.

### 5.10.2 Construction Equipment and Techniques

The FY 1988 case studies identified an excavator/digger, truck, and crane as the principal pieces of construction equipment that would be required for either the lunar or martian construction cases. During the course of the FY89 studies, equipment designers and construction specialists determined that instead of identifying specific pieces of equipment, such as a truck, greater freedom would be provided in concept design if the general functions and required capacities were identified and the designer was given freedom to conceive of equipment to provide the capability for those functions. For example, the excavator/digger, truck, and crane were recommended to be replaced in the manifest wording by prime mover with attachments, transport capability and lifting capability.

A "prime mover" or mobile work platform with a number of removable or replaceable implements that could be placed onto and off of the equipment as the need arose was suggested. This would provide the most versatility at minimum mass and power demand. The use of combined pieces of equipment such as two transport vehicles connected into a lifting device has also been suggested by Pacer Works, Ltd., and appears to have a great deal of merit. To dedicate a single piece of equipment to infrequent, peak effort activities such as heavy lifting does not appear to be justified. It appears feasible that methods can be devised to combine relatively small pieces of equipment into configurations that provide the lift and transport capability for the infrequent heavy loads. Design efforts are underway to achieve this kind of periodic function of combined pieces of equipment with continuous and routine functions of a smaller capability for hauling and soil moving and similar activities. Redundancy would also be achieved.

Table 5.10.2-I lists multipurpose equipment and replaceable implements with their functions. Figures 5.10.2-1 and 2 show a concept for a prime mover with attachments. Fundamental to the design of the equipment, of course, are the tasks that must be performed, the functioning of the equipment to conduct those tasks, the rate at which the tasks must be accomplished, and the ability to operate the equipment robotically with a minimum of extravehicular activity (EVA) and intravehicular activity (IVA) and consequent safety for human beings. The equipment functions generally have to deal with assembly tasks and for removing, transporting, placing and smoothing the soil or consolidating or compacting it.

Figure 5.10.2-3 shows a possible construction sequence for a half-buried, inflatable sphere habitat. First, a multipurpose construction vehicle digs a hole that will contain half the habitat. Second, the constructible package arrives and is loaded on a transporter. The package is mounted on a foundation grid in the pit and opened and the habitat is deployed. The inflated sphere is attached to the foundation grid. Tunnels are attached and the pit is backfilled. The interior construction is done in less than full pressure to reduce airlock operations. An outer stand-off shell is assembled over the pressure skin. The exterior is covered with large sandbags. The habitat is fully inflated upon completion of the interior.

The mobility of the equipment is crucial and the traction of the equipment on the soil under the reduced

TABLE 5.10.2-I.-
MULTIPURPOSE EQUIPMENT IMPLEMENTS

Prime Mover, 10-40 kWe, with replaceable implements:

Reverse Clam Shell Digger
Crane Assembly
Robotic Arm with End Effectors
Drill Assembly
Regolith Bagger
Grader Blade
Servicing Module ("tool box")
Conveyor, Belt
Cargo Interface
Supervisory Module ("fobot," foreman)

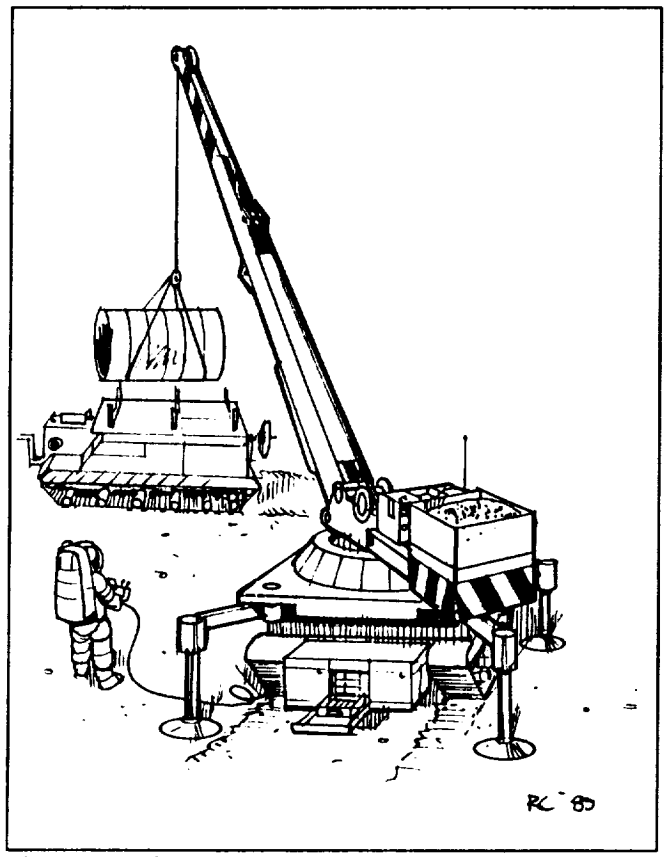


Figure 5.10.2-1.- Prime Mover with Attachments.

gravity conditions of either the Moon or Mars is one of the principal problems that must be solved. The knowledge that is available from the Apollo missions regarding the regolith on the Moon describes essentially two layers of soil, the top 10 centimeters or so being a very fine powder, almost the consistency of talcum powder, with underlying subsoil that apparently is quite cohesive and has a generally good load-bearing capacity and shear resistance. What is not known is whether the

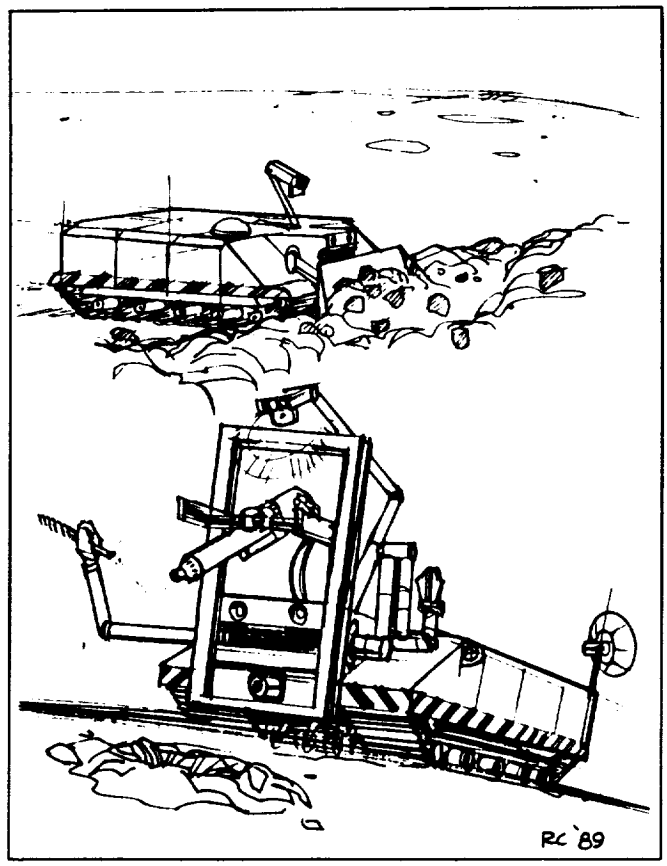


Figure 5.10.2-2.- Prime Mover with More Attachments.

subsoil will break up and deconsolidate, rut, washboard, or form potholes upon being passed over repeatedly by vehicle wheels or tracks such as along a roadway. Walking vehicles may be useful in avoiding surface soil disturbance. The ability to push soil (as in a grader or bulldozer) and, to some extent, the ability to turn curves at given speeds, and so forth, depends on the amount of traction.

The equipment mass obviously must be minimum from the standpoint of transported equipment to the Moon due to costs, and yet there is a need for greater weight on the surface to effect the degree of traction that is necessary. The added mass as dead load may adversely affect the overall power required as well as the inertial properties of mobile equipment. The use of reaction forces other than weight or traction may be useful. Functional parts such as beams may be obtainable from the landers that are not going to be reused. Coordination between the lander and construction equipment designers will facilitate the use of parts on the lander that would have reuse in construction without adverse mass impacts on the lander.

Earlier considerations of bulldozers and cranes may have been somewhat optimistic; an evaluation and preliminary analysis by two groups of engineers working indepen-

1. Dig hole.
2. Constructible package arrives.
3. Constructible package mounted on foundation.
4. Package is opened.
5. Inflation.
6. Attach sphere to foundation.
7. Attach tunnels, construct interior, backfill.
8. Complete interior.
9. Assemble standoff shell.
10. Cover with sandbags.
11. Completion, full pressure.

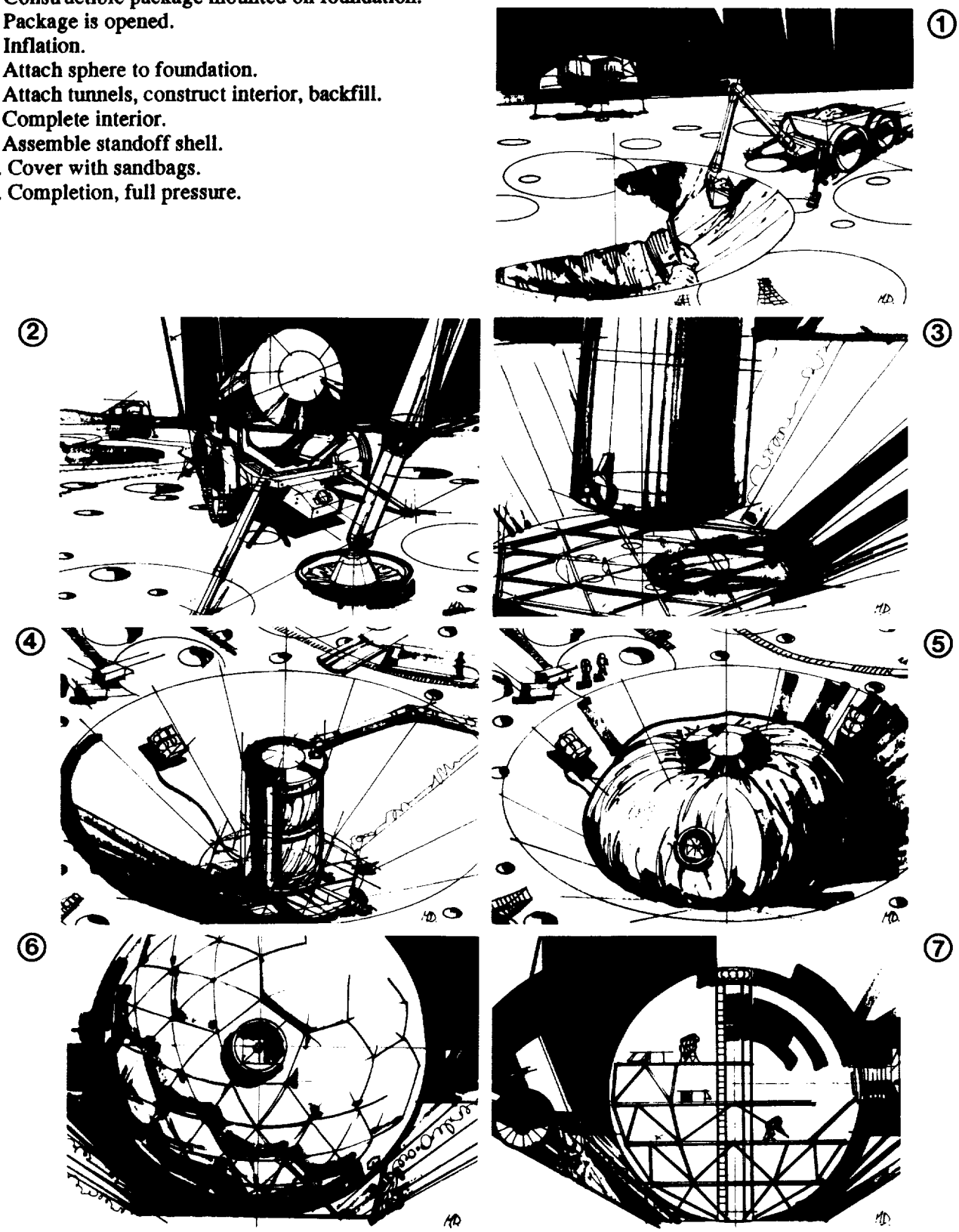



Figure 5.10.2-3.- Possible Construction Sequence for Constructible Habitat.
(continued on next page).

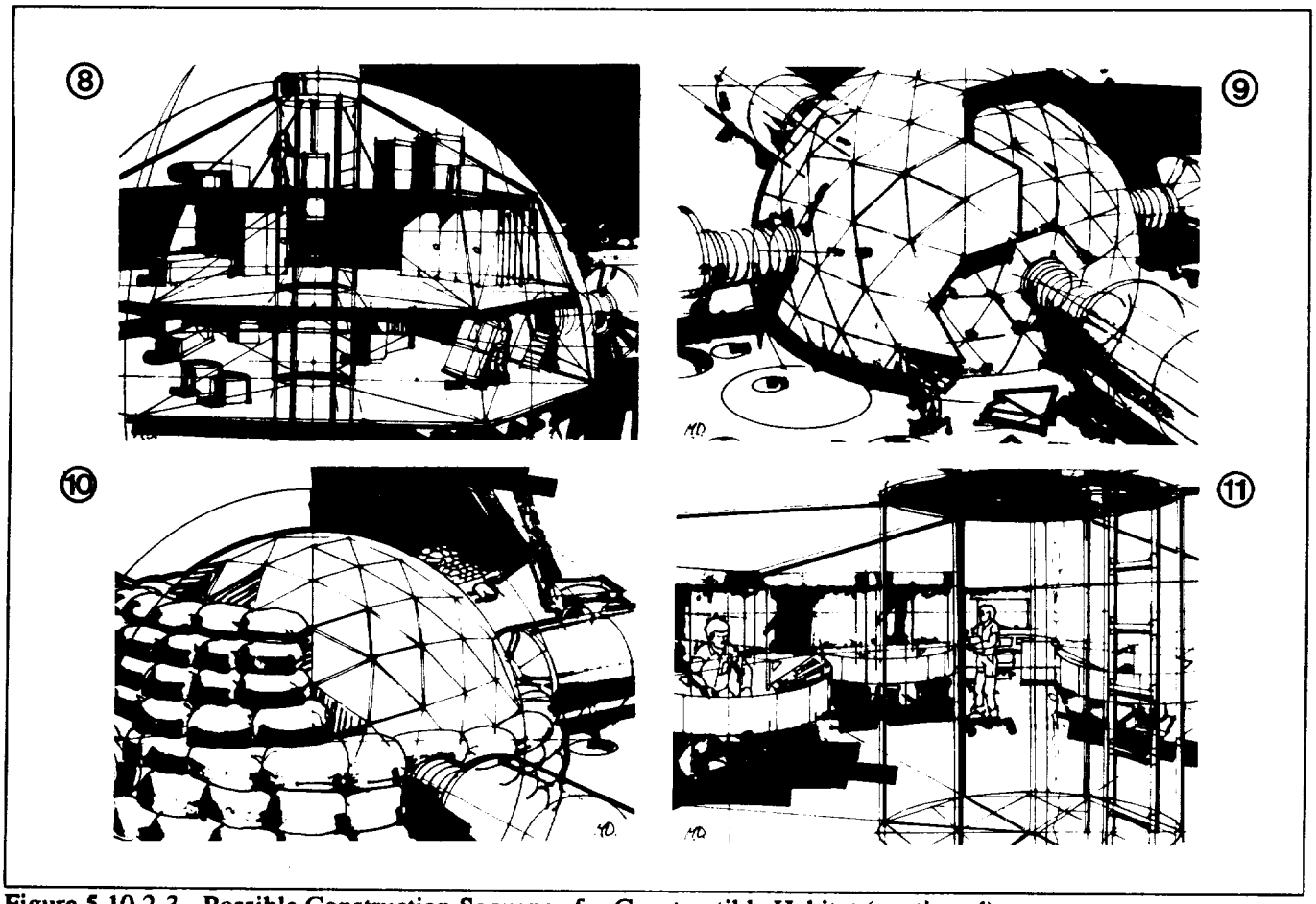


Figure 5.10.2-3.- Possible Construction Sequence for Constructible Habitat (continued).

dently, particularly with respect to the cranes for lifting heavy loads off landers (the heavy loads being the prefabricated, outfitted habitat modules, the photovoltaic solar array and later the 1-MWe nuclear power plant and the inflatable habitat) indicated that the crane would have to be very large and capable of handling significant weights. For example, the boom crane, whether a single boom or double boom, would have to essentially lift a four tonne weight (actually a twenty tonne mass) from the top of what is essentially equal to a four or five story building and lower it to a transport vehicle on the surface. Such tasks on Earth are difficult and time consuming and are not commonly done with mobile cranes, at least not to the extent that it is a smooth, routine operation. To provide the components of such a crane, or other large lifting device of that sort, would be very mass and volume intensive to the transport system. Since it is desired that the crane mass not exceed about 10 percent of the mass of the heavier loads to be handled, other handling means such as wing jacks like the ones used to lift aircraft on Earth may be useful.

During the course of the study and particularly during a workshop that was conducted on mining and construction, the potential need for standoff cover support structures for the habitable module and the inflatable habitat was considered. There is a growing concern about placing regolith directly against the somewhat fragile skin of the habitable module or inflatable structure in a matter that would prevent periodic inspection of that life-protecting membrane. Methods of forming and assembling standoff structures capable of supporting the necessary layer of regolith to provide radiation protection were considered. It appears that a roll former using coils of thin flat metal and shaping it into structurally stiff sections could be used; such a roll former is currently used on Earth. Furthermore, such roll forming could also be used in a number of applications for different size and shape shelters and structures.

The equipment to be used on the Moon and Mars must be as mechanically simple as possible in its design and operation. Simplicity suggests easy repair, perhaps greater reliability, less downtime required for maintainability, and potentially greater durability. There has been no information located or conceived that, at this point, can provide the desired operational reliability data. The mean time between failures of components has not been estimated since the equipment has not been designed to a level where specific components such as

electric motors, gears, power transmission, wear materials, and similar items can be identified specifically for the application. It appears necessary and highly desirable to proceed to the preliminary design of equipment as early as possible. Then, the equipment can be fabricated and subjected to necessary engineering tests and evaluations so that design refinements can be made prior to finalizing a design for the flight/mission hardware. There will be a need for terrestrial testbeds in which to evaluate the performance of individual components as well as the completed equipment in the preliminary design stage. The test bed offers the opportunity to verify functional characteristics and, to some extent, establish the durability of the components so as to project logistical support and downtime for equipment lifetimes.

### 5.10.3 Trade-off Considerations

It will be necessary to develop fundamental design criteria for the construction and assembly equipment. The designs and experience of terrestrial construction equipment provide a basis for these guidelines. The effects of gravity and weight, inertial properties, environment and material selection all affect the design of the equipment for the Moon and Mars. Standard terrestrial equipment can be used as a basis for considering the relationship between weight and power. Performance of tasks such as volume of soil moved per unit of time and the ability to turn (the traction aspects of wheel, track or foot design) can be inferred from corresponding terrestrial equipment. Figure 5.10.3-1 describes some of these relationships. However, it is not clear that terrestrial design guides can be used for lunar and martian surface equipment. Conservation of weight or energy is normally not a primary concern in terrestrial equipment, but transportation mass and volume costs make them paramount concerns for equipment for extraterrestrial use. The low power desired (10-40kWe) for a piece of construction equipment for extraterrestrial surface use will require very creative balancing of mass, speed and capabilities.

One of the early construction tasks, whether on the Moon or Mars, will be to place regolith cover for the occupied habitation module as protection against thermal change, solar flare radiation, galactic cosmic radiation and micrometeorites. As figure 5.10.3-2 shows, there are a number of possibilities for regolith placement. Options include no external shielding, sandbagging, shingle bagging, hosebagging, piling loose regolith, and placing the regolith inside a membrane or inside a tiered retaining wall. Simply piling loose regolith over the habitat involves moving more material than any of the other schemes and makes operations and connections around the habitat more difficult. A method of covering the habitat that does not require much regolith moving and is reasonably practical and not labor or massive equipment intensive is desired. Simple calculations concerning moving material have indicated that 1/2 burial is a good approach. The sandbagging type techniques have been favored, but more work is required to select a final method. Figure 5.10.3-3 compares bagging and loose piling techniques.

The placement and stability of the soil is relatively straightforward as an operational feature; the time available for regolith placement will provide the necessary degree of definition of the capability of the equipment to do that work. The subsection on construction operations (5.10.6) addresses these factors in more detail. The work rate relationship for the construction equipment, based on the operational needs, is essential information to permit the most mass conservative designs possible.

### 5.10.4 Automation and Robotics

Studies conducted by Ames Research Center have predicted that technology levels currently are favorable for use of automated and robotic devices for use in surface operations on the Moon and Mars. The work that has been done in support of Space Station Freedom on robotic assembly and control of equipment and manipulators appears to be adaptable to surface operations. Due to safety considerations, humans may not be permitted to be adjacent to working equipment; autonomous operation is desirable. Furthermore, some tasks cannot be performed by humans in EVA, making reliance on autonomous operation essential.

It will be necessary to adapt sensors, controls, functions, feedback force and sensitivity to provide the back flow of information necessary for a remote operator on Earth, in orbit or on the planetary surface to be able to properly control the equipment via the robot. The nature of general construction tasks are such that relatively broad tolerances of precision will be sufficient. It is unclear at this point whether artificial intelligence will be available to make the operation of the equipment totally autonomous; nor is it certain that this is necessary.

A significant consideration that deserves emphasis is that the robots or automation devices will be the onboard operators of the equipment and as such perform the functions that a human being would perform. In this sense, it is necessary to regard the design and function of the robot to be completely subservient and responsive to the construction and assembly equipment tasks and operations. It is inappropriate to design the construction equipment and its function and capabilities to be secondary to the capabilities of automation and robotics.

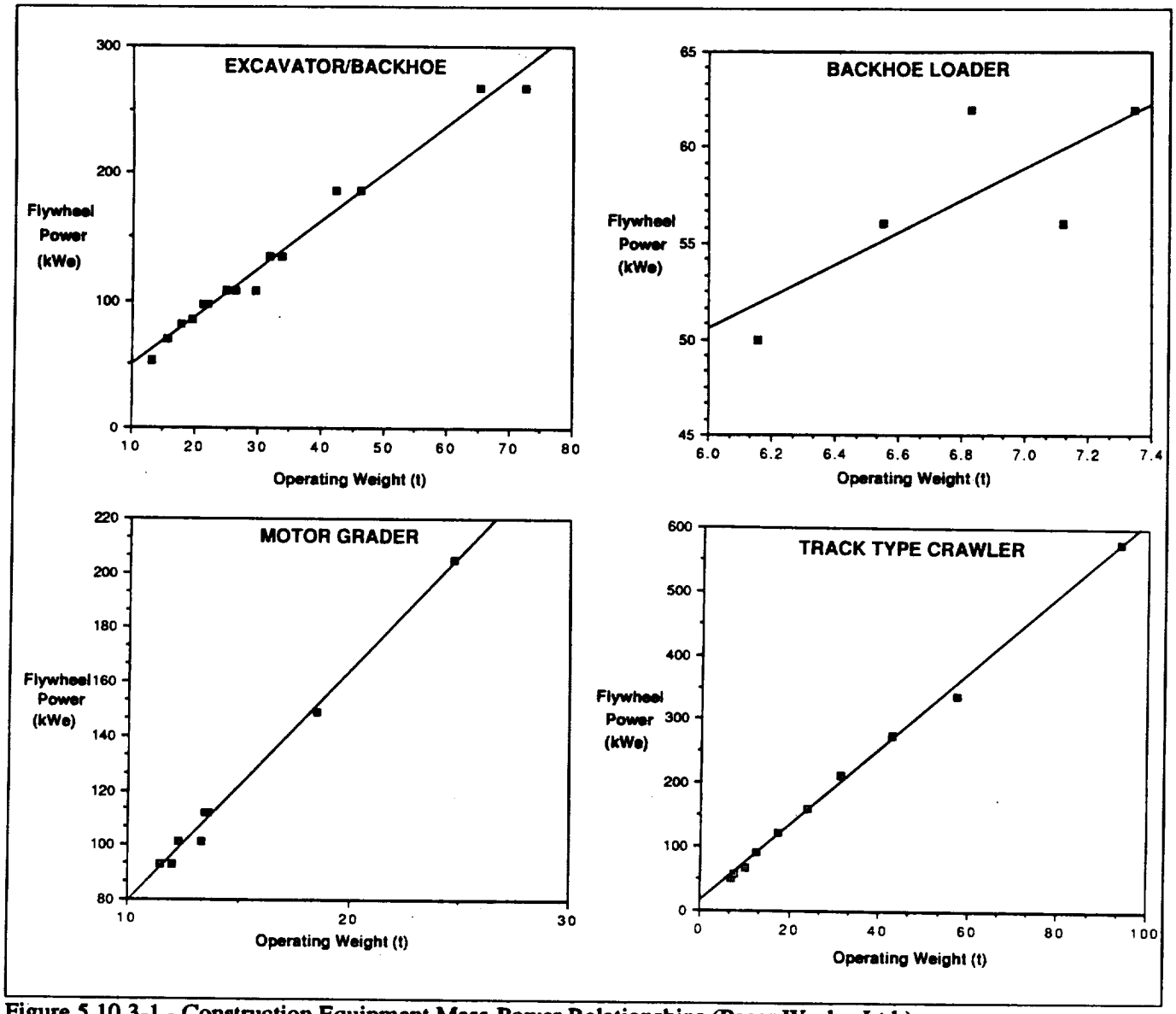



Figure 5.10.3-1.- Construction Equipment Mass-Power Relationships (Pacer Works, Ltd.).

### 5.10.5 Use of In Situ Resources

The procedures to be used in constructing habitats on the Moon or Mars all take advantage of the presence of regolith to be used as a shielding material to provide protection from thermal extremes, solar flare radiation, and micrometeorites. The in situ resource utilization (ISRU) will be piling up of loose regolith, followed by bagging regolith as a most crude form of consolidation. Various later stages will involve consolidating regolith, including quasi-ceramic or sintered or fused mixtures of the unrefined regolith, using cast basalt (by melting the basalt and forming it into shapes), drawing the molten basalt into fibers for use as tension members and eventually unrefined metal byproducts from ISRU extraction processes.

In the design of habitable structures for the Moon or Mars, it is important to provide tension force resisting capability, since most of the habitats are tensile load (from interior pressurization) based structure designs, as compared to the compressive load designs that are typical on earth. The required internal pressures provide a continuous expansive force on the envelope of the habitat. These forces are in the opposite direction to the designs that are normally encountered in habitats on Earth. The use of the regolith mass to counteract the internal tensile forces would require a thick layer of regolith cover as an overburden in order to achieve the desired balance of forces; that amount of regolith cover would be several meters thick and does not appear to be practical at this time. As the designs of inflatable habitats and deliverable module habitats mature, it can

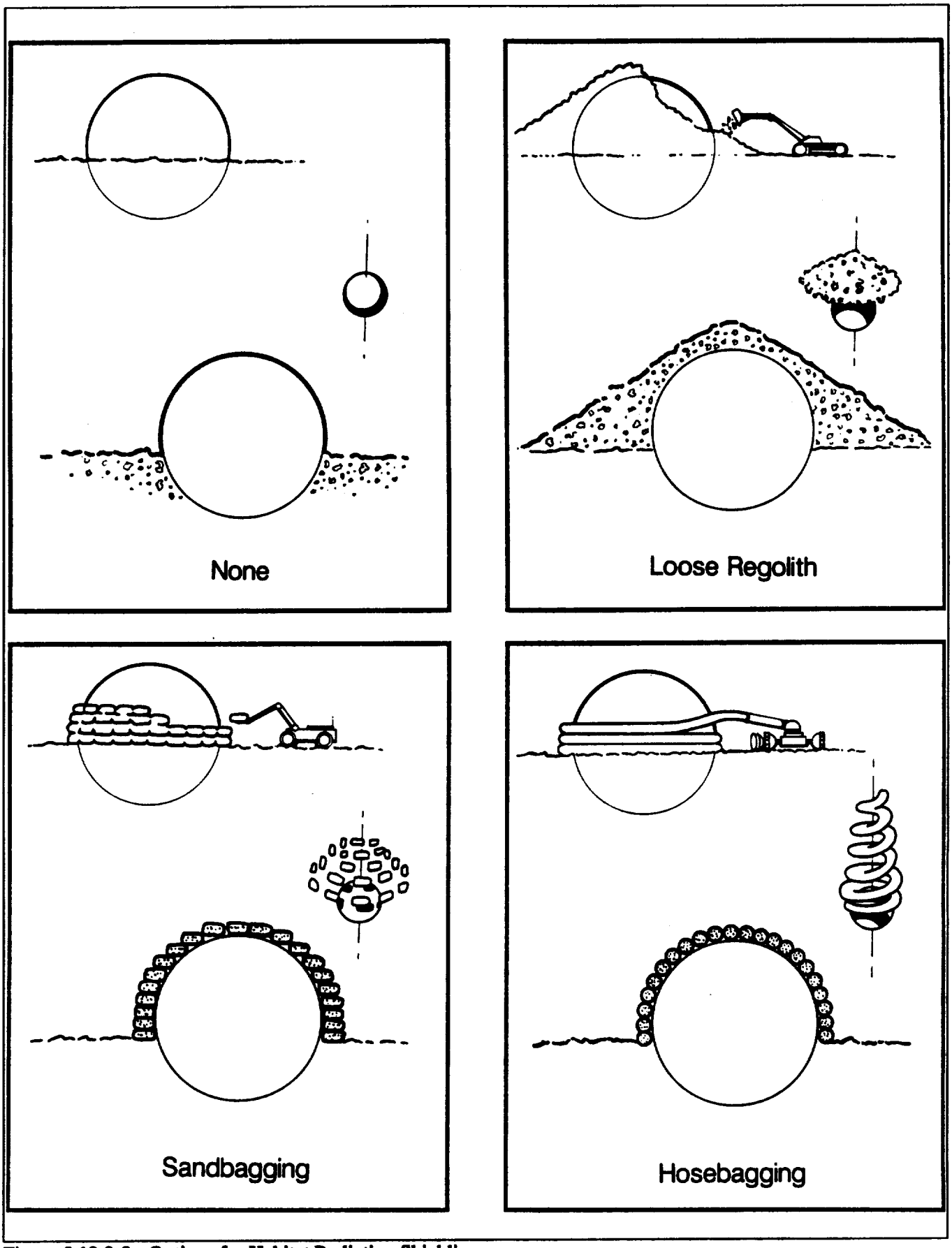



**Figure 5.10.3-2.- Options for Habitat Radiation Shielding.**

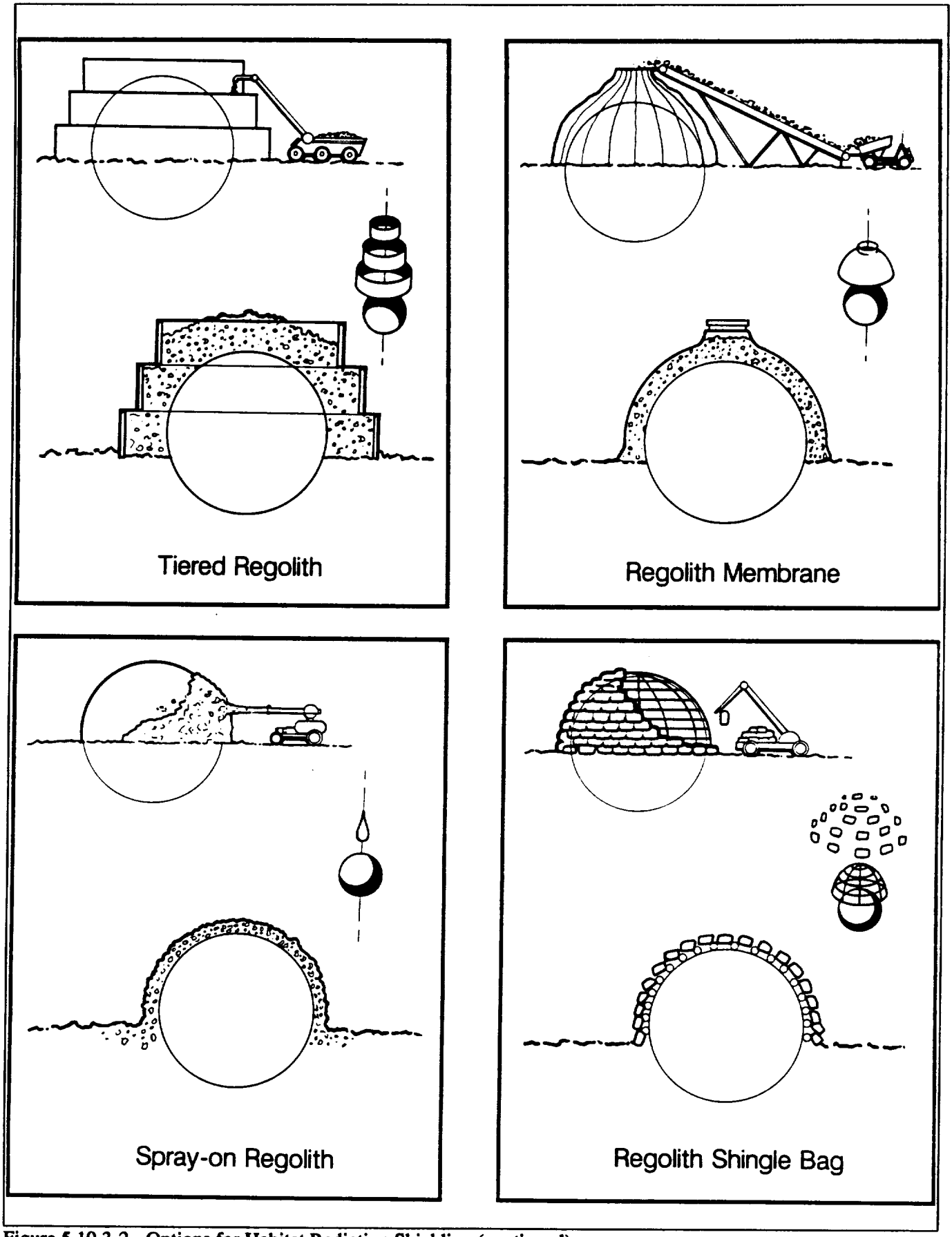



Figure 5.10.3-2.- Options for Habitat Radiation Shielding (continued).

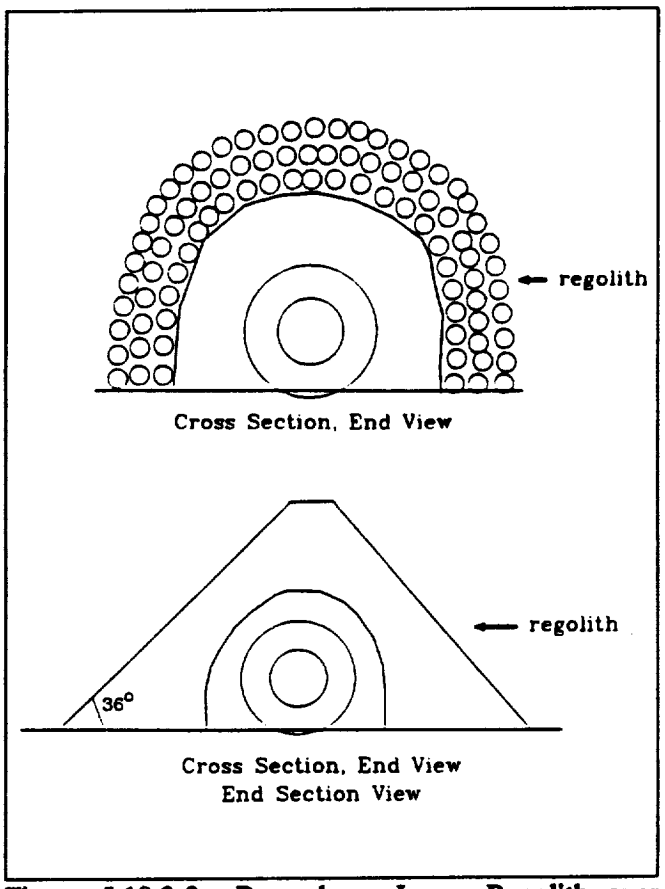



Figure 5.10.3-3.- Bagged vs. Loose Regolith over Modular Habitat.

be expected that refinements will be made and that significant reductions in the mass of the inflatable structure may be possible. However, it may not be practical to directly bury these structures in regolith due to subsequent settlement, thermal strain and vibrations that may eventually cause penetrations of the protective envelope by contact with sharp particles of rock or rubble. In addition, flotation of the module or inflatable structure by buoyancy effects may occur due to the differences in their overall density as compared to the bulk density of the regolith.

### 5.10.6 Operational Concerns

The establishment of productivity rates based upon speed, volume and mass properties of the materials to be handled will determine the operational designs of the equipment. The equipment mass and its corresponding weight will determine the amount of power that is required both as motive power to move the equipment around and the power required for the ability to lift, push or haul loads.

The power requirement will relate to the power source that must be provided for the equipment. The design of the power source, whether batteries or regenerable fuel cells, and corresponding power density and duty cycle will provide some information as to the expectation of downtime for power system changeout or recharging. The operation of construction equipment may occur either during the daylight cycle only or during both the daylight and nighttime cycles. Illumination control could be required in both cases since the sensitivity of video cameras or other observation sensors may require either shadowing or providing shade contrast during daytime and illumination during the period of darkness.

Also to be considered in the equipment design are factors of reach and lift, loads to be carried, and the speed and frequency of use. It seems reasonable to try to provide for essentially continuous duty of the equipment to make the most efficient use of it. However, certain downtimes must be provided for recharging batteries or changing out the power supply and for periodic and preventive maintenance (such things as lubrication), replacement of parts as they either break or wear out or as they need calibration or checkout to verify proper functioning.

Also, an operational concern that was not included in the FY 1988 report is the possible need for standoff structures and shelters that were discussed earlier. The load capacity of the standoff shelters will depend on the depth of regolith that is required for providing the necessary level of protection. Various figures have been estimated; they vary from 50 centimeters to several meters depth. The amount of regolith that must be moved obviously affects both the equipment to move it within a constrained time or allocating a longer time for constrained capability of horsepower and volume of the equipment. It would be inappropriate to design equipment to do vast amounts of work in a very short time unless that was absolutely necessary. A more rational approach is to design equipment that does work at a slower rate over longer duty cycles. This is contingent, of course, on the time available for completion of tasks. The use of roll-forming equipment to make components of structures, if they are indeed required, also provides a leverage potential of using that same metal forming equipment in making components for future structures. Only the additional rolls of metal to be formed would have to be transported to the planet's surface.

Tasks and rates of construction operations that will be conducted are discussed in detail in section 6.2 and only a brief summary of more prominent activities are provided in table 5.10.6-I.

TABLE 5.10.6-I.- CONSTRUCTION OPERATIONS TASKS AND UNITS

| Task | Unit | Productivity |
|---|---|---|
| Survey | Points | 15 min/point |
| Grade | 2 passes/area | 20 $m^2$/hr |
| Boulder removal (small) | # of boulders | 15 min/boulder |
| Excavate | Volume, $m^3$ | 3 $m^3$/hr |
| Regolith transport | Volume, $m^3$, distance | 2 $m^3$, 75 m/hr |
| Emplace | # pieces (sm., med., lg.) | 15 min/piece |
| Connect Pieces | # pieces (sm., med., lg.) | 15 min/piece |
| Backfill | Volume, $m^3$ | 4.5 $m^3$/hr |
| Cover, elevated | Volume, $m^3$ | 3 $m^3$/hr |
| Inspect | Points | 15 min/point |
| Pressurize | Volume, $m^3$ | 75 $m^3$/hr |
| Test and Activate | # of systems | 15 min/system |
| Anchor | # of anchor points | 30 min/point |
| Smooth | # passes/area | 30 $m^2$/hr |
| Trench | # passes, length | 50 m/hr |
| Equipment Ingress | # pieces., volume | 15 min/piece |
| Boulder removal (large) | # of boulders | 3.5 hr/boulder |
| Equipment transport | # pieces., mass, distance | 100 m/hr |

### 5.10.7 Technology, Programmatics, and Precursors

With regard to technology needs and engineering development that must occur before establishing a long-term presence on the Moon or Mars, most of the technologies already exist. They will have to be altered, adapted and advanced by some amount, but fundamentally the various technologies of excavating, smoothing, hauling, retaining and consolidating soils are understood. Thus, most of the effort in phase A/B will be directed toward engineering developments and refinements with the attendant refinements and changes in design criteria and operational criteria.

Certain precursor needs do exist. Prominent among them is a greater knowledge of the soil and surface conditions on both the Moon and Mars. Based on the Apollo missions, some reasonably good information about surface conditions and, to some extent and for specific locations, what the underlying soil is like is known. Information from the Mars missions that have been conducted have provided less detailed information. The soil and the surface may be quite different than that on the Moon. A considerable amount of gravelly rubble and larger rocks appear to exist. Topographical features are also quite different. This kind of information provides some parameters that must be addressed in the design and operations of construction equipment. The nature of the meteorology of Mars is also necessary in that the storms cause loads that must be considered in structure design and building. Corrosiveness of the soil affects the selection of the materials that will be in contact with the soil. This applies to the construction equipment, the habitable modules, and other equipment that is to be placed in or upon the soil. Without precursor mission information, the concept design and preliminary design of equipment will tend to be more conservative than may be necessary.

It is recognized that the cost and time involved in obtaining the precursor mission data may be such that more conservative designs and attendant mass penalties in transporting equipment to the Moon or Mars may be much less costly and thus preferable to performing the precursor missions. Table 5.10.7-I provides a listing of engineering development needs that have been identified for designing the construction equipment and for predicting the operational capabilities. Figure 2.7.1-2 lists the milestones for construction equipment development. The development of construction management plans will closely follow the equipment development. Table 5.10.7-II identifies precursor needs that have been stated in the FY 1989 studies as being desirable.

## 5.11 LAUNCH AND LANDING SERVICES

Launch and landing services include a description of the flight vehicle turnaround on the lunar surface, an identification of the surface support equipment (SSE) required, a discussion of flight vehicle features that can

TABLE 5.10.7-I.- ENGINEERING DEVELOPMENT NEEDS

- Packaging and protection of equipment computers
- Utilities connections
- Materials fabrication and testing for long-life inflated structures
- Automatic monitoring of pressurized habitat over a long term ("smart building")
- Means of reliably testing MTBF in lunar and martian environments
- Sensory feedback for robots
- Materials for extreme temperature operations (and other environmental effects)
- Soil simulants for use in testing equipment, construction components, and consolidation
- Thermal energy management/dissipation from mobile equipment
- Mobility improvement (wheel, tread design, life cycle, traction)
- Truck, walker, hybrid equipment for lunar and martian construction and mining
- Means of testing wear, maintenance of equipment working in the lunar and martian areas
- Materials handling in vacuum
- Resistance of seals, bearings, and mechanical parts to dust and soil abrasion, erosion, and corrosion in lunar and martian environments

TABLE 5.10.7-II.- PRECURSOR NEEDS

Engineering soil mechanics
Key to design of equipment, foundations, landing/launch pads, roadways, anchors; digging, moving, piling, and consolidating regolith.

Subsurface features
Large boulders and solid outcropping of rocks pose removal and avoidance problems. Large voids pose safety problems.

Topography and terrain
Equipment design, operations; rate of traverse; stability, safety.

Seismic Activity
Transmission of ground motions on building, excavation plant designs, foundation and anchoring.

Meterology (Mars)
Wind speeds, direction, entrained sand and dust are needed design criteria for structures, foundations, and anchors.

TABLE 5.11.1-I.- OVERALL GROUNDRULES AND ASSUMPTIONS

- Onboard automatic problem detection, isolation, and corrective action recommendation
- Onboard time and cycle tracking
- Onboard test programs executable by uplink command
- No manloading for active lunar base participation in low lunar orbit activities
- No manloading for active lunar base involvement in flight vehicle landing and ascent except for potential range safety intervention on unmanned cargo missions
- Automated parts inventory and location data
- Corrective action procedure and resource requirements data base
- EVA times are ground equivalent earth times
- No attempt to identify parallel operations
- Assumes a perfect flight vehicle

simplify turnaround operations, translation of results to the martian environment, and an identification of areas requiring further definition or study. The launch and landing discussion in this Planetary Surface Systems volume is highly condensed; additional details are included in volume 5.

### 5.11.1 Flight Vehicle Turnaround Scenario

A minimum effort generic flight vehicle turnaround scenario was developed by reviewing all KSC turnaround tasks and scrubbing these down to a minimum set of requirements. A turnaround scenario was developed that included only those tasks considered unaviodable and assumed a *perfect* vehicle. The turn-around times produced are therefore the minimum reasonable times. A real design will almost certainly require more than this minimum work. The groundrules and assumptions used are shown in table 5.11.1-I.

The flight vehicle turnaround scenario is shown in figure 5.11.1-1. The boxes of this scenario represent individual functional flow diagrams (FFD) that detail the required tasks; and the times above each box equal the sums of the individual task times in each FFD. The numbers in the lower right corner of each box correspond to the number of the FFD that it represents. Volume 5 contains the detailed derivations and other sources for the times given. This is a generic scenario, and those items that apply only to a piloted lunar excursion vehicle (LEV) are indicated by an asterisk (*). The

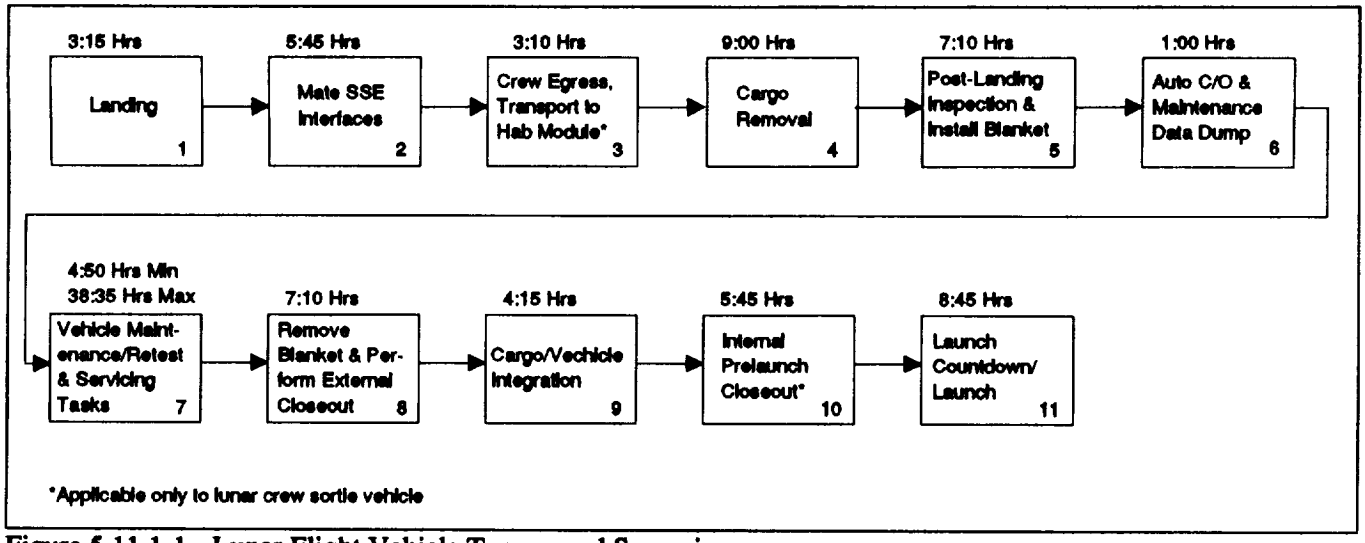


Figure 5.11.1-1.- Lunar Flight Vehicle Turnaround Scenario.

total required turnaround time is estimated to be 55 hours, 15 minutes, exclusive of flight and surface systems maintenance, which is a variable.

### 5.11.1.1 Landing

The landing phase will begin with a visual inspection of surface systems in the landing area. Its purpose is to ensure that these systems have sustained no obvious physical damage or dislocation since last checked. The inspection will be performed remotely from the base using teleoperated television cameras, and will be followed by an operational check of the various landing systems and equipment to ensure its readiness to support the landing.

Base personnel will track and monitor the vehicle during the descent phase through touchdown, and will be prepared to perform rescue/contingency operations, if necessary. Upon landing, the vehicle will be safed, essentially completing the landing phase, which will consume an estimated 3 hours, 15 minutes. After safing, one person will be on standby continuously, to respond to any caution and warning alarms or out-of-tolerance conditions flagged by the surface systems control and monitor system (SSCMS).

### 5.11.1.2 Mate SSE Interfaces

Immediately after landing, the next phase will mate interfaces between the flight vehicle and SSE. It is assumed that all required SSE can be towed, trailered, or carried on the unpressurized rover in one 30 minute trip.

Surface systems electrical power interfaces will be mated, the lander thermal control cart will be connected, and flight vehicle systems will then be transferred to and operation verified on surface systems power and cooling. The hydrogen and oxygen boiloff capture and reliquefaction systems will be connected and activated to permit both liquid hydrogen ($LH_2$) and liquid oxygen ($LO_2$) to be stored on the surface in the flight vehicle tanks. Once lunar liquid oxygem is available, a boiloff vent line will be used to carry gaseous oxygen from the immediate area. Connections will be made between the flight vehicle water tank and the fuel cell water deservicer, and interfaces will be mated to the waste management system deservicer. Total elapsed time for this phase is estimated to be 5 hours, 45 minutes.

### 5.11.1.3 Crew Egress & Transport to Habitat

Once the flight vehicle is operating on surface utilities, the next phase, applicable only for the manned LEV, will be to transfer the flight crew to the habitat. The pressurized utility vehicle (PUV) will be activated and driven to the pad. This scenario assumes that the PUV will have a capability for elevating its pressurized cabin to the level of the LEV hatch as illustrated in figure 5.11.1-2, thereby permitting it to mate directly with the LEV and obviating the need for a separate tunnel ramp. This capability would be beneficial for moving between the various pressurized facilities and vehicles at the lunar base. The operator will elevate the pressurized cabin to the level of the LEV crew module hatch, and activate the docking hatch mechanism. The LEV crew will egress into the PUV, and the PUV will be undocked and prepared for its drive to the habitat. Total elapsed time for this phase of the turnaround will be 3 hours, 10 minutes.

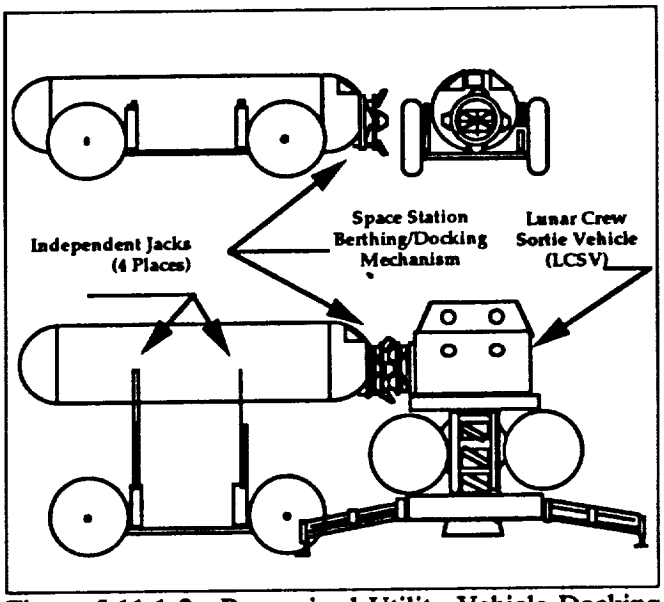


Figure 5.11.1-2.- Pressurized Utility Vehicle Docking with LCSV Crew Module.

### 5.11.1.4 Cargo Removal

It was assumed that the cargo will consist of a package or container that will be removed from the flight vehicle as a single unit using a single point lift in one removal operation. It was also assumed that the cargo weight and center of gravity will be within handling tolerances so that cargo shifts can be controlled by a two-man tag line crew.

Access and handling equipment will be deployed and attached to the cargo, and cargo power and cooling will be shutdown and the interfaces safed and disconnected. The cargo retention latches will be remotely released, and while the extravehicular crewmen stabilize the cargo with tag lines, the intravehicular crewman will lift the cargo and then lower it onto a transporter. The cargo will be secured to its transporter, relocated to its use location, and off-loaded. Total elapsed time for this phase is estimated to be 9 hours. Several areas of concern are the cargo center-of-gravity with respect to the cargo lift points, and the ability of the extravehicular crewmen to control the cargo using tag lines as the cargo is lifted from the flight vehicle.

### 5.11.1.5 Post-Landing Inspection and Blanket Installation

After the cargo has been removed, the flight vehicle will be inspected and its thermal blanket installed to protect it from solar heat input during its long-term storage on the lunar surface. The thermal blanket erection scenario was based upon an assumed configuration, and the process is described in Volume 5. Note that the time duration of this task could change significantly with different blanket and frame designs. In addition, the visual inspection could be performed as a parallel operation by video from inside the habitat if a suitable teleoperated vehicle or teleoperated assistant were available. Total elapsed time is projected to be 7 hours, 10 minutes. At this point the flight vehicle is ready for long-term surface storage.

### 5.11.1.6 Automatic Checkout and Maintenance Data Dump

The flight vehicle and surface support equipment will be activated and monitored using the SSCMS. On-board built-in test equipment (BITE) will be activated for the various systems and the results will be displayed by the SSCMS. Anomalous performance by any system or component will be identified, and required corrective action will be recommended. Total task time is estimated to be one hour.

### 5.11.1.7 Flight Vehicle Maintenance and Retest

The scope of the maintenance and retest task for flight vehicle turnaround will vary from vehicle-to-vehicle and from flight-to-flight. The definition of the task will result from the combination of the visual inspection and the maintenance data dump. Also, the SSCMS will monitor system performance and flag any additional maintenance or repair items as they occur.

This scenario was to assume a perfect vehicle in order to drive out the minimum set of turnaround operations; therefore, the entire spectrum of maintenance tasks has not been addressed. The scenario has addressed, however, what is believed to be the two ends of the spectrum. The removal, replacement, and retest of an avionics box requiring 4 hours 50 minutes, represents the low end of the spectrum, while the removal, cannibalization, and replacement of an engine, requiring 38 hours, 35 minutes, represents the high end. Total elapsed time for this task will be a variable depending upon the quantity and types of maintenance actions required.

### 5.11.1.8 Remove Blanket and External Closeout

The end of the flight vehicle long-term storage period will be marked by removal of its protective thermal blanket. Details of this task for the assumed configuration are discussed in Volume 5. Total elapsed time is projected to be 7 hours, 10 minutes, but it must be realized that this task time, like that for blanket installation, could change significantly with different blanket and frame designs.

#### 5.11.1.9 Cargo/Vehicle Integration

Upon removal of the thermal blanket, the flight vehicle will be ready for cargo installation and cargo-vehicle interface verification. The cargo will be lifted by crane onto its transporter and relocated to the flight vehicle. The cargo lift will be executed via teleoperation with two crewmen on extravehicular activity (EVA) manning tag lines. It is assumed that the flight vehicle will have alignment aids, such as tapered pins, to assist in the alignment and mechanical mate of the cargo. Once the cargo is in place, mechanical latches will be remotely activated and visually inspected. Interface connectors will be mated and the interfaces activated and tested. Total elapsed time is estimated to be 4 hours, 15 minutes. Once this phase is complete, unmanned vehicles will be ready for launch countdown and the LEV will be ready for internal closeout.

#### 5.11.1.10 Internal Prelaunch Closeout

The internal prelaunch closeout phase applies only to the manned LEV; however, automated system checkout will be required to verify pre-countdown readiness of all vehicles. The LEV environmental control and life support system (ECLSS) will be activated, and when the LEV ECLSS parameters are acceptable, two crewmen will drive the PUV to the pad and dock to the LEV crew module hatch. They will perform an automated LEV checkout to verify system readiness for launch countdown, followed by module control checks and stowage of late cabin cargo items. The crew will then egress to the PUV, demate, and return to the Habitat. Total elapsed time is estimated to require 5 hours, 45 minutes.

#### 5.11.1.11 Launch Countdown/Launch (LEV)

The launch countdown is described for a manned LEV, as it contains several tasks that will not be required for the unmanned vehicles.

Once lunar liquid oxygen is available from surface production facilities, a two-man EVA crew will load equipment onto the unpressurized rover, pick up a loaded liquid oxygen tanker, and drive to the pad. Interfaces to the flight vehicle will be mated, while fill lines and one of the main liquid oxygen tanks will be chilled and filled. The process will then be repeated for the other main liquid hydrogen tank and the fuel cell liquid oxygen tank. It may be possible to load all three tanks simultaneously. Fill time will depend upon the size of the transfer line and the pressures used. The fill line will be drained, disconnected, and stowed. Equipment will be removed to the liquid oxygen storage area, where the tanker will be connected and residual liquid oxygen returned to the storage tank.

Once flight vehicle liquid oxygen boiloff has stabilized, the flight crew will enter the PUV with one base crewman, drive to the pad, and dock with the LEV crew module hatch. The flight crew will ingress the LEV crew module and stow personal items. The vehicle will then be transferred from surface systems services to flight vehicle services, where a automated test of vehicle systems is conducted, followed by module control checks to ensure launch readiness.

Once the residuals in the liquid oxygen tanker have been off-loaded, the two-man EVA crew will return to the pad to disconnect and remove the equipment used to provide surface systems services to the flight vehicle.

The automatic launch sequence will be initiated with T-0 timed to achieve lunar orbit rendezvous with the lunar piloted vehicle. The vehicle downlink data will be monitored during ascent, and after launch, the teleoperated assistant will be dispatched to the pad for a post-launch video inspection. Total elapsed time is expected to be 8 hours, 45 minutes.

### 5.11.2 Element Descriptions

Several items of SSE will be required to accomplish the turnaround scenario. Some of these items, listed in table 5.11.2.-I, are unique to the launch and landing area; however, the majority will also be required by other functional areas. The table shows a cross reference to the phase of the turnaround scenario that requires the use of each item. The need for each of these items is described briefly below:

Lander thermal control cart--required to dissipate heat generated by flight vehicle systems while operating from surface systems services.

Hydrogen and oxygen boiloff capture and reliquefaction systems--required to preclude loss of the launch propellant supply while the flight vehicle is stored on the lunar surface.

Oxygen boiloff vent line--required when lunar liquid oxygen becomes available to route residual liquid oxygen boiloff to lunar vacuum so as to preclude the possibility of gaseous oxygen collection beneath the thermal blanket or other enclosed structures.

Landing/navigation aids--required to ensure accurate landing at the proper launch and landing pad.

Thermal blanket--Required to protect each flight vehicle from direct and reflected solar thermal radiation during the lunar day. The blanket will also provide some

TABLE 5.11.2-I.- HARDWARE UNIQUE TO LAUNCH AND LANDING

| Surface Element | Phase in Turnaround | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Landing | Mate SSE I/F | Crew Egress | Cargo Removal | Install Blanket | Auto Maint. Dump | Maint. & Test | Remove Blanket | Cargo Integr. | Internal Closeout | C/D & Launch |
| Lander Thermal Control Cart | | x | x | x | x | x | x | x | x | x | x |
| $H_2$ and $O_2$ Reliquefaction Systems | | x | x | x | x | x | x | x | x | x | x |
| Oxyfen Boiloff Vent Line | | x | x | x | x | x | x | x | x | x | x |
| Landing/Navigation Aids | x | | | | | | | | | | |
| Thermal Blanket | | | | | x | x | x | x | | | |
| Electrical Grounding System | | x | x | x | x | x | x | x | x | x | x |
| Range Safety System | x | | | | | | | | | | x |
| Engine Handling Fixture | | | | | | | x | | | | |
| Pad Electrical Power | x | x | x | x | x | x | x | x | x | x | x |
| Blast Protection | x | | | | | | | | | | x |

degree of micrometeoroid protection. Figure 5.11.2-1 shows one concept for this blanket.

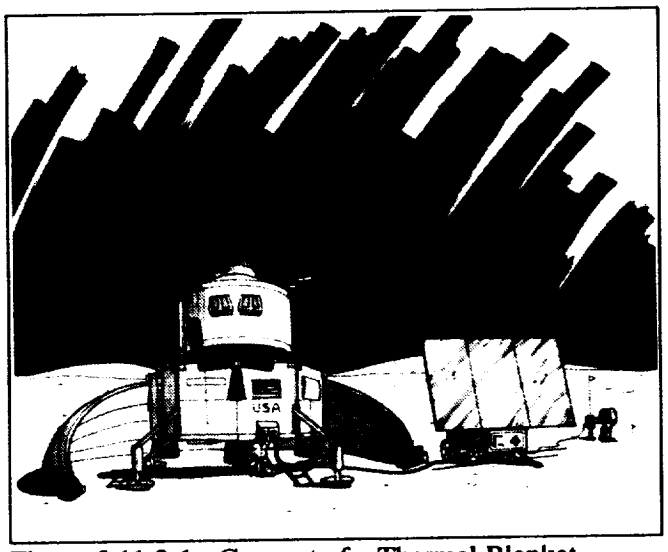


Figure 5.11.2-1.- Concept of a Thermal Blanket.

Electrical grounding system--required to ensure that the several pieces of flight and surface systems equipment involved in an operation are at equipotential, and thereby prevent equipment damage through static discharge.

Range safety system--required to protect the lunar base from errant unmanned flight vehicles during launch and landing.

Engine handling fixture--Required if engine removal and replacement are to be accomplished on the lunar surface.

Electrical power at launch and landing pad--(options include: power cord cart, fuel cell power cart, and beamed power cart). Required to operate electrically driven surface systems, power tools, equipment, and the flight vehicles at the launch and landing pads.

Blast protection--required to protect surface systems equipment and facilities in the launch and landing area from surface ejecta generated during vehicle launch and landing.

Those items needed for launch and landing operations that are also be required by other areas are listed in table 5.11.2-II, with a cross reference to the phase of the turnaround scenario that requires its use. Some of the items are required infrequently during the scenario. These items, designated in the table by "Stays Connected," will be transported and connected at initial use. In order to save time and resources, they will be left connected until their final use before being removed from the pad area. However, they could be removed and used elsewhere should the need arise.

### 5.11.3 Vehicle Versus Surface Accommodations

Every opportunity to simplify or minimize the required level of human involvement in flight vehicle maintenance and turnaround must be evaluated. The following are features of flight vehicle design that should be considered as candidates for such future evaluation. Further explanation and justification is contained in Volume 5.

- A pressurized maintenance area should be provided within the flight vehicle, which includes most high maintenance items, such as: engine pumps and

TABLE 5.11.2-II.- HARDWARE SHARED WITH OTHER BASE OPERATIONS

| | Landing | Mate SSE I/F | Crew Egress | Cargo Removal | Install Blanket | Auto Maint. Dump | Maint. & Test | Remove Blanket | Cargo Integr. | Internal Closeout | C/D & Launch |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unpressurized Rover | | x | | x | x | | x | x | x | | x |
| Pressurized Utility Vehicle | x | | x | | | | x | | | x | x |
| Mobile Crane | | | | x | x | | x | x | x | | |
| Cargo Transport Vehicle | | | | x | | | | | x | | |
| Contamination Removal System | | x | x | x | x | | x | x | x | x | |
| Cryogen Tanker(s) | | | | | | | | | | | x |
| Fuel Cell Maintenance Cart | | x | | Stays Connected | | | x | Stays Connected | | | x |
| ECLSS Maintenance Cart | | | | | | | x | | | | |
| GN2 Handler | | | | x | | | x | | | | |
| Waste Mgmt. System Deservicer | | x | | Stays Connected | | | x | Stays Connected | | | x |
| Surface Operations Lighting System | | x | | x | x | | x | x | x | | x |
| Inspection Equipment | | | | | | x | | | | | |
| Access Devices | | x | | x | x | | x | x | x | | x |
| LOX Cleaning Capability | | | | | | x | | | | | |
| Communications Systems | x | x | x | x | x | x | x | x | x | x | x |
| Control & Monitor System | x | x | x | x | x | x | x | x | x | x | x |
| Auto Performance Monitor | x | x | x | x | | x | x | | x | x | x |
| Mobile Teleoperated Assist. | x | x | | x | x | | x | x | x | | x |
| Remove Telerobotic Serv. Sys. | | | | x | x | | x | x | x | | |

turbo-machinery, avionics boxes, fluids components.

- Design for all flight vehicle systems and components should be made with, and reviewed for, consideration of maintenance in the lunar environment.

- Surface finishes and interface connections must be designed for insensitivity to and/or easy removal of lunar dust, and should avoid surface irregularities and indentations that would tend to collect dust.

- Onboard automated monitoring, logging, and forecasting of component operating times and operating cycles for limited life components, should be performed to identify those components expected to exceed their operating life during the next mission.

- Onboard BITE that automatically monitors the active systems performance for anomalous conditions or trends that are approaching operating limits.

- The vehicles should either have stored onboard, or be able to accept via uplink, standard software programs to functionally test vehicle systems and perform diagnostic testing as necessary to isolate problems. These programs, capable of being executed and controlled by uplink, and monitored by downlink, will greatly simplify any required surface diagnostic testing and post-maintenance retest.

- Flight vehicle-surface systems interfaces (fluid, power, data, and communications) should be combined ("ganged") and co-located whenever possible. Safety considerations should be the only reason for overriding this groundrule.

- The cargo-flight vehicle interface must be designed to simplify cargo alignment and installation. If only a single lifting device (crane) will be available, the lift vector should intersect that center of cargo mass, to avoid any tendency for the cargo to rotate about the lift point once the cargo clears the flight vehicle cargo alignment pins. KSC has historically attempted to control cargo shifting with tag lines, and at the present, no alternative is apparent for use on the lunar surface. This problem is an item for further study.

### 5.11.4 Translation of Results to Mars Launch and Landing

Flight vehicle turnaround operations conducted on Mars environment are anticipated to be minimal when compared to those conducted on the Moon. The major differences will result from the flight vehicle design (the martian vehicle is far more likely to be expendable), the presence of the martian atmosphere, and the higher gravity on Mars.

#### 5.11.4.1 Impact of Flight Vehicle Design

The flight vehicle is currently conceived as having a separate ascent stage that uses some sort of "storable" propellant. Hypergolic propellants are highly corrosive, however, and liquid oxygen/kerosene propellants have the problem of liquid oxygen boiloff. The choice of propellants will determine what operations are required. Simulated launch countdowns will be conducted shortly after landing to identify any required maintenance items, and again before launch to ensure launch readiness.

#### 5.11.4.2 Impact of Martain Atmosphere

On Mars, launch and landing personnel will have the added problem of wind loads on structures and equipment. Airborne contamination and its effect on equipment performance such as radiators and photo-voltaic arrays will also be a concern. Martian soil, having been wind blown, should be less abrasive than lunar soil. On the positive side, the presence of an atmosphere makes thermal cycles, radiation levels, and meteoroid frequency less severe, thereby reducing the need for cooling and thermal blankets. Another change will be differences in the propagation of blast effects and the required separation of launch and landing facilities.

#### 5.11.4.3 Impact of Martian Gravity

Mars' gravity, which is approximately twice the Moon's, will have several impacts on launch and landing operations. Structures and vehicles will have to be built more sturdily to support the same mass. Personnel will be able to lift only half as much mass, thereby increasing the need for lifting devices. The EVA suits and portable life support systems will be heavier, further reducing both the load that can be carried and the EVA duration possible with a single backpack.

More specific impacts cannot be determined until the equipment to be used on Mars is defined in more detail.

### 5.11.5 Areas Needing Further Definition or Trade Studies

Several types of precursor data and additional information are required for lunar and martian launch and landing operations. The need for several of these are discussed below.

Cargo handling--techniques must be developed to safely handle massive and bulky cargo with limited manpower and equipment resources.

Hydrogen-oxygen characteristics--there are several unanswered questions concerning the performance of hydrogen and oxygen in the lunar and martian environments. One is how each propellant will disperse in event of a spill or leak. Is there any possibility of them collecting in hazardous concentrations? In event of a vehicle explosion, there are no data on how close structures can be safely placed to avoid fragmentation and overpressure damage.

Smart structures--Safe and non-labor-intensive techniques must be devised for inspection and flight readiness certification of structures and pressure vessels.

Contamination avoidance and control--methods must be developed to avoid and control surface contamination in both the lunar and martian environments.

Thermal blanket--Alternative thermal blanket concepts and/or alternatives to the thermal blanket must be studied to determine the most economical approach to achieving thermal and micrometeoroid protection for the flight vehicles.

Launch and landing architecture--alternative launch and landing scenarios must be studied to determine the most economical operations approach under various traffic conditions. For example, compare operations conducted at the several launch and landing pads versus at a central operations/maintenance facility.

Residual oxygen handling--alternatives for handling residual flight vehicle liquid oxygen must be compared to determine whether and at what point it is more economical to capture and save residual $LO_2$ and/or $LO_2$ boiloff or to dispose of it and replace it with in situ production.

Expendable vs. reusable flight vehicles vs. flight rate--The relative costs of using expendable versus reusable flight vehicles for unmanned cargo delivery must be examined as a function of flight frequency. This includes investigation into how expended flight vehicles can be used to advantage by various surface operations.

Differences between martian and lunar operations--Further study is required to better define the differences in launch and landing operations to be conducted on Mars versus those to be conducted on the Moon.

## 5.12 USER ACCOMMODATIONS

A key motivation to establish a planetary surface base is the desire to explore and live on new frontiers and a quest for scientific knowledge. A permanently occupied base will provide many new science opportunities. The

science community will play a significant role in determining base activities, infrastructure, and location(s).

With respect to the studies discussed in this volume, the scientific research community is designated by the term user. This term implies that the base acts as a service support system to accommodate the science customer's particular needs. Thus a particular functional area is specified for user accommodations. The Planetary Surface System Requirements Document (Roberts, 1989) defines user accommodations as "pertaining to those elements and operations that do not directly support the surface infrastructure and its designated operations and projects." Basically, user accommodations refer to scientific activities operating with mandates independent of the surface base functions.

### 5.12.1 User Accommodations Disciplines

User accommodations are classified according to three main disciplines: astronomy, planetary science, and life science. Astronomy involves the sensing of distant objects and signals with observations directed away from the planetary body on which the surface systems are deployed. Exemplary astronomical equipment include radio interferometers, monitoring telescopes, and low frequency arrays. With respect to location of astronomy observatories, the lunar surface rather than the martian surface offers substantial advantages. Particular lunar environmental factors include the absence of a planetary magnetic field, no atmosphere, and a slow rotation rate.

Planetary science refers to the study of the inhabited planetary body, with a particular emphasis on geochemistry, petrology, and geophysics. Typical elements include seismic arrays, meteorological stations, and sample collection. Planetary science activities on the lunar or martian surfaces involve both field operations (exploration beyond the inhabited base site) and laboratory analysis (research at the base facilities). Atmospheric and meteorological studies are limited to Mars due to the Moon's lack of an atmosphere.

Life science focuses on the study of human factors, physiology, biology, and psychology in a non-terrestrial environment. A permanent base on the Moon or Mars provides a prime location for monitoring human, animal, and plant responses to such factors as partial gravity and radiation. Life science research is located at the base laboratory facilities. Particular labs of interest include higher animal and plant labs, microbial animal and plant labs, and a biomedical lab.

In addition to the three main disciplines, a generic category is included to account for pure science activities, such as physics analysis. Research and demonstrations with an applied objective (e.g., propellant plant demonstrations) are not considered part of user accommodations.

### 5.12.2 User Accommodations and Base Support

The surface system infrastructure that comprises the planetary base is responsible for supporting the various user accommodations. Base support includes both resources, such as energy or crew, and facilities, such as pressurized laboratories or surface transportation. The actual amount of support is dependent upon the base's phase of development--emplacement, consolidation, or utilization. Thus, the level of scientific activity is determined by the availability of base resources and facilities.

Most user elements require some source of electrical power. The type of energy resource is dependent upon the function and location of the element. Laboratory experiments located in the base's pressurized facilities as well as telescopes placed in close proximity to the base rely on the main power source supplying the total base. Depending on the phase, this power source may be a photovoltaic/regenerative fuel cell system or a nuclear power system. For scientific activities operating at field locations, such as portable geophysical experiment packages, the utility transport vehicle (pressurized or unpressurized) provides energy from the supporting power cart. Energy is also available for remote scientific instruments, such as meteorological balloons and geophysical stations, in the form of rechargeable batteries.

A permanently inhabited base offers the science community a critical resource in the form of crew support. The user elements require crew participation for construction, set-up, operations, monitoring, and analysis. A two-person team is needed for extravehicular activity (EVA), such as deploying geophysical equipment, performing sample collection, and maintaining long-term equipment. An EVA/exploration team, ranging from three to four persons, is also responsible for participating in scientific expeditions away from the main base site. In conjunction with EVA, intravehicular activity (IVA) personnel are required to monitor the local and away EVA/exploration teams from inside the habitat facilities. The IVA crew is also responsible for laboratory operations pertaining to all user disciplines as well as monitoring surface equipment performance and rover teleoperations.

Certain scientific activities, particularly life science laboratories, require pressurized facilities for operation. Various environments are available depending upon the base phase. For example, the crew sortie vehicle is used initially for Mars surface analysis, but as permanently-

occupied habitats are emplaced, laboratory facilities become extensive. Pressurized utility vehicles also provide area for scientific analysis, specifically in support of planetary science expeditions. Example capabilities in the pressurized rover include a glove box, monitoring station, and multiple microscope set-ups.

In order to perform extensive scientific research, surface transportation beyond the immediate locale of the base site must be available. An unpressurized rover, with a range of 10 km, or a pressurized utility vehicle, with a range from 100 km to 1,000 km, will be provided. The unpressurized rover enhances the crew's EVA capability for science operations local to the base, such as maintaining astronomical observatories. The pressurized utility vehicle offers extended-duration opportunities, from four days to two weeks, for extensive surface exploration. Long-range, planetary science activities are also carried out by telerobotic/autonomous rovers. These rovers, host to a variety of scientific instrumentation, are responsible for scouting new terrain, retrieving distant samples, and performing geophysical measurements.

Some of the user elements require communications and data transfer capability. Depending on the data transfer requirements and the location of the data analysis, communications for science elements are either independent of or dependent on the base. For example, particular lunar astronomical observatories require large data rates for transfer; therefore, a dedicated link for intermittant transmission between the observatories and the Earth is provided with no main base interaction. Other science activities involve generating data from base laboratory analysis which implies dependence on base communication systems for data transfer and discussion with Earth-based analytical labs. Additional communications support for the user by the base is required for exploration teams. Surface-to-surface, continuous communications are necessary between the monitoring crew at the base and the EVA crew plus pressurized rover operator.

### 5.12.3 Lunar User Accommodations

#### 5.12.3.1 Base Phasing and Lunar Science Strategy

A logical progression follows between the phasing of the lunar base and the strategy of the science users. As the base develops its surface system capabilities for user support, the level of science grows and advances. The emplacement phase characterizes the initial steps to man's permanency on the lunar surface. During this phase the base provides solar power with an emphasis on daytime operations, a small crew, EVA and short-range surface transportation, and low-volume pressurized facilities. With minimal support systems and crew, the science objective is to perform local exploration within 10 km of the established base site. The focus during this early phase is to characterize lunar rocks and regolith with respect to composition, mineralogy and geomorphology. Additional lunar samples are returned to Earth for further analysis and age dating. Geophysical data is also acquired with the emplacement of a science station to study long and short period seismicity, heat flow, atmospheric volatiles, and flux. In order to enhance base development, the emplacement phase science strategy includes determining subsurface shallow and deep structure for future civil engineering as well as establishing the location, compositional variation, and distribution of resources on the Moon.

The enhancement of the lunar surface systems defines the consolidation phase. Larger pressurized facilities are established, surface transportation extends its range with pressurization, crews inhabit the base for longer durations, and power availability increases. With extended support the planetary fact-finding missions continue as manned exploration extends to 100 km traverses and teleoperated rover operations begin sample selection and collection. During this phase the user strategy establishes the astronomical capabilities on the near-side. A variety of telescopes are deployed, such as optical, gamma-ray, X-ray, ultraviolet, radio and infrared. Although utilizing different observational techniques, the objective of these telescopes is to determine the origin, evolution, and current state of planets, varied stars, gaseous nebulae, galaxies, black holes, supernovae, and interstellar dust clouds. Solar observation is also part of the consolidation phase with the intent of studying sunspots, the corona and chromospheric features and providing the base with solar flare activity information. In addition to the astronomy and planetary science surface infrastructure, the lunar base at this phase is capable of supporting analytical laboratories. Lab facilities include ample pressurized volume, continuous power supply, data transfer capability, and available trained crew.

The utilization phase substantiates man's permanent presence on the Moon with the exploitation of local resources and expansion of surface mobility. Enhanced surface resources include a larger crew with increased stay-times and a ballistic vehicle. Near-side planetary science activity continues with revisits to geologic areas of interest for additional studies and sampling. During this phase, scientific exploration takes on new meaning with the capability to send crews on ballistic reconnaisance to the lunar far-side and polar regions. The focus of the far-side expedition is to deploy the low frequency radio interferometer which measures galactic radio objects at very long wavelengths without Earth

interference. The polar candidate mission is intended to expand lunar geophysical knowledge and search for possible water deposits.

### 5.12.3.2 Lunar Science Equipment

The following list briefly describes potential user elements from all disciplines for a multi-phase lunar base.

Planetary Science:

a. Geologic field equipment--rocks, hammers, rakes, scoops, shallow drills, and sample containers.

b. Geochemical/petrology lab--binocular microscope, electron dispersive x-ray device, thin-section facility, petrographic microscope, electron microprobe, and remnant magnetism experiments.

c. Portable geophysical exploration package 1--shallow-profiling active seismic array, explosive packages, magnetometers, gravimeters, and solar wind experiments.

d. Portable geophysical exploration package 2--deep-profiling active seismic array, explosive packages, magnetometers, gravimeters, and solar wind experiments.

e. Traverse experiment package--traverse magnetometers and spectrometers: neutron-ray, gamma-ray, x-ray, visual and near-infrared.

f. Field geology equipment--film cameras, trenching tools, surveying equipment, sample collection tools, inclinometers, and gyro-compasses.

g. Penetrators and sieves

h. Geophysical stations--seismometer, heat-flow probe, mass spectrometer, tidal gravimeter, solar wind experiments, charged particle detector, ion detector, and lunar ejecta and micrometeorite experiments.

Other:

i. Physics instrumentation--Earth aurora/magnetosphere/plasma detector and imager, solar wind detector, and cosmic-ray experiment.

Astronomy:

j. Optical telescope--first, second and third meter scale operating in the ultraviolet, visible, and near-infrared.

k. Low frequency array--radio telescope operating at very low frequency (1 to 10 MHz).

l. Radio interferometer--15 m steerable telescope with a resolution of 30 microarcseconds.

m. Gamma-ray telescope--coded aperture telescope collecting gamma-rays (<1 Å) and x-rays (< several Å).

n. X-ray telescope--grazing incidence telescope to collect x-rays (several Å to 100 Å) and extreme UV (100 to several 100 Å).

o. Ultraviolet telescope--telescope observing the extreme UV (100 Å to 1000 Å).

p. Infrared telescope--telescope observing in the thermal IR region (3 to 1000 microns).

q. Solar observatory--H-alpha telescope, white-light coronagraph, x-ray spectroheliograph, UV spectrometer, x-ray telescope, visual wavelength spectrograph, and radiometer.

r. Earth observatory--H-alpha telescope, UV spectrometer, UV camera, visual wavelength spectrograph, and visual wavelength camera.

s. Monitoring telescope--30 cm class telescope observing individual stars in the visible range (4000 to 7000 Å).

Life Sciences:

t. Higher animal/plant lab--specimens (mice, rats, rhesus monkeys), modular habitats, hematology kit, histology kit, incubator, and dissecting microscope.

u. Microbial animal/plant lab--reuter centrifugal sampler, incubator, low power microscope, photomicrographic set-up, millipore filtration kit, and freezer.

v. Advanced closed ecological life support system (CELSS) lab--centrifuge, microscope, plant growth facility, plant specimens, nutrients, and ph-specific ion analyzer.

w. Biomedical lab--ergometer, passive dosimeter, hematology system, urine collection system, oscilloscope, and electrocardiograph/ultrasound.

This same element list is further detailed in table 5.12.3-I (Roberts, 1988). The table characterizes the science equipment in terms of launch mass and the following support requirements--power, pressurized volume, data rate, operational IVA, and operational EVA. The large power users include the geochemistry/petrology lab, the life sciences labs, and the optical and UV telescopes. The higher animal/plant lab dominates the pressurized volume requirement with the advanced CELSS also

TABLE 5.12.3-I.- LUNAR SCIENCE EQUIPMENT

| | Launch Mass (kg) | Power Required (kW) | Press. Volume ($m^3$) | Data Rate Required (kbps) | Operational IVA (hrs/week) | Operational EVA (hrs/op) |
|---|---|---|---|---|---|---|
| Geologic Field Equipment | 80 | 0 | 0 | 0 | 0 | 6 |
| Prelim. Petrology Analysis Lab | 1,200 | 10.7 | 6.5 | 0 | 16 | 0 |
| Port. Geo. Exp. Pkg.--shallow | 1,220 | 0.1 | 0 | 20 | 0 | 6 |
| Port. Geo. Exp. Pkg.--deep | 50 | 0.1 | 0 | 20 | 0 | 6 |
| Traverse Exploration Package | 110 | 0.3 | 0 | 24 | 0 | 6 |
| Field Geology Equipment | 90 | 0 | 0 | 0 | 0 | 6 |
| Penetrators & Sieves | 100 | 0.2 | 0 | 2 | 0 | 3 |
| Geophysical Stations | 111 | 0 | 0 | 1.5 | 0 | 6 |
| Physics Instrumentation | 100 | 0 | 0 | 0 | 0 | 3 |
| Optical Telescope (1 m) | 870 | 4.0 | 0 | 1,100 | 0 | 0 |
| Initial Low Frequency Array | 100 | 0 | 0 | 0 | 0 | 0 |
| Radio Interferometer | 2,100 | 0.7 | 0 | 144,000 | 0 | 0 |
| Gamma Ray Telescope | 3,820 | 0.3 | 0 | 250 | 0 | 0 |
| X-Ray Telescope | 2,850 | 1.0 | 0 | 8 | 0 | 0 |
| Ultraviolet Telescope | 730 | 4.0 | 0 | 1,100 | 0 | 0 |
| Infrared Telescope | 5,700 | 1.2 | 0 | 50 | 0 | 0 |
| Solar Observatory | 2,300 | 3.0 | 0 | 16 | 2 | 0 |
| Earth Observatory | 2,100 | 3.0 | 0 | 16 | 0 | 0 |
| Initial Monitoring Telescope | 100 | 0.4 | 0 | 30 | 0 | 6 |
| Monitoring Telescope | 10 | 0 | 0 | 3 | 0 | 6 |
| Higher Animal Lab | 8,600 | 4.0 | 45.9 | 256 | 12 | 0 |
| Microbial Animal Lab | 400 | 1.9 | 4.5 | 256 | 16 | 0 |
| Higher Plant Lab | 370 | 3.2 | 13.2 | 256 | 12 | 0 |
| Microbial Plant Lab | 400 | 2.4 | 2.4 | 256 | 16 | 0 |
| Advanced CELSS Lab | 5,800 | 4.5 | 22.3 | 256 | 12 | 0 |
| Biomedical Lab | 3,700 | 4.2 | 14.5 | 256 | 8 | 0 |

needing substantial space. The astronomical observatories levy the steepest data rate requirements, particularly the Moon-Earth radio interferometer with 144 Mbps. The operational IVA needs, expressed in hours per week, apply to the laboratories and solar flare monitoring. On the other hand the operational EVA requirements are listed as hours per one-time operation for an EVA team of two persons.

### 5.12.3.3 Base Resources for Lunar User Accommodations

A series of sketches illustrates exemplary science equipment and the reliance on various aspects of base support. Figure 5.12.3-1 shows a deployment sequence of the near-side Moon-Earth radio interferometer (as discussed in construction section 6.2). The larger view depicts the activated telescope with a hard-wire link to the base's main power distribution system and an EVA crewmember available for check-out procedures.

Figure 5.12.3-2 shows an EVA crew performing a core-sample drilling in order to acquire subsurface rock samples. To the right of the team is a geophysical station manually deployed, checked and activated by the crew. The various geophysical and environmental experiments are connected to an independent radioisotope thermoelectric generator (RTG) power source (replaceable after its nominal lifetime) and a central data processing and transmission station. Also providing support for the local exploration and scientific activities is an unpressurized rover in the background.

Figure 5.12.3-3 illustrates the scientific support capabilities inside the pressurized utility vehicle. The long-range exploration team is shown detonating a deep-profiling active seismic array. In the foreground of the picture, a crewmember visually monitors the explosion and tracks the subsurface seismic data during real-time operations. The pressurized vehicle offers multiple surface-viewing stations (actual and electronic) and geochemical analysis with a glovebox and flow bench.

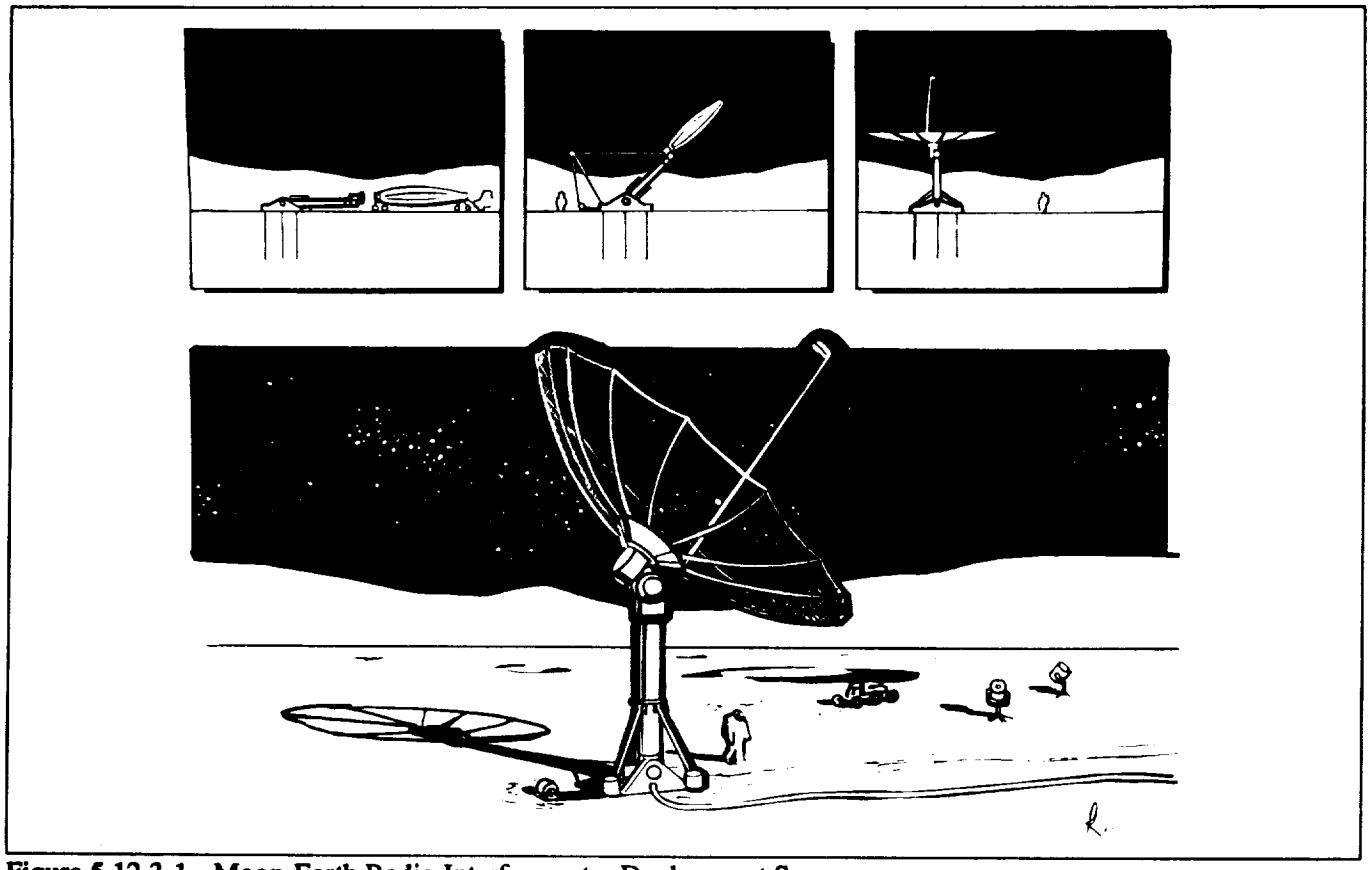


Figure 5.12.3-1.- Moon-Earth Radio Interferometer Deployment Sequence.

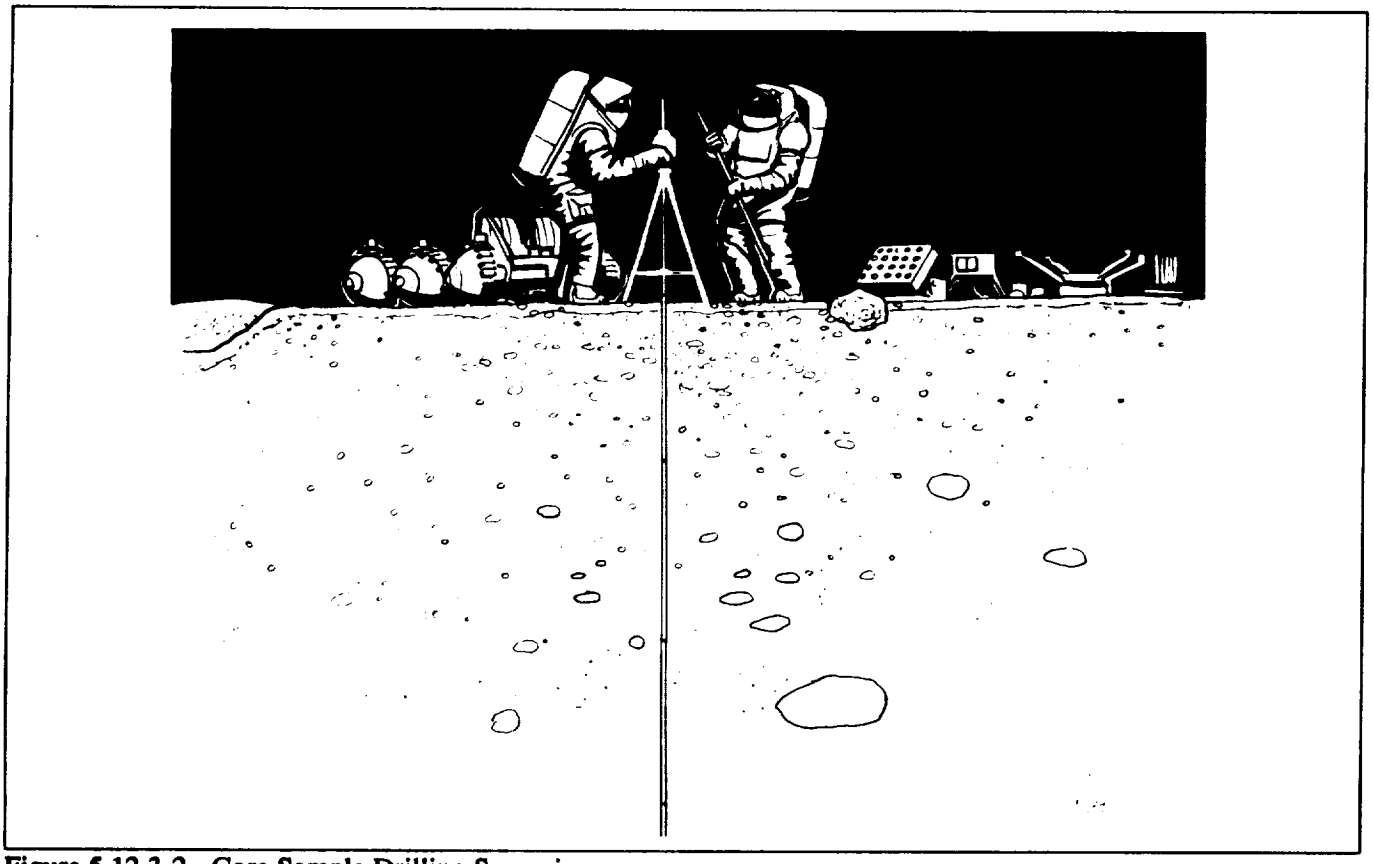


Figure 5.12.3-2.- Core Sample Drilling Scenario.

Figure 5.12.3-3.- Scientific Support Capabilities of Pressurized Utility Vehicle.

The last pictoral example of base support for user elements depicts a life sciences laboratory located in the base's main habitat facility. In the foreground of figure 5.12.3-4, a crewmember examines an advanced plant growth chamber to verify water and nutrient distribution lines. Adjacent to the CELSS lab is the biomedical research lab with one person undergoing cardiovascular monitoring on a treadmill and another performing analysis with an electron microscope.

## 5.12.4 Mars User Accommodations

### 5.12.4.1 Base Phasing and Mars Science Strategy

The martian base development follows a similar phasing pattern as the lunar scenario with the phases defined as emplacement, consolidation, and utilization. The emplacement phase for Mars is characterized by man's first landing on the martian surface and the selection/-establishment of a permanent base site. The support capabilities during this phase are minimal--a solar power generation system, a small crew, lander and a low-volume pressurized facility, and local unpressurized/pressurized mobility. The science objective for this initial phase is to gather key environmental information via manned and unmanned exploration. The manned operations include local traverses up to tens of kilometers for sample collection, geophysical station deployment, and deep/shallow seismic tests for subsurface structural analysis. During this phase a semi-autonomous rover is delivered to the martian surface to assist in site planning and selection as well as mapping terrain for future manned exploration. In addition to gathering background geophysical data, the emplacement phase initiates atmospheric studies with meteorological balloon launches and upper atmosphere sounding rockets.

The build-up of the martian surface systems defines the consolidation phase. Enhanced communications equipment are stationed, additional pressurized surface transportation is delivered, larger crews inhabit the base for a longer duration, and power availability increases. The science strategy continues to focus on planetary science, particularly geophysical and atmospheric analyses. During this phase the crew ventures on regional expeditions (100 km) as a result of the findings by the autonomous rover. Possible expedition sites include terrain north and south of the base and the Ganges canyon. Robotic rovers continue to scout new territory and perform preliminary sample collection and analysis. The Mars science objective also includes the expansion of atmospheric sciences and meteorology with

Figure 5.12.3-4.- Life Sciences Laboratory.

increased balloon and sounding rocket coverage.

The utilization phase establishes man's permanent presence on the martian surface with expanded surface facilities, initiation of martian surface resource use, and demonstration of global exploration capabilities. The additional surface system support includes larger habitation facilities, extended power generation capability, growth in crew size, and a ballistic vehicle. Longer-range pressurized rovers allow the crew to continue geologic, geophysical, and exobiological exploration. Global access capability is introduced with the Mars ballistic vehicle, with ballistic reconnaissance initiated to search for and characterize water resources in northern latitudes. With the emplacement of a larger permanent habitat and added crew support, the Mars science strategy expands to laboratory science for biomedical, geochemical, and microbial analyses.

### 5.12.4.2 Mars Science Equipment

The following list briefly describes potential user elements from all disciplines for a multi-phase martian base.

Planetary Sciences:

a. Traverse experiment package--traverse magnetometers and spectrometers: neutron-ray, gamma-ray, x-ray, visual and near-infrared.

b. Geophysical/atmospheric stations--seismometer, heat-flow probe, mass spectrometer, tidal gravimeter, magnetometer, anemometer, pressure and temperature sensors, dew point device, and particulate accumulometer.

c. Geologic exploration equipment--rocks, hammers, rakes, scoops, shallow drills, and sample containers, trenching tools, surveying equipment, inclinometers, and gyro-compasses.

d. Portable geophysical exploration package 1--shallow-profiling active seismic array, explosive packages, magnetometers, and gravimeters.

e. Portable geophysical exploration package 2--deep-profiling active seismic array, explosive packages, magnetometers, and gravimeters.

f. Meteorological balloons--temperature sensors, pressure sensors, dew point devices, nephelometers, and doppler tracking equipment.

g. Upper atmosphere balloons--temperature sensors, pressure sensors, mass spectrometers, nephelometers, and doppler tracking equipment.

h. Upper atmosphere sounding rockets--temperature sensors, neutral mass spectrometers, ion mass spectrometers, electric field detectors, electron temperature probes, and charged-particle retarding potential analyzers.

i. Semi-autonomous rover--stereo imager, multispectral sensor, high resolution imager, gravimeter, magnetometer, spectrometers (alpha, proton, x-ray, neutron), and sample collector, packager, and storer.

j. Geological engineering equipment--sieves, soil penetrometers, gamma-ray backscatter experiment, and density experiment.

k. Laser light-detecting radar.

l. Geochemical/petrology lab--binocular microscope, electron dispersive x-ray device, thin-section facility, petrographic microscope, electron microprobe, and remnant magnetism instruments.

Life Sciences:
m. Biomedical lab--ergometer, passive dosimeter, hematology system, urine collection system, oscilloscope, and echocardiograph/ultrasound.

n. Microbial animal and plant lab--reuter centrifugal sampler, incubator, low power microscope, photomicrographic set-up, millipore filtration kit, and freezer.

o. Contamination/isolation lab--freezer, incubator, refrigerator, culture chamber, and microscope.

Other:
p. Field and particles instruments--magnetosphere/plasma detector and imager, solar wind detector, and cosmic-ray experiment.

This same element list is further detailed in table 5.12.4-I (Roberts, 1988). The table characterizes the science equipment in terms of launch mass and the following support requirements--power, pressurized volume, operational IVA, and operational EVA. The large power users include the geochemistry analytical lab, the microbial lab, and the biomedical instruments. The microbial animal/plant lab dominates the pressurized volume requirement with the geochemical and biomedical labs also needing substantial space. The operational IVA needs, expressed in hours per week, apply to the laboratories and monitoring of the semi-autonomous rover. On the other hand the operational EVA requirements are listed as hours per one-time operation for an EVA team of two persons.

### 5.12.4.3 Base Resources for Mars User Accommodations

A series of sketches illustrates exemplary science equipment and the reliance on various aspects of base support. Figure 5.12.4-1 shows a manual deployment of a meteorological balloon by an EVA crew of two persons. Surface system support, besides manpower, includes a trailer for carting large science payloads to their deployment location plus a pressurized utility vehicle for extended mobility. In the background of the picture, an upper atmosphere sounding rocket is being launched from a control station inside the pressurized utility vehicle. The figure emphasizes the unique science opportunity on Mars for advanced atmospheric studies. The balloons and sounding rockets are used to determine the composition, concentration, and diurnal and yearly variations of the martian atmosphere. Meteorological data to collect include temperature, wind speed and direction, pressure, humidity, cloud cover, and ice and dust accumulations.

Figure 5.12.4-2 depicts a manned geologic expedition possibly in the Ganges canyon. The pressurized rover is supporting the deployment of an active seismic array to be operated and observed from the interior of the rover. In addition to providing a power source, a data link, and camera monitoring, the vehicle enables the EVA crewmember to access a variety of tools from unpressurized service compartments for sample collection purposes.

Geologic exploration is further enhanced on the Mars surface with the use of a robotic rover (figure 5.12.4-3). While the crew is not stationed on Mars, the rover maintains semi-autonomous capability to scout new terrain for possible future manned expeditions and collect samples for a broader array of geologic analysis. The robotic rover is equipped with stereo and high resolution imagers for visual faculties, manipulator systems with end-affectors for sample retrieval, cannister storage tray for multiple samples, and a variety of spectrometers for initial geophysical data. Once completing its semi-autonomous mission, the rover returns to the established base site and delivers samples and data to the current crew. While a crew is stationed at Mars, the rover is operated telerobotically from the base facilities for additional surface scouting. (See section 5.4 for more information regarding the robotic rover.)

TABLE 5.12.4-I.- MARTIAN SCIENCE EQUIPMENT

| User Elements | Launch Mass (kg) | Power Required (kW) | Press. Volume ($m^3$) | Operational IVA (hrs/week) | Operational EVA (hrs/op) |
|---|---|---|---|---|---|
| Traverse Exploration Package | 110 | 0.3 | 0 | 0 | 6 |
| Geological/Atmospheric Station | 150 | 0 | 0 | 0 | 6 |
| Geological Exploration Equipment | 100 | 0 | 0 | 0 | 6 |
| Portable Geo. Exp. Pkg.--shallow | 1,220 | 0.4 | 0 | 0 | 6 |
| Portable Geo. Exp. Pkg.--deep | 50 | 0.4 | 0 | 0 | 6 |
| Meteorological Balloons | 25 | 0 | 0 | 0 | 3 |
| Upper Atmosphere Baloons | 200 | 0 | 0 | 0 | 3 |
| Upper Atmosphere Sounding Rocket | 100 | 0 | 0 | 0 | 6 |
| Semi-Autonomous Rover | 2,900 | 0.5 | 0 | 16 | 0 |
| Sieves & Soil Penetrometer | 200 | 0 | 0 | 0 | 3 |
| Laser Light-Detecting Radar | 100 | 0 | 0 | 0 | 3 |
| Fields and Particles | 100 | 0 | 0 | 0 | 3 |
| Biomedical Instruments | 1,000 | 4.2 | 7 | 8 | 0 |
| Geochemical Analytical Lab | 1,200 | 10.7 | 6.5 | 16 | 0 |
| Microbial Plant & Animal Lab | 8,000 | 11.4 | 20 | 12 | 0 |
| Contamination/Isolation Lab | 400 | 3.6 | 1.7 | 4 | 0 |

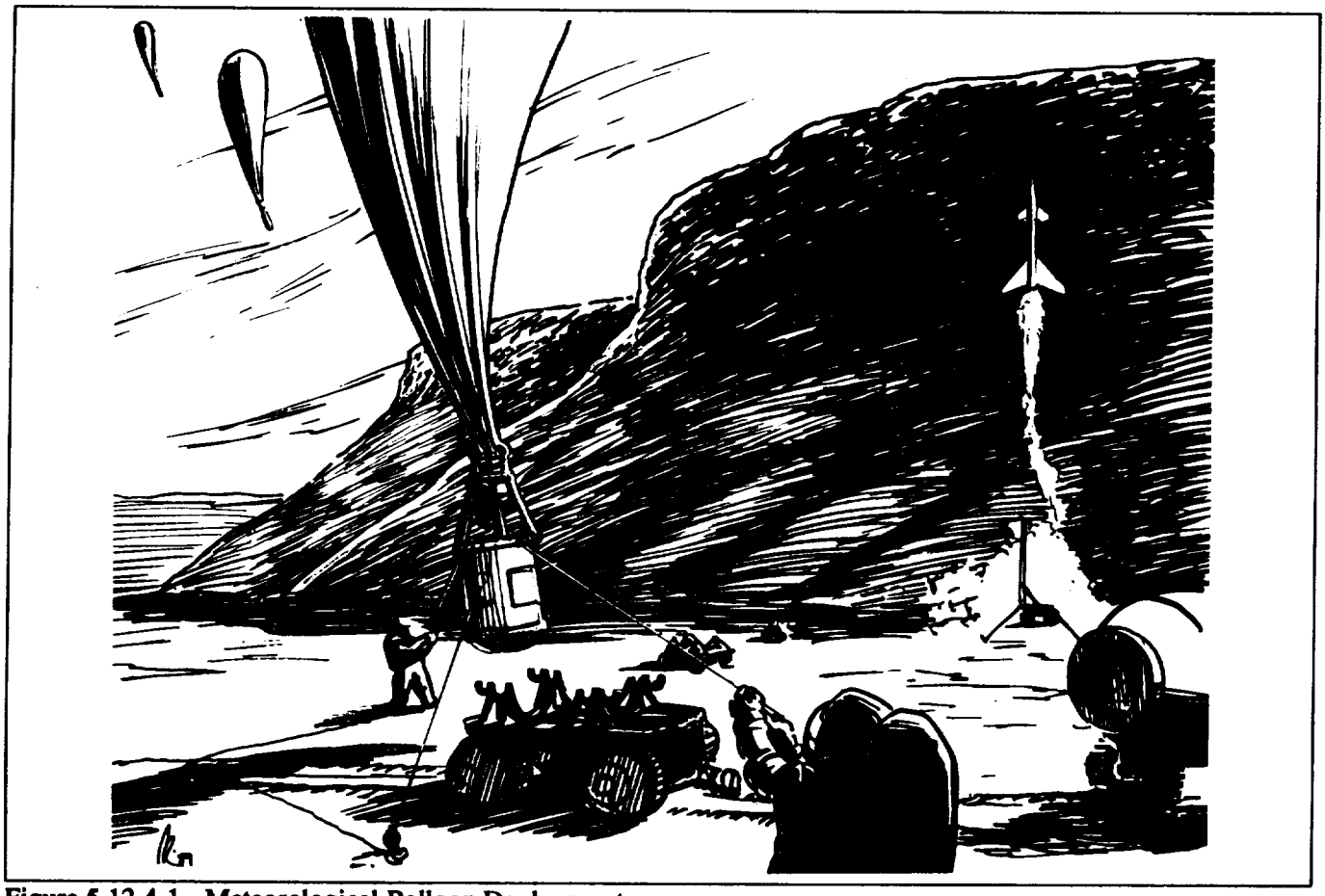


Figure 5.12.4-1.- Meteorological Balloon Deployment.

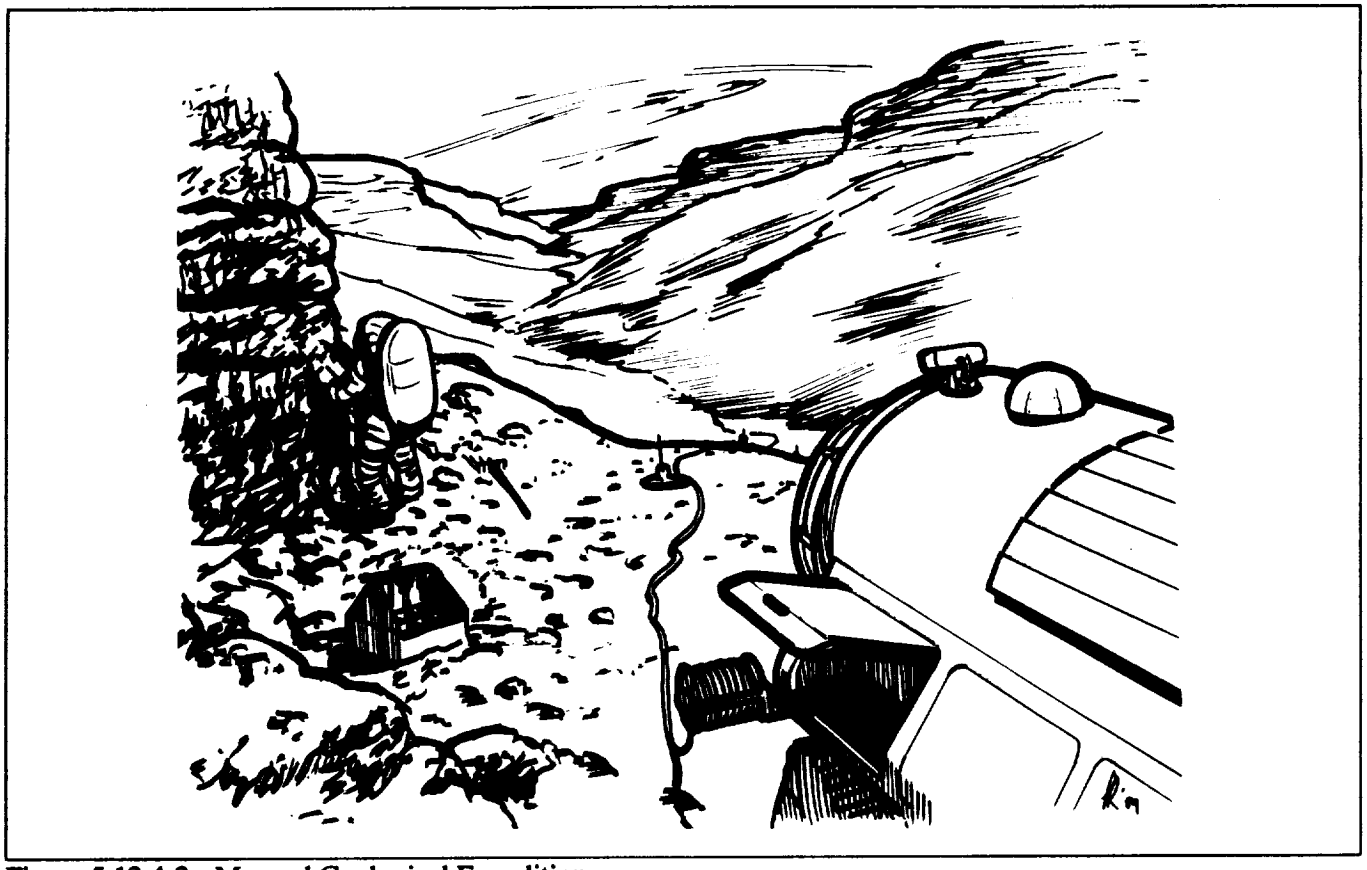


Figure 5.12.4-2.- Manned Geological Expedition.

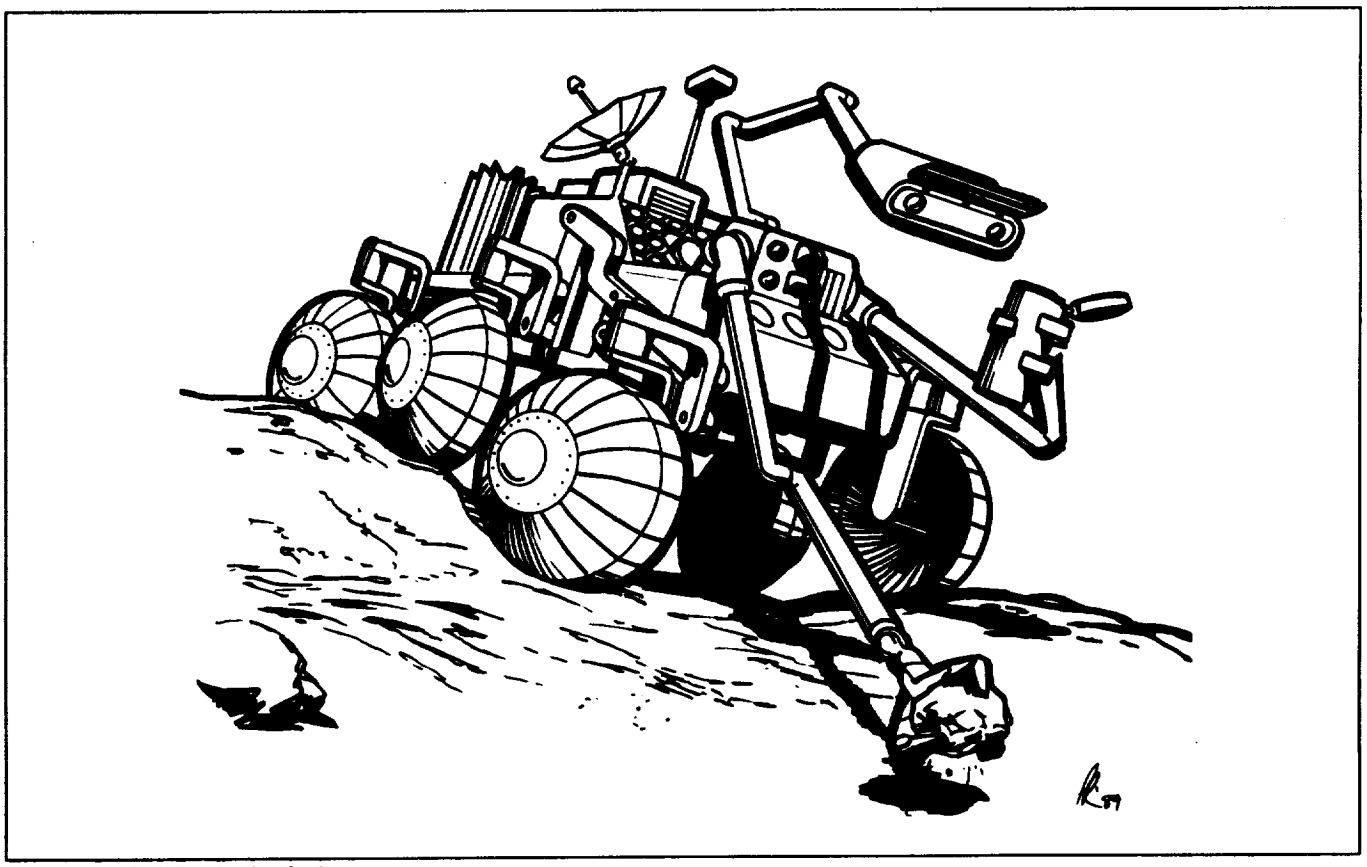


Figure 5.12.4-3.- Robotic Rover.

### 5.12.5 Technology and Programmatic Issues

In order for user accommodations to be successful for both lunar and Mars mission scenarios, a synergistic strategy between the science community and the base developers needs to exist. Programmatic issues arise with respect to such a strategy, including:

- the need for surface resources to be available before science equipment is manifested,
- the need for facilities to be designed according to science operational requirements, e.g. pressurized utility vehicle,
- the need for an optimal mix between science activities operated at the base, on Earth, or robotically,
- the need to understand the specialization requirements of certain sciences in order to determine crew skill levels, and
- the need for designing science technology according to feasible base resources, e.g. equipment power required versus power generation allotted for science.

# Section 6

# Surface Operations

Surface operations is a "people oriented" activity. It involves human interaction both directly, using extravehicular activity (EVA), and indirectly, using telerobotics. The type of operations for surface systems on the Moon and Mars are functions of the scheduled deliverables to each location. For example, the first major effort for outposts on both the Moon and Mars is the emplacement of equipment consisting of a habitat and power and science equipment. This involves considerable assembly and construction effort (EVA and telerobotic operations).

A solution to many difficult operations is employment of automation and robotics. Although an emphasis has been placed on the use of sophisticated, automated systems to accomplish much of the work, a host of tasks that only humans are capable of performing still remains.

There are four missions that figure heavily into the successful operation of the lunar base. These missions are scientific operations, launch and landing, mining, and propellant production. These same four, plus mining of Phobos, are the major operations drivers for Mars.

Section 6.1 describes the operations concepts and strategies pursued by the surface systems integration agent. Section 6.2 is a description and analysis of construction operations. Section 6.3 discusses the logistics support requirements for surface systems. It includes an evaluation of cargo handling requirements, storage requirements, and inventory methodology and controls necessary for an integrated logistics system (ILS).

## 6.1 OPERATIONS CONCEPTS AND STRATEGIES

There are a number of operations and maintenance activities to be performed. Each crew member must be capable of accomplishing a multitude of tasks and must possess a myriad of skills. The major difference between lunar and martian operations is that self sufficiency is more important for Mars. This section discusses the anticipated operations and recommends strategies.

There are management tasks dealing with personnel, reporting status, and involvement with various phases of operations. Also, there are support tasks; e.g., logistics, communications, medical, dental, transportation, facilities upkeep, administration, waste disposal, garbage disposal, civil engineering and construction, and personal hygiene equipment maintenance.

The person in charge of a lunar or martian outpost is designated as the commander. The commander is responsible for all activities. The deputy commander, is charged with the responsibility of assuming these duties should the need arise. An organizational chart, figure 6.1-1, depicts various functional areas of responsibility that apply to lunar and martian cases.

The commander is responsible for ensuring that all tasks are accomplished in a timely manner. He also develops work schedules and training sessions. These include a combination of simulation and hands-on training. He initiates and/or reviews all recurring and exception reports that are transmitted to Earth.

All systems affecting life support for the crew are at least dual redundant. Safe haven areas are also built into the initial design of the base facilities. The commander ensures that all crew members are aware of emergency procedures. Training exercises are carried out each week. These exercises are designed to maintain crew proficiency.

A solar flare radiation event alert is an example of a real-time emergency condition. Finding immediate shelter from this hazard is essential to the well being of each individual assigned to either the lunar or martian base.

Similar operations training is performed by each crew member. Some of the training will be modified as experience is gained at the lunar and martian facilities. All modifications to training exercises and procedures will be evaluated by NASA staff members on Earth before implementation.

Most reports will be simplified to reduce handling time. Routine reporting of personnel and equipment health status are automated and transmitted to Earth without filtering at the base. Exception reporting in these two areas is filtered and the commander is informed of any potential problems.

A great deal of time during a work period is spent by each crew member at a command and control workstation monitoring and performing assigned duties.

One of the crew members is a medically trained and qualified doctor. Each person on Mars is a certified

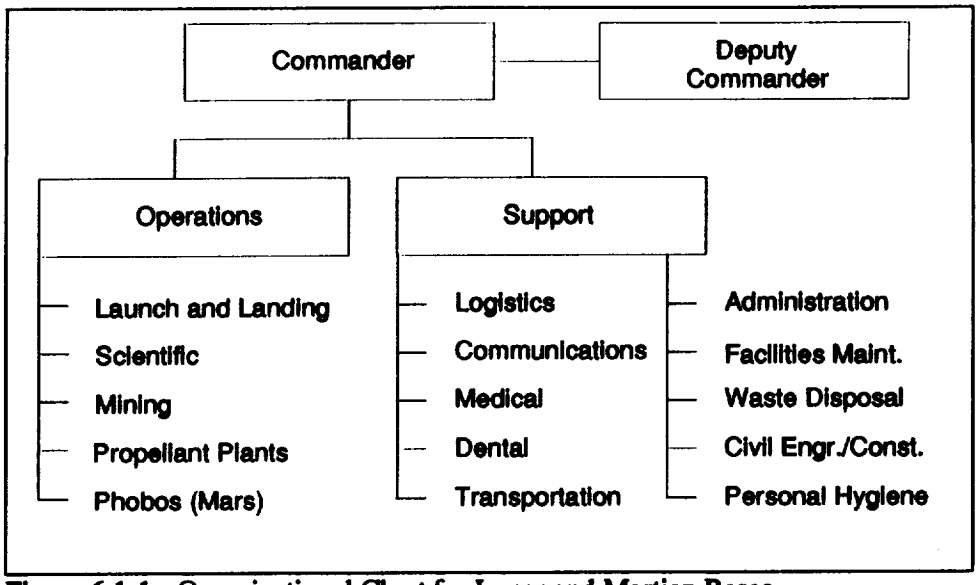


Figure 6.1-1.- Organizational Chart for Lunar and Martian Bases.

paramedic. Only half of the crew members at the lunar base are certified because there is not the same need on the Moon for these skills as there is on Mars.

Engineering crew members are multidisciplined in more than one engineering field and are skilled technicians as well. The same holds true for those who head scientific endeavors in physics, chemistry, biology, geology, metallurgy, and other disciplines.

The propellant plants, mining, and scientific operations for the Moon, Mars, and Phobos are remotely controlled and managed in an automated or teleoperated mode. EVA maintenance work may be required, however. Information is sent via telemetry links to the command and control center for monitoring and action as needed.

When and where feasible, the majority of the data is sent directly to the Earth, but is available to the local crews for analysis on an as-required basis. The stated objective has been to minimize extravehicular activity (EVA). Table 6.1-I is an illustration, not an analysis, of typical lunar and martian activities.

Initially, the base camps will be powered by a photovoltaic array (PVA)/regenerative fuel cell (RFC) system. The health and welfare of this system is monitored by a remote sensing system. Problems are reported to the crew. Routine reports are directed to Earth.

Due to the limited number of personnel and the minimal electrical power available initially, two shifts of operation are desirable. A two-shift operation improves situations where resources, such as living space, are at a premium. The off-duty shift has the habitation area to themselves, while the on-duty shift has more laboratory and command center resources available. This approach reduces conflicts in scheduling, while supporting scientific equipment for a one-shift operation.

One Space Station Freedom-derivative habitat module along with adequate work area modules are sufficient for a six to eight person crew in zero gravity, where living volume is the chief concern. In a gravity field, living area is of more importance. The constraints imposed by limited pressurized space and area affect shift operations.

Operations on an extraterrestrial surface are similar to those on Earth except for the hostile environment and difference in gravity. However, to deal with these conditions, and use the crew effectively, a 10 to 12 hour work cycle is proposed. Figure 6.1-2 depicts a typical two-shift workday cycle.

A 6 to 8 hour work cycle during the lunar night can be used to reduce the load on the power system and to make maximum use of the time available to conduct mission tasks during daylight hours.

In accordance with the manifest schedule, nuclear power will be brought on line when the various plants go into production; e.g., oxygen, ceramics, volatiles extraction, etc. This will eliminate the nighttime power problem.

Real time status of the operation of the nuclear power plants will be accomplished via data links. The nuclear facilities will be remotely located from the habitation and command center sites.

Major crew tasks are certifying various processes on a small scale and proving or identifying "fixes" for large scale plants: e.g., liquid oxygen production, food

TABLE 6-1-I.- EXAMPLE IVA/EVA WORKLOAD ACTIVITIES SUMMARY

| Activity[1] | Tele-op hours | IVA hours | EVA hours[2] |
|---|---|---|---|
| Site grading | | | |
| - survey/layout | 5.7 | | |
| - clear boulders | 23.0 | | |
| - backfill/level | 12.4 | | 4.4 |
| Subtotal | 41.1 | | 4.4 |
| Utility installation | 8.8 | 8.8 | 10.0 |
| **Total of above** | **49.9** | **8.8** | **14.4** |
| Vehicle preparation landing pad | 2.4 | | |
| Pad preparation | 34.1 | | 3.4 |
| Install navigation beacons | 4.8 | | |
| Road preparation | 118.4 | | 15.0 |
| Build pad blast walls | 52.4 | | |
| Remove spent lander stage | 4.1 | 3.6 | 7.6 |
| Cargo handling | 4.0 | 2.2 | 13.0 |
| Bury modules | 69.2 | 40.8 | 157.2 |
| Radiation protection | 121.3 | 26.3 | 85.4 |
| Install power system | 20.3 | 10.9 | 39.0 |
| Install radiator system | 14.8 | 7.2 | 32.0 |
| Install communication system | 21.6 | 13.9 | 36.0 |
| Install liquid oxygen plant | 28.7 | 18.9 | 38.0 |
| Operate liquid oxygen 720 hr/mo. | 744.2 | 24.2 | 10.0 |
| Install propellant loading facilities | 22.1 | 7.5 | 37.4 |
| Liquid oxygen loading | | | 7.4 |
| Emplace geological science equipment | 55.8 | 54.8 | 9.4 |
| Crater dating | 64.1 | 125.1 | 608.0 |
| Deep drilling | 211.5 | 810.5 | 18.0 |

Notes:
[1]The scope of work for each activity is detailed elsewhere in this document; e.g., size of craters, number of craters, depth of drilled holes, distances, width of roads, size of pad, etc. This table is not an analysis, but rather an illustration of the typical workload one may expect at the lunar or martian outposts.

[2]All EVA hours are based on a two-person operation. To obtain EVA hours per person, divide by two.

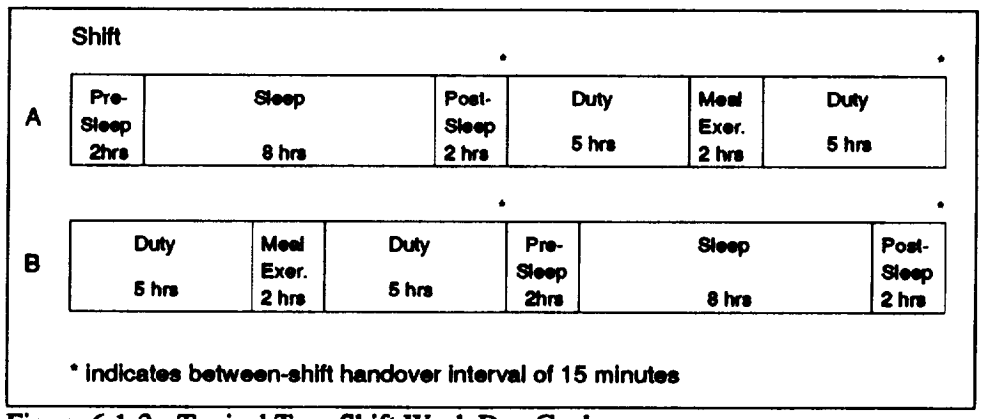


Figure 6.1-2.- Typical Two-Shift Work Day Cycle.

production, and volatiles extraction.

Mundane chores such as physical inspections of equipment and facilities will be carried out by the crew. Initial checklists will be provided. As the lunar and martian base activities evolve, additions to the checklists will be made. Janitorial and garbage disposal duties are shared by all crew members.

The mental health of the crew is monitored on a weekly basis. A panel of three psychiatrists interviews each crew member on a scheduled basis. Interviews are conducted over a video channel from the private quarters of the crew member to the panel on Earth. The lunar crew will be subjected to both physical and mental stress not only from the job, but also from the isolation and habitat/planetary environment. Crew stress on Mars is expected to be greater than on the Moon.

Although the Earth is not that far away, there is a sense of isolation felt on the Moon that cannot be duplicated on Earth. For this reason alone, it is essential to maintain an ongoing program of documenting and evaluating both the mental and physical state of each member of the lunar crew. This data will aid in the selection process for crews for martian and future planetary missions.

The lunar launch and landing operation is critical. The launch and landing site is located 5 kilometers from habitation and operations facilities to provide a level of safety for the surface crews.

Lander ingress and egress is controlled and monitored by the surface crew at the command center. Two crew members are dispatched to the launch and landing site to aid in the on and/or off loading operation. Loading and transport of propellants are also accomplished. A lander thermal control unit and auxiliary power cart are used in launch and landing operations.

Safety requirements for crew escape will heavily influence the design of the launch and landing facility. Equipment to support hydrogen boil-off recapture is also a major design consideration. As a result of early planning and design, launch and landing pad operations can be simplified for lander and surface crews.

A remote, telerobotic control station for the prime equipment movers is used. This station is designed to be comfortable and to give the operator the "feel" of operating a particular machine. The station is located in the command and control center. The equipment is designed to facilitate lunar teleoperations from mission control in Houston or from any other Earth-based control station so equipped. The majority of martian teleoperations is expected to be accomplished from the martian control center. Table 6.1-II lists general controls required for prime machines.

TABLE 6.1-II.- GENERAL CONTROLS FOR PRIME MACHINES

| |
|---|
| Start/park |
| Initiate diagnostic |
| Remain stationary |
| Accelerate forward to variable set speed |
| Decelerate to stop |
| Accelerate reverse to variable set speed |
| Turn right |
| Turn left |
| Raise implement |
| Lower implement |
| Turn power take off (PTO) clockwise |
| Turn PTO counter-clockwise |
| Turn PTO off |
| Open bucket |
| Release bucket |
| Turn vision system on/off |
| Turn lights on/off |
| Pan vision lights right/left |
| Tilt vision lights up/down |
| Zoom vision in/out |

The control station has a caution and warning system that informs the operator of a contingency or emergency condition. General monitoring measurement (caution and warning) requirements include: diagnostic warnings, loads on the implements, temperatures, radiation, time until service due, and equipment time totalizers.

Figure 6.1-3 is a graphic illustration of an operator and various teleoperated activities for the post year 2000 time period.

An assessment has been made of the daily "static" activities that a crew member is involved in. The results of that assessment are documented in table 6.1-III. Activities dealing with launch and landing, science, mining, etc. are covered in detail in appropriate sections of this report.

The crews at the lunar and martian bases are dedicated and know that the future of a sustained human presence on the Moon and Mars depends on how successfully they carry out their mission tasks. Self-sufficiency is a primary goal. Water production, oxygen production, food production, and an environmentally safe habitat are fundamental to obtaining self-sufficiency and the ability to sustain life on the Moon and Mars without resupply from Earth.

TABLE 6.1-III.- MANNING ASSESSMENT FOR LUNAR AND MARTIAN ACTIVITIES

| Activity | Hr/Day |
|---|---|
| Non-Productive Time | |
| Exercise | 1.0 |
| Meals--includes preparation, eating, cleaning, and disposal | 3.0 |
| Sleep | 8.0 |
| Personal Care | 1.7 |
| Recreation | 1.5 |
| Medical Evaluation | 0.2 |
| Non-mission training | 0.3 |
| Sick leave/lost time | 0.3 |
| **Total Non-Productive Time** | **16.0** |
| Mission O&M Tasks | |
| Science--normal local and remote operations, special excursions, food production | - - |
| Mining--local operations, remote operations, safety, transporting ores, processing ores, storage, environmental controls | - - |
| Propellant production--lunar oxygen production, martian carbon dioxide electrolysis, safety, monitoring and control, environmental controls | 8.0 (Moon)<br>2.0 (Mars) |
| Training | 0.7 |
| **Total Mission O&M** | **8.7 (Moon)**<br>**2.7 (Mars)** |
| Non-Mission O&M Tasks | |
| Transportation--vehicles and subsystems, computers, automated devices, roads and grounds | 0.40 |
| Logistics--cargo handling, storage of materials, inventory control | 0.35 |
| Utilities--waste disposal, communications, power systems | 0.65 |
| Facilities Maintenance--janitorial, filter changes, repairs, appliances, thermal systems | 0.90 |
| **Total Non-Mission O&M** | **2.3** |

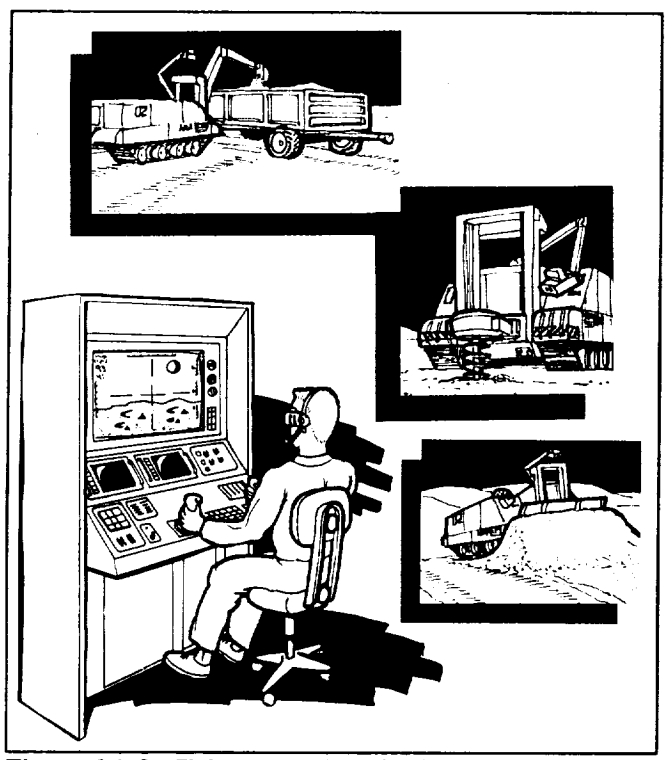


Figure 6.1-3.- Teleoperated Activities.

## 6.2 CONSTRUCTION OPERATIONS

The construction of extraterrestrial surface bases will depend on careful coordination of activities so that the crew and equipment are used effectively. Schedules of construction operations for the lunar and Mars evolutionary bases are presented here to provide an initial reference from which refined timelines can be developed. The approach used to schedule the construction activities involved analysis and evaluation of resources, tasks, and precedence relationships. The resources available for construction tasks were determined by the delivery schedule of cargo and crew and by a set of construction equipment, functional within a limited mass and power envelope. Tasks and their precedence relationships were driven by the physical characteristics of surface elements and by considerations of program objectives, operational priorities, and crew safety.

### 6.2.1 Applications to Lunar and Mars Case Studies

The lunar and Mars base evolution scenarios are characterized by a set of surface elements that are assembled in

TABLE 6.2.1-I.- START AND END DATES FOR CONSTRUCTION PROJECTS

| | ------- Moon ------- | | ------- Mars ------- | |
|---|---|---|---|---|
| **Project Name** | **Earliest Start Date (ESD)** | **Latest End Date (LED)** | **Earliest Start Date (ESD)** | **Latest End Date (LED)** |
| Initial Habitat Module | Feb. 2004 | Mar. 2004 | Feb. 2008 | Mar. 2008 |
| Constructible Habitat | Jan. 2006 | Jan. 2009 | Dec. 2015 | July 2016 |
| Nuclear Power Plant | Jan. 2009 | Aug. 2010 | N/A | N/A |
| Pilot Oxygen Plant | June 2010 | Nov. 2010 | N/A | N/A |
| Science Lab Installation | July 2011 | Sep. 2011 | June 2014 | Aug. 2014 |
| Oxygen Production Facility | Feb. 2012 | Sep. 2012 | June 2012 | July 2012 |
| Remote Science Installation | Apr. 2013 | July 2013 | N/A | N/A |

Initial Habitat Module
- Lunar ESD based on the start date of the first manned visit and the assumption that the project cannot begin until crew is present.
- Lunar LED based on the nominal visit duration of 30 days and the requirement that the habitat be operational prior to the second manned visit.
- Mars ESD based on the start date of the first manned visit and the assumption that the project cannot begin until crew is present.
- Mars LED based on the nominal surface stay time of 20-30 days and the requirement that the habitat be operational prior to the second manned visit.

Constructible Habitat
- Lunar ESD based on the scheduled delivery date of the habitat (July 2006) with a lead time of 6 months for site preparation.
- Lunar LED based on the growth of base population to 8 persons.
- Mars ESD based on the scheduled delivery date of the habitat (Jan. 2014) with a lead time of 1 month for site preparation (no radiation protection measures are included).
- Mars LED based on the objective of permanent habitation by July 2016.

Nuclear Power Plant
- Lunar ESD based on the scheduled delivery date of the 825 kW nuclear power plant (July 2009) with a lead time of 4 months for site preparation.
- Lunar LED based on the date when the oxygen pilot plant requires power for testing.
- Mars manifest does not indicate a nuclear power plant.

Pilot Oxygen Plant
- Lunar ESD based on the scheduled delivery date of the pilot plant (July 2010) with a lead time of 1 month for site preparation.
- Lunar LED based on the assumption that the plant should be in operation for at least 12 months prior to the date needed to demonstrate the capability for refueling a lander by Dec. 2011 (note that the propellant refill vehicle arrives July 2011 and the first use of lunar oxygen for a lander is scheduled for Jan. 2013).
- Mars manifest does not indicate a pilot oxygen plant.

Science Lab Installation
- Lunar ESD based on the scheduled delivery date of the science lab hardware (July 2011).
- Lunar LED based on the assumption that the lab should be operational as soon as possible after hardware delivery.
- Mars ESD based on the scheduled delivery date of the science lab hardware (June 2014).
- Mars LED based on the assumption that the lab should be operational as soon as possible after hardware delivery.

Oxygen Production Facility
- Lunar ESD based on the scheduled delivery date of the first plant after the pilot plant (Jan. 2012).
- Lunar LED based on the scheduled delivery of the last oxygen plant indicated in the manifest (July 2012) plus a period of two months to complete installation and testing for the last plant.
- Mars ESD based on the delivery of crew to the site of the Phobos propellant plant (Jun. 2012).
- Mars LED based on the assumption that the surface stay time on Phobos be between 10 and 20 days.

Remote Science Installation
- Lunar ESD based on the scheduled delivery date of the low frequency array (Jan. 2013).
- Lunar LED based on a period of three months to install the array on the farside.
- Mars manifest does not indicate a remote science installation.

sequence according to the base objectives established by the Study Requirements Document (SRD) and related manifests. To facilitate the scheduling process, major construction projects were identified with earliest possible start dates and latest possible end dates. These projects are indicated in table 6.2.1-I. Each of these construction projects may be defined in greater detail as a sequence of tasks. A set of general tasks and their associated work units is provided in table 6.2.1-II.

The set of resources assumed to be available to perform the construction tasks and their dates of initial availability is shown in table 6.2.1-III. These resources, used in various combinations, can be used to accomplish a broad set of generalized construction tasks.

Table 6.2.1-IV provides a more detailed account of resource availability as the base progresses. Note that manpower, differentiated as intravehicular or extravehicular, is included as a construction resource. The number of crew that is available for any given phase of construction will be based on the level of manpower required for other base activities as well as the priority of the construction tasks to be performed. In the first 30 day mission of the lunar base program, for example, the primary focus of the effort is the assembly and initialization of life sustaining equipment and structures.

TABLE 6.2.1-II.- PRODUCTIVITY AND RESOURCE ASSIGNMENTS FOR BASIC CONSTRUCTION TASKS

| Generic Task | Unit of Work | Productivity[1] | Resources[2] |
|---|---|---|---|
| Direct | | | |
| Survey | points | 12 points/hr | A M O |
| Excavate | volume | 3 $m^3$/hr | B D G L O |
| Remove boulders | pieces | 4 pcs/hr | B C D E H |
| Break up large boulders | pieces | 0.25 pcs/hr | A D I M O |
| Transport bulk cargo | vol., dist. | 2 $m^3$ @ 4 km/hr | B C E L O |
| Trench | volume | 3 $m^3$/hr | B D G L O |
| Grade | volume | 3 $m^3$/hr | B D K L O |
| Backfill | volume | 6 $m^3$/hr | B D G L O |
| Offload | pallets | 0.2 pallets/hr | A B D F L O |
| Transport pallets | distance | 1 km/hr | B C E L O |
| Emplace large pieces | pieces | 0.2 pcs/hr | A B D F L O |
| Emplace medium pieces | pieces | 2 pcs/hr | A D H L O |
| Emplace small pieces | pieces | 4 pcs/hr | A M |
| Emplace utilities | length | 500 m/hr | B D H L O |
| Inspect | points | 4 pts/hr | A M |
| Set anchors | points | 1 pts/hr | B D I L O |
| Elevate bulk cargo | volume | 3 $m^3$/hr | B D G N L O or B D J L O |
| Connect/disconnect | points | 4 pts/hr | A M |
| Activate/test | systems | 4 systems/hr | A M or B M |
| Repair/startup | systems | 0.5 systems/hr | A M |
| Indirect | | | |
| Transport crew | distance | 10 km/hr | B D E O or B P O |
| Restation wheeled machines | distance | 4 km/hr | B D E L O, B C E L O |
| Restation walking machines | distance | 1 km/hr | B D L O |
| Configure machines | functions | 1 function/hr | A M |
| Set up task | systems | 2 systems/hr | A M |

Notes:
[1]For tasks requiring an EVA team, the productivity is based on the amount of work that can be accomplished by a two-person EVA crew on average.

[2]See table 6.2-III for explanation of resource codes.

TABLE 6.2.1-III.- CONSTRUCTION RESOURCES AND THEIR INITIAL AVAILABILITY

| Resource Name | Code | Moon | Mars |
|---|---|---|---|
| EVA Crew | A | Feb. 2004 | Apr. 2005 |
| IVA Crew | B | Feb. 2004 | Apr. 2005 |
| Cargo Bin | C | Sep. 2003 | Jan. 2006 |
| Mobile Work Platforms | D | Sep. 2003 | Jan. 2006 |
| Casters | E | Sep. 2003 | Jan. 2006 |
| Crane Assembly | F | Sep. 2003 | Jan. 2006 |
| Reverse Clam Shell Digger | G | Sep. 2003 | Jan. 2006 |
| Robotic Arm | H | Sep. 2003 | Jan. 2006 |
| Drill Implement | I | Feb. 2004 | Jan. 2006 |
| Regolith Bagging Implement | J | Feb. 2004 | Jan. 2006 |
| Grader Blade | K | Sep. 2003 | Jan. 2006 |
| Supervisory Module | L | Sep. 2003 | Jan. 2006 |
| Servicing Module* | M | Sep. 2003 | Jan. 2006 |
| Belt Conveyor | N | Sep. 2003 | Jan. 2006 |
| Energy Storage Unit | O | Sep. 2003 | Jan. 2006 |
| Unpressurized Rover | P | July 2004 | Feb. 2008 |
| Mining Equipment | Q | July 2010 | N/A |

*Includes hand tools.

TABLE 6.2.1-IV.- CONSTRUCTION RESOURCE AVAILABILITY

| Resource / Year | 03 | 04 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flight # | 1 | 2 | 3 | 4,5 | 6,7 | 8,9 | 10 | 12 | 14 | 16 | 18 | 20 | 21 | 22 |
| EVA Crew | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| IVA Crew | 0 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Cargo Bin | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Mobile Work Platforms | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Casters | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Crane Assembly | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Reverse Clam Shell Digger | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Robotic Arm | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Drill Implement | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Regolith Bagging Implement | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Grader Blade | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Supervisory Module | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Servicing Module* | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Belt Conveyor | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Energy Storage Unit | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Unpressurized Rover | 0 | 0 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Mining Equipment | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |

*Includes hand tools.

The construction equipment is assumed to be remotely controlled with occasional local human presence required for initial set-up and inspection. This implies that continuous operations like trenching or leveling can be predominantly managed from the lander or habitat. However, more precise and difficult maneuvers will require local control at close proximity via EVA. Such operations include unloading, assembly, and loading tasks and assembly tasks.

Another important aspect of the construction plan is the order in which the operations must be performed. A set of precedence relationships was developed to simplify the ordering of tasks within a construction project. One of the objectives of each construction project was to complete the surface preparation activities needed for installation of a surface element prior to its delivery to the base. Note that the following discussions on construction examples apply to the lunar evolution case study.

### 6.2.1.1 Initial Base Establishment

The initial construction phase for the lunar base begins with the arrival of the first crew in February, 2004. The major areas of work for the crew are shown in figure 6.2.1-1. A top-level description of this activity network for the initial construction phase is as follows. The power system is installed first in order to provide electrical support to the equipment and the lander. Next, the habitat and utilities are installed. With the utilities connected, operations and performance testing occurs. Activation of the equipment consists of powering-up the mobile work platforms, testing the platform systems and "walking" the platforms off of the lander. The platforms subsequently off-load the balance of the equipment, which in turn are powered up and tested.

Although not a construction task, stocking of the habitat is included here, assuming some crew reside in the habitat for the last part of the stay. The initial launch and landing facilities are prepared by leveling and by the installation of self-powered navigation beacons. Emplacement of the science equipment requires leveling of the science area and installation of utilities. Temporary utilities will be placed on the surface rather than being buried. Table 6.2.1-V contains a top-level task breakdown with corresponding durations for the construction of the initial base establishment. Note that a machine shift is equal to 8 hours. Figure 6.2.1-2 represents, using a Gantt chart, the activities distributed across a timeline of three months. The chart indicates that the 30-day period with a full crew operating during both the lunar night and day is insufficient to complete all of the identified tasks. A duration of 90 days is more reasonable for constructing the initial base. However, the habitat may be readied for occupancy within approximately 30 days, allowing a longer stay time to complete the remaining tasks.

### 6.2.1.2 Roadways and Landing Pads

Leveling and clearing of roadways requires grading, cut and fill, surface stabilization, and rock removal operations. The most effective method of surface stabilization has yet to be determined through a comparative study with actual experimentation. This analysis assumes that only minor compaction is required and provided by each pass of the construction equipment during normal grading operations. Cut and fill operations are kept to a minimum due to careful selection of sites and avoidance of large craters and boulders whenever possible. Smaller boulders can be readily picked up and moved by the mobile equipment platform with the robotic arm attachment. Larger boulders are assumed to be drilled, blasted,

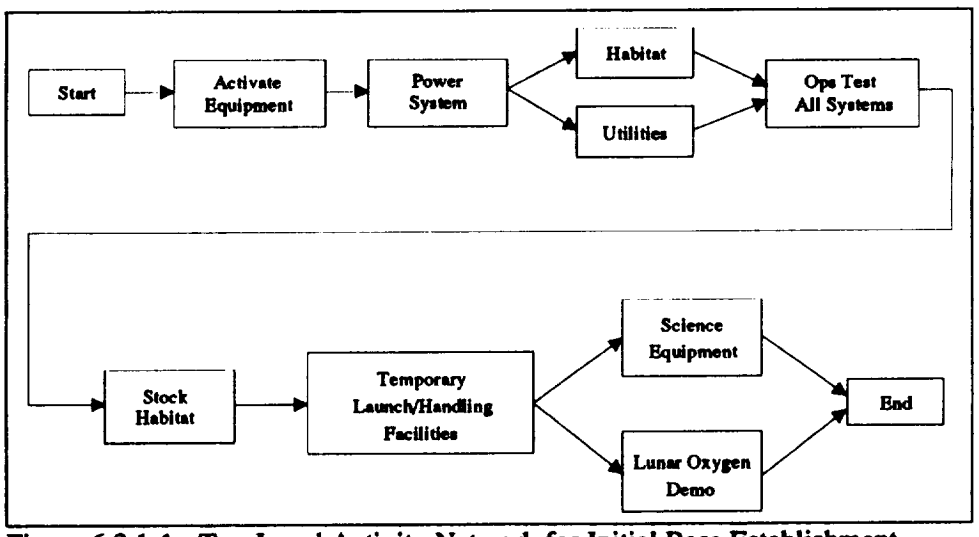



Figure 6.2.1-1.- Top-Level Activity Network for Initial Base Establishment.

TABLE 6.2.1-V.- ACTIVITY SUMMARY FOR INITIAL BASE ESTABLISHMENT

| Activity Name | Machine Days | Machine Hours | IVA Crew Days | IVA Hours | EVA Crew Days | EVA Hours |
|---|---|---|---|---|---|---|
| Activate Equipment | 3 | 20 | 1 | 5 | 5 | 20 |
| PVA/RFC Power | 14 | 110 | 5 | 40 | 14 | 90 |
| Habitat | 14 | 110 | 3 | 20 | 17 | 100 |
| Utilities | 3 | 20 | 2 | 10 | 7 | 40 |
| Test Habitat and Power Systems | 0 | 0 | 3 | 20 | 4 | 20 |
| Stock Habitat | 2 | 10 | 2 | 10 | 2 | 10 |
| Temp. Launch and Landing Facilities | 34 | 270 | 25 | 200 | 29 | 170 |
| Science Area | 8 | 60 | 4 | 40 | 9 | 50 |
| Liquid Oxygen Demonstration | 2 | 10 | 1 | 5 | 2 | 10 |

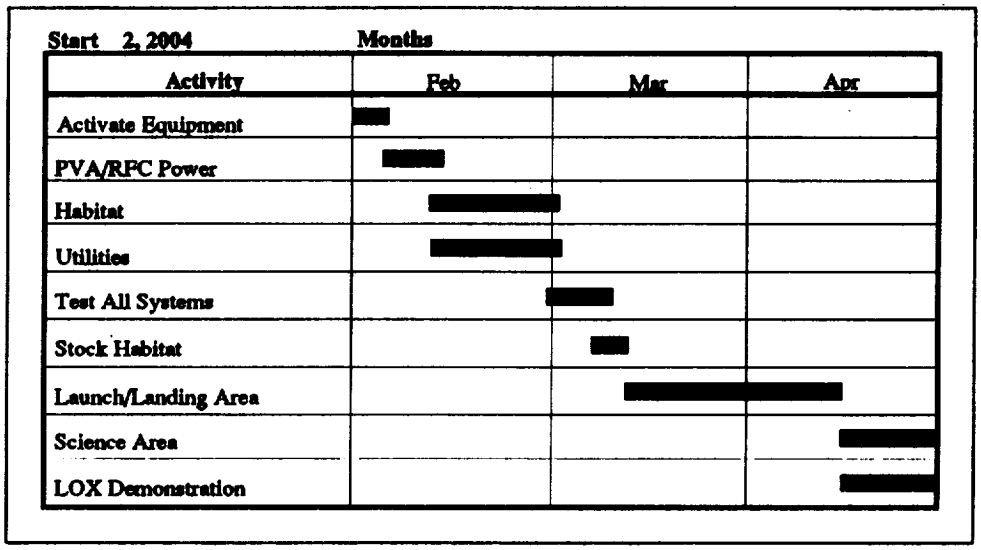



Figure 6.2.1-2.- Gantt Chart for Initial Construction Period.

and removed in smaller pieces. The average slope in the mare regions spanning 25 meters is 4.7 degrees (EEI, 1988). The grading operation is defined as moving an average of 0.25 cubic meters per square meter of surface area leveled as shown in figure 6.2.1-3. The 0.25 cubic meters per square meter is reduced to 0.15 for facility locations and 0.05 for roadways to reflect the assumption that these areas have different slope tolerances. Note that for this regolith moving exercise, considerations for swelling or compaction are not included.

### 6.2.1.3 Utility Ways

Several options for utility installation can be considered for extraterrestrial base construction. The utilities can be installed in conduits, left bare, placed on the surface, buried, or elevated. Conduits may offer maximum protection, but they cost more in launch mass. Simple burial offers protection from micro-meteorites and other hazards, but makes access for repairs and/or modifications difficult. Either surface or elevated utility ways provide ease of access, but expose utilities to other hazards. Burial is assumed for this case study. It is important to note that all present and future utilities should be considered for initial burial so that additional trenching and/or disturbance of existing utility ways can be avoided.

### 6.2.1.4 Advanced Habitation Provision

The constructible habitat is intended to be delivered in separate installments to facilitate its transport from Earth. Manifest decisions regarding the timing and packaging of these installments have a large impact on the construction project duration. For the lunar case, the initial configuration is delivered in three flights over an 18-month period. A 32-week period, primarily driven by the excavation task, is needed to prepare the site for

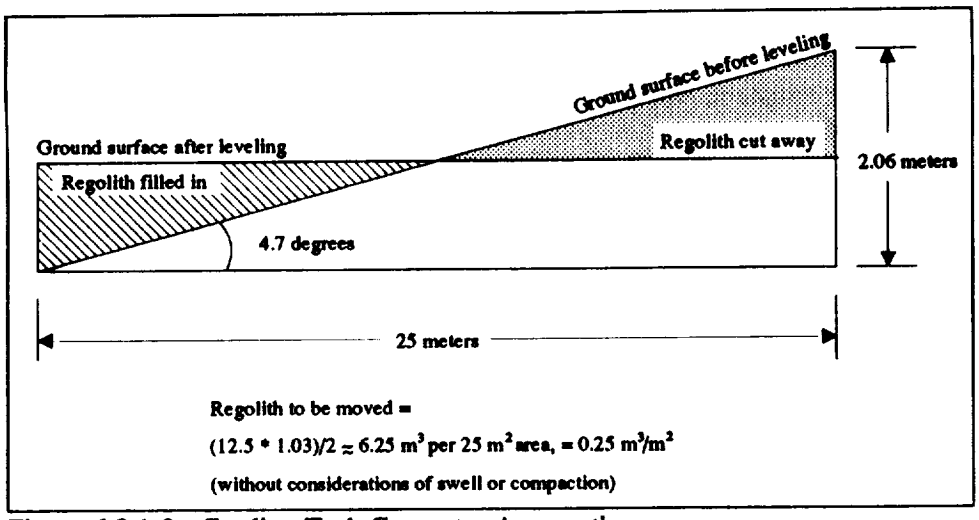



Figure 6.2.1-3.- Grading Task Geometry Assumption.

emplacement of the structure, so the project start date is 11, 2005. The depth of excavation assumed in this study is 8.5 meters. The emplacement, backfill, and cover operations take an additional 29 weeks once the first installment of structure is delivered in July 2006. The installation of the full complement of thermal control system equipment begins in January 2007 and requires two weeks to complete. A third flight delivers the life support equipment for the inflatable in July 2007. The installation of the life support equipment and a total system test is then performed over a three week period. The inflatable can accommodate crew as early as August 2007, but the five month period prior to the arrival of additional crew can be used as a trial period for monitoring and validation of critical system performance. An additional installment of laboratory equipment arrives three years later, with the set-up estimated at approximately two weeks. Extensive laboratory work could then begin in August 2011. Figure 6.2.1-4 indicates the progression of tasks during the course of the construction project.

### 6.2.1.5 Power System Provision

The installation of a photovoltaic array (PVA) and regenerative fuel cell (RFC) is a critical construction activity during the first manned visit to the lunar surface (February through March 2004). Prior to the layout of the solar array panels, an area is cleared using the grader configuration of the mobile equipment platform. Degradation that may occur to existing photovoltaic surfaces during later installation activities can be minimized by clearing a 3,200 square meter area during this phase of construction. No excavation tasks are assumed for the site preparation activities because the hydrogen, oxygen, and water tanks of the regenerative fuel cell system do not require burial. The time allocated for the placement of the array assumes that a two-person extravehicular

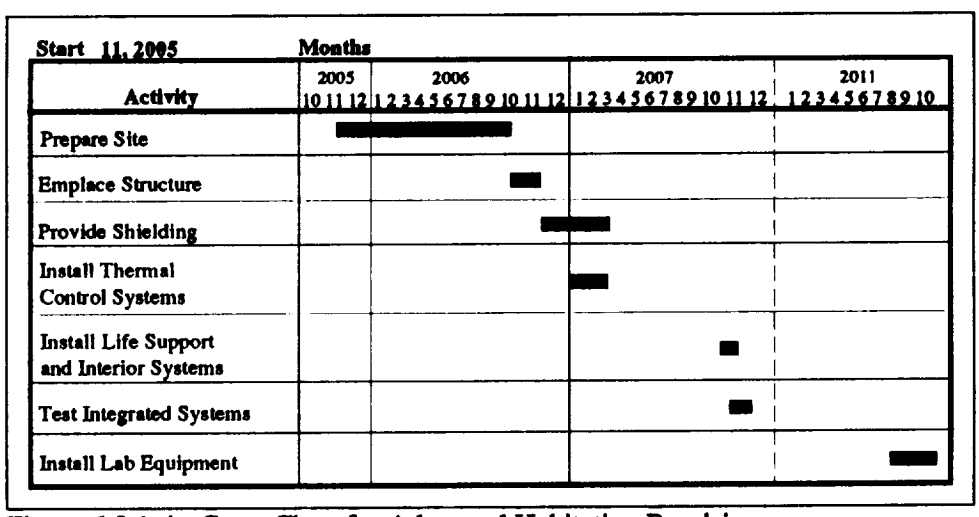



Figure 6.2.1-4.- Gantt Chart for Advanced Habitation Provision.

activity (EVA) crew with appropriate equipment set up some form of stand-off structure and subsequently unroll flexible panels on top of the structure. An alternative design integrates the stand-off structure with the photovoltaic material in rigid panels. The difference in set-up time between these two methods of installation has not been determined. A more detailed description of the hardware is needed before this determination can be made.

The tasks listed in table 6.2.1-VI are repeated for the installation of an additional PVA/RFC unit in the second manned activity period (July 2004 through January 2005). The time required to complete the installation of the additional panels is approximately eleven days. This duration is based on the analysis performed for the initial PVA/RFC construction task, together with a scaling that accounts for the additional connections and emplacement procedures associated with the larger installment.

TABLE 6.2.1-VI.- PVA/RFC SYSTEM INSTALLATION

| Task Description | Duration (hours) |
|---|---|
| Survey and Layout | 1 |
| Surface Preparation | 45 |
| Unload PVA/RFC | 5 |
| Transport PVA/RFC | 1 |
| Emplace PVA | 2 |
| Emplace RFC | 5 |
| Anchor PVA | 4 |
| Connect PVA | 2 |
| Anchor RFC | 4 |
| Connect PVA and RFC | 1 |
| Inspect | 1 |
| Test | 1 |
| Repair/Start Up | 2 |
| Final Preparation and Cleanup | 1 |

The later phases of power system evolution make use of an SP-100 reactor. The landing of a self-contained unit that uses thermionic conversion to produce 100 kW of electricity occurs in February 2006. The basic construction tasks of surveying, trenching, and grading are completed prior to the delivery of the surface element. The time estimated for site survey and grading, 12 hours, is based on the number of points to be marked and the surface area to be cleared prior to element placement. A separation distance of 500 m is defined as the minimum safe distance between the nuclear plant and the habitation zone. This assumption resulted in the estimation of 16 hours of teleoperated machine activity for the construction of a 50 m trench to carry the lines clear of the immediate plant site and a 350 m trench section to provide protection from the transmission line in the high-traffic areas in the habitat zone. The remaining 100 m of cable are laid out on the surface with markers to indicate the existence of a high voltage power line. There may be some advantages to providing additional insulation by covering the entire length of power cable with lunar regolith, namely improved transmission efficiency and extended material life. At this time, however, the magnitude of these benefits do not seem to warrant the additional trench and backfill operations associated with complete cable burial.

When the nuclear power system is delivered to the surface, it is off-loaded, transported to the designated site, and positioned. Utility connections are made and a thorough system inspection is performed. Assembly tasks other than utility connects are not assumed since the plant is designed as a self-contained, pre-assembled unit (Hickman, 1989). The trenches containing the power cable are backfilled and any remaining debris from the construction activity is removed from the site. The SP-100 is delivered on a lander with other cargo. Off-loading tasks involve the unloading of the lander of additional materials prior to transporting the SP-100 to the construction site.

The 825 kWe nuclear power plant is delivered in July 2009. A considerably greater construction effort is required for the installation of this surface element. After surveying the site for the plant, a pit (4.2 m in depth, 2.5 m in radius) is excavated for burial of the reactor. The reactor, bulkhead, Stirling engines, and radiators are then assembled. Figure 6.2.1-5 provides a timeline for each task required to install the plant.

### 6.2.1.6 Oxygen Production Facilities

The surface elements associated with the development of an oxygen production facility at the lunar base include the lunar-derived liquid oxygen (LLOX) demonstration unit, the LLOX pilot plant, and LLOX production plants #2 through #4. Since a modular approach to the facility build-up is taken, the pilot plant and production plants are essentially the same systems. The construction tasks needed to install the modular plants are listed in table 6.2.1-VII with associated work loads and task times.

### 6.2.1.7 Science Installations

The construction needed for the science missions scheduled for the lunar base is minimal except for the very low frequency radio telescope located on the far side in 2013. Table 6.2.1-VIII lists the construction projects related to the lunar science installations and the time needed to complete each project.

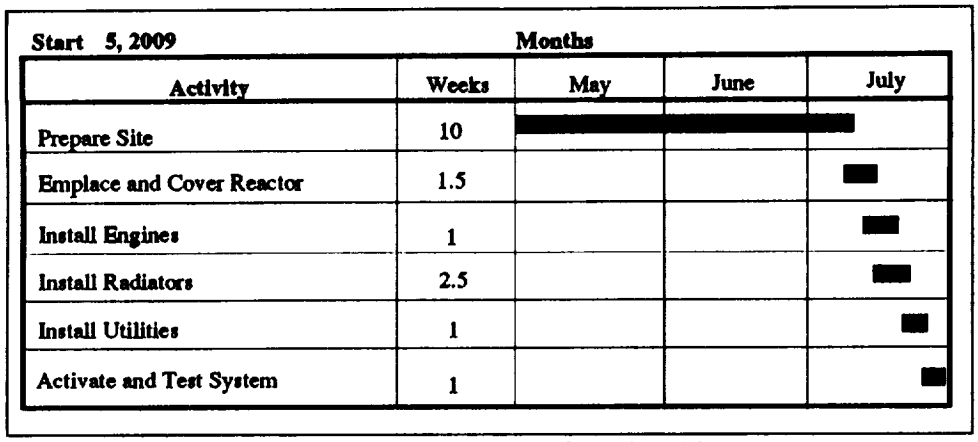


Figure 6.2.1-5.- Gantt Chart for Construction of Nuclear Plant.

### 6.2.2 Issues for Discussion

#### 6.2.2.1 Radiation Protection Measures

The amount of in situ shielding needed to provide adequate protection from both galactic cosmic rays (GCR's) and solar particle events is a major driver of construction operations timelines. The requirement for GCR protection has not yet been determined for the lunar or Mars evolution case studies, but the value is expected to lie in the range of 50 to 700 g/cm$^2$ for tours of duty greater than 6 months. In addition to being especially sensitive to the amount of cover to be provided, the task of providing in situ protection also depends greatly on the technique used to cover the habitats. Since project durations are especially sensitive to the soil handling requirements, this study looked at the impact of cover thickness and cover technique with respect to total project duration. Figure 6.2.2-1 shows the comparison between direct burial, direct burial with retaining walls, and contoured cover for a range of

TABLE 6.2.1-VII.- LLOX PLANT CONSTRUCTION TASKS

| Task | Work Load | EVA Crew Days | EVA Hours | IVA Crew Days | IVA Hours |
|---|---|---|---|---|---|
| Select and survey plant and mine sites | 36 points | 1 | 6 | 1 | 3 |
| Prepare utility routings | 12 m$^3$ | 0 | 0 | 2 | 10 |
| Grade area for processing unit | 10 m$^3$ | 1 | 2 | 1 | 2 |
| Prepare pit for LLOX storage tanks | 60 m$^3$ | 1 | 2 | 3 | 20 |
| Set anchors for plant | 3 points | 1 | 2 | 1 | 4 |
| Offload cargo | 7 pallets | 1 | 2 | 5 | 37 |
| Transport pallets to site | 5 km | 1 | 2 | 1 | 4 |
| Emplace pit scalper | 1 large pc. | 0 | 0 | 1 | 5 |
| Emplace process structure | 1 large pc. | 0 | 0 | 1 | 5 |
| Emplace external systems | 16 med. pcs. | 0 | 0 | 1 | 8 |
| Emplace utilities | 200 m | 0 | 0 | 1 | 2 |
| Connect utilities | 12 points | 1 | 6 | 1 | 3 |
| Test utility connectors | 12 tests | 1 | 6 | 1 | 3 |
| Emplace thermal control system | 4 med. pcs. | 0 | 0 | 1 | 2 |
| Connect thermal control system | 12 points | 1 | 6 | 1 | 3 |
| Emplace storage tanks | 3 med. pcs. | 0 | 0 | 1 | 2 |
| Emplace piping | 250 m | 4 | 24 | 4 | 26 |
| Connect piping | 24 points | 2 | 12 | 1 | 6 |
| Cover tanks (backfill and elevation) | 100 m$^3$ | 0 | 0 | 4 | 30 |
| Activate and test systems | 400 tests | 8 | 48 | 19 | 148 |
| Finish and clean up site | 100 m$^2$ site | 2 | 12 | 1 | 6 |

TABLE 6.2.1-VIII.- TASKS FOR SCIENCE INSTALLATIONS

| Science Installation | Hardware Delivery Date | Project Duration (crew days) | Operational Readiness Date |
|---|---|---|---|
| Geophysical Station #1 | Feb. 2004 | 1 | Feb. 2004 |
| Laser Reflectometer | Feb. 2004 | 1 | Feb. 2004 |
| Solar Observatory | Feb. 2004 | 2 | Feb. 2004 |
| Optical Telescope #1 | July 2005 | 4 | July 2005 |
| MERI | July 2005 | 6 | Aug. 2005 |
| Biology Lab | July 2005 | 5 | July 2011 |
| Analysis Lab | July 2005 | 5 | July 2011 |
| Earth Observatory | July 2005 | 4 | July 2005 |
| Monitoring Telescope | July 2005 | 4 | Aug. 2005 |
| Infrared Telescope | July 2006 | 4 | July 2006 |
| Ultraviolet Telescope | July 2006 | 4 | Aug. 2006 |
| Optical Telescope #2 | July 2007 | 4 | July 2007 |
| Optical Telescope #3 | Jan. 2008 | 4 | Jan. 2008 |
| Gamma-Ray Telescope | July 2010 | 4 | July 2010 |
| X-Ray Telescope | July 2011 | 4 | July 2011 |
| Plant Lab | July 2011 | 5 | July 2011 |
| Animal Lab | July 2011 | 5 | Aug. 2011 |
| Microbe Lab | July 2011 | 5 | Aug. 2011 |
| Geophysical Station #2 | July 2012 | 2 | July 2012 |
| Monitoring Telescope | July 2012 | 2 | July 2012 |
| VLF Telescope* | Jan. 2013 | 54 | Sep. 2013 |
| Geophysical Staiton #3 | Jan. 2014 | 2 | Jan. 2014 |
| Monitoring Telescope | Jan. 2014 | 2 | Feb. 2014 |
| Geophysical Staiton #4 | Jan. 2015 | 2 | Jan. 2015 |
| Monitoring Telescope | Jan. 2015 | 2 | Feb. 2015 |

*Battelle, 1989

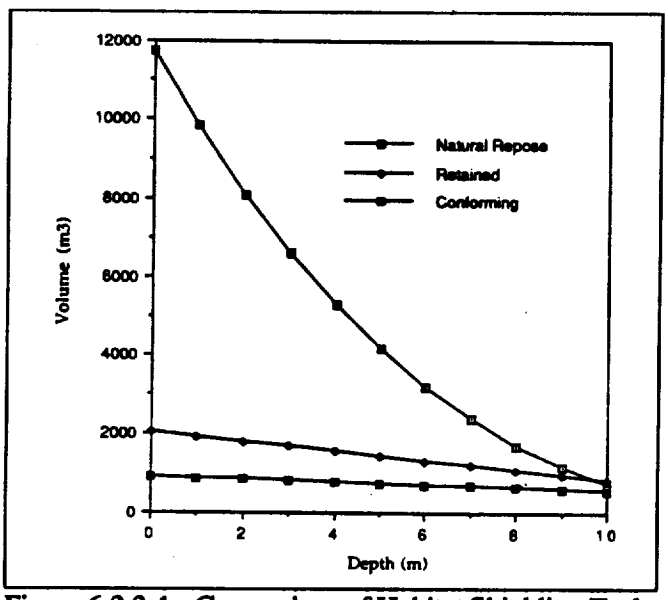



Figure 6.2.2-1.- Comparison of Habitat Shielding Techniques.

radiation protection requirements for the constructible habitat. The duration of the shielding task is directly proportional to the volume of regolith needed for the cover techniques investigated. The use of a stand-off structure in conjunction with these shielding techniques was not included in this analysis but is an important area for future investigation.

For the burial techniques mentioned above, the depth of the pit is another important consideration. Figure 6.2.2-2 shows the relationship between the pit depth and the volume of regolith that is handled in the excavation, backfill, and cover tasks. Since the productivity of the digging task can be an order of magnitude lower for the layer of lunar regolith below the top 15 cm of gardened regolith, it may be better to pursue techniques that do not require digging below 15 cm. Instead, it may be wise to place the habitats on the surface and pile the easily accessed top-layer regolith as a cover. Alternatively, a pit could be created using explosives and then shaped with a digger and/or grader prior to habitat emplacement.

The use of stand-off structures and/or retaining walls is especially important for covering habitats placed at ground level in order to minimize the volume of regolith involved. A stand-off structure is also desirable for flexible, evolving radiation protection strategies because it reduces the direct structural loadings induced by the addition or subtraction of regolith cover. A trade between the amount of work required versus the additional launch mass of the stand-off structure is needed before a conclusion can be drawn.

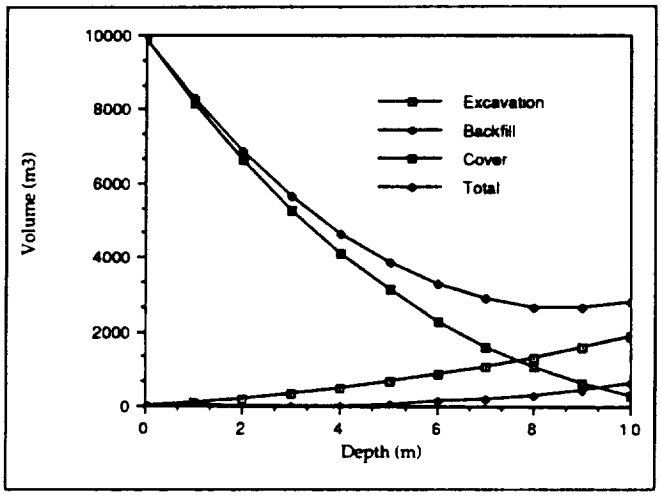



Figure 6.2.2-2.- Volume of Regolith as a Function of Pit Depth for Natural Repose Shielding Technique.

#### 6.2.2.2 Interior Outfitting of Pressurized Volumes

An important consideration in planning the timeline for outfitting the inflatable habitat is the packaging of interior system hardware. Packaging configurations determine the time needed for off-loading the pallets from the lunar landers, disconnecting the packages from their space transport pallets, transferring the packages from vacuum to the pressurized volume, and installing the interior systems. Each hardware element is limited in size by the dimensions of the airlock used for cargo ingress and the material-handling capabilities of the crew. If some of the pieces are very large, a temporary, larger airlock may be required.

#### 6.2.2.3 Utility Routing and Accessibility

The routing of utilities between surface elements should be planned with long-term base operation in mind. To facilitate the testing and potential replacement of utility segments, access stations at various points along the route may prove advantageous. High-voltage power transmission lines can be used to transmit communications signals, especially in cases where few terminals exist to break up the signal path. This may be an important feature for monitoring the status of remote equipment that is tied into the base power system. The frequency range of interest for this low-bandwidth service is 30 to 500 kHz.

#### 6.2.2.4 Manpower and Man/Machine Coordination

The coordination of man and machine to accomplish construction tasks is based on the level of autonomy expected for the time period under consideration. A teleoperator inside the pressurized work area or on Earth is assumed to operate the machinery during a large fraction of the time needed to excavate, grade, trench, and transport regolith. Any detailed manipulation of the equipment needed to refine the site prior to placement and assembly can be performed by an EVA crew if necessary. The connection of pieces and utilities, testing, and troubleshooting during the project is assigned to an EVA crew who may or may not be assisted by an intravehicular crew member manipulating the robotic arm. Prior to the initiation of a new construction project, an EVA crew will survey the site, set up any command, control, and communications equipment, and configure the machines for the scheduled tasks. Periodically throughout the project, the EVA crew will be called upon to change out a regenerative fuel cell unit or reconfigure a machine.

A typical schedule of activities for a construction project over a 24-hour period during the daylight portion of the lunar cycle is shown in figure 6.2.2-3. This schedule assumes that the base operates on a single crew shift and can only allocate a maximum of three crew members to the construction project at any one time. In addition, only four EVA periods are scheduled for construction tasks during a work week. Figure 6.2.2-4 illustrates the additional capability afforded when the base population grows to eight crew and a double shift is adopted (an alternative approach). The coordination of EVA shifts with the regenerative fuel cell operational use cycle is an important consideration when the maximum utilization of construction machinery is required. The 48-hour periods are illustrated to emphasize the repetition in the daily cycle.

## 6.3 LOGISTICS

Logistics support is critical when the distance between Earth and the Moon is considered, not to mention the distance between Earth and Mars. Ample supplies are essential to the health and well being of crews that will serve at the lunar and martian outposts. For this reason, special effort was placed on identifying the requirements of a logistics lifeline to each location, with emphasis on the martian case.

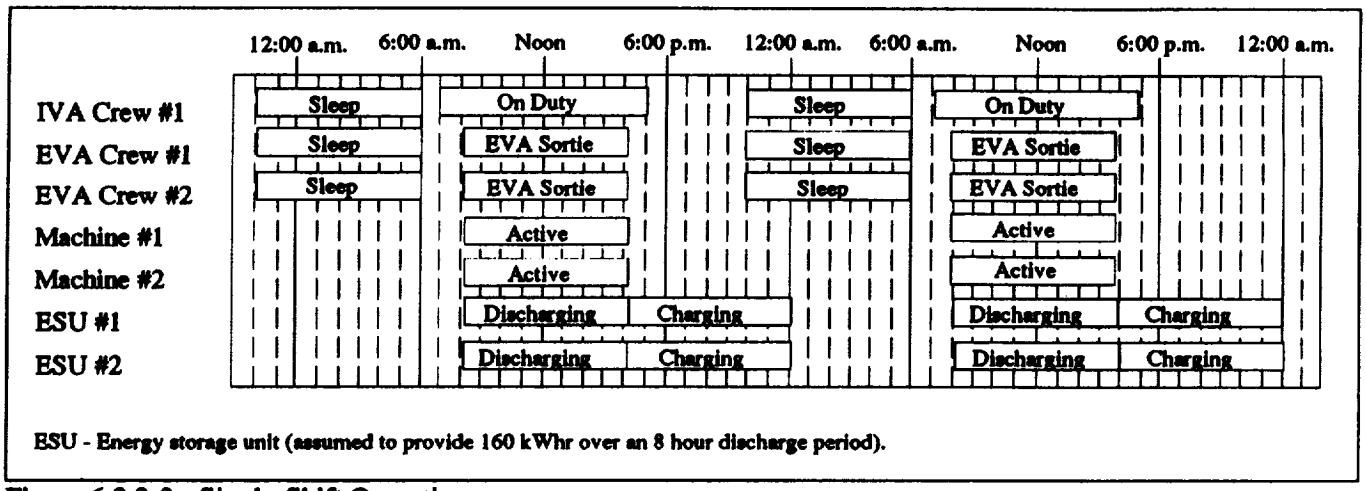



Figure 6.2.2-3.- Single-Shift Operations.

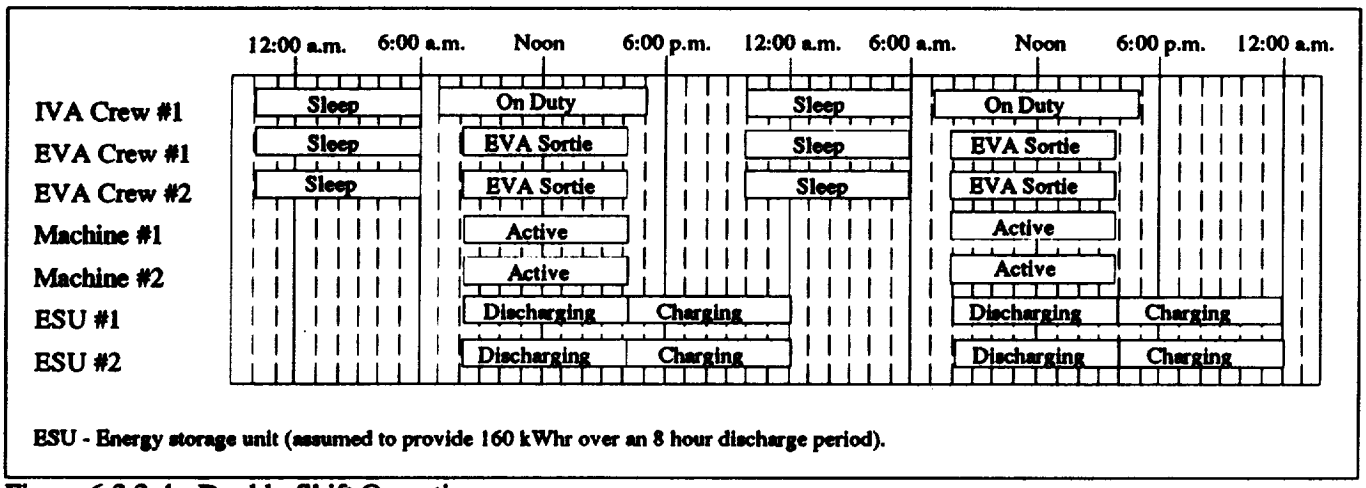



Figure 6.2.2-4.- Double-Shift Operations.

Three areas of logistics support have been investigated thus far for Planet Surface Systems Integration Agent (PSSIA) consideration. These areas are cargo handling requirements, storage needs, and inventory management.

Cargo handling involves off-loading, transporting, storing (stocking), vehicle, and special handling equipment and tools requirements. Tradeoffs have been identified concerning each category and are scheduled for evaluation next year. Considerations include the division of labor between EVA and telerobotic operations in each category.

The methodology of transporting, storing, and maintaining an accurate accounting of cargo is integral to achieving a successful and meaningful logistics support program. Logistics support touches on almost every aspect of any major program. A viable integrated logistics support (ILS) program is essential for extraterrestrial bases. For example, storage facilities with adequate mass and storage space are required. Types of storage facilities are also important; e.g., pressurized vs. unpressurized, temporary facilities, shelf life constraints, food storage, perishables, and radiation protection considerations.

An accurate accounting system must be maintained. Questions that must be answered include how to "tag" the items; e.g., bar coding, color coding, stock class, etc. Other important aspects of inventory control are access, accounting procedures, and reporting requirements. A further part of inventory management involves establishing quantities required to be maintained for the base camp. Quantities will vary according to need and the phase of base development. For example, different quantities will be maintained for 30-day, 60-day, 90-day, 180-day, 12-month, 18-month, and 24-month shelf time. A final part of an effective inventory management program is prioritization. This is especially critical for any item that is considered essential to life support.

Figure 6.3-1 illustrates the number of interfaces that are involved for a typical integrated logistics support program.

The most important logistics aspect of the martian case is that the physical design of the martian base and its operation are driven by the long lifeline between Earth and Mars. Contingencies play a major role, so a balance must be reached between performance and the considerations of reliability, maintainabliity, availability, commonality, and a robust reconfiguration capability for the martian outpost.

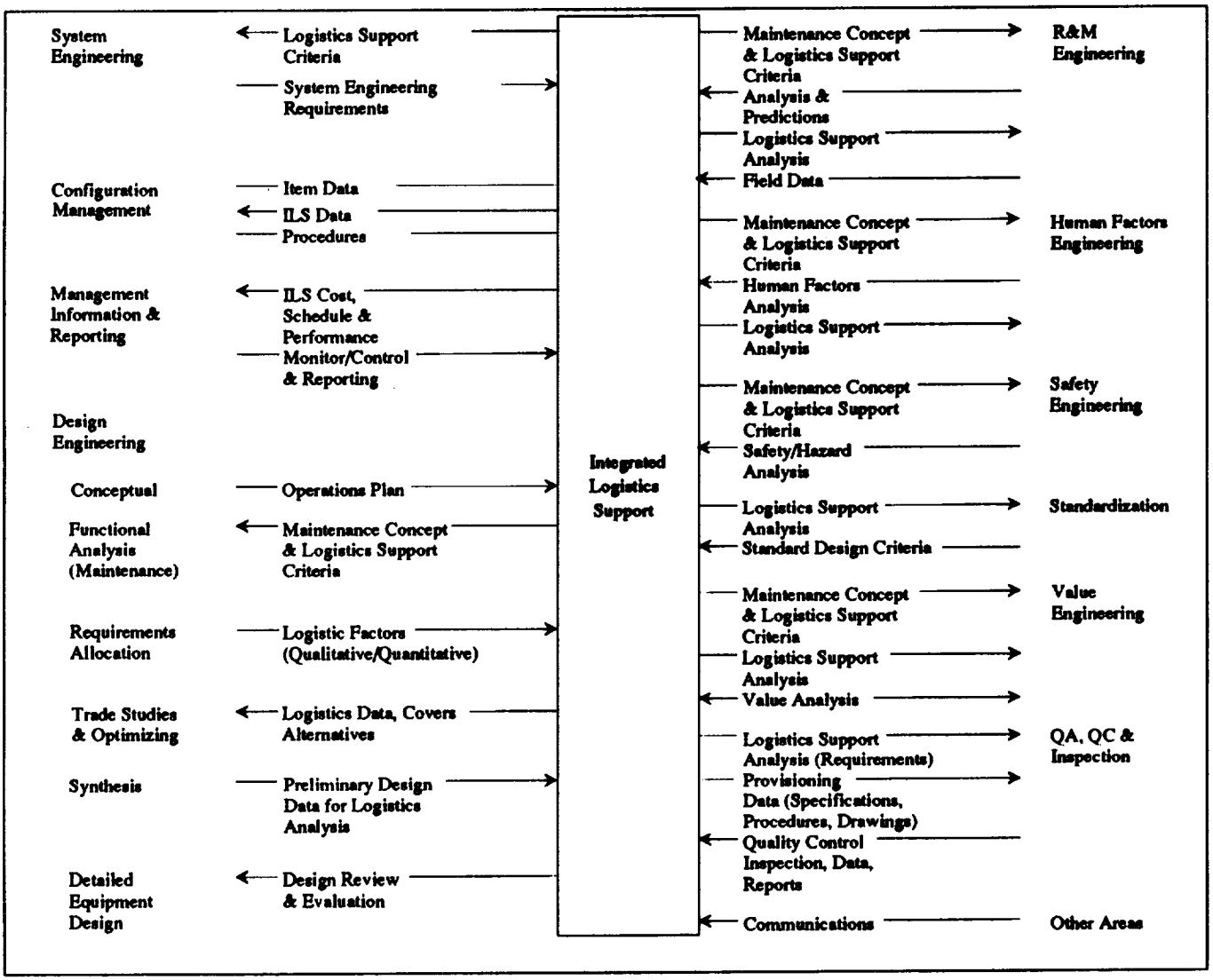



Figure 6.3-1.- Major ILS Interfaces.

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| XE/M. Culp | 6 | 6 | | | | | |
| IE2/L. Pieniazek | 3 | 3 | 1 | 10 | 1 | 1 | 1 |
| IE2/W. Holdenbach | 3 | 3 | 3 | 6 | 3 | 3 | 3 |
| B12/Kathy Plowman | 1 | 1 | | | | | |
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| Ominplan Corp/J. J. Culp | 1 | 1 | | | | | |
| Rockwell International/D. L. Finley | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| XM/J. Soldner | 3 | 3 | 1 | 1 | 1 | 1 | 1 |
| SII/Space Industries/R. Humble | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| JL4/Stellacom, Inc., D. Shadle | 1 | 1 | | | | | |
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| **Corps of Engineers**<br>Research Lab<br>P.O. Box 4005<br>Champaign, IL 61820-1305<br>Alvin Smith | 1 | 1 | | 1 | | | |
| **Department of Energy**<br>Washington D. C. 20545<br>John P. Warren, P.E. | 1 | 1 | | | | | |
| **U.S. Geological Survey**<br>345 Middlefield Rd.<br>Menlo Park, CA 94025 | | | | | | | |
| 946/Dr. Michael Carr | 1 | 1 | 1 | | | | |
| **U.S. Geological Survey**<br>2255 N. Gemini Dr.<br>Flagstaff, AZ 86001 | | | | | | | |
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## INDUSTRY

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| **GE Aerospace**<br>San Jose CA. 95153-5354<br>N. Deane | 1 | | | | | | 1 |
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| **Lockheed Space Operations Company**<br>1100 Lockheed Way<br>Titusville, FL 32780<br>Attention: Steve Burns/J.F. Madwell | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
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| **Rockwell International Corporation**<br>Space Systems Div.<br>12214 Lakewood Blvd.<br>Downey CA. 90241<br>Mail code AA51, S15, E16<br>Attn: Len Meyerhoff, X4897 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
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# Appendix

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ALSS | advanced life support system |
| BITE | built-in test equipment |
| CELSS | Controlled ecological life support system |
| DC | direct current |
| DDT&E | design, development, test, and engineering |
| DIPS | dynamic isotopic power supply |
| DLRV | dual mode lunar roving vehicle |
| ECLSS | environmental control and life support system |
| EEI | Eagle Engineering, Inc. |
| ELSS | emergency life support system |
| EMI | electromagnetic interference |
| EMU | extravehicular mobility unit |
| ESD | earliest start date |
| EVA | extravehicular activity |
| FDM | frequency-division multiplexed |
| FEL | Front end loader |
| FFD | functional flow diagram |
| FY | fiscal year |
| GCR | galactic cosmic radiation |
| GPS | global positioning system |
| GRS | geosynchronous relay satellite |
| GSFC | Goddard Space Flight Center |
| GT | ground terminal |
| HMF | health maintenance facility |
| ILS | integrated logistics support |
| ILSS | initial life support system |
| IM | information management |
| ISRU | in situ resource utilization |
| IVA | intravehicular activity |
| JPL | Jet Propulsion Laboratory |
| KSC | Kennedy Space Center |
| LANL | Los Alamos National Laboratories |
| LaRC | Langley Research Center |
| LED | latest end date |
| LEDS | lunar exploration data system |
| LEO | low Earth orbit |
| LESC | Lockheed Engineering and Sciences Company |
| LEV | lunar excursion vehicle |
| LLO | low lunar orbit |
| LLOX | lunar-derived liquid oxygen |
| LRS | lunar relay satellite |
| LSPI | Large Scale Programs Institute |
| LSS | life support system |
| LST | lunar surface terminal |
| MASE | Mission Analysis and System Engineering |
| MCSV | martian crew sortie vehicle |
| MERI | Moon-Earth radio interferometer |
| MEV | Mars excursion vehicle |
| MLSS | mature life support system |
| MOLAB | mobile lunar laboratory |
| MOSAP | mobile surface applications traverse vehicle |
| MPV | Mars piloted vehicle |
| MRSR | Mars rover/sample return |
| N/A | not applicable |
| NASA | National Aeronautics and Space Administration |
| NSTS | National Space Transportation System |
| O&M | operations and management |
| OAST | Office of Aeronautics and Space Technology |
| OEXP | Office of Exploration |
| OSO | Office of Space Operations |
| PCRV | primary control research vehicle |
| PLSS | portable life support system |
| PMU | Phobos maneuvering unit |
| PSS | Planet Surface Systems |
| PSSIA | Planet Surface Systems Integration Agent |
| PSSRD | Planet Surface Systems Requirements Document |
| PTO | power take-off |
| PUV | pressurized utility vehicle |
| PVA | photovoltaic array |
| RF | radio frequency |
| RFC | regenerative fuel cell |
| RSS | root sum square |
| RSAT | relay satellite |
| RTG | radio isotope thermoelectric generators |
| SCWO | supercritical water oxidation |
| SLRV | surveyor lunar rover vehicle |
| SPE | solid polymer electrolyte |
| SRD | Study Requirements Document |
| SSCMS | surface systems control and monitor system |
| SSE | surface support equipment |
| SSF | Space Station Freedom |
| T&DA | tracking and data acquisitions |
| TBD | to be determined |
| TBS | to be supplied |
| TCS | thermal control system |
| TDM | time-division multiplexed |
| TDRSS | tracking and data relay satellite system |
| TEI | trans-Earth injection |
| TNIM | telecommunications, navigation, and information management |
| UHF | ultra high frequency |
| USACE | U. S. Army Corps of Engineers |
| VCS | vapor cycle system |
| VHF | very high frequency |
| VLF | very low frequency |
| WAN | wide area network |

## UNITS OF MEASURE

| | |
|---|---|
| Å | Angstrom |
| cm | centimeter |
| g | gram |
| hr | hour |
| kbps | kilobits per second |
| kg | kilogram |
| $kg_f$ | kilogram-force |
| kHz | kilohertz |
| km | kilometer |
| kPa | kilopascal |
| kW | kilowatt |
| kWe | kilowatt electric |
| lb | pound |
| m | meter |
| mb | millibar |
| Mbps | megabits per second |
| MHz | megahertz |
| MW | megawatt |
| psi | pounds per square inch |
| psia | pounds per square inch atmospheric |
| s | second |
| t | metric ton (1,000 kg) |
| W | Watt |
| °C | degrees Celsius |
| °K | degrees Kelvin |

## GLOSSARY

**Adsorption**--the assimilation of gas, vapor, or dissolved matter by the surface of a solid or liquid.

**Anorthite**--a plagioclase feldspar with high calcium oxide content, found in igneous rocks.

**Architecture**--the overall management structure describing the total occupation of the planetary surface, consisting of elements, their interfaces, organization, and layout.

**Assembly and construction**--the functional area involving the establishment of base systems, routing of utilities, and surface improvement.

**Ballistic vehicle**--a modified lunar lander used for suborbital "hops" from one location to another on the surface of the planet.

**Bandwidth**--the number of cycles per second expressing the difference between the limiting frequencies of a band of wavelengths.

**Base layout**--an assemblage of elements selected to meet the lunar and martian evolution mission objectives. The elements are grouped into particular physical areas referred to as zones, where each zone is identified by a function or activity. Zone placement is based on optimizing surface operations and functional linkages between systems. Lunar and martian bases are divided into five zones: habitation (zone 1), science users (zone 2), in situ resource utilization (zone 3), launch and landing (zone 4), and power generation and distribution (zone 5).

**Beneficiate**--to concentrate or otherwise prepare for processing, esp. by sorting or magnetic concentration.

**Bevameter/penetrometer**--a device for measuring the penetrability of a surface, in this case yielding important engineering design data about the lunar or martian surface.

**Blood-forming organ**--structures in the body, esp. the bone marrow, which are sites of rapid cell division and are accordingly the most sensitive to damage by ionizing radiation.

**Boiloff**--loss of cryogens (in this case liquid oxygen and hydrogen) by evaporation.

**Broadband link**--frequency bandwidth of 6 to 70 MHz (local area).

**Busbar**--a heavy rigid conductor used for high power feeders.

**Carbonaceous chondrite**--a carbon-bearing meteoric stone composed of rounded granules of cosmic origin.

**Case study**--the results of a formal analysis conducted to determine the methodology and associated options needed to satisfy a set of specified parameters and requirements.

**Chromosphere**--an incandescent, transparent layer of gas, chiefly hydrogen, several thousand miles in depth, that lies above and surrounds the photosphere of the sun but is distinctly separate from the corona.

**Closure**--the goal of an advanced life support system, in which all air, water, and food are recycled or locally derived, eliminating the need for periodic resupply.

**Consolidation phase**--the second of three phases in the evolution of a lunar or martian base. During this phase, habitation facilities are expanded, and scientific experimentation and in situ resource utilization activities begin. Dependence on Earth support will be reduced.

**Constructible habitat**--a habitat that is constructed to some significant degree on the planetary surface.

**Consumables**--supplies such as food and propellants which require replacement to ensure continuous operation.

**Controlled ecological life support system**--a life support system that continually recycles solid, liquid, and gaseous materials essential for sustaining human life.

**Data compression**--encoding technique used to increase throughput of information over a communications link for a given period of time.

**Demodulation or detection**--process of separating a modulated signal from a modulated carrier frequency.

**Demultiplex**--process used to separate channel(s) of communications from either a frequency division or time division information transmission system.

**Diurnal**--variation absorption factor K, given by the formula, $K = 0.142 + 0.858 \cos X$, where X is the sun's zenith angle (equal to zero when sun is directly overhead). K is for average daily absorption.

**Doppler range**--process of determining range information through integration of measured velocity.

**Dynamic isotope power system**--one with a power radioisotope heat source coupled to heat engines for power conversion.

**Electrolysis**--decomposition of a chemical substance by application of an electric current.

**Electrostatic wickets**--alternately changed and grounded brush-like arrangements of conductors which neutralize the static electric charge of lunar dust, reducing its tendency to cling to EVA suits and equipment.

**Element**--a major hardware item, such as a rover, habitat module, or power plant.

**Emplacement phase**--the first of three phases in the evolution of a lunar or martian base. During this phase, techniques and technologies for planetary surface habitation are learned and the initial habitation facilities are constructed. Dependence on Earth support is relatively high.

**Energy**--the functional area dealing with the generation, storage, management, and distribution of power.

**Expendables**--supplies, such as building materials and spare parts, that may or may not require resupply to ensure continuous operations.

**Extravehicular activity**--human activity that requires a spacesuit, taking place outside of a pressurized, temperature-controlled environment such as a habitation or vehicle.

**Extravehicular mobility unit (EMU)**--a unit consisting of a pressure suit and a portable life support system, allowing humans to move and work outside of pressurized vehicles and habitats.

**Flow bench**--an experimental work area fitted with an updraft hood for drawing away potentially noxious vapors generated during sample handling.

**Frequency translated link**--a communications link which moves a modulated radio frequency (RF) carrier signal to a new location in the frequency spectrum without disturbing the relationship of the carrier to its sidebands.

**Frequency-division multiplexed**--a process whereby communications channels are separated in the frequency domain.

**Functional area**--elements and activities with related functions and attributes. There are eight functional areas in the FY 1989 planetary surface systems studies: human systems; energy; telecommunications, navigation, and information management; surface transportation; in situ resource utilization; assembly and construction; launch and landing operations; and user accommodations.

**Functional closure**--the percentage of closure of a life support system with respect to the atmospheric and water system cycles.

**Habitat/habitation**--area or volume capable of sustaining human life.

**Halo orbit**--a proposed orbit for earth-moon communication satellites, in which the spacecraft is made to wander about the vicinity of Lagrange points 1 or 2, resulting in full coverage of the near or far side of the moon.

**Heat acquisition**--the process of removing excess heat from habitats, equipment, etc. by transferring it to a cooler liquid or other medium.

**Human systems**--the functional area relating directly to crew well-being or crew operations. Human systems include life support systems, habitation facilities, extravehicular activity systems, habitat thermal control systems, and radiation protection.

**Human-tended facility**--a facility that may be manned by humans on a periodic or as required basis.

**Hydroponics**--the cultivation of plants in water containing inorganic nutrients.

**Ilmenite**--a lustrous black-to-brownish ore, chiefly $FeTiO_3$.

**In situ resource utilization**--the functional area involving the processing of native planetary materials to produce useful commodities.

**Infrared emissivity**--the ratio of the energy in infrared radiation given off by a surface to that given off by a black body at the same temperature.

**Infrastructure**--all of the facilities, systems, and associated functions needed to support the space exploration program.

**Insolation**--the solar radiation incident on the earth or other planet.

**Integration agent**--a NASA individual responsible for integrating the results of a particular area of a case study; e.g., planet surface systems, transportation, and nodes.

**Intravehicular activity**--any human activity performed inside a shirt-sleeve environment, such as a habitat or spacecraft crew module.

**Ionizing radiation**--any radiation (electrons, protons, neutrons, atomic nuclei, gamma- and x-rays, etc.) with energy greater than a few KeV, which can knock electrons from atoms (or fragment nuclei), causing chemical changes to occur in the target material.

**Joist**--any of the parallel beams set from wall to wall to support the panels of a floor or ceiling.

**Ka band**--frequencies used for communications 20 MHz (space-to-earth) and 30 MHz (earth-to-space) transmission.

**Klystron**--an electron tube for amplifying or generating radio waves to microwave range frequencies by means of velocity modulation.

**Launch and landing operations**--the functional area involving activities associated with landers, such as payload integration, servicing, and propellant loading.

**Libration point**--one of 5 locations in the earth-moon system that are equilibrium points of the gravitational field (often called Lagrange points).

**Local/trunk circuits**--common user communications main lines used by a local area private automatic branch exchange (PABX) to output/input to/from a long distance system, e.g. a satellite or microwave system.

**Lunar day**--the period during which a point on the lunar surface is exposed to the Sun. The mean lunar day lasts for 14 24-hour Earth days.

**Lunar night**--the period during which a point on the lunar surface is hidden from the Sun. The mean lunar night lasts for 14 24-hour Earth days.

**Lunar evolution case study**--a case study focusing on the gradual establishment of a permanently manned base on the surface of the Moon.

**Magma**--molten matter beneath a planet's crust, from which igneous rock is formed by cooling.

**Magnetosphere**--an asymmetric region surrounding the earth, extending from approximately 400 to several thousand miles above the surface, in which charged particles are trapped and their behavior is dominated by the earth's magnetic field.

**Maria**--the relative smooth, dark, lava-filled basins of the Moon.

**Martian day**--the period during which a point on the martian surface is exposed to the Sun. The mean martian day lasts 12 hours, 18 minutes.

**Martian night**--the period during which a point on the martian surface is hidden from the Sun. The mean martian night lasts 12 hours, 18 minutes.

**Microgravity**--a term used to denote the near-zero gravity condition experienced by a spacecraft when it is not boosting; gravity levels less than $10^{-6}$ g.

**Modular habitat**--a habitat consisting of one or more modules fabricated on Earth and transported to the planet surface.

**Nephelometer**--an apparatus for measuring the size and composition of particles suspended in a gas by analysis of light transmitted through or reflected by the gas.

**Neutron backscattering processes**--interactions between incident neutrons and, for example, shielding material, in which secondary particles are produced which can be more dangerous to living tissue than the original neutrons themselves.

**Nucleon**--a proton or neutron, esp. as part of an atomic nucleus.

**Packet switched**--process by which information is formatted and packed for switching in a communications network.

**Permafrost**--permanently frozen subsoil.

**Petrology**--the study of the origin, composition, structure, and alteration of rocks.

**Phobos maneuvering unit**--a device used to transport crew members across the surface of the martian moon Phobos.

**Photovoltaic**--capable of producing a voltage when exposed to sunlight.

**Portable life support system**--a life support system that is part of an extravehicular mobility unit.

**Pre-breathing**--a period of time before EVA in which an astronaut adjusts to the difference between habitat and suit pressures.

**Rad**--a unit of energy absorbed from ionizing radiation, equal to 100 ergs per gram of irradiated material.

**Range safety**--primarily regulatory measures used to insure the safety and well being of worker and management personnel in the vicinity of spaceport.

**Regenerable**--used in this case to denote the ability of a life support system to recover and reuse gasses and liquids (such as oxygen and water), reducing or eliminating the need for resupply of these items.

**Regolith**--the layer of loose rock material resting on bedrock, making up the surface of most land.

**Rem**--roentgen equivalent man, the amount of radiation that results in a biological effect equivalent to 1 rad of X radiation.

**RF cavity**--shaped metallic waveguide to operate in the microwave radio frequency (RF) range.

**Roll former**--a metal forming device which can take coiled stock material, conveniently packaged for transportation, and bend or "form" it into useful shapes.

**RTG**--radioisotope thermoelectric generator, an extremely long-lived, reliable electric power sourced used mainly in spacecraft applications.

**Rutile**--the lustrous red, reddish-brown, or black natural form of titanium dioxide, $TiO_2$.

**Segment I navigation**--Earth-based navigation system similar to current Earth-based planetary systems.

**Segment II navigation**--on-board navigation for real-time navigation during critical operations, e.g.; aerocapture, and long-range rover missions.

**Segment III navigation**--Mars-based network navigation system employing beacons/transponders and, ultimately, GPS-type navigation satellites.

**Single phased pumped water loop**--a thermal control subsystem consisting of water-bearing pipes in which the water does not undergo a phase change between the high temperature heat acquisition area and the lower temperature heat rejection area.

**Sintering**--welding together by heating without melting.

**Solar wind**--plasma (mostly protons and electrons) ejected at high speeds from the sun's surface.

**Solar particle event**--an explosion of the Sun's chromosphere resulting in the expulsion of high-energy protons; commonly called a solar flare.

**Solar absorptivity**--the ratio of solar radiation absorbed to the amount incident on a body.

**Stationary power**--those power sources that are used by fixed facilities such as radio stations, habitats, or laboratories.

**Subsystem**--a major functional system that performs a specific operation for an element. Life support systems and thermal control systems are examples of subsystems.

**Super critical water oxidation**--a process which converts organic waste material to carbon dioxide and water.

**Tailings**--refuse remaining from a process such as distilling or milling.

**Taxonomy**--terminology used to define the hierarchy of terms used in an architecture. For example, a subsystem is defined as a part of an element in the PSS architecture.

**Technical paybacks**--benefits gained as a result of selecting a particular methodology or option over other methodologies or options.

**Telemetry restoration**--process or method used (hardware and software) to restore telemetry link and recover information.

**Telerobotic operations**--telerobotic operations is defined as all activities that are performed by robots via remote control.

**Telerobotic**--remote controllable, with some level of on-board intelligence for hazard recognition, autonomous action, etc.

**Three-drum slusher**--a stationary mining system which consists of three pylon supported cables from which a scoop is suspended and dragged across the surface.

**Transceiver**--a module composed of a radio receiver and transmitter.

**Trunk transmission**--primary link(s) used for transmission of information between the command center and a long distance media such as a microwave or satellite system.

**User accommodations**--the functional area relating to the scientific experiments to be conducted on the planetary surface.

**User**--any group or individual who uses space elements or space environs associated with the execution of an exploration initiative for scientific, technology development, or commercial application objectives.

**Utilization phase**--the third of three phases in the evolution of a lunar or martian base. During this phase, base development is curtailed, while experimentation and in situ resource utilization activities increase. Dependence on Earth support is minimal.

**Virtual circuits**--allows one physical space channel to be shared among multiple traffic schemes, each of which may have different service requirements.

**Volatiles**--chemical elements such as C, H, N, etc. which evaporate at low temperatures (compared to metals) and are severely depleted in lunar rocks and soil.

**wide area network**--network used to link several users over a distributed communications system.

**Wing jacket**--a simple jack mechanism with a tall extension: used i this case to lift a payload so that the lander can be dragged from underneath and replaced by a transporter.

**X-band**--a band of frequencies used for communication and navigation which falls in the range 5.2 to 10.9 GHz.

**Zenith angle**--the angle between a direction of interest and the local vertical.

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16. Abstract

The Office of Exploration (OEXP) at NASA Headquarters has been tasked with defining and recommending alternatives for an early 1990's national decision on a focused program of human exploration of the solar system. The Mission Analysis and System Engineering (MASE) group, which is managed by the Exploration Studies Office at the Lyndon B. Johnson Space Center, is responsible for coordinating the technical studies necessary for accomplishing such a task. This technical report, produced by the MASE, describes the process that has been developed in a "case study" approach. The three case studies that were developed in FY 1989 include:
1. Lunar Evolution Case Study, 2. Mars Evolution Case Study, 3. Mars Expedition Case Study. The final outcome of this effort is a set of programmatic and technical conclusions and recommendations for the following year's work.

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